The GPS Space Service Volume

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ABSTRACT

Prior to the advent of artificial satellites, the concept of navigating in space and the desire to understand and validate the laws of planetary and satellite motion dates back centuries. At the initiation of orbital flight in 1957, space navigation was dominated by inertial and ground-based tracking methods, underpinned by the laws of planetary motion. It was early in the 1980s that GPS was first explored as a system useful for refining the position, velocity, and timing (PVT) of other spacecraft equipped

with GPS receivers. As a result, an entirely new GPS utility was developed beyond its original purpose of providing PVT services for land, maritime, and air applications. Spacecraft both above and below the GPS constellation now receive the GPS signals, including the signals that spill over the limb of the Earth. The use of radionavigation satellite services for space navigation in High Earth Orbits is in fact a capability unique to GPS. Support to GPS space applications is being studied and planned as an important improvement to GPS. This paper discusses the formalization of PVT services in space as part of an overall GPS improvement effort. It describes the GPS Space Service Volume (SSV) and compares it to the Terrestrial Service Volume (TSV). It also discusses SSV coverage with the current GPS constellation, coverage characteristics as a function of altitude, expected power levels, and coverage figures of merit.

BACKGROUND

Until the launch of Sputnik in 1957, orbital maneuvering, let alone space navigation, was not even a practical problem. The ability to maneuver and navigate in space is now a reality with requirements for precision and accuracy that have grown by orders of magnitude [1]. The breakthroughs of radar and inertial-based systems in the 1940s and 1950s, coupled with classic Newtonian analysis, laid the foundation for rocket guidance and space navigation. With the underpinning provided by the laws of planetary motion, navigation in the first two decades of space flight was dominated by inertial and ground-based tracking methods.

GPS was originally designed as a PVT utility for land, maritime, and air applications. Although not specifically designed to provide services to space users, spaceborne applications of GPS were envisioned early in the development stages of the NAVSTAR GPS. Early papers in the mid to late 1970s examined using GPS for Space Shuttle navigation [3],[4]. The first spaceborne GPS receiver was flown in 1982 onboard the Landsat 4 spacecraft [2]. In 1992, the Ocean Topography Experiment (TOPEX/Poseidon) was launched with the objective of better understanding the ocean circulation and measuring sea surface height, wave height, and winds over the global oceans [6]. Instrumental to the mission's success was the data obtained from the NASA-provided onboard GPS demonstration receiver, which has enabled recovery of the satellite position from the Earth's center to within 3 centimeters. More recently, spaceborne applications of GPS in low Earth orbit (LEO) have become commonplace [21], with decimeter-level, real-time onboard performance (and accuracies approaching 1 cm for non real-time applications) representing the current state of the art [13].

Many current space applications of GPS extend far beyond the utility the system was designed to provide. A prime example of this is the exploitation of GPS signals for spacecraft navigation in high Earth orbits (HEO), even in locations where fewer than four satellites are available simultaneously. The first known measurements of GPS signals recorded from beyond LEO were made during a period in 1997 when three different flight experiments launched GPS receivers into highly eccentric orbits extending above the GPS constellation altitude [8],[11]. Other flight demonstrations have followed, including an experiment that began to characterize the performance of GPS side lobe signals [7], and a geostationary Earth orbit (GEO) spacecraft that has been using GPS signals for routine orbit determination for years [9]. Recent advances in GPS receiver design and signal processing capabilities make it feasible to use GPS for autonomous, onboard navigation for GEO or highly-eccentric orbits extending to perhaps 50 Earth radii. Several receivers are becoming available that are specifically designed to operate at HEO, capable of tracking weaker GPS signals and include an integrated orbit determination filter to sequentially process sparsely available pseudorange measurements. Some of the groups that have developed GPS receivers with these special capabilities include NASA Goddard Space Flight Center (GSFC) [12], Astrium, Alcatel/CNES (Center National d'Etudes Spatiales), General Dynamics, and Surrey Satellite Technology Limited.

Given the wide range of GPS applications in LEO such as real-time spacecraft navigation and formation flying, three-axis attitude control, precise time synchronization, precision orbit determination, and atmospheric profiling, it is not surprising there is interest in expanding the utility of GPS to a wider range of space missions such as HEO operations [21]. Engineers and scientists are eager to exploit GPS in HEO orbits to achieve improved accuracy and enable onboard spacecraft autonomy. Improved navigation performance for HEO space vehicles will enable new engineering and science innovations, including improved Earth and Space weather prediction, space vehicle formation flying, and Earth and Space science research, exploration missions to the Moon and beyond, as well as military applications. Some of the specific missions expected to utilize GPS signals in the SSV include the National Oceanic and Atmospheric Administration's (NOAA) next generation of Geostationary Operational Environmental Satellites (GOES) weather satellites, Tracking Data Relay Satellite System (TDRSS) developed by the NASA, a wide range of commercial telecommunication satellites, as well as science and exploration missions such as the Magnetospheric Multiscale (MMS) constellation, Lunar Exploration, and military and international applications. A robust, modernized GPS signal capability for space users will enable innovative satellite concepts to evolve from the civil and DoD communities.

However, HEO operations introduce unique technical challenges as a result of the weak GPS signal levels and poor GPS signal coverage at higher altitudes. Moreover, there exists some mission risk for critical space applications in the HEO environment due to the absence of specifications governing GPS signal strength and availability at these altitudes.

Originally, the specification on the minimum received GPS power levels (for a user on the surface of the Earth receiving a signal at 5° elevation) covered only those GPS signals illuminating the Earth, or GPS transmitter antenna half-beamwidth of approximately 14°. Although space users have demonstrated great utility by exploiting signals outside of this 14° cone, no explicit requirements existed to guarantee that these signals would not change in future blocks of GPS satellites. In fact, significant changes in received power and antenna beamwidth have already been observed in these signals between different blocks of GPS satellites [7]. Requirements on availability of PVT services from GPS were specified only for users on or near the surface of the Earth. This posed significant concerns in the space user community. Space users wanted to benefit from GPS but needed formal assurances that specifications for space user signal strength and satellite availability were incorporated in the GPS system specifications.

The GPS Operational Requirements Document (ORD) [19], released in February 2000 incorporated the first space user requirements, including the first description of a SSV. This ORD was released to support the modernization upgrade of the dual-use signal capabilities expected for GPS Block IIF. The SSV, defined in this ORD, was a shell extending from 3,000 km altitude to approximately the geostationary altitude, or 36,000 km. Space user signal availability and signal level was defined only for Geostationary equatorial users, through specification of gain performance and signal availability of the GPS transmitter antenna at a half-angle of 23.5°.

This paper describes an initiative to create a new SSV definition for GPS and to document formal, comprehensive requirements on the GPS services provided to space users beginning with the GPS III program. The objectives were two-fold: first, to specify a minimum level of performance for users in different regions of interest that would guarantee backward compatibility with the GPS performance enjoyed today, and second, to identify areas in which improved capability or performance might enable new applications or new capabilities in the future. The remainder of the paper describes in detail the characteristics of GPS signals present at HEO, discusses the formulation of the SSV for GPS, and documents some of the supporting analysis that was used to assess current constellation performance and set the requirements that would be adopted for GPS III.

CHARACTERISTICS OF GPS SIGNALS AS A FUNCTION OF ALTITUDE

Apart from the high dynamic effects due to space orbit velocities, a GPS user in a LEO sees similar GPS signal characteristics enjoyed by terrestrial users; GPS satellites are uniformly distributed in the sky, their signals are generally available through a zenith-pointing receiving antenna, and received GPS power levels in LEO are uniform and consistent with GPS signals available on the ground. This is true because users in LEO are still completely within the influence of the primary transmitted beamwidth of the GPS satellites which are directed toward the Earth. In the context of GPS observability, LEO is considered to be any orbit below approximately 3,000 km to 4,000 km altitude. At altitudes above LEO, the user begins to leave the influence of the GPS main beam signals and the signal characteristics and conditions for tracking begin to change significantly.

Figure A illustrates the geometry for receiving GPS signals for a spacecraft that spans a range of altitudes from LEO to beyond GEO. A spacecraft that is in an orbit higher than the GPS constellation must track GPS satellites crossing the limb of the Earth through a nadir-pointing receiving antenna. In some cases a suitably-equipped receiver may be able to acquire GPS side-lobe transmissions at these high altitudes; however, it is important to note that Figure A is a two-dimensional depiction of a three-dimensional problem. Not depicted is the fact that the GPS main lobe and side lobe signals exhibit variations as a function of rotation about the transmitter boresight. Regardless, GPS signals reaching these high altitudes are significantly weaker than the signals available on the Earth's surface due to increased space losses and reduced transmitter antenna gain at larger off-nadir angles with respect to the GPS satellite antenna. Consequently, high-altitude users experience significant outages during which no GPS signals are available at a power level suitable for tracking. Specialized GPS receivers are required to provide increased acquisition and tracking sensitivity as well as an integrated navigation filter for state estimation when fewer than four satellites are available.

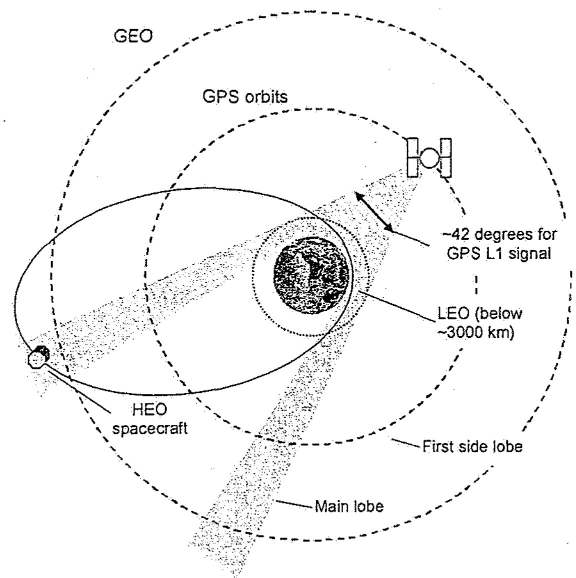

Figure A: Geometry for reception of GPS signals by a HEO spacecraft.

Spacecraft in orbits above LEO but still below the GPS constellation may still benefit from some GPS satellites that are above the vehicle (tracked through a zenith receiving antenna), but rely increasingly on satellites tracked across the limb of the Earth through a nadir receiving antenna. These users may also experience "self-interference," during brief periods when a GPS satellite passes directly over the vehicle within close range (the near-far problem).

Another consideration for high-altitude space users are signal delays, caused when the GPS signal passes through the Earth's ionosphere. Peak electron densities typically occur in the range of 400-500 km altitude, and become negligible above approximately 1,000 km altitude. Peak signal delays may be higher than seen by terrestrial users because the path through the ionosphere is twice as long in some cases. Signals that are more than 1,000 km above the Earth's limb are essentially ionosphere-free, thus a single-frequency GPS user may choose to employ an ionosphere mask altitude below which signals are not used. Alternatively, a dual-frequency receiver may directly measure the differential delay across different carrier frequencies and produce ionosphere-free measurements much closer to the Earth's limb.

Figure B can be used to help understand the changing GPS signal characteristics and varying coverage between zenith and nadir receiving antennas as a function of altitude. The top plot shows the number of GPS satellites visible to a spacecraft as a function of altitude, broken out between zenith and nadir receiving antennas. In LEO, GPS observability comes primarily from the zenith receiving antenna. Above approximately 4,000 km altitude the number of satellites available through a zenith antenna begins to drop off rapidly, obviously reaching zero at the GPS constellation altitude. This plot clearly shows that above approximately 5,000 km altitude, the majority of GPS observability comes from satellites located below the user, tracked through a nadir receiving antenna. This also indicates that a single, hemispherical receiving antenna may not be adequate when GPS signals originate from both above and below the vehicle.

The lower plot in Figure B assumes a user antenna with no gain and illustrates how received power levels vary with altitude. This plot illustrates several interesting points. Most importantly, a majority of the signals present at the higher altitudes are actually weaker than the typical minimum power levels experienced by terrestrial users; however these signal levels drop off gradually with increasing altitude. This plot also indicates that received power levels from satellites tracked through a zenith receiving antenna may be very high when the receiver approaches the altitude of the GPS satellites; although referring to number of GPS satellites tracked through the zenith antenna, these conditions occur infrequently. Ultimately the receiver must be able to accommodate a wide range in received power levels.

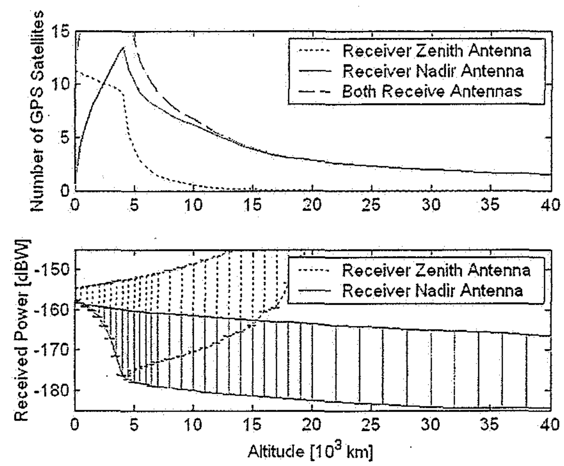

Figure B: (Top) Number of GPS satellites visible and (Bottom) received power broken out between zenith and nadir receiving antennas as a function of altitude. Assumes L1 C/A signals from a Block IIA GPS earth coverage antenna with a 23.5° beamwidth (side lobe signals excluded).

SPACE SERVICE VOLUME REQUIREMENTS FOR GPS III

Based on the unique characteristics of GPS signals as a function of altitude, requirements for GPS performance have been allocated to two service volumes. The TSV which includes all terrestrial and space GPS users extending to an altitude of 3,000 km, and the SSV, which extends from 3,000 km to approximately the geostationary altitude or 36,000 km.

Terrestrial Service Volume: The TSV can be viewed as a shell that begins at the surface of the Earth and extends to 3,000 km altitude. The definition of the TSV extends the same PVT performance enjoyed by terrestrial users to all users up to 3,000 km altitude. The TSV encompasses all terrestrial-based GPS applications as well as the vast majority of existing space applications of GPS. Users in the TSV enjoy uniform received power levels and have fully overlapping coverage from the main beams of the GPS satellites, providing nearly 100% GPS coverage and enabling instantaneous navigation solutions.

Space Service Volume: As stated, the 2000 GPS ORD [19] defined the SSV as a shell extending from 3,000 km altitude to approximately the geostationary altitude, or 36,000 km. An updated definition of the SSV for GPS III creates new requirements for the GPS signals available to space users above 3,000 km altitude. To accommodate the differing needs of users operating in the SSV, the SSV is now further subdivided into two regimes: (1) the medium Earth orbit (MEO) SSV (3,000 km to 8,000 km), and (2) the HEO/GEO SSV (8,000 km to 36,000 km).

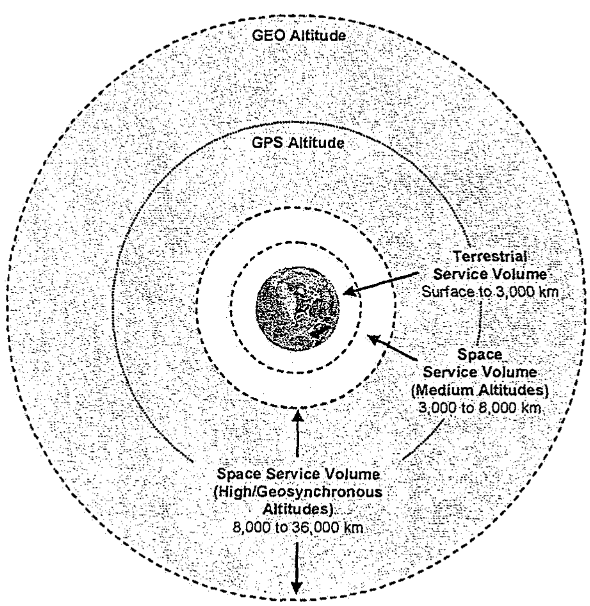

Figure C: Terrestrial and Space Service Volumes

Figure C illustrates the relationship between the three altitude regimes described above. Calling out distinct regions of space allows the varying levels of performance as a function of altitude to be accurately captured. The TSV defines the existing terrestrial requirements for GPS performance to apply up to an altitude of 3,000 km. The MEO SSV is a region of space where four GPS signals will still typically be available simultaneously, and one-meter orbit accuracies are feasible. Within the HEO/GEO SSV, nearly all GPS signals emanate from GPS satellites across the limb of the Earth; users may experience periods when no GPS satellites are available; and received power levels will be weaker than the TSV or MEO SSV. Nevertheless, a suitably-equipped receiver should be capable of sub-100 meter positioning accuracies even at geostationary altitude [23].

Since users in the SSV cannot typically rely on the conventional, instantaneous GPS position solutions, performance requirements are set by specifying three parameters: (1) pseudorange accuracy, (2) received power, and (3) signal availability. Each of these parameters is examined below, and the specific requirements for the SSV are presented along with the supporting analysis or rationale for the requirements.

It is important to note that each service volume covers a range of altitudes, and the GPS performance is known to degrade with increasing altitude. The SSV requirements must be met at the worst-case location within the SSV, which is typically the highest altitude within that region. Although not an explicit requirement, the performance is expected to degrade gradually between one specified altitude and another. The requirements stated below are minimum performance or "threshold" requirements, which are intended to be consistent with the levels of performance provided by the current GPS constellation. In some cases an objective requirement or goal is stated to reflect an area where an improvement in GPS performance would be beneficial to space users. An example of a performance goal that is above and beyond today's GPS performance is that users in the SSV minimize the time when no GPS satellites are available to improve performance and reduce receiver complexity/cost/risk.

SSV PSEUDORANGE ACCURACY

<u>Background and Current Performance</u>
Users in the SSV do not typically utilize the standard instantaneous GPS "point solution." Consequently the quality of GPS performance for the SSV is not specified as a positioning accuracy, but rather as accuracy on the pseudorange observable. The pseudorange accuracy, or sometimes referred to as User Range Error (URE) is basically an error bound on the GPS range measurement and is a function of the accuracy of the GPS orbit and clock solutions generated by the Control Segment, the age of solution (how long since the last GPS broadcast ephemeris upload from the Control Segment), as well as uncertainty in physical and modeling parameters related to the GPS satellites. Due to improvements in the GPS satellites and improved modeling and data analysis techniques used by the Operational Control Segment

(OCS), URE performance has continually improved over the years from a level of approximately 4 to 5 meters in 1990 to approximately 1.1 meters in November 2004 [20].

One of the physical parameters of the GPS satellites contributing to the URE is the uncertainty in the electrical phase center of the transmitter antenna. The antenna phase center is not perfectly co-located with the center of mass of the spacecraft, and the precise location varies between different GPS satellites. Moreover, the apparent phase center location varies as a function of the user's geometry with respect to the GPS satellite. These variations contribute to the observed URE as well as the group delay differential between the different signals transmitted from the GPS satellites. For surface or LEO users (GPS signals transmitted within a half-beamwidth of approximately 14°) these variations are small as the existing GPS satellites have been optimized for these users. Furthermore, significant efforts have been made to precisely calibrate or map these phase center variations for each GPS satellite [13]. Direct measurements of the GPS phase variations corresponding to larger half-beamwidth angles are not yet available, but ground-based tests performed by GPS satellite vendors have indicated larger phase variations for signals at half beamwidths approaching 23.5° for L1 and 26.0° for L2 and L5 where use of the GPS signal in the SSV is critical.

The pseudorange accuracy for the SSV was set in consideration of the URE provided by GPS today, with the provision that a correction may be required to achieve the full accuracy levels for some of the signals available within the SSV. The feasibility of such correction factors are yet to be explored, and if found to be practical, would be provided in the GPS Interface Specification for GPS III.

Pseudorange Accuracy Requirement

The SSV pseudorange accuracy provided by GPS III shall be less than or equal to 0.8 m (rms), with a goal of less than or equal to 0.2 m (rms).

SSV RECEIVED POWER

Background and Current Performance

Received power levels available to SSV users today were evaluated using a MATLAB® simulation of the GPS link budget that models signal path losses and GPS satellite antenna gain patterns for L1, L2, and L5 signals. A determination of the current performance is not completely straightforward because the current GPS constellation consists of a mixture of Block IIA, IIR, and IIR-M satellites, each with different antenna gain characteristics. Thus, the received power was evaluated separately using specific antenna models for each of the Block II/IIA, IIR, IIR-M, and IIF satellites, using data from ground-based tests obtained from the GPS satellite vendors. There have been some direct measurements of actual received power levels in the SSV from previous flight experiments [7],[9]; however the amount of data available on the GPS satellite gain patterns from these experiments is fairly limited. Unfortunately only the data on the Block II/IIA satellites is currently in the public domain and may be included in this paper [14].

The transmitted power of each GPS signal was assumed to be the power required to meet the specified minimum power levels for a terrestrial user, based on the link assumptions from the GPS Interface Specification: The minimum received power is measured at the output of a 3 dBi linearly polarized user receiving antenna (located near ground) at worst-normal orientation, when the GPS SV is above a 5° elevation angle [15]. Using the same assumptions but with atmospheric losses set to zero and a zero dB right-hand circularly polarized (RHCP) receive antenna, it was then possible to determine the nominal received power for a user at different altitudes in the SSV as a function of GPS half-beamwidth angle.

Figure D shows an example of the modeled L1 C/A received power levels from a Block IIA satellite as a function of GPS half-beamwidth. Note that the plot indicates the increased path losses between a terrestrial user and a GEO user are approximately 9 dB. For the GEO user, power levels are highest for the signals closest to the limb of the Earth, but drop off rapidly for larger transmitter off-nadir angles. Beyond 25°, power begins to increase due to gain from the transmitting antenna's first side lobe. The L2 (and L5) transmitter gain generally drops off more gradually than L1, resulting in a slightly wider effective beamwidth for these signals. It is important to note that this plot is the mean or typical L1 received power curve for a Block IIA satellite, and that there is significant variability in the transmitted power from the different blocks of GPS satellites, particularly for off-nadir angles beyond approximately 23°. This variability is to be expected since previously, there was no specification on the received power provided by GPS beyond the limb of the Earth (14°).

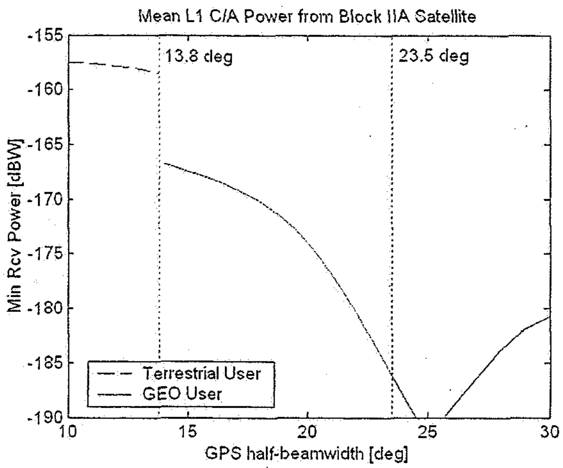

Figure D: Illustration of minimum received power levels as a function of transmitter half-beamwidth angle assuming Block IIA gain pattern [14]

Received Power Requirement
A minimum or threshold SSV received power requirement for GPS III was developed by evaluating the received power provided by each of the existing (and planned) blocks of GPS satellites at a specific transmitter half-beamwidth that would provide approximately uniform received power levels for civilian signals across L1, L2, and L5. For L1 signals, a half beamwidth of 23.5° was chosen. For L2 and L5, a half-beamwidth of 26.0° was used. Table A lists the minimum or threshold received power levels for the individual signals that will be provided by GPS III. The table provides the minimum signal levels for a terrestrial user (TSV), the minimum power level for the SSV, and the corresponding half-beamwidth for that reference power level. This specification guarantees that SSV minimum received power levels on all civil signals (L1, L2, and L5) will be between -184 to -182 dBW. Note that these signal levels are minimums, or the signal levels provided at the worst-case (highest) GPS half-beamwidth angle and the worst-case location within the SSV (GEO altitude). Referring to Figures B and D, the actual received power levels will be higher for signals received at lower altitudes or closer to the GPS nadir direction.

Table A – Minimum Received Signal Power (dBW)

Signal	Terrestrial Minimum Power	Planned Minimum Power in SSV[1]	Reference Half-Beamwidth
L1 P(Y)	-161.5	-187.0	23.5°
L1 C/A	-158.5	-184.0	23.5°
L1 M	-158.0	-183.5	23.5°
L1C	-157.0	-182.5	23.5°
L1 composite	-151.2		23.5°
L2 P(Y)	-161.5	-186.0	26.0°
L2 C/A or L2C	-158.5	-183.0	26.0°
L2 M	-158.0	-182.5	26.0°
L2 composite	-151.5		26.0°
L5 I5	-157.0	-182.0	26.0°
L5 Q5	-157.0	-182.0	26.0°
L5 composite	-154.0		26.0°

1. Levels were obtained by determining the worst case azimuthal cut rather than an average of all the azimuthal cuts.

Referring again to Figure D, obviously some side-lobe signals from the Block IIA satellites exceed the received power provided at 23.5°; however, these side-lobe signals vary greatly from satellite to satellite and were NOT included in the assumed "current GPS" performance. Thus the specified power levels (and availability) cited for the GPS III specification are really a conservative assessment of current GPS constellation performance that considers only contributions from the GPS main lobe signals.

SIGNAL AVAILABILITY

Background and Current Performance
The major requirements driver for spacecraft in the MEO SSV is to maximize the availability of GPS signals, with a goal of four satellites always in view. This region is of particular interest for a wide range of elliptical orbits with perigee altitudes located below 8,000 km and to enable GPS tracking support for the trans-lunar injection burns required for lunar missions in support of the President's Vision for Space Exploration.

The major goal for spacecraft in the HEO/GEO SSV is the availability of at least one GPS signal all the time. This ensures precise on-board timing at all times for users within the HEO/GEO SSV, reducing the need for expensive on-board clocks. It also assures that the vehicle's navigation performance is not degraded during stationkeeping maneuvers where a constant GPS signal enables space users to detect and quickly correct the navigation estimate of the vehicle orbit.

This section summarizes the analyses that support the establishment of SSV availability requirements for GPS III. The analyses were conducted to:

- baseline current GPS performance in the SSV
- determine what is required in GPS III to maintain backward compatibility with space users
- identify potential areas for improved performance

A MATLAB® simulation was used to evaluate GPS signal availability as a function of altitude for two assumed transmitter beamwidths, 23.5° and 26.0°. The nominal GPS constellation used for this analysis is the 27 satellite constellation described in a paper by Massat, et al. [22], which is consistent with the 27 satellite constellation used as a baseline for GPS III planning and analysis. The altitudes examined are listed in Table B. Sensitivity of GPS availability was then investigated subject to additional variations in GPS transmitter half-beamwidth, and changes to the number of satellites maintained in a six-plane GPS constellation. GPS availability was evaluated based purely on whether the user was within the defined GPS transmitter beamwidth, and the line-of-sight was not obstructed by the Earth.

Table B - Simulated Altitudes

Altitude	Comment
300 km	Typical LEO altitude
3,000 km	Border between terrestrial service volume and medium orbit service volume in GPS III specification
8,000 km	Border between medium and high orbit service volumes in GPS III specification
15,000 km	Within HEO/GEO SSV, below GPS constellation altitude
25,000 km	Within HEO/GEO SSV, above GPS constellation altitude
36,500 km	Approximate limit of HEO/GEO SSV, geosynchronous altitude
70,000 km	Approximately twice synchronous, or 12 earth radii (Re) radial distance

At each altitude, a grid of evenly-spaced points was generated covering all latitudes and longitudes, as shown in Figure E below. For each grid point, the GPS constellation was propagated forward in time 48 hours (in 60-second steps), and the line-of-sight vectors and L1-link budgets were evaluated for every step in time. The products of a simulation run were time histories of the GPS satellites present and received power levels for every grid point. By computing statistics across all of the grid points, it was possible to estimate global average, best location, and worst location GPS availabilities corresponding to each altitude. The primary metrics examined were:

- Availability of 1, 2, 3, or 4 GPS satellites
- Durations of longest single-fold outages (intervals when no satellites were available)
- Durations of longest four-fold outages (intervals when fewer than four satellites were available)

Each simulation used the baseline simulation parameters listed in Table C.

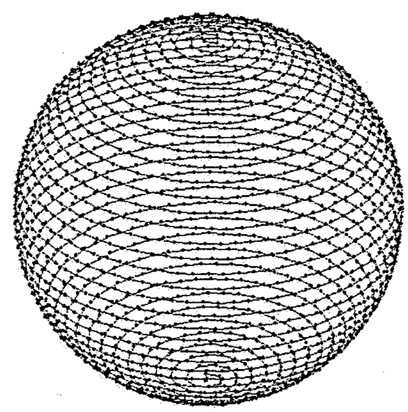

Figure E: Plot of 2000 Grid Points used in a Typical Simulation.

Table C - Baseline Simulation Parameters

Parameter	Nominal Value	Comment
Grid Points	2,000	2,000 grid points results in approx. 6° equatorial grid spacing.
Duration	48 hours	Length of time GPS constellation is propagated.
Step Size	60 sec	Propagation step size.
GPS Half-Beamwidth	23.5° 26.0°	L1 beamwidth assumed to be 23.5°. L2, L5 beamwidth assumed to be 26.0°.
GPS Constellation	27/6	Representative of the current GPS constellation [22]
Availability Constraint	Geometry	Satellite considered visible if line-of-sight is within transmitter beamwidth and not obstructed by the Earth.
Earth Atmosphere Mask	50 km	Satellite considered visible if line of sight does not cross below atmosphere mask altitude.
Epoch	Nov 1991	Simulation epoch is arbitrary, but included for completeness.

GPS Availability for 23.5° and 26.0° Half-Beamwidths

The following plots summarize the availability of GPS satellites and the duration of longest outages (no GPS satellites available) as a function of altitude for transmitter half-beamwidths of 23.5° and 26.0°.

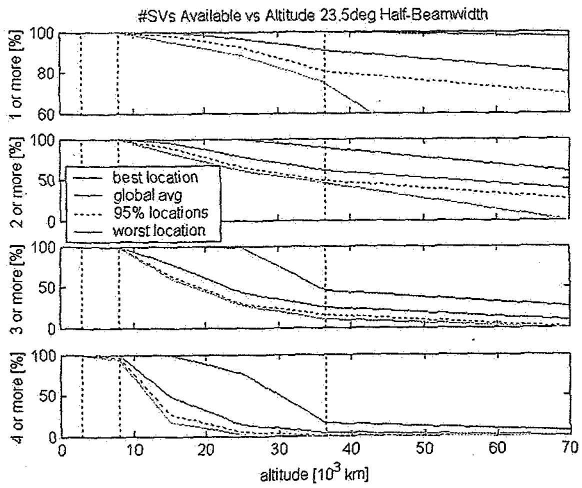

Figure F: GPS availability as a function of altitude for 23.5° half-beamwidth.

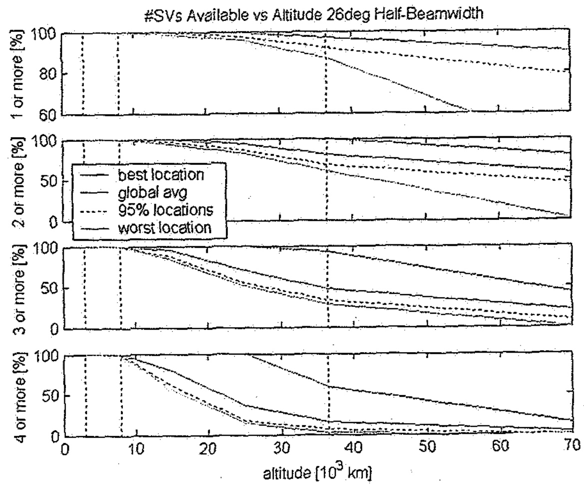

Figure G: GPS availability as a function of altitude for 26.0° half-beamwidth.

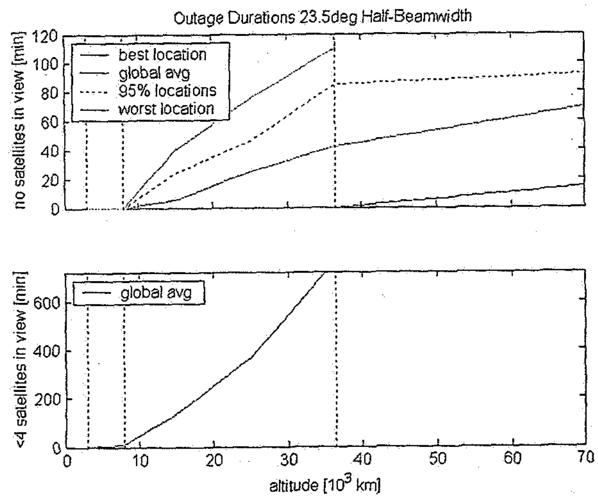

Figure H: Outage durations for 23.5° half-beamwidth.

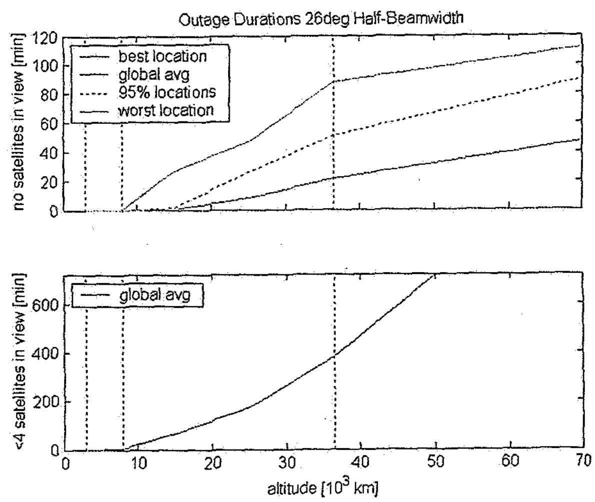

Figure I: Outage durations for 26.0° half-beamwidth.

Tables D and E provide the statistics computed for each transmitter half-beamwidth as a function of altitude. The "Best Location," "Global Average," and "Worst Location" statistics are shown, as well as the "95% Locations" statistic (the minimum performance provided at 95% of the locations at a given altitude). Note that for a GEO user, the single satellite availability (Worst Location) increases from 75% at 23.5° to 87% at 26.0°. Also, the global average outage duration at the geostationary altitude is reduced in half (42 min to 21 min) by increasing the beamwidth from 23.5° to 26.0°.

Table D - 23.5° Half-Beamwidth, 48 Hour Duration

Altitude (km * 10³)	3	8	15	25	36.5	70
Single-Fold Avail. [%]						
Worst Location:	100.0	100.0	95.1	88.4	74.5	0.0
95% Locations:	100.0	100.0	98.2	92.4	80.4	69.4
Global Average:	100.0	100.0	99.6	96.4	90.7	80.0
Best Location:	100.0	100.0	100.0	100.0	100.0	97.4
Four-Fold Avail. [%]						
Worst Location:	100.0	93.9	17.6	2.1	0.0	0.0
95% Locations:	100.0	97.4	27.5	5.1	1.0	0.0
Global Average:	100.0	99.4	49.0	14.4	4.6	1.0
Best Location:	100.0	100.0	100.0	76.6	16.1	6.3
Outage Durations [min]						
Worst Location:	0.0	0.0	40.0	75.0	110.0	2881.0
95% Locations:	0.0	0.0	24.0	46.0	85.0	92.0
Global Average:	0.0	0.0	5.2	24.4	41.6	68.8
Best Location:	0.0	0.0	0.0	0.0	0.0	14.0

Table E – 26.0° Half-Beamwidth, 48 Hour Duration

Altitude (km * 10³)	3	8	15	25	36.5	70
Single-Fold Avail. [%]						
Worst Location:	100.0	100.0	98.1	95.6	86.8	41.2
95% Locations:	100.0	100.0	99.8	97.4	92.0	78.4
Global Average:	100.0	100.0	100.0	99.3	97.1	89.7
Best Location:	100.0	100.0	100.0	100.0	100.0	100.0
Four-Fold Avail. [%]						
Worst Location:	100.0	98.4	54.9	13.4	2.3	0.0
95% Locations:	100.0	100.0	61.4	17.4	6.9	0.0
Global Average:	100.0	100.0	79.0	35.8	15.3	2.8
Best Location:	100.0	100.0	100.0	99.6	58.4	13.7
Outage Durations [min]						
Worst Location:	0.0	0.0	27.0	47.0	88.0	111.0
95% Locations:	0.0	0.0	2.0	26.0	51.0	90.0
Global Average:	0.0	0.0	0.4	8.0	21.4	46.8
Best Location:	0.0	0.0	0.0	0.0	0.0	0.0

Sensitivity to Number of GPS Satellites

Additional simulations were run to evaluate the sensitivity to variations in the number of GPS satellites present in the GPS constellation. The GPS constellations evaluated are described in Table F. The 27/6 constellation was the baseline GPS constellation used in this analysis. Example plots summarizing results for the different GPS constellations follow. Note that the baseline 23.5° transmitter half-angle beamwidth was used in this analysis. Figure J indicates a 10-15% increase in single-fold availability at GEO altitude from adding three satellites to the nominal 27-satellite constellation. Figure K indicates the addition of three satellites reduces the typical single satellite outage duration in half.

Table F - Description of Modeled GPS Constellations

Constellation	Description
24/6	Historical baseline GPS constellation consisting of 24 satellites; 4 in each of 6 orbital planes
27/6	This constellation is very similar to the GPS constellation actually flown in recent years, i.e.: 24 satellite baseline plus three (or more) active spares, and is consistent with the baseline constellation under consideration for GPS III. [22]
30/6	A realistic 30 satellite, six plane constellation, similar to the 24 satellite constellation but with six "expanded slots" for additional satellites.

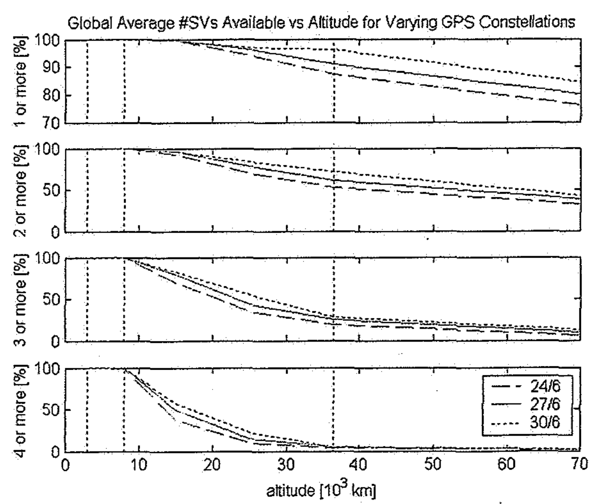

Figure J: Global average of GPS availability as a function of altitude for the 24/6, 27/6, and 30/6 satellite constellations.

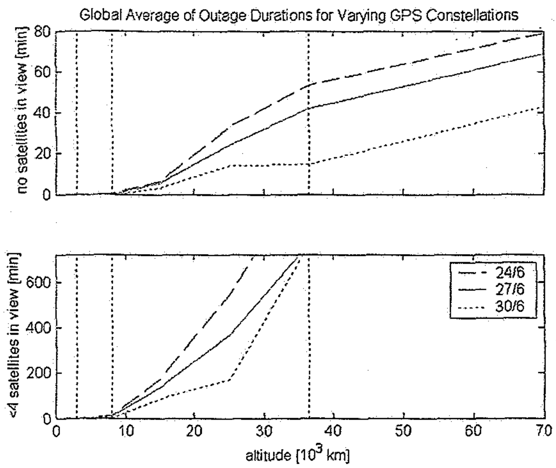

Figure K: The global average of the longest outages as a function of altitude for the 24/6, 27/6, and 30/6 satellite constellations (in six orbital planes). Simply adding three satellites to the six-plane GPS constellation significantly decreases the longest outage duration for users above the GPS constellation.

GPS Availability Through a Zenith Transmitter Antenna on the GPS Satellite

Although not presented in detail in this paper, the contribution to GPS availability from a zenith or "backside" antenna on the GPS satellite was evaluated. A zenith transmitter has long been considered as a means to augment the GPS availability for geostationary users. In Tables D and E it was noted that increasing the GPS half-beamwidth by 2.5° (from 23.5° to 26.0°) improved the worst-location single fold availability from 75% to 87%. To achieve a similar increase in single-fold availability using a zenith antenna on GPS, a 70° zenith half-beamwidth would be required (holding the GPS nadir beamwidth fixed). It should be noted that GPS signals broadcast from the zenith antenna only benefit users above the GPS constellation, and do not provide any improved performance for MEO SSV users.

Signal Availability Requirements

Signal availability is specified separately for the MEO SSV and HEO/GEO SSV. Signal availability is defined as the percent of time over a 24-hour period that the specified numbers of signals meet received power and signal accuracy levels. 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 are planned as listed in Table G.

Table G -Availability of GPS Signals

	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	n/a	100%	≥ 92% 2	≥ 6.5%

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

The signal availability goal is that at least one satellite shall always be in view in the HEO/GEO SSV, and that four or more satellites shall always be in view within the MEO SSV.

CONCLUSIONS AND SUMMARY

There has been significant, growing interest in utilizing GPS for spacecraft navigation in orbits above 3,000 km. However, the space user community was vulnerable to minor design changes in the GPS constellation resulting in major impacts in on-orbit spaceborne receiver performance.

To ensure a robust GPS service that meets the need of civil and military users well into the middle of the 21st century, the GPS III program has specified space user requirements based on analysis and space flight experiments that have flown in HEO.

The space user requirements are defined by a TSV that extends from the Earth's surface to 3,000 km and an SSV that extends from 3,000 km to 36,000 km and is subdivided into two regimes. All three regimes (Terrestrial & 2-Space) include coupled signal strength/availability parameters that have been specified for GPS III. The two SSV regimes encompass a Medium Earth Orbit (MEO) regime from 3,000 km to 8,000 km and a High Earth Orbit/Geosynchronous Earth Orbit (HEO/GEO) regime that extends from 8,000 km to 36,000 km.

Threshold requirements were defined to set the minimum levels of performance required to ensure backwards compatibility with the existing GPS constellation performance, and where appropriate, performance goals were identified that would enable improved navigation performance in the SSV. The major goal for the space vehicles in the MEO volume is to maximize the availability of GPS signals, with four satellites always in view. This ensures robust navigation performance within this volume. The major goal for space vehicles in the HEO/GEO regime is the availability of at least one GPS signal all the time. This ensures precise on-board timing, at all times within the HEO/GEO volume, reducing the need for very expensive clocks on-board. It also assures that the vehicle's navigation performance is not degraded during stationkeeping maneuvers, where a constant GPS signal enables space users to detect and quickly correct the navigation estimate of the vehicle orbit.

These new requirements are a critical step to ensure robust GPS signals in the SSV, opening unprecedented science opportunities for space vehicles within this volume. Improved Earth and Space weather prediction, space vehicle formation flying, and Earth and Space science research, exploration missions to the Moon and beyond, as well as military applications in the SSV will all benefit from these GPS capabilities. These signals will meet the needs of military, civil, and scientific users well into the middle of the 21st century.

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ACRONYMS

CNES – Center National d'Etudes Spatiales
DoD – Department of Defense
GOES – Geostationary Operational Environmental Satellite
GSFC – Goddard Space Flight Center
GPS – Global Positioning System
HEO – High Earth Orbit
ION – Institute of Navigation
LEO – Low Earth Orbit
MATLAB® – Matrix Laboratory
MEO – Medium Earth Orbit
MMS – Magnetospheric Multiscale
NASA – National Aeronautics and Space Administration
NAVSTAR – Navigation Satellite and Timing and Ranging
NOAA – National Oceanic and Atmospheric Administration
ORD – Operational Requirements Document
PVT – Position, Velocity, and Timing
RHCP – Right-Hand Circularly Polarized
RMS – Root Mean Squared
SSV – Space Service Volume
TOPEX – Topography Experiment
TDRSS – Tracking Data Relay Satellite System
TSV – Terrestrial Service Volume
URE – User Range Error

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