The GPS Block IIR and IIR-M Broadcast L-Band Antenna Panel: Its Pattern and Performance

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The Global Positioning System (GPS) Block II Replenishment (IIR) space vehicle (SV) has made up at least one-half of the GPS constellation since 2006. This consists of the 12 original "classic" IIR SVs and the 8 "modernized" IIR-M SVs. As a stepping-stone toward the IIR-M modernization, Lockheed Martin developed and deployed an updated version of the satellite antenna panel for the L-band broadcast signal. This is the signal used by the worldwide GPS user population. This paper describes both antenna panel versions, their broadcast signal patterns, the performance observed in factory testing, and their on-orbit performance. This is the initial publication of these antenna panel patterns. Ground and on-orbit measurements of both versions of the antenna show that all specification requirements are exceeded. They also reflect the increased antenna gain for the new IIR antenna. The L1 signal shows an increase of 1 dB in received power at edge of Earth and L2 shows an increase of 2 dB in received power. All users, both terrestrial and on-orbit, benefit from this enhanced power profile.

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Nomenclature

θ = angle across the face of the antenna panel, deg

φ = angle around the antenna boresight, deg

D = directivity, dB

G = gain, dB

G_{CF} = gain correction factor, dB

I. Introduction

THE Global Positioning System (GPS) Block II Replenishment (IIR) space vehicle (SV) began improving upon its baseline design in 2003 with the launch of the first Block IIR SV retrofitted with a re-designed "improved" antenna panel. This is the Earth-facing panel providing the GPS L-band broadcast signal. This improved antenna panel includes redesigned L-band elements mounted on the SV Earth-facing structure in the same way as the original "legacy" antenna panel. This provided a stepping-stone toward the first new modernized Block IIR-M SV launched in 2005 and has benefitted all GPS users with increased signal strength.

Following a discussion of background concepts (Section II), this paper presents the antenna performance requirements (Section III), highlights design features of both the legacy and improved antenna panels (Section IV), and examines antenna panel performance from factory test data and on-orbit measurements (Section V). Finally, the antenna panel patterns of both antenna designs are also described and presented in this paper (Section VI).

II. Background

In 1989, Lockheed Martin Space Systems Company and its payload system subcontractor, Exelis/ITT were put on contract to build the GPS Block IIR SV (Fig. 1). The direction to modernize 8 of the original 21 SVs into the modernized Block IIR-M version was given in 2001. The exterior view of the IIR-M SV is very similar to the IIR SV (Fig. 1), with the exception of the antenna panel.

Between 1997 and 2009, 20 IIR/IIR-M SVs were placed on-orbit to form the largest portion of the GPS constellation. These SVs, as operated by the Second Space Operations Squadron (2 SOPS) of the Air Force Space Command (AFSPC), continue to provide exceptional accuracy and availability on-orbit [1][2]. The first of the original 21 IIR SVs, Space Vehicle Number 42 (SVN42), was destroyed in a booster accident [3]. The 8 final SVs were retrofitted to incorporate the improved antenna panel, modernized L-band boxes [4][5], and other improved components.

Fig. 1 Two Artist's Concepts of the GPS Block IIR SV

The GPS Block IIR and IIR-M SVs were built with one of two different antenna panel types. The original legacy antenna panel was used on the first 8 of 12 classic IIR SVs. The improved antenna panel was used on the final 4 of 12 classic IIR SVs, and all 8 of the modernized IIR-M SVs. The GPS Block IIR improved antenna includes new antenna element designs and configurations on the panel, which will be described in the next section. Table 1 shows which panel type was used on which SV version, with the SVs listed in launch order from first to last. This table also indicates which 8 of the SVs were modernized from the classic IIR SV configuration to the modernized IIR-M configuration. All SVs with the improved antenna panel benefit from increased power compared to the legacy panel. The 8 IIR-M SVs also provide additional power due to higher power transmitters. These new transmitters have the option to increase power in a few selected configurations. The total power envelope is further increased on IIR-M SVs with the new modernized signals.

Table 1 IIR/IIR-M Versions

SVN (Launch Order)	SV Type		Antenna Panel Type	
	Classic IIR SV	IIR-M SV	Legacy Antenna Panel	Improved Antenna Panel
43	√		√	
46	√		√	
51	√		√	
44	√		√	
41	√		√	
54	√		√	
56	√		√	
45	√		√	
47	√			√
59	√			√
60	√			√
61	√			√
53		√		√
52		√		√
58		√		√
55		√		√
57		√		√
48		√		√
49		√		√
50		√		√

The signal strength for L1 and L2 frequencies is specified by requirements (Section III), and was measured in factory test and on-orbit operation (Section V) with the specific criteria defined at edge of Earth (EoE). EoE is defined as 5° elevation to the ground-based terrestrial user. This is equivalent to 13.8° from antenna boresight for the Earth-facing (nadir) SV antenna panel.

The antenna panel pattern is recorded and presented in terms of beam directivity and phase across the face of the panel. Directivity is the signal power density in a specific direction. Average directivity plots are presented in Section VI for both antenna panel types. SV-specific pattern plots and data, including the directivity, are available online.[‡]

The GPS signal, on each of the L1 and L2 frequencies, is spread through the application of a pseudo-random noise (PRN) code sequence [6]. The classic IIR SVs, with either antenna panel version, have only one code

[‡]SV-specific directivity plots, as well as SV-specific directivity and phase data, are available online at http://www.lockheedmartin.com/us/products/gps/gps-publications.html.

sequence, the precision code (P-code), applied to L2 (thus, abbreviated as “L2P”). On the L1 frequency, there are two different code sequences, C/A and P (thus, “L1C/A” and “L1P”, respectively).

On the newer IIR-M SVs, L1 still has the same two original code sequences as the IIR SVs (L1C/A and L1P), but L2 has a second code sequence, L2C. In addition, both L1 and L2 have side-lobes from a binary offset carrier (BOC) that host the new military code (M-code) sequence (L1M and L2M). These new, modernized code sequences and BOC side lobes increase the total broadcast signal power envelope.

The varying code sequence combinations on the broadcast frequencies affect the signal performance analysis. Comparisons of received signal strength should only be made in terms of code power levels. Combined signal power is generally only applicable to SV system considerations. For example, classic IIR L2P should only be compared to IIR-M L2P, excluding L2C and L2M.

III. Antenna Performance Requirements

Both terrestrial service and space service requirements will be discussed in this section.

A. GPS Terrestrial Service Requirements

The IIR and IIR-M SV broadcast power requirement specifications, as well as factory and on-orbit measured performance data, are quantified in terms of L-band signals and code power at EoE [7]. This is the signal power as received by a terrestrial user. Table 2 shows the L-band power requirements for the various IIR SV configurations and signals. This table lists the IIR/IIR-M SV system-level specification requirements defined by the Air Force. The SV was built to meet these requirements. Also shown in the table are the “derived” total power values for the L1 and L2 frequencies. For L2, this derived value is unchanged since the only code that is carried by L2 is L2P for the classic IIR SV. For L1, the derived total power value is the summation of the L1C/A and L1P values.

The specified received signal strength for the IIR legacy panel (Table 2, column 2) is defined as the signal strength received by a +3 dBi linear antenna. This received strength has been attenuated by a 0.5 dB atmospheric loss for the worst case link (minimum antenna gain and minimum transmitter power) and a 2.0 dB atmospheric loss for the nominal link (nominal gain and transmitter power). The IIR SV with the improved antenna panel was required to meet the same specifications (Table 2, column 3).

The received signal strength for IIR-M is defined in the revised Air Force specification as the signal strength received by a 0 dBi circularly polarized antenna with a 0.5 dB atmospheric loss for the worst case link (minimum antenna gain and minimum transmitter power, averaged about azimuth). The “0 dBi” power levels are specified as -157.7 dBW for L1 C/A, -159.6 dBW for L1P, -157.0 dBW for L1M, -160.0 dBW for L2C, -159.6 dBW for L2P, and -160.0 dBW for L2M. In order to compare the IIR-M specifications with the IIR values, these circular 0 dBi values must be converted into the +3 dBi linear antenna values. This is accomplished by considering the antenna’s axial ratio requirements and the resultant impact to the link. The revised IIR-M requirements, as received by a +3 dBi linear antenna, are roughly equal to the values recorded in Table 2, column 4.

Table 2 IIR/IIR-M SV System Specification L-Band Power Requirements (dBW)

	IIR with Legacy Panel	IIR with Improved Panel	IIR-M
L1 C/A	-160.0	-160.0	-158.7
L1P	-163.0	-163.0	-160.6
L1M	—	—	-158.0
L1 Total (Derived)	-158.2	-158.2	-154.2
L2C	—	—	-161.4
L2P	-166.0	-166.0	-160.9
L2M	—	—	-161.4
L2 Total (Derived)	-166.0	-166.0	-156.5

Table 3 shows the GPS Interface Control Document (ICD) or Interface Specification (IS) performance the user expects [8][9]. The ICD/IS requirements provided guidance to the SV specifications in Table 2. The IIR SV design requirements were originally based on the earlier Revision C specification. The most recent Revision H (as well as every version since revision D) specifies higher power and modernized requirements. The 1.5 dB change in the ICD between Rev C and H is due to the removal of conservatism in the atmospheric losses in the link budget. The table also provides the derived values for the total power on L1 and L2.

Table 3 GPS ICD L-Band Power Requirements (dBW)

	ICD-GPS-200C Block IIR	IS-GPS-200H Block IIR	IS-GPS-200H Block IIR-M
L1 C/A	-160.0	-158.5	-158.5
L1P	-163.0	-161.5	-161.5
L1M	—	—	-158.0*
L1 Total (Derived)	-158.2	-156.7	-154.3
L2C	—	—	-160.0**
L2P	-166.0	-164.5	-161.5
L2M	—	—	-161.0*
L2 Total (Derived)	-166.0	-164.5	-156.5**
Terrestrial Req		Measured at EoE	
Space Service Volume Req		None for IIR/IIR-M***	

* Air Force specification
** Per LMSSC exception letter, L2C should be -161.4 dBW
***GPS IIF and GPS III SSV requirements shown in Table 4 for comparison purposes only

The plots of the minimum received power vs. elevation angle, as specified by ICD-GPS-200, are shown in Fig. 2 for Rev. C [8], and Fig. 3 for Rev. H [9]. The elevation angle range for both plots is from EoE to zenith (SV directly overhead). The curves represent the notional terrestrial service received power.

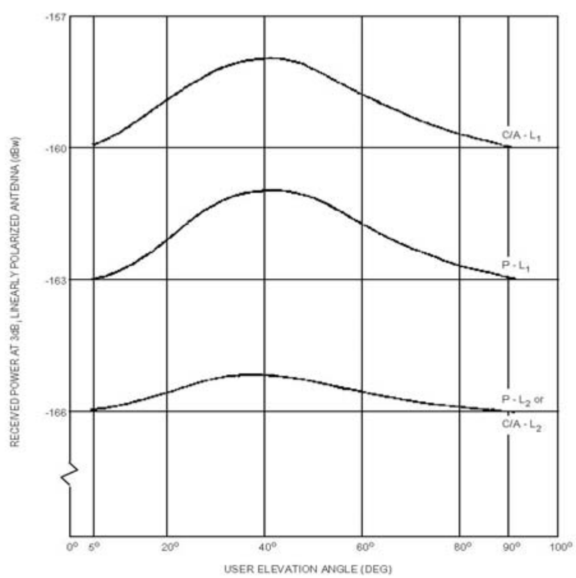

Fig. 2 User Received Minimum Signal Levels (Source ICD-GPS-200C [8])

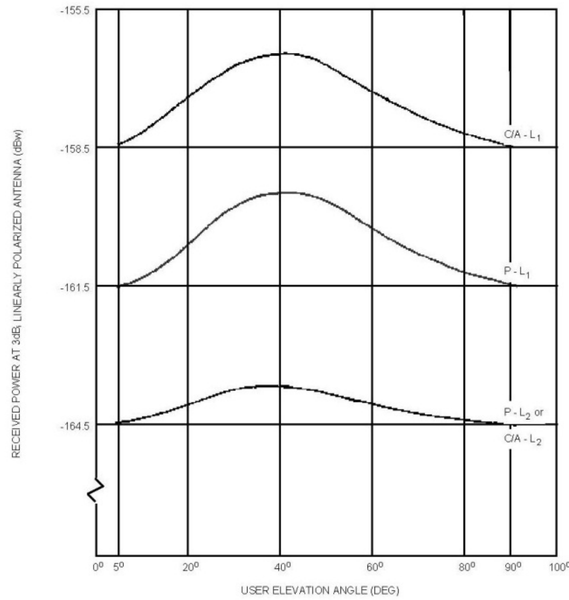

Fig. 3 User Received Minimum Signal Levels (Source IS-GPS-200H [9])

This power is required to extend from nadir to EoE for the classic IIR and IIR-M SVs (13.8° half-cone; a 27.6° cone). This terrestrial service volume is defined as the near-Earth region up to 3,000 km altitude (see Fig. 4).

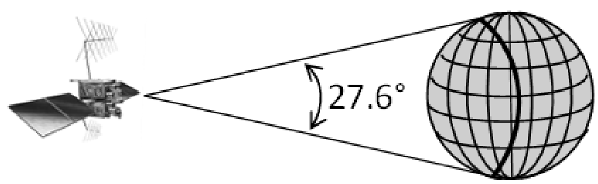

Fig. 4 Earth Terrestrial Service Volume Definition

B. GPS Space Service Requirements

For GPS Block IIF SVs, the broadcast signal also has an orbital environment requirement to extend out from EoE to 23° off-nadir. This is called the space service volume (SSV) (Fig. 5) [10]. The SSV is defined as the spherical shell up to 36,000 km altitude (approximately the geosynchronous orbit altitude). The new GPS III SV also has an SSV requirement which is defined at 23.5° for L1 and 26° for L2 and L5. Table 4 summarizes the SSV requirements for GPS Block IIF and GPS III.

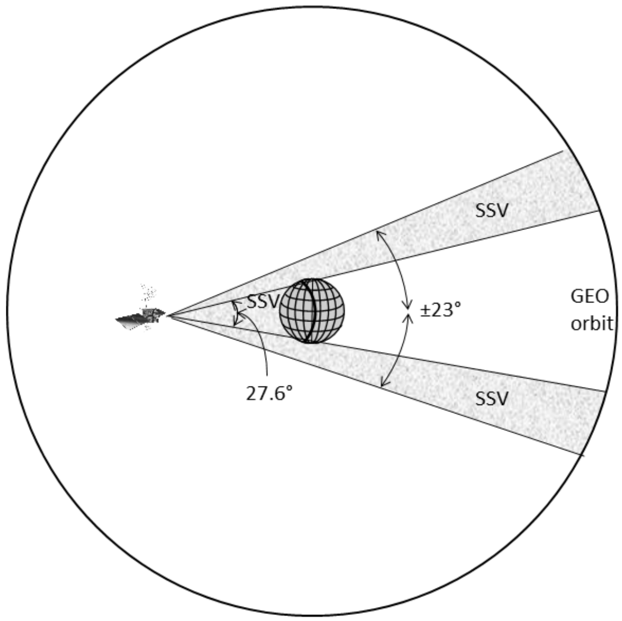

Fig. 5 Space Service Volume Definition

Table 4   GPS Block IIF and GPS III Space Service Volume Requirements

	GPS Block IIF*		GPS III*	
	from EoE out to 20° off-nadir	from EoE out to 23° off-nadir, decrease monotonically down to …	from EoE out to 23.5° off-nadir	from EoE out to 26° off-nadir, decrease monotonically down to …
L1 C/A (dBW) L1 P(Y) (dBW)	< 10 dB decrease	< 18 dB decrease	-184.0 -187.0	N/A
L2 P(Y) (dBW) L2C (dBW)	N/A	< 10 dB decrease	N/A	-186.0 -183.0

*Ref. IS-GPS-200H [9]

The SSV is not a requirement for GPS Block IIR/IIR-M SVs, but some service is available (Section V). Recent SSV use of the GPS signal is reflected in references relating to geosynchronous use such as [11], [12], [13] [14], [15], [16], [17], [18], [19], [20], [21], [22] and [23], references relating to high Earth orbit use such as [24], [25], [26], and [27], and references relating to use for Lunar missions, such as [28], [29], and [30].

IV. GPS IIR/IIR-M Antenna Panel Description

The two antenna panel variations are the legacy antenna panel and the improved antenna panel. This section will highlight some of the basic design features of each, with an emphasis on the differences.

A. Legacy Antenna Panel Design

The GPS Block IIR legacy antenna panel is pictured in Fig. 6. This panel was installed on the first 8 of 12 IIR SVs. It consists of 8 helix elements positioned in a circle with 4 helix elements in the center on the Earth-facing antenna panel. These elements are the taller, thinner, pointed structures seen in the picture. The shorter, thicker, antenna elements seen in Fig. 6 serve the ultra-high frequency (UHF) communications of the SV. This subsystem is beyond the scope of this paper.

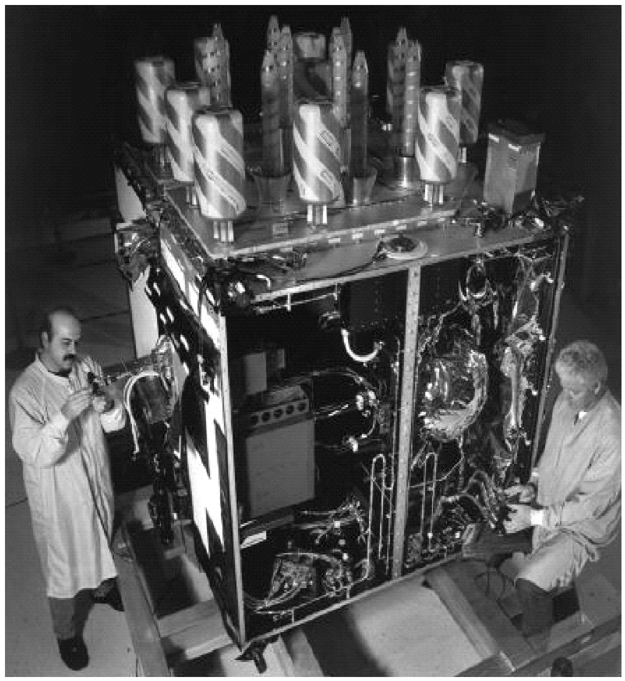

Fig. 6 Legacy (Classic) Antenna Panel

The 12 antenna elements are fed by a low loss Beam Forming Network (BFN) consisting of several coaxial cables and a 12-way power divider. The BFN supplies a weighted signal power distribution to the elements including the addition of a phase offset between the two rings. This differential phasing provides a balanced power over the horizon-to-nadir Earth coverage range of the antenna panel (13.8°). The nominal antenna panel directivity pattern curves from the two rings are shown in Fig. 7. The directivity pattern from the inner ring of 4 L-band elements (a wide-angle broadcast) combined with a phase-offset of the directivity pattern from the outer 8 L-band elements (a narrow-angle broadcast) produces a total pattern with the desired Earth-shaped result. Overall, the array forms a shaped, 27.6° Earth coverage pattern with signal power roll-off and side lobes extending beyond the EoE.

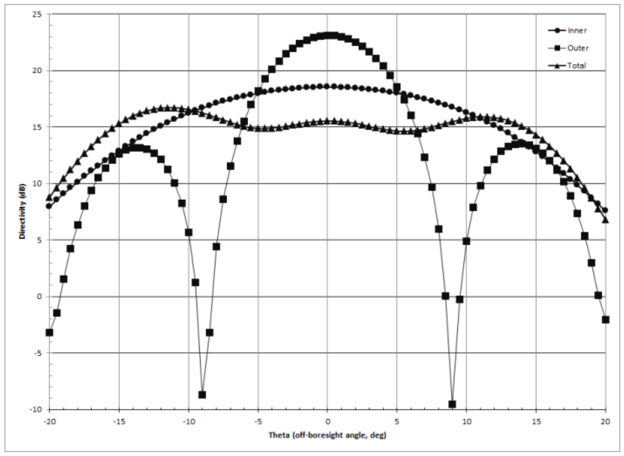

Fig. 7 Nominal Antenna Panel Pattern from Inner and Outer Rings

B. Improved Antenna Panel Design

The final 4 classic IIR and all 8 modernized IIR-M SVs were retrofitted with the improved antenna panel [31]. This panel is pictured in Fig. 8. The new panel reused the existing structure and L-band transmitter interface. New element designs and optimized alignment on the panel provide the improved performance.

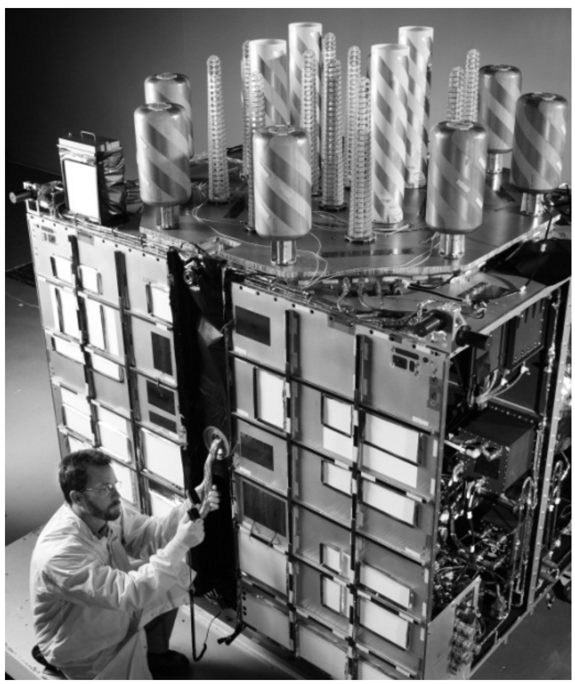

Fig. 8 Improved Antenna Panel

The new L-band elements are formed from copper wire in a helix shape on a tapered G10 core as opposed to the earlier design of copper tape on a cylindrical structure with a conical top.

As with the legacy panel, a BFN distributes the L-band power to the antenna elements. This provides the proper amplitude weighting and phasing between the inner and outer rings.

C. Antenna Panel Coordinate System and SV Mounting Alignment

This section describes the antenna panel coordinate system and the mounting alignment (orientation) of the antenna panel on the SV. This information may be used in conjunction with the IIR SV yaw model [32][33] to predict the alignment of the broadcast L-band pattern at a particular receiver location as is done in references [34], [35] and [36].

The IIR SV body axes are shown in Fig. 9. They are defined as:

- +Z axis directed toward Earth (nadir)
- +Y axis along the "positive" solar array axis
- +X completes right-handed system

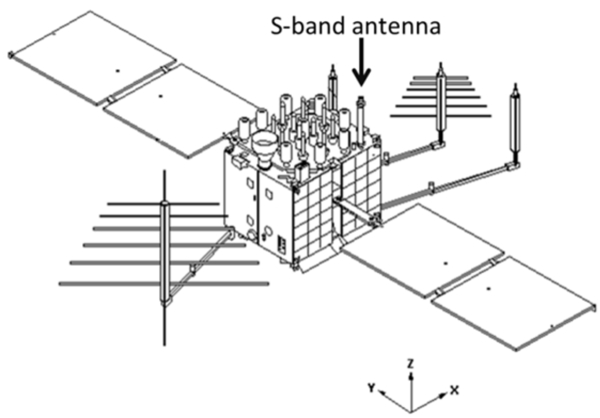

Fig. 9 SV Body Axis Definition

The location of the S-band antenna is identified in Fig. 9 to serve as a reference point. The antenna panel is oriented on the SV such that the tall S-band antenna element is located in the (+X, -Y) corner of the SV structure. Both versions of the antenna panels are mounted to the SV structure in the same orientation.

D. Antenna Panel Pattern Measurement Coordinates

The antenna panel pattern measurement coordinates are defined by two angles: phi (φ) and theta (θ). The angles φ and θ are used in the description of the antenna panel patterns in Section VI. Refer to Fig. 10, Fig. 11, and Fig. 12 for visualization of the φ and θ angle definitions. The view of the SV in Fig. 10 and in Fig. 11 is in the –Z direction (into the antenna panel).

- φ = the angle that is counter-clockwise around the antenna panel boresight (earth-facing) axis with a range of 0° - 360° (Fig. 10). The axis of rotation of φ is around the SV +Z axis (which is in the direction of the SV yaw attitude angle), with φ = 0° referenced to the IIR SV +X axis.
- θ = the angle that is across the face of antenna panel, from the +Y solar array (θ = -90°), through the nadir direction (θ = 0°), to the -Y solar array (θ = +90°) (Fig. 11 and Fig. 12). The axis of rotation of θ is around the SV +X axis. Recall that the EoE boresight angle is defined as θ = ±13.8° for the GPS orbit.

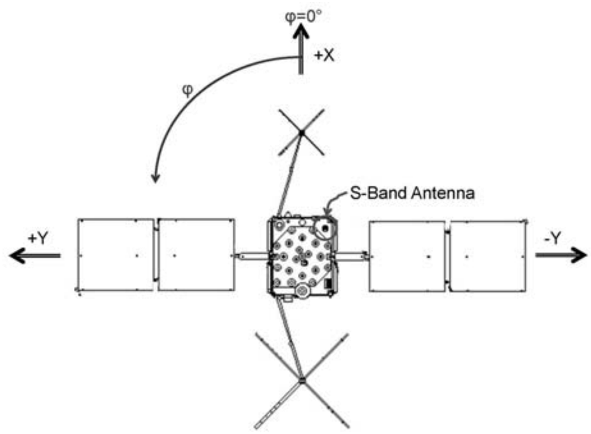

Fig. 10 Antenna Orientation - Around Boresight

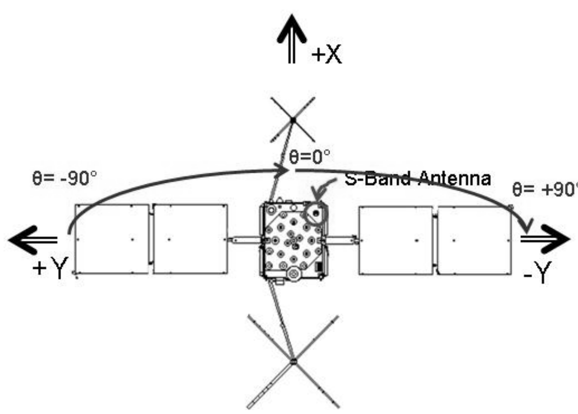

Fig. 11 Antenna Orientation - Off-Boresight

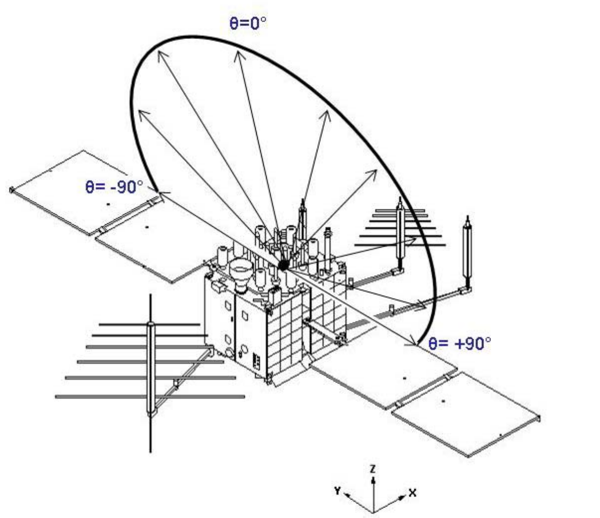

Fig. 12 Antenna Orientation - Off-Boresight, Side View

The antenna panel mounting orientation on the Earth face of the IIR SV is specified as having the panel reference line, φ = -90°, aligned along the -Y SV body axis (SV S-band antenna boom in the “upper right” corner). This can be seen in Fig. 10.

V. The GPS IIR/IIR-M Antenna Panel Performance

This section will present the factory and on-orbit performance measurements for the L1 and L2 signals on both the legacy and improved antenna panels. The focus will be on the signal strength received by the terrestrial user and its comparison with the specifications described previously in Section III.

A. Factory Measured Performance

The legacy and improved antenna panel versions were both tested throughout development. Each antenna panel was characterized prior to installation on the SV structure. The legacy antenna panels were tested in the spherical near-field range at the Lockheed Martin Valley Forge factory. The improved antenna panels were tested in the spherical near-field range at the Lockheed Martin Newtown factory. The developmental panel for the improved antenna was tested in the Valley Forge range and also verified in a compact range in Newtown, PA. Test results of the improved panel showed consistent results over all the SVs exceeding the required specifications for both IIR and IIR-M. On-orbit performance closely matched predictions that were based on factory test data.

The range measurements were made with the antenna deck (ground plane and elements) mounted on an SV Earth-deck simulator which simulated the nadir (Earth-facing) panel of the SV and included all items that are present on the SV. These structures included the Earth sensors, environment sensors, and the S-band antenna mast.

The directivity and phase data were collected at multiple φ angles from 0° to 360°. The step size was 7.5° for the L-band spectrum, which met the Nyquist criteria. The raw measurement data were processed through software that averaged the redundant scans to remove range effects and then processed into spherical modes. From the spherical modes, any far-field or near-field pattern can be generated. The raw data were fairly clean, with very similar far-field patterns resulting from processing the entire file versus processing the "first" or the "second" half of the measurement pattern.

Tests were also performed at Pt. Mugu Naval Warfare Center Radar Reflectivity Laboratory on a range configuration which provided a far-field indoors baseline (Fig. 13). This test on an independent range provided verification of range measurement accuracy and also validated IIR antenna performance for L-band gain and axial ratio.

Fig. 13 Antenna Panel Test Configuration

The factory-measured performance for the improved antenna panel was plotted in comparison with the legacy panel. This is shown in Fig. 14 for L1. These patterns are based on actual measurements of flight panels and transmitters. Measurements from the legacy panel originally built for SVN47 were compared with the improved panel for the same SV once it was retrofitted. This provided a before-and-after check.

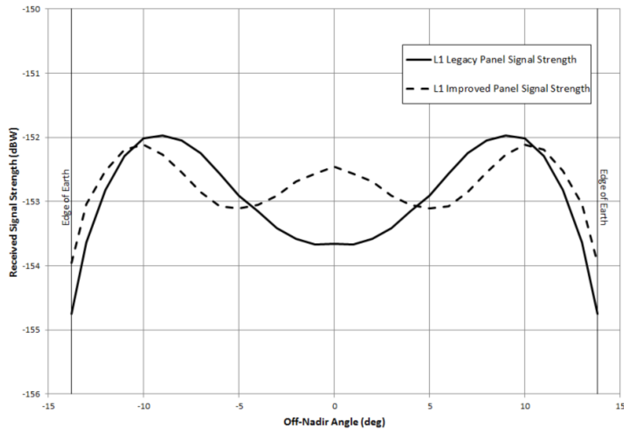

Fig. 14 Factory Measured L1 Total Power - Legacy vs Improved

This figure shows the typical measured performance for L1 total signal power. The legacy panel exceeds the -158.2 dBW derived requirement (Table 3) by over 3 dB at EoE. The improved panel shows an additional improvement of 1 dB (26%) at EoE.

The typical improved performance for the L2 signal is shown in Fig. 15. As with L1, the measured patterns are based on actual measurements of flight panels and transmitters. An improvement of approximately 2 dB (58%) over the legacy panel can be seen at EoE. This improved performance exceeds the IIR L2 requirement (-164.5 dBW) by over 5 dB.

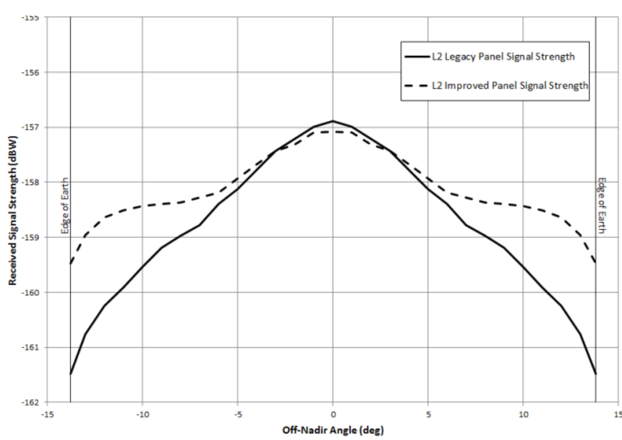

Fig. 15 Factory Measured L2 Total Power - Legacy vs Improved

B. On-Orbit L1 Signal Performance

SRI Inc (formerly known as the Stanford Research Institute) is based in the San Francisco area with the ability to measure the signal power and track the codes of the GPS signals. SRI has a 150 ft antenna and a 10 ft antenna. They perform periodic and event-driven measurements of the GPS signals using either antenna, depending upon availability. Periodic (quarterly or monthly) signal state-of-health measurements are performed for all SVs in the constellation. In addition, as each new SV is launched and the L-band transmitters are turned on, SRI tracks the initial signal to ensure it is performing properly. Measurement accuracy is typically seen to be on the order of 0.5 dB due to local atmospheric conditions and ground-based interference.

A comparison of several GPS Block II, Block IIA, and Block IIR SVs is shown in Fig. 16. This figure shows the L1 frequency total power (L1C/A plus L1P) measured for three candidate Block IIR SVs (SVNs 43, 44, and 46), a representative Block II SV (SVN13), and a Block IIA SV (SVN37). The curves are labeled for the SV number as well as the year and day-of-year of measurement (e.g., “1999-320” for November 16, 1999). Some curves double back from low elevation to high elevation to low elevation if a longer pass was tracked.

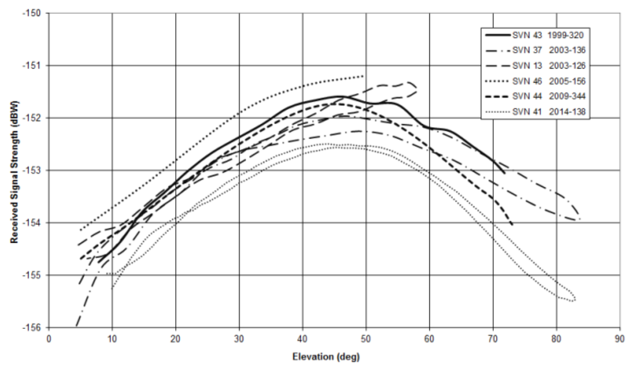

Fig. 16 L1 Power - Block II/IIA/IIR SVs

This data, obtained over a period of several years, shows that the signal strength performance of all SVs exceed the -156.7 dBW derived specification (Table 3). The figure also shows that the curve shapes generally match the notional curve shown in the ICD (Fig. 3). No significant difference can be detected between Block II, Block IIA or Block IIR SV performance.

The L1 frequency measured power is plotted in Fig. 17 for all 8 Block IIR SVs with legacy antenna panels. All SVs can be seen to exceed the specification in ICD-GPS-200 [8]. As with Fig. 16, these measurements were obtained over several years and also show performance similar to the ICD notional curve in Fig. 3.

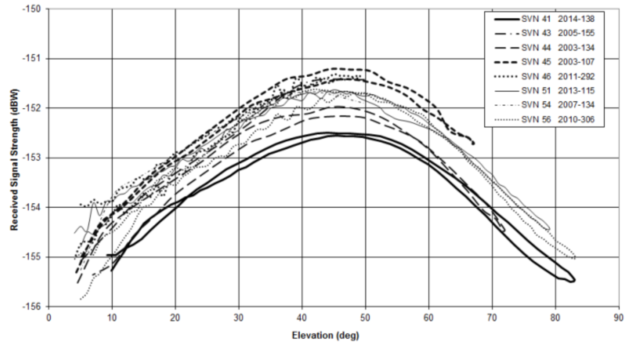

Fig. 17 L1 Power - Legacy Panel Block IIR SVs

SVN43 is the oldest GPS Block IIR SV. SVN43's lifetime trend of measured L1 total power is traced in Fig. 18. The curves cover 15 of its 17 years on-orbit. The plot shows that SVN43 exceeds the specification in ICD-GPS-200 [8] and has had a consistent performance over its entire life span.

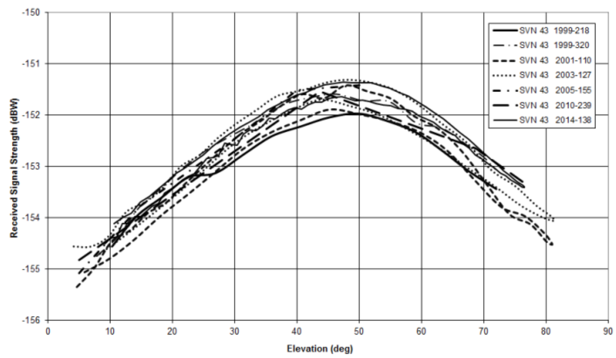

Fig. 18 L1 Power - SVN 43 History, 1999-2014

The L1 signal performance of the improved antenna panels in comparison to the legacy panels is shown in Fig. 19. The four classic IIR SVs with the improved panels are seen in solid lines near the top of the set of curves. The other 8 curves are the 8 Block IIR SVs with the legacy panels. It is clear that the L1 EoE performance is improved by at least 1 dB. For L1 total power at EoE, the improved panel performance exceeds the ICD/IS requirements by at least 2 dB.

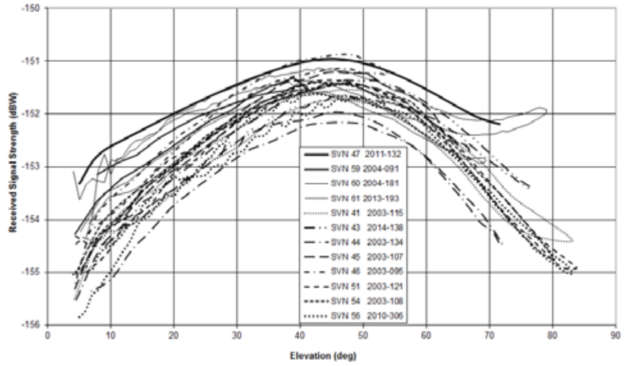

Fig. 19 L1 Power - Legacy vs. Improved Panels

The L1 signal total power measurements for all 8 IIR-M SVs are shown in Fig. 20. All SVs demonstrate consistent performance and all SVs exceed the specified requirements.

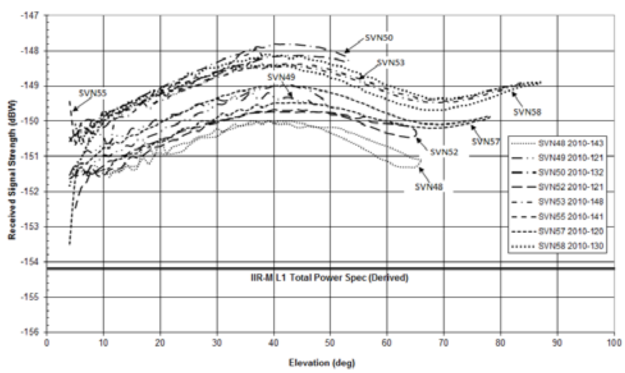

Fig. 20 Power Measurements for All IIR-M SVs – L1

C. On-Orbit L2 Signal Performance

The comparison of the L2 signal performance of the improved antenna panels and the legacy panels is shown in Fig. 21. The four classic IIR SVs with the improved panels are seen in solid lines near the top of the curves. The other 8 curves are the 8 Block IIR SVs with the legacy panels. It is clear that the L2 EoE performance is improved by at least 2 dB. The entire L2 curve, from EoE to zenith, shows general improvement with the new panel. For the L2 signal at EoE, the improved panel exceeds the original ICD/IS requirements by at least 5 dB.

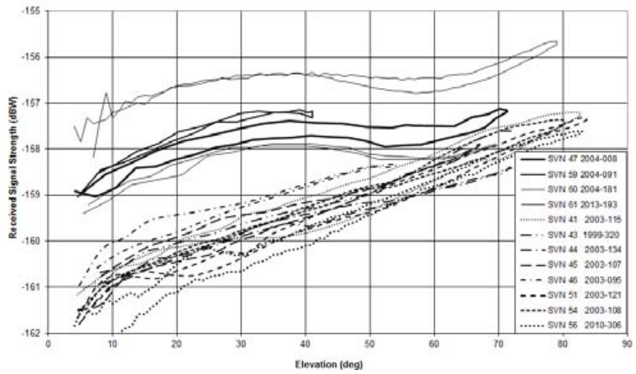

Fig. 21 L2 Power - Legacy vs. Improved Panels

The L2 signal total power measurements for all 8 IIR-M SVs are shown in Fig. 22. All SVs demonstrate consistent performance and all SVs exceed the specified requirements.

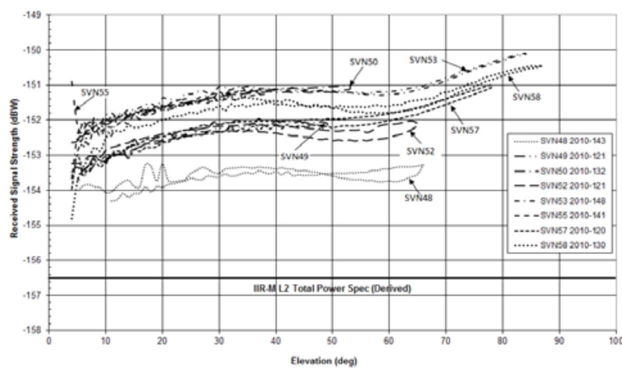

Fig. 22 Power Measurements for All IIR-M SVs – L2

D. On-Orbit Code Power Performance

This section will examine the code power results for both L1 and L2, as opposed to the total power measurements seen in the previous three sections. For L1, the code power comparison is shown for several SVs in Fig. 23: SVN30 (a Block IIA), SVN51 (a Block IIR with a legacy antenna panel), SVN47 (a Block IIR with an improved antenna panel), and SVN53 (a Block IIR-M). The plot shows three groups of curves, distinguishing the several code power levels. The lowest grouping shows L1P power for SVNs 30, 51, 47, and 53, in ascending order based on the EoE values. The middle grouping in Fig. 23 shows L1 total power (L1C/A plus L1P) for SVNs 30, 51, and 47 in ascending order. The top line in the plot shows the SVN53 total power (L1C/A plus L1P plus L1M). Also shown in the figure are the specification requirements to be met at EoE for each of the codes. It can be seen that all SVs exceed the specified requirements. To avoid unnecessary plot complexity, L1C/A is not shown.

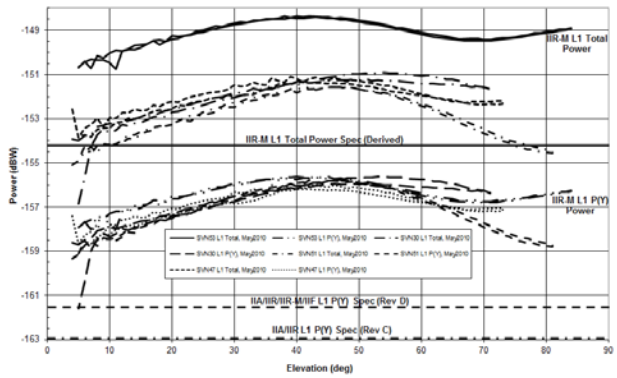

Fig. 23 Code Power Measurements - L1

The L1M and L2M specific power levels have been previously reported [37][38][39] and found to exceed specified required levels at all points.

In a similar fashion, Fig. 24 shows three code power groupings for L2: L2P, L2C, and L2 total. The specification requirements are also shown. This figure shows that all SVs exceed the specified requirements.

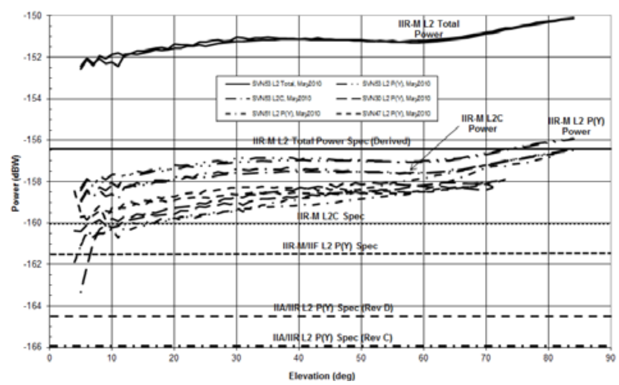

Fig. 24 Code Power Measurements - L2

E. Summation of Performance Results, Terrestrial and Space

Table 5 shows a comparison between the requirements and the performance of the classic IIR SVs with the improved antenna panel. The IIR legacy panel exceeds specifications for L1 (L1P and L1C/A), and for L2 (L2P). The improved panel on the classic IIR SVs (with a higher specification level) exceeds specifications for L1 (L1P and L1C/A) and for L2 (L2P). The improved panel on the IIR-Ms SV (also with a higher specification level) exceeds specifications for L1 (L1P, L1C/A, and L1M) and for L2 (L2P, L2C, and L2M).

The results show that IIR performance exceeds all ICD/IS requirements, and the IIR improved antenna panel provides a stronger terrestrial service signal. The new IIR-M SV also performs better, due to the higher power L-band transmitters combined with the improved antenna panel.

Table 5 Legacy and Improved Panel Results vs. Terrestrial Requirements (dBW)

	IIR System Requirements IIR/IIR-M	ICD Rev C Requirements [8]	IS Rev H Requirements [9] IIR/IIR-M	Classic IIR SV Legacy Panel Measured Performance	Classic IIR SV Improved Panel Measured Performance	IIR-M SV Improved Panel Measured Performance
L1 C/A	-160.0/-158.7	-160.0	-158.5	-157.7	-156.9	-155.2
L1P	-163.0/-160.6	-163.0	-161.5	-159.2	-158.7	-157.9
L2C	—/-161.4	—	—/-160.0	—	—	-158.9
L2P	-166.0/-160.9	-166.0	-164.5/-161.5	-161.8	-159.4	-158.4

Table 6 shows SSV results for both the legacy and improved panels. The results show that some SSV is available from IIR and IIR-M, though not all levels specified for GPS Block IIF and GPS III are met. Recall that the SSV service is not a requirement for GPS Block IIR/IIR-M.

The IIR improved panel provides stronger SSV signal than the legacy panel.

Table 6 IIR/IIR-M Space Service Volume Results

	Though not a IIR requirement, the following service is provided at the levels presented in IS-GPS-200H:			
	L1, at 20° off-nadir	L1, at 23° off-nadir	L2, at 23° off-nadir	L2, at 26° off-nadir
IIR Legacy Panel	At some SV yaw angles	At some SV yaw angles	Yes	At some SV yaw angles
IIR Improved Panel	At some SV yaw angles	Yes	Yes	Yes

VI. The GPS IIR/IIR-M Antenna Panel Pattern

The antenna panel pattern is described by beam directivity and phase around the shape of the panel in θ and φ coordinates. The plots presented in this section are the average directivity for each type of antenna panel at the L1 and L2 frequencies. SV-specific plots and data for the 20 GPS Block IIR/IIR-M SVs are available online.[§] The directivity measurement uncertainty is typically +/-0.25 dB.

Antenna gain (G) is derived from the directivity (D) by applying the gain correction factor (G_{CF}) value for each SV using equation (1).

$$G = D + G_{CF} \tag{1}$$

[§]SV-specific directivity plots, as well as SV-specific directivity and phase data, are available online at http://www.lockheedmartin.com/us/products/gps/gps-publications.html.

The gain correction factor, G_{CF}, is computed from the measurement of a standard gain horn, the measurement of the panel, and the directivities for each frequency. It is the antenna loss in dB at the L1 and L2 frequencies. Table 7 provides the measured G_{CF} values at L1 and L2 for all IIR and IIR-M SVs.

Table 7 IIR/IIR-M Gain Correction Factor (G_{CF}) Values

SVN (Launch Order)	L1 G_{CF} (dB)	L2 G_{CF} (dB)
43	-0.9	-1.1
46	-1.0	-1.2
51	-0.7	-1.2
44	-1.1	-1.0
41	-0.9	-1.1
54	-0.8	-1.0
56	-0.7	-1.1
45	-1.1	-1.2
47	-1.3	-0.8
59	-1.3	-0.8
60	-1.3	-0.7
61	-1.2	-0.8
53	-1.4	-0.8
52	-1.2	-0.7
58	-1.3	-0.9
55	-1.3	-0.8
57	-1.3	-0.8
48	-1.4	-0.9
49	-1.3	-0.8
50	-1.3	-0.8

A. Average Antenna Panel Pattern - L1 Signal

The average L1 directivity pattern from both the 8 legacy and 12 improved panels will be presented and compared in this section. SV-specific plots and data for the 20 GPS Block IIR/IIR-M SVs are available.[**]

[**] SV-specific directivity plots, directivity data, phase data, and accompanying data are available online at http://www.lockheedmartin.com/us/products/gps/gps-publications.html.

1. Legacy Antenna Panel Pattern, L1 Signal

The legacy antenna pattern for L1 is seen in Fig. 25. This figure shows plots of the average of the 8 legacy panels for L1 directivity as a function of off-boresite angle (θ), for φ cuts every 10°. Each of the 36 curves (in φ) in the complex plot is a cut through the broadcast pattern with θ varying from -90° to +90°. The terrestrial service is labeled ("Earth Service") on the plot for θ = -13.8° to θ = +13.8°. The space service is from θ = -13.8° to θ = -90° (the left side of the plots) as well as from θ = +13.8° to θ = +90° (the right side of the plots). These plot ranges cover well beyond the specific SSV definition in Fig. 5.

The Earth-shaped pattern is clearly seen for the designated Earth service region. At the edge of each side of the Earth service pattern, the directivity drops off significantly to the -20° or +20° angle off-boresight. Beyond that, on each side of the plot, the side-lobes of the signal are seen to vary significantly over the changing φ angle.

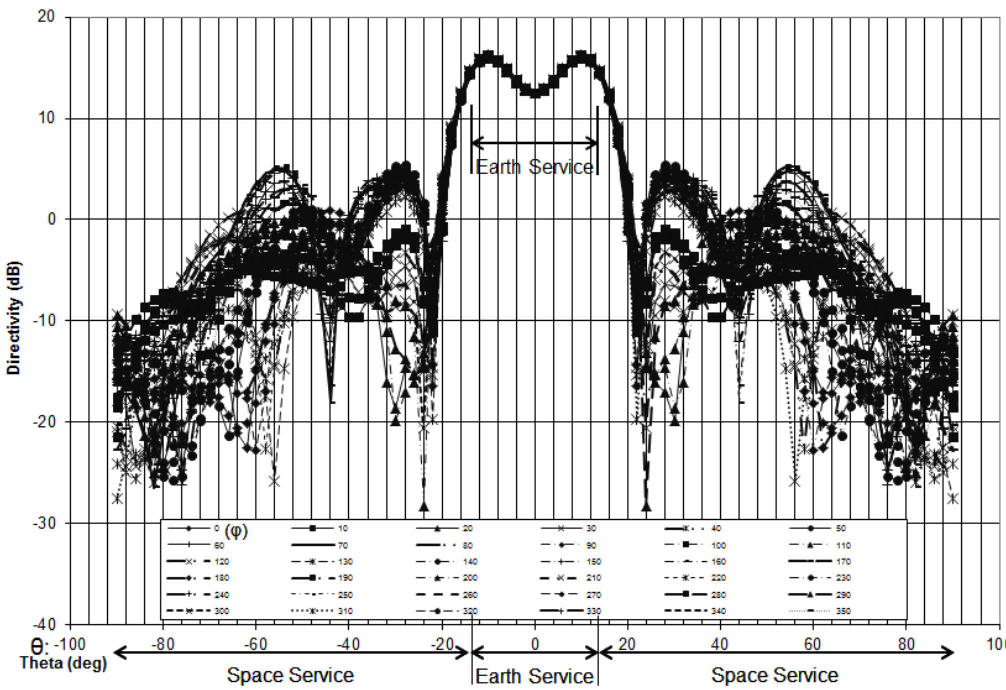

Fig. 25 Average Legacy Antenna Pattern - L1

2. Improved Antenna Panel Pattern, L1 Signal

The improved antenna pattern is seen in Fig. 26. This figure shows plots of the average of the 12 improved panels for L1 directivity as a function of off-boresite angle (θ), for φ cuts every 10°.

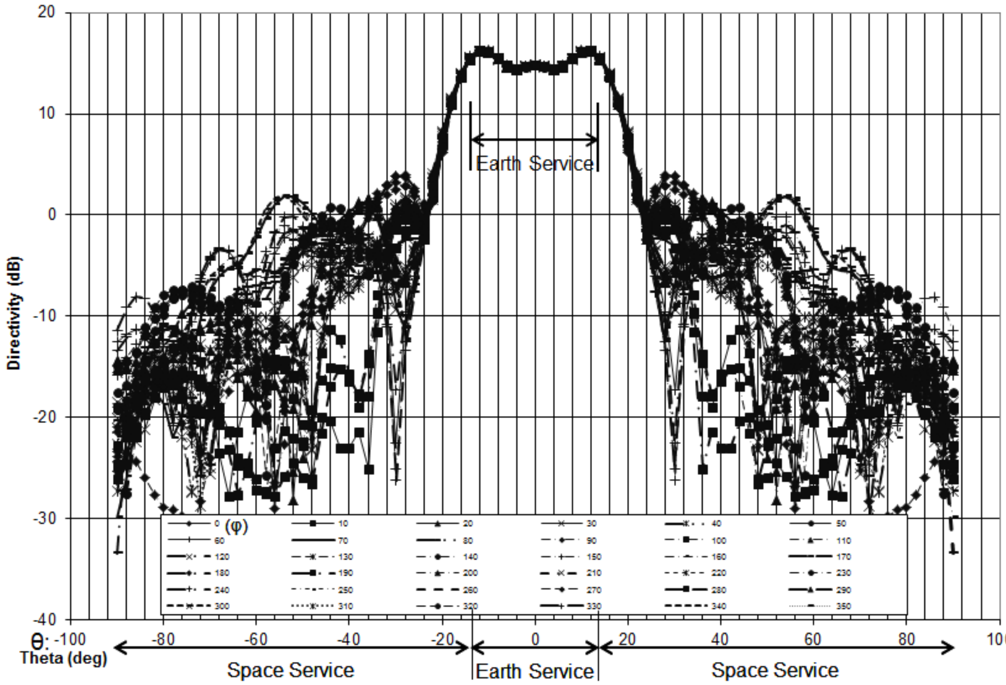

Fig. 26 Average Improved Antenna Pattern - L1

Table 8 presents a comparison between the legacy and the improved antenna panels for the L1 directivity pattern. The terrestrial service is indicated by the EoE performance and the SSV service is indicated by the signal beyond EoE.

It is observed that at EoE, the improved panel signal strength is +1 dB over the legacy panel.

Table 8 Legacy vs. Improved Panel - L1

	Edge of Earth (EoE) (dB)	EoE out to 20°		EoE out to 23°	
		Magnitude (dB)	Reduction (dB)	Magnitude (dB)	Reduction (dB)
Legacy Panel	+15	+4 to -5	-11 to -20	-2 to -19	-17 to -34
Improved Panel	+16	+9 to +5	-7 to -11	+2 to -4	-14 to -20
Change from Legacy to Improved	+1	+5 to +10		+4 to +15	

B. Average Antenna Panel Pattern - L2 Signal

The average L2 directivity pattern from both the legacy and improved panel will be presented and compared in this section.

1. Legacy Antenna Panel Pattern, L2 Signal

The legacy antenna pattern is seen in Fig. 27. This figure shows plots of the average of the 8 legacy panels for L2 directivity as a function of off-boresite angle (θ), for φ cuts every 10°.

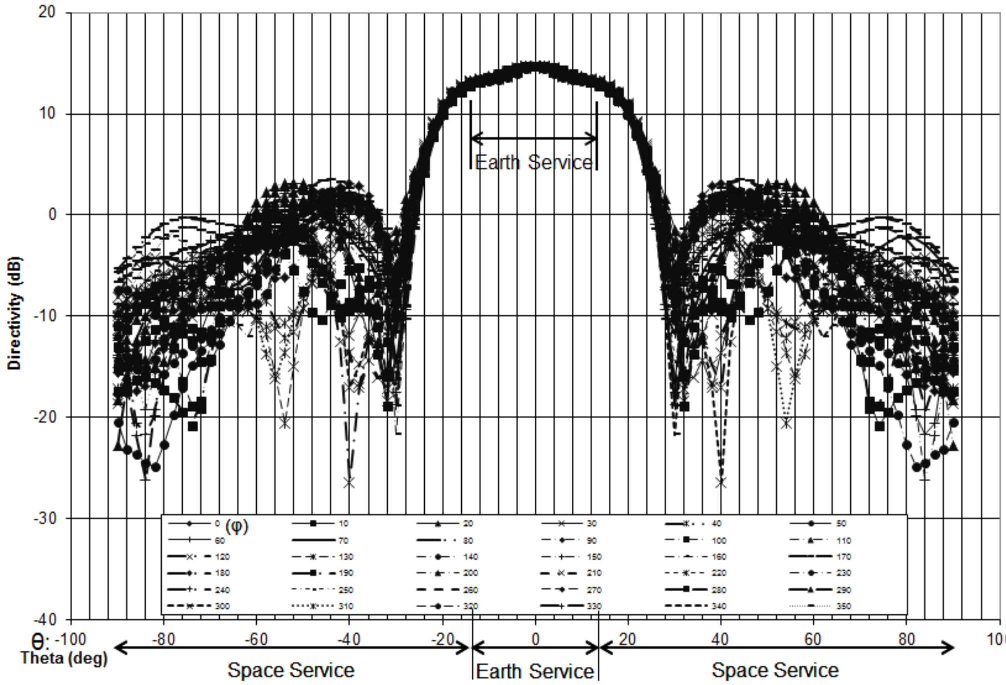

Fig. 27 Average Legacy Antenna Pattern - L2

2. Improved Antenna Panel Pattern, L2 Signal

The improved antenna pattern is seen in Fig. 28. This figure shows plots of the average of the 12 improved panels for L2 directivity as a function of off-boresite angle (θ), for φ cuts every 10°.

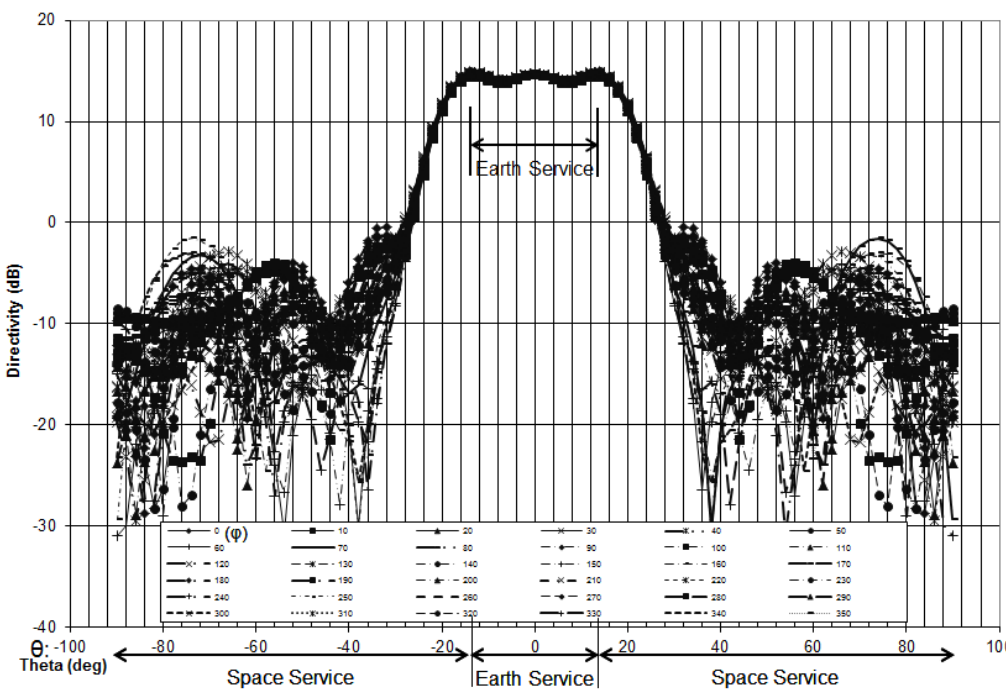

Fig. 28 Average Improved Antenna Pattern - L2

Table 9 presents a comparison between the legacy and the improved antenna panels for the L2 directivity pattern. The terrestrial service is indicated by the EoE performance and the SSV service is indicated by the signal beyond EoE.

It is observed that at EoE, the improved panel signal strength is +2 dB over the legacy panel.

Table 9 Legacy vs. Improved Panel - L2

	Edge of Earth (EoE) (dB)	EoE out to 23°		EoE out to 26°	
		Magnitude (dB)	Reduction (dB)	Magnitude (dB)	Reduction (dB)
Legacy Panel	+13	+9 to +5	-5 to -9	+5 to -3	-9 to -17
Improved Panel	+15	+9 to +6	-6 to -9	+5 to 0	-10 to -15
Change from Legacy to Improved	+2	0 to +1		0 to +3	

VII. Future Work

With 20 GPS Block IIR/IIR-M SVs currently serving as the backbone of the GPS constellation, it is expected that they will continue to provide a quality broadcast L-band service for many years to come. These SVs will continue to be monitored regularly, as they remain active in the GPS constellation.

Additional ground testing is being considered of a spare or engineering design model of the improved antenna panel in a current test facility in order to validate and calibrate on-orbit measurements.

Within the next few years, all of the GPS Block IIF SVs will be launched to replace most of the old IIA SVs. Following this, the new GPS III SVs (Fig. 29) [40] will begin to be launched. The constellation arrangement in Fig. 30 depicts what the GPS constellation might look like in a few years, having a mixture of IIR, IIR-M, IIF, the first few GPS III SVs, and even a couple of lingering IIA SVs.

Fig. 29 GPS III SV

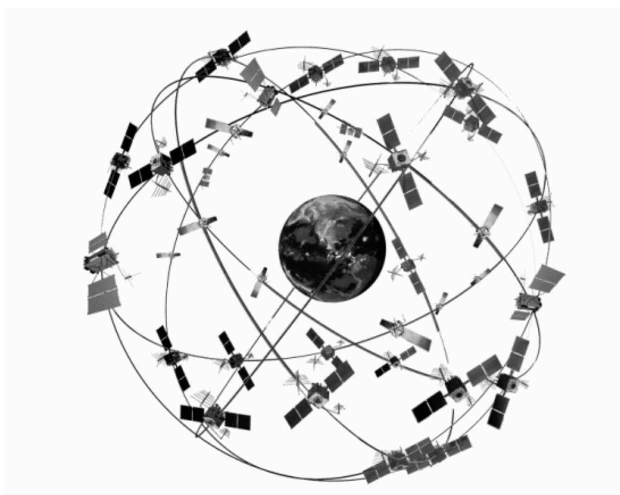

Fig. 30 Possible Near-Future GPS Constellation

Lockheed Martin is currently building the first of the new GPS III SVs. The antenna panel pattern measurements for GPS III are expected to be released at some point after the first SVs have been built, tested, and launched. As with the GPS Block IIR/IIR-M patterns presented in this paper, SSV users are already requesting this information.

VIII. Conclusion

Presented in this paper for the first time are the GPS Block IIR/IIR-M antenna panel patterns. This information is of significant interest to SV designers and mission planners who use the GPS signal in terrestrial or space applications.

The results presented show that the GPS Block IIR and IIR-M SVs exceed all terrestrial service requirements for the GPS broadcast L-band power. The GPS Block IIR and IIR-M SVs provide much of the desired space service volume levels, though these are not applicable requirements to IIR. The GPS IIR improved antenna panel provides stronger terrestrial and space service. Specifically, the improved panel provides at least 1 dB greater received signal strength on L1 at EoE and at least 2 dB greater received power on L2 at EoE. The IIR-M SV also exceeds requirements using this improved antenna panel.

The boost in signal performance should aid tracking by the user in all environments, especially marginal situations such as under dense foliage, in urban canyons, and other signal-challenged environments. This increased performance will enable users to obtain and maintain signal lock in less than optimal conditions.

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