Earth-Facing Antenna Characterization in Complex Ground Plane/Multipath Rich Environment

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***Abstract*—The Space Communications and Navigation (SCAN) Testbed was a Software Defined Radio (SDR)-based payload launched to the International Space Station (ISS) in July of 2012. The purpose of the SCAN Testbed payload was to investigate the applicability of SDRs to NASA space missions in an operational environment, which means that a proper model for system performance in said operational space environment is a necessary condition. The SCAN Testbed has line-of-sight connections to various ground stations with its S-Band Earth-facing Near-Earth-Network Low Gain Antenna (NEN-LGA). Any previous efforts to characterize the NEN-LGA proved difficult, therefore, the NASA Glenn Research Center built its own S-Band ground station, which became operational in 2015, and has been used successfully to characterize the NEN-LGA's in-situ pattern measurements. This methodology allows for a more realistic characterization of the antenna performance, where the pattern oscillation induced by the complex ISS ground plane, as well as shadowing effects due to ISS structural blockage are included into the final performance model. This paper describes the challenges of characterizing an antenna pattern in this environment. It will also discuss the data processing, present the final antenna pattern measurements and derived model, as well as discuss various lessons learned.**

I. INTRODUCTION

The Space Communications and Navigation (SCAN) Testbed is a Software-Defined Radio (SDR)-based payload currently onboard the International Space Station (ISS). Its purpose is to investigate the applicability of SDRs to NASA space missions in an operational environment. The SCAN Testbed payload, developed at NASA's Glenn Research Center (GRC), contains three distinct SDRs that are reprogrammable and run reconfigurable waveform applications. One component of the SCAN Testbed is the Radio Frequency (RF) subsystem which allows the operator to switch the connections between the S-Band SDRs and the payload antennas. This design provides experimental communication link access to the NASA Telemetry and Data Relay Satellite System (TDRSS) via either Ka-Band or S-Band gimbaled SCAN Testbed antennas or an S-Band fixed low gain antenna. In addition, the SCAN Testbed has a fixed low-gain GPS antenna to be used for GPS navigation experiments. Finally, the payload has an Earth-facing fixed low gain antenna that can be used with various ground stations, referred to as the Near-Earth Network Low Gain Antenna (NEN-LGA). The payload is illustrated in the schematic shown in Figure 1 [1]. SCAN Testbed provides an opportunity to develop, demonstrate, and test experimental waveforms in space to reduce cost and risk for future space missions using SDRs.

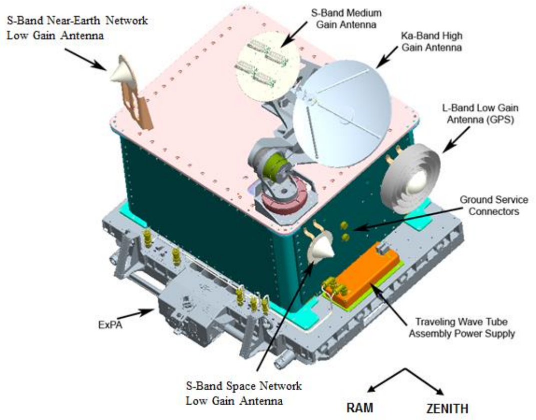


Figure 1. SCAN Testbed Payload Schematic

After installation of the payload, it was necessary to checkout and characterize the various SCAN Testbed antennas, in preparation for future experiment testing. The goal of this activity is to determine a performance truth model for each antenna. While the antennas could be tested for pattern and gain before launch, the complex ground plane and multipath associated with the structure and blockage of the ISS would preclude those results from accurately representing their performance in an orbital environment. The payload is illustrated in Figure 2, with the NEN-LGA boresight vector pointing towards the Earth's horizon shown in orange.

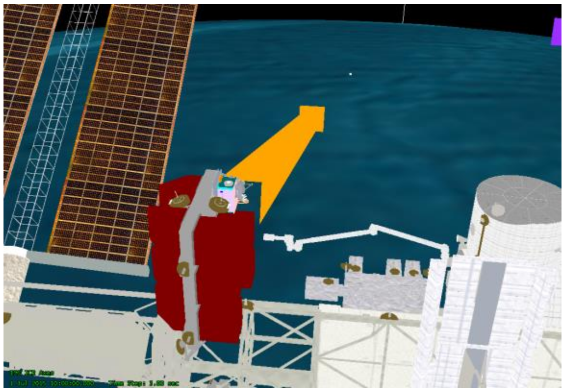


Figure 2. Perspective Behind SCAN Testbed on ISS

II. NEN-LGA SIMULATION MODELS AND RESULTS

Pre-launch activities included simulations in CST Microwave Studio of the NEN-LGA, modeled as a conical spiral on a flat circular ground plane, with and without elements of the complex ground plane [2]. Figure 3 illustrates a simulation model of the NEN-LGA.

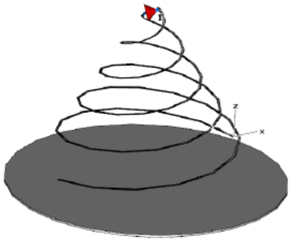
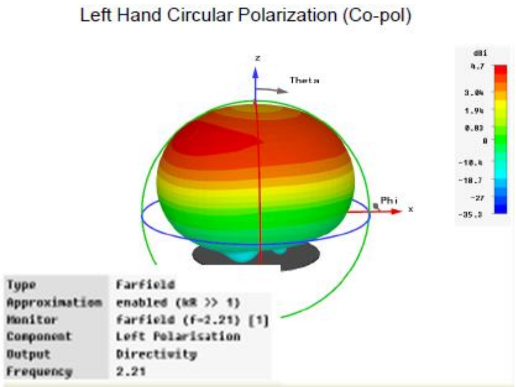


Figure 3. NEN-LGA Simulation Model

The pattern results for this simplistic model are shown in Figure 4 at a frequency of 2210 MHz.


Left Hand Circular Polarization (Co-pol)

Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=2.21) [1]
Component	Left Polarisation
Output	Directivity
Frequency	2.21

Figure 4. NEN-LGA Simulation Model Results

Figure 5 shows a simulation model of the NEN-LGA that includes the mounting bracket and starboard radiator.

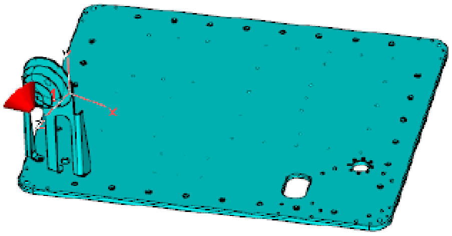
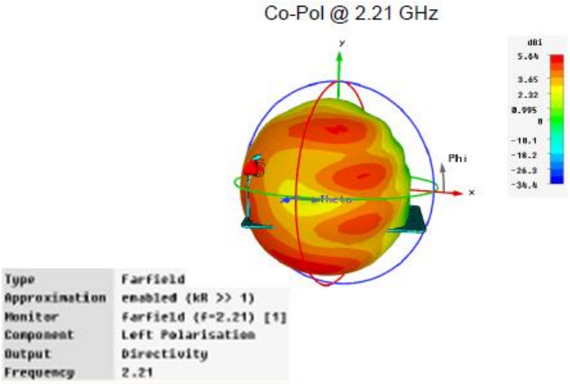


Figure 5. NEN-LGA Simulation Model with Mounting Bracket and Starboard Radiator

Figure 6 shows the simulation results for the pattern at 2210 MHz using this more complex simulation model. Note that results shown in Figure 6 exhibit oscillations in the antenna pattern due to the complex non-uniform local ground plane of the antenna [2].


Co-Pol @ 2.21 GHz

Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=2.21) [1]
Component	Left Polarisation
Output	Directivity
Frequency	2.21

Figure 6. NEN-LGA Simulation Model Results with Mounting Bracket and Starboard Radiator

III. NEN-LGA INITIAL ANTENNA CHARACTERIZATION ACTIVITIES AND ISSUES

The NEN-LGA was initially tested using the Wallops Ground Station (WGS). During this testing, several issues were immediately discovered that were a source of concern for the health of that antenna. Later testing with TDRSS, via non-traditional usage, showed that the antenna was not damaged during launch or installation. The initial issues associated with WGS did not correlate well with the limitations of the two S-Band SDRs as explained below.

The General Dynamics (GD) SDR requires reception of spread spectrum signals in order to properly obtain bit, coding, and phase lock. In this state, this SDR had a fully characterized received power level estimator based on distinct analog and digital Automatic Gain Controller (AGC) telemetry [3]. Unlike the GD SDR, the Jet Propulsion Laboratory (JPL) SDR can operate while receiving spread or non-spread modulated signals. Unfortunately, the launch waveform available at that time did not have a received power level estimator. Therefore, it could not be used to characterize the NEN-LGA receive gain pattern.

There were several other obstacles when trying to complete this characterization using WGS. First, the receive equipment at WGS had limited telemetry available to users which included a crude Carrier to Noise Density (C/N$_0$) that maxed out at signal levels below the levels received from SCAN Testbed. This telemetry also contained WGS gimbal pointing and autotrack angles, but did not have any direct received power level estimators. Second, WGS had restrictions in its spectrum license allocation with SCAN Testbed, where it could only transmit a signal with a bandwidth less than 800 kHz. This bandwidth allocation does not support the spreading rate of nearly 3 MHz required by the GD SDR, and thus, the GD SDR's state machine was unable to reach the state where bit, coding, spreading, and phase are fully locked. Without this lock, the AGC telemetry is not valid and the SDR will continue to search for the spread signal, which in this case is not being transmitted. Third, WGS had issues associated with pointing regarding their auto track algorithm, as learned bias angles would not be kept in memory when transitions out of auto track occurred. Finally, WGS does not provide a real-time bit stream for downlink signals back to GRC, which further limits evaluation of link performance. Table I summarizes the issues experienced using WGS for characterization of the NEN-LGA.

TABLE I. NEN-LGA CHARACTERIZATION ISSUES USING WGS

	Uplink	*Downlink*
GD SDR	Insufficient spectrum WGS pointing	C/N_0 crude measurements WGS pointing Lack of real-time bit flow
JPL SDR	Lack of JPL power estimator WGS pointing	C/N_0 crude measurements WGS pointing Lack of real-time bit flow

Due to these limitations, the Space Communication and Navigation (SCaN) Testbed Project commissioned the installation and checkout testing of a new S-Band Ground Station (GRC-GS) at the NASA Glenn Research Center in Cleveland, Ohio. This ground station will characterize the NEN-LGA and then continue on as an Earth-based node in the direct-to-Earth communication link.

IV. GRC-GS DESCRIPTION

The GRC-GS built at the NASA Glenn Research Center utilizes a 2.4m parabolic reflector mounted to an Elevation over Azimuth gimbal to point towards the SCAN Testbed on the ISS. Figure 7 illustrates the rooftop hardware associated with the GRC-GS [4].

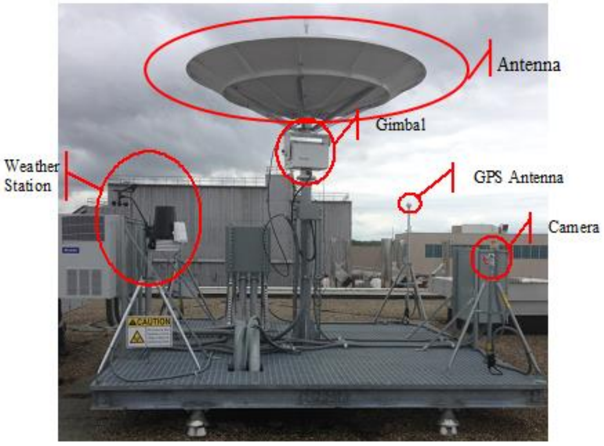


Figure 7. GRC-GS Rooftop Platform

The GRC-GS gimbal is constrained to operations above an Earth elevation angle of 10° off the horizon. This 10° minimum elevation angle limits the region of the ISS orbit accessible from the GRC-GS. Therefore, this elevation angle constraint defines the maximum contact time of any communication link with SCAN Testbed to just over 6 minutes. Figure 8 shows a graphic of the region of space where the ISS orbit can obtain line of sight coverage with the GRC-GS. The graph represents a coverage analysis for 6 months in duration, with contact events colored in pink [4].

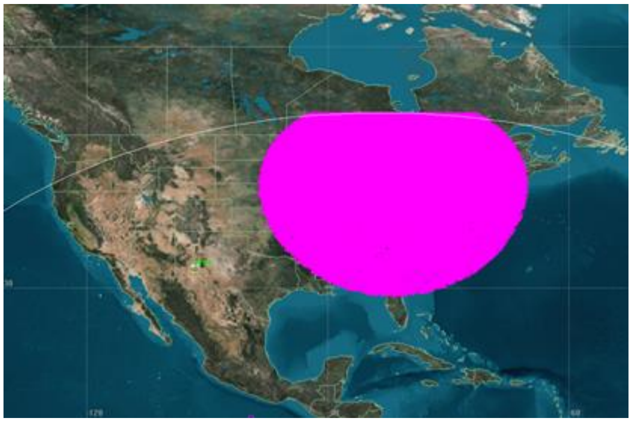


Figure 8. GRC-GS Line of Sight Coverage Zone

V. NEN-LGA CHARACTERIZATION PROCESS

The antenna characterization process is driven by entering measurements of received power levels into basic link budget equations. The link budget equation used in this characterization process is given in (1) [5].

$$P_R = P_T + G_T + L_{CT} + L_{FSP} + L_{ADD} + G_R + L_{CR} \quad (1)$$

Where:

- P_R is the received power level in units of dBm
- P_T is the transmitted power level in units of dBm
- G_T is the transmitter antenna gain in units of dB
- L_{CT} is the circuit losses on the transmit side between the transmitter and the antenna feed in units of dB
- L_{FSP} is the free space path loss in units of dB
- L_{ADD} is the additional link budget losses not accounted for in (1) such as multipath or shadowing in units of dB
- G_R is the receiver antenna gain in units of dB
- L_{CR} is the circuit loss on the receive side between the antenna feed and the received power level measurement in units of dB

For the antenna gain on an uplink transmission where the antenna under test is receiving, (1) is solved for the receiver antenna gain. Likewise, for the antenna gain on the downlink transmission where the antenna under test is transmitting, (1) is solved for the transmitter antenna gain.

In the derivation of antenna gain, it is important to note the origin of specific terms. For the uplink transmission case: P_T, G_T, and L_{CT} are derived from system testing of the GRC-GS [4]; P_R is a measurement from the GD SDR [3]; L_{CR} was a measured value from pre-flight testing [1]; and L_{FSP} is a calculated value by the SCaN Testbed Analysis Tool (STAT) based on the transmission frequency and the actual path length between the GRC-GS and the ISS. Similarly, for the downlink transmission case: P_T and L_{CT} are derived from pre-flight testing [1]; P_R, G_R, and L_{CR} are based on system testing of the GRC-GS [4]; and L_{FSP} is a value calculated by STAT.

In both cases, the term in the link budget L_{ADD} is not known, and therefore the solution of (1) is modified to solve for effective gains, with those unknown losses built into the antenna gain model, since they are indistinguishable in the link performance, solved below in (2) and (3), where G_{R_EFF} is the effective receive antenna gain and G_{T_EFF} is the effective transmit antenna gain. It should also be noted that the term L_{ADD} is unique to each link direction, as the transmit frequency is different in each case.

$$G_{R\_EFF} = P_R - P_T - G_T - L_{CT} - L_{FSP} - L_{CR} \qquad (2)$$

$$G_{T\_EFF} = P_R - P_T - L_{CT} - L_{FSP} - G_R - L_{CR} \qquad (3)$$

As mentioned earlier, the derivation of the free space path loss is based on the frequency of the link direction, as well as the distance between the GRC-GS and the ISS. For uplink transmissions, the two S-Band frequencies are 2041.027 and 2106.406 MHz, with a maximum bandwidth of 6 MHz. For the downlink transmissions, the two S-Band frequencies are 2216.5 and 2287.5 MHz, with a maximum bandwidth of 5 MHz [4].

Pointing angles for GRC-GS towards the ISS are derived from a Standard General Perturbations Satellite Orbit Model 4 (SGP4) process that uses ISS Two-Line Element (TLE) information. The pointing commands are initially defined in the LynxCAT SK Toolbox [6], which creates the Azimuth and Elevation profile table to direct the GRC-GS antenna towards the predicted portion of the ISS orbit. During test events, commanding of the gimbal was done while the LynxCAT SK Toolbox was operating in an open-loop mode. In this configuration, the software is not using received power levels for feedback information as it would in closed-loop operation mode. This was done to avoid injecting NEN-LGA pattern oscillation noise into the tracking process and inadvertently cause poor alignment between the GRC-GS and the ISS.

Derivation of antenna gains is reliant on an archived time series dataset of specific telemetry parameters. In particular, it is necessary to have those derived in (2) and (3). The GRC-GS antenna pointing telemetry is logged by the LynxCAT SK Toolbox, while the RF telemetry is logged by tools built into the GRC-GS RF_Monitor toolset. SCAN Testbed payload telemetry data regarding transmit power and received AGCs are archived, along with specific data about the ISS position, velocity, and attitude. Most of this information is available in either one or five second update intervals. The various datasets are read into STAT, then one of its post-processing modes is selected to aggregate the different inputs together and perform the calculations listed in (2) and (3). STAT makes special note during this calculation of where on the antenna pattern the measurement is occurring. This is shown in Figure 2 by the orange vector indicating NEN-LGA boresight. The NEN-LGA points towards the Earth at a 20° pitch angle below the ISS Ram direction. Subsequently, nominal ISS attitudes only allow half of the antenna to be in view of the Earth's surface. The coordinate system used by STAT is based on a Theta-Phi definition of the antenna pattern, where Theta (in blue) is the angle off the antenna boresight, and Phi (in red) is the direction around the antenna boresight, with nominal 0° Theta co-aligned with antenna boresight and nominal 0° Phi co-aligned with the zenith vector, shown below in Figure 9.

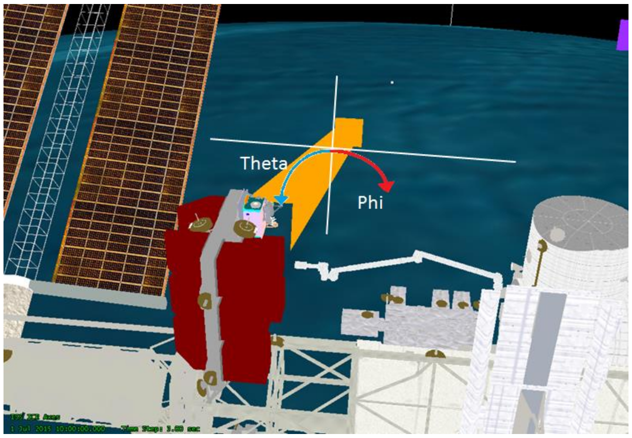


Figure 9. NEN-LGA Coordinate System on ISS

VI. NEN-LGA CHARACTERIZATION RESULTS

NEN-LGA characterization activities were split evenly between the TDRS Single Access (SA) and the TDRS Multiple Access (MA) frequency pairs. The pairs are defined as 2041.027 MHz uplink with 2216.5 MHz downlink, and 2106.406 MHz uplink with 2287.5 MHz downlink, for SA and MA respectively. The complete test plan called for a total of 108 events, 72 of which were associated with the GD SDR and 36 with the JPL SDR. More events were allocated to the GD SDR due to its received power level estimation capability. Half of all possible contacts occurred in the region where the Phi angles were between 90° and 120° and therefore were shorter in duration. Other events were chosen as the Phi coverage was closer to between 160° and 200°, where the events occur with maximum contact duration. An example coverage swath for where a single SA event is shown below in Figure 10, though the total coverage swath for all SA events is shown below in Figure 11.

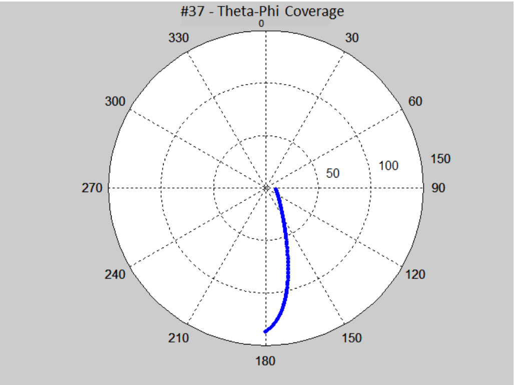


Figure 10. Example SA Event Coverage Swath

The total coverage swath for all SA events is shown below in Figure 11, where breaks in individual event swaths are due to the GRC-GS's gimbal orientation induced azimuthal motion rate limit-based pointing loss issues near the gimbal's keyhole.

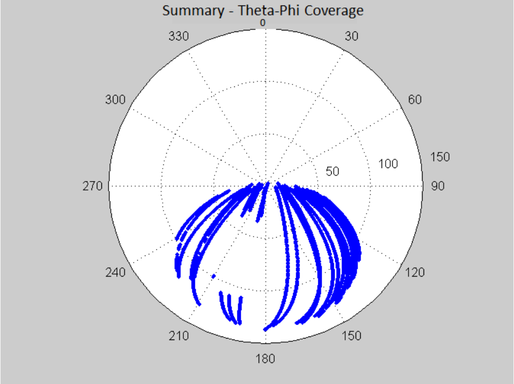


Figure 11. Total SA Event Coverage Swath

An example pattern calculation for the same event shown in Figure 10 is illustrated in Figure 12 for the receive gain and Figure 13 for the transmit gain.

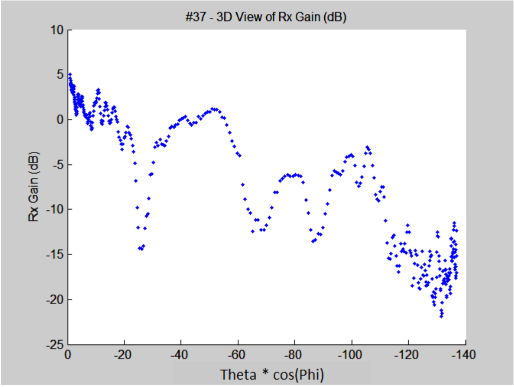


Figure 12. Example SA Event Receive Gain Profile

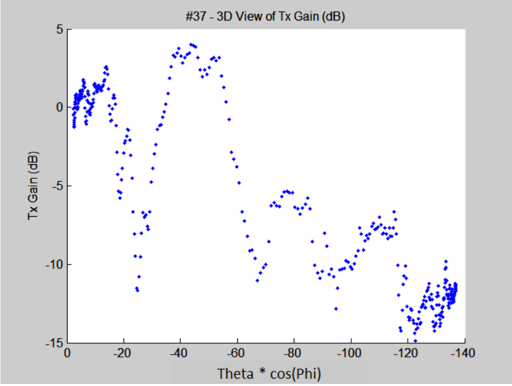


Figure 13. Example SA Event Transmit Gain Profile

Individual event results were grouped and aggregated by link direction and frequency, similar to how event coverage swaths were aggregated in Figure 11. Results for the SA frequency receive antenna gain are provided in Figure 14.

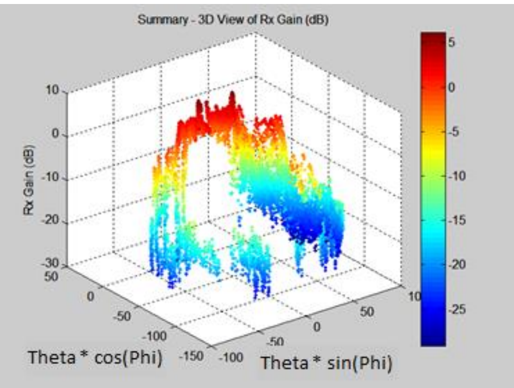


Figure 14. Aggregate SA Receive Gain Profile

To produce a final gain pattern, it is important to understand the requirements for how it will be utilized in the future. In STAT, a Theta-Phi antenna gain pattern can be utilized so that a 3D model of the antenna performance can be specified with fixed intervals in the Theta and Phi axes. For this analysis, the Theta axis was parsed into 1° increments, while the Phi axis was parsed into 10° increments. Each individual pattern was then parsed into Phi slices of the pattern, with the slice results averaged on the Theta axis 1° sets/groupings. Smoothing of the data was performed over two consecutive Theta groupings in the production of final Phi slice performance models. An example of this for the SA frequency receive gain is shown in Figure 15 at Phi = 140°.

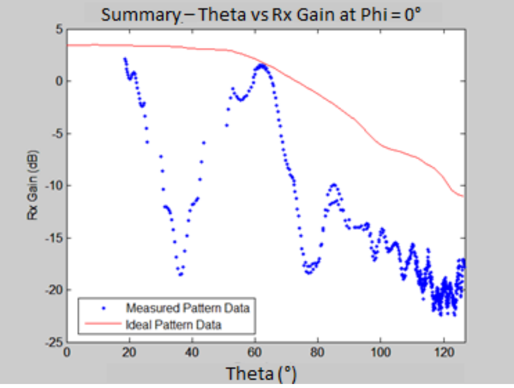


Figure 15. 140° Phi Slice SA Receive Gain

Worth noting in Figure 15 is that Theta angles between 20° and 50° show degraded antenna gain performance against the ideal antenna simulation model. This corresponds to shadowing caused by the ISS Japanese Experiment Module, which can be seen in the lower right hand quadrant of Figure 2. Degraded gain beyond 70° off boresight is due to shadowing and multipath from the ISS structure.

It should also be noted that at boresight, each Phi angle slice should show the same performance, as that point corresponds to the same location on the antenna pattern. To produce the final NEN-LGA gain model, the Phi slices were interpolated by averaging the pattern data in nearby Phi slices and Theta angles. The final SA receive antenna gain obtained from this process is shown below in Figure 16, where pattern data corresponding to antenna coordinates facing zenith are reliant on initial simulation results.

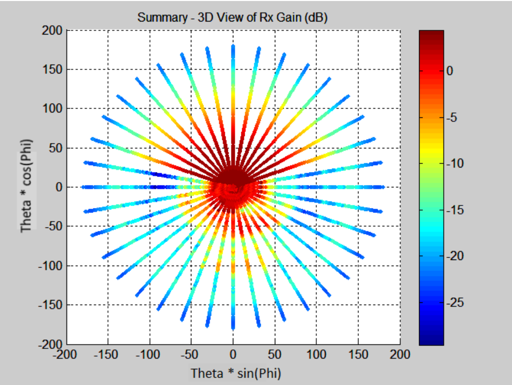


Figure 16. Final SA Receive Gain Profile

VII. CONCLUSIONS AND LESSONS LEARNED

These results show the Earth-facing NEN-LGA was able to be characterized in an environment containing multipath and shadowing effects across multiple frequencies and link directions. This characterization is an important contribution to the performance model of the SCAN Testbed. This model is not only used for link planning and post-processing assessments, but also for long-term experiment planning requires understanding the capabilities and limitations of the link itself.

One area that the SCaN Testbed project is expanding is in adaptive waveforms. Adaptive waveforms respond to changes in link performance to maximize data throughput. This can be accomplished via changing the data rate, coding scheme, or modulation used in the link. Therefore, having a complete model of the link is vital in determining how much variation in link performance can be expected. This is an important factor for comparing how well events have performed and if the link can be improved even further.

These characterization activities have shown that a fully characterized ground node and a proper received power level estimator are the two most important factors in assessing the antenna in this type of communication link. Accuracy in measurements of this type are critical to characterization activities. If, for example, the received power level measurements on the GD SDR were only accurate to 5 dB, then the antenna gain accuracy would be no more precise than the SDR itself. This shows that thorough characterization activities taken on the SCAN Testbed hardware and the GRC-GS are the driving factors in determining the performance of the NEN-LGA. Without proper characterization models of those systems, this type of analysis would not realistically be feasible due to the large uncertainties in the system performance elements.

ACKNOWLEDGEMENT

The authors would like to thank the SCaN Testbed Project for allowing the opportunity to characterize the NEN-LGA with the newly designed, built, and characterized GRC Ground Station. We also would like to thank the SCaN Testbed Mission Operations Team for their early morning and late evening shifts covering operations due to contact times between ISS and NASA GRC.

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