SPHERICAL NEAR-FIELD ANTENNA MEASUREMENTS: A REVIEW OF CORRECTION TECHNIQUES

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Abstract

Following an introductory review of spherical near-field scanning measurements, with emphasis on the general applicability of the technique, we present a survey of the various methods to improve measurement accuracy by correcting the acquired data before performing the transform and by special processing of the resulting data following the transform. A post-processing technique recently receiving additional attention is the ***IsoFilter***™ technique that assists in suppressing extraneous stray signals due to scattering from antenna range apparatus.

Keywords: Antenna Measurements, Spherical Near-Field Measurements, Microwave Antenna Measurements

1. Introduction

The theory of spherical near-field (SNF) scanning was developed in the 1970's following the very successful development of planar near-field scanning. [1], [2], [3] A key milestone of the planar near-field (PNF) era was the invention by David Kerns of the scattering-matrix theory of antennas from which the PNF transmission equation derives. [4], [5] Following the practice pioneered for planar near-field scanning, the spherical technique was developed to include correction for the directivity pattern of the probe antenna. Once the SNF transmission equation was derived, various algorithms were investigated for carrying out the spherical near-field to far-field (NFFF) transform, before the algorithm of Wacker was accepted as optimum. [2], [5] It came to be understood and accepted that the SNF transmission equation can accomodate correction for the probe pattern, provided the modal content of the probe pattern has only modes with azimuthal indices of $\mu = \pm 1$. Because of the complexity of the spherical NFFF algorithm and the challenge it offered to the computation hardware, SNF scanning was later than PNF scanning to see deployment in applications.

Each of the three NFFF transmission equations, cast in Cartesian, cylindrical and spherical coordinates respectively, is based upon fundamental assumptions that make near-field scanning techniques applicable to almost all antennas:

1. Linearity of Antenna's Transmit and Receive Functions
2. Free Space Conditions and Linearity of the Constituitive Parameters that Characterize the Propagation Medium
3. Absence of Any Probe-to-Test-Antenna Multiple-Pass Standing Wave
4. Availabilty of a Suitable Probe Antenna and Complete Knowledge of Probe Characteristic
5. Availability of Perfectly Accurate Positioning and RF Subsystems Measurement Hardware

The one difference that sets spherical near-field scanning apart from planar and cylindrical is its scanning surface does not necessarily have to be truncated. This makes spherical scanning the method of choice for broad-beam antennas with low directivity. The SNF transmission equation is given by the expression: [6]

$$\frac{w'(r_0;\varphi_0,\theta_0,\chi_0)}{v} = \sum_{s\mu mn} \sum_{\sigma\nu} R'_{\sigma\mu\nu} \mathcal{C}^{sn}_{\sigma\mu\nu}(kr_0\hat{z}) \mathcal{D}^{(n)}_{\mu m}(\varphi_0,\theta_0,\chi_0) T_{smn} \tag{1}$$

Here T_{smn} is the scattering matrix coefficient corresponding to the antenna transmitting characteristic for mode s,m,n and $R'_{\sigma\mu\nu}$ is the scattering matrix coefficient corresponding to the probe's receiving characteristic for mode σ,μ,ν. The quantity w' is the received voltage at the port of the probe and v is the voltage of the incident wave at the port of the transmitting test antenna. The quantities $\mathcal{D}^{(n)}_{\mu m}(\phi_0,\theta_0,\chi_0)$ are the rotation matrix elements for vector spherical modes parameterized by Euler angles ϕ_0, θ_0, χ_0; the $\mathcal{C}^{sn}_{\sigma\mu\nu}(kr_0\hat{z})$ are translation matrix elements for vector spherical modes parameterized by k and r_0, where $k = 2\pi/\lambda$. The Euler parameters θ_0 and ϕ_0 turn out to be angles which specify the position of the probe on the measurement scanning sphere, and χ_0 specifies polarization orientation of the probe antenna.

The scattering matrix description of an antenna -- the mathematical approach used in near-field scanning theory to characterize an antenna – is summarized in the basic scattering matrix equation for spherical modes

$$\begin{bmatrix} b_{0'} \\ b_{s'm'n'} \end{bmatrix} = \begin{bmatrix} \Gamma_{0',0} & R_{0,smn} \\ T_{s'm'n',0} & S_{s'm'n',smn} \end{bmatrix} \begin{bmatrix} a_0 \\ a_{smn} \end{bmatrix} \tag{2}$$

where the subscript *0* indicates a quantity pertaining to the single propagating mode of the antenna's port transmission line and the subscripts *s,m,n* indicate a quantity pertaining to spherical mode with index labels *s,m,n.* The individual submatrices within the scattering matrix are identified as follows:

Input Excitation Modal Amplitudes	Scattering Matrix Coefficients	Outgoing Response Modal Amplitudes
a_0 ↔ Port	$R_{0,smn}$ = Receiving Characteristic	b_0 ↔ Port
a_{smn} ↔ Free Space	$T_{s'm'n',0}$ = Transmitting Characteristic	$b_{s'm'n'}$ ↔ Free Space
	$\Gamma_{0,0}$ = Port Reflection Characteristic	
	$S_{s'm'n',smn,}$ = Free-Space Scattering	

Both the probe and the antenna under test are modeled by a scattering matrix. [6] The great advantage of this approach is its generality, as no detailed knowledge of the radiation mechanism is required or assumed.

The process for conducting a spherical near-field antenna measurement and determining the far-field pattern can be described in three steps: (1) Data Acquisition (2) Determination of the AUT Coefficients and (3) Computuation of the Far Field. In a preliminary step, the probe must be calibrated. The basic schematic of a spherical near-field measurement and of a SNF scanning range are shown in Figs. 1 & 2.

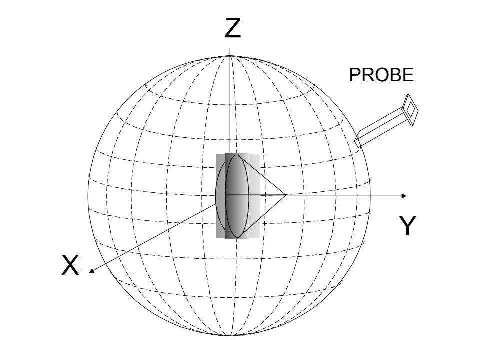

Fig. 1. Schematic – Spherical Near-Field Scanning

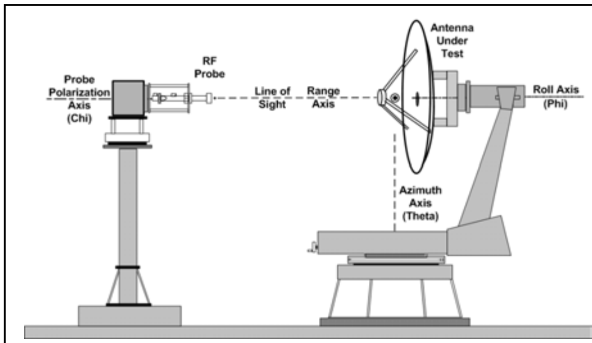

Fig. 2. Roll-Over-Azimuth Spherical Near-Field Range

2. Implementation of SNF Scanning

The fundamental advantage of spherical near-field scanning over other near-field techniques is that it can be applied to the measurement of any antenna – whether directive or nondirective. It does not require that the scan surface be truncated -- an essential consideration when measuring simple very broad-beam patterns. SNF scanning ranges can be thought of as far-field scanning ranges reduced down to short range lengths, ignoring the usual $2D^2/\lambda$ far-field criterion. The spherical NFFF transform is then simply a post-acquisition signal processing step that corrects for the insufficient range length. SNF processing further enables moving line-of-sight SNF ranges to be practical. Line-of-sight ranges were of only limited use for far-field measurements.

Depending upon the requirements of a particular antenna measurement, spherical near-field ranges take different forms. Simple roll-over-azimuth configurations are the most common. Please see Fig. 2. But, elevation-over-azimuth and azimuth-over-elevation configurations are often chosen for their individual advantages. In recent years we have seen the spherical arch employed to permit almost complete spherical coverage over both a wide band of frequencies and a wide variety of antennas. Spherical near-field scanning has also been employed on antenna ranges for measuring vehicle- mounted antennas, either with an arch or with a gantry, above an azimuth turntable. Please see Fig.3. The major issues that one confronts in constructing a SNF range are (1) how to correct for acknowledged imperfections in range hardware and (2) how to increase the speed of data acquisition and range throughput. Here in this paper we address methods of correction of the raw spherical near-field data.

3. The Classical Corrections for Imperfect Data

The correction of acquired data for known and recognizable imperfections in the antenna range and range equipment has been an integral part of near-field antenna metrology since the early days. Here I describe the classical corrections.

Correction for the Directivity Pattern of the Probe -- Modeled Probe Patterns and Measured Probe Patterns

Ever since Kerns first published a means by which it can be carried out for planar near-field scanning; inclusion of this feature has been a criterion of acceptability for any near-field scanning scheme since the 1970's. There are two approaches to ascertaining knowledge of the probe pattern -- (1) pattern data from measurement of the probe antenna on an antenna range [7] and (2) modeled pattern data derived from knowledge of the mechanical dimensions of the probe structure. [8] In general, it is only measured data that satisfies the most critical needs for accuracy, especially for cross-polar fields.

Correction for Amplitude and Phase Non-Linearity in the Measurement Receiver

The recorded data deriving from a microwave receiver can possess small errors due to amplitude and/or phase non-linearities; these effects may be removed from the measured data by use of a calibration table derived from comparison of the receiver readings to a measurement standard such as a standard attenuator.

Thermal Drift Correction

RF components and cable characteristics can drift over the lengthy time interval that a data acquisition process may take. Data taken at widely separated moments in time can be discrepant when compared to data taken close together in time. To correct for this, successive return-to-point (RTP) measurements are used; whereby the effects of thermal drift are measured and removed from individual data points. From a comparison of successive measurements, the corresponding linearized thermal drift correction factors are developed and each scan of the data raster is modified appropriately. [9] Alternatively, tie scans along the step axis can be used for correction.

Correction for Impedance Mismatches in the Gain Calibration Procedure

Correction for impedance mismatch in making gain measurements is often required to achieve acceptable accuracy. The procedure for determination of gain measures the insertion loss of the range by a two-step procedure. The first step requires measurements of the signal at the port of the probe due to the field of the AUT. The second step is a measurement of the input signal at the port of the AUT offered by the signal source. Here the probe and AUT are "by passed" and the range is "short circuited" with a known cable and/or an auxiliary attenuator.

Impedance mismatch correction entails using measured complex impedance values to correct for the effect of impedance mismatch in each of these connections. [5], [6]

Channel Balance Correction

When the two ports of a dual-ported probe are connected through different cables to a two-ported receiver, there will be a small offset in the receiver readings due to differences in the two paths. This imbalance can be corrected for by use of data taken in a simple channel-balance calibration procedure. It consists of rotating a known antenna in front of the probe horn to co-polarize it successively to each of the two probe ports, and storing the correction factors as a function of frequency. The correction is applied prior to the transform. [9]

Correction for Probe-to-Test-Antenna Standing Wave

Analysis and measurement experience have shown that the presence of a multiple-pass standing wave between the probe antenna and the test antenna can easily exist and perturb the near-field data. Often its effect is a function of location of a grid point within the scan. The effect of such a standing wave cannot be removed by use of a mathematical model. The only effective way to eliminate it is to make multiple measurements at several distances a few fractions of a wavelength apart and then to average the results. [10] Provision for taking these averages of the far-field patterns is a feature usually included in near-field software.

Correction for Cable Motion -- Shorted Cable Method, Pilot-Signal Method, Three-Cable Method

Correction for the variations in received phase due to moving cable effects have found application in ranges of large dimension and high frequency. Although generally less sensitive to cable motion, amplitude variations can also be addressed by correction methods.

The shorted cable method operates best for SNF when transmitting through the test antenna. By switching the moving cable end from its connection with the test antenna port into a reflecting short and measuring the returning phasor, one can find through a comparison to a reference value the influence of the cable motion upon the received signal. [11]

The pilot signal method operates by employing a secondary pilot signal having a frequency very near the frequency of interest and then calibrating the relationship between the cable's effect at the two frequencies. Because of the frequency offset, the two signals can be monitored in real time and the cable's variations tracked by the pilot signal while the signal of interest is being used to excite the test antenna that is transmitting. [12]

The three-cable method operates by monitoring the combined transfer characteristic of each of three pairs of cables for each grid point in the two-dimensional scan. There are then three equations and three unknown two-cable transfer characteristics, specific to a given grid point; the three simultaneous equations can be solved for the transfer characteristic of each individual cable; one such cable characteristic is used to correct the received data corresponding to the cable through which the probe's signal passed. Again, comparison to a reference gives the influence of the cable's motion, which can then be mitigated by correction. [13]

4. Recent Innovations to Improve Accuracy by Correction of Imperfect Data

In the past ten years, further correction of acquired data for known and recognizable imperfections in the antenna range and range equipment have been devised. Here I describe these additional correction techniques:

<u>Mechanical Correction of Known Position Errors</u>

Correction for known probe positioning errors is important today for spherical near-field scanning at mm wave frequencies. On-the-fly error sensing of probe position errors with SNF scanning have not yet been implemented. Position error correction in SNF scanning is limited to schemes based upon error maps. One method that has been found practical in the case of the SNF arch system is depicted in Figs. 4 and 5. In this scheme the positioning errors associated with an imperfect arch can be compensated by automatic mechanical re-adjustment of the probe location with an X-Y stage. To increase the maximum frequency at which the arch system can be used, MI has incorporated an additional error-correction mechanism into the circular scanner. This system was designed to apply position corrections in each of three directions:

1. A rotation about the elevation axis ($\Delta\theta$),
2. A translation along the radial direction (ΔR)
3. A translation along the direction normal to the plane of the scan circle (ΔP).

The $\Delta\theta$ correction was accomplished using the existing elevation axis drive train. ΔR and ΔP corrections were accomplished using a pair of orthogonal linear actuators that were mounted on the probe carriage (Fig. 5, Fig. 6). The error terms that were used to generate corrections were based on an error map. This map was constructed using direct measurements of the path of the RF probe aperture as it moves around the scan circle. These measurements were taken by first mounting the retro-reflecting corner mirror target of a tracking laser interferometer at the probe aperture location, then moving the probe carriage through its full range of scan motion. [14]

Fig. 3. Arch-Type SNF Scanning Range

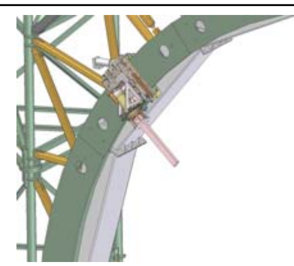

Fig. 4. Error-Correction Stage Mounted on the Carriage

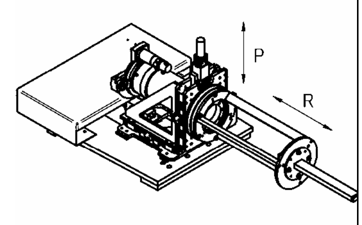

Fig. 5. The Error Correction Stage

Software Correction of Known Position Errors

In the recent past, an algorithm has been developed that is inherently capable of utilizing SNF data that is acquired under conditions of imperfect positioning of the probe during its scan over the almost spherical surface with samples taken at grid points that do not lie on a regular equally-spaced grid. To implement the algorithm, the true spherical coordinate values must be known for each grid point, along with the amplitude and phase of the probe response. A complete data set requires data records for each sample point consisting of two complex phasor values representing the probe responses – one for each polarization – and true spherical coordinate position values. The algorithm is based on modern numerical matrix processing techniques. It employs a Fast Fourier Transform based on unequally-spaced data in θ and ϕ, and interpolation in r. It is an iterative algorithm and requires a PC with greater than a ~ 2 GHz cycle rate to be found useful in a modern laboratory. A single iteration of the NFFF transform is of a computational complexity similar to the complexity of the classical Wacker algorithm, making this approach competitive with others. [15]

Correction for Range Imperfections by Subtraction of Reflected Signals

Several groups of workers have addressed the problem of compensating a pattern measurement for the presence of extraneous reflected signals coming from scattering sources in the range environment. [16] Spherical near-field scanning has been applied in two ways: It has been used for range diagnostics employing a special probe configuration that senses the impinging fields –both desired and extraneous – entering the test zone as they pass through a spherical surface to illuminate the receiving antenna. The modal theory of spherical near-field scanning has also been applied to compensation of the contaminated measurement for the presence of impinging modes that correspond to azimuthal indices other than $\mu = \pm 1$. This is an iterative technique and has been shown to work in several laboratory test cases. It requires that the contaminating signals be significantly weaker than the primary range signal. [17] This technique has not been generally applied in every-day use. Greater familiarity with its operational features is needed before it finds its way into common use. In a further development, the spherical modal expansion of the contaminating field is re-expressed as a discrete finite sum of plane waves, achieving a reduction in the complexity of the compensation algorithm and a corresponding reduction in the number of iterations required. The range field data used to calibrate the range is the same as for the earlier case. [18].

Correction for Range Imperfections by Filtering of Reflected Signals in the Spherical Modal Domain

Recently, success has been reported in reducing the effects of scattering and reflection upon the measured antenna patterns by other means of post-acquisition signal processing other than stray signal subtraction. [19a], [19b] The proprietary technique has been applied to patterns obtained by spherical near-field scanning and stray signal suppression enhancements of 15 to 20 dB over that obtained with moderate quality absorber achieved.

Also recently, we at MI Technologies have reported a method we term the ***IsoFilter***™ technique, which is based upon filtering in the domain of the spherical modal basis set. It provides for suppression and elimination of the effects of unwanted extraneous signals from the patterns produced in spherical near-field scanning. [20 a, b]. With this technique, we have demonstrated that a radiating-source of a composite antenna can be selected for computation of its individual far field from among the entire set of participating sources. Rather than computing the far field of the radiating composite antenna defined by a volume centered upon the crossing point of the positioner axes, we have found that we can center the spherical volume on the antenna, making the filtering process selective of the antenna alone. We have found that from the near-field pattern of the composite antenna we are able to recover to a close approximation, the pattern of the individual antenna alone. The composite antenna consisted of the primary radiating source plus induced sources.

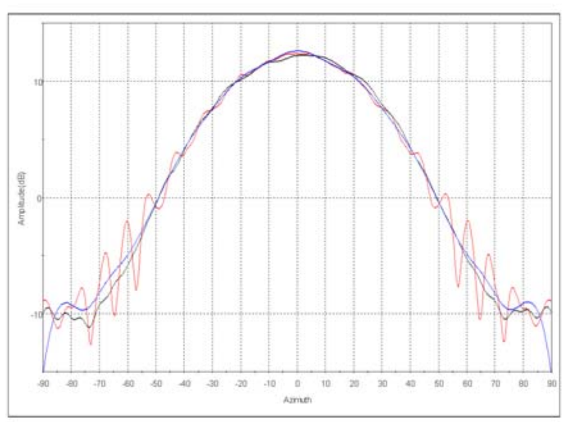

Fig. 6. Comparison of Azimuth Cuts:

No Ground Plane With Ground Plane After ***IsoFilter***

This method proceeds in three successive steps: First over-sample in the scanning data domain and transform to the far field. Then second, effect a translation of the coordinate origin by multiplying the far-field pattern by $e^{ik\vec{r}_0 \cdot \hat{R}}$, on a grid point by grid point basis where $\vec{r}_0$ is the position of the individual radiator and $\hat{R}$ is a unit vector that indicates the far-field grid point's spherical coordinates. Lastly, filter in the domain of the spherical coefficients as the far-field pattern is re-computed and retain only those spherical modes consistent with the minimum sphere of the individual radiator. It is an extension of the usual spherical modal domain filtering.

An example of results obtained using the ***IsoFilter***™ technique is shown in Fig. 6, which are for a principal plane of a small pyramidal horn mounted near the edge of a circular aluminum plate ground plane. The pattern in red is derived from a spherical near-field scan whose minimum sphere includes the antenna and ground plane. The pattern in blue is the far field after applying the ***IsoFilter***™ technique. It derives from filtering the spherical modal set that comprises the pattern so that only those modes consistent with a minimum sphere enclosing the horn aperture alone are kept in the sum. The pattern in black is presented for a reference or baseline. It derives from a spherical near-field scan of the horn alone, centered on the crossing point of the roll and azimuth axes. The vertical scale is 30 dB of dynamic range; the horizontal scale covers ±90° of azimuth axis motion – i.e. the forward hemisphere.

5. Future Trends for SNF Scanning Measurements

The two trends currently at work are the trends to improve (1) accuracy and (2) speed, usually with one being traded for the other. However it should be noted that the thrust of the cellular communications industry is to operate at the lower frequencies and for lower costs. This push toward lowering the cost of testing in the lower frequency bands is important. Measurement techniques that might afford a user the ability to forego the conventional necessity of expensive low frequency absorber hold great attraction. One might expect then that the filtering methods may come into common usage as time progresses.

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