Assessing and Quantifying the Effects of Planar Mathematical Absorber Reflection Suppression Technique

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***Abstract*— Band limiting radiating fields from a finite sized field distribution has been shown to be a highly effective way to eliminate spurious scattered fields from antenna measurements [1, 2, 3]. These techniques have been used with impressive results in many antenna measurement geometries including spherical, cylindrical and planar near-field and far-field [3, 4, 5, 6]. Generally, the objective verification of these suppression techniques on scattered fields can be readily demonstrated, while their impact on the overall facility level uncertainty budget has perhaps been less clear.**

The use of the NIST 18 term range assessment [7, 8] for error analysis of planar near-field antenna test facilities has become a widely accepted technique for antenna measurement error evaluation. This technique identifies the overall effect on the measurement as well as each of the 18 terms individually. Thus, range assessment evaluation provides an effective way to evaluate the impact of planar MARS processing on a given antenna measurement or planar near-field facility. This paper presents results from a recent range assessment campaign that illustrates and quantifies the impact of MARS processing on the facility level error budget on a large planar near-field antenna test system.

***Index Terms*— Planar Near-Field, P-MARS, 18 Term Range Assessment, Modal Expansion.**

I. INTRODUCTION

The NIST 18 term range assessment (RA) has become a widely accepted procedure for deducing the uncertainty budget for a given planar near-field antenna test system [8, 9, 10]. This process has been expanded so that assessments can be made on all geometries of near-field test systems. In many cases automated measurement and analysis techniques have been developed yielding good confidence of expected measurement uncertainty across all antenna types. However, all of these range assessments (RA) are predicated on the following few assumptions and procedures: 1) Theory on which the near-field measurements are based is exact and introduces no uncertainties in the calculated antenna parameters due to inherent approximations such as assuming ideal probe properties, *etc.*. Only one approximation is required in the theory, and that is that multiple reflections between the antenna under test (AUT) and the probe are not included within the transmission equation. This approximation is treated as a source of error in the measured data and so the theory assumption is well founded 2) Numerical techniques that are used are also exact except for round-off and numerical truncation errors which add a very small component to the random error term. 3) Measured near-field data and the probe pattern, polarization and gain data along with the gain of a standard, if used, are the only sources of uncertainty in the final antenna parameters that are calculated by processing the measured data through the near-field to far-field software. It is also assumed that all significant sources of error are accounted for within the 18 term assessment process and that the effect of each term on AUT parameters can be quantified using analysis, measurements or simulation. 4) When near-field measurements on a test antenna are used to estimate an uncertainty term, the tests use a self-comparison approach (involving a single parametric change) which does not depend on knowing the true antenna parameters, or even assuming that the results of a given measurement are free from other sources of error. The tests are designed to be sensitive to only a *single* error source and ideally the difference between two or more measurements will quantify the uncertainty for a single term. The self-comparison tests compare two far-field patterns and the difference between the patterns is used to determine an estimate of the uncertainty for a single error term. 5) Terms that use analysis to estimate the uncertainty, the equations are derived from the basic theory using approximations where necessary to simplify the expressions and focus on the essential factors within the expressions. 6) Each error term is assumed to be independent and uncorrelated to all other terms and the total uncertainty can be estimated with a root sum squared (RSS) combination. In this way the facility level uncertainty budget can be constructed from 18 individual terms. That is to say, that the assessment of each individual term is assumed to be orthogonal to the assessment of every other term. These 18 terms are listed in Table 1 below.

By evaluating each of these individual terms for a given facility and antenna combination, it is possible not only to determine an overall facility level uncertainty budget, but also to establish which of these individual terms make the greatest contribution to that budget.

TABLE I. 18 TERM ERROR MODEL SUMMARY

Term	Error Source	Primary Evaluation Method
1	Probe relative pattern	Computer Simulation
2	Probe polarization ratio	Analysis
3	Gain Standard	Calibration data
4	Probe alignment error	Analysis and simulation
5	Normalization constant/FF Peak	Analysis
6	Impedance mismatch factor	Analysis
7	AUT alignment error	Analysis
10	Probe X and Y position errors	Simulation
11	Probe Z error	Simulation
8	Data point spacing (aliasing)	Measurement
9	Measurement area truncation	Measurement
12	Multiple reflections (probe/AUT)	Measurement
13	Receiver amplitude nonlinearity	Measurement
14	System phase error due to:	Measurement
15	Receiver dynamic range	Measurement
16	Room scattering	Measurement
17	Leakage and crosstalk	Measurement
18	Random errors in amplitude/phase	Measurement

When this assessment process is repeated across a great many different planar facilities and antenna types, it is possible to identify those terms that regularly play the most significant role [8]. Three such terms are: mutual coupling, room scattering, and when testing lower gain antennas, measurement area truncation, *i.e.* terms 9, 12 and 16. Although other terms have a greater or lesser contribution on a case by case basis, these are generally three of the more significant contributors.

II. USE OF LOW DIRECTIVITY ANTERNNAS FOR PLANAR NEAR-FIELD RANGE ASSESSMENTS

NIST-18 term range assessments are an essential part of the validation and verification of planar near-field performance [9, 10]. A number of the 18-terms should be evaluated with the actual antenna that will be used for testing because the antenna characteristics affect the range measurements. Antenna characteristics such directivity, main lobe pointing and field distribution can have a significant impact on the assessments. Unfortunately, at the time the system is to be evaluated it is not always possible to have the final test antenna ready for the range assessment. In these cases a substitute antenna is typically used which radiates at the same frequency as the intended antenna. In some cases, the only antenna that is available is a standard gain horn (SGH). At low frequencies these standard gain antennas can have directivities lower than that which is desired for a planar near-field range and thus present a particular challenge to the range assessment testing. When the AUT has a directivity of greater than 20 dBi it can be reasonably tested on a planar near-field range. However testing lower directive antennas is difficult due to practical limitations of any realized planar near-field range. Low-directive antennas emit significant energy at wide-out angles. Since the planar near-field measurement must capture all significant radiated energy from the AUT in order to accurately compute the far-field pattern, the scan plane needs to be very large (and can become nearly infinite in theory). Unfortunately, the cost, complexity, and inconvenience of having a very large scan plane are not the only problems. As the probe moves towards the extremities of the scan plane and is thus farther removed from the AUT it can move out of the near-field and into the (quasi) far-field region of low-directive (electrically small) antenna, and thus experiences far-field space-loss as $1/r^2$. While this effect is accounted for by the planar near-field to far-field transformation, the practical limitation of the finitely large dynamic range and non-zero RF leakage can become significant. Thus, for a large acquisition interval, many of the sampled near-field points can fall within this region and the proportion of data which become susceptible to these effects can become significant. Hence, even though the amplitude of the error signal may be small, as there are a great many of them and their overall impact becomes appreciable. In practice, even very large planar near-field scanners truncate the measurement data. Even though the signal at the edge of the scan looks very low in the near-field (relative to the maximum measured value), after the near-field to far-field transformation, truncation and leakage effects can still be significant. Recently, exactly this situation was encountered when using a WR-650 standard gain horn to conduct a range assessment at a frequency of 1.12 GHz. This gain horn has a directivity of 14.4 dBi at this frequency. This SGH was measured using a very large (9.5 x 7 m) horizontal planar near-field antenna test system. Fig. 1 contains plots of the measured electric near-field x- and y-axis cuts which show that the field intensity is dropping off at the edges of the scan but which remain relatively high, particularly in the x-axis.

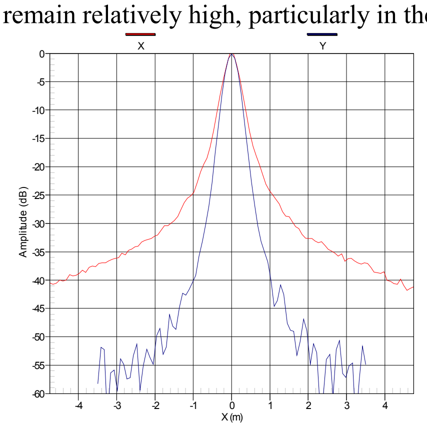

Fig. 1. Near-field X and Y amplitude cuts showing scan plane energy distribution for a WR650 SGH.

When this data was transformed to the far-field several errors were revealed within the results. The corresponding far-field pattern can be seen presented in Fig. 2 in the form of two cardinal cuts. From inspection of Fig. 2 it is clear that a high angular frequency spurious ripple is present within the pattern over the angular span of *circa* 120°. This is a result of spectral leakage which is a consequence of measurement area truncation.

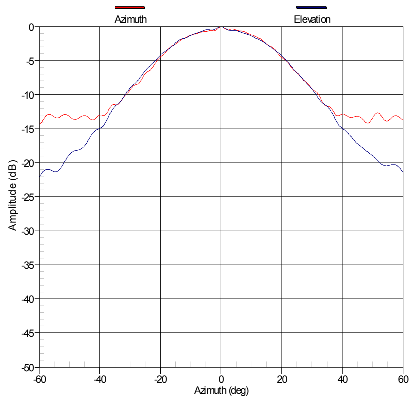

Fig. 2. Principal polarization Azimuth and Elevation cardinal cuts showing effects of scan plane truncation, finite dynamic range, and RF leakage.

In addition, and as is illustrated in Fig. 3, by focusing in on the peak of the pattern, the RF leakage can be seen in the form of a very narrow two-dimensional sinc ($\sin x/x$) function, *i.e.* a blip in the measured pattern, which is exactly at 0° in Azimuth and Elevation. This results from the RF leakage appearing as a small amplitude constant phase signal that is superimposed on the measured near-field data. This corresponds to a plane wave, equal in size to the area of the scan plane that is propagating at a normal to the measurement plane, *i.e.* in the range z-axis. Conceptually, this can be interpreted as corresponding to a very small input signal, amplified by the gain of a very large phased-array antenna with dimensions equal to the size of the scan plane being added vectorally (*i.e.* with due regard to phase) to the original antenna pattern function.

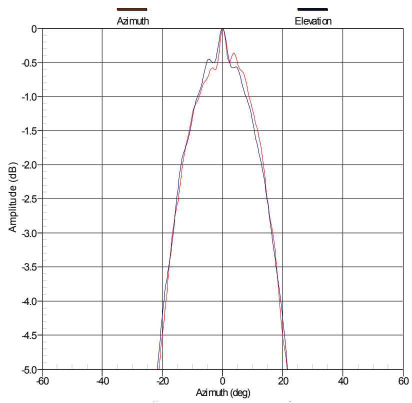

Fig. 3. Leakage effects on large planar scan can be seen to correspond to a very sharp sinc ($\sin x/x$) function centred at 0° in Azimuth and Elevation. Here, axes of the plot have been adjusted to emphasise this effect.

As the scan size increases, the leakage signal continues to increase and corrupt the pattern with a progressively narrower but large peak amplitude beam which is the shape of a two-dimensional sinc function. This type of leakage is very recognizable and hence is comparatively straightforward to diagnose and extract.

The reason these effects can be suppressed so effectively stems from recognizing that an antenna the electrical size of the WR-650 standard gain antenna cannot produce pattern variation with this degree of complexity, *i.e.* the ripple is too "fine". Thus, by filtering out far-field pattern variations in angular frequency higher than which can be produced by the WR-650 SGH, the leakage and other effects with similar characteristics, (*e.g.* measurement area truncation) can be removed. It has been shown that NSI's Planar-Mathematical Absorber Reflection Suppression (MARS) processing can be used to removes these effects very effectively as can be seen illustrated in Fig. 4 below.

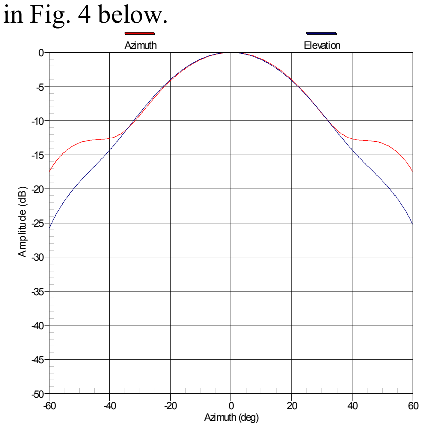

Fig. 4. MARS filtering highly effective at suppressing the effects of leakage and truncation, *c.f.* Fig. 2 above.

It has also been reported that MARS can also ease the impact of truncation on far-field parameters where only a portion of the total radiated near-field is sampled [5]. In practice, conventional planar near-field measurements are always truncated to some degree as measurements cannot be taken in the aperture of the AUT, and as only finitely large planar sampling intervals can be used; the implications of this become especially pronounced when testing lower-gain antennas measured on a planar near-field range such as standard gain horns. Thus, scattering contaminated measurements will always contain ripple resulting from spectral leakage which is caused by omitting some radiated near-fields. The impact that this has on a far-field pattern can be broadly divided into a first and second order truncation effect. The first order effect is that outside a given angle the uncertainty in the far-field pattern tends towards infinity, and secondly, that the ripple arising from Gibb's phenomena, *i.e.* missing plane wave spectra, give rise to high angular frequency ripple over all angles [10]. As MARS attenuates non-physical, high angular frequency components from the far-field pattern, it can effectively suppress, and thereby ease the impact of the spectral leakage (Gibb's ripple) [5].

When truncation is evaluated with MARS Off vs On, the difference is a truncation error of -46 dB (*c.f.* Fig. 5 MARS: OFF) to -91 dB error (*c.f.* Fig. 6 MARS: ON). Here, the difference levels are assessed obtained by computing the root mean square (RMS) difference levels between the respective far-field patterns. A detailed treatment of the applicability and validity of this approach can be found detailed within [11].

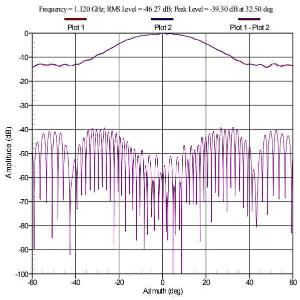

Fig. 5. Truncation level -46.3 dB without MARS (MARS: OFF).

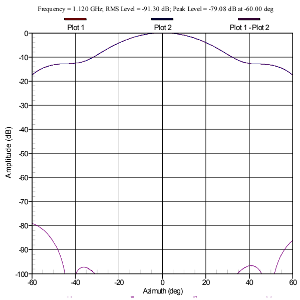

Fig. 6. Truncation level -91 dB with MARS (MARS: ON).

Two further terms that are typically found to be significant components within many facility level error budgets are room scattering, and mutual coupling, *i.e.* terms 16 and 12 of Table I above. The Room scattering term in the NIST-18 term assessment is usually evaluated by moving the AUT and probe relative to the room. By mechanically displacing the AUT and probe together, mutual coupling errors between AUT and probe can be ignored [9]. A comparison of far-field results between a nominal $Z = Z_0$ position and another scan at $Z = Z_0 + \lambda/4$ can be used to indicate the effects of reflections from the walls, ceiling and floor. Without MARS processing, truncation and leakage dominate as errors and tend to mask the room scattering error level. As an illustrative example, Fig. 7 shows that evaluating room scattering without MARS processing leads to a result of -35.7 dB error. As shown in Fig. 8, MARS processing reduces non-scattering errors and allows the pattern to be evaluated directly for room scattering. In this case the result is -51.8 dB (*i.e.* 16 dB lower than without MARS).

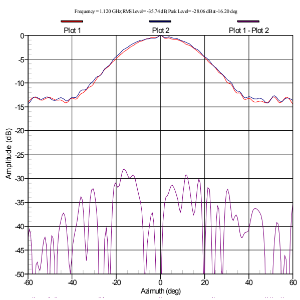

Fig. 7. Room scattering comparison Autz = Z0 vs Z0+λ/4. -35.7 dB RMS level MARS: OFF (includes truncation and leakage errors).

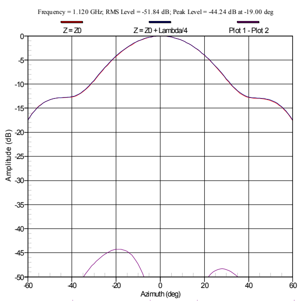

Fig. 8. Room scattering comparison Autz = Z0 vs Z0+λ/4. -51.8 dB RMS level MARS: ON (removes truncation and leakage errors).

A similar issue can be seen when evaluating term-12 Mutual Coupling. This term is typically evaluated by moving the probe relative to the AUT. A comparison of far-field results between a nominal scan at probe $Z = Z_0$ position and another scan at $Z = Z_0 + \lambda/4$ is used to indicate the effects of reflections from the probe [9]. Without MARS, the single-Z mutual coupling term is -36 dB. With MARS the term is -50 dB as shown in Fig. 9 and Fig. 10.

It should be noted also that often when Room Scattering and Mutual coupling terms are evaluated, four or more Z-positions are measured so that they can be averaged together to reduce truncation effects. By using planar MARS processing to evaluate terms 16 and 12, measurements can be made in half the time. In addition, a truncation analysis with and without MARS shows that further scan time reduction can be made as illustrated within in Fig. 11.

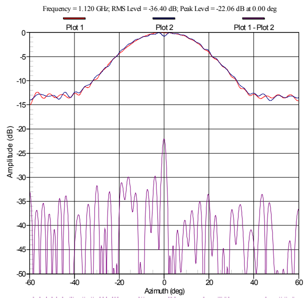

Fig. 9. Mutual coupling comparison ProbeZ = Z0 vs Z0+λ/4. -36.4 dB RMS level MARS: OFF (includes truncation and leakage errors).

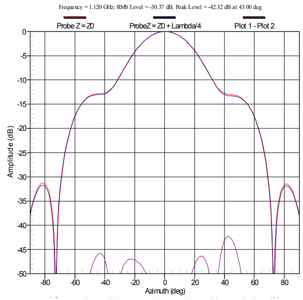

Fig. 10. Mutual coupling comparison ProbeZ = Z0 vs Z0+λ/4. -50.4 dB RMS level MARS: ON (removes truncation and leakage errors).

Fig. 11 shows that by applying planar MARS processing, the over-scan typically associated with planar measurements of low gain antennas can be reduced by nearly 70% for the same level of truncation uncertainty (-46 dB, Fig 5). This significantly reduces scan times by, in this case, *circa* 70%. Although applying MARS has no effect upon the maximum angle of validity, *i.e.* that angle outside of which the uncertainty associated with truncation tends towards infinity, the impact of the second order truncation effect which impacts data across all angles within this span *is* successfully attenuated.

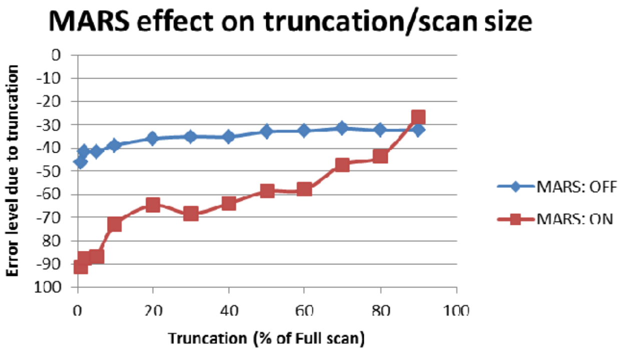

Fig. 11. Truncation analysis with and without applying planar-MARS processing.

III. Summary of The Effect of P-MARS Processing on NIST 18 Term Range Assessment

Table II below summarizes the results of a typical error assessment with and without MARS processing when performed using a low-directive SGH antenna to assess a -20 dB side-lobe level (SLL). Here, the uncertainties that have been considered above have been assessed with and without MARS processing, with the remaining 15 terms being assessed conventionally, and for the sake of brevity, the root summed squares (RSS) combined result tabulated [11]. The total uncertainty is formed from the RSS of the individual terms and is presented within the table. A detailed treatment of the conversion between error/signal level (E/S) and uncertainties as used within Table II can be found presented within [12]. From inspection of this table, it is clear that in the event that recourse to the use of a low directive antenna is unavoidable when performing range assessments, MARS processing should definitely be considered, not only for the improvement in accuracy it offers, but also for the reduced test times that can be achieved. By applying MARS processing, scan sizes can be minimized, and the need for additional Z-positions can be reduced. This is particularly important in the event that the probe, and or the AUT, cannot be accurately and precisely translated. This is all the more crucial in applications where the intended AUT is mechanically large, heavy, or gravitationally sensitive, and where the use of auxiliary mechanical translations are inconvenient, unavailable, or even impossible. Thus, in many installations, appropriate facilities are not automatically available for use by the range assessment procedure.

TABLE II. RANGE ASSESSMENT RESULTS FOR SIDELOBE LEVEL AT -20 DB – COMPARISON OF RESULTS WITH AND WITHOUT MARS PROCESSING

		Without P-MARS		With P-MARS	
Term #	**Error Source**	**Uncertainty (dB)**	**E/S (dB)**	**Uncertainty (dB)**	**E/S (dB)**
9	Measurement Area Truncation	0.41	-26.3	0.00	-71
12	Mutual Coupling (Multiple Reflections) (Single-Z)	1.22	-16.4	0.26	-30.4
16	Room Scattering (Single-Z)	1.32	-15.7	0.22	-31.8
Others	Other NIST-18 term errors	0.50	-24.5	0.50	-24.5
	Total (RSS)	**2.33**	**-12.54**	**0.65**	**-22.9**

IV. SUMMARY AND CONCLUSION

A representative range assessment has been presented for the case where a low gain pyramidal horn has been used. The effects of the planar mathematical absorber reflection suppression technique have been illustrated qualitatively through comparison of far-field patter data, and quantitatively through the computation of a NIST 18 term range assessment. In this way, it was found that the P-MARS measurement and post-processing technique significantly reduces uncertainties associated with bias leakage error, second order truncation effect, room scattering, and mutual coupling (multiple reflections) thereby leading to a worthwhile reduction in the overall measurement uncertainty. In addition, P-MARS reduces range assessment time by significantly reducing the need for large over-scan when low-directive antennas are used.

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