DESIGN, ALIGNMENT, AND CALIBRATION REQUIREMENTS FOR A SUB-MILLIMETER WAVE FREQUENCY TILTABLE LIGHTWEIGHT SCANNER

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ABSTRACT

This paper discusses design aspects related to a tiltable lightweight near-field scanning system for use at sub-millimeter frequencies. It addresses design issues as they relate to accuracy and scanner distortions from multiple causes. Calibration methods to measure and correct for anticipated and unanticipated errors are briefly addressed. Actual test results are presented.

The tiltable scanner being discussed was designed for the Atacama Large Millimeter/submillimeter Array (ALMA) [1] and is being used by the National Radio Astronomy Observatory (NRAO) [2]. It has many other applications by virtue of its light weight (approx. 120 lbs) and ability to be oriented at different angles. These include flight-line testing and other in-situ antenna test applications.

Keywords: sub-millimeter, accuracy, design, ALMA, NRAO, radio astronomy, lightweight, in-situ, flight-line

1.0 Introduction

There is a growing need for higher accuracy scanning systems in the antenna industry. Higher frequency applications are becoming more prevalent in a variety of applications from military communications to radio astronomy. As frequencies increase, so must the accuracy of the scanning systems. Planar near-field systems typically require a planarity near $\lambda/100$ (depending on antenna gain) to minimize errors in the conversion of phase front to angle spectrum using Fourier transform techniques [3]. In addition, X-Y position accuracies can affect the far-field transform's pattern, gain and polarization [4].

Low frequency applications can benefit from more accurate scanning systems as well. Less positioning errors allows more room in error budgets for cable flex, thermal effects, and other error sources (or just better measurement results). In addition, calibration periods can be extended and other component specifications may be relaxed.

This paper will look at some of the issues related to high accuracy positioning as they relate to a tiltable lightweight near-field planar scanning system. The tiltable scanner being discussed was designed for ALMA and is being used by NRAO (see Figure 1). This example is particularly poignant since it mounts directly to a feed assembly and is tilted with the feed. Hence, changes in the gravity vector affect its structure.

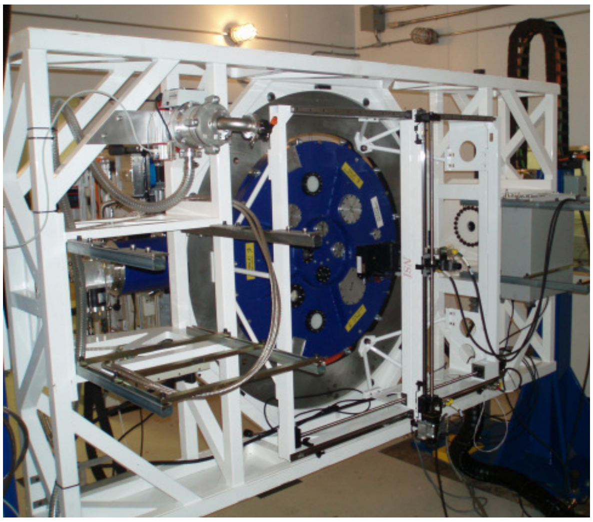

Figure 1 - Scanner and Feed Assembly on Tilting Frame

This scanning system also needed to be lightweight to prevent distortion of the feed assembly. Lightweight systems are more difficult to construct because distortions are more easily generated. The same types of criteria for this system could also be applied to any system designed for in-situ testing of antennas, particularly on radio towers or for flight-line testing.

To facilitate the discussion we will use a Cartesian coordinate system with the X and Y axes parallel to the aperture of the antenna under test (AUT), the Z axis perpendicular to the aperture, and the zero point at the aperture center. The +Z direction is away from the AUT. In this example the coordinate system moves with the AUT as it is rotated.

2.0 Sources of Error

There are two main sources for errors in positioning systems, structural and drive-related. Structural errors can be further categorized as being caused by: 1) manufacturing, assembly, and installation tolerances; 2) thermal distortions; and 3) load related effects. Most antenna measurement scanning systems are not repositioned after installation and do not attach to an AUT (or affect it in any physical manner). As such, they can be designed to have large cross-sections and high mass to minimize thermal and load-related errors. By design, these fixed systems can typically be adjusted during installation and calibration to correct for manufacturing and assembly tolerances, and for known static loads. dynamic structure designers do not have this luxury. Instead they need to understand, minimize, and compensate for all sources of positional error.

Structural Issues:
For the system pictured, structural components were fabricated using the very best commercial practices. All inspection, assembly, and testing was then conducted in a controlled environment to approximate the end-user's conditions. Interface points and other reference surfaces were monitored or periodically checked as components were assembled. In cases where assembling mating parts created unacceptable distortions in the structure, techniques such as shimming or hand lapping were used to minimize or eliminate the distortions.

In an ideal world, the scanner and its components will all be fabricated, assembled, installed, and operated at a single temperature to eliminate structural changes due to thermal variations. Unfortunately, even in the best situations, temperatures vary due to heat dissipation from equipment and air mixing as the scanner and/or AUT is moved during testing. Lightweight scanners are inherently more susceptible to thermal variations due to their low thermal mass. Ambient temperatures can change the structure temperature quickly and residual stresses from machining, assembly, and installation processes will cause unpredictable thermal distortions. Stratification, a large source of thermal distortion in large vertical systems, is not considered to be a cause for concern due to the relatively small size (approximately 4 ft x 4 ft). Thermal plumes from auxiliary equipment and drives can affect the structure. These plumes may not always affect the structure in the same way depending on the structure's angle of orientation. If temperatures are relatively stable over the average test time for an antenna, calibration of the structure can be used to correct planarity errors. If not, structure monitoring techniques may need to be employed [5]. NSI has used these techniques successfully in large aperture precision scanners for some time.

Changes in load are both static and dynamic. Static load changes result from changing probes or other RF equipment on the scanner system. Dynamic load changes result from cables bending or being lifted, accelerations, and how loads are transferred through the support structure as the scanner moves. Complicating the issue even further, dynamic affects change as the system's orientation to the gravity vector changes.

Drive-Related Issues:
For the purposes of discussing drive-related positioning errors, it is useful to define some terminology. For purposes of this paper, the following definitions shall be employed.

> Accuracy is the total uncertainty of moving to any commanded position for a given axis.
> Repeatability is the uncertainty of moving to the same commanded position in the same manner time after time.
> Resolution is the smallest increment of movement that can be made by a given axis.
> Backlash is the amount of commanded movement before the actual movement begins when reversing directions.

By definition, accuracy will include the affects of backlash for a given axis and repeatability will not.

To determine overall accuracy of a system, each component's individual accuracy needs to be determined. In most cases, manufacturers give engineers accuracy information, but the good designer must recognize how the accuracy information is determined. For instance, a stepper motor may have an inherent accuracy (a result of the motor's windings) of anywhere from 1.5 to 5% of a full step (full step = 1.8°) [6]. Operational accuracy of the step motor depends on configuration as well. If the motor is not sized correctly for the load, issues such as empty stepping, ringing, and resonance can cause missed steps/micro-steps and affect overall motor accuracy [7]. Likewise, ball screw accuracies may be given without consideration for backlash. The NRAO scanner uses a step motor coupled to a ball screw for each of its primary axes. Each drive's accuracy depends only on five components: a step motor, coupling, ball screw, the ball screw's nut, and the bearings supporting the ball screw. The baseline accuracy can be determined at any point by correctly summing the accuracy of the individual components. We say correctly because a component's accuracy may or may not be cumulative. For example, the nut accuracy is determined by its lead and backlash or preload, and does not change with position, but the lead accuracy of the ball screw itself may vary with length/position. The overall accuracy must also include compliance of each element at the given load and changes due to thermal variations. Just like the structure, drive components can be affected by temperature changes. Lead (or pitch) of a ball screw (gear) increases with temperature. Compliance can be from strain in tension, compression, torsion and bending, depending on the gravity vector, friction in the system, and other factors.

3. Design Considerations

There are many different ways to solve the issues presented to obtain the desired results. For the NRAO scanner two criteria drove the design more than any others; 1) weight, and 2) maintaining parallelism between the AUT reference plane and the scan plane at different tilt angles. These are competing design considerations which required trades between the two. Prior NSI near-field scanners of similar, but smaller size had loads in the range of 1 to 12 lbs, with weights ranging from 30 lbs (0.006" planarity) to 1,000 lbs (0.0002" planarity). Load to weight ratios vary from 0.03 to 0.012. For this application the load to weight ratio is approximately 0.14, nearly five times that of NSI's standard scanners with required planarity as good as (or better than) the heaviest fixed precision scanners. Analysis quickly showed that uncorrected planarity and parallelism could not be met while meeting the weight requirement, so correction techniques would need to be used. Bending and twisting are the most difficult deformations to control (as the gravity vector changes) and affect the planarity more than other types of strain in the structure. Lightweight thin-walled sections with relatively high moments of inertia were employed to improve stiffness while keeping weight to a minimum. Load locations were aligned with the centroidal axes of structural elements whenever possible. To help decouple the AUT from the scanning system, a three-point kinematic mount was used to attach the scanner directly to the feed assembly. The tilting frame holding both the feed and scanner has a cylindrical plate that acts as a flexible diaphragm to minimize distortions of both the AUT and scanning system.

To prevent motor heat from entering the structure, thermal breaks/isolators were installed between the motor and structure. In other scanners NSI has also put ducting around motors to pull ambient conditioned air across the motors and vent it away from structural elements to prevent thermal plumes. Dissimilar metals were avoided in the construction to preclude distortions caused by differences in temperature between assembly and operation.

Drive system performance was achieved by using best-in-class components. Preloaded bearings and ball nuts were used to minimize backlash and changes in position due to orientation.

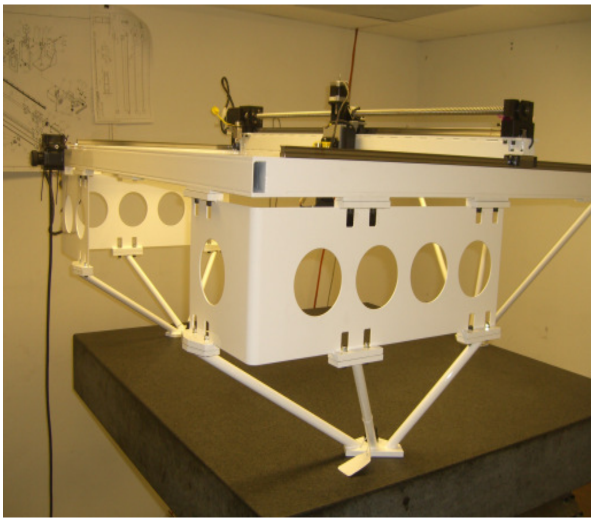

Figure 2: Scanner on Tiltable Granite Surface Table

4. Calibration and Testing

Testing at NSI was done using a dedicated granite surface table mounted on an elevation stage for tilting to various angles of orientation (see figure 2). This method allows the use of precision touch probes to accurately measure planarity and parallelism between the mounting surface and the probe path. A calibrated granite reference beam was used to measure straightness of each axis as well. Laser trackers, spinning lasers with sensors (such as NSI's Z-Plane Laser system), and other optical techniques could also be used, but each has its own uncertainties and complications not found in the direct measurement method. For on-the-fly calibration while on the AUT, different methods are still being considered. Again, the most simple and direct would be a reference plane mounted beyond the RF scan plane (from the AUT).

Items measured included planarity at 3 different angles of orientation, 0, 45, and 90°, and cross-axis error (e.g. x position error with respect to y position). Figures 3 thru 5 show raw planarity measurements. One can easily see the bending and distortion as the scanner is tilted. It also shows the negative X end of the scanner frame is much more rigid than the positive X end (improvements can be made in future designs).

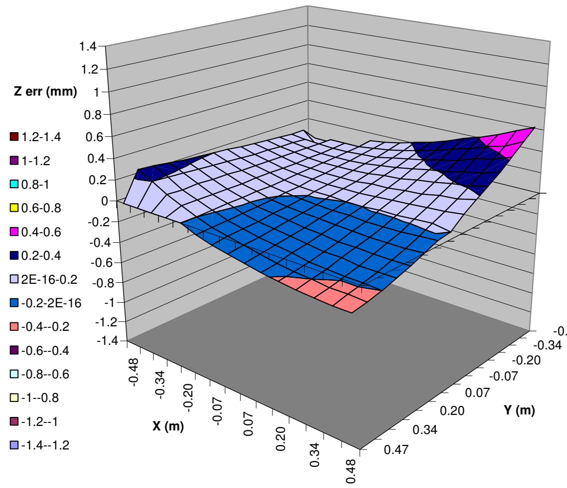

Figure 3: 0° Orientation Raw Planarity Data

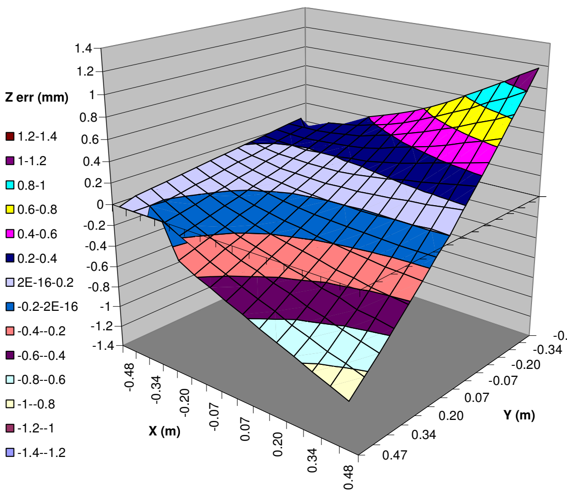

Figure 4: 45° Orientation Raw Planarity Data

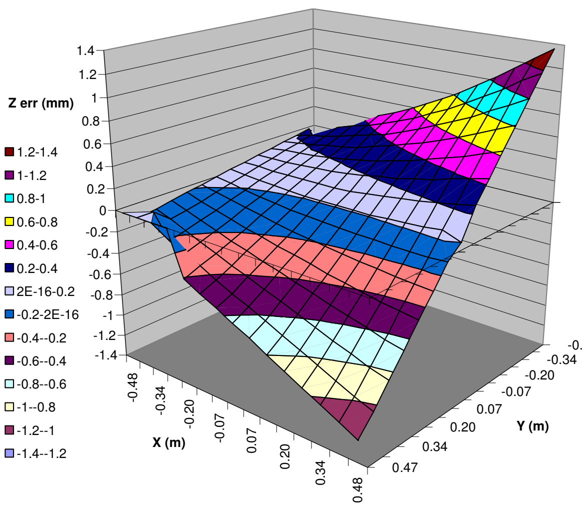

Figure 5: 90° Orientation Raw Planarity Data

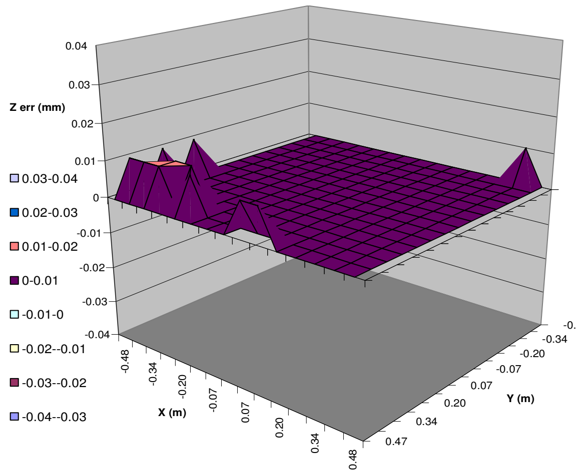

Figure 6: 0° Orientation Best-Fit Corrected Planarity

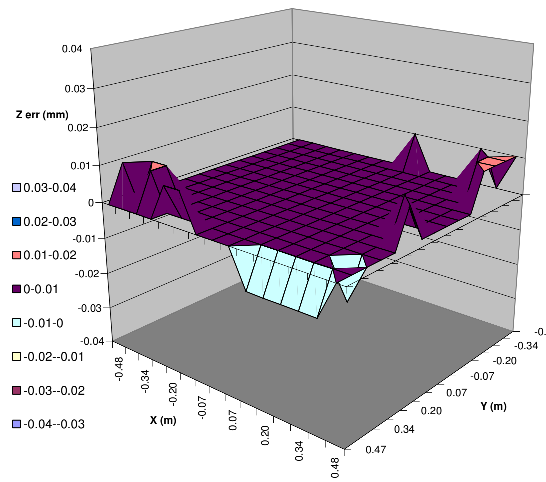

Figure 7: 45° Orientation Best-Fit Corrected Planarity

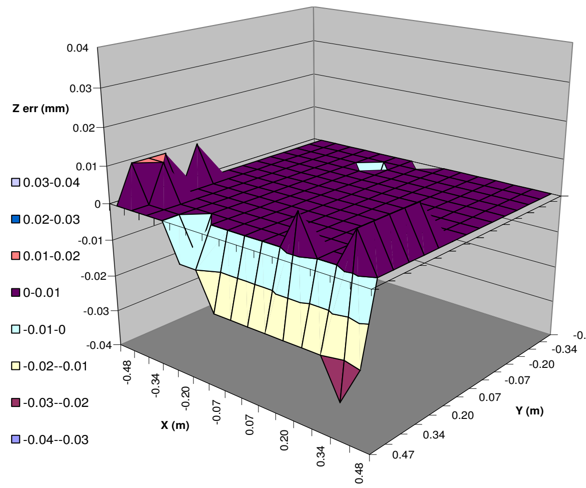

Figure 8: 90° Orientation Best-Fit Corrected Planarity

Figures 6 through 8 show the best-fit corrected planarity at the same angles. Results well within the required planarity were obtained over the entire scan plane, but especially in the center of the scan area. Resolution, repeatability, and accuracy of the Z-axis motion are very important in achieving these results. Corrected data also shows some error that can not be corrected uniformly, such as the structure heating from the motor at the –X corner.

5. Application

The best proof is how the scanner is performing in tests just recently started at NRAO.

As ALMA will operate at 16,500 feet altitude in the Atacama Desert in northern Chile, it is essential that all important parameters of the receivers shall be determined at the test facility in Virginia prior to shipment to Chile. These will be confirmed at spot frequencies by a separate test facility at 10,000 feet altitude before being mounted on the telescopes.

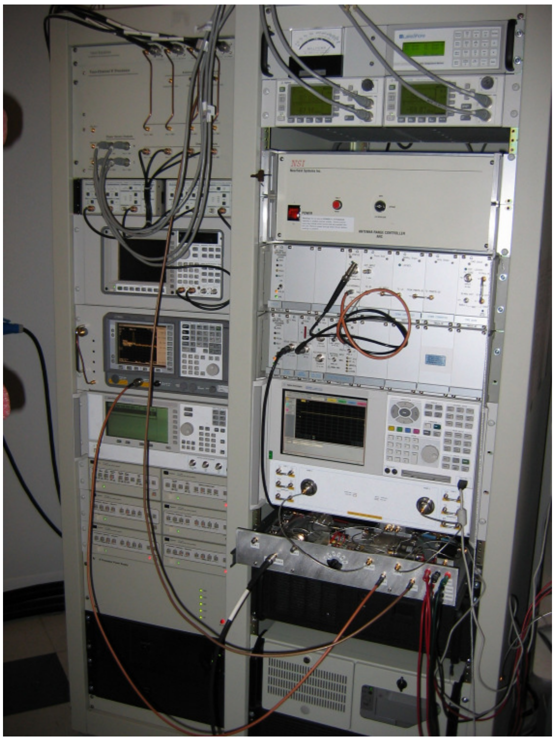

Figure 9: Receiver test system electronics racks

The ALMA front-end cryostat is a cylinder 1-m in diameter and 0.5-m high which holds up to 10 receivers operating in different frequency bands covering the range 33 GHz to 950 GHz- for full details see [8]. Figure 9 shows the receiver test system electronics racks which allows initial RF measurements to be made. Figure 10 shows a close-up picture of the top of the cryostat with the windows for the 10 bands.

Each receiver is inserted into the cryostat base plate and has an o-ring seal. The receiver base plate contains all the electrical and local oscillator (waveguide) feed-troughs'. Each receiver operates in both polarizations (using either an Ortho-mode transducer or a wire grid polarizer). The RF signals enter through windows in the cryostat top plate, which are also sealed with o-rings. The windows for the highest frequency bands are made of quartz with matching layers, while the lower frequency bands are made of HDPE with matching layers machined on both sides.

Each receiver is in an offset position in the telescope focal plane but points towards the center of the secondary mirror of the Cassegrain system. In order to optimize the array performance, very stringent constraints are given, at the project level, for the illumination pattern and the beam position on the secondary.

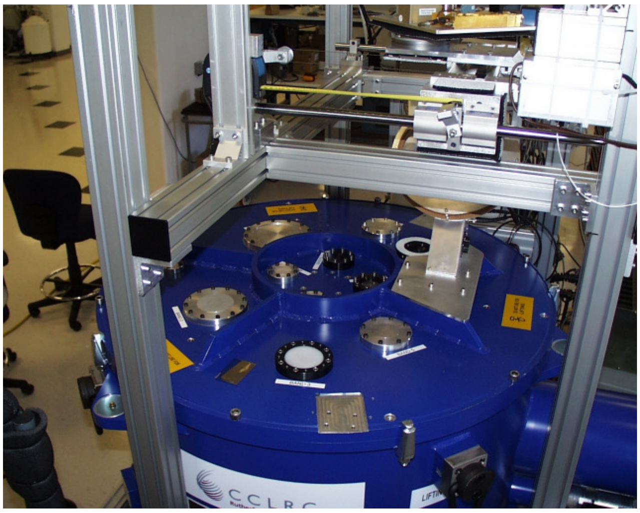

Figure 10: Close-up of the top of the cryostat

As examples of the data obtained with the scanner, figure 11 shows an initial far field map of the band 6 (211 – 275 GHz) receiver made at 217 GHz and figure 12 a far field map of the band 7 (275 – 373 GHz) receiver, made at 317 GHz. Different sources (consisting of multipliers and amplifiers, a 40 GHz synthesizer is the fundamental source) are used for each band and have to be mounted on the scanner as required.

These maps were made at two z distances separated by $\lambda/4$ to remove the effects of residual reflections in the system, even though microwave absorber is used liberally all over the system, at these frequencies some reflections remain.

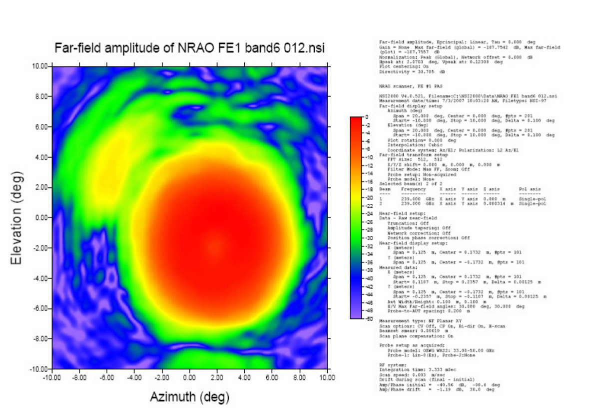

Figure 11: Band 6 Far field beam pattern at 217 GHz.

The side-lobe seen in this pattern has been confirmed by independent measurements of the receiver. However, due to its low level, it will not affect the final receiver performance on the telescope.

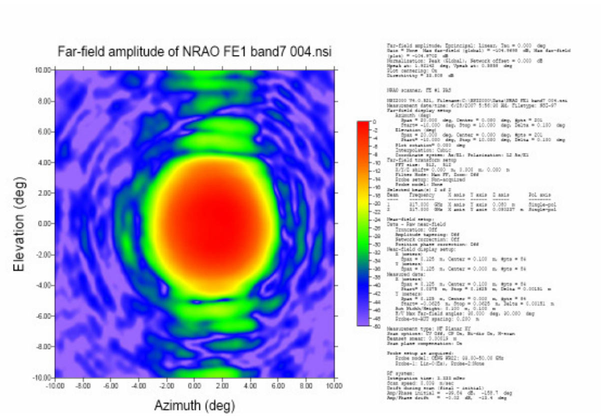

Figure 12: Band 7 Far field beam pattern at 317 GHz.

The vertical structure seen is believed to be due to cable flexure problems and is being investigated further.

Using maps such as these the illumination efficiency (the amount of power intersecting the secondary), spillover efficiency (amount of power missing the secondary), and the pointing angle, which gives the intersect point of the center of the beam on the secondary will be determined. Preliminary measurements indicate that the illumination efficiency can be determined to 0.1 % and the pointing to less than 0.5 milli-radians.

Further work will continue to enable measurements of band 9 (602 – 720 GHz) and to improve the final maps (especially the structure due to cable flexure).

6. Summary

Correcting for significant structural errors in lightweight structures is feasible if attention is paid to details. Improvements can still be made in existing designs using newly developed analytical techniques. As position measurement techniques and tools advance in resolution and accuracy, become faster, and get smaller in size, it will be even more economical to use correction techniques to improve antenna measurements.

8. REFERENCES

[1] The Atacama Large Millimeter Array (ALMA) is an international astronomy facility. It is an equal partnership between Europe and North America, in cooperation with the Republic of Chile. ALMA is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC), and in Europe by the European Southern Observatory (ESO) and Spain. ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI), and on behalf of Europe by ESO.

[2] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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9. ACKNOWLEDGMENTS

The authors wish to thank Mr. Bruce Williams and Greg Hindman of NSI for their suggestions, and Mr. Kirk Crady and Mr. Rick Williams of NRAO for their work on the test systems.