COMPLETION OF A SATELLITE ANTENNA TEST AND REPAIR FACILITY RELOCATION

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Abstract

The maintenance, test, and repair workload for the Air Force's AN/MSQ-118 satellite ground-based receiving communication system has been transferred from the closing McClellan Air Force Repair Facility in Sacramento, California to Tobyhanna Army Depot located in Tobyhanna, Pennsylvania. The workload requires the support of four maintenance shops and two planar near-field ranges. The shops are the antenna repair, power supply repair, low-noise amplifier (LNA) repair, and radome repair shops. The near-field ranges are a 4' x 4' planar scanner used for antenna diagnostics and an 8' x 8' planar scanner used for certification of the repaired antenna-under-test (AUT).

This paper will bring the AMTA community up to date on the status of the new Tobyhanna Antenna Repair Facility, focusing on the techniques and methods used to quantify the alignment and performance characteristics of the planar near-field antenna measurement system used for certification. With the relocation complete, test data obtained at both locations will be analyzed and compared to show differences between the baseline measurements taken at McClellan Air Force Base versus those taken at Tobyhanna Army Depot.

Keywords: Planar Near-Field, Range Verification

I. Background

The Sacramento Air Logistics Center (SM-ALC), located at McClellan Air Force Base, California, is a high-technology industrial center for the Department of Defense. During its period of operation, SM-ALC has maintained communications-electronics systems for aircraft and ground control stations. This included the responsibility of providing maintenance, repair, test, and certification of various military antennas and radar systems.

In the early 1990's, SM-ALC acquired the task of maintaining the AN/MSQ-118 Phased Array Subsystem (PASS) antennas. The PASS antennas are 3' x 4' flat phased arrays that include 128 identical circular elements on two RF circuit boards, two low-noise amplifiers, and a four voltage power supply. The antenna contains four digital cards that provide steering control to the 128 elements. Each element contains a phase-shift circuit consisting of RF diodes, inductors, capacitors, and resistors. For each element, three diode pairs provide shifting in increments of 45 degrees. The remaining major components are the antenna case and radome.

SM-ALC spent several months reverse-engineering the antenna, since it had to be repaired and tested outside of its control system. Simultaneous to the electronic work done on the antenna, an effort was made to develop RF procedures for certifying that repair work [1]. After the successful development of a prototype near-field system at SM-ALC [2], two commercial near-field antenna measurement systems were purchased: one for diagnostics and a similar larger system for certification [3]. Test procedures were derived from the antenna manufacturer's far-field certification plan.

In 1995, the Base Closure and Realignment Commission recommended that McClellan Air Force Base and its Air Logistics Center be closed. The commission also recommended that the common-use ground-communication electronics workload be moved to Tobyhanna Army Depot. This included the repair of the AN/MSQ-118 PASS antenna which was scheduled to move in the Spring of 1999.

Tobyhanna Army Depot (TYAD) is located in the Pocono Mountains of northeastern Pennsylvania, approximately 20 miles southeast of Scranton. The depot is the largest full-service communications-electronics maintenance facility in the Department of Defense, providing full-service support for the entire spectrum of military communications-electronics systems. Its mission includes the design, manufacture, integration, and repair/overhaul of numerous types of communications and electronics systems ranging from radar, electronic warfare, and electronic countermeasures to satellite and radio communications [4].

Despite TYAD's experience with antenna repair/overhaul, they did not initially possess the expertise required to repair/overhaul a PASS antenna panel. Therefore, an extensive training plan was developed to provide TYAD engineers and technicians with the expertise necessary to carry on the PASS antenna repair program at their facility. The plan included six months of training at SM-ALC on the 8' x 8' scanner, one month of training on the electronic and RF/diagnostic tests utilizing the 4' x 4' planar scanner, one month of training on the antenna rebuild and radome application process in the materials lab, two weeks of training on field-level support, and formal training at facilities such as the Georgia Institute of Technology. TYAD personnel also received training on the Antenna Diagnostic Expert System (ANDES), a diagnostic software package developed to capture the expertise of SM-ALC personnel in the repair and certification of the PASS antennas [5].

All of the equipment required to support the PASS antenna workload was shipped to TYAD during the first five months of 1999. The first pieces of equipment delivered were the autoclave and acid-etching glovebox required for application of radomes and total rebuild of the antennas. Later, all specialized test equipment, fixtures, interface test adapters (ITAs), and common test equipment required for repair of the antenna electronics, LNAs, and power supplies were delivered. The last pieces of equipment shipped were those associated with the certification chamber.

The transfer of capability associated with the certification chamber involved the construction of an RF/anechoic chamber and control room at TYAD and the relocation of the 8' x 8' near-field planar scanner with its associated positioning and measurement equipment from SM-ALC. Construction of the chamber and control room was the responsibility of TYAD who hired a private contractor for the project. Responsibility for relocation of the near-field antenna measurement system resided with SM-ALC who hired a private contractor to provide the technical expertise for the task. The contractor conducted all antenna pattern and alignment tests necessary to establish a baseline at McClellan and any alignments and tests necessary to achieve that same baseline *or better* at TYAD. He also provided guidance and direction involved with the disassembly, crating, uncrating, and re-assembly of the 8' x 8' planar near-field scanner.

On March 1, 1999, the contractor arrived at SM-ALC and began the testing required to establish the baseline. Within four weeks, the entire near-field antenna measurement system at SM-ALC had been tested, characterized, disassembled, and packaged for shipment to TYAD. By the 3rd week of April, all of the equipment had arrived at TYAD and was being re-assembled. Test and alignment began the 1st week of May and was completed by the 2nd week of June, the entire project completed within budget and six weeks ahead of schedule.

II. System Assessment and Disassembly at SM-ALC

The first step in the characterization of the near-field antenna measurement system at SM-ALC was the performance measurement of a "gold standard" antenna (SN005) whose results are traceable to the National Institute of Standards and Technology (NIST). SM-ALC personnel had routinely used this antenna to ascertain and prove the general condition of their certification facility. Results outside of the expected range would alert personnel to check their system for properly operating test equipment and correct alignment of the AUT and probe.

Near-field measurements of antenna SN005 were made at four beam states, 0°, 45°, 90°, and 180°. All measurements were made in the LS band using the right-hand circularly polarized (RHCP) antenna port of a probe whose gain had been previously measured at NIST. Data obtained by measuring the complex near field (amplitude and phase) was processed to obtain far-field gain and pattern information for the antenna.

Far-field pattern cuts in azimuth and elevation were viewed for each of the four beam states. Parameters observed and analyzed in each pattern include antenna gain, beam width, side lobes, and nulls. Antenna gain for each beam state was also compared to historical data maintained by SM-ALC personnel over the last 4 years as well as measurement data provided by NIST in 1991 and 1995. To provide a distinctive antenna pattern, SM-ALC personnel had hard-wired two faults (one viewable at beam states 0°, 45°and 90°, the other at beam state 180°) into the gold standard antenna. Near-field 2-dimensional contour plots in amplitude and phase were viewed to verify the presence and location of these inserted faults.

Near-field testing of SN005 took several days. A database was created and the day-to-day results were analyzed for accuracy and repeatability. When stable, accurate, and repeatable results were obtained, conditions of the testing were altered slightly to ascertain their affects on the results. For example, the affects of temperature were observed by running the same test sequence at different times of the day. In another data set, the affects of antenna mounting were observed by taking measurements after removing and then replacing the antenna on the antenna pedestal.

The next test performed was a Z-axis multiple reflection test. To start this test, the AUT pedestal was moved forward until the probe of the scanner was 1 inch away from the center of the AUT. With the AUT transmitting, a total of 100 amplitude measurements were taken at 1-inch intervals while moving the antenna away from the probe in the z-axis. This measurement was made three times with the probe positioned in a different location for each test run. For the second run, the probe was centered over one of the element columns along the edge of the AUT. For the last run, the probe was centered over the last element row near the bottom edge of the AUT. Data from the three runs was plotted on the same graph and compared to the data taken 4 years prior when an optimum z-axis location for near-field testing was selected at SM-ALC.

Additional tests were performed to characterize the individual errors contributing to the overall measurement error of the antenna. They included leakage tests, input/output VSWR measurements of the probe, AUT, and signal generator, and dynamic range and linearity measurements of the receiver. Also measured were the affects of cable flex and probe alignment error due to random placement of the alignment jig/mirror on the face of the probe.

Unless otherwise stated, measurements taken to verify the mechanical alignment of the planar scanner were made using a high-technology laser-based coordinate measurement system, hereafter referred to as the tracker. The tracker uses a laser distance meter, two precision encoders, and proprietary software to calculate, store, and display the 3-dimensional (3-D) position of a mirrored optical target called a Spherically Mounted Retroreflector (SMR). The SMR can be mounted to fixed or moving points on the object to be measured. The beam steering system of the tracker can sense movement of the SMR and direct two servo motors to continuously track it. The tracker will follow the SMR over the range of movement and update its 3-D position at a rate of 1000 times per second. The abundance of data collected yields excellent accuracy and good statistical redundancy.

At SM-ALC, the tracker was positioned between the AUT pedestal's z-position-rails near the entrance of the chamber. Three SMR magnetic mounts were placed on the face of the scanner with an additional mount placed on the scan-plane alignment mirror support. Three-dimensional coordinate measurements were periodically made at these fixed-reference SMR locations to verify the proper operation and calibration of the tracker system. For characterization of the scan plane, the SMR was mounted on the face of the RF probe. Several points within and around the perimeter of the scan plane were chosen as reference points for fixed measurements or endpoints during linear scans. Data taken at these points gave a rough indication of the planarity of the scanner. It also allowed comparison to data taken by SM-ALC and TYAD personnel using a mechanical transit adjusted to level and bucked in along the X-axis.

To allow mapping of the entire scan plane, the scanner controller was programmed for a raster scan of the entire X-Y scan plane. During the scan, the tracker followed the SMR and collected 3-D positional data across the plane on a 4-inch spaced grid. The tracker data processing software was then used to create 2- and 3-dimensional contour plots of the scanner planarity. Additional measurements were also made to characterize the linearity, or rail alignment, of the individual scanner axes. Data plots showing the deviation in z as a function of x and y, deviation in y as a function of x, and deviation in x as a function of y were made to further define the baseline of the scanner.

Disassembly of the scanner began after completion of all tests and measurements required for the baseline. Following removal of the antenna probe from the y-axis table, the y-axis beam was moved to its -x electrical limit and tied off to the left-side wall of the scanner. After the y-axis was disconnected from the top rail, the top cross-member of the scanner was removed. Then the y-axis beam was removed, followed by the left- and right-side scanner walls, and finally the scanner base.

After disassembly of the scanner, it was observed that one of the two linear motion guides (bearing packs) on the bottom rail of the scanner was very difficult to move. Closer examination revealed that one set of continuous bearings inside the guide was missing several bearings and was frozen in place. After discussion with a representative from the manufacturer, a decision was made to replace each of the scanner's eight linear motion guides before re-assembly at TYAD.

III. Installation at Tobyhanna

The new location for the near-field scanner at TYAD is a modular, self-supported, RF-shielded anechoic chamber with approximate dimensions of 23' W x 24' L x 17.5' H. The chamber is installed on a monolithic, geologically-stable concrete isolation pad that provides isolation from any vibrations such as nearby forklift traffic or movement of heavy machinery. Co-located to the chamber is a modular, self-supported RF-shielded control room with approximate dimensions of 20' W x 16' L x 8' H. Four shielded RF penetrations are installed between the two facilities to accommodate cable connections between the scanner and measurement/positioning equipment.

Both structures are isolated from ground by a minimum of 1000 ohms and provide a minimum of 100 dB shielding effectiveness up to a frequency of 10 GHz. The walls and ceiling of the chamber are lined with fire-retardant, 12-inch pyramidal absorber that provides absorption in excess of 50 dB in the Ku band. A set of parallel rails is integrated into the chamber floor that allows movement of the AUT pedestal in the z-axis of the measurement system. The heat, ventilation, and air-conditioning (HVAC) system for the chamber/control room is a self-contained unit able to maintain a temperature range of 55°F to 75°F with a relative humidity range of 40 to 70 percent. The unit provides supply ductwork to two of the four high-hat light assemblies in the chamber and to two waveguide vents installed in the ceiling of the control room. Return air exits the chamber from the two remaining high-hat assemblies and is exhausted into the parent facility. Separate zones are provided for independent control of each facility. A closed circuit television system allows monitoring of activity from three different locations inside the chamber. A view of the finished chamber is shown in Figure 1.

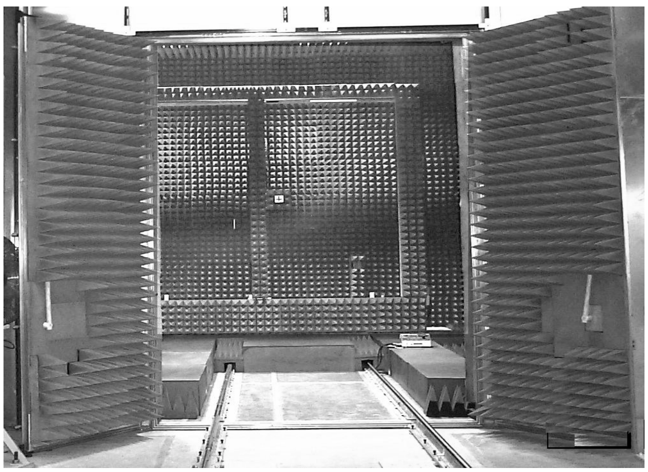

FIGURE 1: TYAD Near-Field Certification Range

The z-rails provided the reference point for installation of the scanner in the new facility at TYAD. To start, the tracker used to establish the baseline at SM-ALC was set in place between the z-rails at the door of the chamber. Following leveling and calibration of the tracker system, measurements were made to define the z-axis. First, the endpoints of one rail were measured to establish a line defining the z-axis for the chamber. Then the tracker's coordinate system was defined using level and the z-rail endpoints, effectively defining the x-axis along which the scanner base would be located.

With the x-axis defined, the base of the scanner was positioned at the end of the z-rails with two leveling blocks placed under each of its three legs. The location of the base was adjusted so that the difference between the z-coordinate values at its endpoints was minimized. Then the base was roughly leveled along the x-axis and anchored to the chamber floor to allow re-assembly of the scanner.

The scanner was re-assembled in the reverse order of disassembly at SM-ALC. Three support angles extending from the sides of the scanner were also installed and loosely anchored to the chamber floor. With the scanner fully assembled, all of the positioning equipment and associated cabling was connected to allow movement of the probe from one location to another in the scan plane.

Adjustments made to align the scanner for optimum planarity were made in 2 phases. First, coarse adjustments to the scanner frame were made to achieve proper orientation of the scanner axes with respect to level and each other. Because of their interaction, these adjustments were repeated as necessary until a stable alignment was achieved. Second, the individual axes (rails) of the scanner were adjusted to achieve maximum linearity from one end of the scan plane to the other.

Frame alignment for optimum planarity began with leveling of the scanner, using the x-axis along the bottom rail as a reference. With the y-axis set to its -y electrical limit, 3-D measurements with respect to level were taken at the endpoints (-x and +x electrical limits) of the x-axis. The difference between the y-coordinate values at the endpoints represented the amount of adjustment required to bring the scanner to level. The adjustment to minimize this difference was made by adjusting the leveling blocks at the ends of the scanner, taking care to adjust the front and rear blocks an equal amount each time an adjustment was made. Two leveling blocks under the center leg of the scanner were temporarily removed for this adjustment.

The y-axis perpendicularity with respect to the x-axis was checked next. Measurements were taken at the +y and -y electrical limits of the scan plane at various locations on the x-axis. The difference between the x-coordinate values at the +y and -y limits represented the amount of adjustment required to make the y-axis perpendicular to the x-axis. The y-axis was adjusted to minimize this difference by moving the location of the pinion gear on the top rack with respect to the bottom rack and pinion. The accuracy of this adjustment is dependent on the spacing between the teeth on the rack, but can be fine-tuned by moving the entire y-axis on its pivoting points where it is mounted on the bearing packs. This adjustment is difficult since the scanner is not mechanically designed to allow movement of this axis in small increments.

To finish the coarse alignment of the scanner frame, the leveling blocks at the back of the scanner were adjusted to minimize the difference between the z-coordinate values of four measurement points located at the corners of the frame. Since the pivot point of this adjustment is essentially the front leveling blocks, the top of the scanner tends to move in or out of the true x-y plane in the z-axis as the back leveling block is raised or lowered. Adjustment to a leveling block is made while monitoring the corresponding top corner of the scanner with the tracker. Measurements for this adjustment are made with respect to level and a line defined by the x-axis endpoints at the -y electrical limit.

With the coarse alignment of the scanner complete, measurement of the individual axes was performed utilizing the tracker. For each case, 3-dimensional measurements were made along the entire length of one axis (as defined by the + and – electrical limits) with the other axis positioned near the center of the scanner. Data plots showing the deviation in z as a function of x and y, deviation in y as a function of x, and deviation in x as a function of y were made to determine the amount of adjustment, if any, that would be performed on each axis. Because replacement of the bearing packs required removal of the bottom rails on the y-axis beam, adjustment of the y-axis rails was necessary to reduce the peak to peak deviation in x and z with respect to y to a level no worse than measured at SM-ALC.

The next step in the installation was the setting of the scan plane reference mirror used for alignment of the probe and AUT. When properly aligned, this mirror sits in the same x-y plane as the scanner. The alignment of the mirror involves the use of an auto-collimator transit and optical square. First, the transit is placed to the side of the scanner and bucked in along the x-axis using a crosshair target on the probe. With an optical square inserted directly in front of the mirror and along the buck-in line of the transit, the reference mirror was adjusted in azimuth until auto-collimation was achieved. Then the transit was moved to a point in front of the mirror along the z-axis of the scanner. After the transit was leveled along the line defined by the azimuth of the mirror, the mirror was adjusted in elevation to once again achieve auto-collimation.

To map the surface of the scanner, the scanner controller was programmed for a raster scan of the entire x-y plane. 3-dimensional measurements were made in 5-inch increments along the x-axis and 4-inch increments along the y-axis. The tracker data processing software was then used to create 2- and 3-dimensional contour plots of the scanner planarity with respect to the z-axis.

With alignment of the scanner completed, all components of the antenna measurement system were connected to allow performance testing of the gold standard antenna SN005. The same tests performed at SM-ALC were repeated at TYAD. Results were analyzed for specification compliance and comparison to results from SM-ALC and NIST.

IV. Analysis of Test Data

Any alignment measurements or test data taken at SM-ALC established a baseline for the near-field antenna measurement system and also established the minimum requirements for installation at TYAD. The primary goal for the relocation effort at TYAD was to achieve alignment and performance results that were *equal to* or *better than* those achieved at SM-ALC. This section will present the data taken for the same measurement at both locations and compare the results.

To characterize the base of the scanner with respect to level, a line was measured along the x-axis from the -x to +x electrical limits of the scan plane with the y-axis set to its -y electrical limit. The difference between the y-coordinate values at the -x and +x limits represented the amount of offset from level. The difference between the maximum and minimum y-coordinate values between the limits represents the peak-to-peak deviation of the entire axis. For the data taken at SM-ALC, the end-to-end error was 36 mils and the peak-to-peak deviation was 46 mils. After installation and alignment at TYAD, the data showed an end-to-end error of 15 mils and a peak-to-peak deviation of 24 mils. This represents a significant improvement in the leveling of the scanner.

To characterize the *coarse* scanner planarity with respect to the z-axis, 3-dimensional measurements were made at the top corners of the scanner with respect to level and a line defined by the x-axis endpoints at the -y electrical limit. At SM-ALC, the z-coordinate values at the top-left and top-right corners of the scanner were -24 mils and -71 mils, respectively. This resulted in an end-to-end deviation of 47 mils. At TYAD, the z-coordinate values at the top-left and top-right corners of the scanner were -2 mils and -8 mils, respectively. This resulted in an end-to-end deviation of 6 mils. This result well exceeded the goals for improvement of the z-frame alignment.

Linearity of the x-axis was determined by measuring 3-D data along the x-axis from the -y to +y electrical limits of the scan plane with the y-axis positioned near the center of the scanner. The y- and z-coordinate deviation defined the linearity for the axis. At SM-ALC, the y-coordinate values along the x-axis yielded a peak-to-peak deviation of 27 mils. At TYAD, that same deviation dropped to 14 mils. The improvement realized at TYAD can be attributed to the proper adjustment of the leveling blocks under the center leg of the scanner.

The deviation of the z-coordinate values as a function of x for both locations is shown in Figures 2 and 3. Comparison of the two figures shows the presence of a high frequency modulation on the data from SM-ALC and the absence of that modulation at TYAD. This improvement can be attributed to an increase in stabilization resulting from the addition of a brace to the probe-mounting fixture on the y-axis beam. The replacement of the x-rail bearing packs may have also contributed to this improvement.

Linearity of the y-axis was determined by measuring 3-D data along the y-axis from the -y to +y electrical limits of the scan plane with the x-axis positioned near the center of the scanner. The x- and z-coordinate deviation defined the linearity for the axis. The peak-to-peak deviation of x with respect to y at SM-ALC was 58 mils as compared to 55 mils at TYAD. The peak-to-peak deviation of z with respect to y was reduced from 21 mils at SM-ALC to 13 mils at TYAD.

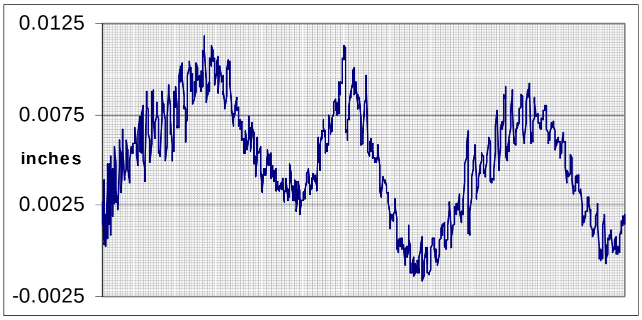

FIGURE 2: Z(X) at SM-ALC

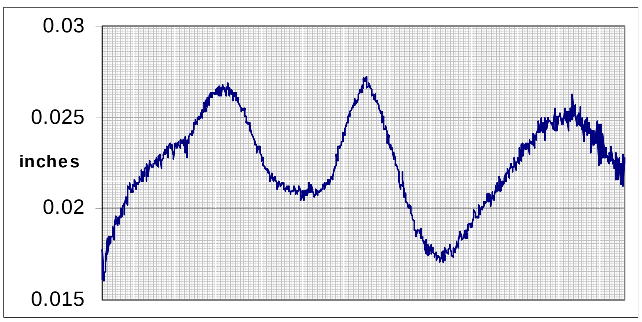

FIGURE 3: Z(X) at TYAD

3-dimensional data taken to map the surface of the scan plane was used to check the planarity of the scanner in the z-plane. Data from SM-ALC showed that the scanner had a peak-to-peak z-planarity error of 80 mils, primarily attributable to the tilt in the upper half of the scan plane. Data from TYAD showed a dramatic improvement in z-planarity with the error reduced to 15 mils peak-to-peak. 2-dimensional contour and 3-dimensional surface plots developed from this data provide an excellent visual representation of the scan planes at both locations.

The near-field performance data for the gold standard antenna for beam states 0° and 45° had excellent repeatability and was within ± 0.15 dB of the 1991 and 1995 data from NIST. However, measurement data for beam-states 90° and 180° would tend to agree with the NIST data from one year, but not the other. Some of the measurements fell outside of the ± 0.3 dB error bounds of the NIST measurements, however this situation was observed at SM-ALC as well as TYAD. Inconsistencies between the 1991 and 1995 NIST data could not be justified, therefore the data for beam states 0° and 45° was used for compliance purposes. Array fault detection at both locations was consistent and repeatable.

V. Summary

The excellent performance and alignment results obtained support the conclusion that the planar near-field antenna system previously located at SM-ALC has been successfully relocated to TYAD. With the relocation complete, TYAD now has the capability to perform the planar near-field antenna measurements required for certification of the AN/MSQ-118 phased-array antenna panels. Coupled with the completion of training and relocation of the antenna support shops, the entire antenna test and repair facility has been re-established at TYAD.

Many factors contributed to the success of the relocation effort. In-depth planning and intense project management at SM-ALC and TYAD helped bring together a host of individuals who displayed a level of teamwork without which this project would have failed. The types of measurements and tests selected and the sequence in which they were performed provided a solid plan for characterizing the system at SM-ALC and re-establishing it at TYAD. From a technical standpoint, the laser tracker used for characterization of the scanner alignment proved to be an invaluable piece of test equipment, allowing fast and accurate 3-dimensional coordinate measurements of the scanner. It also provided a level of testing not possible with a mechanical transit.

As a result of the relocation effort, Tobyhanna Army Depot now has a planar near-field antenna measurement system that is located in a fully RF-shielded, climate controlled, anechoic chamber. It utilizes state-of-the-art measurement equipment built around a proven scanner positioning system. With the superior alignment results achieved, the facility provides an excellent resource for the near-field testing of other higher-frequency antenna systems and could be easily modified for EMI/RFI, TEMPEST, and radar cross-section (RCS) measurements.

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