Closed-Loop Real-Time PNF Position Compensation with a Tracking Laser

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***Abstract*—If a planar near-field (PNF) scanner is large and there is insufficient temperature regulation in the chamber to keep ordinary thermal expansion/contraction from causing unacceptable position errors, then consideration must be given to compensation techniques that can adjust for the changes. Thermal expansion/contraction will affect almost everything in the chamber including the floor, the scanner structure, the encoder or position tapes, the AUT support, and the mount for any extra instrument(s) used to measure and correct for position error. Since the temperature will generally cycle several times during a lengthy acquisition, error-correction solutions must account for the dynamic nature of the temperature effects.**

This paper describes a new automated tracking-laser compensation subsystem that has been designed and developed for very large horizontal PNF systems. The subsystem is active during the acquisition to account for both static and dynamic errors and compensates for those errors in all three dimensions. The compensation involves both open-loop corrections for repeatable errors with high spatial frequency and closed-loop corrections for dynamic errors with low spatial frequency. To close the loop, laser data are measured at a user-defined interval between scans and each scan that follows the laser measurements is fully compensated. The laser measurements are fully automated with no user interaction required during the acquisition.

The challenges, goals, and assumptions for this development are listed, high-level implementation considerations are provided, and resulting measured data are presented.

I. Introduction

To quote the NIST web site, "Everything changes size when the temperature changes."[1] This change in size for a given material is characterized by its Coefficient of Thermal Expansion (CTE). A typical CTE would be a few parts per million per degree Celsius (e.g., about 11 μm of growth per meter of length per °C for spring steel). For most antenna-measurement facilities, the combination of temperature regulation, structural dimensions, and required position accuracy permit these thermal effects to be ignored. However, as steel beams become longer, wavelengths become shorter, and/or temperature regulation becomes less feasible, there will be a threshold where thermal (and/or other) effects on physical structures must be compensated in order to meet measurement-fidelity requirements.

One approach to compensating for temperature effects would be to instrument the range with several temperature sensors, and use those to predict the mechanical deformations. However, the presence of dissimilar and non-homogeneous materials in a constrained structure makes the reliability of such a prediction questionable, and there may be stimuli other than temperature that lead to mechanical drift. Therefore the approach taken here is to dynamically measure the mechanical drift present, from whatever source, and compensate it from those measurements.

MI Technologies has recently introduced the MI-815 Family of Horizontal PNF Scanners. The largest in this family, the MI-815-66x66, forms a cube more than 20 meters (about 66 feet) on each side. These scanners have two X beams that form the X_D axis, and a Y beam that bridges the two X beams. The probe carriage rides along the Y-beam rails. The carriage includes Z_i and Roll axes, plus a precision X_F axis for implementing any dynamic corrections needed in the X dimension. A conceptual drawing of the MI-815-66x66 is shown in Figure 1. The laser subsystem described herein is an available option for the MI-815 family of scanners.

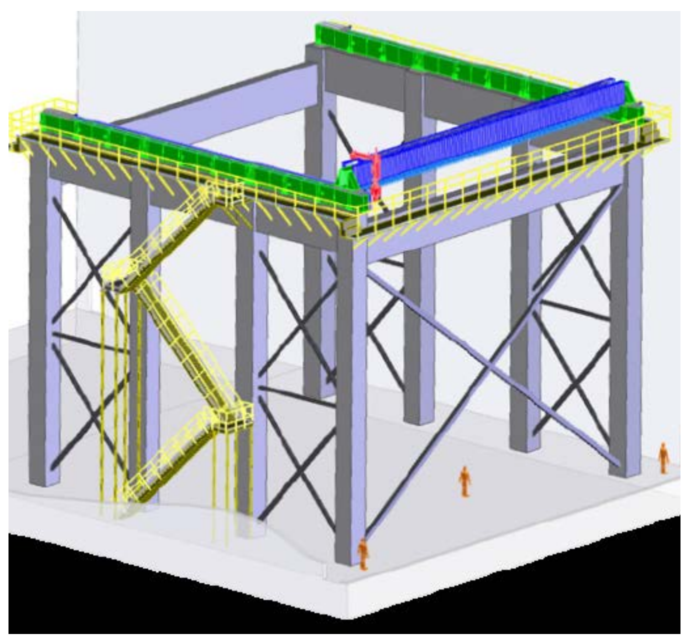

Figure 1. MI-815-66x66

A. *Definition of Terms*

With multiple axes named 'X' and 'Y', including the bases of the range coordinate system, some clarification is in order. The naming convention used herein for the various axes, with subscript clarification in parentheses:

- X,Y,Z: range-coordinate bases, where Z is normal to the floor and zero near the floor, and X is parallel to the X-beam rails' projection onto the floor. The physical axes are only approximately parallel to these basis axes.
- X^+ and X^-: (at positive Y and negative Y) physical axes with one on each X beam. The X^+ and X^- axes cannot be controlled independently, and are forced to be equal during X_D operation.
- X_F: (fine) a precision linear axis on the carriage with limited travel, used for dynamic corrections in the X dimension
- Y_i: (indicated) the physical axis moving along the Y-beam rails
- Z_i: (indicated) the physical axis on the carriage used to maintain the desired distance from the AUT
- Roll: the probe-roll or χ physical axis, used for polarization in normal acquisitions, or for SMR rotation in calibration and/or verification mode
- X_D: (dual) a virtual axis[2] that coordinates X^+ and X^- to move the Y beam. X_D remains stationary during each scan.
- Y_{+R}: (plus roll) a virtual axis that coordinates Roll with Y_i travel to keep the carriage SMR pointed at the laser during calibration, while $Y_i = Y_{+R}$
- Y_C: (corrected) a virtual axis that coordinates X_F, Y_i, and Z_i to effect the desired [X,Y,Z] locations during each scan
- Y_V: (verify) same behavior as Y_C, but also coordinates Roll with Y to keep the carriage SMR pointed at the laser during the software's verification mode

Other definitions:

- Spherically Mounted Retro-reflector (SMR): a standard tracking-laser target. There are several of these (a configurable number) permanently mounted in the range.
- Y Beam: the blue beam in Figure 1 that bridges the two green X beams
- Probe Simulator: a fixture with an SMR nest located on the Roll axis of rotation a known distance from the probe-mounting interface, used for calibration and verification
- Return to Point (RTP): optional RF measurements taken periodically during the acquisition at a specific [X,Y] location, used for RF drift correction.

B. *Comparison to Earlier Approaches*

Lasers have been applied in many ways over the years toward improving a PNF scanner's fidelity. These applications include:

- Off-line measurements with a commercial off-the-shelf (COTS) tracking laser to form a map of corrections to be either followed during acquisition or applied as post-processing phase shifts as a function of X and Y[3][4]
- A COTS tracking laser that measures probe positions during the acquisition for direct use during post-processing [5]
- A COTS spinning laser that defines the X-Y plane the probe should track[6][7][8]
- A proprietary two-axis interferometer for X-Y position correction[7][8]

The method described herein implements a fully automated two-stage real-time correction for X, Y, and Z with a COTS tracking laser. The first correction stage takes off-line measurements to form a map of corrections to be followed as a function of Y_i travel, and also characterizes the Y-beam shape with respect to that corrected path. The second correction stage is performed periodically during each acquisition, updating as necessary the dX, dY, and dZ path corrections vs. Y_i and constraining the probe plane's distance from the AUT. The first correction stage represents open-loop real-time correction of repeatable errors. The second correction stage represents low-rate closed-loop real-time correction of dynamic errors with low spatial frequency. The rate of these correction updates is measured in minutes, which should be adequate for the errors being compensated.

II. Challenges

The fundamental goal of a conventional PNF measurement is to sample the electric field in an X-Y plane, at a known and fixed distance ΔZ from the antenna under test (AUT), and on a grid with known and fixed spacing ΔX and ΔY within that plane. There are numerous challenges toward meeting this goal that include:

- Uncorrected probe motion along X_D and Y_i will not occur in a perfect plane even at a fixed temperature. The larger the scan plane, the more difficult it is to achieve a particular level of planarity.
- The 20-meter vertical posts supporting the X-Y scanner will change in length with temperature. Due to the size of the range, it is quite possible that each post will see a different temperature history, and thus grow differently.
- The platform supporting the AUT at an appropriate distance from the probe will have its own CTE, and temperature change will therefore cause the AUT to translate relative to the floor.
- The floor has its own CTE that is different from that of steel, and will therefore expand and contract at a different rate than that of the X-Y scanner parallel to it. This non-uniformity of growth can be expected to distort the shape of the uncorrected scan plane.
- With 20-meter spring-steel encoder tapes and ±2°C temperature variation, the tapes themselves will change in length by approximately ±0.44 mm over the course of a

long acquisition. Naturally, the CTE of the encoder tape and its mounting surface must be chosen to be similar.

- The location and attitude of any device placed in the range for the purpose of improving the fidelity cannot be assumed to be constant.
- Since everything in the range is expected to be translating and perhaps rotating, the definition of the range coordinate system in this environment is non-trivial.
- Any devices placed in the range for the purpose of improving the fidelity must
    - maintain the necessary visibility amongst themselves throughout scanner travel with the probe and AUT mounted
    - have a way of periodically synchronizing to the range coordinate system
    - have a way to periodically determine changes to the uncorrected probe path and update the corrections accordingly
    - minimize the stray RF signal they produce
- Thermal gradients, if and when present in the range, will refract the laser beam. The temporal frequency of these fluctuations tends to be low, such that simple averaging on the laser does not attenuate the error.
- Measurements to support drift correction, when taken, need to be especially well compensated. Those measurements are generally not made at a location near recent scans, such that using a recent history of corrections would not be appropriate.
- The measured encoder positions do not represent range coordinates, and are therefore not suitable for use in latency removal.

III. Assumptions

The following simplifying assumptions were made in developing the solution:

- If Z is defined normal to the floor, then the AUT's X-Y location is assumed not to change during the acquisition. Any tilt of the floor is thus expected to tilt the AUT support by the same amount.
- As with any near-field measurement, the AUT is assumed to have a fixed size and shape throughout the acquisition.
- The floor is assumed to grow or shrink radially relative to any reference point on the floor near the center of the scan area.
- There is assumed to be no twist over time of the Y beam about the range Y axis.
- The correcting axes have reasonable orthogonality, accuracy, and straightness.
- The mechanical drift of the X, Y, and Z positioning errors is assumed to be limited to low spatial frequencies vs. Y_i.
- When reporting residual errors, it is assumed that removal of a small scalar offset from a 2D data set in each of X, Y, and Z is acceptable, since the offset results are still relative to a uniform X-Y grid in a plane of fixed Z. This assumption relieves the tolerance on the straightness of the correcting axes. With such an offset, the residual's RMS becomes the standard deviation of the errors.

IV. Concept

A. *Range Coordinate System*

In a range where everything is assumed to be moving relative to everything else, the definition of the range coordinate system is both non-trivial and critical. The range coordinate system is defined as follows:

- The one point that is declared to remain fixed in the range coordinate system is a spot on or near the floor near the center of the scan area. This spot is defined to be the range origin.
- The one direction vector that is declared to remain fixed in the range is the upward floor normal. The floor normal, as determined from a set of monuments on the floor, is defined to be the Z basis vector.
- Carriage travel along X_D with Y_i fixed at one of its ends is initially used to define the range X axis, clocking the coordinate system about the Z axis defined above. The range Y axis is defined to be normal to both Z and the carriage travel measured here.
- Later recall of the coordinate system establishes range Z the same way, and then clocks range X and range Y in Phi based on the known Phi angles of each of the range monuments.

B. *Correction Mechanism*

The virtual-axis capability[2] within the MI-710C Position Controller is used for all corrections. The virtual Y_C (or Y_V) axis coordinates the X_F, Y_i, and Z_i axes as needed to cause RF data to be taken with the probe at the desired X, Y, and Z range coordinates.

A two-stage correction mechanism is employed. The first stage is an automated off-line calibration that characterizes $dX(Y_i)$ and $dZ(Y_i)$ at a single (and somewhat arbitrary) location of X_D. During acquisition, the second stage periodically measures the AUT height plus the shape of the Y beam to determine tilt, translation, and/or distortion in each dimension. Parameters that quantify those changes are then communicated to the MI-710C to update the corrections being applied in real time. The second stage also performs laser self-compensation and/or coordinate-system recall at a user-specified rate.

C. *Laser Location*

The laser must be located where it can see several things over the full range of X-Y travel, even with an AUT present in the range:

- Probe simulator (carriage SMR) when appropriate

- Entire length of Y beam
- Enough range monuments to reconstruct the coordinate system

The most straightforward way to meet these requirements is to place the laser on the scanner structure near the level of the probe. This placement nearly guarantees that the laser location and attitude in the range coordinate system vary with time, but the overall concept accommodates those variations. This placement also makes the laser readings sensitive to vibrations in the scanner structure, and also perhaps to location of the Y beam along the X_D axis. For this reason, laser measurements (other than verification and calibration scans) are only attempted with scanner motion stopped.

D. Calibration

An automated off-line calibration procedure is supplied with the system. Its primary tasks include:

- Defines the range coordinate system and the known locations of the range monuments. Stores those monument locations for use in later coordinate-system recall.
- Finds the Y-beam SMRs, and determines the range of X_D where each is visible to the laser.
- Measures several uncorrected scans along Y_{+R} with X_i=Z_i=0, and builds path-correction files for the MI-710C.
- Without moving the Y beam, measures the SMRs on the Y beam, and stores their locations with respect to the corrected path.

E. Y-Beam Shape

The shape of the Y beam is defined to be straight at the completion of calibration, since any deviations from straightness are measured and stored in the MI-710C for path correction[2]. Several SMRs are permanently mounted on the Y beam, and those SMRs' locations relative to the corrected probe path are stored during calibration. When the range coordinates of those same SMRs are measured periodically during acquisition, it is straightforward to predict the path the probe would take without further correction, thus yielding the additional corrections to be applied.

F. Synchronization with Acquisition

In this approach, the Y-beam laser measurements need to occur prior to every return-to-point (drift-correction) measurement, plus every N^{th} scan (where N is a user-entered parameter), and need to occur with the positioner stationary. Some acquisition-system synchronization is therefore required to schedule the laser measurements, to allow communication with the MI-710C position controllers, and to hold off acquisition until the measurements are completed. The MI-3000 Arena Data Acquisition and Analysis Software provides multiple mechanisms for such synchronization and external control.

V. FEATURES

A. Configurability

There are several configuration parameters that need to be determined for each installation. These parameters include:

- Number of range monuments
- Number of SMR stations along the Y beam
- Number of SMRs at each station to provide adequate field of view
- Number of iterations through monument and Y-beam measurements needed to overcome thermal refraction effects
- Frequency of Y-beam measurements during acquisition
- Frequency of coordinate-system recall during acquisition
- Frequency of laser compensation during acquisition

B. Data Repository

A simple MS Access database is provided to hold a wide assortment of data. It contains data that tell the software the IP addresses, axis numbers, etc., it needs to talk to. It also contains calibration outputs needed during acquisition, plus user inputs that affect fidelity. There are several automatically populated tables that form a history of things like temperature, Y-beam measurements, coordinate-system recall results, and verification results. All of the data plotted within this paper were mined from the Data Repository or other files automatically generated during operation. The database also contains forms that provide a simple GUI to configure and run the off-line portions of the subsystem.

C. Synchronization to AUT Height

Since the fundamental goal of PNF is not to scan a plane a constant distance from the floor, but rather a known and constant distance from the AUT, the changing height of the AUT must be known throughout the acquisition. The laser subsystem does that through the use of an 'AUT-height SMR' that the user places somewhere in the range, preferably on the AUT. If it is not located on the AUT, then it should be on a post with the same CTE as that of the AUT support. A simple script is provided that guides the user to find that SMR with the laser, either manually or with the laser's camera. Only the Z coordinate of this SMR is used, and the user-entered probe-AUT separation is relative to this height.

D. Verification Mode

During normal acquisitions, there is no SMR on the carriage. A verification mode is provided that expects the probe simulator and its SMR to be present, and takes self-triggered laser data along each scan in the acquisition. Several plots are available as a user option, and the verification data are stored in the Data Repository.

E. Calibrated Latency Removal

The MI-3000 and the MI-3044 PNF software each have the capability to remove the mean latency from each scan based on measured position data. As stated in Section II, however, there are no encoders that indicate range coordinates, such that use of the encoder positions in standard latency removal would actually remove some of the laser correction applied during the acquisition. The laser subsystem therefore provides the capability to convert monitored Y_i encoder positions into range Y positions (using the beam-shape data stored in the Data Repository during each acquisition) prior to the latency removal process.

F. Spatial Analyzer Interface

All communication with the tracking laser and some of the data manipulations are performed within the Spatial Analyzer (SA) software package from New River Kinematics. At the end of each acquisition or measurement sequence, SA is left running such that additional interactive laser measurements (e.g. for AUT alignment to the range) can take place with the range coordinate frame already established, and with point groups (like the range monuments) available to automatically re-measure if necessary. A sample script is also provided that quickly establishes that coordinate frame and imports the known locations of the fixed monuments.

VI. Measured Data

The data presented here were measured with a portion of the MI-815-66x66 installed in the MI factory. Nearly all of the mechanical alignments that MI typically performs on an X-Y scanner were intentionally left out to ensure that there was significant error to be corrected. The temporary installation provided full 20-meter travel in Y_i, but only 2.7 meters along X_D. Instead of having the laser and probe over 20 meters off the floor, the scan plane was at a height of just over three meters, and the laser height was only two meters. The range monuments spanned a much smaller area than is intended in the final installation. Some aspects of the factory installation make it easier to correct the errors, and other aspects make it more difficult.

A calibration was performed before the sequence of measurements. Figure 2 shows the zero-mean uncorrected $dZ(Y_i)$, and Figure 3 shows $dX(Y_i)$, both in range coordinates. Note that, as intended, there were significant errors to be compensated. Figure 2 shows sag in the 20-meter long Y beam, along with a lack of straightness of the rails after their attachment. Figure 3 shows a lack of orthogonality between X_D and Y_i, plus a lack of rail straightness.

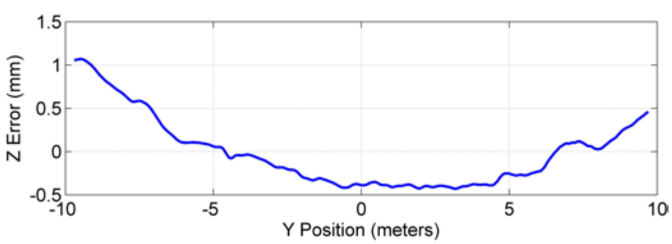

Figure 2. $dZ(Y_i)$ From Off-Line Calibration

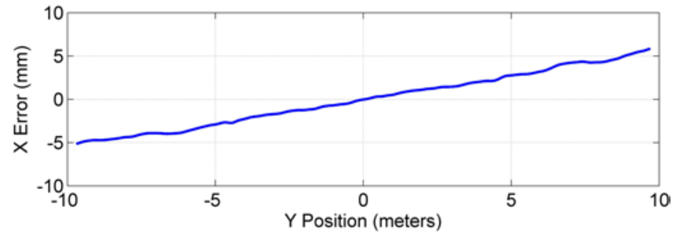

Figure 3. $dX(Y_i)$ From Off-Line Calibration

Following the calibration, a sequence of repeated long acquisitions over the available scan plane was performed in the laser subsystem's verification mode. Each acquisition was intentionally made to run slowly, so that each took about 23 hours to complete. The sequence was run over a three-day holiday weekend, such that three full acquisitions and most of a fourth were completed.

Figure 4 shows the verification results in Z from one of the completed acquisitions, and Figure 5 shows the results in X from the same acquisition. All three completed acquisitions, plus the one that was still running Monday morning, yielded similar results. The top plot in each figure represents over 400,000 laser measurements in the range coordinate system (which was re-defined over 40 times during the acquisition), offset slightly to be zero-mean over the entire acquisition. The center plot in each figure shows the Y-beam shape measured and compensated during the acquisition (also made zero-mean for plotting purposes). The bottom plot estimates the uncorrected error that would have been measured by adding the beam-shape in the middle plot and path-correction data from Figure 2 or Figure 3 to the laser measurements in the top plot.

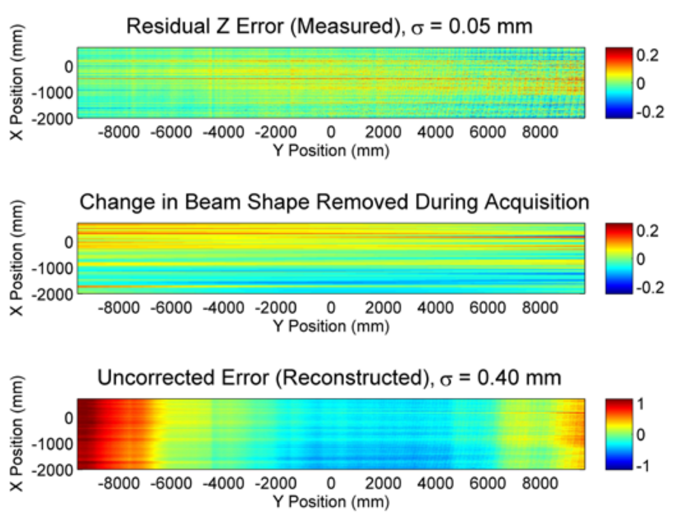

Figure 4. MI-815-66x66 Planarity Correction

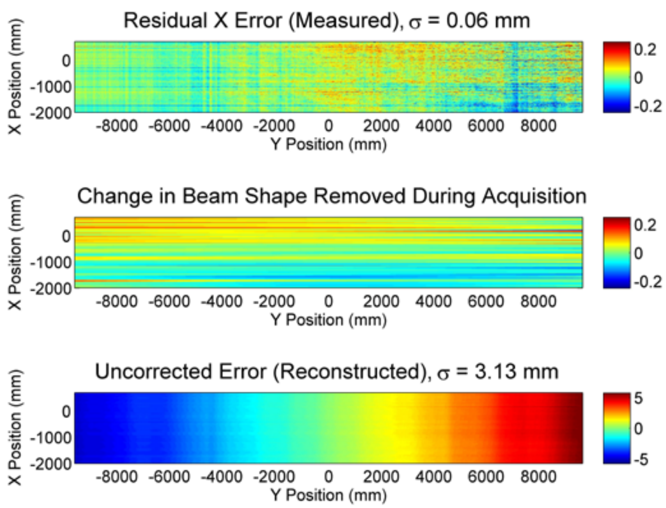

Figure 5. MI-815-66x66 X-Axis Correction

The residual Z errors in the top plot of Figure 4 are shown in 2D form in Figure 6. Similarly, the residual X errors are shown in 2D form in Figure 7.

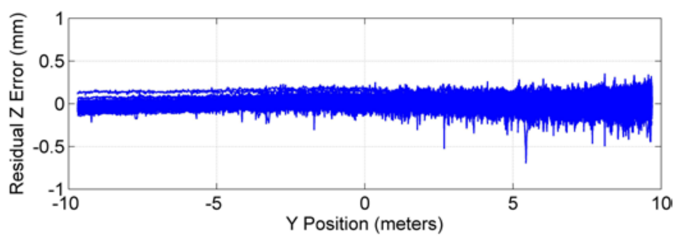

Figure 6. Residual Z Errors

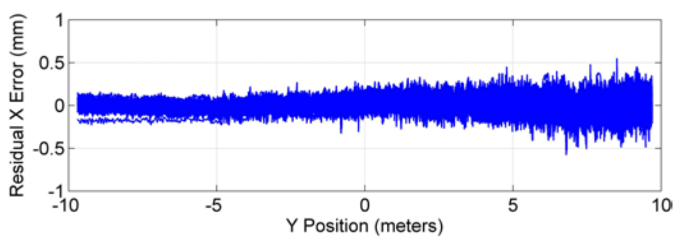

Figure 7. Residual X Errors

When scanning along the Y dimension, it is easy to capture X and Z errors vs. Y, and those results are shown in Figure 4 and Figure 5. It is much less straightforward to capture errors in Y vs. moving Y due to the tight correlation requirements between the time when RF sampling would occur and when laser readings are taken.

Figure 8 shows the repeatability in each dimension during the RTP measurements that would be used for drift correction. Because these were taken with the carriage stopped, we are able to measure all three coordinates where RF data would have been taken. 110 RTP measurements were taken during the four acquisitions and are represented in Figure 8.

During the course of the acquisition analyzed, the temperature varied by 2°C. The growth of the 20-meter Y beam was tightly correlated to the temperature, and its length varied by 0.4mm (0.015") during the same time period. The Y beam was also seen to translate along Y by about 0.15mm (0.006") during the acquisition, with a shape similar to that of the measured temperature. Figure 8 shows that those temperature effects were adequately compensated.

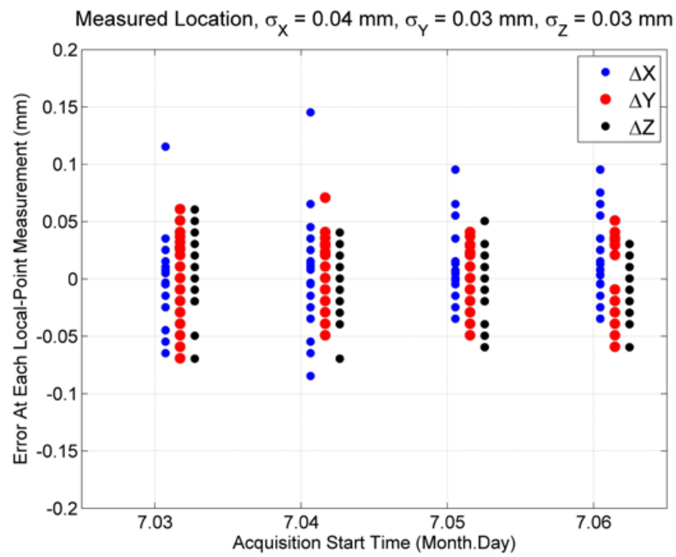

Figure 8. MI-815-66x66 Residual Errors During RTP

VII. CONCLUSIONS

MI Technologies has developed a new laser-based position-compensation subsystem for use with very large horizontal PNF scanners. The approach taken makes the subsystem relatively insensitive to mechanical drift due to temperature and other effects. The subsystem automatically synchronizes with the MI-3000 data acquisition to update the corrections in all three dimensions at a user-specified rate. Repeated measurements on an intentionally misaligned scanner consistently yielded planarity within 0.05 mm (0.002") RMS, and X-Y fidelity well within 0.10 mm (0.004").

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