THE DEVELOPMENT OF OBJECTIVE MEASURES OF COMPARISON BETWEEN ANTENNA PATTERN DATA SETS

McCormick J.[1], Gregson S.F.[1,2], Parini C.G.[2]

BAE SYSTEMS[1], Queen Mary, University of London[2]

ABSTRACT

Frequently one is required to compare two or more supposedly identical data sets, for example the far-field three-dimensional radiation pattern of the same antenna measured on two different ranges. The requirement for objective, quantitative and robust methods of assessing such data, will be discussed and confirmed. The constraints placed on these methods, applied by the nature of the measurement process and the measurand, will be highlighted.

Data sets that can be used to illustrate the application of these techniques will be presented and a preliminary assessment of them made using previously established techniques. These data sets embody a variety of subtle and specific characteristics that stem from particular known error sources. The limitations of these established assessment techniques will be discussed and used to motivate the development of newer more sophisticated analysis, where the data sets will be further processed to yield objective measures of comparison.

A variety of new assessment techniques that satisfy the aforementioned constraints are developed, these techniques consider the interval, ordinal and combined aspects of the data. They are employed to extract not only the extent but also the nature of the differences between the data sets. These techniques are presented and their various merits are compared and contrasted to illustrate their applicability to the classification and analysis of large data sets derived from near field antenna measurements.

1. INTRODUCTION

Attempts to produce objective quantitative measures of comparison between data sets, that can be used to assess the accuracy, sensitivity and repeatability associated with the production of the data sets has been widely reported [1,2,3].

The utility of such a measure of adjacency lies not only within its ability to determine the degree of similarity between various data sets but also in its ability to categorise the way in which they differ. Without the ability to produce such metrics of similarity any judgement as to the integrity of a data set is necessarily reduced to subjective value judgements.

For antenna patterns a more fundamental physical interpretation of the process of radiative emission/absorption, *i.e.* that of the Schrodinger wave equation, the Dirac equation, or Quantum Electrodynamics (QED) can be useful when attempting to assess data sets produced when measuring antenna-to-antenna coupling.

Here, the antenna pattern is described by electron-photon-electron interactions that can only be specified by the probability of interaction, where this probability is formed by the superposition of complex probability amplitudes. Thus, the antenna pattern, that is classically considered as defining the relative power flux density propagating to or from an antenna, is more correctly described as the probability of discrete electron-photon-electron interactions. Here, the probability of interaction is given as having occurred over known solid angles, relative to the AUT placed at the centre of an inertial frame of reference. This frame of reference is coincident and synonymous with the fixed mechanical interface, relative to which the antenna pattern is usually calculated. Consequently, the AUT pattern can be legitimately interpreted as a frequency distribution that when normalised to unity can be recognised as a probability density function for the process of electromagnetic interaction.

Previously, the comparison of such large data sets that can be recognised as probability density distributions has been significantly simplified by the techniques of statistical pattern recognition [2]. The application of statistical techniques is particularly appropriate to antenna patterns as stated above when the nature of the pattern is not constrained to the conventional classical interpretation, *i.e.* is not restricted to being considered as an angular spectrum of electromagnetic waves propagating in diverse directions.

Furthermore, the statistical approach has the inherent advantage that it considers the global features of the data set and distils the complexity of the pattern into an alternative, dimensionally reduced, set of virtually unique features that can be utilised to describe the data. This extraction of global features is of particular relevance for antenna patterns as it takes account of the inherently anti-reductionist and holistic nature of the integral transforms that relate the aperture excitation to the angular far field pattern.

2. PARTIAL SCANS

Partial scan techniques which attempt to reduce truncation errors in near field antenna measurements are areas that produce data sets that require detailed analysis to asses that applicability and utility of the measurement process. Moving the AUT between successive partial scans will necessarily involve the disturbance of the reference path of the RF subsystem and introduce further imperfections in the alignment between the antenna and the range.

In the absence of a detailed understanding of the uncertainties associated with this technique, a number of metrics have been produced to compare the results of this partial scan process to more conventional near field antenna measurement techniques. A description of these partial scan techniques described in [4] is not the purpose of this paper. To illustrate the assessment processes a number of simulated measurements with in built errors where produced. These simulations were designed to replicate the degree of misalignment between adjacent scans that has been observed in practice.

Hitherto the purpose of measurement simulations has been limited to the assessment of the relative merits of various transformation algorithms and measurement configurations. Here however, the simulation technique was utilised to produce a series of measurement simulations that could be used to yield a knowledge of the nature and magnitude of two alignment errors that were thought to be particularly pertinent to the auxiliary rotation partial scan technique under consideration.

3. MEASUREMENT ERROR SIMULATIONS

In the absence of some overriding definitive standard or infallible model, the only practical methodology for assessing the ability of any test facility to make measurements is by way of repetition of these measurements. This repetition can be accomplished without alteration in the measurement configuration, to simply address repeatability, or with the inclusion of parametric variations to assess sensitivity. The parametric variations can also be used to assess the accuracy of the measurement if enough thought is devoted to the nature and extent of the parametric variations to be used, along with the types of analysis that are to be employed in the assessment process.

As repeatability is inherently a statistical process the validity of any conclusions drawn will greatly depend upon the size of the sample. Thus it is preferable in this case to utilise as large a number of simulations as is practical.

a) Simulation of Partial Scan Plane Pointing Error

Simulation software was modified to enable the specification of angular and distance errors to partial scan configurations. The magnitude of the angular error introduced by the AUT positioner was estimated from observations of the variation in the boresight direction reported during active alignment correction verification measurements [5]. The azimuth, elevation and roll errors, used in the simulation of the acquisition planes, were based on uniformly distributed pseudo random numbers with a maximum range of plus or minus three times the standard deviation of the pointing error observed empirically. The use of a uniform distribution was though to be preferable to the more commonly employed normal distribution, as the former will inevitably produce a more pessimistic set of simulations.

The assessment of each of these errors entailed the simulation of ninety-nine tri-scan measurements, *i.e.* two hundred and ninety seven individual partial planes. These measurement sets were transformed to the far field using the existing transformation computer code assuming that the data sets contained *no* imperfections in their alignment. Figure 1 below contains overlaid Ludwig III co-polar azimuth cardinal cuts from all of the transforms.

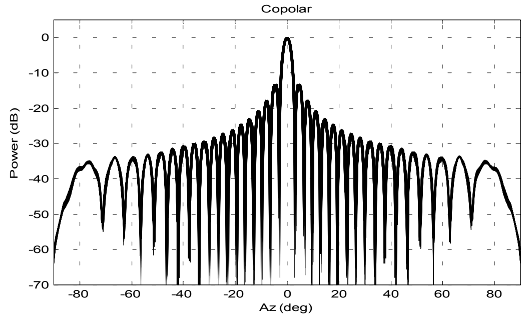

Figure 1 Far field azimuth cut of error simulations.

Clearly, the pointing errors introduce pattern measurement errors at all angles and at all levels in the far field. The equivalent multipath error (EMPL) was calculated between the ideal pattern and each of the error simulations. This can be though of as the amplitude necessary to force the different pattern values to be equal. The maximum EMPL, *i.e.* the worst case, value at each angle can be found plotted below in figure 2 together with the ideal cardinal cut.

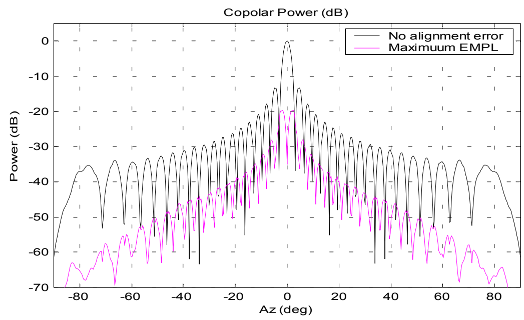

Figure 2 Far field azimuth cut of ideal simulation and maximum EMPL.

The perfect alignment result plotted with the upper bound EMPL value at each angle from all 99 simulations shows that away from boresight the EMPL seems to demonstrate, a good degree of correlation, that the error term is proportional to the signal level. Although raising the maximum EMPL to perhaps as little as 20dB below to the error free signal, the auxiliary rotation system shows a degree of resilience to angular errors in the positioning of the partial scans and is sufficiently resilient to avoid a catastrophic break down. Thus as its failure is gradual this illustrates a degree of robustness that should be observed in practice.

b) Simulation of AUT-to-Probe Separation Error

Range length errors were modelled in the same fashion as the angular errors however the maximum variation was determined from an error analysis of the fabrication and use of the AUT mechanical positioner. Ninety-nine measurement simulations were generated, transformed to the far field, and plotted. Cardinal cuts can be seen overlaid in figure 3 below.

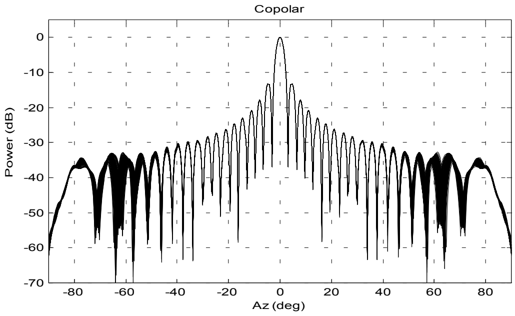

Figure 3 Far field azimuth cut of all simulations.

Figure 3 above appears to illustrate that the errors associated with the probe separation error are of limited angular extent centred about angles that correspond to directions in which similar strength signals are combined from different acquisition planes. Additionally, the error becomes smallest for angles that are derived purely from a single scan. Inevitably, such interference effects are at wide angles where the overall signal strength is reduced.

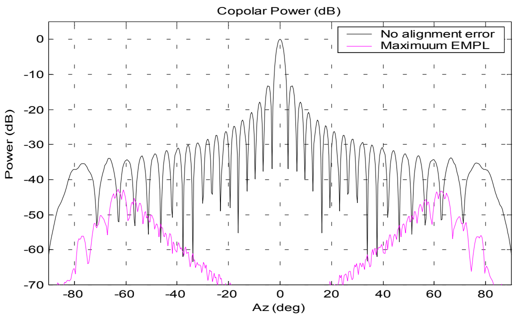

Figure 4 Far field azimuth cut of ideal simulation and maximum EMPL.

Figure 4 again contains the perfect alignment result plotted with the maximum EMPL value at each of the angles from all 99 simulations. This clearly confirms that the greatest errors are observed over a limited wide out angular range. Although raising the EMPL to perhaps as little as 10dB below the error free signal at ±60°, the auxiliary rotation system was again sufficiently resilient not to break down catastrophically. Again, its failure is gradual illustrating a degree of robustness that should be observed in practice.

Unfortunately, although the EMPL is useful for highlighting differences between patterns and measurement errors it fails to deliver a single quantitative metric of similarity between patterns that can be used to determine which of these different phenomena is most important.

4. INTERVAL MEASURE OF CORRESPONDENCE

An interval measurement of correspondence based on calculating the moments of antenna pattern when it is treated as a probability distribution has already been reported [2]. Moments of a probability density function describing area, centroid, variance, kurtosis and skewness yield 15 numerical values that characterise the data. Viewing these 15 variables in a 15 dimensional feature space yields a vector and comparison of 2 such vectors will enable comparison of the 2 data sets. The technique used here is to construct an orthogonal vector to the first data set and then take the dot product with the second to form the comparison. Here, if they are exactly the same the dot product will be zero. The vectors modulus and argument form the comparison of similarity between the two patterns. Figures 5 and 6 below illustrate the calculated error vectors plotted on a feature plane from the interval moment assessment method for the angular error and range length error simulations respectively.

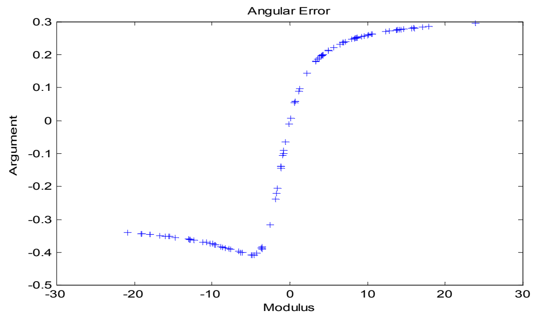

Figure 5 Feature plane plot of interval moment assessment method for angular errors.

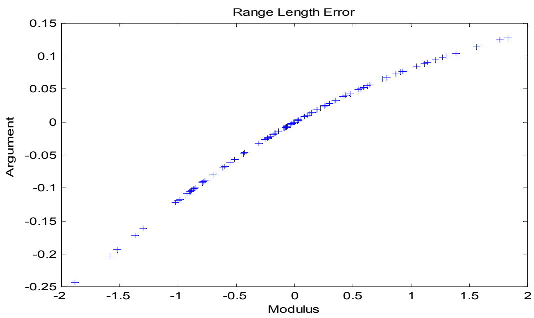

Figure 6 Feature plane plot of interval moment assessment method for range length errors.

The central region of figure 5 aligns closely with that of figure 6 but the large values of EMPL associated with the angular errors extend the error points through the vector error space to produce a more extended trajectory through the error vector space. This is expected, as the error terms obtained during the range length analysis were located principally in regions of small field intensity. This trajectory appears to be related both to the extent of the errors angular nature of the errors, and to the shape of the underlying pattern.

However there are two specific aspects of the measurement methodology that handicap any interval pattern assessment of antenna patterns produced by near field scanning.

- The very high dynamic range of the measurement system
- The interferometric nature of the measurement and the lack of uniformity of the reference source.

Both of these mean that interval assessment of the data sets can lead to misleading results.

5. ORDINAL MEASURE OF CORRESPONDENCE

An ordinal measure of association that overcomes this limitation can be derived if the interval nature of the data is ignored. If the values in the data sets are ranked, assuming the data sets are the same, then they each contain the same elements. The only possible variation is in where these elements are to be found in the data sets. Therefore the 2 × 99 data sets all represent different permutations of the same data.

This provides the opportunity to construct a measure of association based on the inverse permutation of data sets with respect to each other. This will produce a metric of correspondence that is immune to many of the pathological inconsistencies of such large interval data sets.

Any proposed objective measure of correlation, or association, between data sets would be required to be:

- A single coefficient, independent of scaling or shift due to the differences in reference levels,
- Insensitive to the large dynamic range of the data,
- Normalised *i.e.* give correlation value ranging between 1 and –1, and finally,
- Symmetrical or commutative to the operation of correspondence.

Such a measure has already been proposed and demonstrated [6] and applied to the assessment of antenna patterns [3].

The ordinal coefficient of correlation *k* was computed between the reference data set and each of the results from the error simulation contained in figures 1 and 3. Each of these 99 coefficients can be found plotted below in figure 7. For the sake of clarity, the discrete *k* values are presented in terms of a line graph. Table 1 below contains the mean value, median value, standard deviation and 99% confidence interval for the range of *k* values obtained for the angular error simulations.

Metric	***k***
Mean	0.8132
Median	0.8160
Standard deviation, σ	0.0879
3σ (99% Confidence level)	0.2638

Table 1 k values for azimuth cut of angular error simulations.

This operation was repeated for the simulations based upon range length errors. The ordinal coefficient of correlation *k* was computed and the results can be found presented below in figure 8. Again, the mean value, median value, standard deviation and 99% confidence interval for the ranges of *k* values obtain can be found presented in table 2 below.

Metric	***k***
Mean	0.8758
Median	0.8800
Standard deviation, σ	0.0546
3σ (99% Confidence level)	0.1638

Table 2 k values for azimuth cut of range length error simulations.

The results of the ordinal measure clearly show that the small but systematic errors introduced into the simulations can be accurately quantified in the calculation of the *k* value. However from figures 1 and 2 it is clear that the angular distribution of errors is independent of far field angle for the angular error case whilst it is correlated to specific far field angles for the range length case, *c.f.* figures 3 and 4.

The ordinal process of ranking the data to produce permutations takes no account of either the absolute amplitude or spatial angles at which the data is found, thus every region of the pattern is judged to be equally important in the calculation of *k*. This is clearly illustrated by comparison of the mean average values of *k* determined from the two different error simulations.

To differentiate between errors that are not uniformly located across the data sets some method of isolating the effects of these localised errors must be established. In figure 4 the errors are differentiated by being located around specific angles relative to boresight and being at distinguishable amplitudes relative to boresight. Therefore, any process that distinguishes between areas in the pattern in terms of spatial angle or relative amplitude could be used to modify the data prior to ranking so that the resultant permutations would be biased to reflect these localised areas in the patterns.

By inspection of figure 4 it is clear that the differences observed equate to lower signal levels than those in figure 2 however, this is *not* reflected by a significant difference in their respective *k* values.

5. INTERVAL EXTENSION TO THE ORDINAL MEASURE OF CORRESPONDENCE

This section details the application of a novel technique for determining the adjacency of two data sets. The ordinal measure of association can be readily modified to take account of different regions of interest by re tabulating the data in such a way as to attribute more samples to regions of greatest interest prior to ranking the data. This approach minimises the impact of numerical instabilities as observed when using a purely interval assessment technique.

Assuming that the patterns are sufficiently well sampled, this can readily be determined for the case of antenna radiation patterns, such a re-tabulation can be accomplished rigorously through the application of the sampling theorem *i.e.* Whittaker interpolation. Alternatively this can be performed efficiently albeit with approximation, using piecewise polynomial functions, *i.e.* cubic spline or cubic convolution interpolation.

The blue trace in Figure 7 below contains results from calculations of the *k* value pertaining to the angular error simulation. The red trace represents the *k* values obtained from the hybrid ordinal-interval technique where the data was re tabulated so that more samples were attributed to regions of larger field intensity.

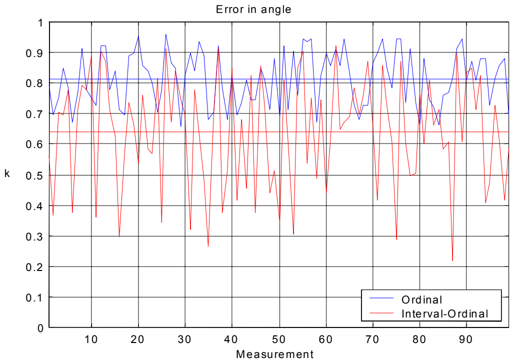

Figure 7 Plot of ordinal k and modified interval-ordinal k as a function of simulation.

Figure 8 below contains similar data obtained from the range length error simulation.

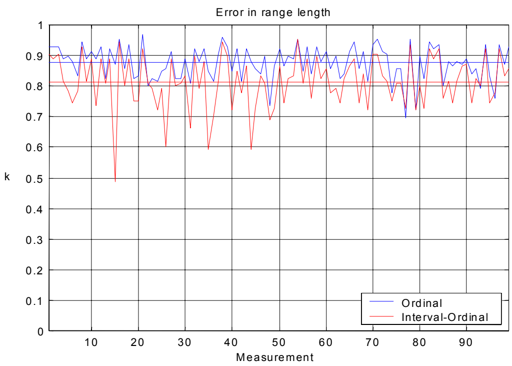

Figure 8 Plot of ordinal k and modified interval-ordinal k as a function of simulation.

This illustrates that the hybrid technique is better able to isolate errors in the data sets that display amplitude specific traits. The mean hybrid coefficient of correlation for the angular error simulation was 0.6395 whilst that obtained from the range length simulation was 0.8113 reflecting the greater impact of angular errors in regions of higher field strengths around boresight.

The extent with which the hybrid interval-ordinal method discriminates between differences in element corresponding to signal magnitudes can be readily varied on a case by case basis to emphasise or de-emphasise the particular feature under investigation.

6. DISCUSSION AND CONCLUSIONS

Two principal sources of error within auxiliary rotation partial scan measurement systems have been modelled. The effects of these errors on the far field vector pattern functions have been analysed using conventional metrics of determining measurement repeatability and their shortcomings noted.

The far field patterns have been reassessed using two existing statistical techniques that consider the interval and ordinal aspects of the data. A new hybrid technique has been presented that extends to the ordinal technique an ability to differentiate specific distributed features in the data sets. This allows more detailed characterisation and classification of specific error sources in the measurements, allowing the interval or angular nature of the data to influence the ordinal permutations that are abstracted from the data.

This hybrid technique therefore automatically, enables greater importance to be attributed to values corresponding to larger or smaller field strengths, the choice is entirely arbitrary. Furthermore, the technique can similarly be extended to take greater account of data occupying particular angular regions of space. Thus the comparison process can be tailored to characterise specific error sources in the measured data sets and to assess their importance.

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