# A Multi-Robot Large Antenna Positioning System for Over-The-Air Testing at the National Institute of Standards and Technology[1]

David R. Novotny‡, Joshua A. Gordon, Michel S. Allman, Alexandra E. Curtin, Jeff R. Guerrieri
*Communications Technology Laboratory*
*National Institute of Standards and Technology*
Boulder, CO
‡david.novotny@nist.gov

Kim Hassett, Quang Ton, George McAdams
*NSI-MI Technologies*
Torrance, CA

***Abstract*— To address dynamic testing requirements of new communications systems and RF processes that use non-static beam forming, NIST proposed the Large Antenna Positioning System (LAPS). The LAPS consists of two kinematically-linked six axis robotic arms, one of which is integrated with a 7 m linear rail system. This repositionable, multi-robot system can perform arbitrary scans around a device under test. The dynamic 13 degree-of-motion capability is designed to perform complex spatial interrogation of systems.**

**The coordinated-motion capabilities of the system are key to support not only traditional antenna measurement geometries (i.e. spherical, cylindrical, planar, gain-extrapolation), but are also intended to be used to dynamically interact with changing RF conditions. The robots can independently scan or interrogate multiple bearings toward a device under test, perform MIMO illumination, or trace out complex 6D paths during system testing.**

**Initial RF and mechanical testing results in the factory where it was built show deviations from an ideal linear scan at 0.032 ± 0.02 mm, much better than the $\lambda/50$ system design specification at 30 GHz. Further improvements to the basic kinematic models of each robot will allow this generation of robotic antenna range to operate open loop without laser tracker feedback.**

***Keywords*— antennas; near-field measurements; robots; positioning; gain, pattern; extrapolation; MIMO.**

## I. Introduction

Industrial robotics offer a large range of motion, high speed automation, and well-developed kinematics for a wide variety of tasks. The large production volumes (i.e., economies of scale) reduce the cost, time, and infrastructure needed to develop applications (in our case, antenna and over-the-air (OTA) communications tests). To complement configurability advantages, the Robot Operating System (ROS) project is currently working on developing plug-and-play interfaces with the goal of allowing computer code and applications to become relatively robot independent, similar to the universal serial bus (USB) interface for consumer level equipment [1].

Historically, improvements in industrial robotics have been focused primarily on increasing tool speed and repeatability. New manufacturing processes are driving the need for better repeatability. Absolute accuracy is not as critical as long as processes can be repeated within manufacturing tolerances. However in recent years, there has been a concerted effort to improve the absolute accuracy of multi-axis articulated robotic arms [2-4]. The combination of lower cost, versatility, easy-to-use hardware and software integration tools, and improving accuracies lead the National Institute of Standards and Technology (NIST) to develop the configurable robotic milli-meter-wave antenna (CROMMA) facility [5]. The CROMMA facility demonstrated 0.03 mm RMS accuracies ($\lambda/50 \approx 200$ GHz) over a 2 m diameter volume, but it required a laser tracker, very selective RF cable routing, and constant monitoring [5-7]. The intent for CROMMA was to push the upper frequency range of antenna scanning metrology [8,9]. It soon became apparent the arbitrary and configurable nature of the system showed possibilities for utility in lower frequency bands of operation [10,11]. Multiple input, multiple output (MIMO) testing at arbitrary angles, testing dynamic paths, investigating Doppler effects, and integrated testing of communications systems where test RF signals cannot be injected into the system antennas were prime applications for taking advantage of this technology.

The Large Antenna Positioning System (LAPS), Fig. 1, was proposed to address these needs. A large scan volume

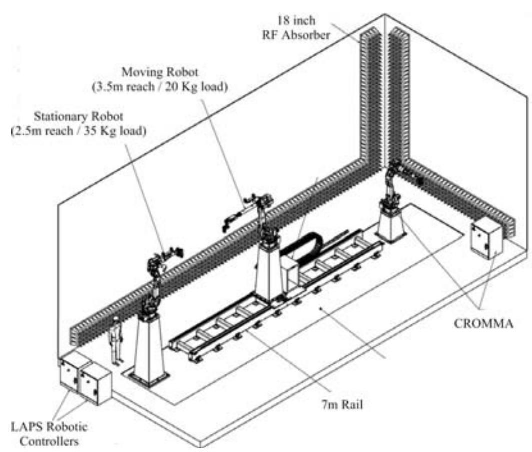


Figure 1. The Large Antenna Positioning System and CROMMA co-located in the NIST Advanced Communications Metrology Laboratory.

suitable for testing across common communications bands (500 MHz - 30 GHz) with modest absolute RMS accuracies of least 0.250 mm was desired. This combination of range (> 8 m separation) and accuracy allows for standard near–field testing and gain extrapolation, and physical separation required to ensure reasonable field uniformity when illuminating small devices with moderate gain antennas. The use of multiple robots allows for multiple bearings to a device, simultaneous emissions and immunity analysis, and interference testing. The push for an accurate open-loop robot calibration, one that does not require a laser tracker or other metrology during the measurement, allows for more dynamic movements by the positioning system, faster robot movements, and the ability of the system to rapidly respond to stimuli [12].

## II. The Large Antenna Positioning System

The LAPS was designed around two commercially available six-axis robots: a moving robot on a base rail (MR) and a stationary robot (SR) on a pedestal located at one end of the rail. The economy-of-scale advantages become apparent when the additive features are examined. Inherent to the robot controllers are a large number of required functionalities that aid in rapid integration. Some of these functions, listed below, require large investments in design and test and, are available mainly because of the size of the articulated robotic arm automation industry. In addition to the RF-dictated positional requirements, there are many functional tools common to the industrial robotic community that are being leveraged.

### A. Multi-Robot Positional Integration

The robot controller can be linked through kinematic models to an external “base” axis, Fig 2., so that the robot is aware of the tool relative to the “robot” frame of reference and the base axis orientation and location. This allows calculation of position and trajectory from multiple robot systems with a single interface that is routinely updated. The MR is linked to a 7 m base rail. Configuring the rail carriage as a “base” enables the controller to recognize/define the 5 m (H) x 6 m (W) x 10m (L) working envelope from a kinematic perspective. The terminology for “base” as the location of the external axis and “robot” as the nominal location of the robot come from definitions of the Yaskawa† robots used in the LAPS [12]. Alignment between the robot and the base rail is fine-tuned using a laser tracker and the final orientation of the rail to the manipulator in 6D can be inputted into the robot kinematic model to account for gross misalignments between the system components.

The multiple robotic controllers in the LAPS are linked together to share the same kinematic space. This allows the robots to position antennas, probes, and devices under test (DUT) either absolutely in space or relative to each other.

There are practical limitations to this model. The Denavit Hartenburg (DH) parameters implemented in many commercial systems are mainly idealized to minimize cycle time, so effects from inaccuracies such as encoder/servo non-uniformity, axis warping, and motor eccentricities are not addressed at the typical controller level but can be seen and are addressed in many near-field ranges. These present practical limitations to a linear model of the robot are being partially addressed using more complex models [12].

### B. Alignment

Alignment for antenna testing can often be more time consuming than measurements. The LAPS robot controllers have multi-point teaching algorithms that allow fiducials of the antennas to be manually positioned to a common point in space and then used to calculate the transform between the robot interface and antenna orientation, known as the tool control point (TCP) [13]. This allows the antenna (or tool) to be incorporated into the kinematic model of the robot, and desired antenna positions and orientations to be directly input without the need to calculate offsets. This multi-point teach method yields typically sub-mm TCP location knowledge. For applications where better antenna-robot position accuracies are required, or if physical contact with the antennas are problematic, we use a NIST designed, non-contact alignment method with less than 0.030 mm of uncertainty [14].

### C. Performance Specifications

The LAPS targets antenna and systems testing in the 500MHz to 30 GHz frequency range. The $\lambda$/50 rule of thumb, namely to get accurate measurements 50 dB below the peak signal level typically requires 1/50$^{th}$ of a wavelength positioning knowledge, guided the basic design. It is assumed that the primary operational mode of the LAPS will not employ a laser tracker, so data are dependent on the coordinate reporting of the robot controller to determine location.

Table 1. Basic Physical Design Specifications of the LAPS

| Moving Robot (MR) and Rail | |
|---|---|
| Robot horizontal reach | 3.5 m |
| Robot vertical reach | 5 m |
| Robot path repeatability | 0.15 mm |
| Robot payload | 20 Kg |
| Minimum planar scan plane size | 2.5 m x 3 m |
| Minimum spherical radius (with a 356 mm probe) | 1 m |
| Rail travel | 7 m |
| TCP wobble at scan plane center (deviation from best fit line) | RMS: 0.25mm |
| TCP wobble at scan plane center (deviation from best fit line) | MAX: 0.5 mm |
| Stationary Robot (SR) | |
| Robot horizontal reach | 2.5 m |
| Robot vertical reach | 4 m |
| Robot path repeatability | 0.07 mm |
| Robot payload | 35 Kg |
| Minimum planar scan plane size | 2 m x 2.5 m |
| Minimum spherical radius (with a 356 mm probe) | 1 m |

### D. Additional Calibration

There are two major tasks in accurately characterizing a serial robotic system: extrinsic and intrinsic calibrations [12]. Extrinsic calibrations, Fig. 2, which typically remove the majority of the systematic accuracy uncertainties, measure the robot relative to external references, i.e., define where the robot

† The use of trade names does not constitute an endorsement by the U.S. Government. Mention is for informational purposes only.

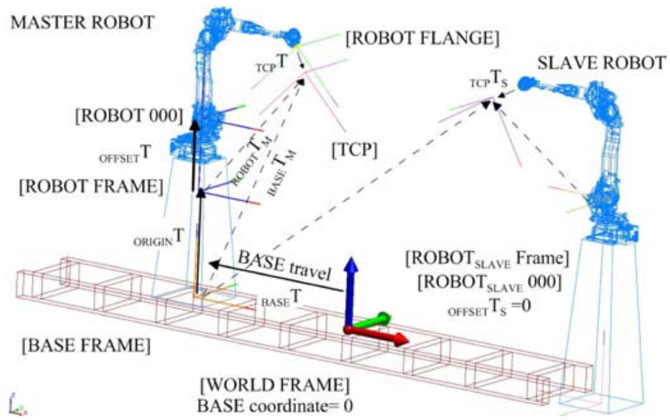


Figure 2. Extrinsic frames, e.g. [BASE], and the 6D solid-line transforms ($_{BASE}T$, $_{ORIGIN}T$, $_{OFFSET}T$, $_{TCP}T$) between them, determined during calibration of a robot's kinematic model. This allows more accurate knowledge of tool location (dashed lines: $_{ROBOT}T_M$, $_{BASE}T_M$) using only the robot controller. Similar measurements are made for the SLAVE/stationary robot (SR).

frame is physically located and determine the location and orientations of base axes and TCPs. This can typically reduce errors to the millimeter level or less in the LAPS class of robot.

Intrinsic calibrations characterize the error in the robot's DH composition, differences of robot link lengths, offsets, and orientations differences from nominal. For the class of robots such as the LAPS, this should bring the typical accuracy errors into the ±0.2 mm range [12].

### *E. Safety – Collision Avoidance*

The LAPS is integrated with a Functional Safety Unit† (FSU) that is aware of the unified coordinate space of the entire LAPS system. It is designed to prevent the collision of robots with themselves and each other and any attached antennas (or tooling), and limit collisions with the surrounding environment.

### *F. Safety – Personnel Avoidance*

The FSU has redundant systems to protect operators. The robots can have large kinetic potentials and control of these potentials are integral to safe operation. The controllers are equipped with laser safety radars that stop autonomous motion when the working volume of the LAPS is encroached upon. When personnel are in the working envelope, for example during manual operation, alignment or mounting, enabling devices to allow robot movement must be positively activated prior to servo activation.

## III. The LAPS Measurement Capabilities

The LAPS is tasked with performing a large suite of measurements. Traditional near-field scanning: planar, cylindrical and spherical geometries, gain extrapolation and polarization ratio, and hybrid geometries which involve moving both robots and interrogating systems from multiple dynamic bearings.

### *A. Robot Scan Capabilities*

The MR is configured as the LAPS master robot controller; it is responsible for all safety and robot positioning commands. The load capacity is rated at 20 Kg for a full speed stop at maximum kinetic loading. Sample scan geometries, Figs. 3-4, are not the maximum achievable by the MR (or SR in the case of Figs. 5-6) but are chosen to minimize the gravity deflections of larger loads, which tend to be most pronounced at extended arm reach [3].

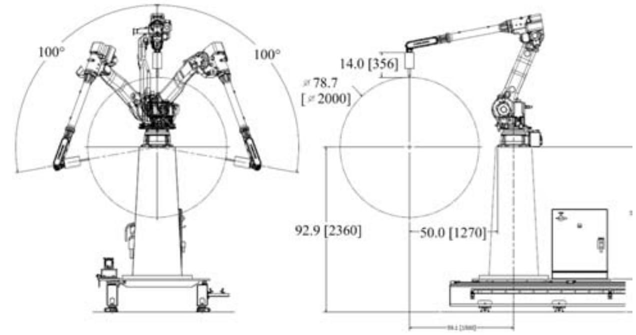


Figure 3. Moving Robot typical spherical scan plane geometry in inches [mm].

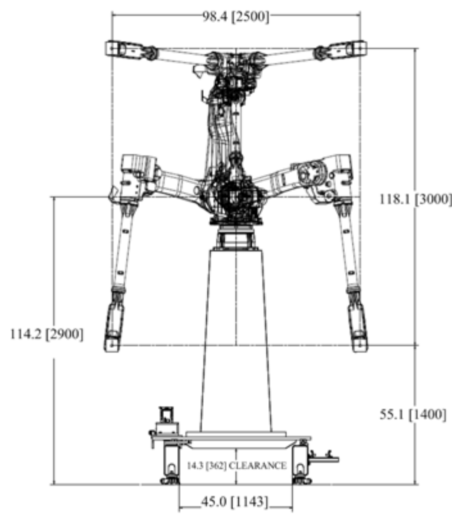


Figure 4. Moving Robot typical planar scan size in inches [mm].

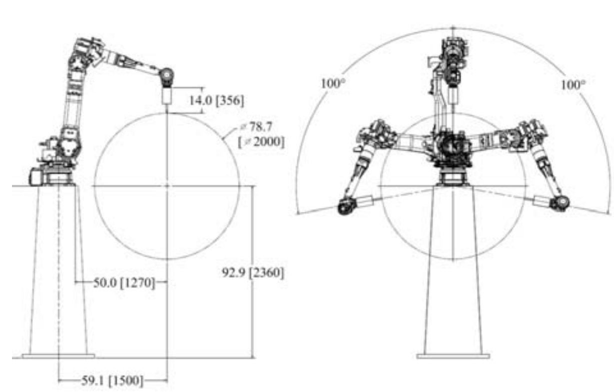


Figure 5. Stationary Robot typical spherical scan plane geometry in inches [mm].

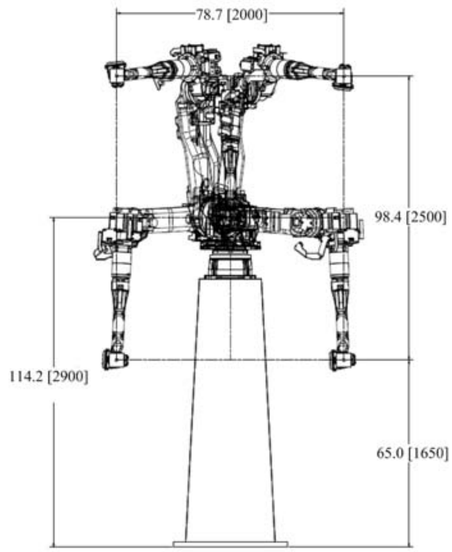


Figure 6. Stationary Robot planar scan size in inches [mm].

### B. *Maximum Scan Plane Using the Rail*

Using the rail in conjunction with the MR, a 5 m x 7.5 m scan plane can be realized, Fig 7. Since the MR and rail are kinematically linked, coordinated motion between the two motion systems is controlled with a single command and timing between the systems is accounted for to the level of the robot cycle time.

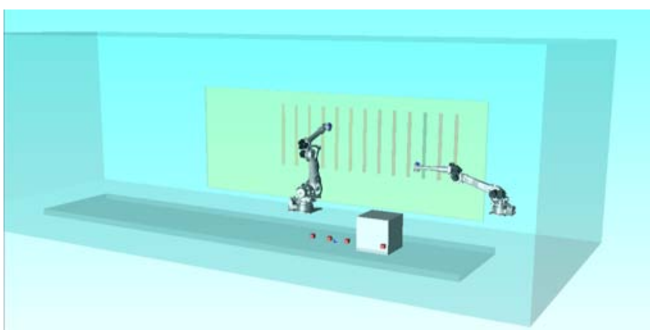

Figure 7. A robot reach simulation of the LAPS scanning a large planar structure, the MR on its base rail can perform a scan up to 5 m x 7.5 m.

### C. *OTA Testing*

In addition to the standard near field geometries, LAPS will be able to perform active OTA interrogation of communication systems. Figs. 8-9 show two possible multi-interrogation test scenarios. Fig. 8 describes a scenario of testing a beam-forming network by sampling the high signal-to-noise (SNR) region while simultaneously and coherently measuring off-axis performance.

By sampling the emissions coherently, in the near-field, pattern analysis can be made without the injection of a test RF signal into the system under test. We propose that a more realistic test of these systems could be developed using the system itself as the stimulus and response. The success of this type of test will depend on ensuring enough high SNR reference samples are taken to assure good pattern SNR over the frequency range of interest.

Fig 9 depicts multiple sources interrogating a single DUT, as in the case of a MIMO test. By utilizing the 2.5 to 5 m reach of the robots and the rail, a suitably uniform field may be generated to illuminate the DUT under conditions resembling the far-field. Arbitrary angles, to a limited degree (the system will limit robot collisions and upwards facing angles), might be used as a platform to develop OTA MIMO tests with rapidly varying spatial and Doppler conditions.

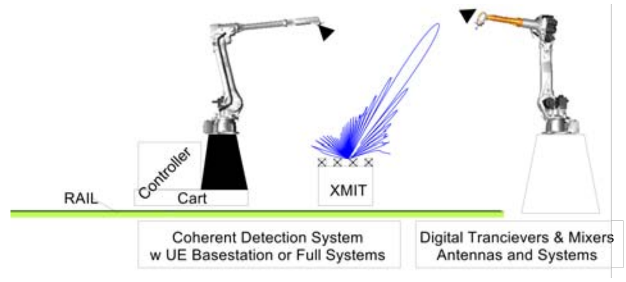


Figure 8. A depiction of simultaneous measurements of a beam-forming system with the LAPS; SR (right) is measuring the main beam while the MR is probing off angle performance.

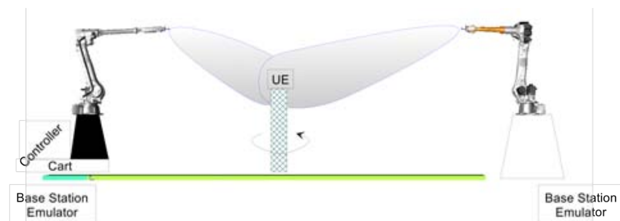


Figure 9. A depiction of multiple interrogation of a beam-forming system with the LAPS; SR (right) and MR are illuminating the UE in a MIMO fashion from multiple orientations

## IV. Initial Validation

The achievable accuracy of the LAPS in open-loop operation, i.e., without in-situ external positional metrology, is going to be limited mainly by the tolerances of the robots and the rail system. Systematic offsets and inaccuracies can be corrected by calibration. However non-modeled errors in the LAPS, such as rail straightness and variable errors such as robot vibrations and backlash are harder to correct. NIST performed pre-validation testing of some parameters in the non-ideal manufacturing facility where the LAPS was assembled. The initial tests were done to show viability of the overall system.

### A. *Basic Deviation of the Rail*

The TCP wobble specification in Table 1 is a major component of positional uncertainty that is difficult to correct. It is affected by MR posture and loading, rail flatness, cart motion, the MR riser stiffness, and rail deflection under varying load conditions. The influence of the rail variations is magnified by the distance from the rail to the MR TCP. The variability of these errors makes them difficult to correct so minimizing them at the outset is the most straight-forward approach to dealing with these error sources.

Laser tracker targets were mounted to the MR pedestal (~1.3 m above the rail) and the end of the MR in an extended pose with a 5 kg load (~4.1 m above the rail), Figs. 10,11. They were tracked the MR was moved through a 2-m span of the rail at a constant rate of 23 mm/sec. The pedestal-mounted target had a small deviation from the best fit line: 14 ± 7 μm, with a 61 μm maximum, Fig. 12. A satisfying TCP wobble result, compared to specification in Table 1, from the target mounted near the antenna was a 32 ± 20 μm deviation with a 182 μm maximum. The maximum deviations in both cases occurred at the beginning of the sweep when the robot starts motion.

These results demonstrate the basic mechanical capabilities of the system seem to be more than adequate for λ/50 (200 μm) operation at 30 GHz.

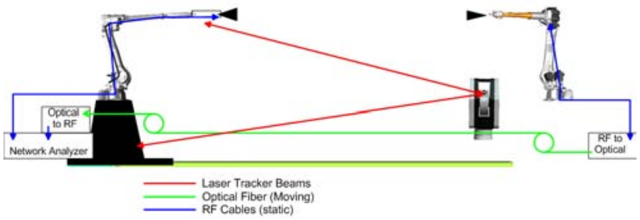


Figure 10. RF setup of the measurement system to compare commanded position by the robot controller, measured position by the laser tracker, and RF insertion distance by the network analyzer.


Figure 11. Positions of the laser tracker targets on the MR base and TCP to measure cross range movement while the MR is moving.

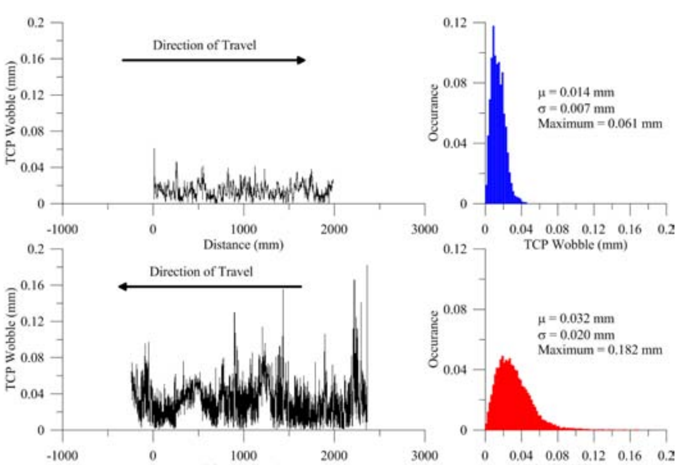


Figure 12. Base wobble and distribution for the target on the MR base (top), and the TCP wobble and distribution for the target on the robot arm (bottom).

## B. Dynamic Motion of the Rail

The system is intended to be used for testing during dynamic motion. This will stress the need for coordination between the timing of an attached RF system with the motions of the LAPS. A measurement controller that synchronizes the robot and external equipment is an integral part of the delivered system. To help assess the basic dynamic wobble of a tool during MR stop-motion, travel in both directions was measured. The rail was commanded in 2.5-mm steps at a speed of 30 mm/sec. Motion was stopped at each position, then RF insertion data and laser tracker data were taken prior to motion commencing. The expectation was that the rapid-stop motion in different directions would highlight the vibrational modes of the system. The setup of the measurement is seen in fig. 10. Fig. 13 shows the insertion loss between the antennas and the difference between the antenna separation inferred from the laser tracker and the RF measurement at 9 GHz.

The laser tracker position data, fig. 13, is directly inferred by measuring the target near the TCP (TCP target), fig. 11. Previously, the horns we aligned parallel to the axis of movement determined from the best fit line for the measurements highlighted in fig. 12. Then the apertures were confirmed with the tracker and the nominal separation relative to the TCP target was determined. The antenna separation is then derived from the movement of the TCP target.

If more than 4 points per wavelength are taken, the RF separation, $d_{phase}$, is determined by taking the phase of the insertion measurement, $RF_i$, unwrapping the phase versus distance and then converting phase to distance [15]:

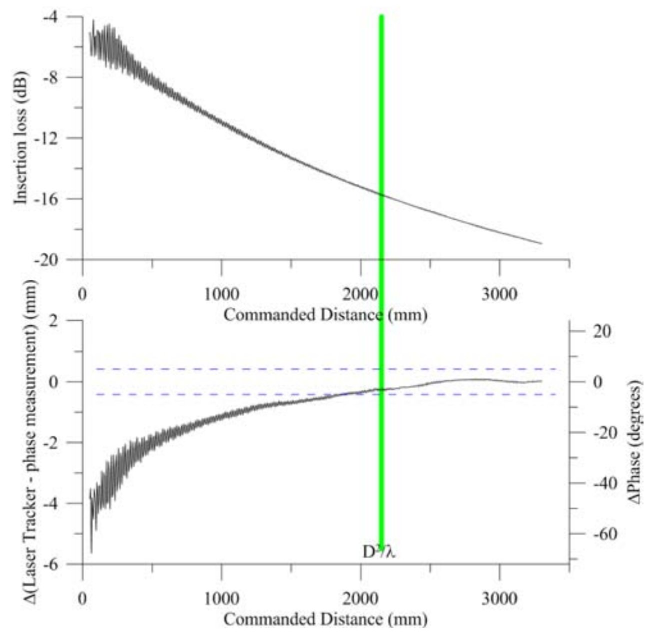


Figure 13. Results of an RF insertion measurement at 9 GHz using the LAPS, the amplitude (top) shows near-field horn-to-horn effects at closer distances than $D^2/\lambda$. The antenna separation (bottom) measured by the laser tracker and inferred from the RF data shows good correlation as the separation gets larger. At close distances, the deviations from linear phase are more apparent than *1/r* amplitude variations. The ±5° lines (dotted blue) show that the system is stable and predictable enough for accurate extrapolation measurements [15].

$$d_{phase} = \operatorname{atan}\left(\frac{\operatorname{Re}(RF_i)}{\operatorname{Im}(RF_i)}\right)\frac{\lambda}{2\pi}360 \qquad (1)$$

The correlation of laser tracker and RF inferred distance show that the robot and cabling are not experiencing excessive movement during position and velocity changes.

## V. Conclusions

While the LAPS can perform standard near-field antenna pattern and gain testing, the goal is to perform dynamic multi-pronged OTA system tests. Initial validation of the LAPS at the factory, Fig. 14, show that basic mechanical operation of the system is within the specified design tolerances for static and dynamic testing to at least the designed 30 GHz operational specification. The measured antenna (or TCP) wobble of $32 \pm 20$ µm with a 181 µm maximum deviation over a limited range highlights the overall rigidity and stability of the MR portion of the LAPS.

Figure 14. The LAPS in the manufacturing facility during preliminary system testing.

## VI. Future Work

These were the first operational tests of the LAPS. Testing at extended reach, especially when the robots are extended across the rail are important to determining suitability for fast planar and rapid OTA test scenarios. System timing using the measurement controller, and verification of motion when the robots are loaded with RF absorber are also needed to ensure adequacy for the wide series of measurements planned for the system.

## References


[1] The ROS project: http://www.ros.org.

[2] A. Nubiola and I.A. Bonev, "Absolute calibration of an ABB IRB 1600 robot using a laser tracker," *Robotics and Computer-Integrated Manufacturing*, Vol. 29, No. 1, 2013, pp. 236–245.

[3] H.N. Nguyen, J. Zhou, H.J. Kang, "A New Full Pose Measurement Method for Robot Calibration," *Sensors*, vol 13, pp 9132-9147, 2013: doi:10.3390/s130709132.

[4] R. Swanson, G. Balandran, S. Sandwith, "50-micron Hole Position Drilling Using Laser Tracker Controlled Robots," in *Jour. of the Coordinate Systems Metrology Conf*, Vol 9, No 1, Spring 2014

[5] D. Novotny, J. Gordon, J. Coder, M. Francis and J. Guerrieri, "Performance evaluation of a robotically controlled millimeter-wave near-field pattern range at the NIST," *2013 7th European Conference on Antennas and Propagation (EuCAP)*, Gothenburg, 2013, pp. 4086-4089.

[6] J. A. Gordon *et al*., "Millimeter-Wave Near-Field Measurements Using Coordinated Robotics," in *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 12, pp. 5351-5362, Dec. 2015. doi: 10.1109/TAP.2015.2496110

[7] J. A. Gordon *et al*., "An All-Metal, 3-D-Printed CubeSat Feed Horn: An assessment of performance conducted at 118.7503 GHz using a robotic antenna range," in *IEEE Antennas and Propagation Magazine*, vol. 59, no.2, pp. 96-102, April 2017. doi: 10.1109/MAP.2017.2655574

[8] F. Ferrero *et al*., "Spherical Scanning Measurement Challenge for Future Millimeter-Wave Applications," in *Proc. of the Antenna Measurement Techniques Assoc.*, Nov 2015.

[9] J. Snow, B. Slowey, "SCARA Scanner for Portable Near-Field Antenna Testing," *Proc. of the Antenna Measurement Techniques Assoc.*, Nov. 2005.

[10] J. Hatzis, P. Pelland, G. Hindman," Implementation of a Combination Planar and Spherical Near-Field Antenna Measurement System using an Industrial 6-Axis Robot," in *Proc. of the Antenna Measurement Techniques Assoc.*, Nov 2016.

[11] K. A. Remley *et al*., "Measurement Challenges for 5G and Beyond: An Update from the National Institute of Standards and Technology," in *IEEE Microwave Magazine*, vol. 18, no. 5, pp. 41-56, July-Aug. 2017. doi: 10.1109/MMM.2017.2690882

[12] M.S. Allman *et al*., "Serial Robotic Arm Joint Characterization Measurements for Antenna Metrology," in *Proc. of the Antenna Measurement Techniques Assoc.*, Nov 2017 (in process).

[13] *DX100 Instructions: FOR NORTH AMERICAN (ANSI/RIA) STANDARD*, Part No. 155494-1CD, Rev. 2, Yaskawa Electric Corporation, pp 8-23,29.

[14] J.A Gordon, D.R. Novotny, A.E. Curtin, "A Single Pixel Touchless Laser Tracker Probe," in *Jour. of the Coordinate Systems Metrology Conf*, vol. 10, no. 2, Autumn 2015.

[15] J. Coder, D.R. Novotny, M Francis, J. Guerrieri, "On the Use of Phase Data When Conducting an Extrapolation Measurement," *Proc. of the Antenna Measurement Techniques Assoc.*, Nov. 2013.