DEVELOPMENT OF A SPHERICAL NEAR FIELD MEASUREMENT SYSTEM FOR PHASED ARRAY ANTENNAS

D.J. Mistry, J.P. Szczepanik, E. Phillips, R. Kalra

Phasor Solutions, The Record Hall, 16 Baldwin Gardens, London, EC1N 7RJ

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ABSTRACT

Near-Field measurement of antenna patterns has gained popularity over the last few decades. This is due to its ability to provide excellent measurement accuracy in controlled lab conditions, without the complexities of testing in an outdoor range. A common application for this technique is the calibration and measurement of phased array antennas in the far-field. After array calibration the phased array antenna will beam-form a radiation pattern in the desired direction across a range of operating conditions.

Phasor have spent the last few years developing their own in-house Spherical Near Field (SNF) measurement system, which is capable of characterising the next generation of phased array antennas. The purpose of this paper is to outline the key features of Phasor's SNF measurement system and discuss its capabilities in measuring phased array antenna performance.

Introduction

Specifications for microwave antennas continue to be become more challenging due to new end user requirements, and in the case of phased array antennas, improvements in the underlying architecture. These factors drive the demand for precision measurement and characterisation. As a result, the domain of antenna measurement continues to attract considerable interest and investment to meet these new challenges.

Antenna measurements aim to probe the electromagnetic (EM) field distribution around an antenna. This is a function of both the distance from the antenna and the angular position at which the field is observed. The EM field around an antenna is normally divided into three regions; Reactive Near-Field (NF), Radiating Near Field and Far-Field (FF).

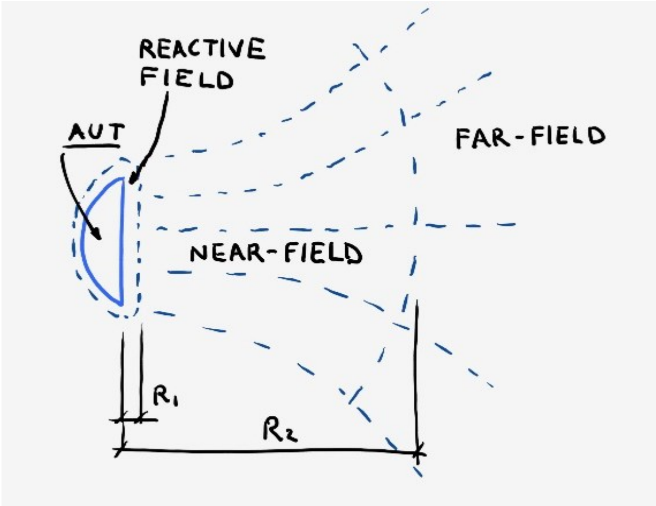

Figure 1. Illustration of the field regions surrounding an antenna.

As a general rule of thumb, the FF is defined as a distance greater than $2D^2/\lambda$. Any distance smaller than this is considered to be near field. Where D is the maximum dimension of the Antenna Under Test (AUT) and λ is the wavelength of the radiated EM field.

From Fig. 1 it is clear that the measurement technique is dependent on the field region in which the antenna is measured. In most cases the far-field characteristics of an antenna are of prime importance, as most antennas are operated in this region. Testing in the FF involves a number of difficulties due to the infrastructure costs required to achieve a good accuracy at large distances [1]. For example, an 80cm x 80cm array antenna at Ku-band, assuming 14GHz, would require a test range of ~ 121.6m in length.

NF measurement of an AUT is commonly used to overcome the aforementioned challenges of testing in the far-field. From this data the FF beam parameters can be inferred using mathematical methods which have been developed to convert the measured NF data to the FF. The nature of the mathematical transform depends on the type of near field measurement system - which are aptly named by the coordinate systems used i.e. planar, cylindrical and spherical.

This paper will focus on the Spherical Near Field (SNF) measurement system, which offers a number of benefits over the other system implementations, see Fig. 2.

1. Convenient Co-ordinate System

- Radiation patterns are measured in the spherical coordinate system which is identical to that used to describe FF characteristics.
- In the near-field the far-field set-up has been collapsed to a shorter distance from the AUT.

2. Accurate Gain Measurement

- The mathematical transform for SNF measurement directly produces the AUT directivity, which is useful for accurately determining the gain of antenna, providing the ohmic losses are known.
- Alternatively, the AUT gain can be determined using a substitution method with a standard gain horn.

3. Flexibility in Mechanical Design

- SNF systems can be configured in a number of different mechanical implementations, depending on the movement of the AUT or probe, either independently or together.

4. No errors due to Field Truncation

- The measurement surface is a sphere, so is not limited by truncation errors like a planar system, due to only sampling the radiation pattern over a small angular region.

5. Ability to measure different beam sizes

- SNF measurement is able to measure a range of beam sizes, including narrow beam (i.e. large aperture) or broad beam antennas.

Figure 2. The benefits of Spherical Near Field Measurement over other near field measurement techniques [2].

Spherical Near Field Measurement

The purpose of a SNF measurement system is to sample the tangential electric field components, denoted E_ϑ and E_φ, on a spherical surface around the AUT in a spherical polar coordinate system. A general requirement is that the angular increments of measurement points in the theta and phi directions are equal.

This field distribution can be represented by a spherical wave expansion (SWE) which is a unique solution to Maxwell's equations, that describes the EM fields as a summation of modes and coefficients [3]. The SWE is based on three assumptions; the whole AUT is contained within a minimum sphere, there are no RF sources outside this sphere and the sphere is centred on the origin of the SNF coordinate system.

The radius of this sphere is determined by the largest distance from the centre of the coordinate system required to enclose the whole AUT. It is best practice to locate the AUT as close to the origin of the coordinate system as possible to reduce the radius of the minimum sphere, and to simplify geometrical referencing on the AUT aperture.

The SWE of a radiating field can be described using up to an infinite number of modes at the expense of increasing computational time. However, by truncating the number of modes (N) using the rule of thumb represented by Eq. 1, it is possible to determine the SWE using the minimum number of polar modes.

$$N = \frac{2\pi}{\lambda} r_0 + n_1 \qquad \text{[Eq. 1]}$$

Where, λ is the wavelength of the AUT, r_0 is the radius of the minimum sphere and n_1 is an additional term which depends on r_0, in the case that the AUT is well centred in the coordinate system n_1 is equal to 10 [2].

In summary, the measurement of two orthogonal E-field components (E_ϑ and E_φ) over a spherical surface circumscribing the AUT in the near-field can be used to determine all antenna beam parameters related to its FF field distribution. By using a Fourier Transform the field anywhere outside the measurement sphere can be determined using the SWE. It is also possible to use a 2D Fourier Transform to back project the E-fields in the FF to the surface of the array aperture to visualise the amplitude and phase distribution. This technique is known as Microwave Holographic Imaging (MHM) and is a useful tool in phased array antenna calibration.

A number of practical aspects need to be addressed to achieve the accuracy required to sample these complex radiation fields around an AUT, see below.

1. **Measurement probe**
   The probe must be able to transmit/receive over the desired frequency range for two orthogonal polarisations. In the case that the probe is linearly polarised, it will need to be rotated to acquire the orthogonal polarisation in a separate measurement.

   Probe directivity is of particular interest as this can be used to suppress signals from outside the test zone and receive stronger signals from the AUT. It is also important to have the probe calibrated to determine the radiation and polarisation pattern which can be used to apply probe correction during the NF-FF transform.

2. **Mechanical System**
   The geometry of the mechanical system needs to allow for measurement over the spherical surface with accurate positioning at the desired angular resolution. Depending on the mechanical design of the system there will be a number of moving stages which will need to be controlled by software and used to trigger measurement equipment. The size of the AUT and the operating frequency will determine the number of measurement points required in the NF, so scan speed is important to reduce measurement time.

   Prior to measurement the SNF measurement system must be aligned so that the theta and phi axes intersect at right angles, and to ensure that their intersection point is the centre of the measurement sphere. The probe must also be pointing to the centre of the measurement sphere when the AUT is pointing boresight.

3. **RF Sub-System**
   The RF sub-system includes the components/equipment required to power the AUT and those required to measure the signal from the probe. The time required for a complete scan of the E-fields over the spherical surface could vary from minutes to days depending on the number of sample points and measurement speed. As such the RF sub-system needs to exhibit good amplitude/phase stability and have fixed electrical lengths.

System Development

This section outlines the key design features of the system and the steps taken to benchmark its performance.

System Requirements

1. A mechanical configuration which enables repeatable and accurate positioning of the probe circumscribing a number of measurement points on a sphere around an AUT.
2. The ability to manually adjust all moving stages to perform an alignment of the scanner system prior to measurement.
3. Measurement equipment triggered by turntable stages to enable data acquisition of the complex orthogonal E-fields.
4. A flexible set-up to enable easy access to change the AUT and feed in the appropriate interconnects for different AUT configurations.
5. Software to acquire data, perform NF-FF transformations, and data processing.

Mechanical Design

Phasor's approach utilises a 'Theta-Phi' configuration [4], whereby the probe moves in the theta direction and the AUT rotates about the phi direction, see Fig. 3. In this way the theta and phi axes are independent and therefore don't exhibit Euler Lock. Due to the size of the arch which the probe moves along an additional 'z-stage' was added to ensure that the radius through which the probe moves is fixed with respect to the origin of the coordinate system.

The size of the turntable and arch were determined by the maximum AUT size which could be up to (800mm x 1100mm). A small hole was left in the turntable to act as a cable conduit for interconnects required by the various AUT's. The interior of the chamber was lined with metallic sheets and any gaps between the sheets were lined with copper tape. These sheets were lined with radiation absorbent material (RAM) to minimise and attenuate RF reflections inside the chamber.

A number of additional features were added to the SNF measurement system to improve monitoring and diagnostics. To maintain a stable ambient temperature inside the chamber an exhaust fan was installed in the chamber. At a later stage a webcam was installed to monitor the system remotely during scanning, and LED strip lighting was placed within the RAM to illuminate the chamber. The low profile of the LED lighting coupled with the DC power supply meant there were no measured adverse effects on RF measurement capability.

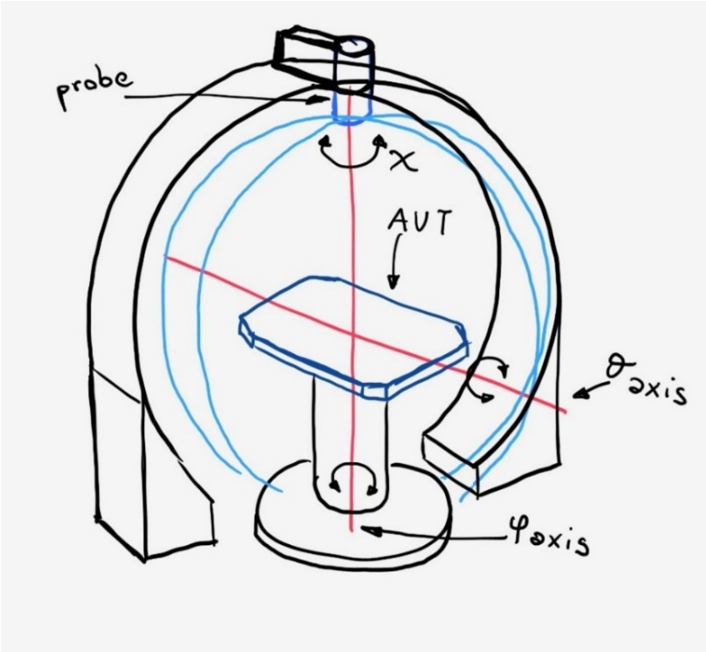

Figure 3. The mechanical design concept for the Phasor SNF measurement system.

The current method of scanning the measurement sphere involves rotating the turntable stage (phi) between 0 – 180°, and then acquiring a theta cut between +/-90°. For early testing the measurement speed was limited to verify performance and operation of the motorised control system. During development a robust fixture was designed to hold the measurement probe to a carriage on the arch which moves in the theta direction using a rack and pinion gear mechanism. This ensures that the probe stays in a fixed angular position during scanning and can only be moved by the z-stage.

An important step in the mechanical design of the system is that of alignment. This is normally achieved using a theodolite or laser tracking system to align the various moving stages prior to measurement. Phasor have used a laser tracker to align the measurement system using a number of reflector mirrors positioned on key features of the system, namely the probe and turntable Fig. 4. By taking a number of standard measurements and processing the data in MATLAB an alignment procedure has been developed. This generates a set of alignment instructions which are carried out manually on each of the moving stages to align the system. After any major change is made to the system, such as mechanical modification or a new AUT install the alignment process is repeated.

RF Design

A dual polarised OEWG (Open Ended Wave Guide) probe is used which has > 30dB isolation between the measurement ports. The probe has three interchangeable apertures which can be used to adjust the frequency range and directivity depending on the AUT. This set-up reduces the test time two-fold as both E-field polarisations can be measured simultaneously.

A consequence of this mechanical design choice is that signals from the probe are carried through cables in an e-chain which move during scanning. This places a stringent requirement on the RF cable phase stability due to constant flexure during scanning. To assess the phase stability of the cables, tests were performed by measuring the S21 and S11 parameters with a short on the cables after traversing many cycle of the arch between +/ 90°. This was found to be a useful test to verify the performance of the cables over operating life.

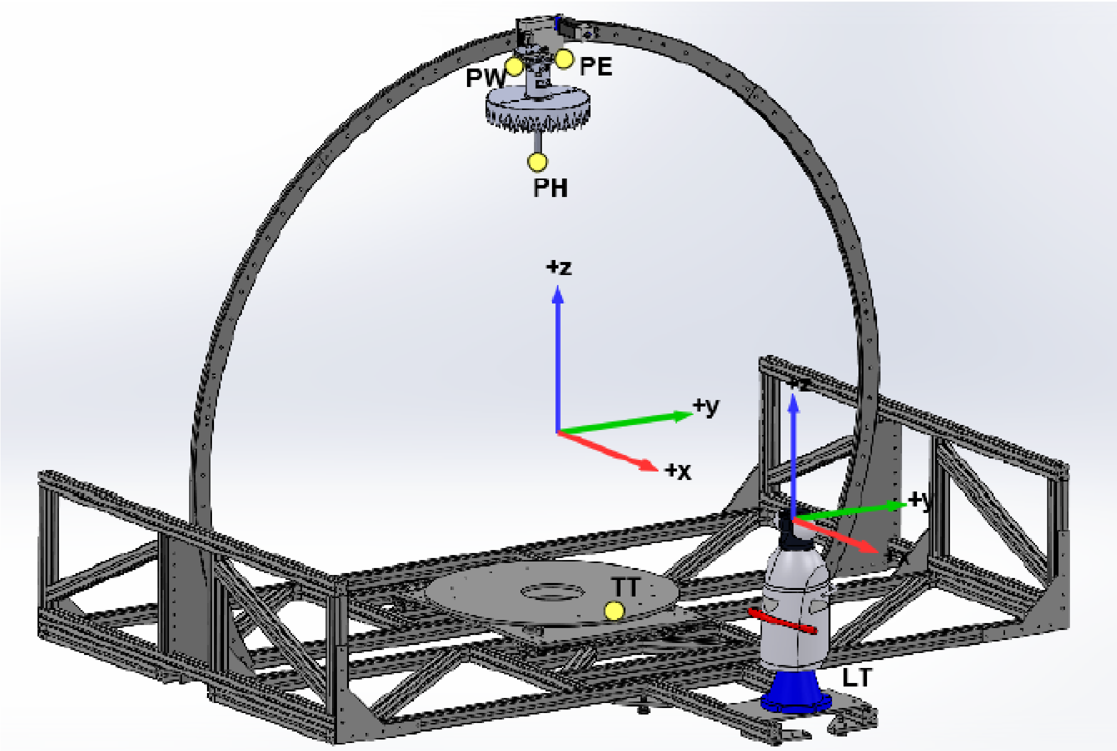

Figure 4. Phasor's SNF measurement system and coordinate system. Yellow circles denote the positions for prism ball reflectors for laser alignment measurements. Note: LT denotes the Laser Tracker, PH, PE, PW stand for Probe Head, Probe East and Probe West respectively.

The cables from the e-chain connect to a 4-port VNA located outside the test system. Although the e-chain RF cables are phase matched, it is important to note that other components in the RF chain can introduce differences in electrical length. These effects need to be accounted for during data processing to eliminate phase errors.

All test equipment is located in an external rack, and depending on the AUT the appropriate signals are fed under the chamber via a hole in the turntable. The door to the chamber is lined with RF absorbing strips to prevent leakage from the door. The probe has its own RAM assembly which eliminates unwanted RF reflections. Similarly, the AUT is lined with a bespoke RAM layering, however care has to be taken to ensure that the RAM does not inhibit the probe at large theta angles.

Data Collection and Processing

The Phasor system has been developed around in-house software which can be used to acquire amplitude and phase data from a 4-port VNA configuration over the measurement sphere. The VNA is triggered by the motion controllers and the data is stored in a text file for processing. Most of the data processing is carried out in MATLAB, with the exception of the NF-FF transform which is performed using SNIFT software developed by TICRA.

Standard Gain Horn Measurement

A standard gain horn was used to benchmark the system. This is standard practice as it allows the user to compare the FF performance to known values measured by the manufacturer.

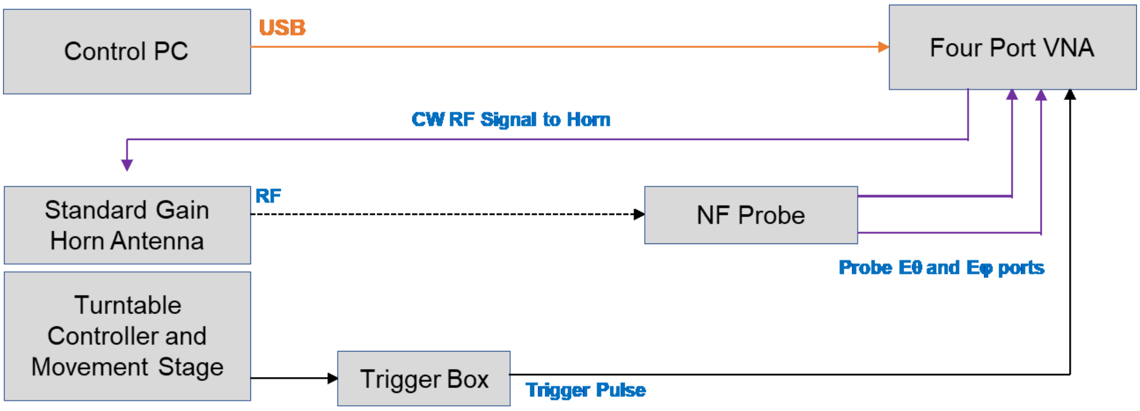

Figure 5. Experimental set-up for standard gain horn measurement in SNF measurement system.

The FF characteristics were determined using the steps outlined previously and the beam parameters were found to be in good agreement with a HFSS simulation of the standard gain horn, see Fig. 6.

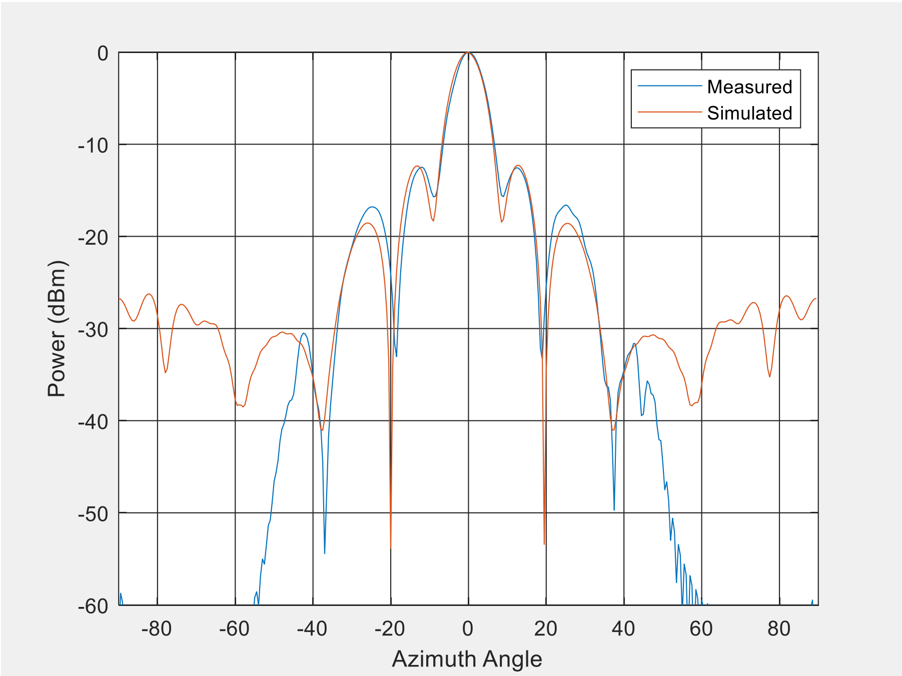

Figure 6. FF radiation patterns of a standard gain horn at 14GHz showing the H-plane cut.

Measurement Capability

The Phasor SNF measurement system is used to calibrate and measure the FF performance of phased array antennas manufactured by Phasor. Array calibration is an important process for phased array antennas to ensure that each element is transmitting the corrected power and phase to form a beam at a desired distance from the array [5].

Preliminary testing was performed with transmit (Tx) antennas of a small aperture (15 x 28cm) with 612 active elements. After developing the calibration process the antenna was measured at several different frequencies across the Ku-band (14 – 14.5GHz) to determine the FF performance. To determine the accuracy of the measured FF pattern a comparison was made with respect to simulated data of the AUT. This highlighted a good agreement in 3dB beam width, sidelobe level and directivity.

With the current system architecture, the following measurements are now possible:

- Near-field measurement of E_ϑ and E_φ field components
- Data Processing and computation of FF beam parameters
- Microwave holographic imaging of the AUT. This is particularly helpful in diagnosing errors with particular elements in the phased array. In this process the FF radiation pattern is back projected to the array aperture, which is assumed to be at the origin of the SNF coordinate system using a Fourier Transform, see Fig. 7.

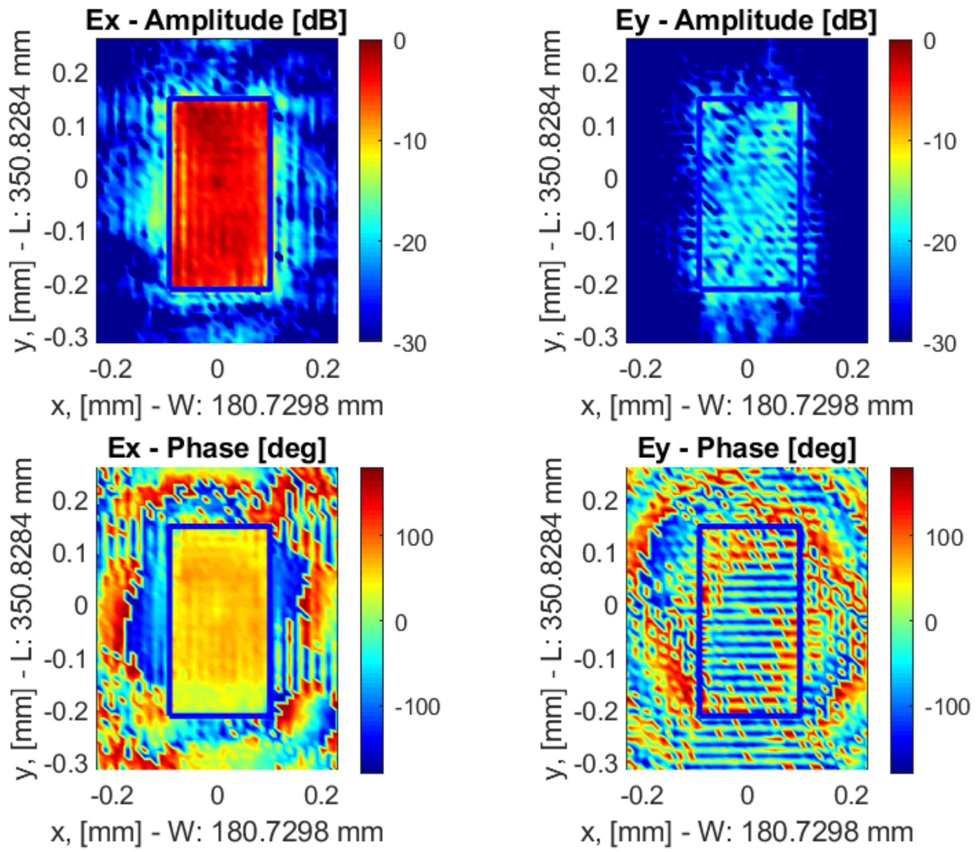

Figure 7. A hologram plot of Phasor Tx module with 612 elements showing the co (Ex) and cross-polar (Ey) amplitude and phase patterns over the array aperture.

Conclusions

Spherical Near Field measurement is a useful tool for characterising the performance of phased array antennas. The complexity of the measurement system demands precision and reliability across several disciplines of engineering to achieve the desired performance.

Phasor's system has been in development over a number of years and its performance has been benchmarked using a standard gain horn. At present various phased array antennas have been characterised with promising results. In the future this system will be used as a standard production test platform for the next generation of phased array antennas produced by Phasor.

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