Sub-millimeter Wave Planar Near-field Antenna Testing

Daniël Janse van Rensburg[1], Greg Hindman[2]

[#] *Nearfield Systems Inc, 19730 Magellan Drive, Torrance, CA, 90502-1104, USA*

[1]drensburg@nearfield.com

[2]ghindman@nearfield.com

***Abstract*— This paper provides an overview of planar near-field antenna test systems developed for sub-millimeter wave testing. Special techniques that have been developed to overcome technical restrictions that usually limit performance at very high RF frequencies are presented. Aspects like thermal structural change, RF cable phase instability, scanner planarity and probe translation during polarization rotation are addressed. These methods have been implemented and validated on systems up to 660 GHz and 950 GHz. These cases have lead to the development of low cost commercial test systems, making antenna testing in the V and W-bands (40 – 110 GHz) cost effective.**

I. Introduction

Since the introduction of commercial near-field antenna test systems in the 1980's these systems have found application at ever higher frequencies, requiring new innovations to overcome technological limitations. This paper gives an overview of some of these systems and the techniques employed to overcome aspects like thermal structural change, RF cable phase instability, scanner planarity and probe polarization misalignment [1-9].

Millimeter and sub-millimeter wave technology developments are principally driven by earth observation and radio astronomy applications. Based on the electrical antenna aperture sizes, all of these applications qualify as high gain test cases and are therefore ideally suited for planar near-field testing. This type of test also has the added advantage that it does not require motion of the antenna. However, motion of the near-field probe (both translation and rotation) requires flexure of the RF path and this introduces uncertainty in the measurement. We address this aspect in this paper and describe potential solutions.

Due to the nature of a synthetic aperture test technique like planar near-field testing, a measurement process can last from several minutes to several hours. During this period of time there will be RF sub-system phase and amplitude drift as well as structural thermal drift of the scanner. In this paper we describe the NSI Motion Tracking Interferometer (MTI) as a technique for addressing this problem.

A third aspect of crucial importance is that of scanner planarity since this supports the fundamental assumption of a planar near-field scanning test. Active structure correction, originally developed for accuracy enhancement of largescanners, can be employed to achieve the planarity required at sub-millimeter wave frequencies.

A fourth and final aspect presented in this paper is the correction for probe translation effects during polarization rotation and to correct for that offset in the far-field. This technique is essential for addressing mechanical alignment of bulky microwave up-conversion probe hardware.

Section II of this paper describes three planar near-field scanners that were developed for such test cases in recent years and that represent (to our knowledge) the highest frequency near-field applications to date. Section III describes some of the techniques developed to overcome the technological limitations mentioned before, enabling these systems and a summary is presented in Section IV.

II. Sub-Millimeter Wave Planar Near-field Scanners

NSI provided the first sub-millimeter wave (550GHz – 545 µm) planar near-field scanner in support of the NASA Sub Millimeter Wave Astronomy Satellite (SWAS). The scanner was designated the NSI-901V-3x3 (0.9 m x 0.9 m) and has a planarity of 3 µm RMS and uses an air bearing / granite construction [1]. As part of this system, NSI developed and patented the Motion Tracking Interferometer software [2] that corrects for thermal structural and RF drift during testing. This technique is further described in Section III.

A follow-up scanner was provided in support of the JPL Earth Observing System Microwave Limb Sounder at 650 - 660 GHz [3]. This sub-millimeter wave (650GHz – 461 µm) planar near-field scanner was designated the NSI-905V-8x8 (2.4 m x 2.4 m) and has a planarity of 5 µm RMS. This scanner is shown in Fig. 1 and uses a granite base and tower for thermal stability and extensive air cooling over the vertical tower to minimize structural deformation due to ambient temperature variation. A subset of the scanner specifications are shown in Table I below.

TABLE I
NSI-905V-8X8 SPECIFICATION

Scan Area:	2.4 m x 2.4 m (8' x 8')
Planarity:	< 0.005 mm (0.0002") RMS
Resolution (x,y):	0.025 mm (0.001")
Scan Speed (x,y):	0.15 m/s (6 in/s) in x 0.38 m/s (15 in/s) in y

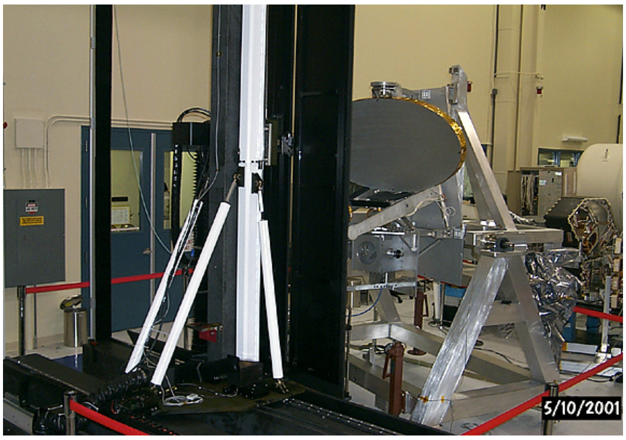

Fig. 1 NSI Planar near-field scanner model NSI-905V-8x8 shown with exposed granite base and tower.

The scanner construction consists of two parallel granite beams forming the X-axis with a vertical granite tower forming the Y-axis. This construction provides precise surfaces with low frequency spatial errors. The scanner also relies on separate probe, drive and counterweight carriages and an active thermal control system. The latter removes heat from the motors and RF up-converter.

The test setup used for 118 – 660 GHz testing is shown in Fig. 1 with the AUT visible. Test data taken at 660 GHz is shown in Fig. 2 with the reflector shape clearly identifiable.

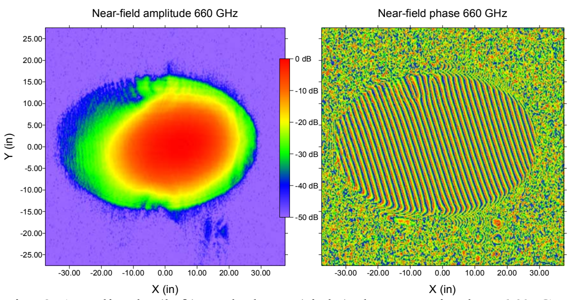

Fig. 2 Amplitude (left) and phase (right) data acquired at 660 GHz for test depicted in Fig. 1 with signal in lower right due to secondary spillover.

NSI's most recent sub-millimeter wave scanner was built in support of the Atacama Large Millimeter Array (ALMA) program at 950 GHz [5]. This sub-millimeter wave (950GHz – 316 µm) tiltable planar near-field scanner was designated the NSI-906HT-3x3 (0.9 m x 0.9 m) and has a planarity of 20 µm RMS in any scan plane orientation, from vertical to horizontal. This scanner is shown in Fig. 3 (attached to the AUT cryostat positioning fixture). A subset of the scanner specifications are shown in Table II below.

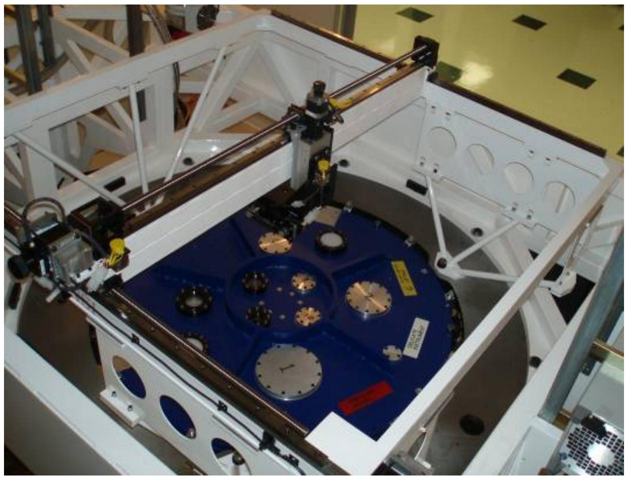

Fig. 3 NSI tiltable planar near-field scanner model NSI-906HT-3x3 built for testing ALMA receiver modules up to 950 GHz.

Table II
NSI-906HT-3x3 SPECIFICATION

Scan Area	0.9 m x 0.9 m (3' x 3')
Planarity	< 0.02 mm (0.0008") RMS
Resolution (x,y)	0.02 mm (0.0008")
Scan Speed (x,y)	0.1 m/s (3.9 in/s)

As part of this system development NSI employed active structure correction to enhance the scanner planarity. In this implementation no laser is being used for structure monitoring, but a predetermined structural data set is used for planarity correction during acquisition by using a z-directed linear actuator.

III. CORRECTION TECHNIQUES

A. RF Cable Flexure

It is well known that planar near-field measurements are impacted by flex cable induced amplitude and phase instabilities. In Fig. 4 a simplified block diagram is shown of the RF down conversion process, depicting the flex cable in the dashed box. In this system there is an RF source, an LO source and two mixers as shown. This diagram represents systems as used on many NSI planar near-field scanners and the antenna under test (AUT) (which in this case is the transmitter) is connected to an RF source that contains a frequency multiplier to provide the required RF signal. The LO source drives both test and reference mixers and is phase locked to the RF source. The fact that this cable is excited at a much lower LO frequency overcomes the cables loss (amplitude) concern but not the cable phase concern since LO phase variation is multiplied by the harmonic of the RF down conversion process.

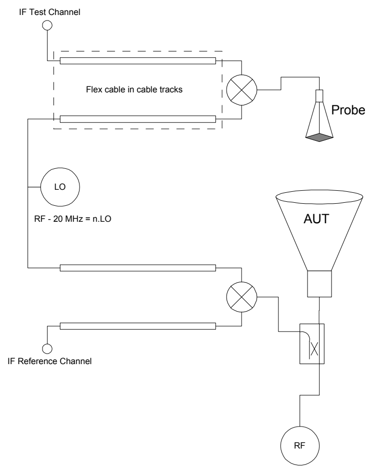

Fig. 4 Schematic diagram of the RF system and flex cables.

Different techniques have been employed to counter the flex cable problem. For the scanner described in [1], articulating arms consisting of rigid coaxial cables interconnected with RF rotary joints was used. These proved to be effective but expensive to manufacture and difficult to adjust and maintain. An alternative, but very costly approach is that described in [6]. This method employs a three cable technique allowing for the complete correction of the cable induced effect. A simpler hardware based method was described in [7] and also allows for the correction of the flex cable effect. However, with the improvement of coaxial cable technology and the proper handling of flex cables during scanning this risk can be mitigated to acceptable levels. In [8] NSI demonstrated a technique for the evaluation of these flex cable effects and assessment of their impact on measurement accuracy. This method relies on the measurement of cable amplitude and phase response as a function of scanner position and removing the cable effect from the measured radiation pattern data. This approach has allowed the use of flex coaxial cables on the scanners depicted in both Fig. 1 and Fig. 3 without resorting to any special compensation methods. For the NSI-905V-8x8 scanner, NSI demonstrated performance of about 8 µm equivalent RMS due to the flex cable phase effects.

B. Motion Tracking Interferometer

The Motion Tracking Interferometer technique [2] is based on periodically measuring the complex near-field signal level at 4 pre-defined locations in the scan plane (as depicted in Fig. 5). These data points provide a set of three dimensional references as a function of time and allow one to derive the motion between the scanner and test article via a least squares process. From this data AUT drift along the scanner Z-axis as well as rotation in azimuth and elevation can be detected and corrected for. Fig. 6 shows a 640 GHz far-field result after MTI correction. Phase error during measurement leads to an error level of about -45 dB effect on the AUT main beam that is suppressed by MTI.

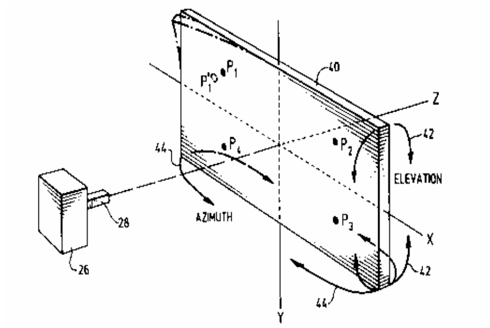

Fig. 5 Motion Tracking Interferometer (MTI) measures time varying azimuth, elevation, and Z-motion between AUT and scan plane. MTI measurements are made at 4 spatial points in a higher energy radiation region.

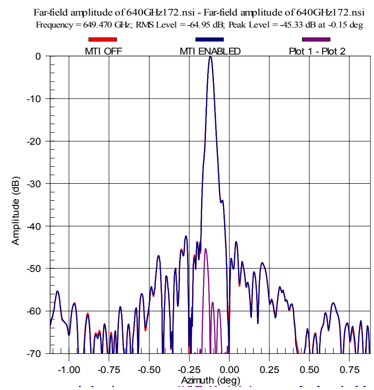

Fig. 6 Far-field result before and after MTI correction with an error level of about -45 dB that is suppressed by MTI.

C. Structure Correction

The purpose of active structure correction is to enhance scanner axis straightness, orthogonality and scan plane planarity [4]. For most sub-millimeter wave scanners it is planarity that is of most concern. In the implementation an optical recording of the scanner physical behaviour is made through the use of a spinning laser and detector, a theodolite or a laser tracker. This data is then used to compensate for any imperfection through real-time linear actuators during data acquisition. Measured scanner planarity for the NSI-906HT-3x3 scanner at a tilt angle of 45° shows a peak to peak variation of roughly 2 mm. The corrected planarity after enabling active structure correction reduces this number to roughly 0.02 mm [5].

D. Probe Translation Correction

It is common practice to use a single linearly polarized near-field probe for planar near-field testing of antennas of arbitrary polarization. During such an acquisition two orthogonally polarized data sets are measured. In keeping with the original near-field formulation that requires the use of two distinct probes, this is achieved by simple polarization rotation of a single probe. These two orthogonal data sets are then independently processed to obtain probe corrected far-field radiation pattern information and can be combined to constitute slant linear or circular polarization, depending on the polarization definition required [9]. This polarization processing assumes only rotation of the probe and any translation (which is due to mechanical misalignment of the probe z-axis with respect to the axis of rotation) is usually neglected. For most low frequency applications this is a reasonable assumption. However, for high frequency applications the physical size of the probe makes mechanical alignment more challenging and when that probe is attached to a bulky mm-wave RF module, the alignment of the entire assembly becomes challenging. A typical mm-wave probe and associated waveguide components are shown in Fig. 7.

Fig. 7 Typical near-field probe mm-wave hardware and fixturing mounted on a planar near-field scanner.

Fig. 8 depicts the typical probe translation observed during rotation from polarization position #1 (Pol = 0°) to polarization position #2 (Pol = 90°), where the axis of rotation is the *z*-axis. Measurement of the depicted offset distances allows for compensation of the probe translation as described in [9].

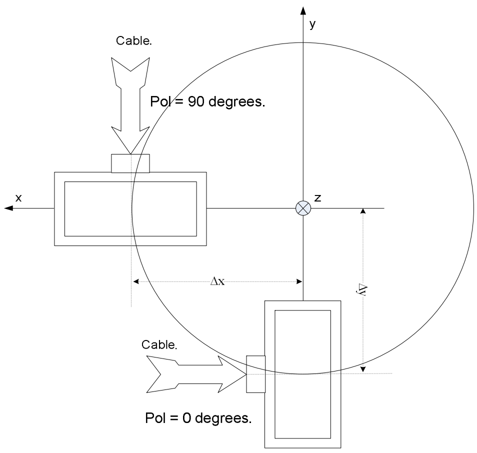

Fig. 8 Probe translation from Pol = 0˚ position to Pol = 90˚ position.

In Fig. 9 the measured near-field intensity is shown for a circularly polarized (CP) horn antenna, measured with a linearly polarized (LP) open ended waveguide probe at 94 GHz. In this instance Δx and Δy were measured mechanically and determined to be Δx = 4mm (1.25λ) and Δy = -4.5mm (1.4λ) respectively. Compensating for this probe translation distance one obtains the far-field result depicted in Fig. 10. Fig. 10 also shows a reference pattern, where < 1 mm probe translation was present during polarization rotation. It is clear in this comparison what the impact of the correction is and that the reference pattern can be recovered with reasonable fidelity.

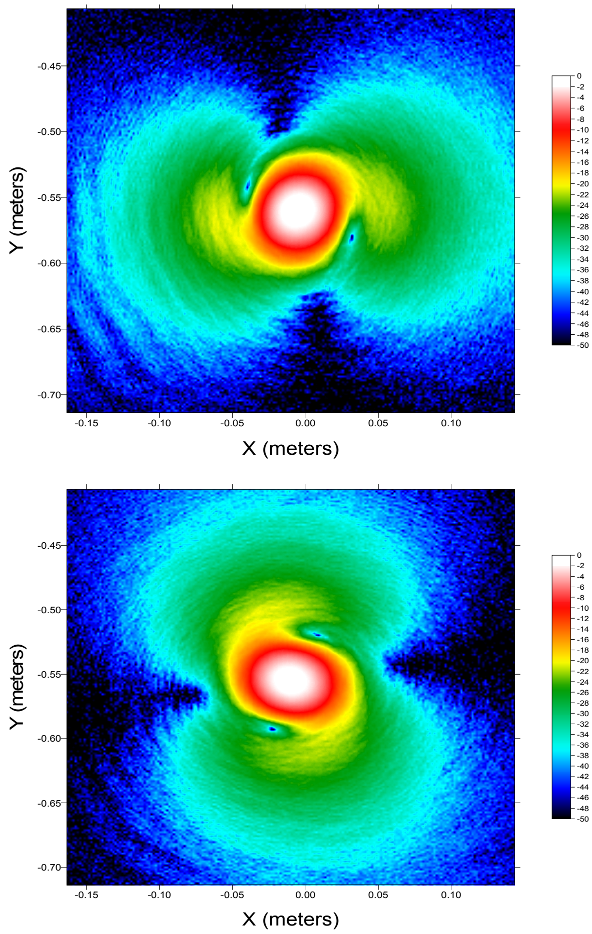

Fig. 9 Near-field intensity for CP antenna measured with LP probe. T = 4mm (x) – 4.5mm (y). Dynamic range shown is 50 dB.

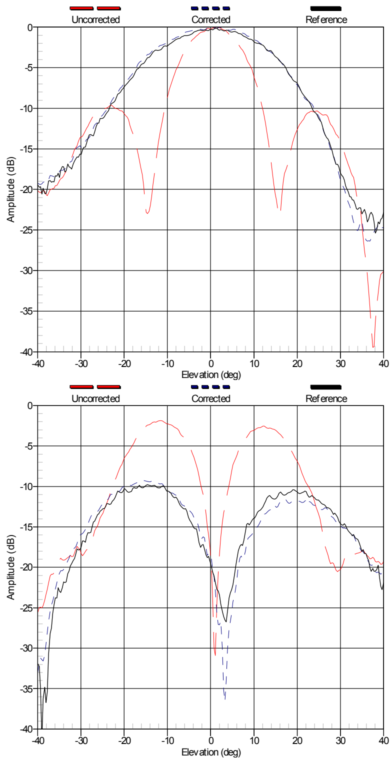

Fig. 10 Elevation plane co-polarized (top) and cross-polarized (bottom) patterns for 94 GHz CP horn. Original uncorrected data (red), corrected (blue) and reference data (purple). T = 4mm (x) – 4.5mm (y).

IV. Conclusion

This paper provides an overview of sub-millimeter wave planar near-field scanners that have been built and are being used in industry today. The system examples shown here are believed to be the highest frequency near-field test systems that have been built to date. We also provide a brief overview of some of the key correction techniques that have been developed to overcome the effects of RF cable phase variation, thermally induced structural drift, scanner planarity imperfections and probe translation effects during polarization rotation. These techniques collectively, have made the implementation of the mentioned systems possible. These techniques have also developed planar near-field technology as applied to lower frequency applications and have made commercial near-field test systems in the V and W-bands common place.

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