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Enabling a Fully Interoperable GNSS Space Service Volume

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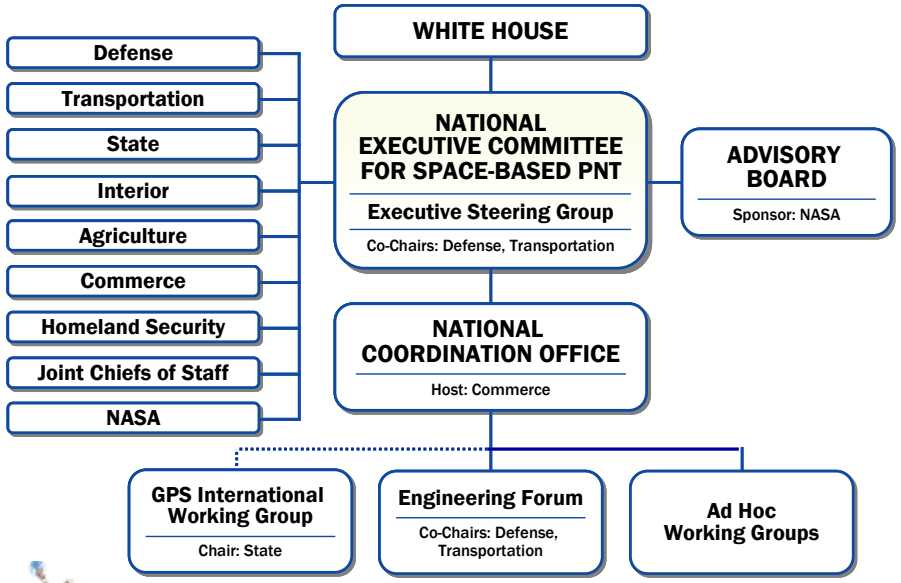
U.S. PNT / Space Policy and NASA's Role

- The 2004 U.S. Space-Based Positioning, Navigation, and Timing (PNT) Policy tasks the NASA Administrator, in coordination with the Secretary of Commerce, to develop and provide requirements for the use of GPS and its augmentations to support civil space systems.

- The 2010 National Space Policy reaffirms PNT Policy commitments to GPS service provisions, international cooperation, and interference mitigation.

- GPS enables space users to maximize the "autonomy" of spacecraft and reduces the burden and costs of network operations. It also enables new methods of spaceflight such as precision formation flying, station-keeping, and unique science measurements.

- NASA is engaging with other space agencies at venues such as the International Committee for GNSS (ICG) and the Interagency Operations Advisory Group (IOAG) to seek similar benefits from other PNT constellations to maximize performance, robustness, and interoperability for all.

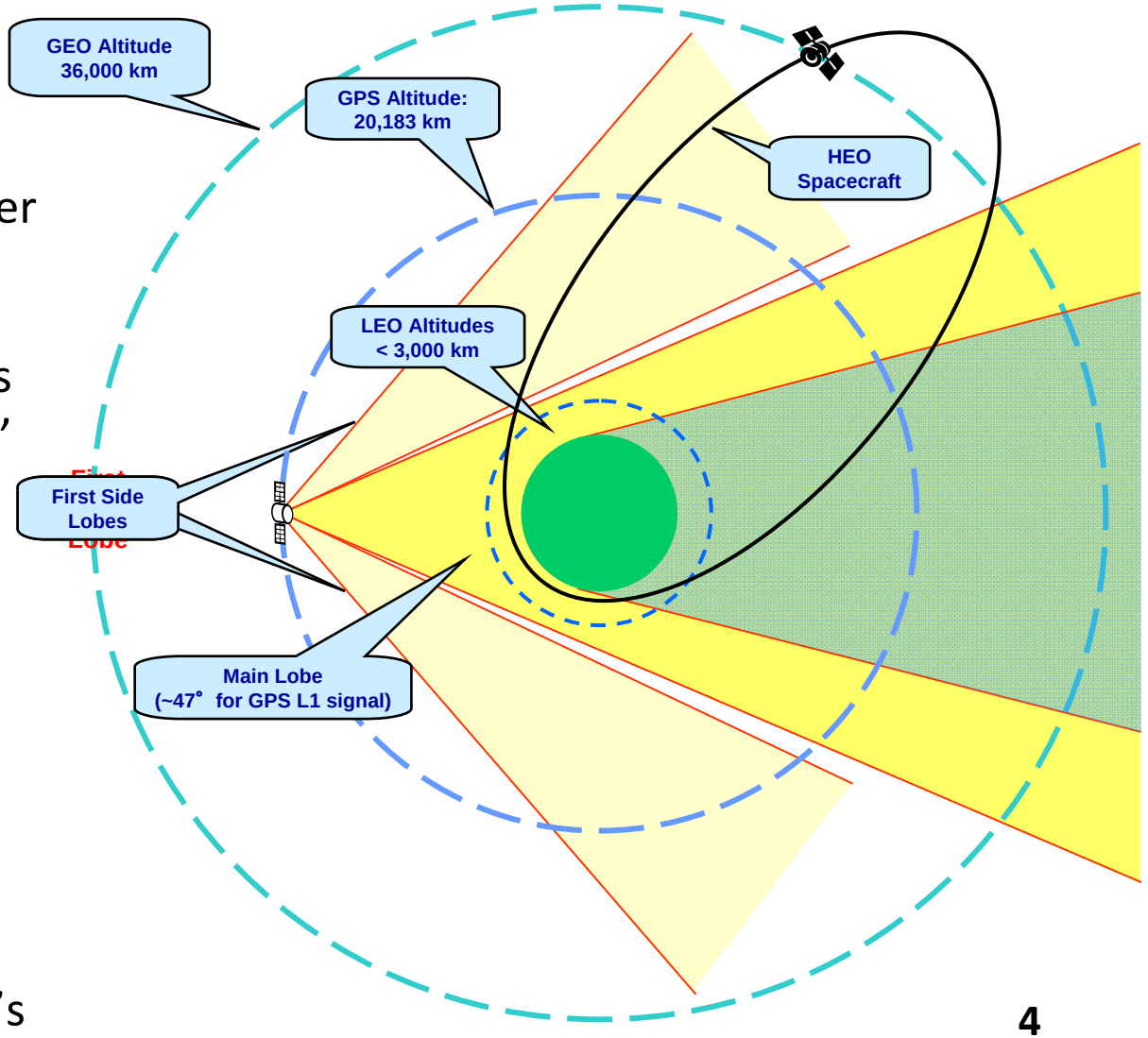


Expanding Space Applications of GPS

- GPS performance for Positioning, Navigation, and Timing (PNT) services was originally specified for users on or near the Earth surface:
  - For example, transmitted power levels specified at edge-of-Earth, 14.3 degrees off-nadir
- Space programs rely on GPS for spacecraft navigation and science applications
  - Most space users are in Low-Earth Orbits
  - Increasing number of users in higher orbits (altitudes > 3,000 km)
- US Government has defined a “Space Service Volume” for GPS
  - Specifies minimum performance parameters applicable to space users in higher Earth orbits beginning with GPS III satellites
- At geopolitical level, NASA seeks to encourage other PNT systems (Galileo, GLONASS, & COMPASS, etc.,) to define Space Service Volume performance characteristics
  - Contributes to greater overall system interoperability
  - Increased performance will be possible in the Space Service Volume if signals from multiple GNSS systems can be used together
  - Will enable more innovative space infrastructure applications to be developed

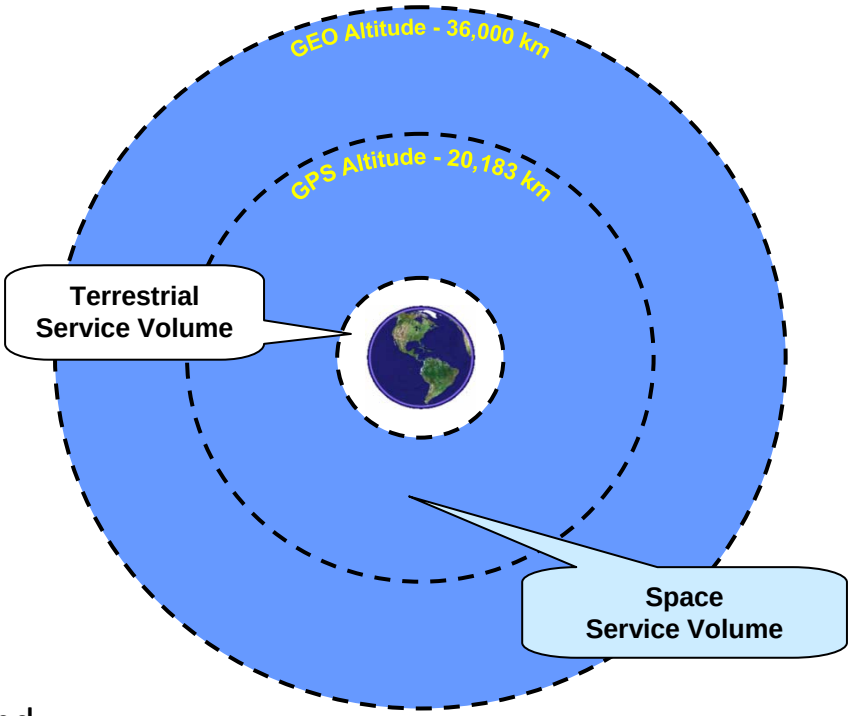
Using GPS Beyond LEO: Reception Geometry for GPS Signals

- When operating at higher orbits, the GPS receiver collects signals broadcast by the GPS satellites on the other side of the Earth
- This is sometimes referred as 'above the GPS constellation' navigation
- Fewer signals are available, and signals are weaker than for Earth-based users.
- Prior to ~2005, no performance specifications existed for GPS signals transmitted above the Earth's limb



Defining the Space Service Volume: GPS Services in Space

- The volume of space where GPS provides PNT service is referred to as a *Service Volume*
- Terrestrial Service Volume (TSV)
  - –The volume of space between the surface, and an altitude of 3,000 km (which includes much of LEO) is referred to as the *Terrestrial Service Volume*, or TSV
  - –Thus, most space users operate within the Terrestrial Service Volume.
  - –The performance characteristics of GPS within the Terrestrial Service Volume are described in the *GPS Standard Positioning Service (SPS) Performance Standard:* http://www.gps.gov/technical/ps/
- Space Service Volume (SSV)
  - –The volume of space between 3,000 km altitude, and geosynchronous (GEO) altitude (36,000 km) is referred to as the Space Service Volume



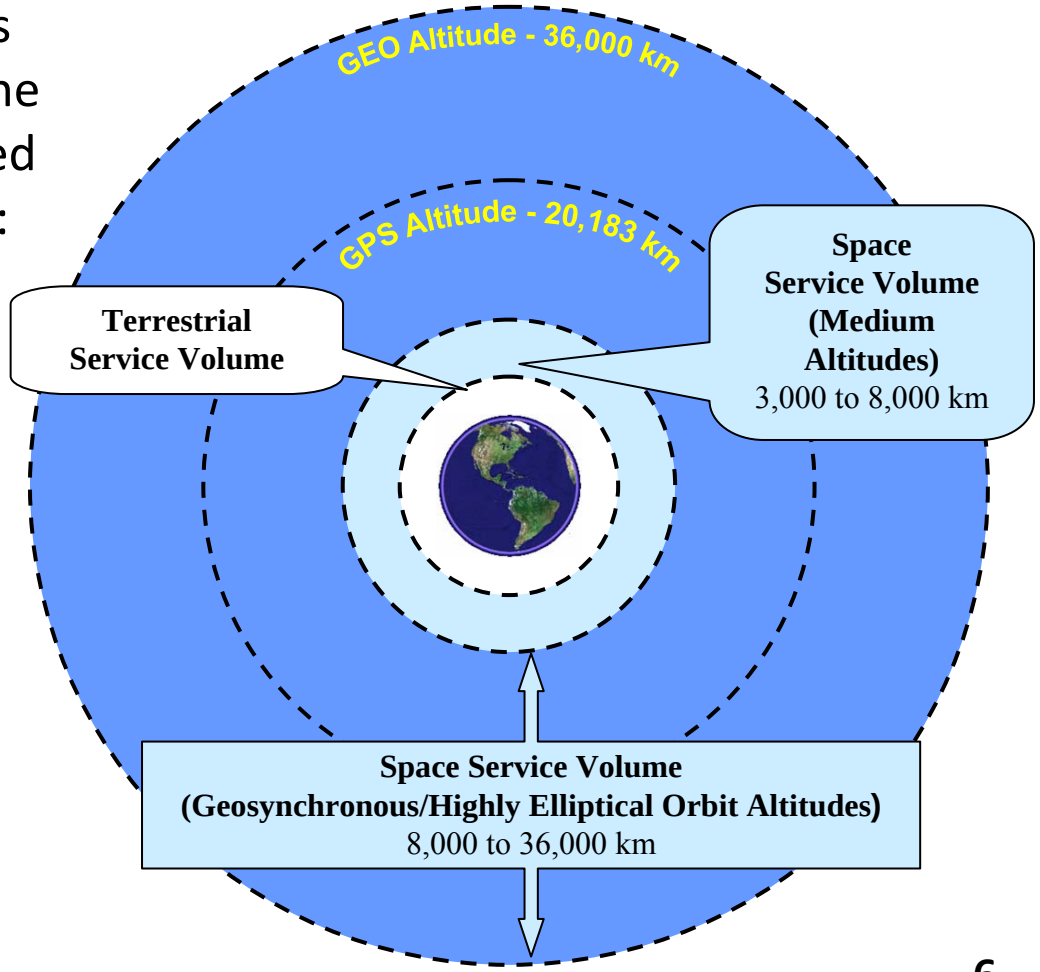
"To scale" visualization of the terrestrial and space service volumes defined to specify space use of GPS

F.H. Bauer, M.C. Moreau, M.E. Dahle-Melsaether, W.P. Petrofski, B.J. Stanton, S. Thomason, G.A Harris, R.P. Sena, L. Parker Temple III, The GPS Space Service Volume, ION GNSS, September 2006.

Defining the Space Service Volume

- Due to GPS performance variations based on altitude and geometry, the overall GPS SSV is in turn subdivided into two separate service domains:

- SSV for Medium Altitudes:
  - 3,000 to 8,000 km altitude
  - Visible GPS satellites can be present both above and below the user
- SSV for GEO/HEO Altitudes:
  - 8,000 to 36,000 km altitude
  - Visible GPS satellites are predominantly below the user



Space Service Volume Characteristics

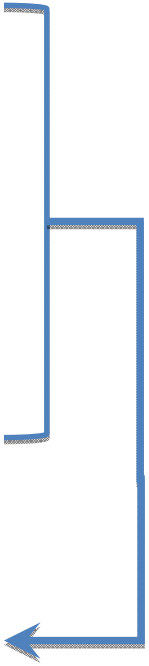
- The characteristics that differentiate the SSV for Medium Altitudes & SSV for GEO/HEO Altitudes are as follows,

- **Medium Altitudes (3,000 – 8,000 km)**
  - Four GPS signals available simultaneously a majority of the time
  - Conventional space GPS receivers will have difficulty
  - GPS signals over the limb of the Earth become increasingly important
  - Wide range of received GPS signal strength
  - One-meter orbit accuracies feasible

- **GEO/HEO Altitudes (8,000 – 36,000 km)**
  - Nearly all GPS signals received over the limb of the Earth
  - Users will experience periods when no GPS satellites are available
  - Received power levels will be weaker than those in TSV or Medium Altitudes SSV
  - A properly designed receiver should be capable of accuracies ranging between 10 and 100 meters depending on receiver sensitivity and local oscillator stability

Specifications to Support SSV Users

- Three parameters are used to determine the characteristics of GPS signals to support positioning, navigation, and timing (PNT) in the SSV
  - **Received Power:** the minimum power level at the GPS/GNSS receiver
  - **Pseudorange Accuracy:** measure of the error contributed by the GPS/GNSS system to the measurement of the distance between a GPS/GNSS satellite and a GPS/GNSS receiver
  - **Signal Availability:** the number of GPS/GNSS satellites in direct line-of-sight with the receiver at any given time



Specifications (1): Received Signal Power

Signal	Terrestrial Minimum Power (dBW)	SSV Minimum Power (dBW)*	Reference Half-beamwidth
L1 C/A	-158.5	-184.0	23.5
L1C	-157.0	-182.5	23.5
L2C	-158.5	-183.0	26
L5	-157.0	-182.0	26

(*) SSV Minimum power from a 0 dBi antenna at GEO

- SSV minimum power levels were specified based on the worst-case (minimum) gain across the Block IIA, IIR, IIR-M, and IIF satellites

- Some signals have several dB margin with respect to these specifications at reference off-nadir point

Specifications (2): Pseudorange Accuracy

- In the Terrestrial Service Volume, a position accuracy is specified. In the Space Service Volume, pseudorange accuracy is specified.
- Position accuracy within the space service volume is dependent on many mission specific factors, which are unique to this class of user, such as user spacecraft orbit, CONOPS, navigation algorithm, and User Equipment.
- Specification: The space service volume pseudorange accuracy shall be ≤ 0.8 m (rms) (**Threshold**); and ≤ 0.2 m (rms) (**Objective**).
- In order for GPS to meet the SSV accuracy requirement, additional data must be provided to users:
  - The group delay differential parameters for the radiated signal with respect to the Earth Coverage signal for users of the Space Service Volume will be provided at http://www.igs.org/products/ssv

Specifications (3): Signal Availability

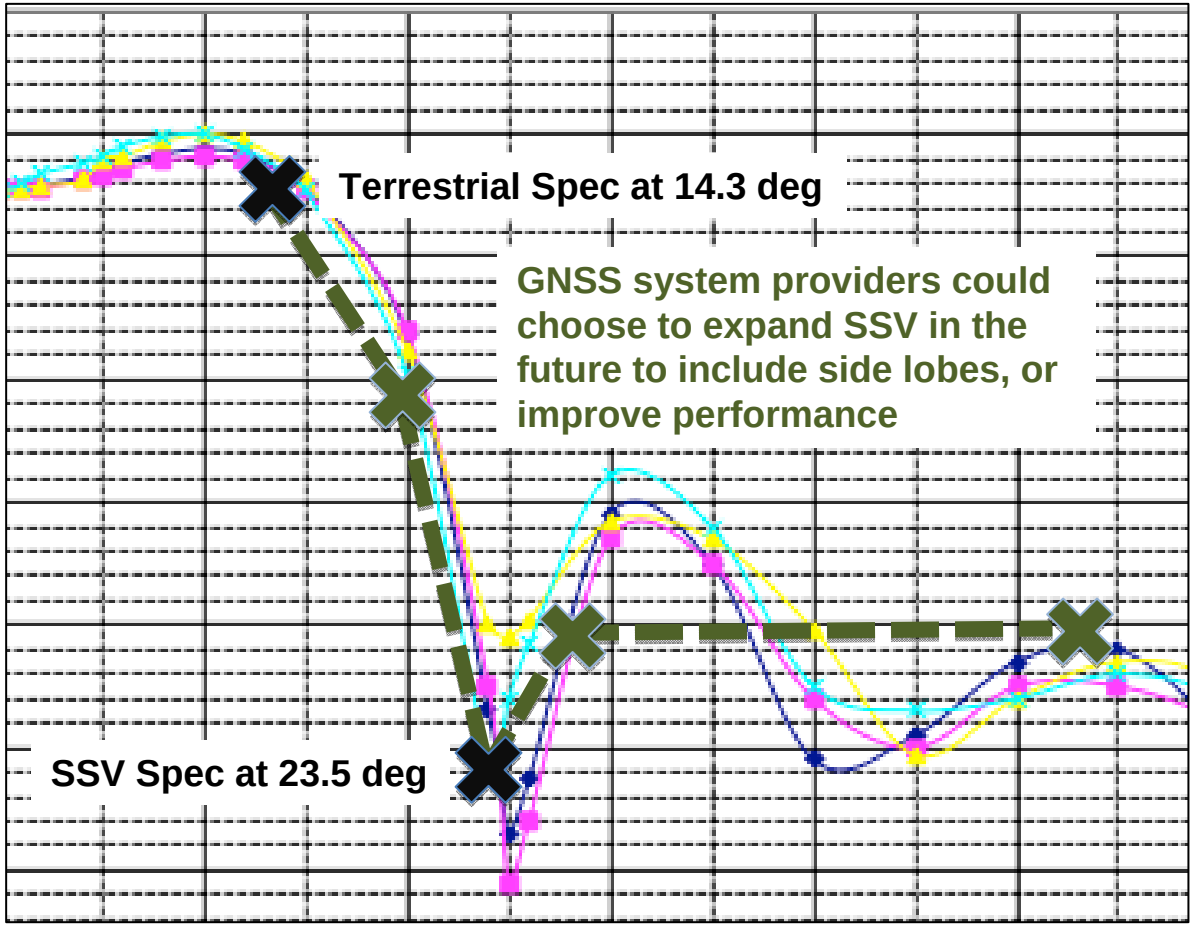
- Assuming a nominal, optimized GPS constellation and no GPS spacecraft failures, signal availability at 95% of the areas at a specific altitude within the specified SSV should be as follows:

	MEO SSV		HEO/GEO SSV	
	at least 1 signal	4 or more signals	at least 1 signal	4 or more signals
L1	100%	≥ 97%	≥ 80% [1]	≥ 1%
L2, L5	100%	100%	≥ 92% [2]	≥ 6.5%

1. With less than 108 minutes of continuous outage time.
2. With less than 84 minutes of continuous outage time.

- Objective:
  - MEO SSV: 4 GPS satellites always in view
  - HEO/GEO SSV: at least 1 GPS satellite always in view

Summary of SSV Requirement, And Future…



- Previously GPS performance was specified only for signals transmitted within 14.3 degrees off-nadir
- SSV added a specification for *minimum power* and *signal accuracy* within wider off-nadir angle (23.5 degrees for L1)
- SSV *signal availability* at a given altitude follows from the specified reference point

- Other GNSS systems could go further – by specifying higher performance levels, specifying performance associated with larger off-nadir angles, etc.

Space Service Volume Status

- Space Service Volume requirements were developed through inter-agency process and formally adopted as part of the GPS III baseline requirements in 2006 timeframe
- GPS III satellites designed to be compliant with SSV requirements
  - Legacy GPS satellites also meet the requirements
- Recent revisions to GPS Interface Specifications (ISs) reflect these new parameters
- NASA and other scientific/high accuracy users of GPS continue to look for opportunities to improve the performance of GPS, and increase interoperability with other GNSS systems
  - As a first step, NASA has developed a template to facilitate discussion and documentation of Space Service Volume performance of other GNSS systems

GPS/GNSS Antenna Requirements for Space Users (Terrestrial and Space Service Volumes)

- Space science applications require accurate calibration/stability among carrier phases and ranging codes
  - Measurement of global sea level change requires sub-mm accuracy
  - Gravity field missions require 0.15 ns time transfer and cm-level formation flying
- Science users of GNSS require
  - Transmit antenna knowledge and stability
    - Antenna phase and delay center
    - Variations of phase and delay with angle
  - In signal generation:
    - Determination and monitoring of inter-signal range biases
    - Commensurability among carriers

GNSS Transmit Antenna Requirements for SSV Use

- The antenna performance is also critical for GNSS SSV use:
  - Antenna design should minimize phase and delay variations in the far field
  - The antenna best-fit phase center should be accurately provided to system users
  - A table of phase and delay variations vs angle should be provided to system users
  - Signal availability from the SSV should not degrade with subsequent generations of GNSS satellites

Summary

- NASA and other space users increasingly rely on GPS/GNSS over an expanding range of orbital applications to serve Earth populations in countless ways
- The GPS Space Service Volume introduces a formal specification for GPS performance available to space users, however there is a strong interest in continuing to improve future performance and interoperability with other emerging systems
- The opportunity now exists to expand the GPS SSV concept (**GNSS SSV**) so that all PNT constellation signals are fully interoperable out to GEO, enabling core space domain performance parameters to be well understood, documented, and used
- A template has been provided to facilitate coordination amongst PNT service providers:
  - To assist other PNT service providers in documenting desired performance parameters for current and evolving system Interface Control Docs (ICDs), Interface Specs (ISs), etc.,.
  - To encourage capability and coverage improvements as PNT constellations evolve, modernize, and become more interoperable
  - To assist each PNT service provider with a “stepping stone” in which to work through their own respective organizational bureaucracies towards implementing these space user capabilities