Space Based PNT Technical Concepts

1 Introduction

1. This document presents a summary of the Technical Concept Development work carried out under the Space Based PNT Programme (SBPP). It describes the work achieved since the outset of the programme in October 2020 through the initial selection of technical ideas, the identification of the Technical Concepts and the refinement of those Concepts up to the Outline Business Case Product produced in November 2021.

2. The Technical Concept Development work underpins SBPP's assessment of cost, risk, schedule, and performance. Throughout the work, the team has been asked to maximise and maintain a degree of optionality, which has resulted in a broad range of possible technical approaches to deliver a UK Space-based PNT capability.

3. This document describes the outcomes from the work, the services provided, the approach to defining the concepts, a user perspective, an overview of each concept and conclusions. The Annex B of this document provides a slightly more detailed description of each of the final 10 technical concepts.

4. Throughout this document a number of technical terms are used but not necessarily explained in detail. The definitions of these terms are provided in Annex A.

2 Outcomes from Technical Work

5. Considerable technical analysis of each of the concepts was conducted during SBPP. This document does not attempt to present the results of that analysis. The key lessons taken from the Technical work are summarised below:

a. **Performance** – space-based PNT (SB-PNT) performance comparable to or better than extant systems can be achieved, or traded off against other features such as resilience or cost.

b. **International Regulations** – Radio Frequency selection is heavily constrained and central to system viability / user experience.

c. **LEO Concepts**[1] – These are broadly viable provided that further work is conducted to manage the associated complexity and technical risk in the delivery of LEO-based approaches. Specialised antenna designs will be needed for systems working from Low Earth Orbit.

d. **Regional vs Global** – Regional PNT is only marginally less costly / complex than global PNT for a nation at the UK's latitude.

e. **Resilience –** The resilience of the service is more heavily influenced by the signal design and the signal power than it is by the choice of orbit or system architecture. This is taken on the assumption that the most significant threats are jamming and/or spoofing of the signal.

f. **Cryptography** – Cryptographic equipment capable of maintaining security in a Quantum-computing context will be required.

g. **Diversity** – Space Based PNT can only be fundamentally delivered through a limited number of methods (either "Time of Arrival" or "Doppler based ranging"). However, there is still a range of diversity in the way that the service is technically achieved – which is demonstrated through the 10 concepts presented.

h. **Risk** – All Technical Concepts have associated technical and programmatic risk. This is understandable, as Space based PNT is a complex endeavour. Some concepts clearly

[1] Note that SBPP did not examine in detail the concept of delivering PNT from a commercial LEO communications constellation as it is impossible to estimate the cost of of PNT delivered by such an approach and the degree to which PNT performance is compromised by the primary communications mission would be a commercial decision for the operator.

have more technical and programmatic risk associated to them due to their complex nature or the use of novel technologies. Having an awareness now of these risks through the work achieved will clearly help future development of space based PNT services.

i. **R&D –** If a spaced based PNT solution is to form part of the UK system of systems for resilient PNT then a national programme of SB-PNT technology research and development is strongly recommended.

6. A customer-endorsed set of SMART mission objectives are necessary in order to develop, optimise and evaluate technical concepts to greater detail. In particular, the overarching goal of improved 'resilience' needs refinement, based on constructive dialogue with a pro-active customer / sponsor and user representatives. This will then allow SBPP to set use cases and mission requirements which respond to a commonly recognised risk appetite and gap analysis.

3 Services Provided

7. Throughout this document there are references to three core services and an optional service. These services are primarily used as a framework for analysis of the concepts and are not part of any government endorsed requirement. The number and nature of services for any UK space based PNT service needs to be defined by clearly identified and endorsed user requirements. The services referred to in this document are:

a. **Open Service (OS).** A service which is accessible to all and does not have an encrypted ranging signal. The signal may include a form of navigation message authentication (digital signature).

b. **Government Authorised User Service (GAUS).** A service provided specifically for UK Critical National Infrastructure and potentially offered to other nations for their critical national infrastructure. It is expected that the signal would be encrypted using commercial grade encryption to prevent spoofing and the signal characteristics designed to enhance protection against jamming and increase positioning performance compared to the open service. Access to the service will be controlled and the service will trade levels of assurance against performance for user groups with differing levels of security need and capability.

c. **Encrypted Service (ES).** This service is targeted at UK military and national security users and may be offered to UK Allies. The service will encrypt the ranging code with high grade UK accredited encryption. The signal characteristics will have enhanced properties to protect against jamming and meet the needs of military users. Reversionary modes will be made available under UK sovereign control that will enhance capability during conflict and other times of emergency.

d. **Alerting Service.** The alerting service is optional. This provides short form alert messages to users via the signals broadcast from the PNT satellites. These can be received by devices that include a UK PNT receiver such as mobile phones and can alert users anywhere on the globe to local threats such as natural disasters or terrorist attacks even when local communications are not available.

8. All services are expected to be global. Not all the technical concepts can offer all these services. The services that are provided by a concept are listed in the concept descriptions.

Working Assumptions

9. For the purposes of supporting analysis and allowing an assessment of resilience and performance, working assumptions for the signal definitions for each service and concept have been made and are captured in a Signal Definition and Characterisation technical note. These working assumptions are summarised as follows:

a. Signals broadcast from satellites in LEO that use conventional Time of Arrival (ToA) techniques include:

i. An OS signal that is similar to existing GNSS open signals with slightly better performance and more power than for GPS CA code and a simple signal structure that is readily adopted by receiver manufacturers.

ii. A GAUS signal that has 10 times more power than current open signals and has signal characteristics that enhance robustness to jamming and interference whilst providing superior positioning performance to the OS.

iii. An ES that has signal characteristics that are compatible with current military use cases and scenarios, provide enhanced positioning performance and can be boosted by a factor of 10 for areas of conflict or in times of emergency.

b. Signals broadcast from MEO that use conventional ToA techniques have the same OS signal and:

i. A GAUS signal that has the same signal characteristics as for LEO GAUS except that it is the same power level as the OS signal and can be boosted by up to 2.5 times in times of national emergency.

ii. An ES signal that has the same signal characteristics as for LEO ES signal but can only be boosted by a factor of 2.5.

c. Signals broadcast from GEO have the same characteristics as those from MEO except that both GAUS and ES can be supplemented by a high-power spot beam with 10 times the nominal power of the GAUS and ES signals.

d. Concept 9 uses a narrowband signal that has higher raw signal power, but by virtue of the fact that is narrowband is more easily jammed than the signals specified for all other concepts except Concept 10.

e. Concept 10 uses signals broadcast from existing communications satellite in LEO. These are generally more easily jammed than GNSS signals.

10. With the exception of the signal for Concept 9 each service will provide signals in multiple frequency bands. For example, the OS for ToA concepts will be provided in both the L1 band and the L5b band.

4 Technical Concept Definition - Context

11. The main phases of the Technical Concept Development work since the outset of the SBPP programme are illustrated in the figure below.

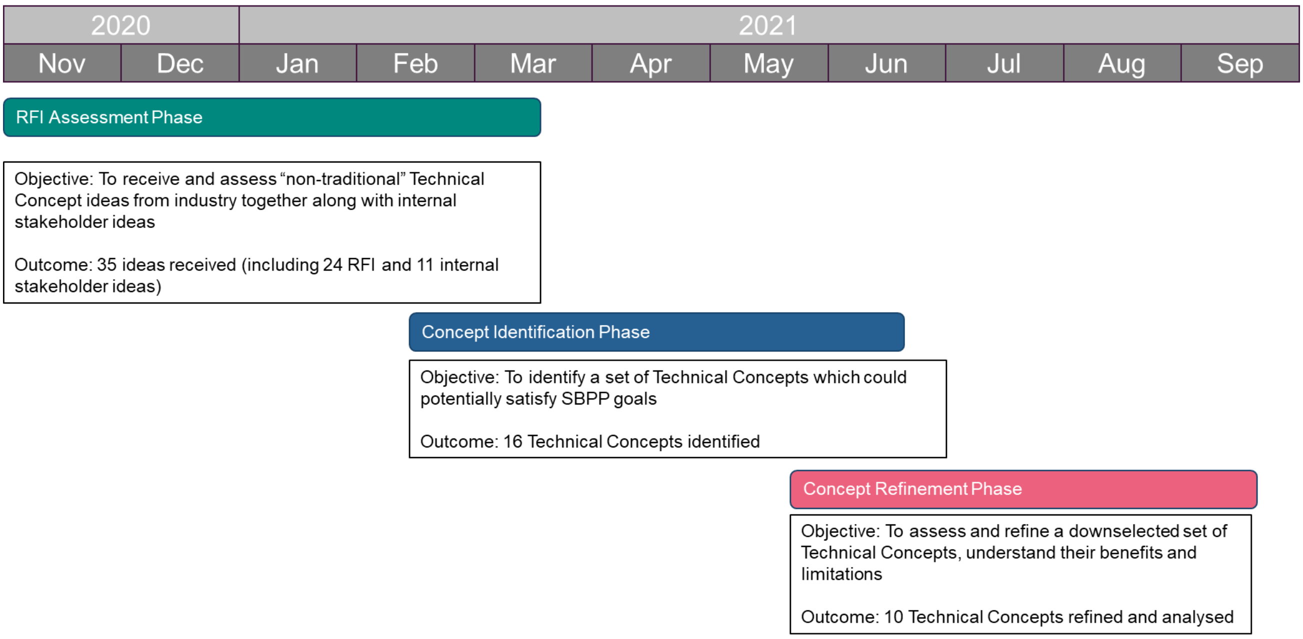


Figure 1 – Technical Concept Definition – Main Phases

12. During the initial phase (RFI assessment) a set of "non-traditional" Technical approaches (i.e. unlike established concepts such as GPS and Galileo) were received from industry/academia and these were assessed together with internally generated stakeholder ideas. The programme received 20 RFI responses from industry containing 24 ideas, and together with 11 stakeholder ideas this resulted in 35 technical ideas.

13. Following assessment, a total of 16 distinct technical Concepts were identified and analysed during the Concept Identification Phase. Following further assessment and governance approval, 10 principal concepts were taken forward which were explored during the Concept Refinement phase, through the support of an industrial Expert Support Team.

14. A set of technical documentation has been generated throughout the activity and this is illustrated below.

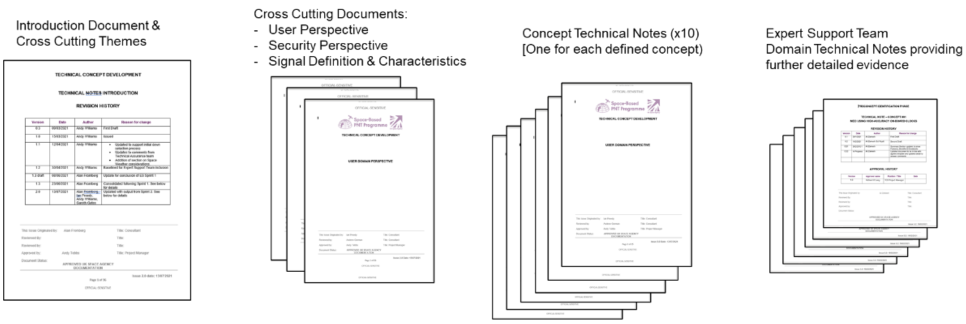


Figure 2 – Technical Documentation

5 User Domain Perspective

15. The User Domain has been an important part of the Technical Concept development activities with a User Strategy defined and endorsed by the programme and a separate Technical Note discussing the technical concepts from a user perspective.

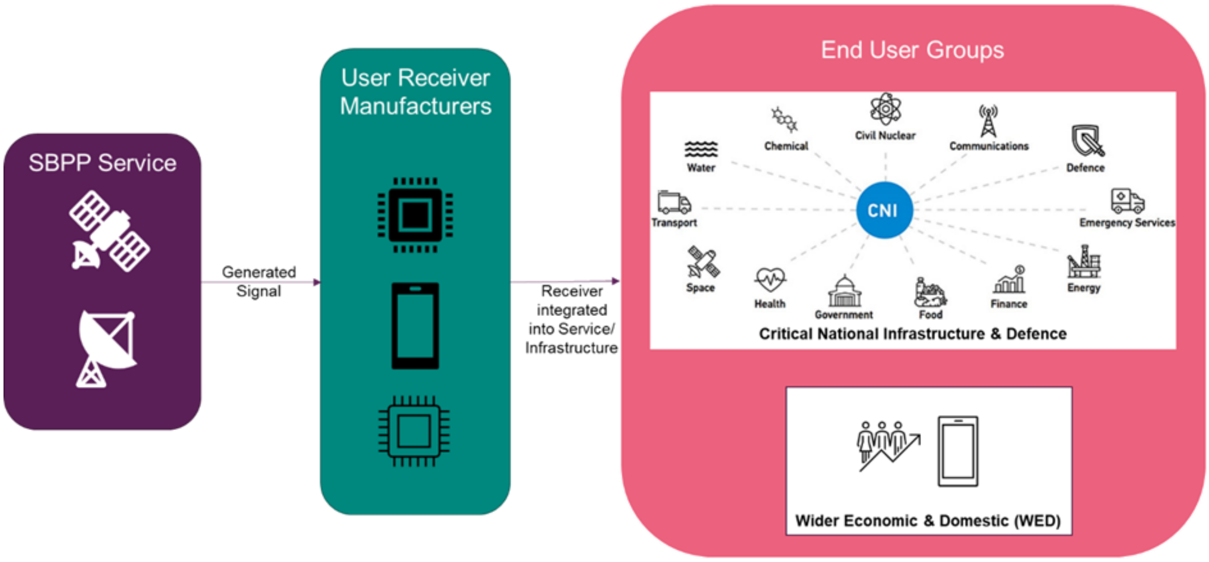


Figure 3 – User Perspective - The User Receiver Manufacturers are the key user of the actual SBPP signal

16. The end-user groups have been defined as Critical National Infrastructure (including Defence) and Wider Economic & Domestic (WED) – i.e. public users. From a signal perspective the user is the User Receiver Manufacturer. The user receiver is the primary communication device with the space based PNT service and is integrated into whichever infrastructure the PNT service is supporting (be it for example; a tank, ambulance or mobile phone). The adoption of a UK space based PNT service by user receiver manufacturers into their PNT equipment is crucial to success. There are different ways that this can be achieved, including implementing signal choices that ease integration for the manufacturer; provide significant benefits to user receiver market growth; or incentivise through government-sponsored initiatives.

17. The user domain key observations related to interoperability, supplier appetite and UK manufacturing base.

18. Interoperability is greatly increased for all concepts by maintaining L-Band frequencies. However, the more complex and distinct from extant GNSS a concept is the more impact was perceived on user equipment and ability to meet mass market uptake. This is in tension with ‘diversity’ for resilience, which would favour use of new frequencies.

19. The drive for supplier appetite to fund R&D activities along with integration into mass market devices reduces in line with this increase in concept complexity. The UK manufacturing base is relatively weak in the mass market areas relating to the Open Signal but much stronger for GAUS and ES. The need for front-loaded Government investment into R&D, de-risking, prototyping and test receivers is seen as essential to the success of the wider program.

20. A User Domain Perspective Technical Note was produced in the SBPP which provides context of the technical concept development work through the lens of the user domain. It includes:

a. User Domain Market analysis and details of the potential types of Services that could be offered (including Open Service (OS), Government Assured User Service (GAUS), Encrypted Service (ES) and an Alerting service).

b. Relationship between potential services offered and key CNI sectors.

c. Presentation of defined Use Cases and their relationship to the services offered.

d. Analysis of the main user segment design features, including consideration of Size, Weight, Power and Cost of User Receiver Equipment.

e. Cost & Schedule Analysis with respect to User equipment.

f. Supplier Analysis (User Receiver Manufacturers).

21. The degree to which uptake of an open signal by the general public is necessary for programme objectives to be met will significantly influence eventual system design.

6 Overview of Technical Concepts

22. The Technical concepts are presented below. Initially 16 main technical concepts were identified, and this was reduced during the programme to 10 primary Technical Concepts which were analysed and refined further. A high-level summary of these 10 concepts is presented below. Further details of the Concepts can be found in Annex B. The figure below illustrates the concepts.

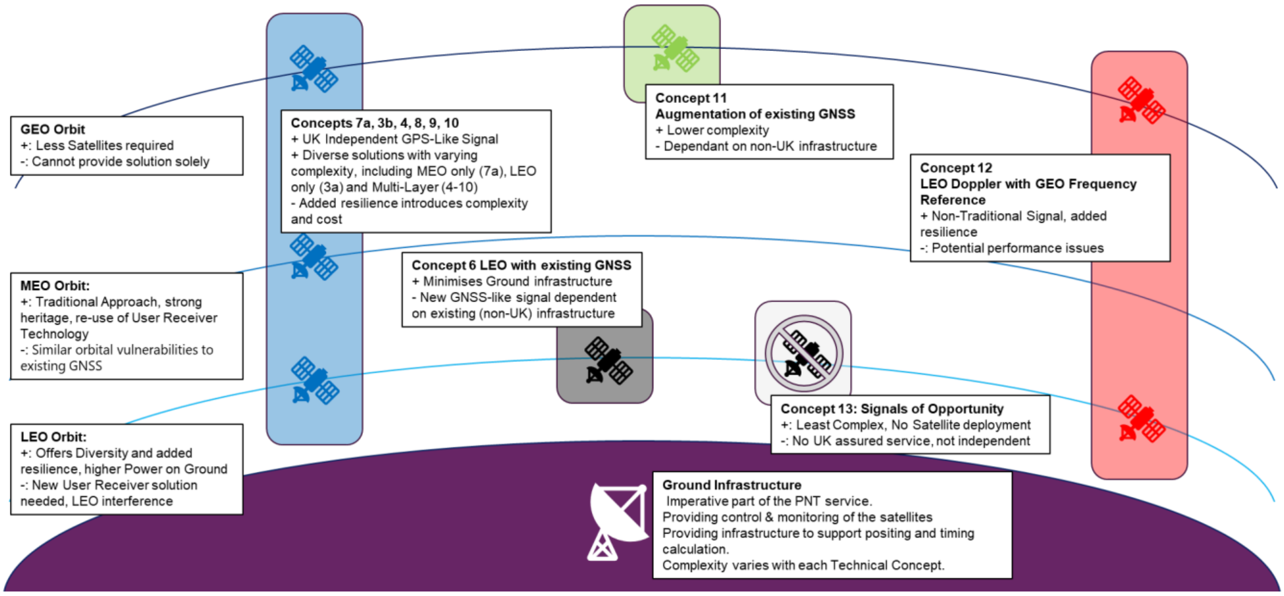


Figure 4 – The Technical Concepts: An overview from a signal perspective

23. The 10 baseline Technical Concepts are summarised in the table below. Note that the shaded concepts are those that have been removed through the down-selection process.

24.

Concept ID	Description	Rational for Approach
1	LEO using Low-Cost Clock (with Auto-Nav)	LEO ToA solution where Orbit determination and time synchronisation is calculated onboard the satellite
2	LEO using Timing from GEO In-Orbit Clocks	LEO ToA solution where the navigation message content is communicated to the LEO satellites via a GEO satellite
3	LEO based on Existing GNSS	LEO ToA solution where orbit determination and time synchronisation is achieved using signals from existing MEO GNSS
4	MEO using High-Accuracy On-Board Clocks with Autonav	MEO ToA solution where Orbit determination and time synchronisation is calculated onboard the satellite
5	Multi-Layer GSO / LEO	Hybrid ToA solution with ranging signals from both LEO and IGSO satellites
6	Multi-Layer GSO / MEO	Hybrid ToA solution with ranging signals from both MEO and IGSO satellites
7	Multi-Layer MEO / LEO	Hybrid ToA solution with ranging signals from both MEO and LEO satellites, with the LEO satellites deriving their orbit and time from the MEO satellites.
8	GSO Space-Based Augmentation to Existing GNSS	GSO satellites providing additional information to improve resilience and accuracy of existing GNSS
9	LEO Doppler-Based Ranging with GEO Frequency Reference	LEO Doppler solution with a frequency standard provided by GEO spacecraft
10	Signals of Opportunity	A system exploiting signals from non-GNSS satellites to calculate a Doppler PNT solution

Figure 5 – Summary of Technical Concepts

25. The following subsections presents each of the current 10 concepts under consideration with a short narrative description of the concepts and table providing a summary of the characteristics of each concept under seven headings:

a. **Performance**: The performance of the system compared to existing “traditional” Space based solution such as GPS.

b. **Advantage**: The UK operational advantage compared to the status quo.

c. **Resilience**: The foreseen resilience of the solution.

d. **Schedule**: The programmatic schedule considering the development of the concept.

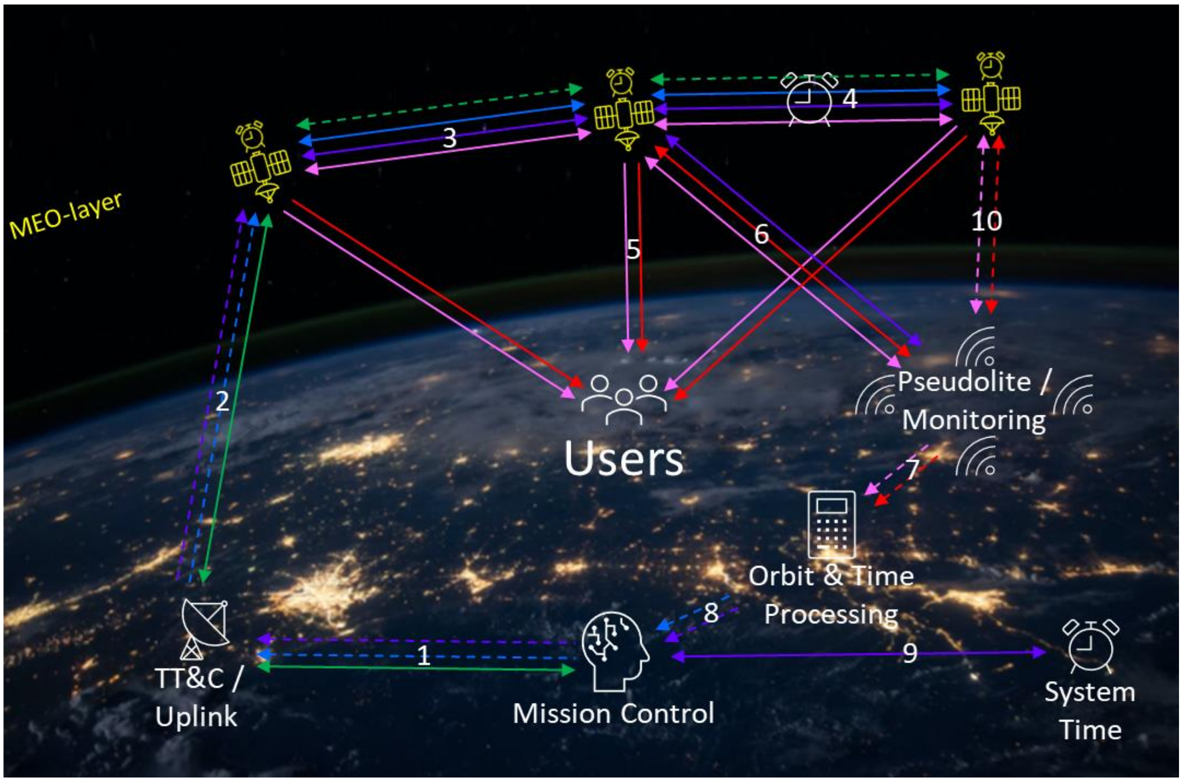
e. **User and Value**: The foreseen benefit to the User domain considering the added value to the User.

f. **Risk to Deliverability**: The programmatic risk to the deliverability of the solution.

g. **System Security**: The security implications of the concept considering the system architecture.

26. The concepts are presented below in a logical sequence reflecting an increasing level of divergence from conventional GNSS time of arrival (ToA) services. The concept numbers are retained in each heading as a shorthand for referencing each concept.

1.6.1 MEO Constellation with Auto-Navigation (Concept 4)



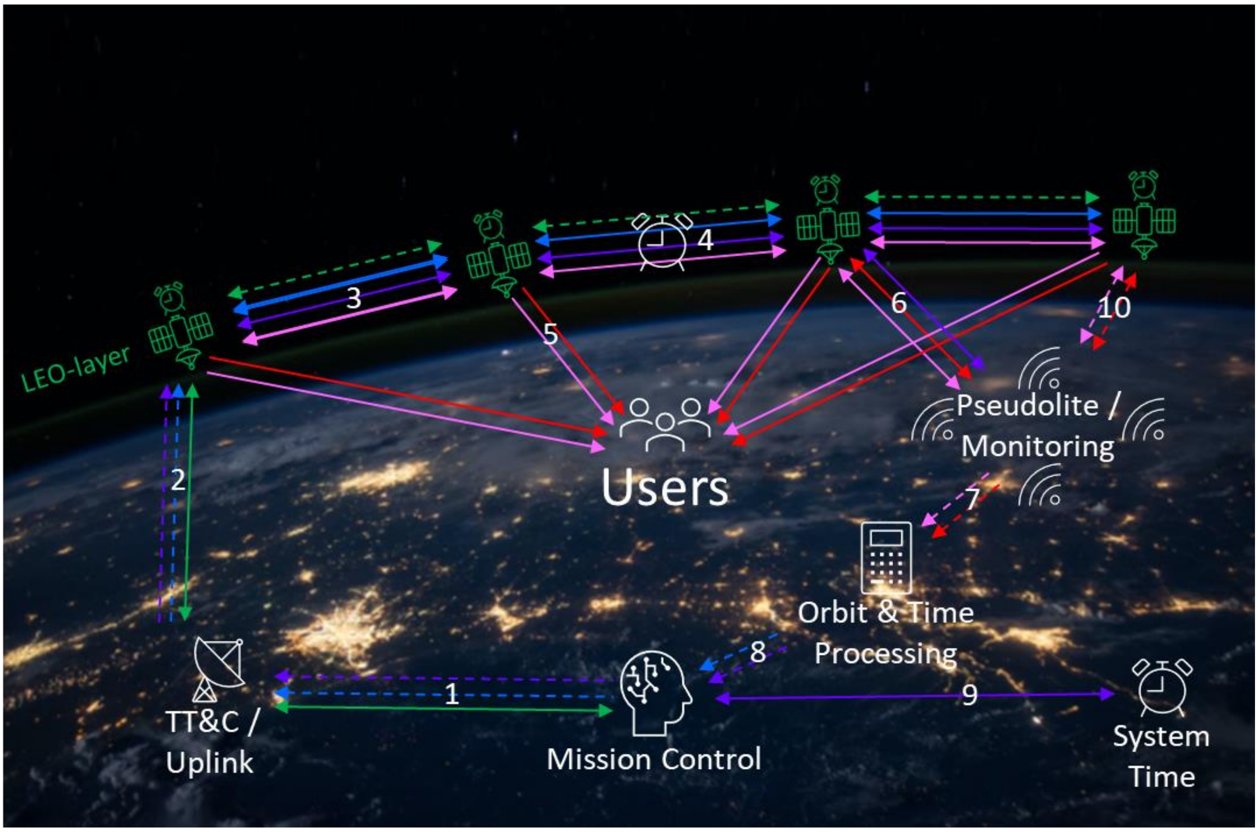
27. This concept is a constellation of 24 satellites in an orbit with an altitude of 21500km. Each satellite exploits Auto-navigation principles to reduce the level of monitoring and communication required from the ground by computing the navigation solution more autonomously in-orbit. Auto-navigation is a principle by which space-based PNT constellations autonomously determine their own positioning and time synchronisation, with minimal ground intervention, using Inter-Satellite Links (ISL). Individual satellites contain redundant atomic clocks and utilise 7 pseudolites on the ground to maintain an offset from ground derived system time and a terrestrial reference frame. A further 25 monitoring stations would be needed were an Integrity service to be implemented. It offers a fully global PNT service, independent of other GNSS systems, and can support OS, GAUS and ES user groups individually, as well as providing alerting if desired. Note that the Galileo Public Regulated Service (an encrypted navigation service for governmental EU-authorised users and sensitive applications), as a MEO based concept, could be considered comparable to Concept 7A (without the additional resilience provided by the Autonav feature).

Criterion	Comment
Performance	Service performance similar to existing GNSS and fully independent. Provides OS, ES and GAUS by design, from the LEO satellites to the designated user groups. Alerting Service could be provided.
Advantage to the UK	Autonav allows for simplified operations for UK operators. Possibility to revert to traditional a MEO GNSS system if development of autonav technology proves infeasible. An independent system which contributes to freedom of action.
Resilience	ISL allows commanding when MEO satellites are not visible to a ground station and with more secure links than on the ground. Autonav offers holdover capacity if ground segment contact is lost. ES and GAUS signal characteristics offer improved resilience

	Lack of orbit diversity with other GNSS mean that it would be likely to suffer from common cause failures (such as a major space weather event impacting MEO altitudes).
Schedule	Full operational capability (FOC) is expected 8 years after kick-off, driven by long lead procurement of atomic clocks. No obvious initial operational capability since all planes needed to provide service.
User & Value	By using L-band frequencies used by other GNSSs the current user devices will not require significant hardware changes and only need software/firmware re-configuration.
Risk to deliverability	MEO constellation brings with it a strong heritage especially regarding PNT applications making it the lowest risk development option amongst the Time of Arrival concepts. Introduction of auto-navigation and intersatellite links increases the risk of delays in payload development and in orbit validation. High accuracy clock used on board each spacecraft need to be procured from outside the UK with potentially extended lead times.
System Security	Autonav and ISLs allow some of the security implications to be moved from the ground segment to the space segment offering improved security.

Table 1 – Concept 7A Summary

1.6.2 LEO Constellation with Auto-Navigation (Concept 1)



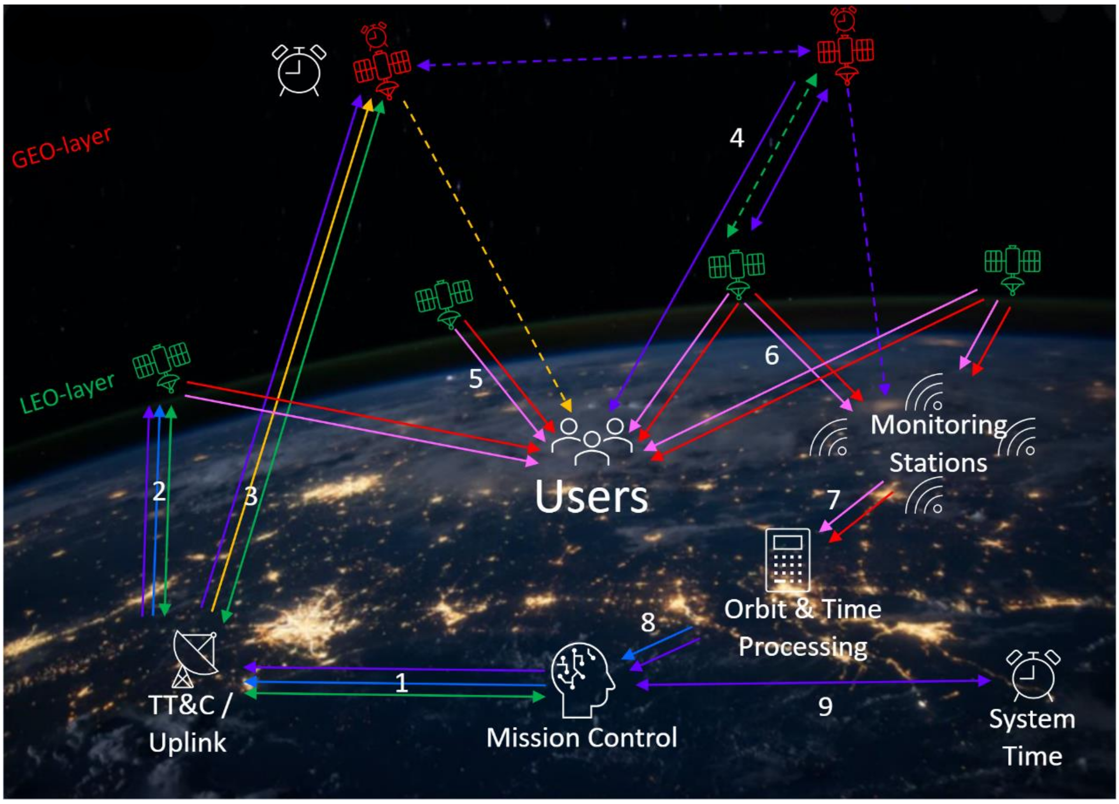
28. This concept is a constellation of 208 satellites in a 1200km altitude orbit. Individual satellites contain relatively low performance low-cost clocks. Each satellite exploits Auto-navigation principles in the same fashion as the Concept above, with 7 pseudolites, but the lower orbit, larger number of satellites and reduced clock stability makes an auto-navigation solution far more demanding to develop than at MEO. A further 25 monitoring stations would be needed were an Integrity service to be implemented. The lower altitude also requires a more complex antenna design to maintain relatively constant power on ground. It offers a fully global PNT service, independent of other GNSS systems, and can support OS, GAUS and ES user groups individually, as well as providing alerting if desired.

Criterion	Comment
Performance	LEO constellation designed to provide service performance similar to existing GNSS and fully independent. Provides OS, ES and GAUS by design, from the LEO satellites to the designated user groups. Alerting Service could be provided.
Advantage to the UK	Independent GNSS providing signals from LEO. Potential to deliver higher power on ground over a small footprint region of concern, due to lower altitude, subject to ITU regulation. Autonav allows for simplified operations for UK operators. Very large ground segment both for uplink and monitoring would be required in order to revert to traditional GNSS orbit determination if autonav or ISL technology proves infeasible. Independent system contributes to freedom of action.
Resilience	ISL allows commanding when LEO satellites are not visible to a ground station and with more secure links than on the ground. Autonav offers holdover capacity if ground segment contact is lost. ES and GAUS signal characteristics offer improved resilience especially from LEO

	Using the LEO Orbit presents a different geometry to users, which may mitigate multi-path interference and improve convergence. It may provide better resilience against space weather and external factors which could affect all MEO constellations.
Schedule	FOC is expected 8 years after kick-off. Assumes that pre-developments are initiated early on including the navigation antenna (est. 4 years), Inter-satellite links (est. 1.5 years) and AutoNavigation processor (est 2.5 years). Possibility to declare initial capability with degraded performance once 50% launched.
User & Value	User equipment modifications may be needed to cope with the increased Doppler. More frequent handover between satellites increases complexity and slightly increases power consumption in the receiver.
Risk to deliverability	Novelty of navigation antenna and introduction of auto-navigation and intersatellite links increases the risk of delays in payload development and in orbit validation. Production capacity may need to be developed to deliver satellites at desired rate or price. In orbit validation could identify major design changes delaying FOC. Variations in LEO satellite lifetime might lead to more expensive replenishment approach.
System Security	Some of the security implications can be moved from the ground segment to the space segment due to the level of autonomy onboard.

Table 2 – Concept 1 Summary

1.6.3 LEO with High Accuracy In-Orbit Clocks in GEO (Concept 2)



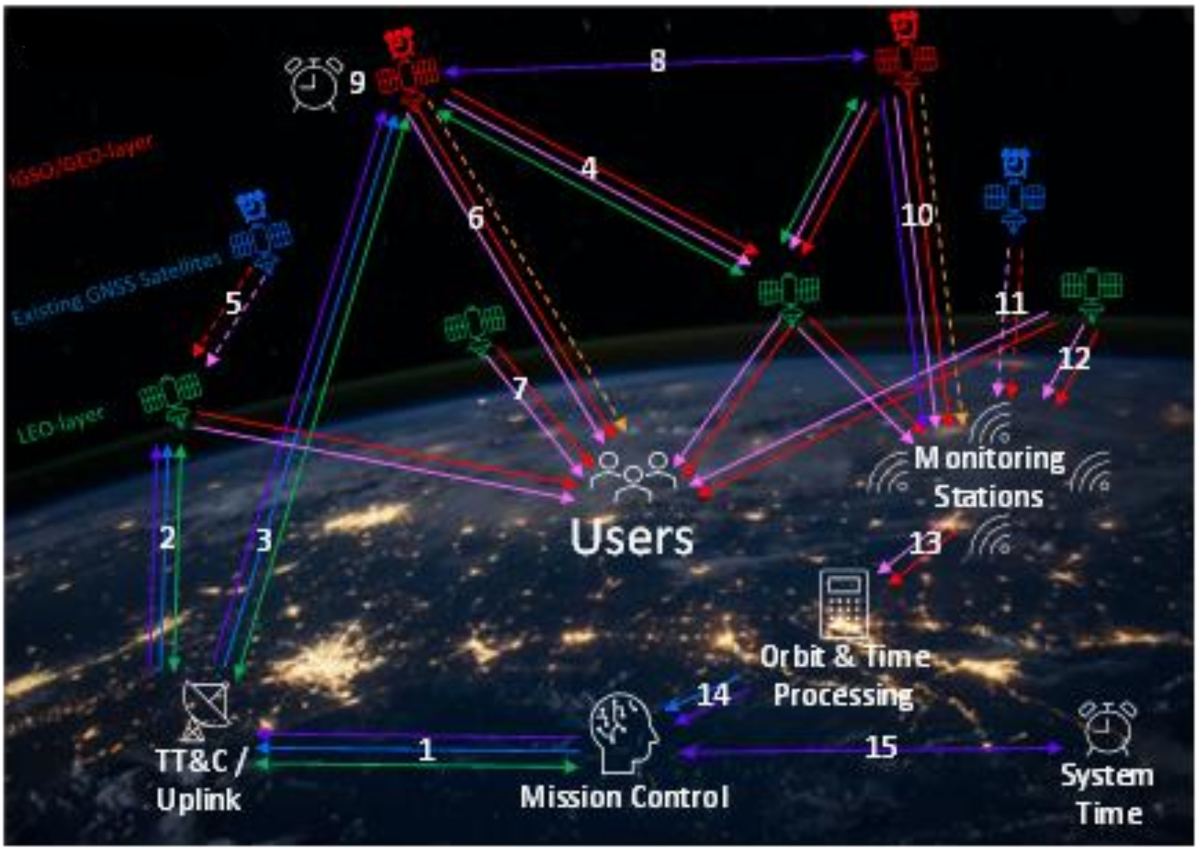
29. This concept is a constellation of 168 satellites in a 1200km altitude orbit combined with 6 payloads hosted on geostationary satellites. GEO payloads include redundant atomic clocks and broadcast a complete PNT signal. Individual LEO satellites contain relatively low performance clocks which are regularly updated from GEO. A conventional Orbit determination and timing synchronisation with redundant control facilities & 48 monitoring stations on the ground generates the navigation messages. These are communicated to the LEO layer via seven single head TT&C stations and the GEO layer ensuring that the age of data remains low. The LEO altitude requires a more complex antenna design to maintain relatively constant power on ground, similar to concept 1. This concept offers a fully global PNT service, independent of other GNSS systems, and can support OS, GAUS and ES user groups individually, as well as providing alerting if desired.

Criterion	Comment
Performance	Hybrid LEO/GEO constellation designed to provide service performance similar to existing GNSS and fully independent. Reduced performance at high latitude, especially in the vertical dimension. Performance could be impacted by manoeuvres initiated by the GEO host platform. Provides OS, ES and GAUS by design, from the LEO satellites to the designated user groups. Alerting Service could be provided.
Advantage to the UK	Potential to deliver higher power on ground over a small footprint region of concern, due to lower altitude, subject to ITU regulation. Dedicated monitoring station functionality will be needed for accurate Georanging in up to 48 monitoring stations. Hosted payload and single point failure limits freedom of action.
Resilience	Communication via the GEO layer provides regular updates to the LEO layer without the need for multiple uplink stations. ES and GAUS signal characteristics offer improved resilience especially from LEO

	In the current configuration LEO layer depends upon GEO for timing and ephemerides so no significant orbital diversity benefit is achieved.
Schedule	FOC is expected 8 years after kick-off. Assumes that pre-developments are initiated early on including the navigation antenna (est. 4 years) and Inter-satellite links (est. 1.5 years) Potential for initial operating capability delivering timing service from the GEO layer as soon as the hosted payload is launched.
User & Value	User equipment modifications may be needed to cope with the increased Doppler. Ephemeris delivery from GEO should partially mitigate the receiver power consumption issue of Concept 1.
Risk to deliverability	Novelty of navigation antenna and intersatellite links increases the risk of delays in payload development and in orbit validation. Production capacity may need to be developed to deliver satellites at desired rate or price. Host GEO platform lifecycle may not be compatible with navigation payload. Variations in LEO satellite lifetime might lead to more expensive replenishment approach. Ground segment development and/or deployment could take longer than expected, due to the number and geographical distribution of monitoring stations needed and the associated access agreements / issues
System Security	ISLs allow some of the security implications to be moved from the ground segment to the space segment offering improved security of telecommand and telemetry. The large monitoring network needed to generate the navigation solution introduces some vulnerability, particularly if they cannot all be located in friendly territory.

Table 3 – Concept 2 Summary

1.6.4 Multi-Layered Inclined GEO Synchronous Orbit (IGSO) & LEO (Concept 5)



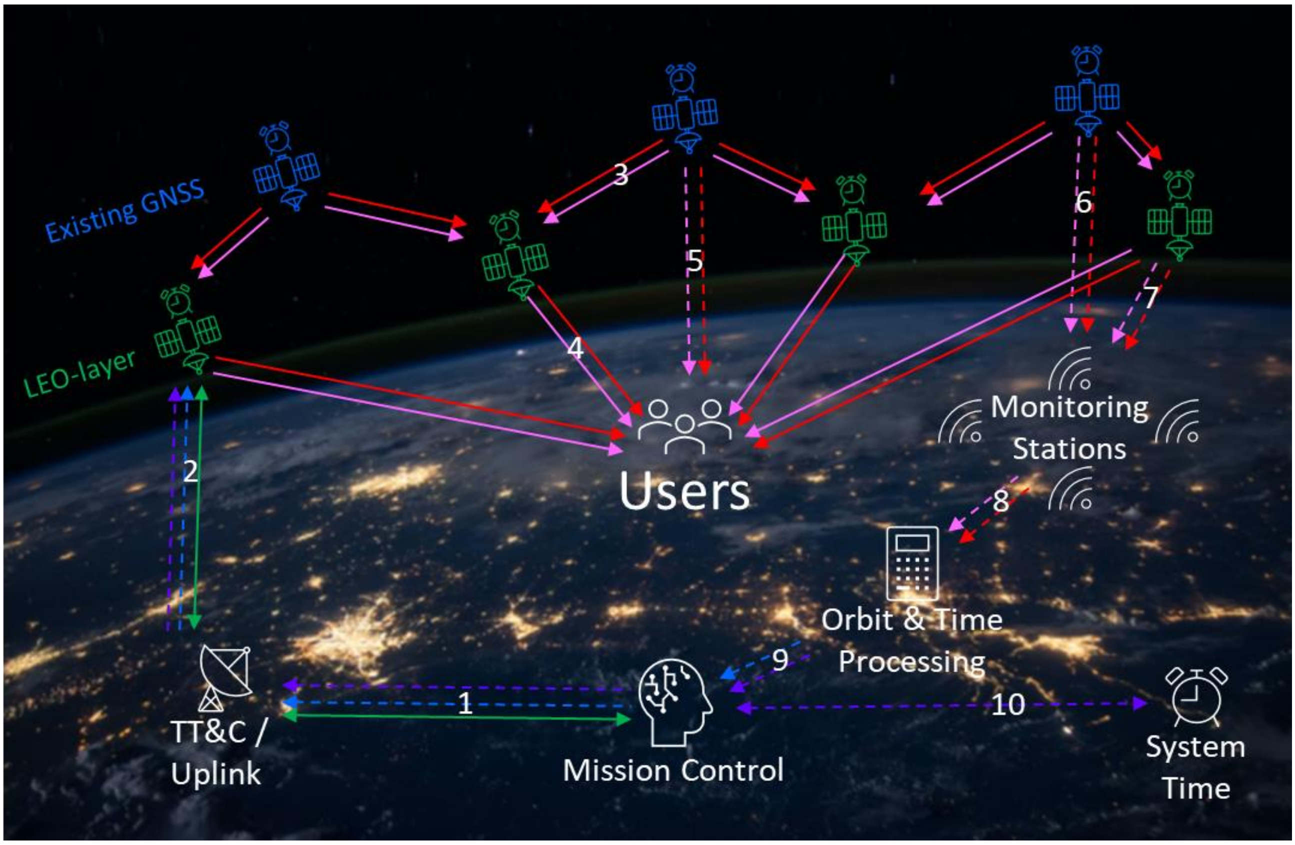
30. This concept is a constellation of 80 satellites in a 1200km altitude orbit and nine dedicated satellites in IGSO. IGSO payloads include redundant atomic clocks and broadcast a complete PNT signal. Individual LEO satellites contain relatively low performance clocks which are regularly updated from IGSO. A conventional orbit determination and timing synchronisation with redundant control facilities & 12 monitoring stations on the ground generates the navigation messages for the

IGSO layer. These are communicated to the LEO layer via six single head TT&C stations and the GEO layer (for relay) ensuring that the Age of data remains low. System time offsets will need to be maintained for each of the IGSO satellites, whilst 2-way ISLs will be used to compute LEO clock offset and a Kalman filtering approach similar to Autonavigation will be used to compute a PNT solution within the LEO layer. A further 20 monitoring stations would be needed were an Integrity service to be implemented. The LEO altitude requires a more complex antenna design to maintain relatively constant power on ground, like previous concepts. This concept offers a fully global PNT service, independent of other GNSS systems, and can support OS, GAUS and ES user groups individually, as well as providing alerting if desired.

Criterion	Comment
Performance	Hybrid LEO/IGSO constellation designed to provide service performance similar to existing GNSS and fully independent. Improved performance at high latitude, offset by lower equatorial positioning performance. Provides OS, ES and GAUS by design, from the LEO satellites to the designated user groups. Alerting Service could be provided.
Advantage to the UK	Potential to deliver higher power on ground over a small footprint region of concern, due to lower altitude, subject to ITU regulation. An independent system which contributes to freedom of action.
Resilience	Communication via the IGSO layer provides regular updates to the LEO layer without the need for multiple uplink stations. ES and GAUS signal characteristics offer improved resilience especially from LEO In the current configuration LEO layer depends upon IGSO for timing and ephemerides so no significant orbital diversity achieved.
Schedule	FOC is expected 9 years after kick-off, due to the need to develop and deploy a dedicated IGSO spacecraft Assumes that pre-developments are initiated early on including the navigation antenna (est. 4 years) and Inter-satellite links (est. 1.5 years). Potential for initial operating capability delivering timing & augmentation service from the IGSO layer potentially on a regional basis as early as 5 years after kick-off.
User & Value	User equipment modifications may be needed to cope with the increased Doppler. Ephemeris delivery from IGSO should partially mitigate the receiver complexity issue of Concept 1.
Risk to deliverability	Novelty of navigation antenna and intersatellite links increases the risk of delays in payload development and in orbit validation. In orbit validation could identify major design changes delaying FOC. Development of a dedicated IGSO platform takes longer than planned. Variations in LEO satellite lifetime might lead to more expensive replenishment approach.
System Security	ISLs between IGSO and LEO allow some of the security implications to be moved from the ground segment to the space segment offering improved security of telecommand and telemetry. The smaller monitoring network needed to generate the navigation solution, relative to Concept 2, reduces vulnerability, since all can be located in friendly territory.

Table 4 – Concept 5 Summary

1.6.5 LEO Based using other GNSS (Concept 3)



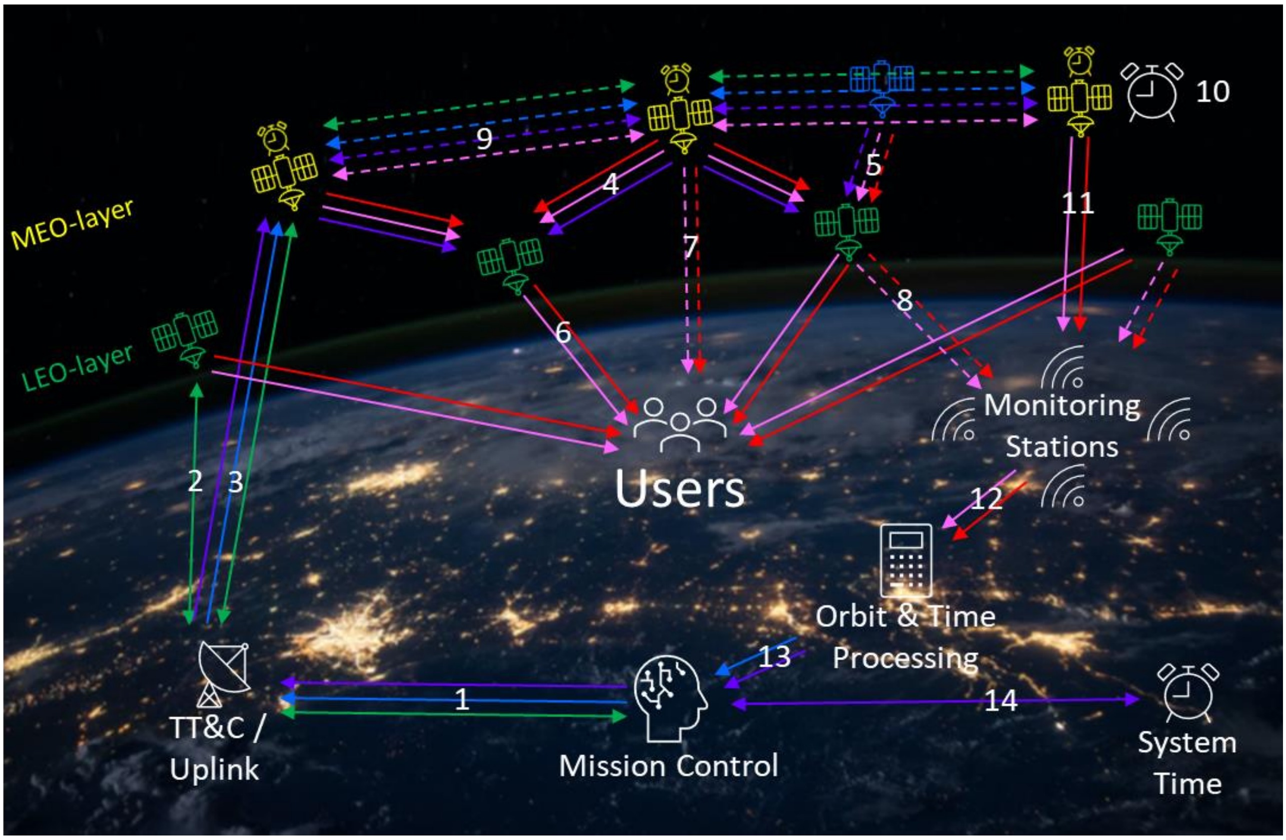
31. This concept is a constellation of 168 satellites in a 1200km altitude orbit. The satellites compute position and time based upon existing (3rd party) GNSS signals in space and contain relatively low performance clocks for holdover purposes, should time not be computable periodically. 32 monitoring stations would be needed were an Integrity service to be implemented but no navigation ground station is strictly required for this service. Seven TT&C stations would be required purely for conventional telecommand and telemetry purposes. The LEO altitude requires a more complex antenna design to maintain relatively constant power on ground. If transmitting in the GNSS spectrum, the satellites would need to toggle between listening and transmitting modes. An onboard computation similar to auto-navigation would be required to predict time and position. This concept offers a fully global PNT service, wholly dependent on other GNSS systems, and can support OS, GAUS and ES user groups individually, as well as providing alerting, although this would increase number of uplink heads and potentially require dedicated stations.

Criterion	Comment
Performance	LEO constellation designed to provide service performance lower than or at best the same as existing GNSS and wholly dependent upon access to those signals. Provides OS, ES and GAUS by design, from the LEO satellites to the designated user groups. Alerting Service could be provided
Advantage to the UK	Potential to deliver higher power on ground over a small footprint region of concern, due to lower altitude, subject to ITU regulation. Lack of two-way communication with other GNSS limits accuracy of PNT computation Lack of control of PNT source limits freedom of action.
Resilience	Limited resilience because it relies on at least one GNSS service providing an open service. ES and GAUS signal characteristics offer improved resilience especially from LEO

Schedule	FOC is expected 5 years after kick-off, due to the relative simplicity of the platform and payload. Assumes that pre-development of the LEO navigation antenna is initiated early (est. 4 years).
User & Value	User equipment modifications may be needed to cope with the increased Doppler. More frequent handover between satellites increases complexity and slightly increases power consumption in the receiver.
Risk to deliverability	Novelty of navigation antenna and local PNT solution computation increases the risk of delays in payload development and in orbit validation. Production line can't deliver satellites at desired rate or price Variations in LEO satellite lifetime might lead to more expensive replenishment approach.
System Security	Ground segment limited to TT&C and alerting service, minimising risk of interference. External reliance introduces challenges to assurance and security agility.

Table 5 – Concept 3 Summary

1.6.6 Multi-Layer MEO & LEO (Concept 7)



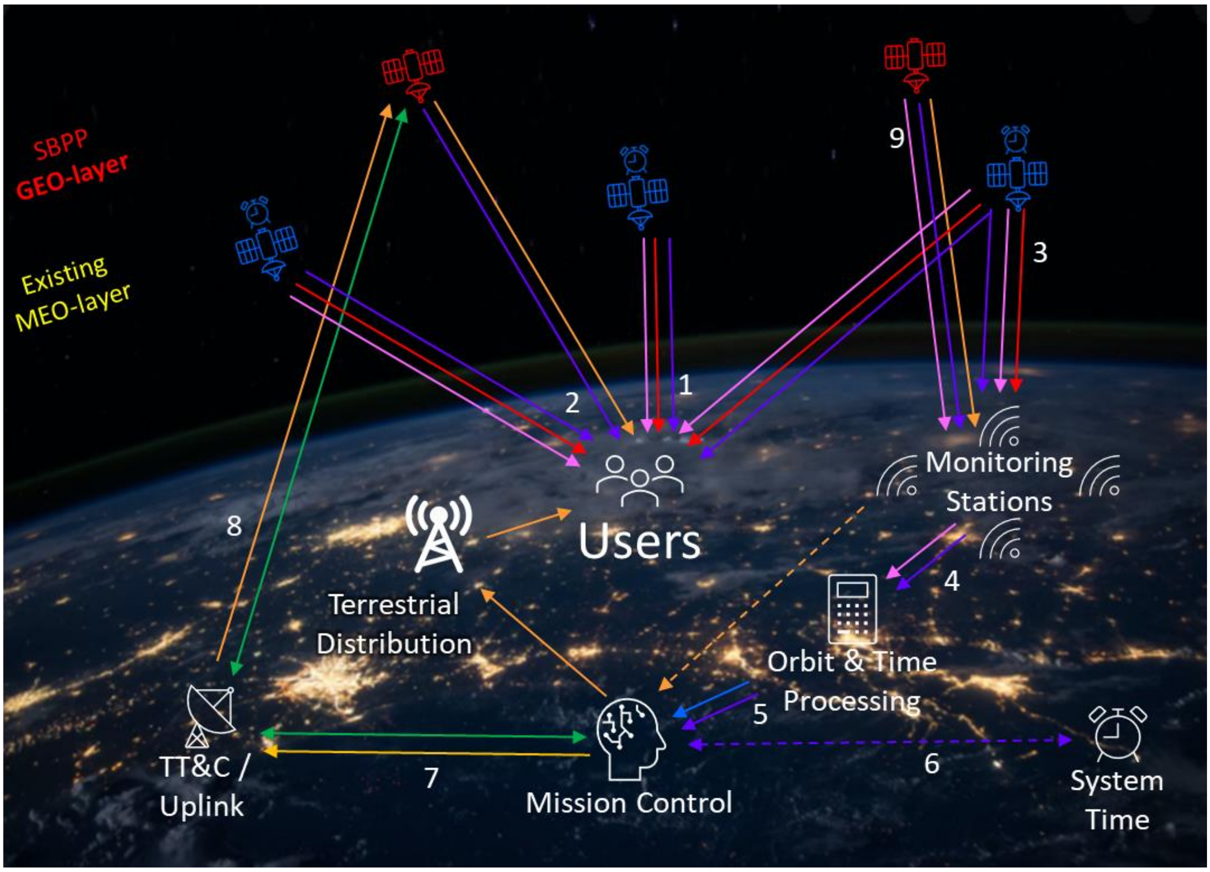
32. This concept effectively substitutes a MEO layer of its own in place of the existing GNSS in Concept 3, to deliver a GNSS signal that is used by the LEO layer to compute PNT. The MEO layer also broadcasts an L-band signal in space that can be used by user receivers. 18 satellites at 21,500 km altitude with redundant high accuracy atomic clocks provide conventional GNSS signals derived from a conventional orbit determination and timing synchronisation with redundant control facilities & 17 monitoring stations on the ground. A further 15 monitoring stations would be needed were an Integrity service to be implemented. A LEO layer of 80 satellites derives its PNT solution from the MEO layer. The LEO altitude requires a more complex antenna design to maintain relatively constant power on ground, similar to previous concepts. A two-way ISL avoids the LEO timing inaccuracy and facilitates continuous transmission from LEO. A Kalman filtering approach similar to Autonavigation will be used to compute a PNT solution within the LEO layer. 5 TT&C stations are required for distribution of the telecommand, telemetry and alert messages to the MEO layer for onward communication to the LEO layer. This concept offers a fully global PNT service, independent of other GNSS systems, and can support OS, GAUS and ES user groups individually, as well as providing alerting if desired.

Criterion	Comment
Performance	The PNT services are transmitted from both layers of satellites, which results in excellent coverage across the globe, with lower PDOP than any other concept. Provides OS, ES and GAUS by design, from the LEO satellites to the designated user groups. Alerting Service could be provided
Advantage to the UK	Potential to deliver higher power on ground from the LEO layer, over a small footprint region of concern, due to lower altitude, subject to ITU regulation. Independent system contributes to freedom of action.
Resilience	Orbital diversity and potential for increased power on ground make this the most resilient option.

	A level of orbital diversity is achieved, since MEO signal would provide a level of service in the absence of the LEO layer and the LEO could revert to Concept 3. ES and GAUS signal characteristics offer improved resilience especially from LEO Dependence upon MEO layer for PNT signal means that it would be likely to suffer from common cause failures with other GNSS (such as a major space weather event).
Schedule	FOC is expected 8 years after kick-off, although this would imply developing and producing the LEO and MEO platforms and payloads in parallel. Assumes that pre-developments are initiated early on including the navigation antenna (est. 4 years) and Inter-satellite links (est. 1.5 years). Potential for IOC from either the LEO layer (reverting to Concept 3) or the MEO layer as a conventional MEO GNSS depending upon preferred deployment strategy.
User & Value	User equipment modifications may be needed to cope with the increased Doppler. Ephemeris delivery from MEO should partially mitigate the receiver complexity issue of Concept 3.
Risk to deliverability	Production line can't deliver satellites at desired rate or price Novelty of LEO navigation antenna, local PNT solution computation and intersatellite links increases the risk of delays in payload development. In orbit validation could identify major design changes delaying FOC. Development and deployment of ground segment takes longer than planned. Variations in LEO satellite lifetime might lead to more expensive replenishment approach.
System Security	System requires both a conventional ground monitoring and computation network and intersatellite links to deliver telecommand, telemetry and navigation data.

Table 6 – Concept 7 Summary

1.6.7 GSO Space-based Augmentation to Existing GNSS (Concept 8)



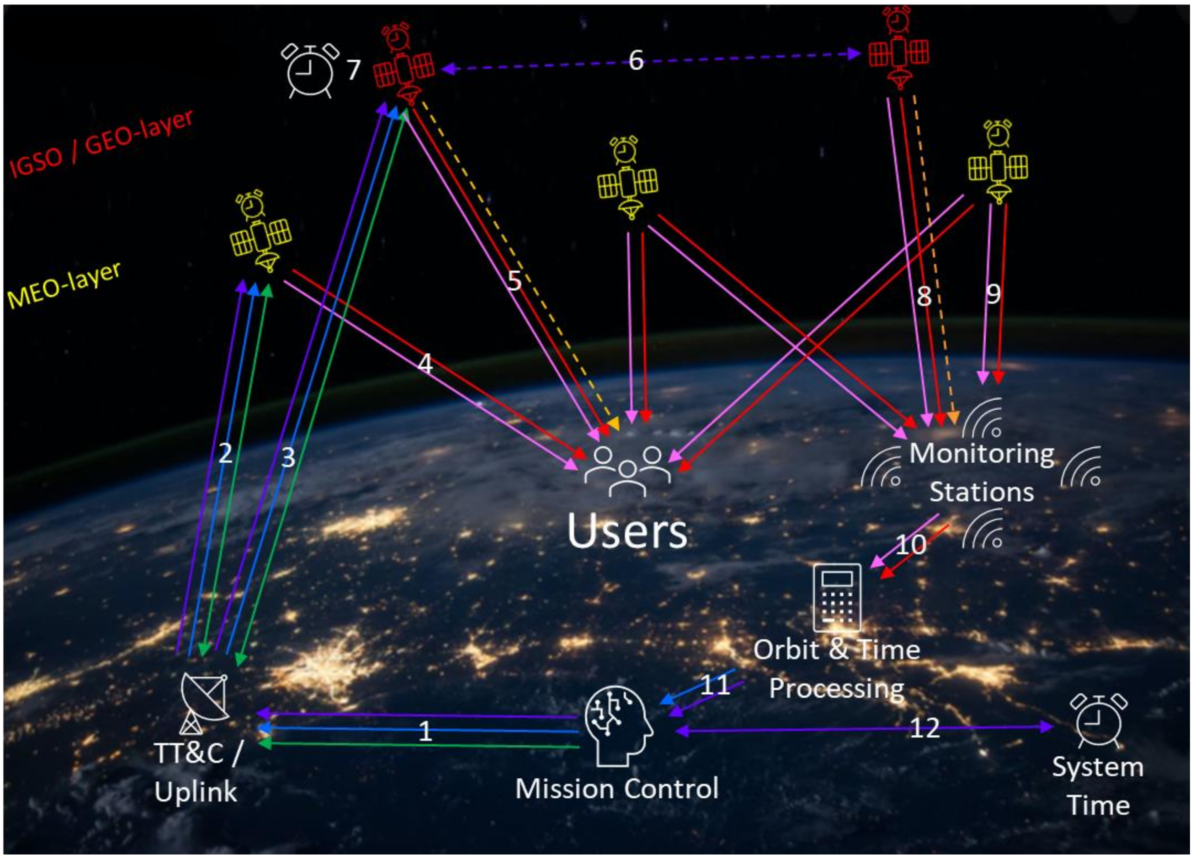
33. This concept provides users with a UK assured timing signal and enables spoof detection of GNSS signals and SBAS like integrity messages. This is achieved by augmenting existing GNSS,

providing the user with a timing signal with augmentation information containing time offset per GNSS satellite and information to support identification of spoofing. This augmentation information is provided to the user equipment via an additional L-band communications channel from a constellation of 6 dedicated spacecraft in GEO, which include redundant atomic clocks. 17 ground monitoring stations would be required for any independent SBAS like augmentation and to improve timing service performance. Main & redundant control facilities and 3 TT&C stations would be needed to operate the service.

Criterion	Comment
Performance	Provides a UK assured timing service and augmentations to improve integrity and improve jamming and spoofing resilience of existing GNSS services as an open service. Alerting could be provided via the GEO signals. No ES or GAUS is foreseen. Delivery from GEO implies limited coverage in polar regions.
Advantage to the UK	Supports detection of spoofing through the provision of a cryptographically protected signal to users Not an independent solution, as reliant on other GNSS. No contribution to freedom of action.
Resilience	Limited resilience due to reliance on at least one GNSS service providing an open service.
Schedule	FOC is expected 5 years after kick-off, due to the relative simplicity of the platform and payload. Potential for an initial regional service using only redundant, potentially hosted payloads.
User & Value	Limited modifications required to back-end of user equipment to receive augmentation information.
Risk to deliverability	Challenging to find 6 GEO spacecraft to act as hosts from which to deliver the service. Which may result in the need for dedicated GEO spacecraft greatly increasing costs.
System Security	Limited ground segment and simple uplink from friendly territory minimises vulnerability. External reliance introduces challenges to assurance and security agility.

Table 7 – Concept 8 Summary

1.6.8 Multi-Layer GEO & MEO (Concept 6)



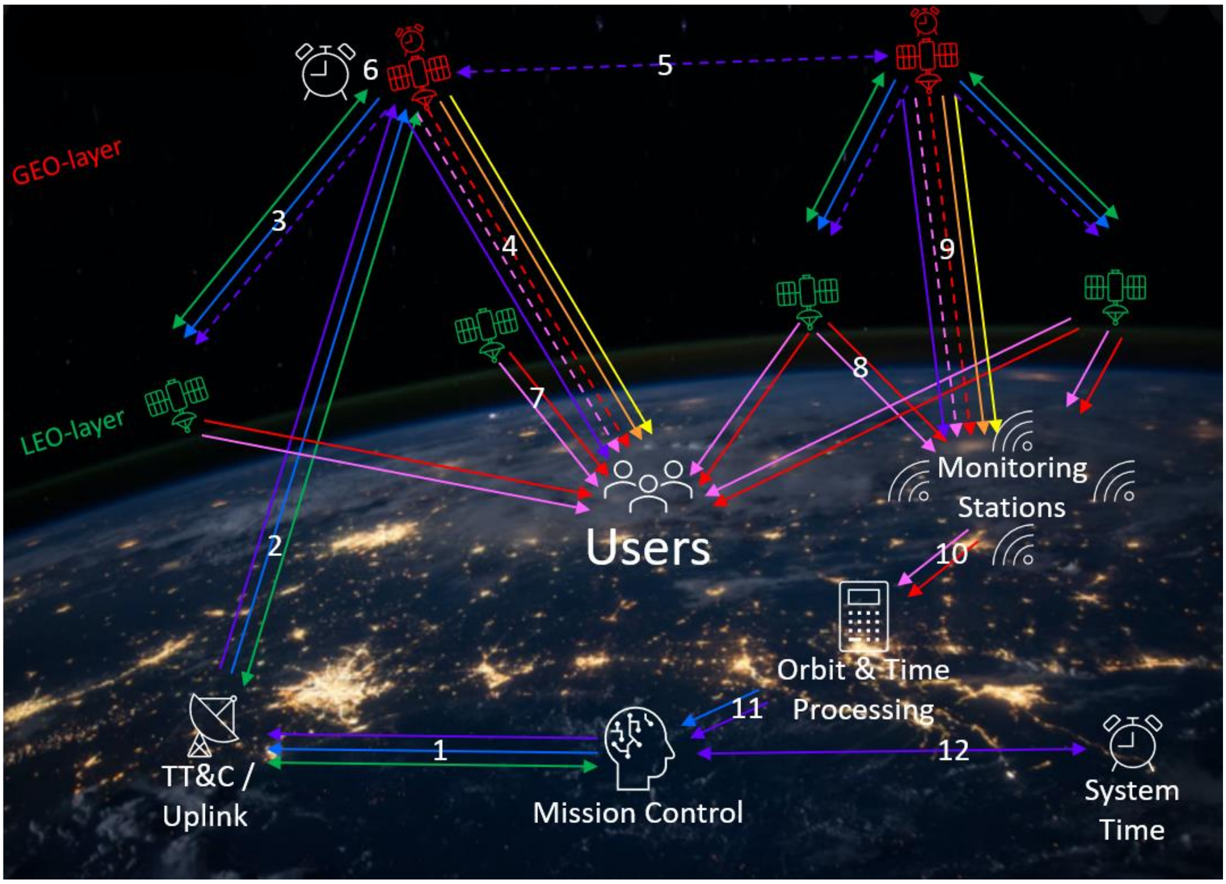
34. This hybrid concept combines the MEO PNT service from concept 7 with the Augmentation and timing service of Concept 8 to deliver a global PNT service. 18 satellites at 21,500 km altitude with redundant high accuracy atomic clocks provide conventional GNSS signals. Six similar satellites in GEO provide ranging and timing services and the augmentations described for the concept 8. GNSS signals are derived from a conventional orbit determination and timing synchronisation with redundant control facilities & 17 monitoring stations on the ground. 5 TT&C stations are required for distribution of control and navigation messages to the MEO & GEO layers, which also receive augmentation data. This concept offers a fully global PNT service, independent of other GNSS systems, and can support OS, GAUS and ES user groups individually, as well as providing alerting if desired.

Criterion	Comment
Performance	Provides PNT from the MEO & GEO layer, which can provide timing and augmentation services similar to concept 8 without the MEO layer. Timing applications for fixed surveyed receivers can be provided from a single free-drift GEO SV at any time. Analysis has shown large and consistent patches of poor positioning performance at temperate latitudes effecting large user communities and poor coverage at high latitudes. Provides OS, ES and GAUS by design, from the MEO & GEO satellites to the designated user groups. Alerting Service could be provided
Advantage to the UK	Independent system contributes to freedom of action.
Resilience	Service depends upon signals from both layers so lacks orbital redundancy. Dependence upon MEO layer for PNT signal means that it would be likely to suffer from common cause failures with other GNSS (such as a major space weather event).

Schedule	FOC is expected 8 years after kick-off, although this would imply developing and producing the LEO and MEO platforms and payloads in parallel. Assumes that pre-developments are initiated early on including the navigation antenna (est. 4 years) and Inter-satellite links (est. 1.5 years). Potential IOC providing time services from the GEO layer.
User & Value	Limited modifications required to back-end of user equipment to receive augmentation information and new UK signals.
Risk to deliverability	Challenging to find 6 GEO spacecraft to act as hosts from which to deliver the service. Which may result in the need for dedicated GEO spacecraft greatly increasing costs. MEO constellation brings strong heritage especially regarding PNT applications. High accuracy clock used on board each spacecraft need to be procured from outside the UK with potentially extended lead times.
System Security	The monitoring and TT&C networks are similar in size to conventional GNSS, so there is advantage over conventional GNSS with respect to securing these locations.

Table 8 – Concept 6 Summary

1.6.9 Multi-Layer LEO Doppler with GEO Frequency Source (Concept 9)



35. This concept uses a Doppler-based ranging technique, using signals from satellites in Low Earth Orbit (LEO) and frequency reference signals from satellites in Geostationary orbit (GEO). The frequency reference based on a high performance atomic clocks, from 6 GEO hosted payloads are used to compare the Doppler shifted signals arriving from 80 LEO satellites, which only require simple oscillators. 32 monitoring stations feed redundant monitoring and control facilities with 3 TT&C stations disseminating signals and monitoring and control data via the GEO layer.

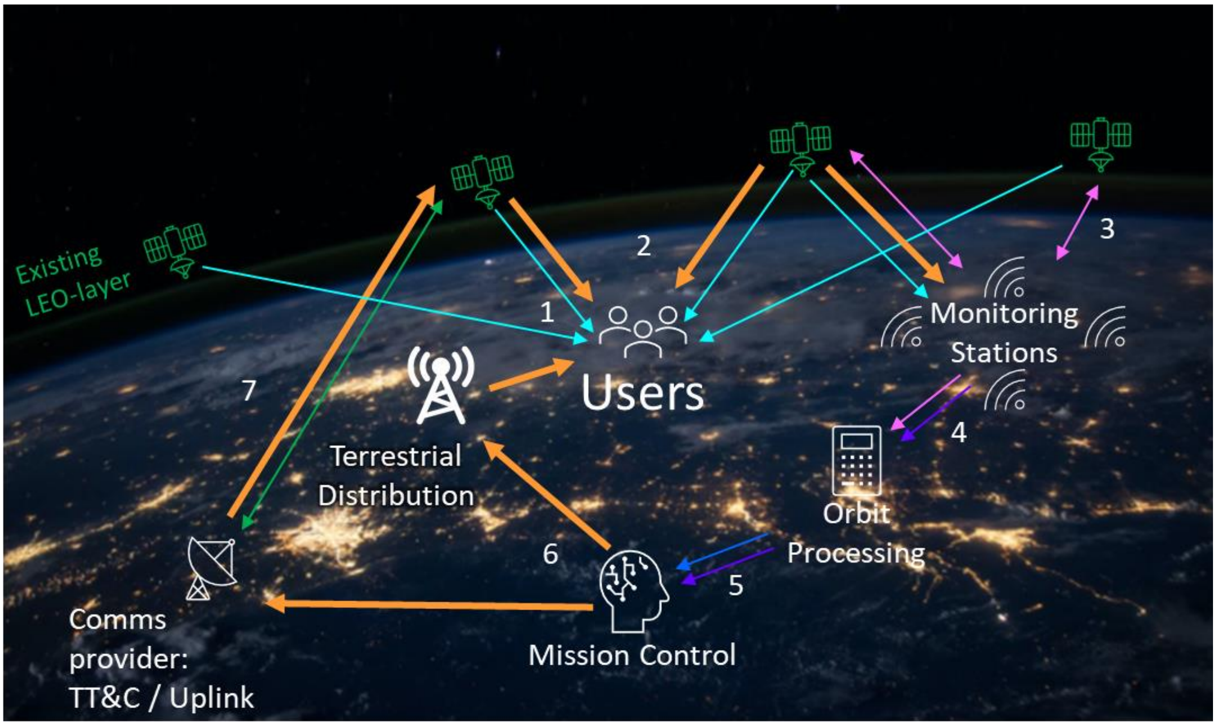
36. The frequency reference could be used to deliver a timing service and broadcast augmentation services, in a manner similar to concept 8. Doppler ranging suffers from challenges related to accuracy when used for highly dynamic users. This concept offers a fully global PNT service, independent of other GNSS systems, and provides an authenticated open service only. It can provide an alerting service if desired.

Criterion	Comment
Performance	Provides position to the user with an estimated accuracy of 10’s meters, although dynamic users will require a fused IMU to be assured of this accuracy during manoeuvres. Performance limited at high latitudes due to lack of visibility of GEO time reference. Provides a UK assured timing service and augmentations to improve integrity and improve jamming and spoofing resilience of existing GNSS services as an open service. Alerting could be provided via the GEO signals.
Advantage to the UK	Provides a PNT service completely decoupled from conventional GNSS. Independent system contributes to freedom of action.
Resilience	Service depends upon signals from both layers so lacks orbital redundancy. Divergence from existing GNSS provides some limited protection from spoofing and jamming, but the narrowband signals are inherently more vulnerable to jamming and the Doppler approach is at least as vulnerable to spoofing. Authentication provides some protection against spoofing.

Schedule	FOC is expected 9 years after kick-off, allowing sufficient time for development of the doppler payload. Initial operational capability similar to concept 8 could be available within 6 years subject to host platform availability.
User & Value	Complete development of a novel Doppler receiver would be required. This would need to fuse inertial signals to accommodate dynamic users.
Risk to deliverability	Novel user equipment not available in time for user uptake due to unexpected complexity at receiver level. Hosted Payload - lifecycle of hosting system not coherent with the schedule for the space based PNT deployment. Ground segment development & deployment takes longer than planned.
System Security	Will require an extensive ground monitoring capability, potentially using locations beyond friendly territory.

Table 9 – Concept 9 Summary

1.6.10 Signals of Opportunity (Concept 10)



37. ‘Signals of opportunity’ (SOO) refers to making use of extant space-based signals transmitted from the various LEO communication satellite constellations that are in operation currently and being extensively developed over the coming years. This concept therefore makes use of existing space assets and requires no dedicated space segment. Instead signals from multiple satellites are monitored to better predict their orbitography such that available downlinks can be used to generate a PNT solution parasitically. A ground segment similar to a conventional GNSS but with 59 monitoring stations, is required to generate the orbitography which then has to be distributed to user receivers via a communications channel. Doppler receivers similar to those for Concept 9 would need to be developed. For highly dynamic users it needs additional input of its own velocity and acceleration, for example from an inertial measurement unit.

38. Resilience is achieved through the diversity of the number of constellations that can be used to compute the User’s position, for example, in the instance where a satellite is out of use, it is only one of several signals than can inform the position determination.

Criterion	Comment
Performance	Provides position to the user with an estimated accuracy of 10’s meters, although dynamic users will require a fused IMU to measure velocity. Does not provide a highly accurate time signal. Orbitography data would be communicated via a subscription service.
Advantage to the UK	Provides a PNT service completely decoupled from conventional GNSS. Does not require any additional space infrastructure. Different approach offers improved assurance and plurality a degree of freedom of action.
Resilience	Service depends upon signals from operators not under the control of the service. There are multiple satellite communications systems that can be exploited which provides resilience through redundancy, but the number that can actually be exploited depends on the tolerable level of complexity in the receiver as a wide range of frequencies are used. Low resilience to jamming because SOO signals are generally more vulnerable to jamming than GNSS signals. Again, this is dependent on the level of complexity, size weight and power consumption that can be tolerated in the receiver.

Schedule	FOC is expected 5 years after kick-off, with development limit to the monitoring and ODTS functions. Assumes that pre-development of a suitable receiver (est. 4 years), are initiated early.
User & Value	Complete development of a novel doppler receiver would be required. This would need to fuse inertial signals to accommodate dynamic users.
Risk to deliverability	Lowest risk solution as no space infrastructure must be deployed. Novel user equipment not available in time for user uptake due to unexpected complexity at receiver level. Denial of access to suitable Signals of Opportunity prevents service viability.
System Security	Will require an extensive ground monitoring capability, likely to involve using locations beyond friendly territory. Dependency on signals outside system control introduces challenges to assurance and security agility.

Table 10 – Concept 10 Summary

7 Conclusions

39. SBPP has demonstrated that a range of technical approaches are possible to deliver PNT from space. This has been achieved via:

a. An RFI within the FVEYS community.

b. A subsequent filtering and consolidation process.

c. Targeted technical analysis and exploration of the SB-PNT ‘problem space’.

d. Engagement of expert support from across the UK space sector.

40. Work has been successfully completed within a challenging schedule and operating environment considering the range of optionality mandated by the programme, and all of this within the context of the COVID pandemic.

41. The technical work has been monitored and assured via independent teams throughout the programme, including technical experts from Aerospace Corporation (US) and KISPE / Border Consulting (UK).

42. The resulting Technical Concepts provide an input to senior stakeholders and decision makers, helping to inform decisions about the UK’s future space based PNT needs. The process of generating the Concepts has emphasised the necessity for clarity on mission objectives and Space Based PNT requirements.

43. Once a set of endorsed Space based PNT requirements are derived from an agreed user community across multiple government departments, technical concepts and procurement options can be optimised through engagement with the market (e.g. via the ECSS Phases of space mission procurement). Ideally, a System of Systems analysis across the wider PNT community is needed, which can then help identify and isolate what is required from the space-based service.

44. The programme has identified a range of concepts with variations that could be used to meet the needs as specified by stakeholders. The Technical Concepts have shown the range of what is possible – but they are not refined or optimised against a specific set of endorsed requirements. The Concepts can now be used, iteratively, to help guide discussion with stakeholders about their needs.