CHANGING THE ECONOMICS OF SPACE

NAVISP Industry Day
17/Jan/2019
Complementary PNT Infrastructure in LEO

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Agenda

- Background and Objectives
- Scope
- Use Cases and System Concepts
- System Analysis
- Task 2 Preliminary Conclusions

Background and Objectives

- Global economy relies on GNSS
- Opportunities/Challenges:
  - There are growing concerns about resilience
  - Opportunity exists to serve evolving user base (IoT)
  - User expectations are broadening (use indoors, in urban environments, at poles)
- How can these issues be addressed?
  - Provision of further MEO satellites, or
  - A constellation of cheaper LEO PNT satellites

Objectives:

- Take benefit from the GNSS services available from MEO
- Consider a Complementary LEO-based PNT
- Perform a system study
- Consider various implementations of a LEO PNT to meet use cases

- Preliminary Findings:
  - A LEO service can provide benefits
  - But challenges exist

Scope

Identify appropriate use cases → Identify candidate system concepts → Investigate system scenarios and map to user cases → Assess system ability to provide value → Determine complexity, deployment plan, outline costs

- Detailed Work Breakdown
  - Task 1: Consolidate use cases and system concepts — complete
  - Task 2: System analysis of system concepts — In progress
  - Task 3: Consolidation of architecture for selected system scenarios — Not started
  - Task 4: Synthesis of results to justify an investment decision — Not started

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Mapping of Use Cases to System Concepts

System Concepts \ Use Cases	1.1 Polar Coverage	1.2 Penetration into urban environments and indoor	1.3 Resilience against Interference	2 Low Energy Positioning	3 Improved Timing and Authentication	4 Improved Off-Earth Positioning	5 Signal re-configuration	6 Support to Autonomous Vehicles
A/B: On-board GNSS Receiver	✓	✓	✓	✓	✓		✓	✓
C: Two transmitting Antennas (Zenith and Nadir)	✓	✓	✓		✓	✓	✓	
D: LEO PNT as an Augmentation System	✓	✓	✓	✓	✓			✓
E: Inter-Satellite Links	✓	✓	✓	✓	✓		✓	✓
F: Hosted Payload	✓	✓	✓	✓				✓

✓ = Has applicability

Mapping of Use Cases to System Concepts

System Concepts / Use Cases	1.1 Polar Coverage	1.2 Penetration into urban environments and indoor	1.3 Resilience against Interference	2 Low Energy Positioning	3 Improved Timing and Authentication	4 Improved Off-Earth Positioning	5 Signal re-configuration	6 Support to Autonomous Vehicles
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E: Inter-Satellite Links	✓	✓	✓	✓	✓		✓	✓
F: Hosted Payload	✓	✓	✓	✓				✓

✓ = Has applicability

[green box] = Main focus of system analysis in Task 2

Key Properties and Drivers for Use Cases

Use Cases / Key Properties	1.2 Penetration into urban environments and indoor	1.3 Resilience against Interference	2 Low Energy Positioning	3 Improved Timing and Authentication
User Masking Angle (UMA)	25º (average of 5º to 45º)	25º (better at steeper UMA)	5º sufficient	5º sufficient
Power on Ground needed	High	High	High	Not critical
Intermittent or full time service needed	Full time	Full time	Intermittent	Intermittent
Number of potential users	Billions	Millions	Millions	Thousands-millions

Key Drivers:

Various UMAs

High power better and achievable due to closer proximity of LEO to Earth

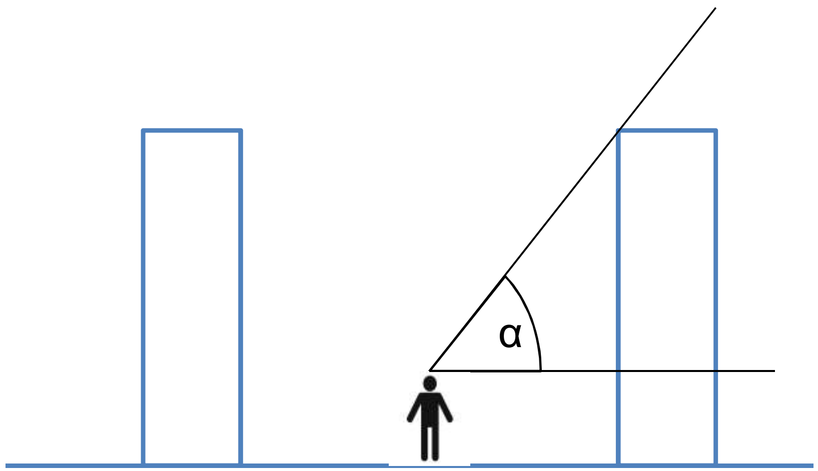
Both full time and intermittent service of interest

UC 1.2 is main focus

The system design in Task 2 will examine a system designs focusing on these drivers.

Choice of User Masking Angle for analysis

- For use case with open field of view
  - 5º UMA is realistic
- For urban canyons
  - 5º is reasonable along street, but maybe 45º cross-street
  - Do we take a mean of 25º for system analysis?
  - PDOP is good when there is a diversity of SV elevations – some at low elevation, others high.
  - Restricting UMA to 25º limits diversity and limits coverage
  - May give overly pessimistic results but more detailed study required to investigate.

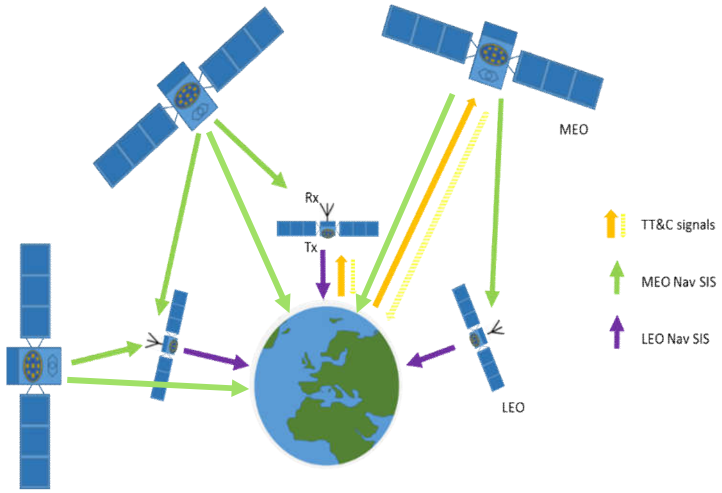


Note on MEO Complementarity

A useful LEO PNT service without reliance on a MEO constellation carries several challenges

A LEO service can be complementary to MEO in several ways:

- Additional signals in space (SiS) for the user
- Provision of timing from MEO to LEO to avoid need for atomic clocks in LEO
- LEO can utilise MEO positioning for orbit determination to simplify ground segment
- Measurement diversity (higher Doppler, different multipath behaviour, etc)

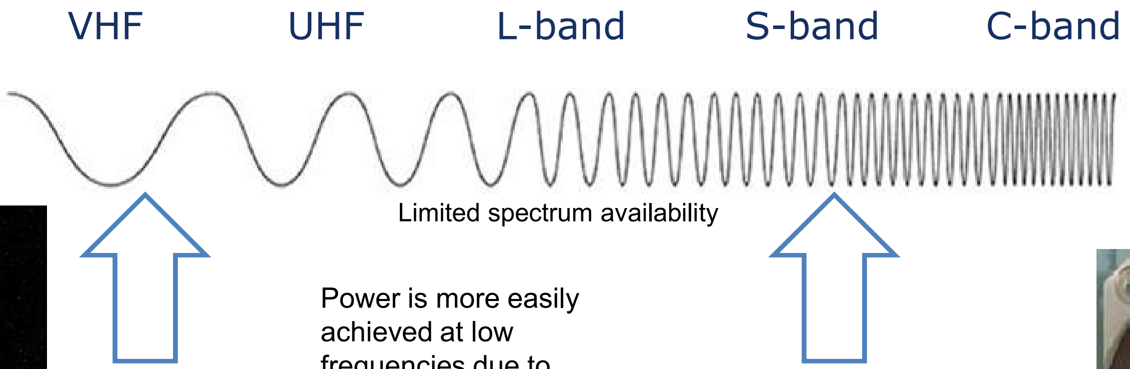


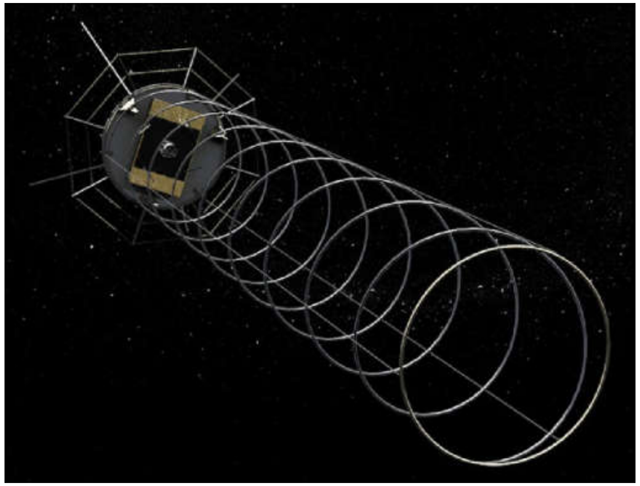
A LEO L-band service supplementing MEO not considered to address use cases

- Increased noise floor to other PNT users/systems

Frequency Selection

Choice of frequencies include:





2.5m long VHF helix antenna
(Ref German Aerospace Centre, Schuetze-Staebe)

80mm long S-band patch antenna
(Ref SSTL)

An independent high power SiS using VHF or spot beam S-band has been considered

System Analysis
Trade-offs

- We have identified the key drivers to provide
- A system trade study will now be performed to identify a suitable system
- The following system trades are considered:
  - Altitude: Radiation vs number of satellites
  - Link budgets: Power on ground vs frequency and beam width
  - Optimal plane inclination vs coverage
  - Optimal ratio of satellites in plane to number of planes
  - Performance from 2 spot beams per satellite
  - Performance from 4 spot beams per satellite

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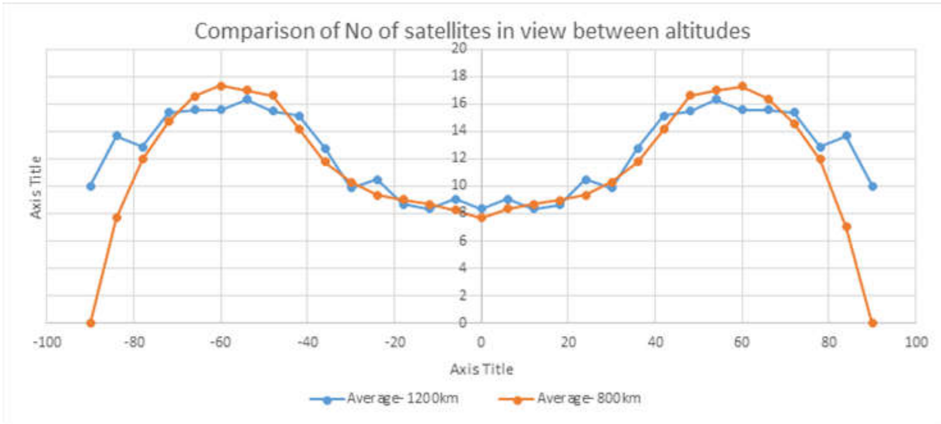
System Analysis

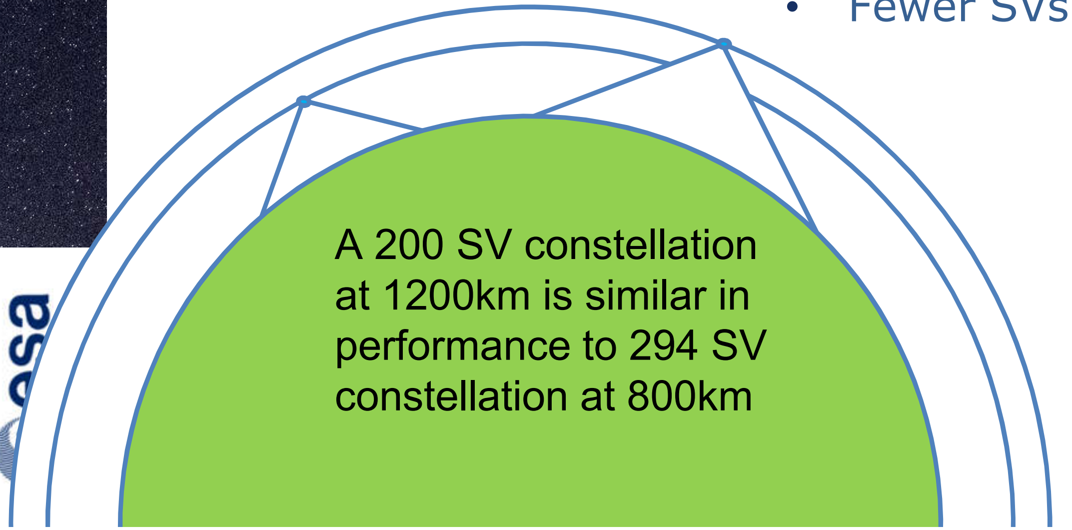
Altitude

A high altitude provided better coverage but is subject to higher radiation levels. Which altitude is preferred?

- 800km
- COTS components OK
- 40% more SVs req'd is achieve similar cover

- 1200km
- Rad Hard components req'd
- Fewer SVs





10 yr life cost for 1200km is estimated as 3x that of 800km case

Conclusion: 800km is the selected altitude

System Analysis

Link Budgets

- 2 frequencies considered: VHF and S-band
- For 5W broadcast power, Power on Ground (PoG) is always greater than GNSS in MEO

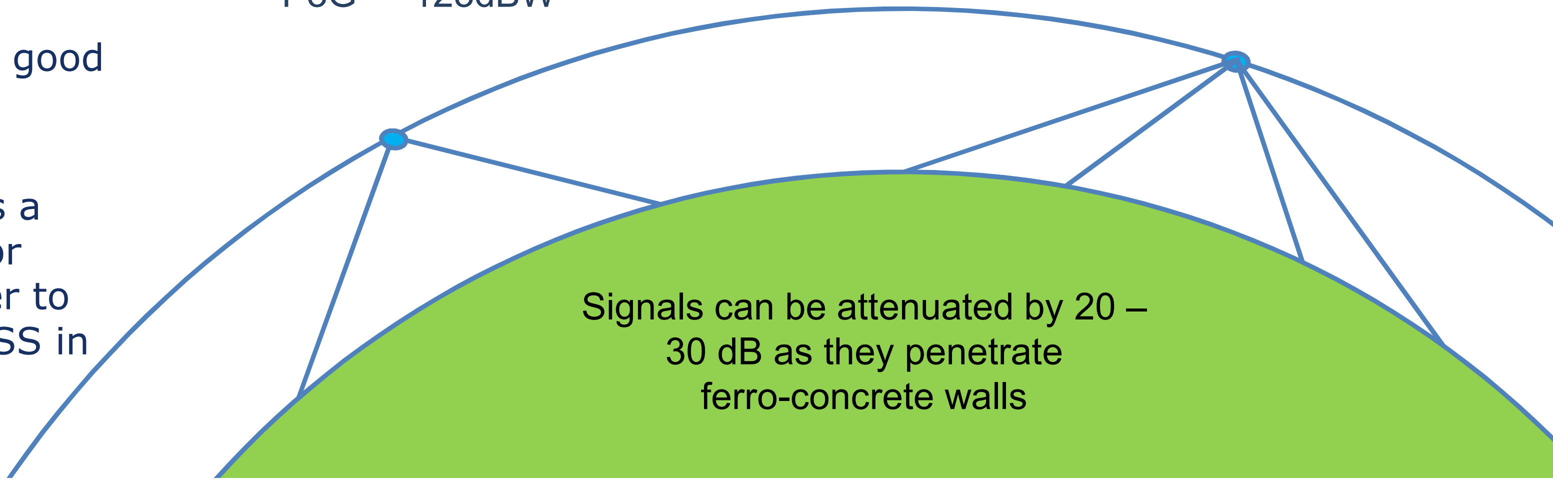
-160dBW

Reasonable power output for a small LEOsat (30kg)

S-band: 2.5 GHz, spot beam antenna (G=~15dB)
PoG = -144 to -154 dBW (depending on range)

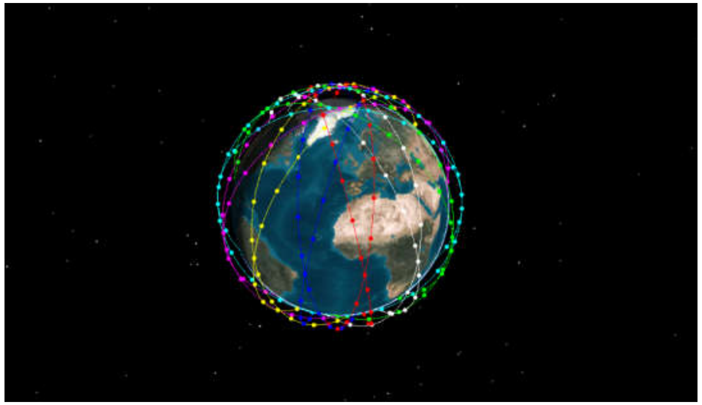
VHF: 120 MHz, wide beam antenna (G=~6dB)
PoG = -123dBW

- Conclusion:
  - ➢ VHF PoG allows good penetration of buildings
  - ➢ S band requires a focused beam or higher SV power to improve on GNSS in MEO

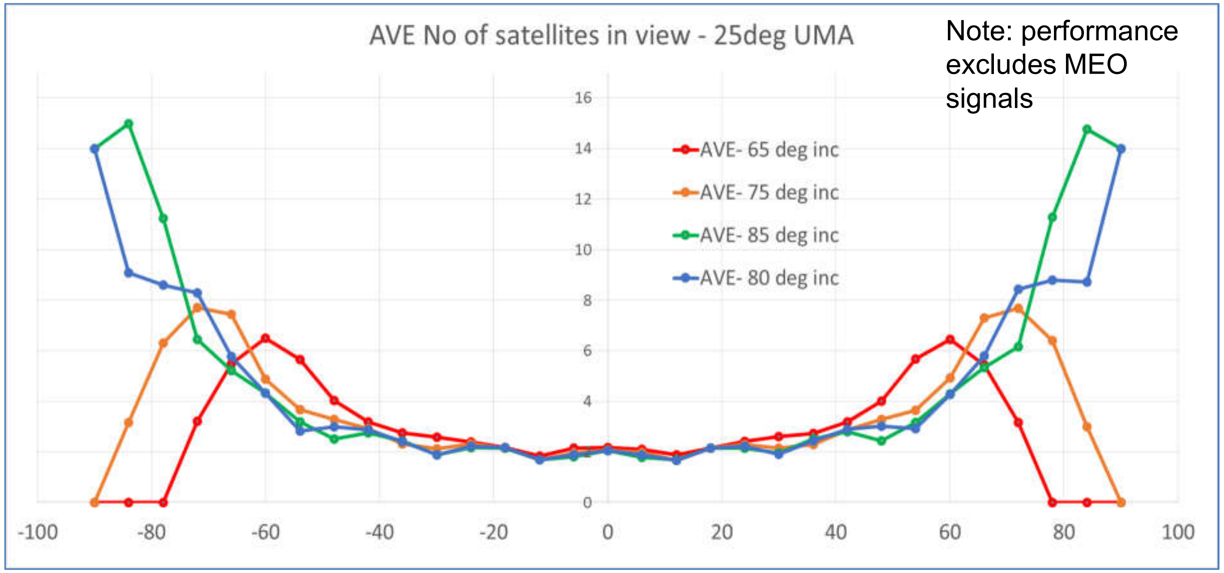


System Analysis

Optimal plane inclination (single inclination)

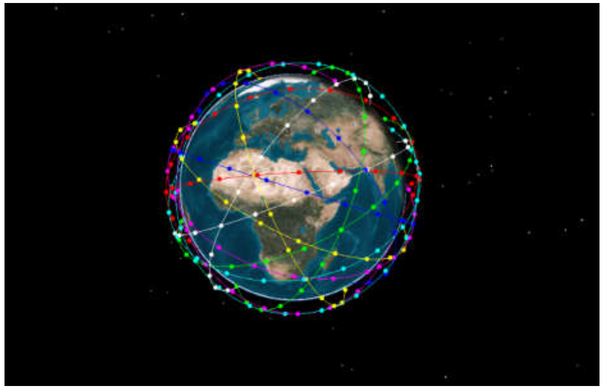


- Inclinations checked for 294 SVs in 14 planes of 21 SVs, 25° User Masking Angle
  - Poor coverage in low latitudes
  - Performance at poles better, especially at high inclinations
  - Marginal differences

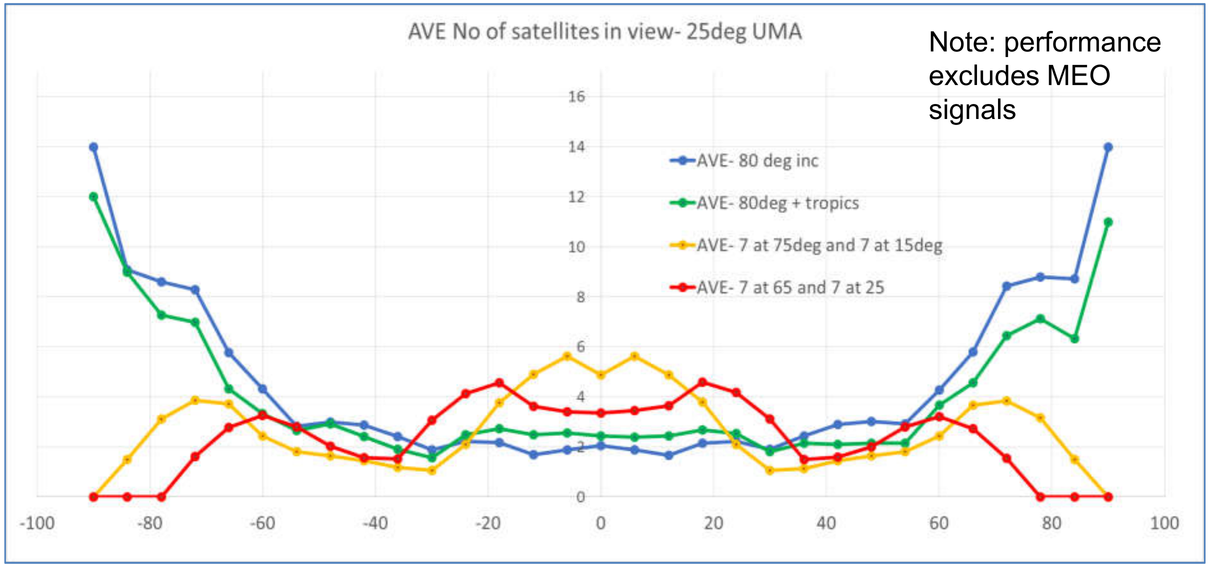


System Analysis

Optimal plane inclination (multiple inclinations)



- If some planes are re-assigned to equatorial and tropical orbits
  - Coverage improves near the equator, but still weak in mid-latitudes
  - AS number of SVs is low, PDOP results are poor
  - Best solution is 7 pl at 65º and 7 pl at 25º
  - Further SVs are needed to improve performance
  - Alternatively, reduction in UMA to 15º shows significant improvement



Note: performance excludes MEO signals

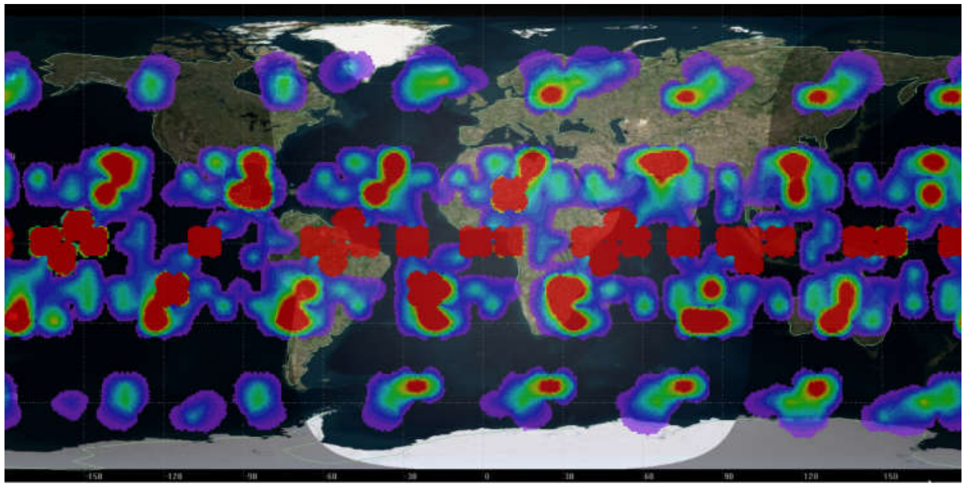
System Analysis

Optimal plane inclinations

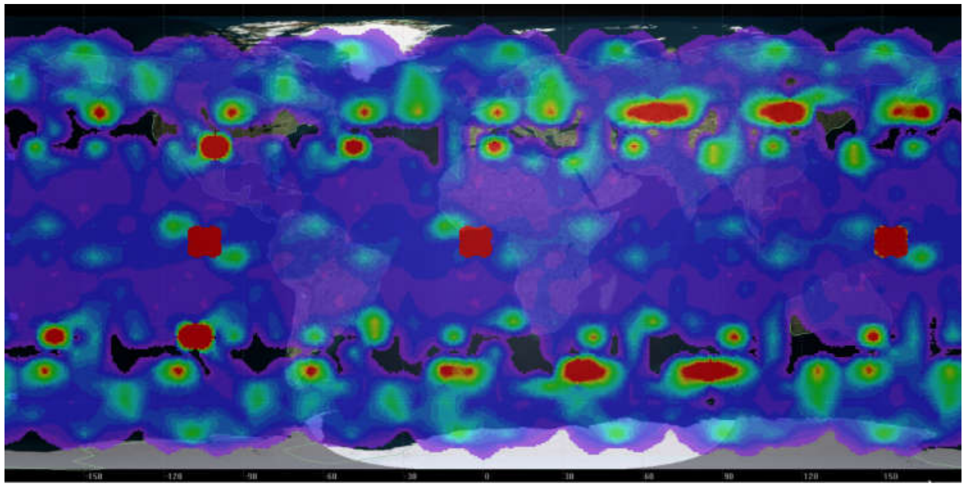
- PDOP results for best case:
  7 planes of 21 SVs at 65° and
  7 planes of 21 SVs at 25°

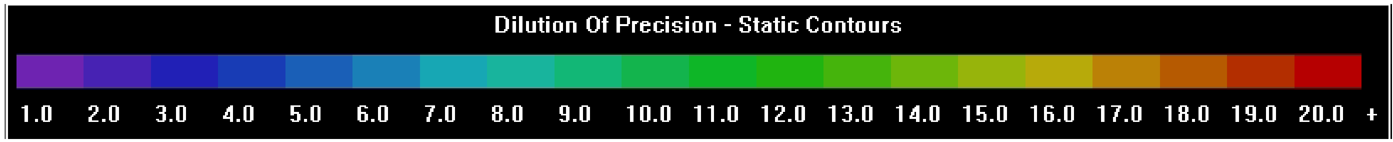
- ➢ 25° UMA gives very poor PDOP – intermittent coverage
- ➢ 15° UMA improves PDOP considerably (though weakness remains over Europe)

25° UMA



15° UMA





System Analysis

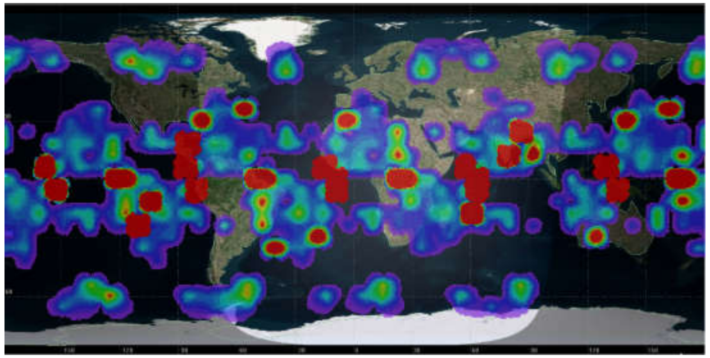
Optimal SV to plane ratio

Note: performance excludes MEO signals

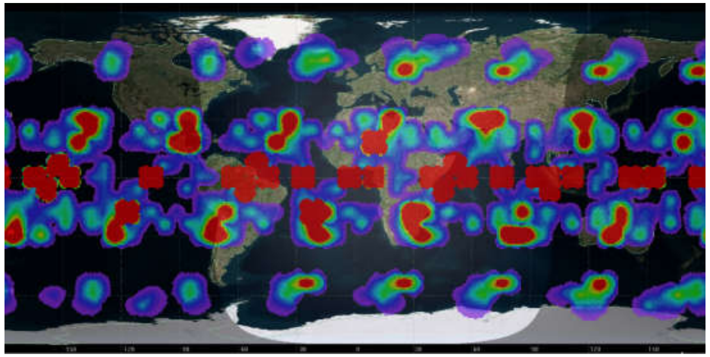
- Three cases examined:
- Highest SV:plane ratio (top map) shows best general coverage
  - More blue
- Also more SVs per plane provides lower launch and replenishment cost

25° UMA

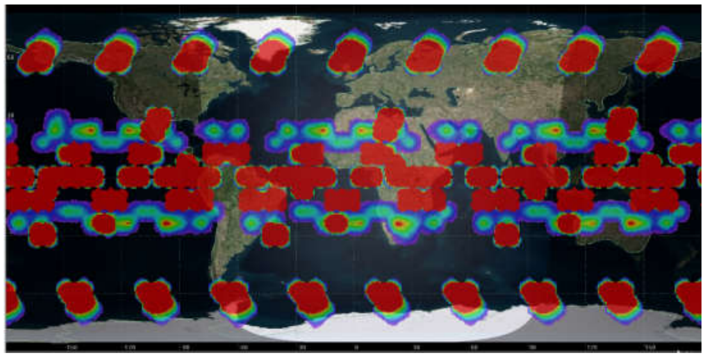
5 planes of 29 SVs at 65° and 5 planes of 29 SVs at 25° (SV:plane = 2.9)

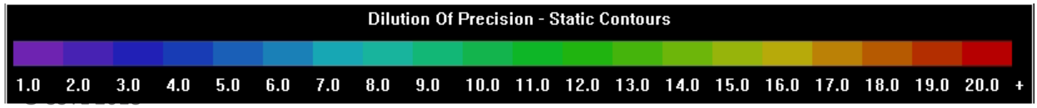


7 planes of 21 SVs at 65° and 7 planes of 21 SVs at 25° (SV:plane = 1.5)



9 planes of 16 SVs at 65° and 9 planes of 16 SVs at 25° (SV:plane = 0.9)





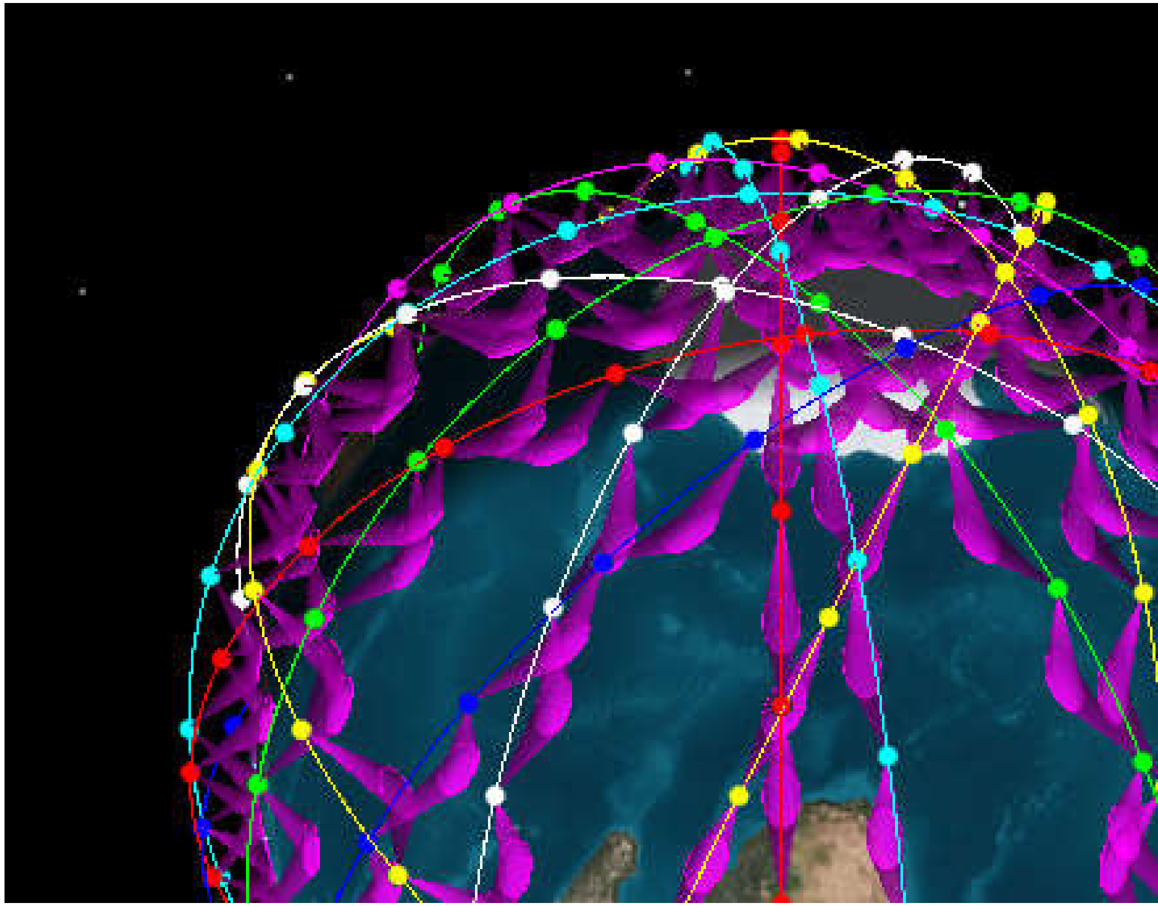
System Analysis

Power on Ground vs Usable Coverage
2 beams

- For S-band, spot beams are required to achieve good PoG

- Two beam solution:
  - ➢ Overlap beams from adjacent SVs on each ring
  - ➢ Maintains constant patch with 2 beam coverage which travels around the globe
  - ➢ Patches occasionally overlap to give 4 SVs in view

7 planes of 21 SVs at 65° and 7 planes of 21 SVs at 15°



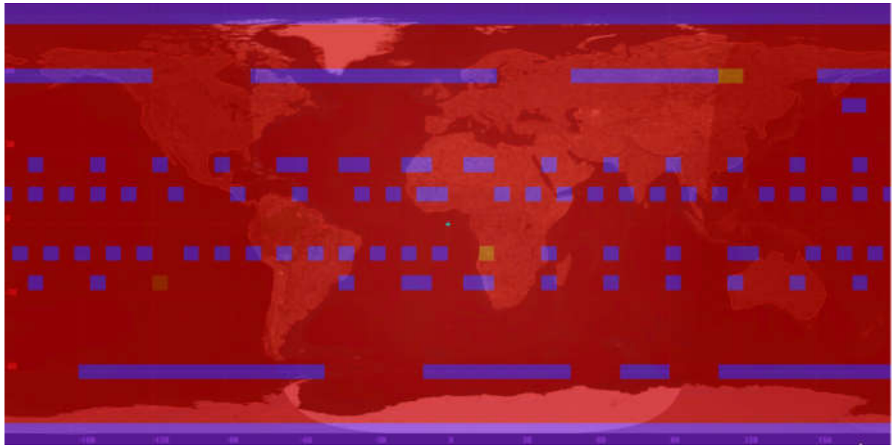
System Analysis

Power on Ground vs Usable Coverage
2 beams

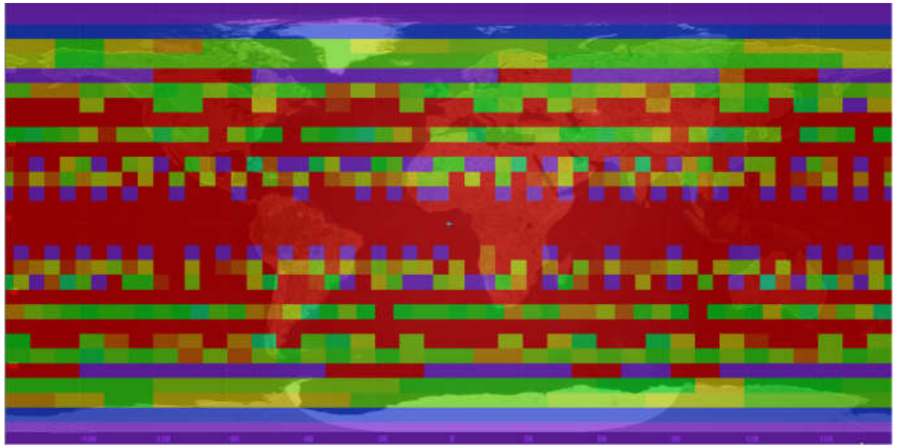
Note: performance excludes MEO signals

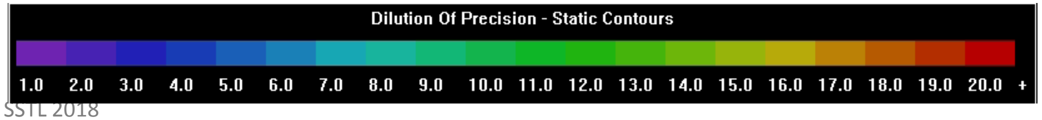
- PDOP good at points of 4 beam overlap (PDOP=2)
- But incidents of 4 beam overlap are rare
- Allows position fix only intermittently (except at poles)

Max PDOP (worst case)



Min PDOP (best case)

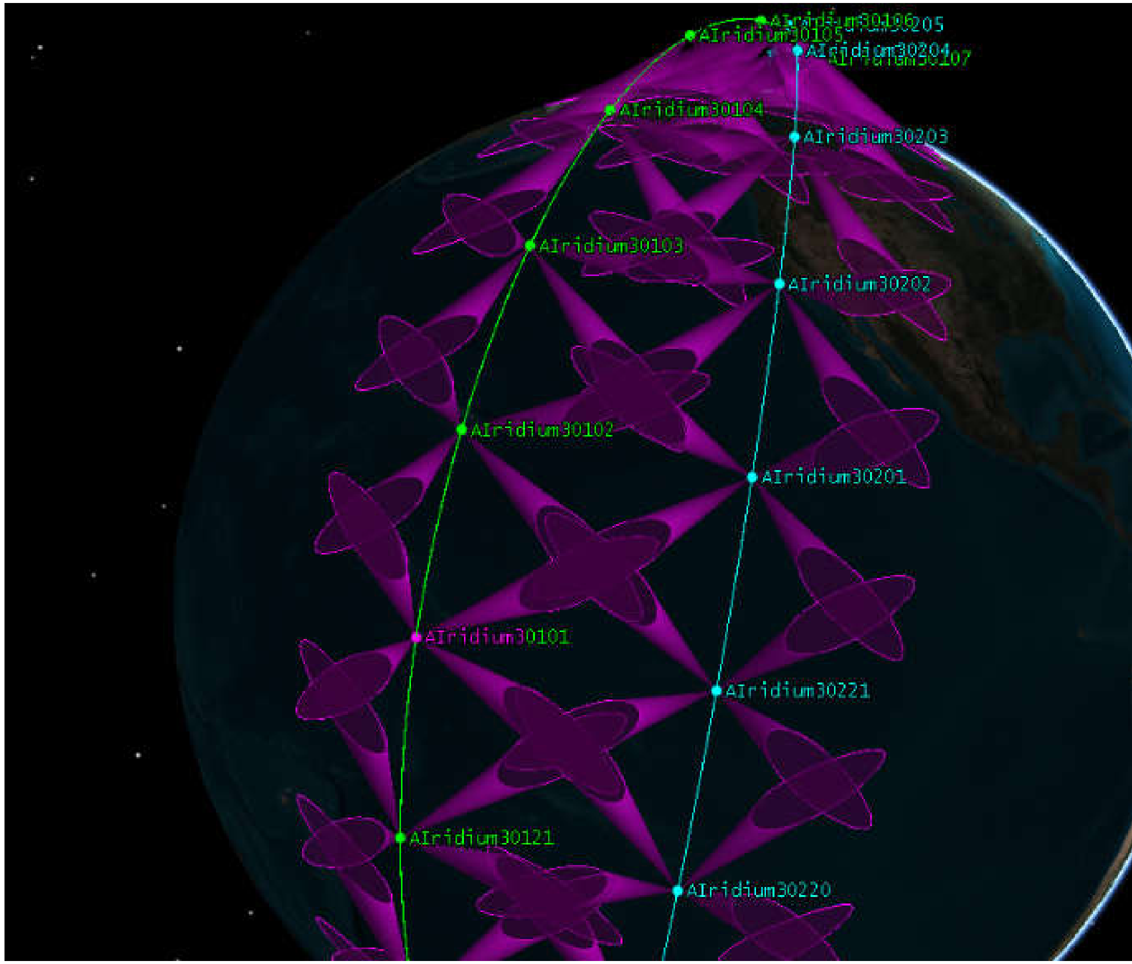




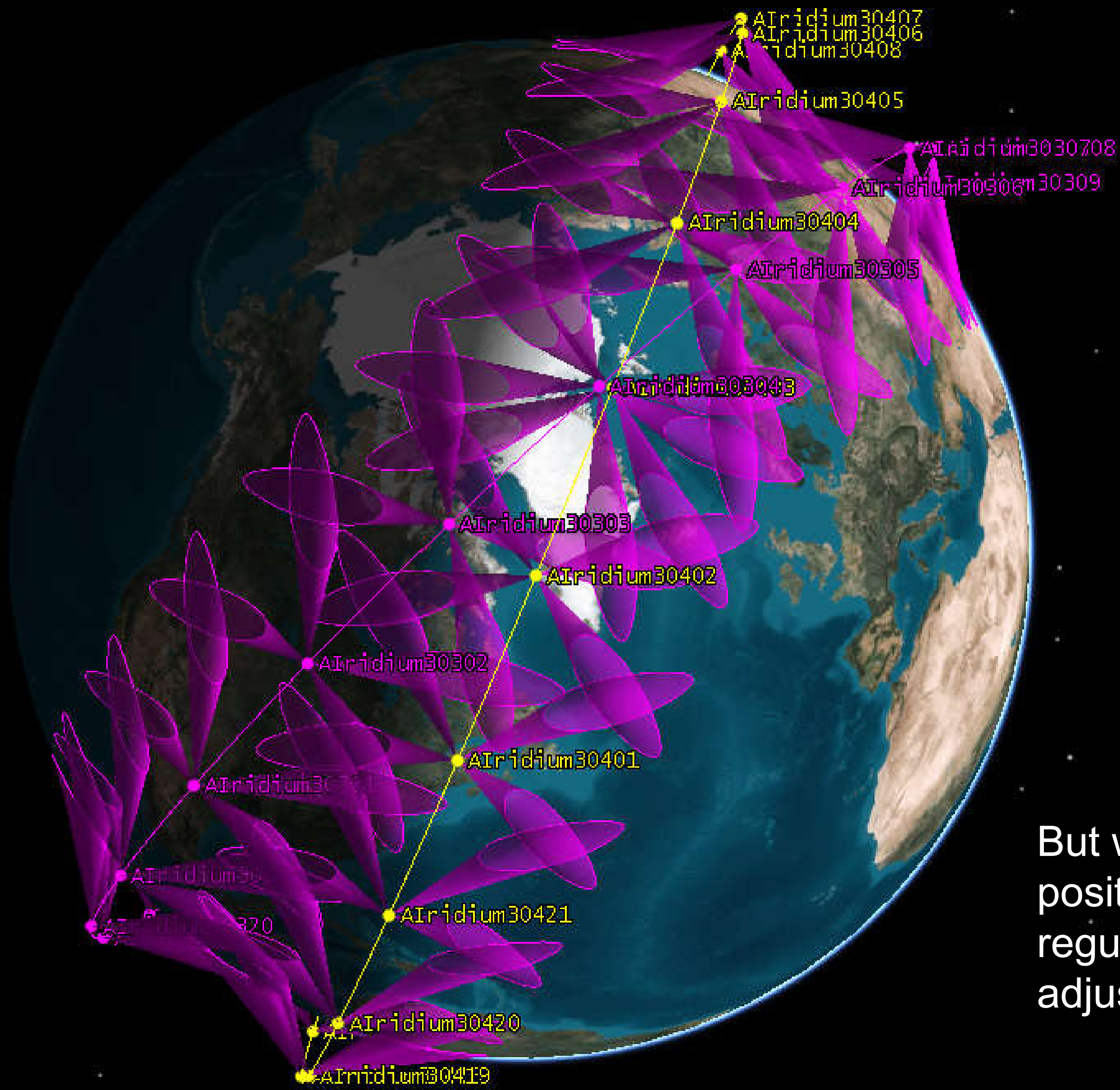
System Analysis

Power on Ground vs Usable Coverage
4 beams

- Four beam solution:
  - ➢ Overlap 4 beams from adjacent SVs on each ring and on adjacent rings
  - ➢ Polar configuation
  - ➢ Solution needs to be tuned for a specific latitude
  - ➢ Allows position fix intermittently with good PDOP (2)



- Patch of 4 SVs in view degrades as SVs move away from tuned latitude
- Performance degradation compensated by higher density of patches near the poles



But will SVs stay in position or need regular orbit adjustment?

Evaluation of Systems

Systems selected:

System	System Description	Description	Take Forward?
1	VHF wide beam	Good PoG Good coverage, full time Maybe spectrum constrained Large antenna	Yes
2	VHF Spot beam	Impractical antenna design Unnecessarily high power	No
3	S-band Wide beam	Very low PoG (similar to GNSS in MEO)	No
4	S-band 2 beam	Medium PoG Poor coverage, very intermittent, only UMA 5^o to 45^o Good PDOPs only achieved in very localised areas Twin beams stay synchronised	?
5	S-band 4 beam	Medium PoG Poor coverage, intermittent, only UMA 5^o to 45^o Good PDOPs achieved where beams overlap 4 beams need to be tuned for a target latitude SVs may desynchronise	?

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Preliminary Conclusions from Task 2

1. Use cases are best addressed with high power of ground
2. VHF is the best frequency to provide this power, though S-band can be used in a focused beam
3. 800km altitude is selected for analysis
4. Best systems solutions to date:
   - At least 294 SVs (to support a UMA over 15^{o})
   - VHF with a wide beam (G=6dB). 5 planes of 29 SVs at 65^{o} and 5 planes of 29 SVs at 25^{o}
   - S-band with focussed beams (G=15dB).
5. 4SV (with 25^{o} UMA) coverage is only achieved intermittently
6. Methods exist to obtain a fix using fewer satellites

Mapping of Systems to System Concepts

System selected:

System	Frequency	Beam	Coverage	Altitude	No. of SVs	Configuration
1	VHF	Wide	Full	800km	294 min	5 planes of 29 SVs at 65° and 5 planes of 29 SVs at 25°
2	S-band	Spot	Intermittent	800km	294 min	10 planes of 29 SVs at 80°

Mapping:

System Concepts / System	On-Board GNSS Receiver	Inter-Satellite Links	Hosted Payload
1 VHF	Yes	TBA	No (Antenna too large)
2 S-Band	Yes	TBA	TBA

Example of Mapping of Use Cases to Key Properties

System	Frequency	Beam	Coverage
1	VHF	Wide	Full
2	S-band	Spot	Intermittent

System 1: VHF

Use Cases / Key Properties	1.2 Penetration into urban environments and indoor	1.3 Resilience against Interference	2 Low Energy Positioning	3 Improved Timing and Authentication
User Masking Angle (UMA)	25º (average of 5º to 45º)	25º (better at steeper UMA)	5º sufficient	5º sufficient
Power on Ground needed	High	High	High	Not critical
Intermittent or full time service needed	Full time	Full time	Intermittent	Intermittent

System 2: S-Band

Use Cases / Key Properties	1.2 Penetration into urban environments and indoor	1.3 Resilience against Interference	2 Low Energy Positioning	3 Improved Timing and Authentication
User Masking Angle (UMA)	25º (average of 5º to 45º)	25º (better at steeper UMA)	5º sufficient	5º sufficient
Power on Ground needed	High	High	High	Not critical
Intermittent or full time service needed	Full time	Full time	Intermittent	Intermittent

For instance, a preferred solution could be:
System 1 with an On-board GNSS receiver on a dedicated satellite:

- High PoG with low SV power
- Can penetrate urban environments
- Addresses all Use Cases

Work to Complete Project

- Tuning of the selected scenarios
  - Optimise inclinations to cover specific latitudes
  - Whether a reduced no. of satellites will provide a similar service
  - Whether an increased no. of satellites (on host) will provide a better service
- Ground segment sizing
- Value of inclusion of Inter-Satellite Links
- Estimation of satellite masses and powers, and associated costs
- Short Time-to-market considerations
- Deployment considerations

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Thank You