Leveraging the L1Composite Signal to enable autonomous navigation at GEO and beyond

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BIOGRAPHY

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Per Enge is a Professor of Aeronautics and Astronautics at Stanford University, where he is the Kleiner-Perkins, Mayfield, Sequoia Capital Professor in the School of Engineering. He is also the Director of the GPS Research Laboratory, which works with the Federal Aviation Administration, U.S. Navy and U.S. Air Force to pioneer systems that augment the Global Positioning System (GPS). Prof. Enge has received the Kepler, Thurlow and Burka Awards from the Institute of Navigation for his work. He is a Member of the National Academy of Engineers (NAE), a Fellow of the ION, and a Fellow of the IEEE.

ABSTRACT

The Global Positioning System (GPS) was originally conceived to provide the United States military with reliable navigation and timing on and close to Earth. By design, the signals broadcast from the GPS satellites are extremely weak when received on Earth. Signal processing in the user receiver boosts the desired signal to power levels at which they can be acquired and tracked. Today, the primary use of the system is for civilian applications.

The use of GPS and upcoming Global Navigation Satellite System (GNSS) signals for Geostationary Orbit (GEO) and Highly Elliptical Orbit (HEO) missions has special design challenges. In these missions, the GPS receiver is at an altitude above the altitude of the GNSS constellations. Consequently, the only signals reaching the receiver at these altitudes originate from satellites on the opposite side of Earth. The received signals are 10 to 100 times weaker with limited satellite spatial diversity. The Navigator GPS Receiver developed at NASA Goddard Space Flight Center is a space grade receiver with fast signal acquisition and weak signal tracking capabilities. Using the GPS constellation alone, rarely are four or more satellites visible simultaneously. This limits the possibility of autonomous navigation at GEO and beyond.

This paper provides results from a systems engineering analysis of upgrading the Navigator to support multiple constellations. Satellite visibility is evaluated for a combined GPS + Galileo constellation. A combined GPS + Galileo system is chosen to leverage the common L1 composite signal without changing existing rad-hard L1 RF frontends. The analysis assumes the same GPS Block III satellite transmit antenna model for the Galileo satellites as well. Starting with the Block III satellites, the mean beam of the transmitted GPS signals would be enhanced to 23.5 degrees (half angle) compared to the current 21.3 degrees. This will improve visibility of the signal main lobe at GEO and beyond. The Galileo Interface Control Document (ICD) does not specify the transmit signal beam width.

The L1C signal structure allows for lower thresholds compared to the L1 C/A signal. Upgrading the Navigator the support the L1C signal with lower thresholds would significantly improve autonomous navigation in GEO and HEO. At GEO, continuous autonomous navigation is realizable with the combined constellation at current Navigator thresholds. The authors do appreciate the significant implementation challenges in upgrading the receiver. Techniques to achieve lower tracking thresholds for the L1C signal and potential implementation challenges would be addressed in subsequent publications.

INTRODUCTION

Over time, the use of GPS for space applications has been steadily raising. Ingenuity and enhancements in computational capabilities have contributed to this increase. The US government is of the opinion that GPS has transformed the way nations operate in space; from guidance systems for crewed vehicles to the control of communication satellites to entirely new forms of Earth remote sensing. Many of these applications are Low Earth Orbit (LEO) missions wherein the GPS receiver has unobstructed line of site to multiple Medium Earth Orbit (MEO) GPS satellites.

Extending the use of GNSS signals to a wider range of space missions to include GEO and HEO missions is a topic of active research. The use of GNSS signals for such missions will enable new engineering and scientific innovations. These include enhanced Earth and space weather predications, space vehicle formation flying and exploration missions to the Moon. Specific missions which shall utilize GNSS signals include the National Oceanic and Atmospheric Administration's (NOAA) next generation of Geostationary Operational Environmental Satellites (GEOS) weather satellites, the Jet Propulsion Laboratory's Tracking Data Relay Satellite System (TDRSS) satellites, the Magnetospheric Multiscale (MMS) formation flying satellites and potential lunar exploration missions [1].

The use of GNSS signals for Geostationary Orbit (GEO) and during the apogee phase of Highly Elliptical Orbit (HEO) missions poses special design challenges. In these missions, the GPS receiver is at an altitude above the altitude of the GNSS constellations. Consequently, the only signals reaching the receiver at these altitudes originate from satellites on the opposite side of Earth. The received signals are 10 to 100 times weaker with limited satellite spatial diversity [5, 10]. Figure 1 illustrates the notion of GNSS receiver operation "above the constellation". Satellite geometry improvements achievable from a combined GPS plus Galileo constellation is considered in this work.

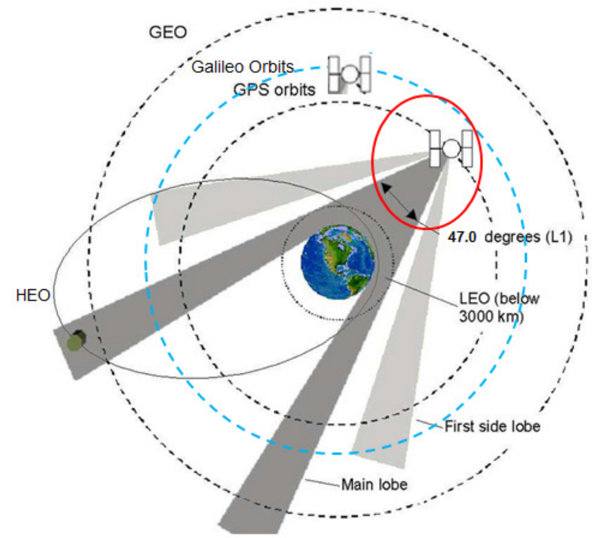

Figure 1: Signal Reception at GEO and Beyond

In its first five revisions, the GPS Interface Control Document (ICD) specified the minimum received GPS power levels for a user on the surface of the Earth receiving a signal at 5 degrees elevation. This specification applied only to those GPS signals illuminating the Earth, using a GPS transmitter antenna half-beamwidth of approximately 14 degrees. Space users benefit from signals outside of this 14 degree cone. Requirements on availability of Position, Navigation and Timing (PNT) services from the GPS satellites were specified only for users on or near the surface of the Earth. No explicit requirements were provided to enable mission modelers to better evaluate guaranteed GPS availability for GEO and HEO missions.

The first official document defining GPS specifications beyond those listed in the ICD was released in February 2000. The GPS Operational Requirements Document (OCD) incorporated the first notion of a GPS Space Service Volume. The SSV, was defined as a shell extending from 3000 km altitude to the geostationary altitude of 36,000 km. Space user signal availability and signal level was defined for Geostationary equatorial users. In particular, gain performance and signal availability was evaluated. The additional recommendation was to enhance the GPS transmit antenna main beam half-angle of 23.5 degrees at the L1 frequency [2].

Starting with the IS-GPS-200F revision of the ICD, explicit specifications characterizing the entire transmit antenna main lobe was incorporated. Tracking signals from the main lobe alone is insufficient to improve geometry at GEO and beyond. This limitation can be substantially enhanced by considering the contribution of the transmit antenna side lobes as well. Using the specifications for the main lobe, analytical models can be derived to characterize the side lobes. This can be achieved using high fidelity computational electromagnetic tools.

This paper can be categorized into three broad sections. Section I describes the modeling methodology and results of a potential GPS transmit antenna layout. No explicit specifications are listed in the Galileo ICD. This work assumes the Galileo transmit antenna performance would be reasonably identical to the GPS transmit antenna performance. The resultant model is used in the sections II and III to evaluate signal visibility and geometry at GEO. Section II considers a combined GPS plus Galileo constellation using only the main lobe of the transmit antenna. Section III considered the main lobe plus the first side lobe extending up to 70 degrees off nadir. The resulting geometry improvement is significant. Further, autonomous navigation can be achieved at GEO at any instant of the day. As a case study, we consider ANIK F1R satellite in sections II and III. This satellite carries a Wide Area Augmentation System (WAAS) payload and is designated as PRN 138. The payload presently broadcasts GPS corrections and integrity information.

GNSS TRANSMIT ANTENNA OVERVIEW

The basis for the GPS transmit antenna design can be traced by to a publication from 1976 [3]. This paper introduces the notion of shaped beam antennas for the GPS satellites. Pencil beam antennas are inefficient for use in satellites which must communicate with the whole of the visible earth. Special beam shaping techniques were shown to be able to yield improvements in earth coverage gain thereby reducing the radiated RF power, which in turn save in the weight of batteries and solar panels.

The paper states that the use of a conventional antenna in GNSS satellites to provide earth coverage is inefficient for two reasons. Power radiated in directions beyond the horizon is totally wasted. Further, more power than necessary is radiated toward the nadir at the expense of the horizon. This can be mitigated by an antenna design where the peak antenna gain isn't at nadir but instead off-nadir. A far field pattern which can generate such a gain pattern is created by a $J_1(x)/x$ illumination function over a circular aperture whose diameter is large enough to encompass the main lobe and first sidelobe ring of the Bessel distribution.

An array antenna has been designed to approximate the $J_1(x)/x$ aperture distribution. The array antenna consisted of twelve helix elements. The main beam of the $J_1(x)/x$ distribution was approximated by four identical helix elements and the first side lobe ring of the $J_1(x)/x$ distribution was approximated by another eight identical helix elements. This layout was the basis of all subsequent GPS and GLONASS transmit antenna designs.

Figures 2 and 3 illustrate the GPS IIA and IIR transmit antenna design and layout. They comprise of 12 helical antennas wrapped around a dielectric core with tapered ends.

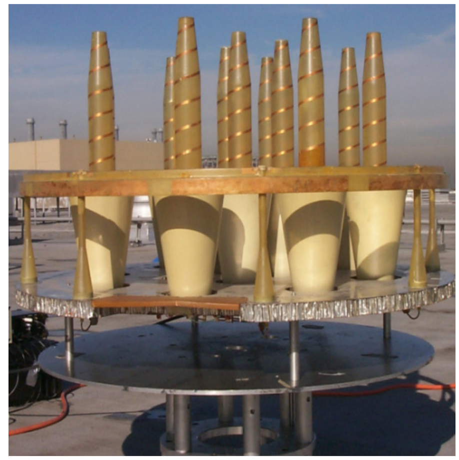

Figure 2: GPS Block IIA Transmit Antenna Array (Courtesy: Boeing)

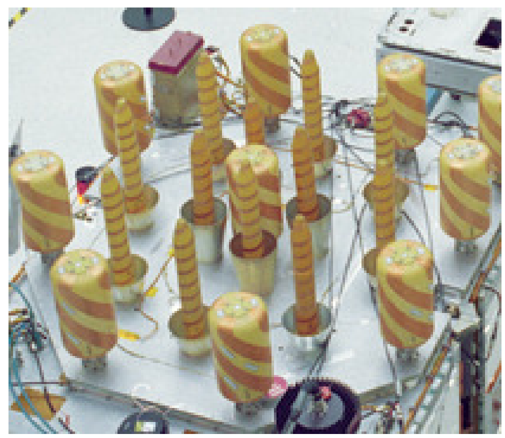

Figure 3: GPS Block IIR Transmit Antenna Array (Courtesy: Lockheed Martin)

Figures 4 and 5 illustrate the GLONASS transmit antennas. It is obvious a design similar to the GPS satellite was adopted for the GLONASS satellites as well.

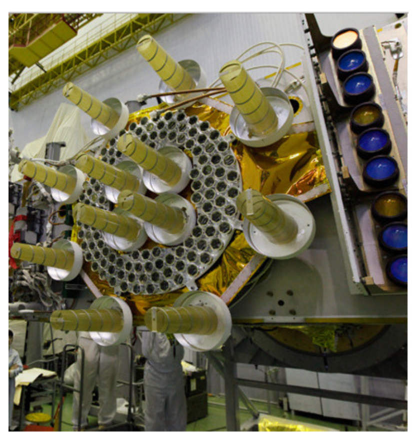

Figure 4: GLONASS-M Transmit Antenna Array (Courtesy: Reshetnev)

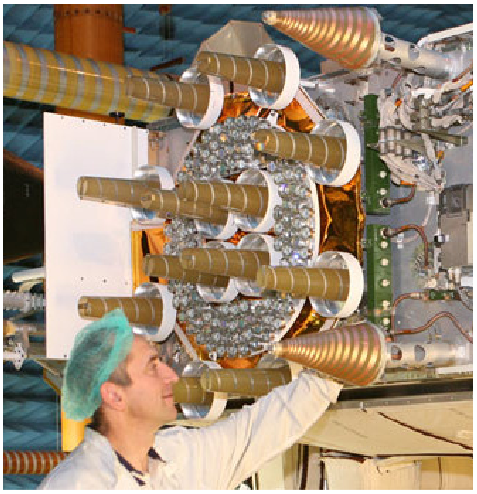

Figure 5: GLONASS-K Transmit Antenna Array (Courtesy: Reshetnev)

The Galileo transmit antenna is a deviation from the helical antenna design. As can be seen in figure 6, the Europeans have decided to adopt patch antennas as their transmit antenna of choice. It is however evident that the fundamental design layout remains unchanged. The main lobe will be generated by the inner four antennas. The first side lobe will be generated from the outer ring of eight antennas. It must be pointed out that there is no publically available information about the Galileo transmit antenna design. The Galileo ICD only stipulates the minimum guaranteed power level for a terrestrial user [4].

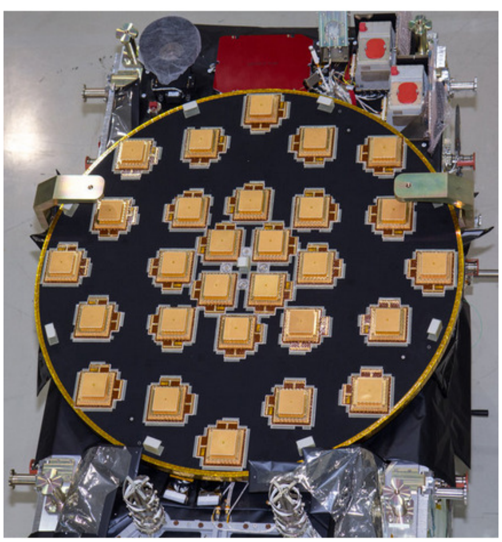

Figure 6: Galileo FOV Transmit Antenna Array (Courtesy: www.technology.org)

MODELLING THE GPS TRANSMIT ANTENNA PATTERN

Starting with the GPS III satellites, the ICD [8] provides explicit specifications for the antenna main lobe performance. The main lobe specifications characterize the expected relative power level with respect to nadir. The Off-Axis Relative Power shall not decrease:

- More than 2 dB from Edge-of-Earth (EoE) to nadir
- More than 10 dB from EOE to 20 degrees off nadir
- More than 19.5 dB from EOE to 23.5 degrees off nadir
- Power will drop monotonically between EoE and ±23.5 degrees off nadir.

A representative main lobe gain pattern is shown in figure 7 which is consistent with the requirements for the GPS Block III antenna specifications. The peak gain occurs not at nadir but 9 degrees off nadir. While the gain at nadir is 13.02 dBi, the peak gain happens to be 14.1361 dBi. The additional gain is necessary to account for the additional path loss the signal will be subject. Further, the gain at the EoE is modeled to be 12.57 dBi. The gain subsequently decreases monotonically down to 23.5 degrees off nadir. The gain at 20 degrees off nadir is modeled as 4.54 dBi. The gain decreases further down to -6.39 dBi at 23.5 degrees off nadir.

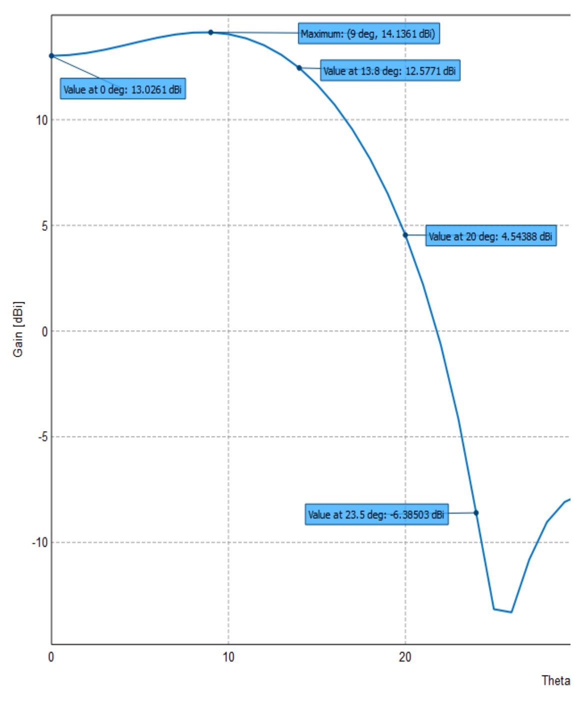

Figure 7: Possible GPS III Transmit Antenna Main Lobe Gain Pattern

The antenna gain pattern shown in figure 7 was obtained using the design methodology illustrated in figure 8. Since [8] does not describe the expected side lobe performance, it was necessary to model the side lobes as well. The only viable methodology to accomplish the twin objectives of modeling both the main and side lobes was to create a representative physical model of the transmit antenna. High fidelity computational electromagnetic (CEM) software was used to model the far field pattern. An iterative approach was necessary to tweak the actual physical geometry of the antenna array. The first step in the design process was to use the best publically available information about the physical design of the transmit antenna design [6, 7]. The next step was to create a CAD model of the physical layout of the antenna array. Finite element method was to finely mesh the constructed CAD model. Time domain and frequency domain CEM methods were applied to evaluate the near-field and far-field response of the antenna array. The relative radii of the inner ring and outer ring control the angular location of the near-circular antenna peak. The elements in the inner circle of the antenna array are fed in-phase with 95% of the total power. The outer circle elements are fed 180 degrees with 5% of the total transmit power.

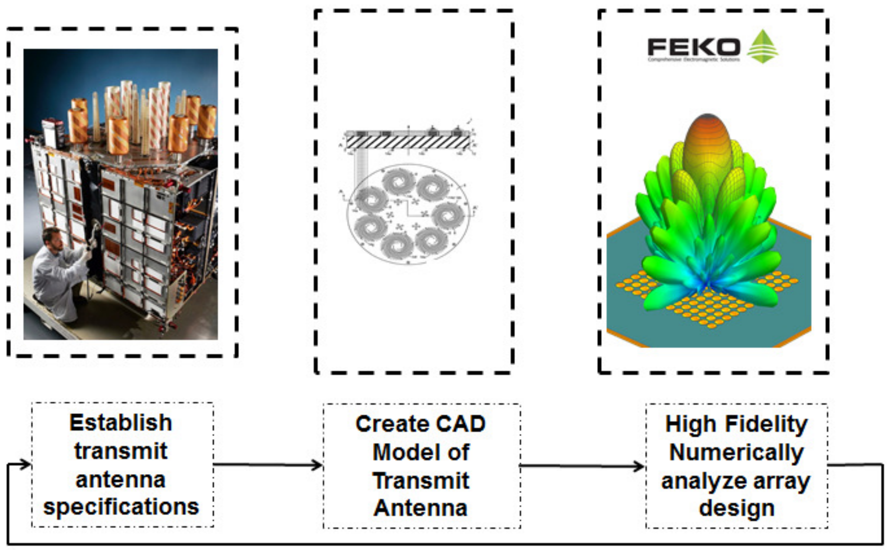

Figure 8: Methodology to Model the Transmit Antenna Far-Field Pattern

Figure 8 is a CAD representation of the GPS transmit antenna layout. The helical antenna design was selected since it is the mostly commonly used in GPS and GLONASS satellites. The helical antenna element is made up of 6 turns with tapered radius over the last two turns. A finite size ground place was considered in the design. A cylindrical helix ground shield was also included in the CAD model.

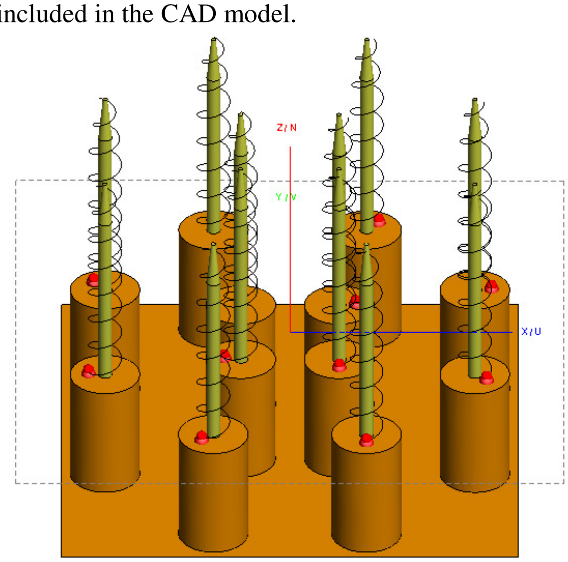

Figure 8: CAD Model of Transmit Antenna Geometry

Figure 9 is an illustration of the model which has been meshed using a finely sized finite element method mesh. The size of the mesh has a direct bearing on the accuracy of the predicated near and far-field gain patterns. The downside to a fine mesh size is the significant increase in the computational burden of running high fidelity CEM on the desired CAD model.

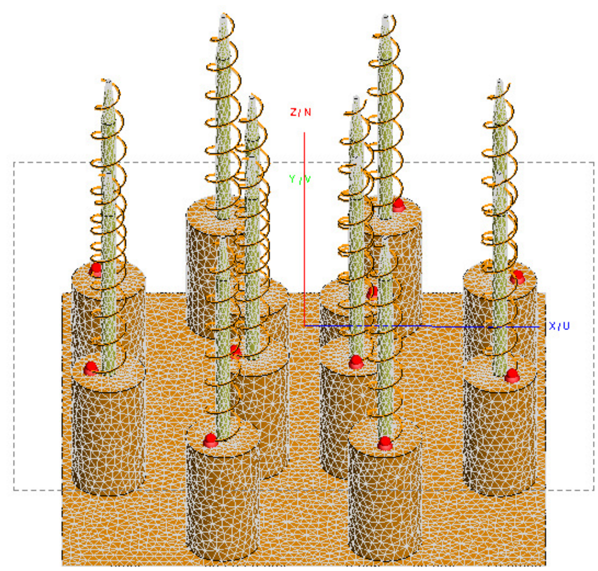

Figure 9: Meshed CAD Model Using Finite Element Method

Figure 10 and 11 depict the result antenna gain pattern obtained using the design methodology shown in figure 7. It is evident in both figures that the peak gain is not at nadir but off-nadir. We also get a first glimpse into the side lobe performance of the transmit antenna. The first and second side lobes are approximately uniform in peak gain. The subsequent side lobes are insignificant. This can be attributed to the effect of the finite ground plane which reduces the amount of back lobe radiation.

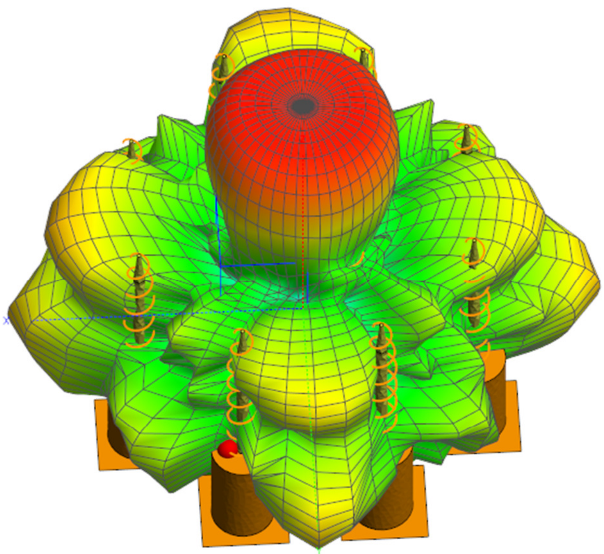

Figure 10: 3-D Antenna Gain Pattern for the Modeled Transmit Antenna Array

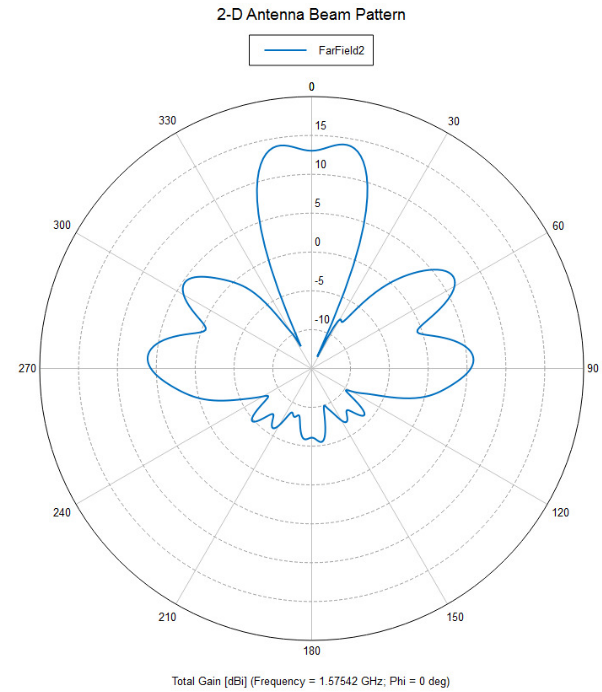

Figure 11: 2-D Antenna Gain Pattern for the Modeled Transmit Antenna Array

Figure 12 is a complete -180 to 180 degree theta span of the resultant far-field gain pattern of the GPS Block III transmit antenna. For the purposes of GNSS visibility and the resultant geometry analysis, only the first side lobe is considered. The first side lobe extends upto 70 degrees off nadir. The expected first side lobe peak gain has been experimentally confirmed in [9]. The AO-40 mission is an Oscar class inter-continental amateur radio communication satellite. The GPS receiver onboard this satellite was able to characterize the side lobe performance of the GPS Block IIA and Block IIR satellites. The side lobe gain for the Block IIR satellites was measured to be about 10 dB lower than the main lobe peak off nadir gain. This experimental measurement further validates the analytical model we constructed to evaluate the main lobe and side lobe performance.

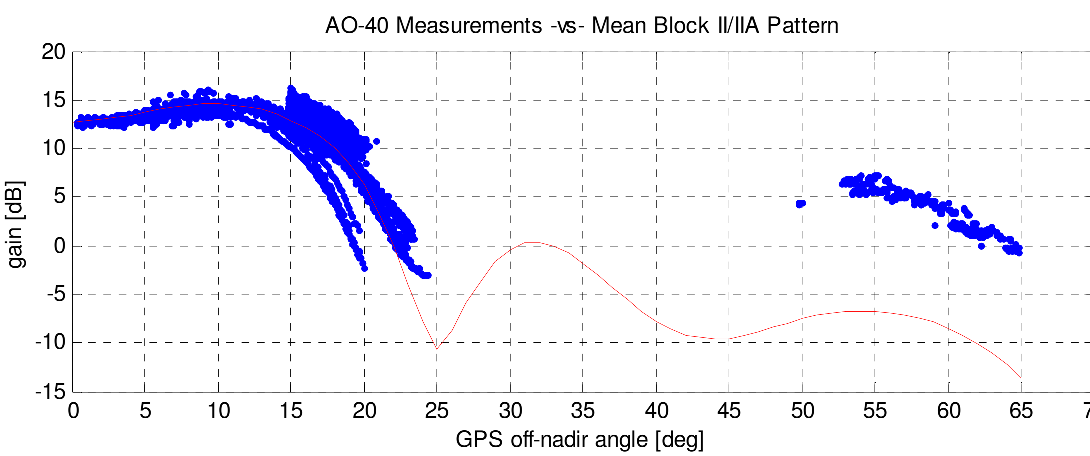

Figure 12: Experimental Results Measuring the GPS Transmit Antenna Side Lobe Gain

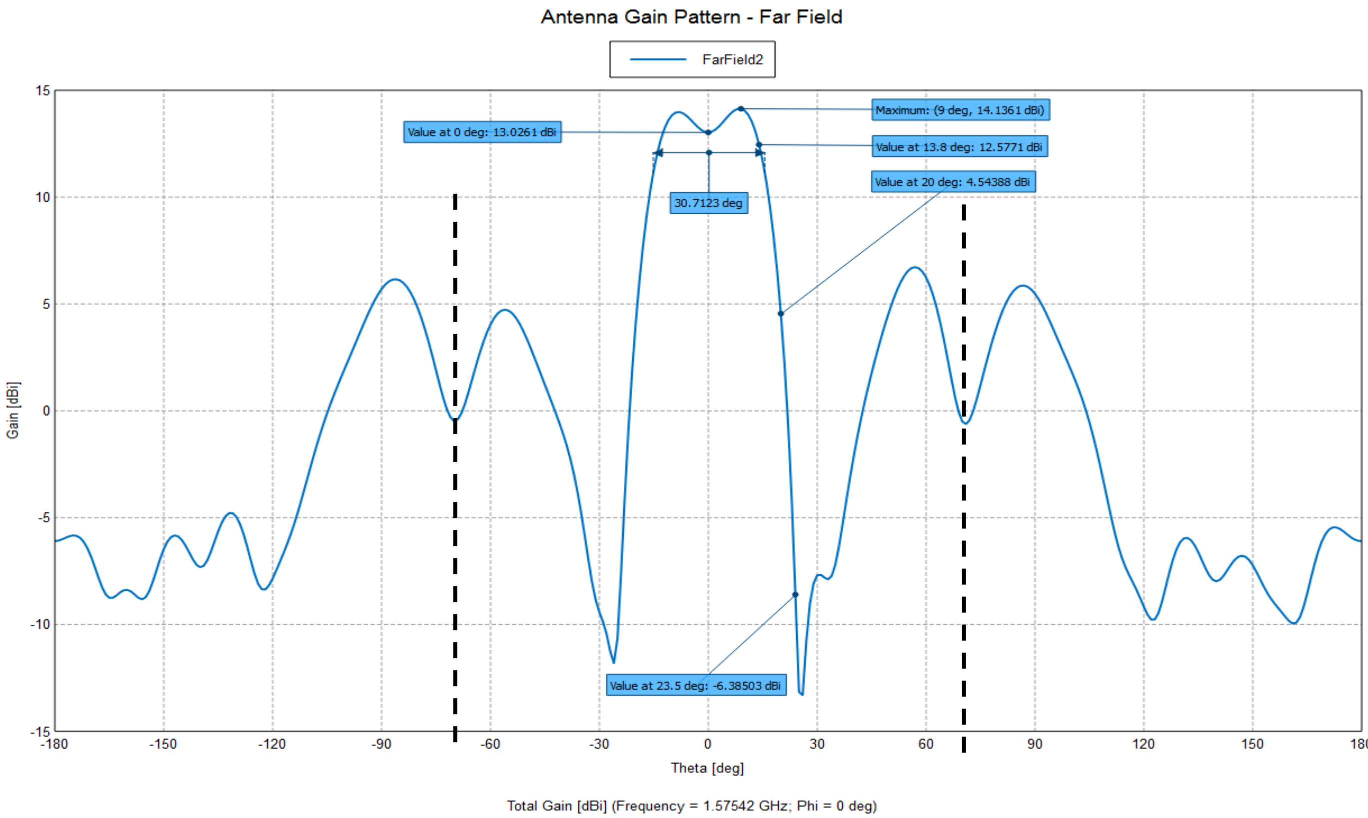

Figure 13: Modeled Transmit Antenna Far-Field Pattern at L1 Center Frequency

VISIBILITY AT GEO – MAIN LOBE ONLY

This section summarizes the availability of GNSS signals at GEO using a transmit antenna gain pattern described in the previous section. In this section, we consider the contribution of only the main lobe of the transmit antenna. The guaranteed end of life L1C signal power at GEO is −182.5 dBW. This threshold value is used in the subsequent sections to evaluate GNSS signal availability onboard the ANIK F1R GEO satellite. In plots which include both the GPS and Galileo constellation, the first 32 PRNs correspond to the GPS satellites. The subsequent 27 PRNs correspond to the Galileo satellites which consist of a Walker 27/3/1 orbit.

Three types of availability plots were generated. The first set of plots illustrate the period of time over a 24 hour duration when each PRN can be viewed at GEO. This timeline plot is generated for three cases: GPS Only, Galileo Only and the combined GPS + Galileo constellation. The second type of plot illustrates the number of satellites visible at any given instant of time over a 24 hour period. This plot will help establish when and for how long, 4 or more satellites are visible. During these epochs, a complete position solution can be obtained. The final plot is a histogram of the distribution of number of satellites visible and the percentage of time over a 24 hour period when each count of number of visible satellites.

The combined GPS + Galileo constellation offers a substantial improvement in the duration of time when four or more satellites are visible. However, as the GDOP plot reveals, the resultant geometry leaves much to be desired. The following table summarizes signal visibility onboard the ANIK F1R GEO satellite.

Table 1: GNSS Visibility at GEO Considering the Main Lobe Only

Constellation	Visibility over 24 Hours	
	At least 1 SV Visible	At least 4 SV Visible
32 SV GPS	80.02 %	6.89 %
27 SV Galileo	94.51 %	12.19 %
59 SV GPS + Galileo	100 %	40.82 %

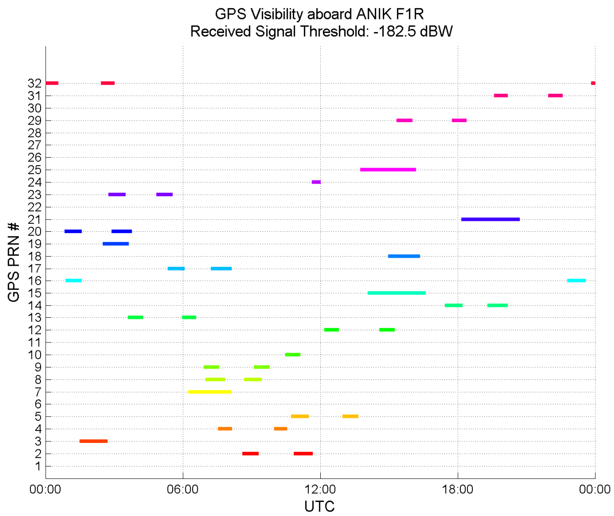

Figure 14: GPS Visibility at GEO Considering the Main Lobe Only

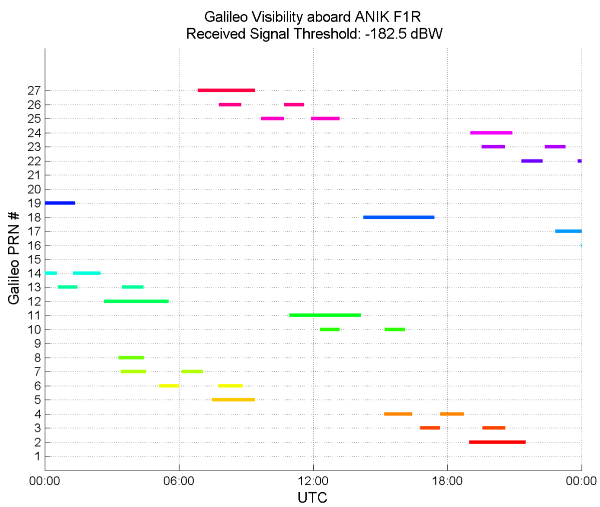

Figure 15: Galileo Visibility at GEO Considering the Main Lobe Only

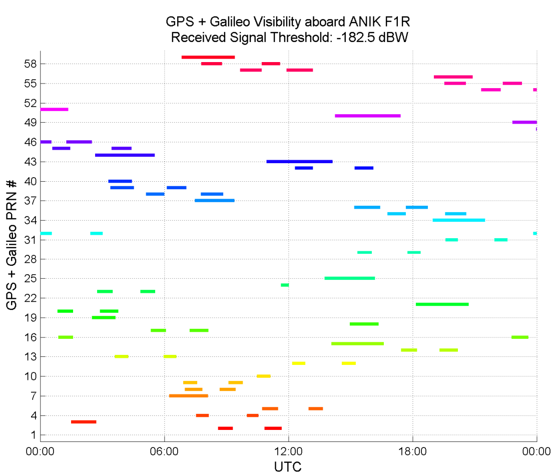

Figure 16: GPS + Galileo Visibility at GEO Considering the Main Lobe Only

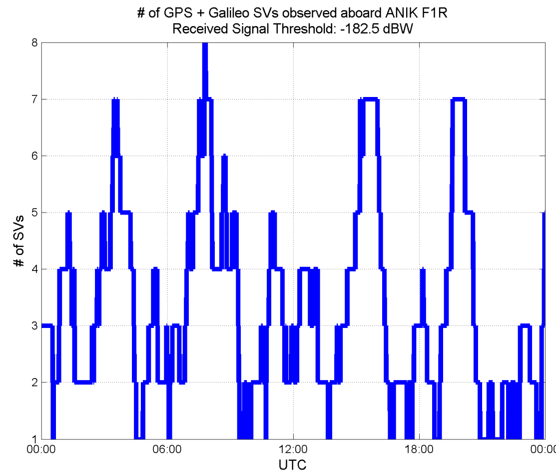

Figure 17: Number of Satellites Visible at GEO over a 24 Hour Period

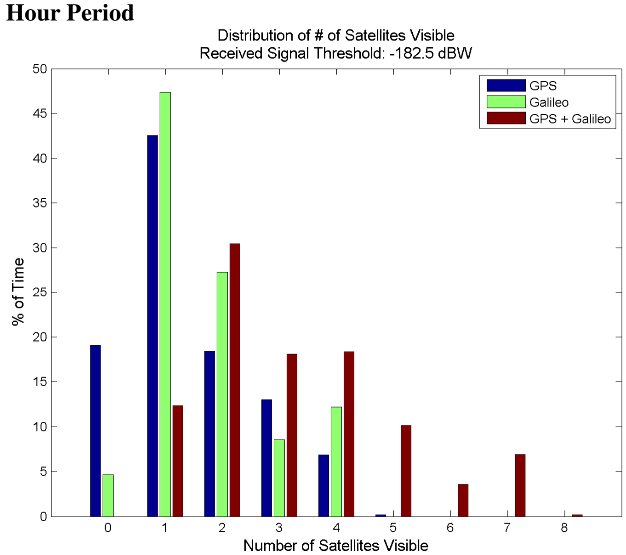

Figure 18: Distribution of Number of Satellites Visible at GEO over a 24 Hour Period

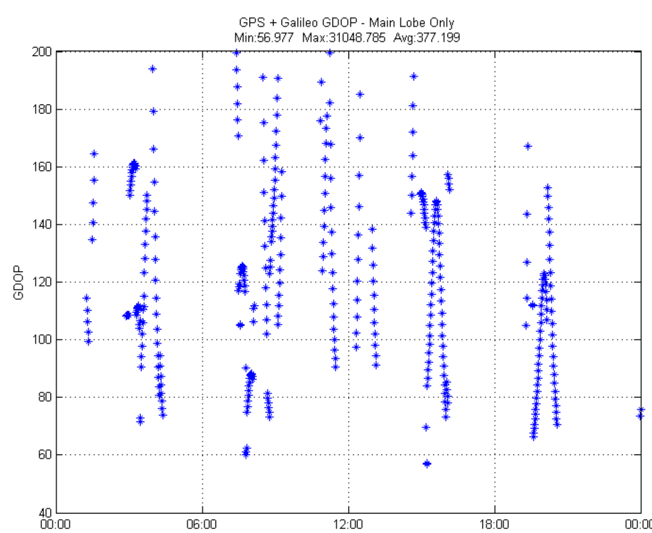

Figure 19: GPS + Galileo GDOP at GEO Using the Main Lobe Only

VISIBILITY AT GEO – MAIN LOBE PLUS FIRST SIDE LOBE

This section summarizes the availability results at GEO. The analysis considers both the main lobe and the first side lobe of the GPS and Galileo transmit antenna. As the plots indicate, including the first side lobe virtually guarantees four or more satellites at all epochs over a 24 hour period. The spatial diversity resulting from the combined GPS plus Galileo constellation helps improve the GDOP to levels more accustomed to terrestrial users.

The challenge when considering the contribution of the side lobe is not one of spare signal visibility. But rather the problem is one of too many satellites. As can be seen in the histogram of the distribution of number of satellites, the median number of satellites visible when using the combined constellation is twenty one. The target implementation of the L1C receiver would be on a Field Programmable Gate Array (FPGA). The Navigator receiver designed at NASA Goddard is an example of a space qualified GPS L1 C/A receiver. Each L1C channel will require 10-15x more FPGA resources compared to a GPS L1 C/A channel. Implementing a twenty one channel receiver on a radiation hardened FPGA may be unfeasible. Consequently, we also present GDOP plot which considers subsets of eight and twelve satellites from all the satellites visible at any epoch. Implementing an eight or twelve channel L1C receiver seems more realistic. The degradation in using only the best eight of all available satellites is negligible.

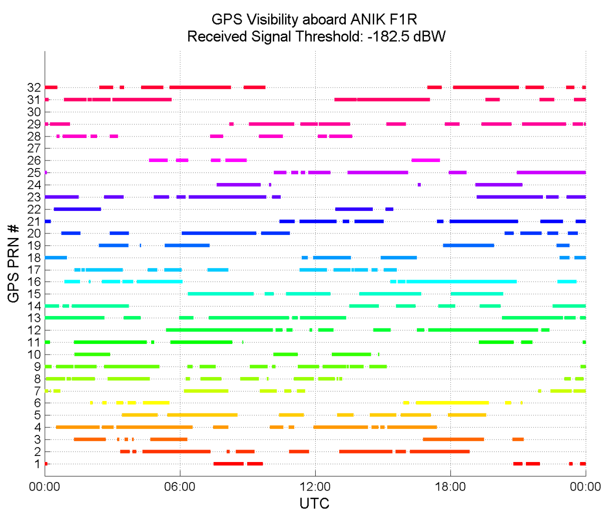

Figure 20: GPS Visibility at GEO using the Main Lobe and First Side Lobe

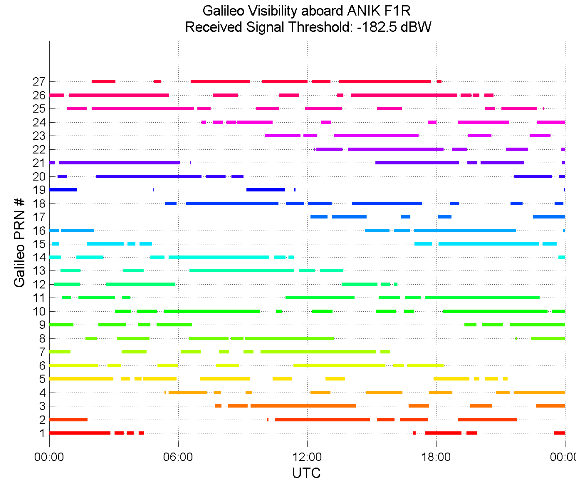

Figure 21: Galileo Visibility at GEO Using the Main Lobe and First Side Lobe

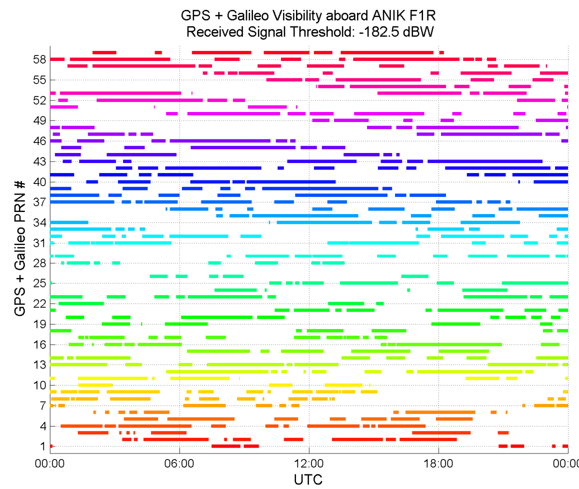

Figure 22: GPS + Galileo Visibility at GEO using the Main Lobe and First Side Lobe

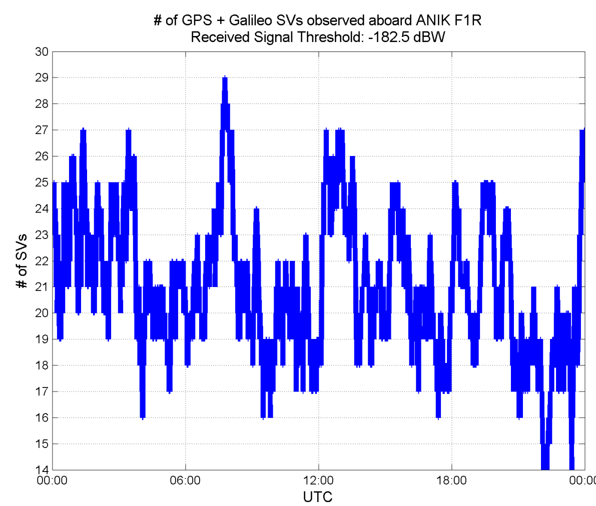

Figure 23: Number of Satellites Visible at GEO over a 24 Hour Period

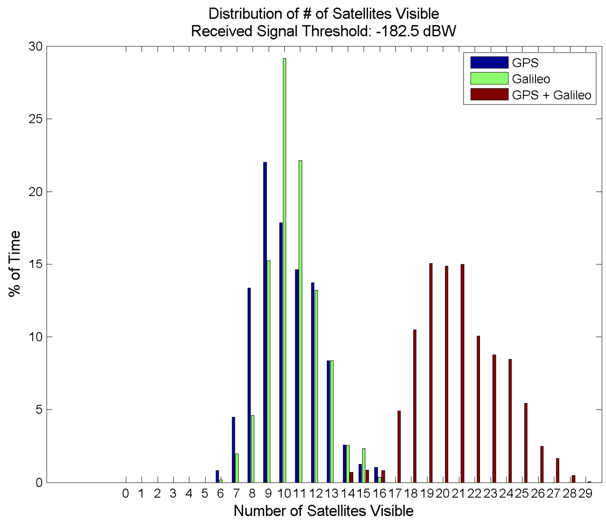

Figure 24: Distribution of Number of Satellites Visible at GEO over a 24 Hour Period

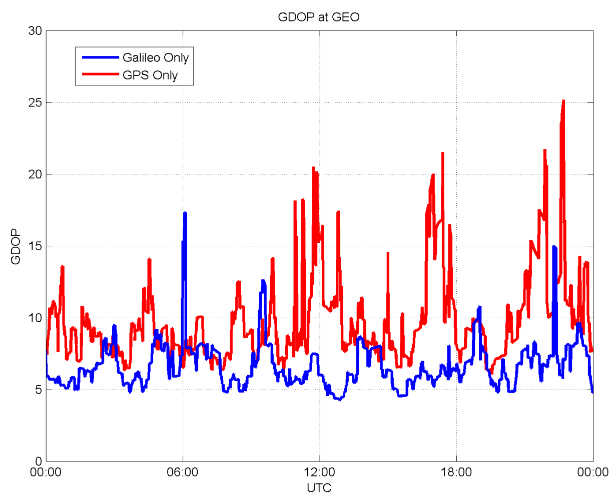

Figure 25: GDOP at GEO Using the Main Lobe and First Side Lobe

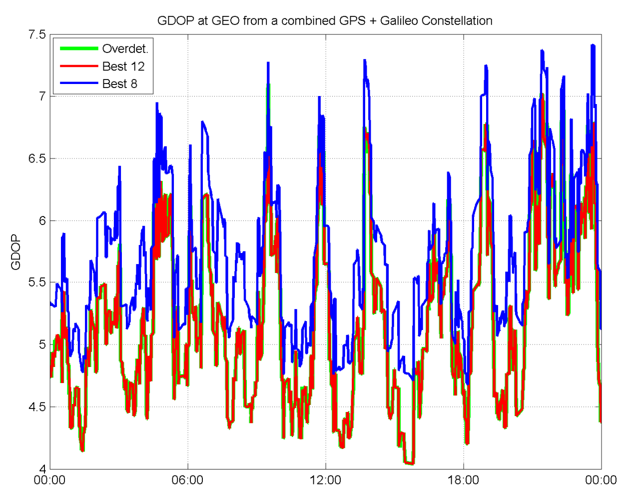

Figure 26: GDOP at GEO from a Combined GPS + Galileo Constellation - All in View, Best 12 and Best 8

GNSS VISIBILITY AT HEO – THE MMS MISSION

Preliminary results indicate that the combined GPS plus Galileo constellation can improve availability during the apogee phase of a HEO mission. In particular, the MMS mission has four satellites flying in a regular tetrahedral formation. With the availability of autonomous position solutions, formation flying can be controlled more precisely. The following three plots illustrate the phase 1 and phase 2 orbits for the MMS mission.

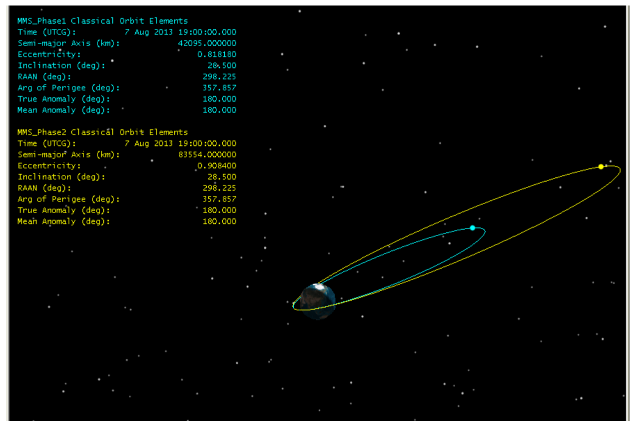

Figure 27: MMS Mission Orbit - Phase 1 and Phase 2

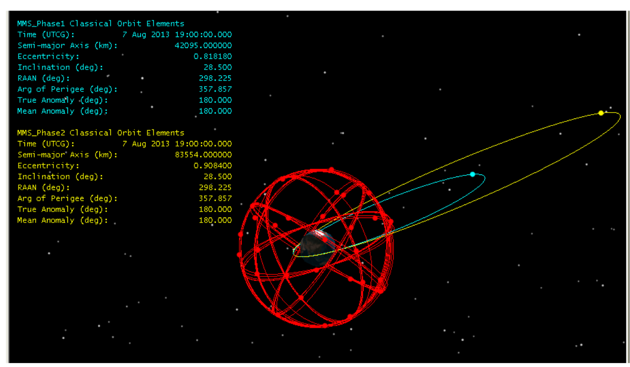

Figure 28: GPS Visibility during Apogee of the MMS Mission

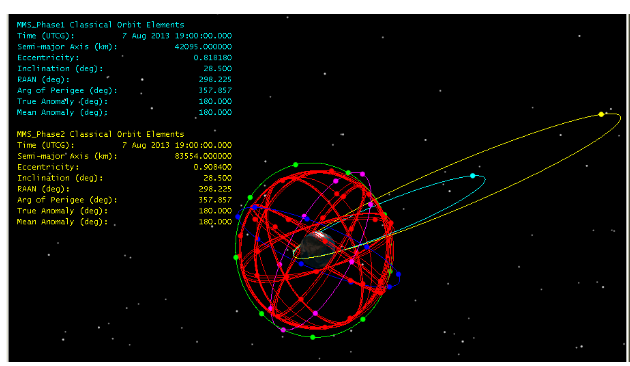

Figure 29: GPS + Galileo Visibility during Apogee of the MMS Mission

SUMMARY

In this paper, we generated GPS III transmit antenna beam pattern using high fidelity computational electromagnetics. This was necessary to evaluate the gain pattern of the side lobes of the GPS transmit antenna. It was assumed for our analysis that the Galileo transmit antenna has a similar gain characteristics as the GPS III transmit antennas. Results serve as a basis to impress upon the need for a Galileo Space Service Volume specification in its ICD. While the GPS ICD explicitly states the main lobe half-beam angle, this information is missing in the Galileo ICD. Using the modeled transmit antenna gain pattern, we compared dual constellation geometry visible at GEO for two cases. In the first case, we considered the contribution from only the main lobe of the transmit antenna. For the second case, we considered both the main lobe and first side lobe extending out to 70 degrees off nadir. For the second case, we propose that a 8 - 12 channel L1C receiver can support autonomous navigation at GEO with good geometric dilution of precision.

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