Modeling and Simulation of Phased Array Antennas to Support Next-Generation Satellite Design

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Developing enhanced simulation capabilities has become a significant priority for the Space Communications and Navigation (SCaN) project at NASA as new space communications technologies are proposed to replace aging NASA communications assets, such as the Tracking and Data Relay Satellite System (TDRSS). When developing the architecture for these new space communications assets, it is important to develop updated modeling and simulation methodologies, such that competing architectures can be weighed against one another and the optimal path forward can be determined. There have been many simulation tools developed here at NASA for the simulation of single RF link budgets, or for the modeling and simulation of an entire network of spacecraft and their supporting SCaN network elements. However, the modeling capabilities are never fully complete and as new technologies are proposed, gaps are identified. One such gap is the ability to rapidly develop high fidelity simulation models of electronically steerable phased array systems. As future relay satellite architectures are proposed that include optical communications links, electronically steerable antennas will become more desirable due to the reduction in platform vibration introduced by mechanically steerable devices. In this research, we investigate how modeling of these antennas can be introduced into out overall simulation and modeling structure.

The ultimate goal of this research is two-fold. First, to enable NASA engineers to model various proposed simulation architectures and determine which proposed architecture meets the given architectural requirements. Second, given a set of communications link requirements for a proposed satellite architecture, determine the optimal configuration for a phased array antenna. There is a variety of tools available that can be used to model phased array antennas. To meet our stated goals, the first objective of this research is to compare the subset of tools available to us, trading-off modeling fidelity of the tool with simulation performance. When comparing several proposed architectures, higher-fidelity modeling may be desirable, however, when iterating a proposed set of communication link requirements across ranges of phased array configuration parameters, the practicality of performance becomes a significant requirement. In either case, a minimum simulation fidelity must be met, regardless of performance considerations, which will be discussed in this research.

Given a suitable set of phased array modeling tools, this research then focuses on integration with current SCaN modeling and simulation tools. While properly modeling the antenna elements of a system are vital, this is only a small part of the end-to-end communication path between a satellite and the supporting ground station and/or relay satellite assets. To properly model a proposed simulation architecture, this toolset must be integrated with other commercial and government development tools, such that the overall architecture can be examined in terms of communications, reliability, and cost. In this research, integration with previously developed communication tools is investigated.

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The end-result of this research paper is not a fully developed modeling environment for phased array antennas, but rather a proposed methodology to rapidly develop phased array models which can then be integrated into an overall system architecture simulation design. As this system model is further developed, this will allow NASA engineers to quickly assess proposed architectures and determine what architectures are acceptable or determine what minimum set of requirements must be met to enable successful space communications.

I. Introduction

Modeling and simulation of space-based communications within NASA currently assumes a specific paradigm in which reflector, or parabolic antennas are primarily used for satellite communications. Calculating the link budget between these reflector antennas is trivial and well-understood as these antennas are mechanically steered towards the intended destination, and thus the response of the antenna is similar in all directions within the pre-defined field of view. When considering advanced communications techniques, such as optical communications, the vibrations induces from these mechanically steerable antennas would potentially render the optical communications path infeasible. Thus, it is desirable, in this new paradigm of optical communications, to utilize electronically steerable antennas which can focus their gain in a particular direction without inducing undesirable vibrations on the supporting platform.

Within NASA, the analysis of these RF links has been well-documented and many tools have been developed to assist in the design and implementation of such communication links. When considering these advanced communications techniques such as optical and phased array Radio Frequency (RF) communications, new tools must be developed which can characterize these new communication links. In the past several years, a new tool has been developed which can model optical communications links at sufficient fidelity to support systems architecture trade-studies within the NASA SCaN Program. The SCaN Optical Link Assessment Tool was developed to model these links, and to co-simulate these communication links with the SCaN accepted orbital dynamics calculation tools, such as System Toolkit (STK). This tool, however, is not capable of designing high fidelity phased array antenna models, and, prior to this research, was not capable of integrating output from phased array modeling tools, to support system architectures of this type. In this paper, we investigate several detailed phased array modeling software programs which can bring this capability to NASA.

While the analysis of the link between the transmitter and receiver has been characterized by RF link budget tools, the analysis currently does not have an accurate model of phased array antenna. Although measurements of the *in-situ* antenna can be made to characterize a phased array, taking measurements for each antenna design is costly in both time and resources, and in many cases impractical. Development of high fidelity models of phased arrays is difficult because of the challenges inherent in obtaining simulation results of *in-situ* antenna manifolds. An *in-situ* antenna manifold model should capture the effects of the antenna being placed on a platform, mutual coupling, feeding imperfections, and all other physical imperfections in the antenna. In addition to these effects, an antenna mounted on a spacecraft will also face many harsh environmental challenges, such as temperature fluctuations, which may affect the performance of the antenna. In addition, changes in the antenna radiation will occur over the lifespan of the antenna, which may also not be captured by a simulation.

Although simulation will not produce a completely accurate model of an antenna pattern, detailed simulations are well suited for rapid analysis of antennas as they are much quicker and cheaper than taking measurements. Simulations can also be used for initial planning stages to select antenna technologies suitable for further development or measurement. Typically, the more detailed a simulation, the more lengthy the simulation time. Thus, a trade-off between fidelity of the antenna model and simulation time is required. For initial designs, lower fidelity but extremely rapid simulations can be used to narrow down the selection of phased array antennas. Later, more costly effects can be added into simulations in order to obtain more detailed results from promising designs.

Current steered antenna technology includes gimbaled antennas, where the antenna is mechanically steered to a direction for transmission or reception. Physically steering the antenna will move and vibrate the platform, which will impact optical communications.

The use of optical communications links on space-based satellites are very desirable for the inherent ‘coupling efficiency’ that exists between the optical transmitter and ground-based optical receive terminal, i.e., a large portion of the optical beam (>10 %) is intercepted by the receiver. Compare this to >0.01% at RF frequencies. However, the price to be paid for this large coupling efficiency is the need to keep the

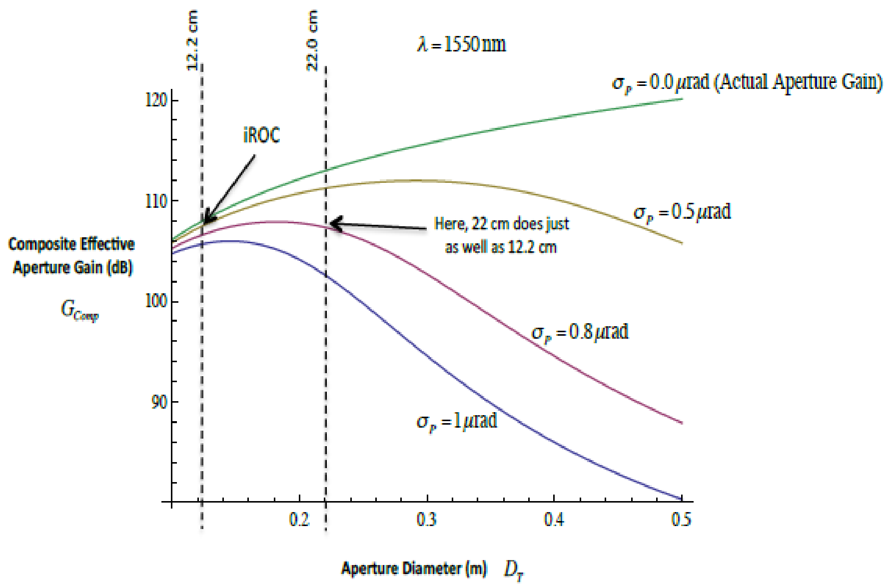

Figure 1. Composite Gain of an Optical Aperture vs. Diameter as A Function of Angular Deviation of Optical Axis For Directed Detection PPM with BER=10^{-6}

movement of the platform containing the optical transmitter to a minimum. Such angular vibration or 'jitter' cannot exceed some prevailing threshold such that the resulting angular displacement of the received beam is on the order of the size of the beam spot itself. This phenomena gives rise to the limitations of optical transmitter aperture size as a function of satellite platform jitter. The figure below shows the degradation of effective aperture (antenna) gain after certain diameters due to

1. The smaller beam size connected with the larger aperture size and
2. The given angular jitter imparted on the smaller beam.

It is thus very important to minimize or even eliminate the source of platform vibrations on a space-based platform when optical links are being considered. The major source of such vibrations comes from the mechanical movement of a steered RF antenna. It is thus necessary to consider electronic steering of the RF antenna in favor of mechanical steering. Hence, the use of phased array antennas is a requirement for the minimization of satellite platform jitter in the presence of optical communication capabilities.

II. Phased Array Antenna Description

A phased array antenna is an array of antennas which are steered through the use of phase shifters on each element. The array can be steered such that it increases gain in a direction, or reduces gain in a direction for interference signals.

The figure shows a general one dimensional linear array. Each element has a phase shifter attached, so that as different directions are desired, the phase shifters will change complex weights to steer each element in the direction. The signals from each of the antennas in the array are combined so that the overall beam will point to the desired direction, and as a result the array will have better performance than that of a singular antenna. There are multiple benefits when using an antenna array, but for this stage of the RF link budget tool, we are mostly concerned with the gain of the antenna. As discussed in Section I because the arrays are electronically steered with a phase shifter, there are no physically moving parts and the phased array will not vibrate the platform.

Initially, the design for the phased array will be a simple array to demonstrate the ability to develop models for the RF link budget tool. The array is designed simply to give adequate gain in the desired field of view, with little consideration given to parameters which will heavily affect the design in later iterations. For

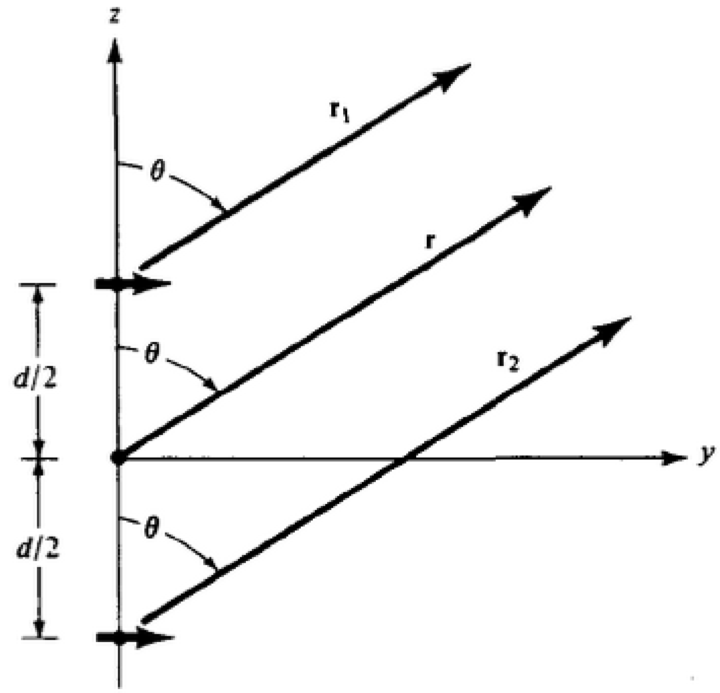

Figure 2. Antenna Array[1]

example, the placement of the antenna in the center of a model satellite, which is likely not to be the actual placement of the antenna in a final system. In addition, the array is composed of simple slot elements, which will not likely be an appropriate element for the final array. As the process for creating arrays becomes more robust, considerations such as size, weight, and power as well as performance over a bandwidth will become more prominent.

A. Capabilities Comparison of Various Phased Array Modeling Software

A few different software have been evaluated for their performance to model phased array antennas at various fidelity. Specifically, for this application we are most concerned with obtaining an accurate estimate of the gain of the antenna for a specific field of view. Previously with older gimbaled antennas, a large margin was given in the link budget calculation to account for losses not captured by simulation or final measurements. With increasing constraints in budget and system complexity, it is desired to obtain a more accurate measure of the *in-situ* array gain.

It is important to keep in mind the trade-off between simulation time, measurement time, cost and the accuracy of the simulation. Of course, it would be ideal to measure each possible antenna array configuration on the target platform in a range, but it is not a practical situation in both time and cost requirements. Instead, simulations can be used to initially analyze antenna performance in order to filter out which antennas to study in more detail. Even within simulation, there are multiple approaches to finding antenna radiation patterns of various accuracy. For example, the platform heavily affects antenna performance, shown in Figures 3 and 4. The two figures show the same antenna on a 20inch diameter ground plane. The second figure shows the effect of moving the antenna 6inches toward the edge of the ground plane. Diffraction off platform edges may cause additional nulls to appear, and cause ripples in the antenna gain. More severely, platform shadowing may prevent the antenna radiation from propagating at all in a direction. Software such as FEKO or HFSS are able to calculated platform effects, but the platform is not considered in MATLABs Phased Array toolbox or STK. While including platform effects will give a more accurate simulation of the in situ manifold, including electrically large platforms in simulation will increase simulation time and memory requirements dramatically. For an initial analysis of an antenna, including platform effects may be unwise if rapid development is desired.

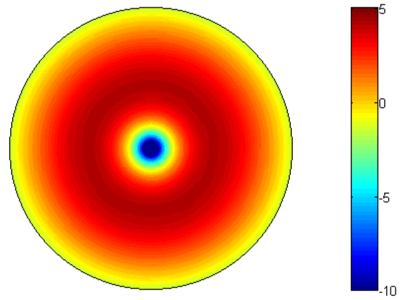

Figure 3. [Simulated Element 1, Gain at 924 MHz

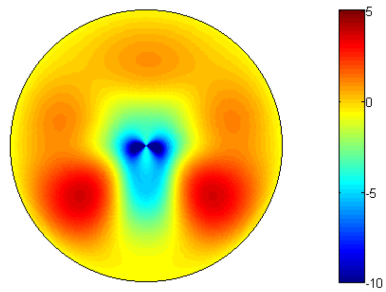

Figure 4. Simulated Element 1 displaced, Gain at 924 MHz

In addition to platform effects, mutual coupling between the antenna elements should also be modeled for simulations to capture the performance of the real antenna. When antennas are placed in an array, its properties will be affected by the other elements which constitute the array. When one of the elements is excited, and the other elements are terminated with a matched load, some of the energy radiated by the excited elements will couple onto the other elements. The overall effect of this coupling will reduce the input impedance of each array element and cause changes in the radiation pattern of the array. Shown in,[2] mutual coupling can affect the radiation pattern of an array, and subsequently the gain of the array quite heavily. Thus, it should be modeled to generate an accurate assessment of phased array capability. Similar to platform effects, including mutual coupling will also increase simulation complexity. It is not necessary to include platform effects, mutual coupling or front end effects for all levels of simulation. Tools such as STK or MATLAB can provide a rough first estimate of the performance of an antenna array within a few seconds rather than simulation times on the order of hours to days. Table 1 shows a general summary of runtime, platform size and antenna complexity for a variety of software.

Table 1. Comparison of Various Phased Array Modeling Software Capabilities

Software	Phased Array Modeling	Platform Effects	Mutual Coupling	Antenna Modeling
MATLAB	Y	N	Y	N
STK	Y	N	N	N
GRASP	Y	Limited	N	Y
GRASP - MoM	Y	Y	Y	Y
HFSS - IE	Y	Y	Y	Y

III. SCaN Link Assessment Tool

The SCaN Link Assessment Tool is a tool that was developed under the NASA SCaN Program at NASA Glenn Research Center (GRC). Initially, this tool was developed to support running dynamic link budget analysis of optical communication links, as current optical communications link budgets were either of insufficient fidelity or were not integrated with the orbital physics tools being used in house (i.e. STK). Based on this research and the evaluation of various software tools available (see Section II.A) it was clear that a similar approach is required with respect to modeling and simulation of Phased Array antennas. While STK now has the capabilities to integrate phased array antennas with their communications package, the fidelity of this model was insufficient for the scale of analyses being performed. Therefore, a goal of this research was to expand the capabilities of the SCaN Link Assessment tool, such that phased array antennas could be supported as well as the more common reflector antennas.

The current version of this tool, currently referred to as "SCaN Optical Link Assessment Tool Version 2", is available from NASA at http://software.nasa.gov. This version of the tool only supports evaluation of optical link budgets. However, an updated version of this tool is being finalized which will support RF analysis for reflector and phased array antennas.

IV. Modeling Analysis

To demonstrate the effectiveness of the NASA GRC RF Link Assessment tool and how this tool can now be used in future test scenarios which utilize phased array antenna technologies, the following test scenario was developed:

Consider a Low Earth Orbit (LEO) Space-based Relay System (SBRS) facing outward from Earth towards one or more user missions. These user missions can range from user missing in Geosynchronous Orbit (GEO) to user missions further out, such as lunar missions. Due to the rapid orbit of the SBRS in LEO, the relay satellite will be required to make rapid adjustments such that it can quickly acquire signal from the scheduled user mission, but can also maintain tracking with the user mission for the duration of the orbital pass. To relay collected science data to ground stations for processing, let us assume that the LEO SBRS utilizes a high data rate optical link to quickly transfer all science data that was buffered while connections to the ground stations are not available. As was mentioned in Section I, mechanically steering a reflector antenna in not feasible in this scenario due to the vibrations induced by the steering mechanism. Therefore, in this scenario, it is preferable to use a electronically steer able phased array antenna on the SBRS facing away from Earth.

To test the capabilities of the tools generated, a scenario was developed in STK to demonstrate the ability to co-simulate satellite communication links which utilize phased array RF communications, and links which utilize optical communications. An overview of this scenario is shown in Figure 5.

Here you can see a LEO SBRS which allows two user missions, one in lunar orbit and one in geosynchronous orbit, to transfer science data over a high-data rate optical communications link to the ground. Facing outward, away from Earth, is a phased array antenna which has been designed using the principals described in Section II. In this scenario, a 38-element phased array was modeled and steered using the tools developed at NASA GRC. In Figure 6 the estimated system response for the phased array can be seen as it is electronically steered towards the destination user mission.

Using the RF Link budget analysis tool described in Section III, we are able to dynamically link the STK model shown in Figure 5 with the output generated by the phased array modeling tools described in Section A to estimate the link budget of the full end-to-end communication link between a given user missing and the ground station supporting that user mission.

For each instance of communications within the given STK scenario, the RF link budget tool will call a custom developed MATLAB script which uses the pre-generated Phased Array Antenna manifolds to estimate the main-lobe gain of the Phased Array Antenna in a given direction. This antenna gain is used in the overall link budget analysis to determine, for each time instance, the received signal strength at the LEO SBRS. For the given scenario, the received $Eb/N0$ was calculated for a time between August 1^{st} and August 16^{th}. The estimated $Eb/N0$ values are shown in Figures 7 and 8. As you can see, the results for the lunar mission to the LEO SBRS are not seen between August 1^{st} and the first half of August 10^{th}. This is due to the orbital mechanics of the chosen scenario which position the lunar user mission out of the field of view of the LEO SBRS. In future studies, we can investigate utilizing multiple field of view, similar to the

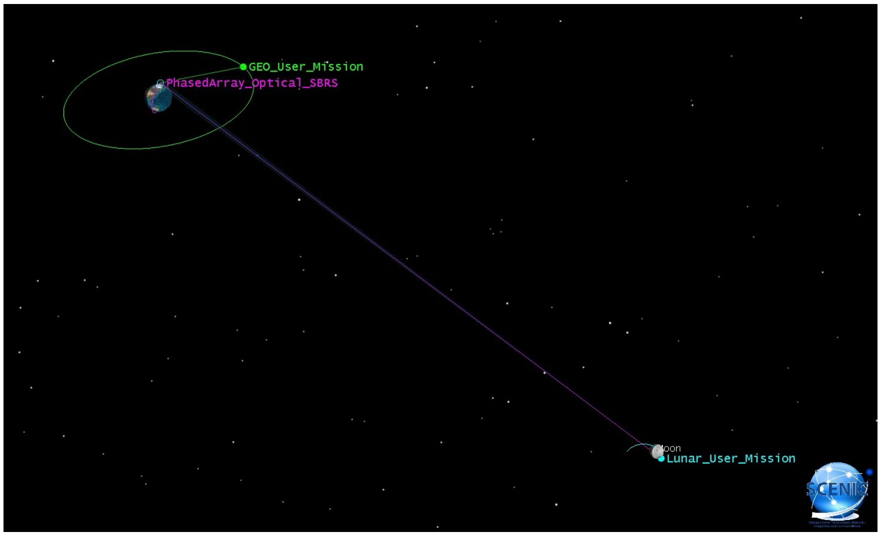

Figure 5. System Toolkit (STK) Test Scenario

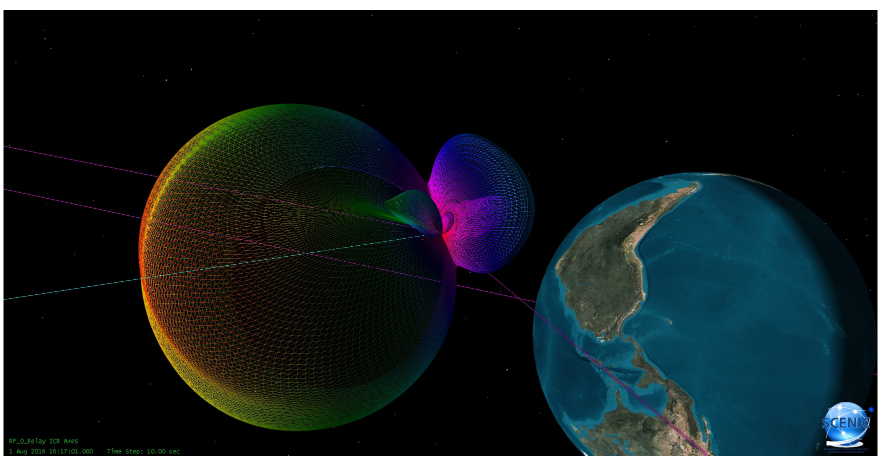

Figure 6. System Toolkit (STK) Modeled Phased Array System Response

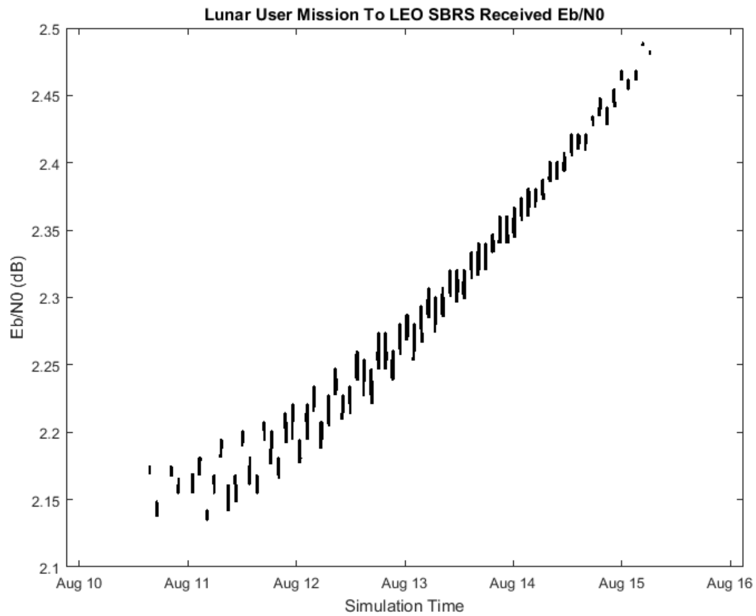

Figure 7. Estimated Received Eb/N0 for Lunar User Mission to LEO SBRS

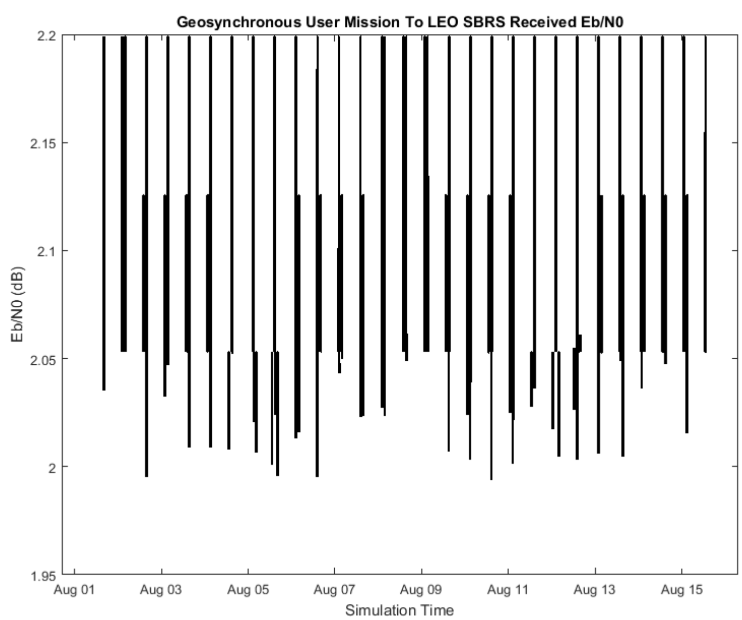

Figure 8. Estimated Received Eb/N0 for GEO User Mission to LEO SBRS

current Tracking and Data Relay Satellite (TDRS), which would trade-off phased array antenna gain, for increased coverage.

V. Conclusions and Future Work

A system to rapidly analyze the gain of a phased antenna array on a spaceborne platform for use in an RF link budget tool has been presented. In the future, one of the main barriers to rapid analysis of the phased array will be obtaining the array manifold when the antenna array is mounted on a platform of interest. To find the *in-situ* antenna performance, that is the antenna performance on the desired platform, the most accurate results are obtained by measuring each element response over the frequency band of interest. This is generally impractical as the platform will likely be too large for test ranges, and the costs associated with measuring the antenna on the platform may be too high. Instead, one may use an equivalent currents method, where measured data from a simple platform and a set of equivalent currents can be used to construct the antenna pattern on a complex platform. Some computational electromagnetics software, such as FEKO have included solvers for equivalent current generation.[3] Utilizing this method allows for rapid analysis from a simple set of measured patterns how the antenna will likely radiate on the actual spaceborne platform, and allow for more accurate estimation of antenna gain in the RF link budget tool.

Acronyms

GEO Geosynchronous Orbit

GRC Glenn Research Center

LEO Low Earth Orbit

iROC Integrated RF and Optical Communications

FEM Finite Element Method

IE Integral Equation

MoM Method of Moments

RF Radio Frequency

SBRS Space-based Relay System

SCaN Space Communications and Navigation

SCENIC Strategic Center for Education Networking Integration and Communications

STK System Toolkit

TDRS Tracking and Data Relay Satellite

TDRSS Tracking and Data Relay Satellite System

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References

[1]Balanis, C. A., *Antenna Theory : Analysis and Design*, THoboken, NJ : Wiley Interscience, 3rd ed., 2005.

[2]Gupta, I. and Ksienski, A., "Effect of mutual coupling on the performance of adaptive arrays," *IEEE Transactions on Antennas and Propagation*, Vol. 31, No. 5, Sep 1983, pp. 785–791.

[3]lvarez, Y., Laviada, J., Garca, C., and Las-Heras, F., "On the use of Equivalent Currents for Antenna Interaction with Scaterrers Characterization," *Proc. AMTA*, 2011, pp. 197–202.