Characterization of an In-Situ Ground Terminal via a Geostationary Satellite

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***Abstract*— In 2015, the Space Communications and Navigation (SCaN) Testbed project completed an S-Band ground station located at the NASA Glenn Research Center in Cleveland, Ohio. This S-Band ground station was developed to create a fully characterized and controllable dynamic link environment when testing novel communication techniques for Software Defined Radios and Cognitive Communication Systems. In order to provide a useful environment for potential experimenters, it was necessary to characterize various RF devices at both the component level in the laboratory and at the system level after integration. This paper will discuss some of the laboratory testing of the ground station components, with a particular focus/emphasis on the near-field measurements of the antenna. It will then describe the methodology for characterizing the installed ground station at the system level via a Tracking and Data Relay Satellite (TDRS), with specific focus given to the characterization of the ground station antenna pattern, where the max TDRS transmit power limited the validity of the non-noise floor received power data to the antenna main lobe region. Finally, the paper compares the results of each test as well as provides lessons learned from this type of testing methodology.**

I. INTRODUCTION

The Space Communications and Navigation (SCAN) Testbed is intended to allow researchers to develop, test, and demonstrate new communications, networking, and navigation capabilities in the actual environment of space. After building and launching this payload in 2012 it was determined that a fully characterized and controllable ground station would further facilitate testing novel communication technologies such as software defined radios (SDRs) and cognitive communications. In early winter 2015, the SCaN Testbed Glenn Research Center S-Band Ground Station (GRC-GS) was completed to provide this service.

In order to meet the objective of being a fully characterized system it was essential to do extensive component testing in the laboratory and then re-validate those results once installed in the field. This paper will describe the various tests completed prior to installation with additional attention given to the antenna characterization. It will then describe the revalidation and monitoring put in place during and after installation. Next, it will describe the characterization of the GRC-GS antenna using a geostationary National Aeronautics and Space Administration (NASA) Tracking and Data Relay Satellite (TDRS). Finally, there will be a comparison of the results of the lab and post-installation testing as well as the lessons learned.

II. GROUND STATION DESCRIPTION

The GRC-GS is an S-Band (2.0 – 2.4 GHz) relay station with equipment located in two separate buildings on the GRC campus, Building 333 (B333) and Building 110 (B110). A basic wiring diagram for the main ground station components is shown in Figure 1.

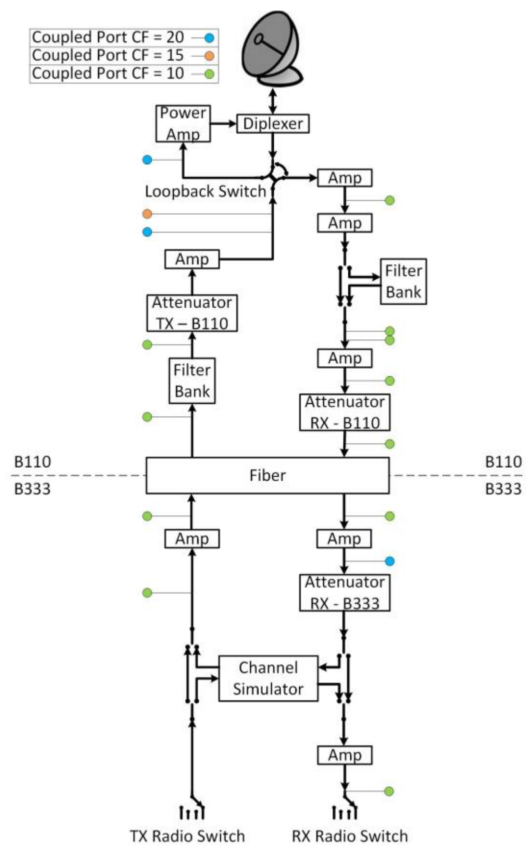

Figure 1. Basic Wiring Diagram for the GRC-GS with Test Points.

B110 equipment includes items such as low noise amplifiers, attenuators, filters, the 2.4m parabolic reflector, and gimbal located on the roof [1]. It has two dedicated fiber pair connections, one for the analog radio frequency (RF) signal and one for data. These are used to connect it with the rest of the equipment located in B333.

Additional amplifiers, attenuators, switches, and a channel simulator are located in B333 as well as the operational controls for the GRC-GS. This arrangement was selected to take advantage of the lack of obstructions and easy access on the roof of B110 while having the controls co-located with the SCAN Testbed payload operators in B333.

The GRC-GS is designed to communicate with either the SCAN testbed located on the International Space Station (ISS) or various Tracking and Data Relay Satellite System (TDRSS) satellites. It accomplishes this via an RF switch connected to the diplexer that isolates the transmit and receive frequency bands. This switch allows the user to select which side of the diplexer is in use for the Receive (RX) and Transmit (TX) signal chains.

During the design phase of the ground station, it was crucial to assess how we would re-validate our component and subsystem characterization after installation, as well as monitor the system for potential deviation from the original measurements over time. To meet this objective, fifteen couplers were integrated into the ground station to function as test points, as shown in Figure 1. They can be used for power meters, spectrum analyzers, or experimenter equipment upon request. Twelve of these test points are typically dedicated to power meters that provide information back to the control software. These readings combined with the cascaded laboratory measurements allow for overall monitoring of the ground station during operations, as well as logging data for post-processing and event debugging. The graphical user interface (GUI) for this software is shown in Figure 2.

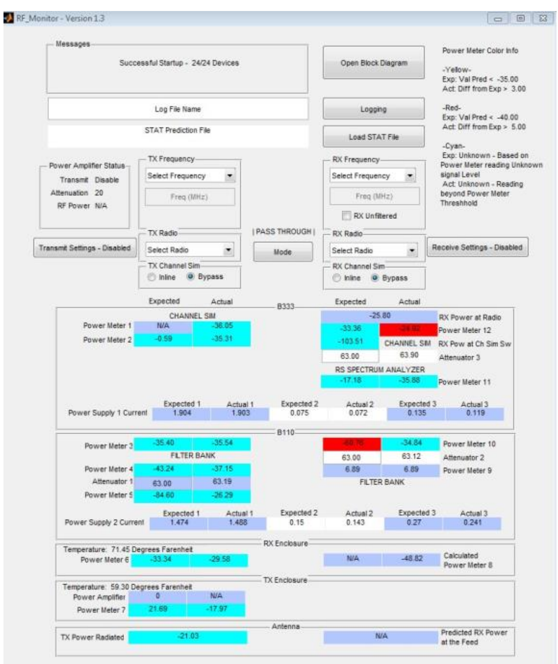

Figure 2. RF_Monitor Control GUI.

In addition to these test points, an RF switch was included that could either allow the ground station to operate in a normal "Pass Through" or "Loopback" mode. Loopback mode was specifically included for testing. It connects the transmit signal chain of the ground station to its receive signal chain. When in this configuration, a signal generator or radio can be used to inject a test signal that can then be monitored at the various test points to confirm if they match the original data.

III. Laboratory Testing Methodology

During the laboratory buildup there were three general groups of testing performed on various components. First, passive components such as cables, filters, diplexers, couplers, adapters, and switches were limited to S-Parameter measurements only. Second, active components such as amplifiers and fiber converters had their gain, noise figure, phase noise, and intermodulation distortion measured in addition to their S-Parameters. Third, the antenna pattern and gain were measured for the parabolic reflector using the GRC Near-Field Antenna Range (GRC-NF) [2], [3].

After testing the individual components, small subsystems were assembled and then remeasured with a vector network analyzer (VNA) to confirm that their combined operation matched the expected performance based on measurements of the individual components.

A. General Testing Example

One example of a subsystem built from components is the TX Filter Bank. This subsystem is assembled from cables, switches, and filters. Each of these components were characterized individually then the filter bank was re-measured after assembly. Figure 3. shows the S21 magnitude measurement for the assembled filter banks as well as the expected value based on combining the various component measurements. Figure 4. shows a zoomed in view of each filter channel.

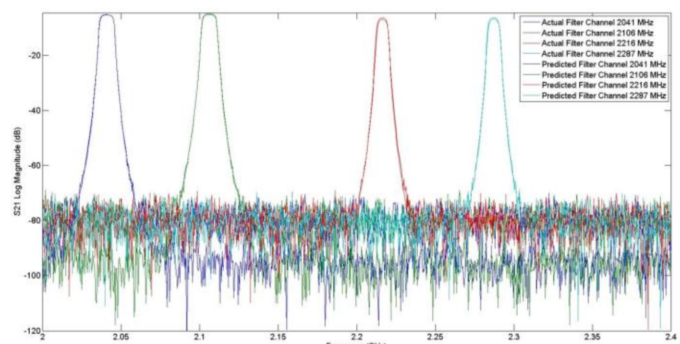

Figure 3. Cascaded TX Filter Bank Components and Subsystem S21 Parameters.

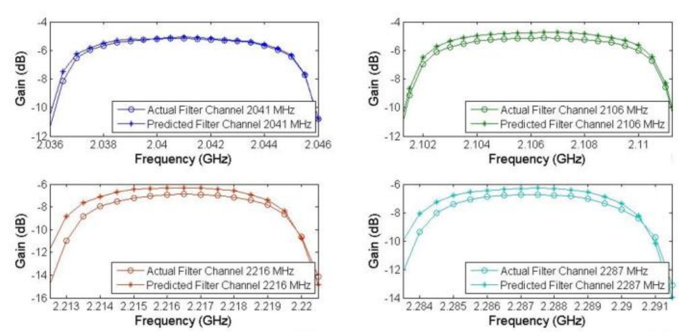

Figure 4. Zoomed in Filtered Channels.

B. Laboratory Antenna Characterization

The ground station uses a 2.4m parabolic dish with a left hand circularly polarized feed as its antenna. The dish is made from a composite material and was delivered in three sections to be assembled on-site before testing in the GRC-NF. Table I. shows the vendor specifications for the antenna.

TABLE I. ANTENNA VENDOR SPECIFICATIONS

Characteristic	Value
Frequency	S-Band
Diameter	2.4m
Polarization	LHC
Half-Power Beamwidth (HPBW)	3.9°
Gain	31.5 dB

For testing, the antenna was assembled and attached to the gimbal. Then the entire assembly was mounted to the pedestal located in the GRC-NF as shown in Figure 5.

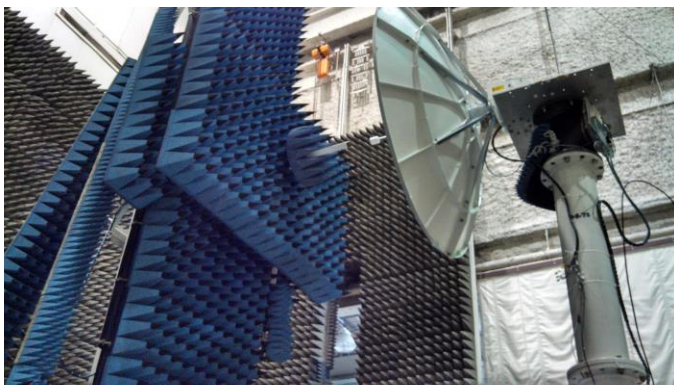

Figure 5. Assembled Antenna and Gimbal in the GRC-NF.

To get an accurate gain and pattern measurement first a known calibrated horn was used to quantify system levels. Then the GRC-NF collected near-field antenna measurements taken at a distance of 50cm between the antenna rim and system probe. First the antenna was measured at the frequencies given in its specification datasheet to confirm that after assembly the setup yielded results which matched expected values. Next, it was measured at each operational frequency for communicating with SCAN Testbed and TDRSS.

Each measurement is processed by the Nearfield Systems Inc. NSI2000 software. This tool transforms near-field measurements into a far-field pattern for any antenna under test. The baseline calibration data taken with the standard feed horn is a part of that transformation process and is used by the software to produce an accurate model of the antenna gain magnitude.

The pattern and gain were collected over a vertical and horizontal span that translates to 60° in both Azimuth and Elevation in the far field with 201 points in each dimension. Figure 6. and Figure 7. show the resulting Vertical and Horizontal Cuts of the pattern, respectively, for each operational frequency.

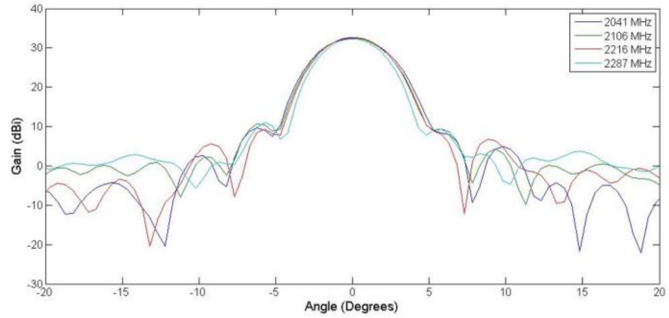

Figure 6. GRC-NF Antenna Pattern Vertical Cut.

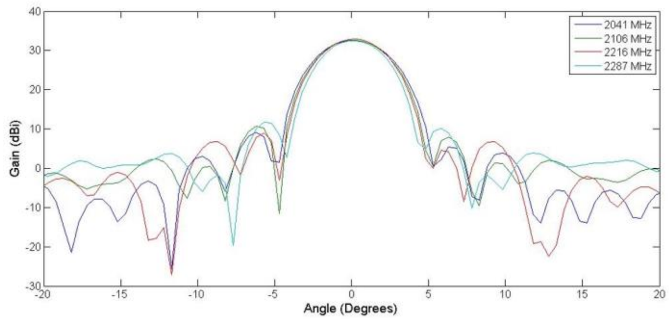

Figure 7. GRC-NF Antenna Pattern Horizontal Cut.

In addition to near field measurements the antenna was scanned using a Leica Geosystems LR200 Laser Radar to complete a non-contact based photogrammetry study of the surface of the parabolic dish. Completing this test allows for simulation of the antenna RF performance via Geometric or Physical Optics techniques as well as detecting any warping in the surface of the dish. This was done before and after characterization in the near-field to examine the dish both after assembly and after a few weeks of use. The laser scan setup is shown in Figure 8.

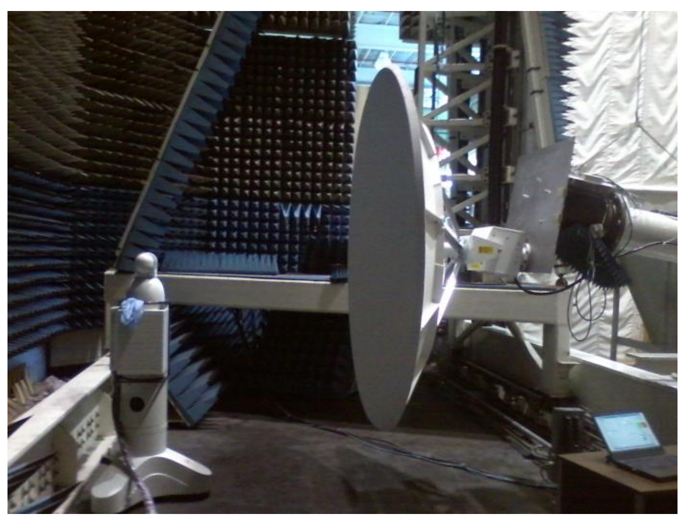

Figure 8. The GRC-GS Antenna being scanned by the laser in the GRC-NF

When completing a scan, the laser measures the distance to a desired surface point via an infrared beam, while a co-aligned red laser beam is projected at the same target for user visualization. Measuring the surface characteristics for the GRC-GS antenna was a two-step process. First, the laser defines a perimeter for the rest of the scan by measuring along the antenna rim. Next, it scans the rest of the area inside that perimeter using an X-Y grid. This grid pattern has a spacing defined as less than the half-wavelength of the highest operating frequency of the antenna.

IV. Installation and In-Situ Validation

After construction and installation on site, it was essential to evaluate the functionality of the equipment both to ensure there was no damage during transportation and assembly and to verify that our original measurements were still accurate and could be used for planning future experiments [4].

A. *Passthrough Testing*

Once installation of the ground station equipment was complete, RF signals were inserted into each signal chain to compare against the original characterization data measured in the lab during build-up. This was done on the TX signal chain by connecting a signal generator to the radio input and reading the power levels at the various test-points as well as through a spectrum analyzer connected to the cable going to the antenna feed. For the RX signal chain, the spectrum analyzer and signal generator were swapped so that the input came from the cable normally connected to the feed and the output was measured at the test-points as well as the radio switch. Figure 9. shows the standard deviation of the actual signal level from the expected value at the power meter immediately after the TX Filter Bank during these tests, as well as subsequent experimenter events.

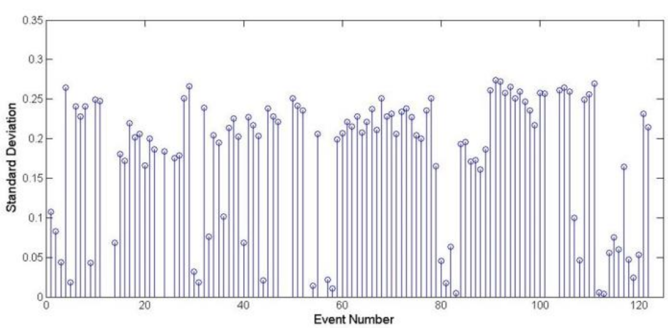

Figure 9. Standard Deviation of the Power Levels at the TX Filter Bank.

B. *Loopback Testing*

To complete Loopback testing a signal generator was used to insert a known carrier wave signal into the transmit chain at each operational frequency using various power levels. Then, using the original test data, the gains and losses were compared at each test point to the expected signal level.

C. *In-Situ Antenna Characterization*

While Loopback testing was able to validate most of the RF equipment performance within the ground station, the signal path did not include the antenna. Therefore characterizing the dish requires a separate measurement. It was determined that using a characterized geostationary satellite would be an ideal choice for this test. By selecting a satellite with a known Equivalent Isotropic Radiated Power (EIRP) and detailed dynamic link budget, a pertinent measurement similar to the one in the GRC-NF could be performed. This led to the selection of two satellites from TDRSS that met all of these criteria.

1) TDRS Information: The GRC-GS contacts with the (TDRSS) are limited to the TDRS orbiting in locations off the East Coast of the US, where the orbital assignments include TDRS-Spare (TDS) and TDRS-East (TDE). The GRC-GS does not have line of sight to TDRS that are located off the West Coast of the US, such as TDRS-West (TDW) or TDRS-171 (TD171). This limitation is a result of gimbal elevation angles that must remain 10° above the horizon. Contacts with TDRSS at TDS or TDE remain available at all times, as TDRS are in a geostationary orbit, and remain close to a fixed point in the sky [1]. They also have known output power levels and their link budget can be calculated using the GRC derived internal project analysis tool SCaN Testbed Analysis Tool (STAT) software [5].

2) Gimbal Pointing: The gimbal used for pointing the antenna and for tracking satellites is shown in Figure 10. It can move at speeds up to 20°/s in azimuth and 4°/s in elevation. It has a field of motion from -90° to 90° in elevation and 210° to -210° in azimuth. While in use for the GRC-GS, the top speed is limited to 4°/s in both azimuth and elevation and its range is limited in elevation to 10° above the horizon. The gimbal is controlled via the LynxCAT toolset. User information for this toolset is captured in the LynxCAT SK User's Guide [6].

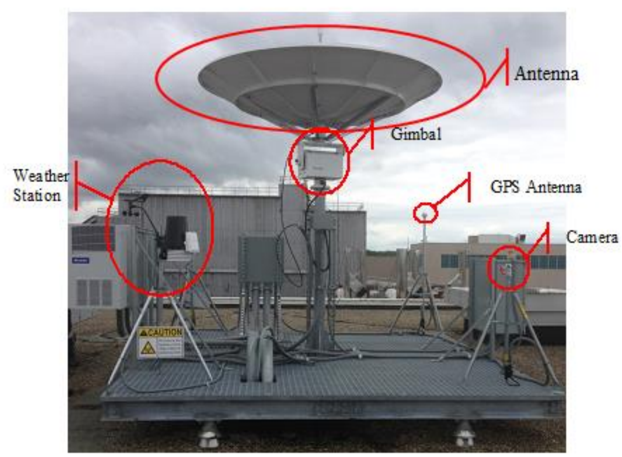

Figure 10. GRC-GS Rooftop platform and equipment.

3) Characterization Setup and Results: The GRC-GS was tested with both TDRS-6 and TDRS-9 at the TDS and TDE orbital slots respectively. This testing was done numerous times during the initial system calibration, however all data shown below is from operations on February 4, 2015 with TDRS-6 on the Single Access (SA) frequency (2041.027 MHz). Note the side-lobes are not typically distinguishable via testing with TDRS, as the received power levels are below the noise floor.

Testing of the GRC-GS antenna was completed using two distinct off-pointing methodologies [7]. First, the GRC-GS was commanded to run a spiral track motion away from the predicted direct path, using the LynxCAT toolbox gimbal controller. This spiral track motion is a quick method for determining the shape and performance of the main beam over the entire relevant antenna surface. Figure 11. shows the data points measured during this spiral track test.

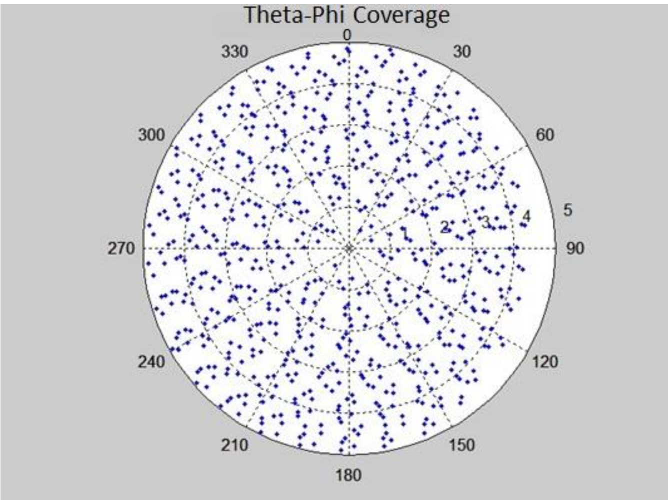

Figure 11. Measured Data Points during TDRS Spiral Testing.

These data points combine to indicate antenna performance at nearly 5° off antenna boresight. The resulting antenna pattern is shown in Figure 12.

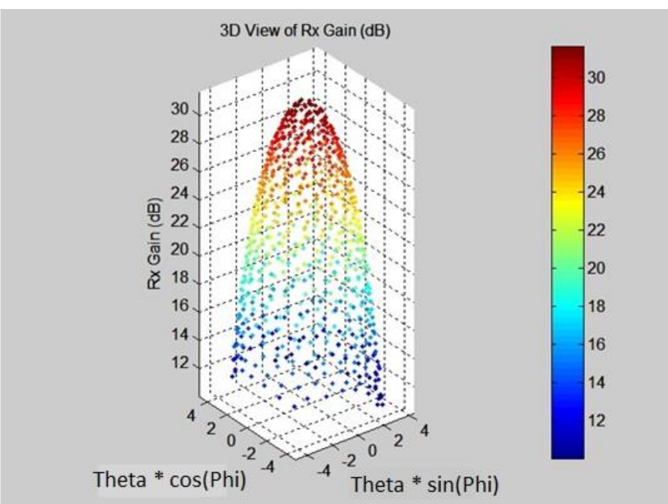

Figure 12. GRC-GS Antenna Pattern Measured Using TDRS Spiral Testing.

The second off-pointing method used in the calibration process was by adding a fixed error offset into the normal direct path commands. For this test the gimbal was pointed directly at TDRS-6 then a pointing offset value would be added in the elevation angle at specific time intervals, while holding the azimuth constant. Figure 13. shows the points measured during this test and Figure 14. shows the resulting pattern.

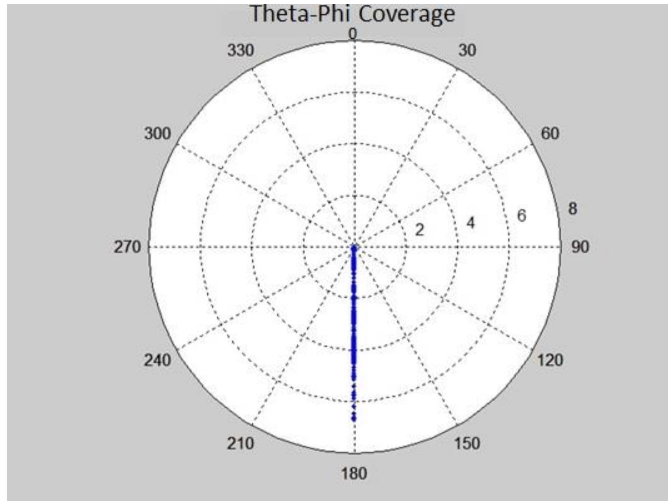

Figure 13. Measured Data Points during TDRS Fixed Offset Testing.

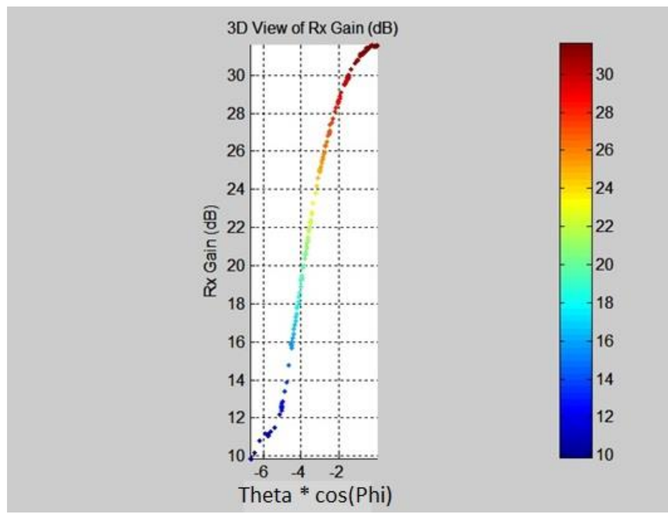

Figure 14. GRC-GS Antenna Pattern Measured Using TDRS Fixed Offset Testing.

This pattern was compared with the original GRC-NF measurements to check for damage during installation. The two patterns are shown in Figure 15.

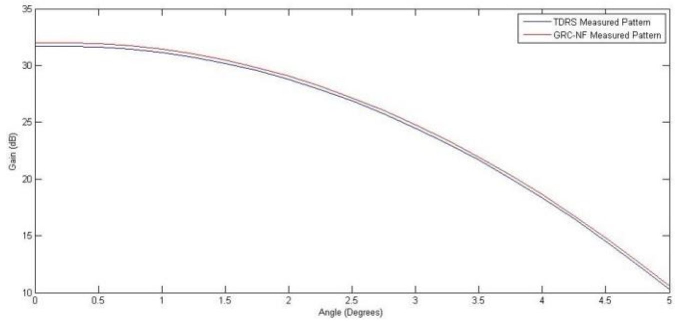

Figure 15. GRC-GS Antenna Pattern Measured Using TDRS and GRC-NF.

Once this testing was complete, patterns for the other frequencies (2106.406 MHz, 2216.5 MHz, and 2287.5 MHz) were extracted from the shape of the measurement completed with TDRS. The patterns for the four operational frequencies are shown in Figure 16.

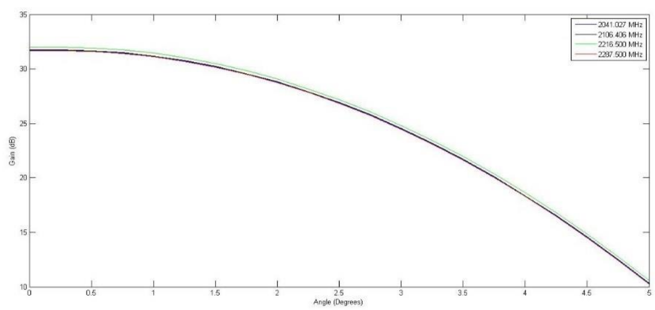

Figure 16. GRC-GS Antenna Pattern for each Operating Frequency.

V. Lessons Learned

The inclusion of equipment to enable long term testing and monitoring of a ground station should be an essential component of the initial design. Once the ground station was built and assembled, these items proved to be invaluable. They have already assisted in troubleshooting various issues quickly and efficiently by narrowing down the location of a problem. Logging the data from the various sensors has enabled straight forward comparisons of performance that are essential for novel communications being tested using this platform.

Using a geostationary satellite to validate the antenna pattern after installation was particularly useful. It allowed verification that removal of the reflector from the GRC-NF and crane lift to the roof of B110 had not damaged the dish. It also allowed comparison between the laboratory and in-situ environments to ensure the antenna was accurately represented in any data provided to experimenters. One specific challenge with this method was interference from local sources. In the GRC-GS case that came predominately from the area broadcasters. When doing this type of measurement it is ideal to have coordinated time to complete the test without these extraneous signals. An alternative is to characterize numerous times and average the results to eliminate some of the noise in the process. This level of detail should allow experimenters to plan and analyze data captured using the ground station with a high level of certainty in the results.

The success of the methods used to characterize this ground station after installation should be of interest to any group desiring to confirm the accuracy of their equipment without needing to disassemble and return to a laboratory for repeated testing. It should also be notable to those who are interested in designing an RF link with a lower margin built into the link budget. A lower margin often translates into cost savings on the individual components which is often a concern for many projects.

Acknowledgement

The authors would like to thank the SCaN Testbed Project for its support in funding the design and construction of this station, as well as to the SCaN Testbed Mission Operations Team for their efforts in coordinating TDRSS events directed to the NASA Glenn Research Center to enable this type of testing to be performed for the first time.

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