Millimeter Wave Near-Field Antenna Testing

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Abstract

This paper provides an overview of antenna test systems that operate in the millimeter and sub-millimeter wave bands. Techniques that have been developed to overcome technical restrictions that usually limit performance at very high RF frequencies are presented. Aspects such as 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 test systems operating from 50 GHz up to 950 GHz.

I. Introduction

Since the introduction of commercial near-field antenna test systems in the 1980s, 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 test systems and highlights the techniques employed to overcome such limitations.

Millimeter and sub-millimeter wave technology developments are most often employed for electrically large antenna aperture, therefore qualifying as high gain test cases. This makes them ideally suited for planar near-field testing. This type of test 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. I 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, I 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 large scanners, can be employed to achieve the planarity required at these high frequencies.

A fourth 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. Section III describes some of the techniques developed to overcome the technological limitations mentioned before, enabling these systems.

Since there is also an emergence of lower gain antennas operating in the millimeter wave bands, a need exists for spherical near-field testing at these frequencies. Section IV of this paper describes a small SNF test system allowing for testing at these high frequencies.
developed to address the critical alignment required for SNF testing at these frequencies.

II. Millimeter Wave Planar Near-Field Scanners
Nearfield Systems, Inc. (NSI) provided the first sub-millimeter wave (550 GHz – 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 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.

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.

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 Figure 1 (attached to the AUT cryostat positioning fixture). A subset of the scanner specifications are shown in Table 1.

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. Planar 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 Figure 2, 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.

Different techniques have been employed to coun-
ter 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 scanner depicted in Figure 1 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 predefined locations in the scan plane (as depicted in Figure 3). 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. Figure 4 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.

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 behavior 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 Figure 5.

If the typical probe translation observed during rotation from polarization position #1 (Pol = 0°) to polarization position #2 (Pol = 90°) for a near-field probe is considered, measurement of this offset distance allows for compensation of the probe translation as described in [9]. In Figure 6, 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 (probe translation vector components) 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 Figure 7. Figure 7 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.

IV. Millimeter Wave Spherical Near-Field Scanners
NSI provided the first millimeter wave (67GHz – 4.5 mm) spherical near-field scanner in 2010. This scanner is based on the NSI-700S-30 and successful operation at this frequency requires mechanical precision, a high degree of alignment accuracy, and proper RF sub-system design. Since propagation loss at 67 GHz exceeds 60 dB for distances further than 1 m,
a near-field antenna test range is a viable alternative to the more traditional far-field ranges. However, the requirement for phase acquisition makes this a more challenging proposition. In Figure 8 and Figure 9 far-field test data is shown for a WR15 standard gain horn acquired using this test facility. Three radiation patterns are shown overlaid. They are: a computed pattern, a finite range pattern (traditional far-field measurement), and a SNF range pattern. The comparisons clearly show the success of the SNF test technique in this instance and also demonstrate how the finite range length limitation is overcome.

V. Spherical Correction Techniques
A. Coordinate System Alignment
NSI uses mechanical alignment techniques for the alignment of SNF test systems. However, these techniques are limited by the resolution of the optical tooling used. This limitation lead to the development of electrical alignment techniques that can enhance the accuracy of the SNF alignment process. The automation of this process is described in [11] and it also allows for the correction of certain alignment errors and to assess their impact. Figure 10 shows an omni-directional antenna measured on a SNF range that suffered a 0.04 $\lambda$ axis non-intersection error. The two radiation patterns show the measured result before and after correction. (The inset shows the upper portion of the pattern magnified). The success of the axis non-intersection (which at 67 GHz is 0.18 mm and hard to correct for mechanically) correction is evident.

This correction technique is critical to the success of SNF test system implementation at millimeter wave frequencies.

VI. Conclusion
This paper provides an overview of millimeter wave 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. I also provide a brief overview of some of the key planar near-field 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. The spherical near-field test system described in this paper represents a unique millimeter wave test facility. The automated alignment technique developed by NSI is crucial to the implementation of such a system.

The corrective techniques collectively have made the implementation of the mentioned systems possible. These techniques have also developed near-field test technology as applied to lower frequency applications and have made commercial near-field test systems in
the V and W-bands common place. To date, NSI has delivered more than 25 millimeter wave antenna test systems worldwide.

References