Precision Optical Antenna Alignment System for Tracking Antennas in 6-DOF

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***Abstract*—We present on an all-optical spatial metrology system, the PiCMM, that aids in the alignment and tracking of antennas with accuracies on the order of 25 microns and 0.01 deg. This system speeds up millimeter-wave antenna alignment, does not require contact, and links spatial measurements to a laser tracker world coordinate frame. An automated Pixel Probe and dark-field imaging are used to directly measure the aperture geometry and its pose. These measurements are absolute in the world-frame of a laser tracker and associated coordinate metrology space of the antenna scanner. Thus, aperture geometries can be linked directly to any laser tracker target (i.e. 6DOF, 3DOF) and data such as that used to calibrate positioner kinematics. For example, the links and joints defining the Denavit-Hartenberg kinematic model of a robotic arm scanner. The new automated aspect of the system reduces alignment time to under an hour. The synergy with laser tracker targets allows for a high level of repeatability. Furthermore, antennas can be exchanged or realigned in the antenna scanner autonomously because antenna geometry and kinematic models reside in the same laser tracker coordinate metrology space.**

I. INTRODUCTION

Aligning millimeter-wave antennas during near-field measurements can be challenging and time consuming. As frequencies climb, aligning and positioning antennas to within λ/50 or even λ/100 can be very challenging. Furthermore, tracking antenna position is useful for post processing correction of non-ideal motion [1] which inevitably exist to some degree in antenna scanning system kinematics. Here we present an all-optical, non-contact alignment system to aid and speed up the alignment of antennas in general, but that is particularly useful at higher millimeter-wave frequencies. Below we give a description of this system and show how it is used for antenna alignment.

II. ALIGNMENT SYSTEM DESIGN

A. PiCMM

For a thorough discussion of this system we refer the reader to [2],[3] here we present a terse discussion for the purpose of applying these concepts to precision antenna alignments. The system is comprised of three main parts: a Pixel Probe, a calibrated XYZ stage, and a laser tracker, and functions somewhat similar to a coordinate measuring machine (CMM) [4] but where the contact ball stylus of a traditional CMM is replaced by a (Pi)xel Probe. This system is therefore called the PiCMM.

The Pixel Probe is constructed from three specifically calibrated cameras [2] arranged in a tetrahedral configuration (see Figure 1) linked to either a six-degree-of freedom (6DOF) laser tracker target or constellation of point spherical mounted reflector (SMR) targets[5].

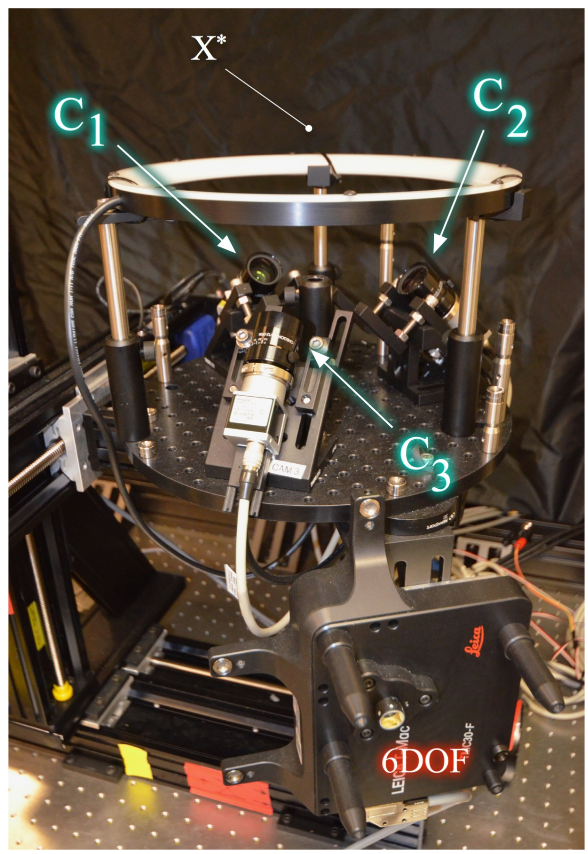

Fig. 1. Pixel Probe comprised of cameras C_1, C_2, C_3 and a 6DOF laser tracker. The location of the projected pixel point $\mathbf{X}^*$ is shown. A ring light is used for dark-field illumination of antenna apertures.

These cameras act to project a pixel to a single 3D coordinate in space represented by the vector $\mathbf{X}^* = [X^*, Y^*, Z^*]$

which has a corresponding 2D pixel coordinate in each of the three cameras C_1, C_2, and C_3.

$$\mathbf{x}_{1*} = \begin{bmatrix} x_{1*} \\ y_{1*} \end{bmatrix} \qquad \mathbf{x}_{2*} = \begin{bmatrix} x_{2*} \\ y_{2*} \end{bmatrix}, \qquad \mathbf{x}_{3*} = \begin{bmatrix} x_{3*} \\ y_{3*} \end{bmatrix} \tag{1}$$

This projection from 3D measurement space to the 2D camera image is uniquely governed by the camera projection $[P_j]$ matrix [2],[6] for each camera via,

$$\mathbf{x}_{j*} = [P_j]\mathbf{X}^* \tag{2}$$

In the images captured by each camera $\mathbf{x}_{j*}$ is represented by a blue highlighted pixel see Figure 2. A ring light (see Figure 1) is used to establish dark-field illumination [7] which accentuates the antenna aperture edge. A dark-field image of a WR-08 wave guide flange as seen through camera C_1 is shown in Figure 2.

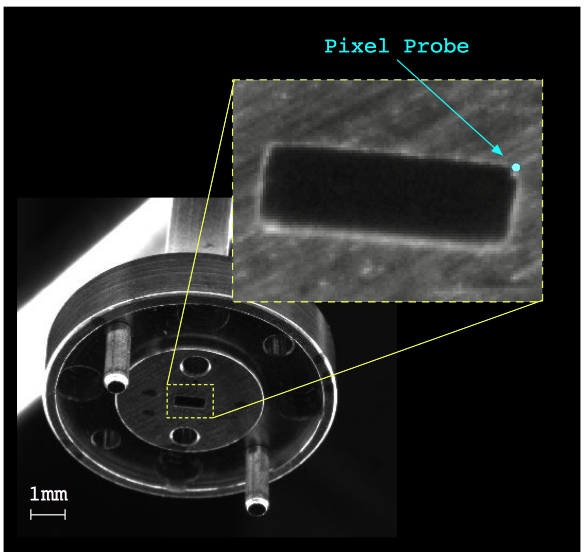

Fig. 2. A dark field image through camera C_1 of a WR-08 wave guide flange. The Pixel Probe shown as the blue dot is at the projected coordinate $[x_{1*}, y_{1*}]$. Blue dot size is exaggerated so it can be seen in the figure.

The function of the Pixel Probe is to link $\mathbf{X}^*$ to a laser tracker such that the location of $\mathbf{X}^*$ is known in the laser tracker's world frame. Anywhere the blue pixel appears at in the images of the cameras corresponds to a 3D coordinate measurable by the laser tracker. The point $\mathbf{X}^*$ thus acts as a small invisible stylus the size of the projected pixel, about 20 μm. The PiCMM is completed by mounting a Pixel Probe on a precision XYZ stage, see Figure 3.

A calibration process discussed in detail in [2] allows the XYZ stage to autonomously drive $\mathbf{X}^*$ to a target coordinate $\mathbf{X}_{target}$ specified by a user. In practice the user works within a graphical user interface (GUI) and specifies $\mathbf{X}_{target}$ through pointing and clicking with a mouse on a location in the images on the computer screen. This "invisible stylus" makes possible dimensional measurements of antenna apertures in the laser tracker world frame without contact and with a resolution of < 25 μm. It also overcomes one of the biggest

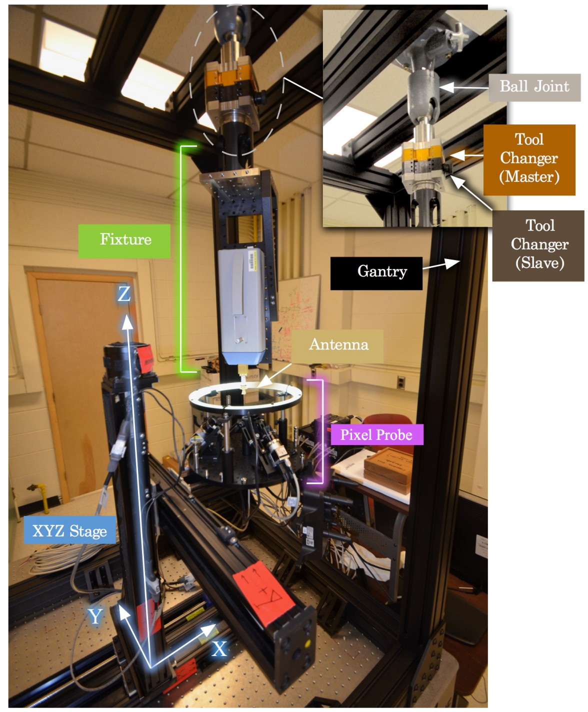

Fig. 3. The PiCMM system and gantry. Supported by the gantry, the fixture attached via the and ball joint and tool changer interface is mounted upside down allowing the antenna aperture to be measured.

challenges for a laser tracker, that is to measure a sharp edge directly. For at this spatial resolution the sharp edge of an antenna aperture appears blunt and becomes easily measurable in a laser trackers world frame. With this spatial resolution small mm-wave antennas that were previously difficult or not possible to measure and track with a laser tracker become straight-forward. Measurements of the antenna aperture are then used to construct a coordinate frame defining the antenna pose (position and orientation). We denote the pose of the antenna with coordinate frame A_0.

B. Gantry

A gantry is used to hold antennas above the PiCMM while being scanned, shown in Figure 3. At the top of the gantry is a ball joint that is lockable via a manual hydraulic clamp (Figure 3) and that has the master side of a manual robot tool changer chuck at the end of it. The slave side of the tool changer is attached to the antenna (discussed below). Although the tool changer is designed to work with robotic arms such as in the NIST CROMMA [8] and LAPS [9] antenna ranges it can be adapted to any scanner. The tool changer provides a seamless way to exchange antennas between the PiCMM for alignment and the robots during measurement. When the antenna is attached to the gantry the ball joint is first disengaged so that the load of the antenna relaxes in alignment with gravity. This effectively relieves extra torque on the gantry that could result in stress and cause unwanted settling and deflection of the antenna pose while it is being measured by the PiCMM. Deflection even on the order of tens of microns can affect alignment at some millimeter-wave frequencies so effort has been made to mitigate sources of alignment error.

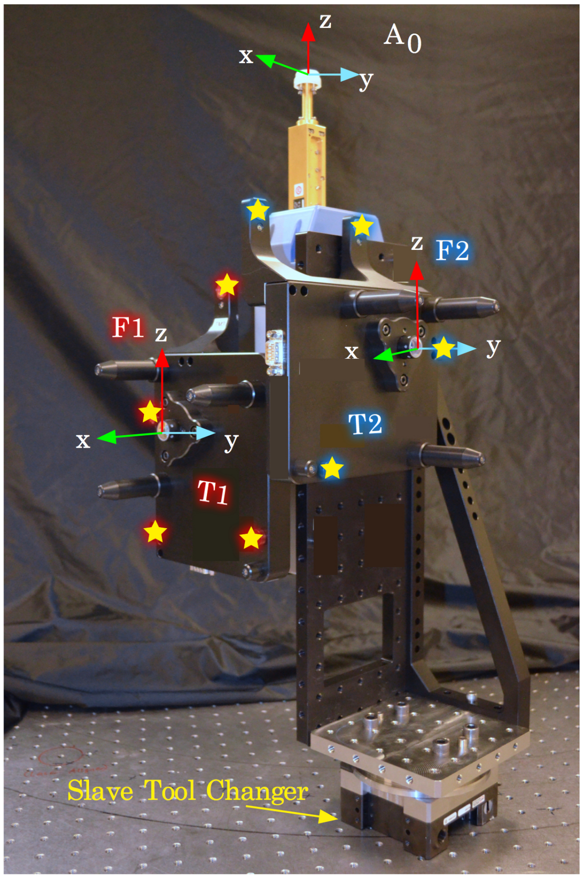

Fig. 4. Antenna fixture holds a frequency extender in fixed relation to 6DOF laser tracker targets T1 and T2. Corresponding coordinate frames F1 and F2 are shown. Stars define the locations of the four points making up CONST1 (red) and CONST2 (blue) each.

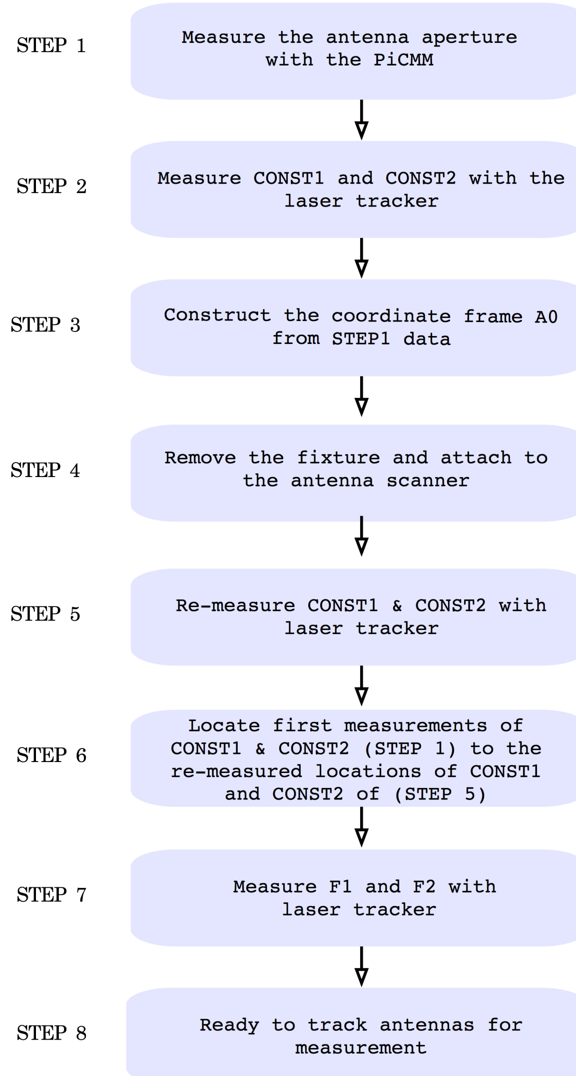

Fig. 5. Flow chart of the 8-step alignment process.

C. Fixture

No matter the antenna scanner design there is some mounting structure required to physically mount and connect the antenna to the scanner. Here we have standardized the physical connection of the antenna to scanner with the tool changer as well as the way the antenna is mounted. Antennas are mounted in a fixture that acts to hold the antenna (along with any frequency extender) in a fixed pose relative to two 6DOF laser tracker targets T1 and T2 mounted nominally 90° from each other (one for each polarization orientation) see Figure 4. The fixture is constructed from optical grade mechanical components such that structural rigidity can be assumed between the the antenna and T1 and T2. When measured with the laser tracker targets T1 and T2 produce a local coordinate frame F1 and F2 respectively. They also have an auxiliary constellation of four additional kinematic magnetic nests that one can fix SMR targets to. When measured with the laser tracker the SMRs produce a constellation of four 3D points for each target that have a fixed relationship to frames F1 and F2. These constellations are denoted as CONST1 and CONST2, see Figure 4. The SMRs can be rotated so that they can be seen over a larger angle by the laser tracker and so they are useful for establishing the pose offset between T1 and T2. In the context of the 6-Axis robot arms of LAPS and CROMMA ranges, the fixture with antenna, frequency extender, and 6DOF targets comprises the robot end effector. This end effector is attached to the gantry via the tool changer. Next we discuss leveraging measurements with the PiCMM for antenna alignments.

III. Alignment Process

In aligning the antennas, the goal is to measure the frame-to-frame transform between the frames produced by the two 6DOF targets (F1 and F2) and the antenna frame A_0. Once established, it is trivial to locate and track the actual antenna coordinate frame (to better than $\approx 30\ \mu$m) with a laser tracker for any pose the antenna is manipulated via the scanner.

Alignment is achieved by measuring the aperture geometry of the antenna with the PiCMM, constructing the antenna coordinate frame A_0, and linking it to CONST1, CONST2, F1 and F2. Commercial spatial metrology software supplied with the laser tracker was used to capture data and to construct the antenna frame A_0 as well as calculate frame-to-frame-transforms and distances between 3D points. The alignment process scales to any antenna and provides a consistent work flow.

After connecting and locking the fixture to the ball joint on the gantry via the tool changer interface, alignment can be summarized in eight easy steps shown in the flow chart in Figure 5. In the current configuration the typical time required to finish the process is 30 min or less.

IV. Measurements

As an example a 15 dB WR-15 standard gain horn was measured. Figure 6 shows the point data taken of the aperture (insert) along with the constructed frame A_0. From these measurements the aperture dimensions were determined to be 10.780 mm $\times$ 7.448 mm which is consistent with the manufacture specified dimensions and tolerances of 10.693 mm ($\pm$0.127 mm) $\times$ 7.366 mm ($\pm$0.127 mm).

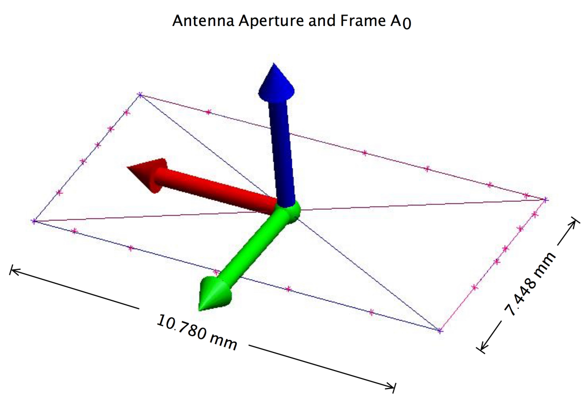

Fig. 6. Aperture measurement of the 15 dB WR-15 standard gain horn obtained with the PiCMM. Red X's mark the measurement locations on the aperture. Frame A_0 is defined such that it is centered and normal to the aperture and clocked perpendicular to the long side. Aperture dimensions measured with the PiCMM were 10.780 mm $\times$ 7.448 mm

The frame-to-frame transform ${}^1_0H$ between F1-to-A_0 and ${}^2_0H$ for F2-to-A_0 given in the form [10] of rotation and translation ${}^A_BH = [R|\mathbf{t}]$ are:

$$ {}^1_0H = \begin{bmatrix} -0.001 & -0.004 & -1.000 & -277.012 \\ 0.006 & 1.000 & -0.004 & -125.219 \\ 1.000 & -0.006 & -0.001 & 38.158 \\ 0.00 & 0.00 & 0.00 & 1.000 \end{bmatrix} \quad (3) $$

$$ {}^2_0H = \begin{bmatrix} -0.003 & 0.007 & 1.000 & 289.963 \\ 1.000 & -0.006 & 0.003 & -127.815 \\ 0.06 & 1.000 & -0.007 & 10.786 \\ 0.000 & 0.000 & 0.000 & 1.000 \end{bmatrix} \quad (4) $$

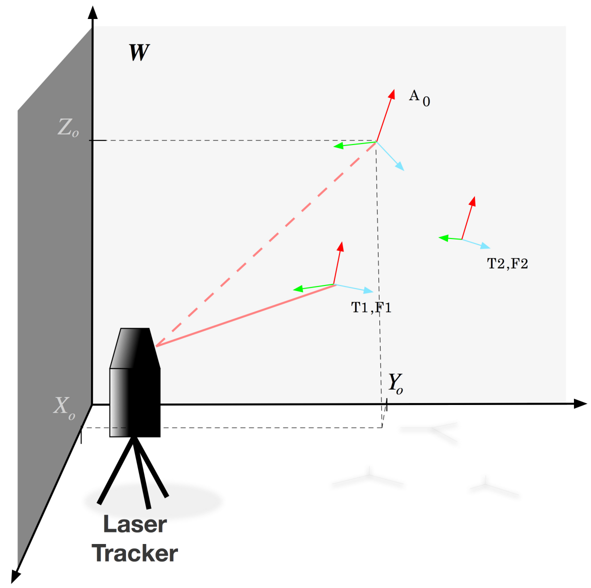

Fig. 7. After establishing the frame-to-frame transforms with the PiCMM, the antenna coordinate frame A_0 can be tracked in the world frame **W**. The Laser Tracker "sees" A_0 centered on coordinate $[X_o, Y_o, Z_o]$ (dotted red line) while it measures the 6DOF target T1 (solid red line).

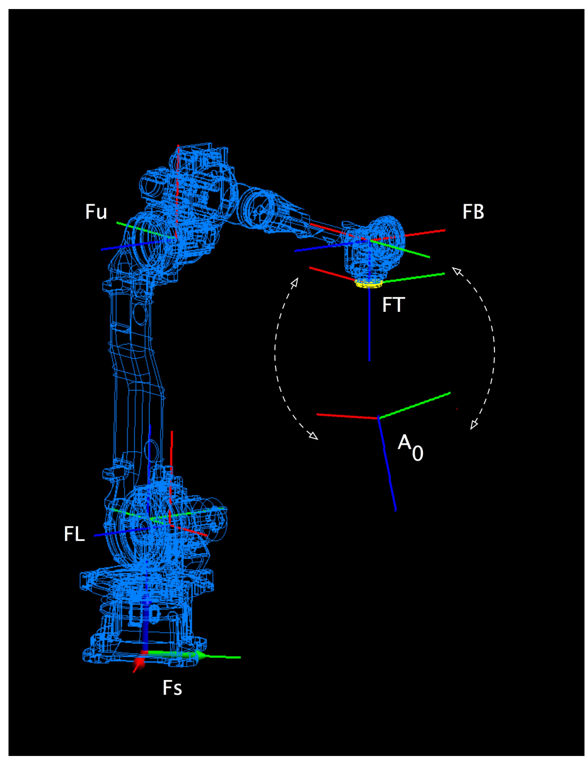

Fig. 8. D-H model seen by laser tracker for a 6-Axis robotic arm antenna scanner. Antenna end effector is located at frame A_0. The PiCMM is used to measure and define the antenna frame A_0 with respect to the last native robot D-H frame FT (dotted arrows). This completes the full D-H model for the 6-Axis robotic antenna scanner.

As can be seen, the largest terms for these transforms are contained in the last column that represents the translation vector **t**. This is consistent with the targets T1 and T2 being mounted with minimal rotation at nominally square orientations in the fixture relative to the antenna aperture. ${}^{1}_{0}H$ and ${}^{2}_{0}H$ for each target need only be input to the laser tracker and the antenna pose can be tracked in real-time and thus manipulated to achieve desired alignment to within the accuracy of the laser tracker (typically up to a few tens of microns). Antenna tracking with this method is depicted in Figure 7.

Completing the kinematic model of an antenna scanner can thus be achieved very accurately using the PiCMM. With respect to 6-Axis robot arm scanners the frame A_0 defines the end effector pose and completes and the D-H model. A complete kinematic model is paramount in achieving closed loop robot position correction for high frequency antenna scanning as in CROMMA [8] as well as proper robot calibration for open loop scanning as in LAPS [11]. The completed D-H model for the CROMMA robot is shown in Figure 8.

V. Conclusion

We have discussed the use of a new spatial metrology tool the PiCMM for precision non-contact antenna alignment and tracking on the order of 25μm. This system is based on previous development of a Pixel Probe non-contact laser tracker probe. The PiCMM acts similar to a coordinate measuring machine, but where the Pixel Probe replaces the ball stylus. The PiCMM allows for non-contact coordinate measurements of antenna apertures with accuracy on the order of 25μm. Coordinate measurements of antenna apertures obtained with the PiCMM also exist in the world frame of a laser tracker. This achieves alignment and tracking of antennas in the laser tracker world frame. Furthermore, the PiCMM allows one to accurately include the antenna aperture in the kinematic chain of an antenna scanner which is paramount for high frequency millimeter-wave antenna metrology. The PiCMM and alignment workflow is presented. Coordinate metrology of a WR-15 standard gain horn using the PiCMM is given.

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