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, the high-level implementation concept is described, and resulting measured data are presented.

***Index Terms*—Near-Field Measurements, Tracking-Laser Corrections**

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 probe motion using those drift 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 on each side, and is shown in Fig. 1. 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. The laser subsystem described herein is an available option for the MI-815 family of scanners.

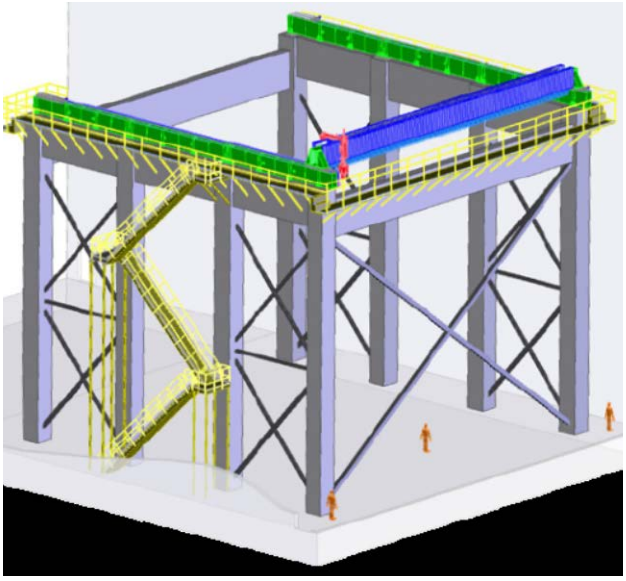

Fig. 1. MI-815-66x66

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 planarity relative to 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 Retroreflector (SMR): a standard tracking-laser target. There are several of these (a configurable number) permanently mounted in the range.
- Y Beam: the beam that bridges the two X beams. The probe carriage rides along the Y-beam rails.
- 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
- Data Repository: a simple MS Access database that stores configuration parameters and logs measurement results

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[6-8]
- 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's distance from the AUT's X-Y plane. 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 laser, and the probe carriage.
- 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 nonuniformity 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.

- The location and attitude of any device (i.e. the laser or SMRs) placed in the range for the purpose of improving the fidelity cannot be assumed to be constant.
- 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
- 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.
- 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 ΔZ. 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 nontrivial and critical.

The range coordinate origin is defined as the geometric center of a constellation of floor monuments. This is the one point that is declared to remain fixed in the range coordinate system. The monument constellation is chosen so that this point is insensitive to temperature change, and is also located near the center of the AUT support. The range Z basis vector is defined as the upward normal to the best-fit plane through those floor monuments.

The clocking of the X and Y axes about Z is initially done during calibration by aligning X with carriage travel along X_D. When recalling the coordinate system, the Phi angles of the floor monuments are examined to compute the appropriate rotation.

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 high-level tasks include initial coordinate-system definition, location and characterization of the several SMRs, and creation of the path-correction maps.

The range coordinate system is defined as stated earlier, with the origin and Z defined from the floor monuments, and the clocking of X and Y based on scans along X_D.

The initial location of the SMRs is done via operator prompts, typically in conjunction with the camera interface in the Faro Vantage tracking laser. Once the initial calibration is completed, subsequent operator assistance in finding SMRs is not required.

Due to the geometry of the moving Y beam and the SMRs' limited field of view, two SMRs are needed at some locations along the Y beam to provide coverage over the scan area. The calibration procedure determines the range of X_D where each of these SMRs is usable.

The MI-710C path-correction maps are measured at a single location of X_D where all of the Y-beam SMRs are usable. The procedure measures several uncorrected scans along Y_{+R} with X_i=Z_i=0, finding the repeatable portion of $\Delta X(Y_i)$ and $\Delta Z(Y_i)$ at that time and value of X_D. Immediately thereafter, the Y-beam SMRs are measured, and their locations relative to the corrected probe path are stored for later use.

E. Monitoring Changes in Y-Beam Shape

The calibration procedure yields the X and Z displacements from the probe path, plus the Y_i locations, of the several Y-beam SMRs. 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 parametric corrections to be applied. The number of Y-beam SMRs is configurable, and depends in part on the expected complexity in the Y-beam shape's change (tilt, translation, sag, etc.) with time.

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.

G. Synchronization to AUT Height

The fundamental goal of PNF is to scan a plane not a constant distance from the floor or the laser, but rather a known and constant distance from the AUT. Therefore, the changing AUT height must be known throughout the acquisition. The laser subsystem monitors 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. Only the Z coordinate of this SMR is used, and the user-entered probe-AUT separation is relative to this height.

H. 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 also logged to the Data Repository.

I. 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.

V. 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.

Fig. 2. shows the Z component of uncorrected Y-beam shape, measured during calibration at a single X_D location over a short time interval. Fig. 3. shows the X component of uncorrected Y-beam shape during the same calibration. These calibration data are used to build a 1D path-correction map[2] for $\Delta X(Y_i)$ and $\Delta Z(Y_i)$ so that subsequent motion along either Y_C or Y_V will automatically cause the X_F and Zi axes to cancel these errors. This map remains fixed until the next calibration.

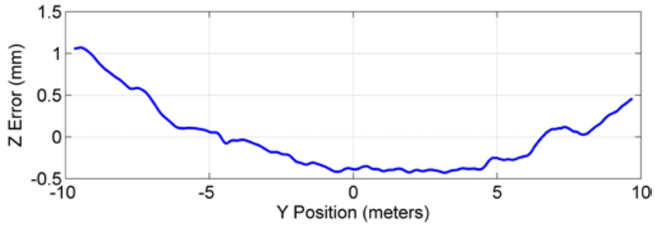

Fig. 2. Uncorrected ΔZ(Y) During Calibration

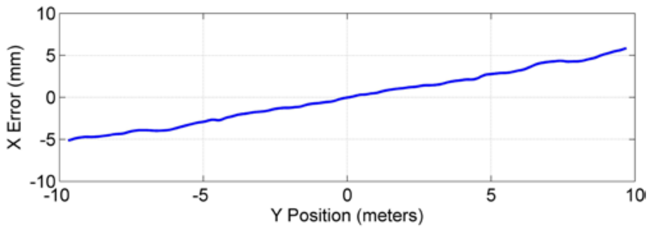

Fig. 3. Uncorrected ΔX(Y) During Calibration

Following 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 included 271 scans and took about 23 hours to complete. Laser measurements were repeated every fourth scan to update the Y-beam shape and the AUT height. The sequence was run over a three-day holiday weekend, such that three full acquisitions were completed.

All three completed acquisitions yielded similar results, and all were within specifications. Over 400,000 laser verification measurements were taken during the scans of each acquisition. These measurements were in the range coordinate system (which was re-defined over 40 times during each acquisition), offset slightly to be zero-mean over the entire acquisition.

Fig. 4. shows the Z component of the 400,000 laser measurements relative to the desired plane above the AUT during the data-acquisition scans. The RMS of the data plotted is 0.05 mm, which is within specifications. Fig. 5 shows the X component of the same laser measurements relative to the probe's commanded range X location. The RMS of these data is 0.06 mm, also within specifications. The laser was located near -10m in Y, and it is therefore likely that the larger spread of errors at +Y is due to laser-measurement noise.

Data were also captured just prior to each of the RTP RF 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 sequence of acquisitions and all were within 0.04mm RMS. These RTP data are plotted in Fig. 6.

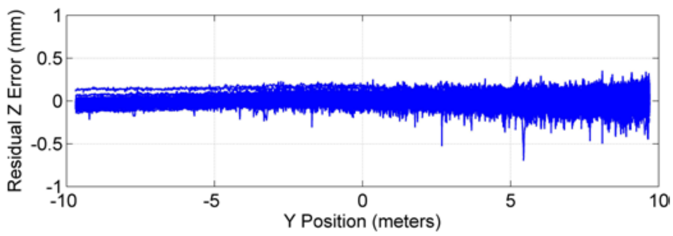

Fig. 4. Residual ΔZ(Y) During Acquisition (0.05 mm RMS)

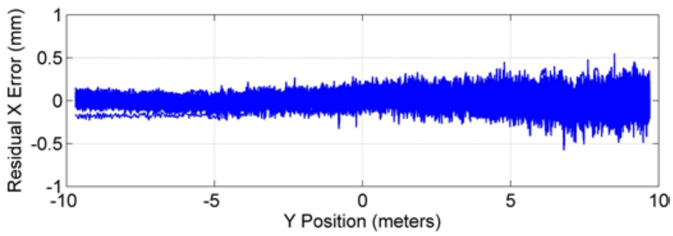

Fig. 5. Residual ΔX(Y) During Acquisition (0.06 mm RMS)

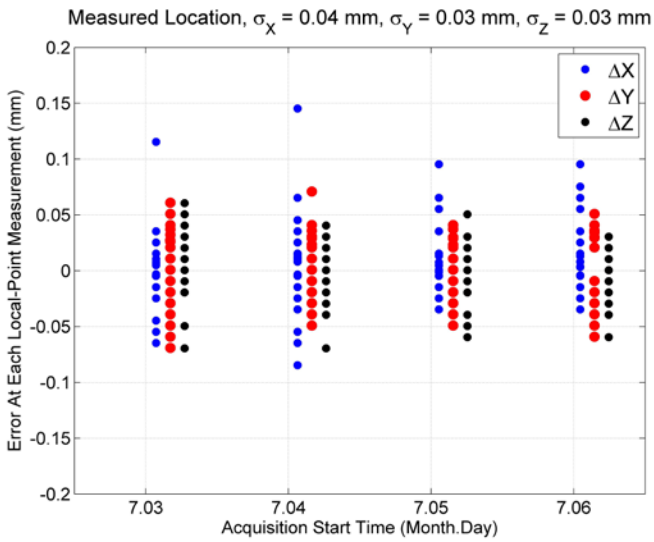

Fig. 6. Return-To-Point Positioning Accuracy

During the course of the acquisitions, 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.

VI. 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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