Performance Evaluation of a Robotically Controlled Millimeter-Wave Near-Field Pattern Range At the NIST

David Novotny[1], Joshua Gordon, Jason Coder, Michael Francis, Jeffrey Guerrieri
Physical Measurements Laboratory
National Institute of Standards and Technology
Boulder, Colorado, United States of America
[1]david.novotny@nist.gov

***Abstract*— The Antenna Metrology Laboratory at the National Institute of Standards and Technology (NIST) is developing a robotically controlled near-field pattern range for measuring antennas and components from 50 GHz to 500 GHz. This new range is intended to address the need for accurate antenna pattern measurements for a variety of applications including remote sensing and imaging. This system incorporates a precision industrial six-axes robot, six-axes parallel kinematic hexapod, and high precision rotation stage. A laser tracker is used to determine position and to calibrate the robot. The robotic positioning arm is programmable and allows scanning in a variety of geometries including spherical, planar, cylindrical, and perform in-situ extrapolation measurements, as well as, other user defined geometries. For the planar geometry, the coverage is a rectangle 1.25 m x 2 m. For spherical, radii from 2 cm to 2 m are possible, while the coverage in θ is ±120° and in φ is ±180°. Robot positioning repeatability has been evaluated and determined to be about 30 µm, and absolute positioning determination via the laser tracker is ~15 µm. Specifics regarding the range evaluation are presented.**

Index—Antenna; calibration; millimeter-wave; near-field; pattern; scanning; terahertz;

I. Introduction

The full-pattern characterization of remote sensing satellites and other high frequency antenna systems (>100 GHz) has been problematic due to the lack of facilities that operate at these frequency ranges [1]. For example, many remote sensing instruments and atmospheric satellites that perform detection in the 100-800 GHz range generally use a combination of three tiers of characterization that are a combination of ground-based hot/cold target characterization, on-board reference targets, and terrestrial-based radiometric cross-calibration techniques [2-4]. As the sensitivity of instruments increase and multi-spectral instruments become more common, pattern characterization and control, become more important. Pattern and absolute gain of the microwave systems can help determine pointing accuracy and aid in overall system calibration [1]. Also, radiometric efficiency measurements above 99% can often require high dynamic range pattern measurements that cover significantly more than the main beam of the antenna. This may necessitate the use of wider angular coverage scans such as spherical, cylindrical, or multiple stitched planar.

Over the last four decades, the Antenna Metrology Project at NIST has implemented various near-field facilities to characterize antennas [5-8]. Over the years, the planar near-field facilities have grown to include spherical and cylindrical pattern ranges. Frequency ranges have steadily grown to recently include the WR-15 and WR-10 bands (50-110 GHz) [9]. Spurred primarily by the requirements of the atmospheric monitoring community's need to better characterize the microwave/sub-terahertz systems and improve overall calibration, NIST is developing a multi-purpose antenna range that will initially operate up to 220 GHz and later to 500 GHz. The range is designed to make planar, spherical, and cylindrical scans; furthermore, it can be easily adapted to measure on arbitrary geometrical surfaces. The wide-angle, spherical-pattern coverage is specifically designed to perform high-efficiency and low-sidelobe measurements to accurately characterize high-sensitivity systems and minimize spurious detection.

II. General Design Concept

A. Basic System Requirements

The basic mechanical specifications are spelled out in [10]. The goal of performing both spherical and planar scans and maintaining required pointing accuracy for gain extrapolation measurements require that positioning is correctable in not only translation (***x,y,z***) but also in pointing angle (***Rx,Ry,Rz***). Additionally, multiple axes need to be aligned (Fig. 1) and the device under test (DUT) aperture needs to be aligned with the ***z*** axis and the robot axes. Maintaining positioning accuracies for pattern measurements at these high frequencies requires not only very accurate positioning; but, also knowledge of the absolute position where the millimeter-wave measurements are perfromed.

978-88-907018-3-2/13 ©2013 IEEE

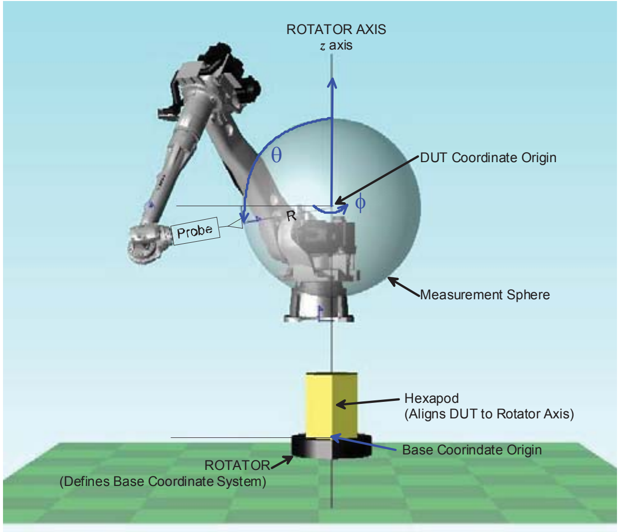

Figure 1. Robot, rotator and coordinate system definitions.

B. A Six-Axes Robot for Coordinated Motion

The choice of an industrial-grade, robotic arm for performing these tasks (Fig. 2) was dominated by the sophistication of coordinated motion available in commercial controllers. The coordinate motion and tool (probe antenna) offsets must provide the ability to maintain pointing and positional accuracy over multiple scan radii, planar geometries, and account for varying probe sizes and weights. This allows for movement of scan centers and surfaces to accommodate larger and offset geometries. The well-developed robotic controller has integrated timing mechanisms that provide signal outputs to easily coordinate other measurement equipment precisely at desired locations. The robot controller can weigh the probe and correct position for the moment arm extending from the end of the robot. Polarization rotation of the probe can

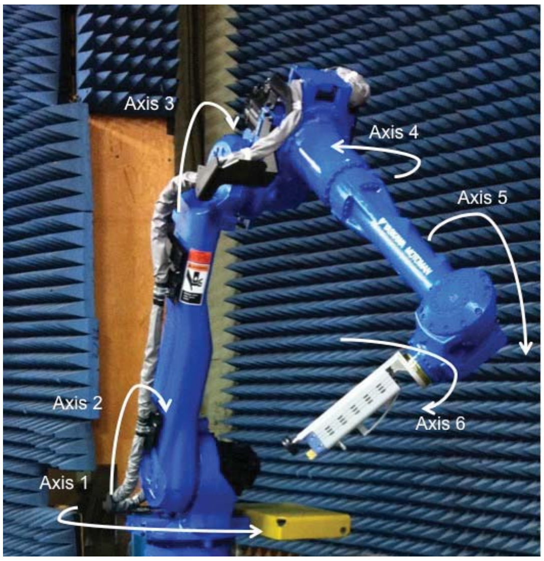

Figure 2.The six-axes robot holding the probe-side millimeter-wave hardware.

be accomplished by inputing the probe offset distance and tilt relative to the robot face (tooling offset) and then selecting a desired polarization by choice of tool rotation. A kinematic alignment interface on the robot face provides for repeatable remounting of the probe antenna to optical tolerances (<10 µm).

The coordinated motion of the robot allows for correction in all six attitudes: 3 degrees of freedom (DOF) in position and 3 DOF in pointing angle. This allows for full probe position correction relative to the DUT and helps in maintaining pointing accuracy to minimize errors throughout the entire scan surface. This level of correction is not possible in most conventional stacked-axes positioning systems, though it does require use of a 6-DOF measuring tool.

C. Rotation Stage and Six-Axes Hexapod for DUT Alignment

Figure 3. DUT and millimeter-wave hardware are supported on the Hexapod, atop the Rotation Stage.

The azimuthal (φ) rotation is accomplished with a servo driven rotation stage with 3,600,000 steps per revolution (0.0001° or 0.36 arc-sec). The rotation stage is fixed (Fig. 3) as stability under loaded conditions (<50 kg) is paramount. The rotational axis of this stage defines the central z axis (Fig. 1) for the entire system. The DUT, robot, and probe must all be aligned to this axis. On top of the φ-rotator sits a six-axes hexapod. The hexapod aligns the DUT aperture to the z axis. The net error and positioning repeatability from the single coordinated movement platform reduces alignment procedures that a stack set of axes requires [11].

D. Laser Tracker for Accurate Position Reporting

The base specification of robot positioning repeatability is ±0.07 mm. Uncorrected absolute positional accuracy is shown to be on the order of 0.3 mm. Assuming a $\lambda/25$ acceptable error, this limits the uncorrected frequency limit to approximately 40 GHz. If the error can be reduced to the base robot repeatability (static position correction), the frequency limit is raised to 170 GHz. A laser tracker with a nominal error of 0.015 mm (within a 5 m spherical volume) is employed to report position of the probe antenna. If dynamic reporting of the antenna position is used, then the positional errors could allow the system to be used well above 500 GHz.

The laser tracker is used to align all the various stages of the system: z axis determination, the DUT to the z axis, the robot, $\boldsymbol{\theta}$ and $\boldsymbol{\varphi}$ axes to the z axis, and determine the DUT to base coordinate offset. Fig. 4 shows the physical layout of the various components.

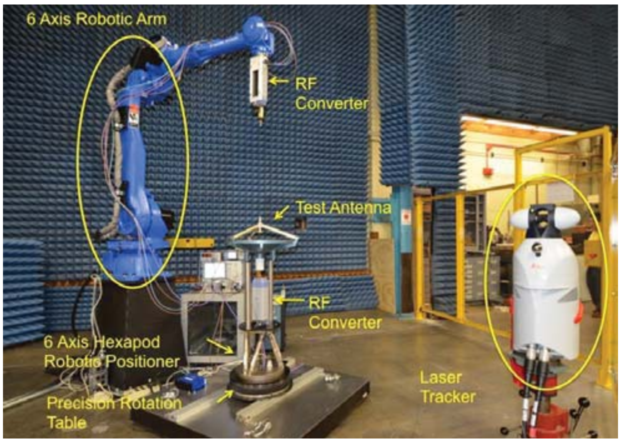

Figure 4. The layout of the mechanical positioning and measurement systems. The laser tracker is positioned to keep the probe within its optimal 5 m measurement volume.

III. Positioning Analysis

A. Movement and Timing

In order to coordinate the position of the measurement probe with the millimeter-wave measurement hardware; the robot movement, and laser tracker and vector network analyzer (VNA) data capture must be synchronized while maintaining probe orientation relative to the DUT. This is done with two major design aspects available via the coordinated motion of the robot: position preparation and anticipated trigger output. To prepare the robot's position and attitude at the desired target point, three movement points are sent to the robot: a leading, target, and trailing point. All three points are on the ideal trajectory (Fig. 5); the leading and trailing points provide that the robot is correctly pointed prior to arriving at the target point. This allows the robot to do any needed position correction and attitude adjustment between the trailing point and the next leading point instead of the period during which the VNA is acquiring data. To ensure smooth and continuous movement, the next three-point set is loaded while the robot is moving between the prior leading and target point. To ensure timing correctness, the robot has an anticipated output function. Based on speed and distance, the robot automatically calculates the required parameters to send a trigger at a set time prior to arriving at the target point. This anticipated output allows for a trigger delay to be set on the laser tracker and VNA to ensure that measurements are centered on the target point. This is of particular importance when data are taken in opposite directions during measurement.

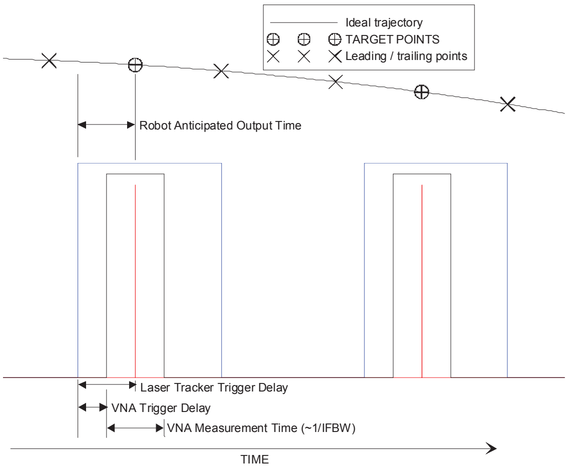

Figure 5. Timing diagram of the robot motion. Leading and trailing points put the robot into the correct attitude throughout the VNA measurement time. The robot sends a trigger prior to reaching the target point. The VNA is delayed to take the millimeter-wave measurement centered on the target point. The laser tracker is delayed so data are coordinated with position and the VNA.

B. Positioning Analysis - Repeatability

The first mechanical parameter assessed is the positioning repeatability of the robot. The probe was moved in a 1 m diameter arc covering $\boldsymbol{\theta}$=-105° to +105°and back to -105° with a data spacing of $\Delta\boldsymbol{\theta}$= 0.5°. Three repeated runs were made at speeds of 25 mm/s and 5 mm/s. Data at individual points were compared run to run, to determine the maximum spread at each point. Fig. 6 shows histograms of the repeatability profiles. Repeatability has a slight dependence on speed but is still generally below 40 µm.

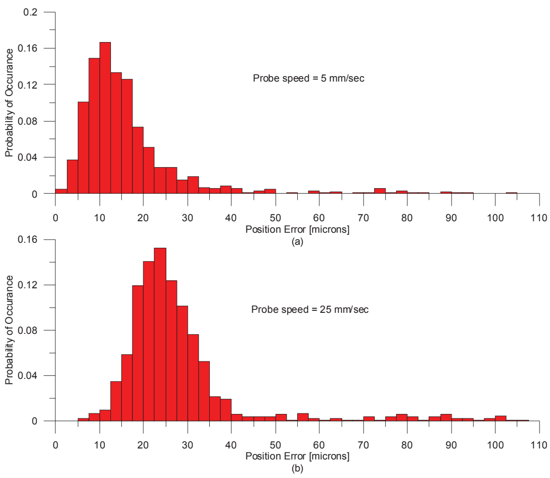

Figure 6. Plots of probe position repeatability at two speeds. Maximum difference between three runs (842 total points). Upper limits of $\mu+2\sigma$ are (a) 40 µm at 5 mm/s and (b) 55 µm at 25 mm/s

C. Positioning Analysis - Accuracy

Data taken from the laser tracker were used to compute the difference between the measured position and the ideal trajectory. The data and trajectory for the 1 m diameter arc at 5 mm/s as used in Section III.B were imported into a kinematic positional analysis software platform and compared. Results shown in Fig. 7, show that the uncorrected/raw error for direct positions is generally less than 0.3 mm.

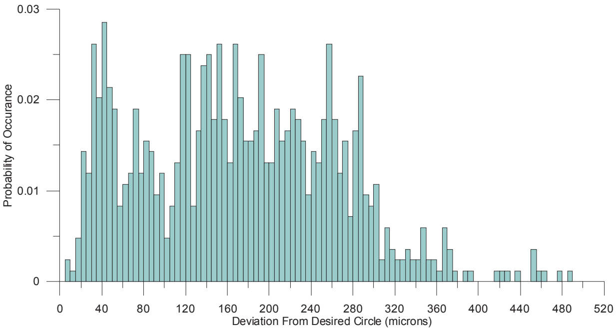

Figure 7. Histogram of differences between desired path and measured path for the robot as it traveled in a round trip path around a 1m arc at 5 mm/s for -105°<θ<105° (842 total points).

The kinematic positional analysis software that determined path deviation was used to correct the original programmed robot target positions by removing the ***x,y,z*** deviations from the original ideal positions. This single-iteration, first-order correction was re-run on the robot. When the path was analyzed, the results, Fig. 8, showed considerable improvement, with the resulting $\mu+2\sigma$ path deviations reduced to ~50 μm.

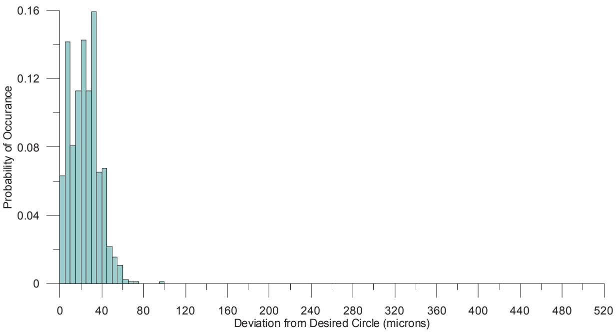

Figure 8. Histogram of deviations from the ideal desired path using corrected positions as measured by the laser tracker. The scale is kept the same as in Fig. 7 for comparison. Note that the deviation level is comparable to the repeatability level in Fig. 6(a). Laser tracker errors are not accounted for.

IV. Uncertaintity Analysis

The expected error for the laser tracker is specified at 15 μm when operating within a 5 m spherical volume. Another source of error is timing in the data capture. Assuming that the timing errors are contained to within 1 ms, probe movement in that period is approximately 5 μm at 5 mm/s probe movement and 25 μm at 25 mm/s. This may account for a large portion of the systematic offset seen in Fig. 6(b). A more thorough timing analysis will be performed with the network analyzer and complex RF signal level compared for the forward and return paths. Additionally, the robot's weight/moment arm correction was not performed for the tests in section III, possibly disregarding a potential method for error reduction. Finally, an in-depth analysis of the systematic errors due to the laser tracker & robot coordinate system alignment was not performed.

V. Conclusion

We have shown that the stable positioning for spherical scanning can be performed to at least the 50 μm absolute accuracy level. Considering a $\lambda/25$ acceptable position error, the corrected-position, frequency limit is approximately 240 GHz. This positional error may be further reduced by use of a multiple iteration position correction and improved timing accuracy.

Finally, we use a laser tracker output for actual in-situ positions during the measurement, the detailed knowledge of the non-ideal sampling may allow for software position correction on the actual millimeter-wave measurement data to reduce effective errors to the uncertainty of the laser tracker (~15 μm / >500 GHz) [11].

References

[1] D Slater, J. Hardy, P. Stek, R. Cofield, R. Dengler, R. Jarnot, R. Swindlehurst, "Large Aperture 650 GHz Near-Field Measurement System for the Earth Observing System Microwave Limb Sounder, A," 2001 Proceed. Antenna Measurement Techniques Assoc, Denver, CO, October 2001, pp468-473.

[2] "Achieving Satellite Instrument Calibration for Climate Change (ASIC3)," G. Ohring editor, National Ocieanic and Atmoshperic Admisitration, August 2007.

[3] J. Liu, Z. Li, Y. Qiao, Y, Liu, Y Zhang, "A new method for cross-calibration of two satellite sensors," Int. J of remote Sensing, vol 25, no 23, pp. 5267-5281, 10 December 2004.

[4] P.M. Teillet, J. L. Barker, B. L Markham, R. R. Irish, G. Fedosejevs, J.C. Storey, "Radiometric cross-calibration of the Landsat-7 ETM+ and Landsat-5 TM sensors based on tandem data sets" (2001). NASA Publication, Paper 13

[5] A. D. Yaghjian, "Near Field Antenna Measurments On A Cylindrical Surface: A Source Scattering-Matrix Formulation", NBS Tech Note 696, September 1977.

[6] R. C. Wittmann, C. F. Stubenrauch, "Spherical Near-Field Scanning: Experimental and Theoretical Studies", NISTIR 3955, July 1990.

[7] R. C. Wittman, B. K. Alpert, M. H. Francis, "Near-Field Antenna Measurments Using Nonideal Measurement Locations", IEEE Trans. Antenn. Prop. Vol. 46, no. 5, 1998.

[8] A. G. Repjar, A. C. Newell, D. T. Tamura, "Extrapolation Range Measurements for Determining Antenna Gain and Polarization", NBS Tech Note 1311, August 1987.

[9] K. MacReynolds, J Guerrieri, M Francis, D Tamura, "Three-Antenna Extrapolation Gain Measurement System at Millimeter Wave Frequencies," 2006 Proceed. Antenna Measurement Techniques Assoc, Austin, TX, October 2006.

[10] J. Gordon, D. Novotny,J Coder, J Guerrieri, B Stillwell ," Robotically Controlled mm-Wave Near-Field Pattern Range," 2012 Proceed. Antenna Measurement Techniques Assoc, Bellview, WA, October 2012, pp 384-389.

[11] R. Wittman, B. Alpert, M. Francis, "Spherical Near-Field Antenna Measurements Using Nonideal Measurement Locations," 2002 Proceed. Antenna Measurement Techniques Assoc, Cleveland, OH, Nov 2002, pp 43-48.