IMAGE CLASSIFICATION AS APPLIED TO THE HOLOGRAPHIC ANALYSIS OF MIS-ALIGNED ANTENNAS

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ABSTRACT

The technique of microwave holographic diagnosis is a well-established method of non-intrusive characterisation of antenna assemblies. The success of this technique is usually dependent upon the careful alignment of a mechanical reference of the antenna to the axes of the test range. An alternative approach is sometimes necessary as the traditional method assumes that alignment of the antenna is convenient, or possible.

When through necessity the antenna is not ideally aligned with the range, a more generalised formulation of the coupling between the antenna under test (AUT) and the probe is required. However, it is an unavoidable consequence of only using a portion of the forward hemisphere of the propagating energy, that each acquired data set will be truncated. Furthermore, the degree of truncation will typically vary from measurement to measurement depending upon the exact range configuration.

The extent to which these errors are manifest in transformed data sets are typically assessed by observation, however, the direct numerical comparison of such data sets has been successfully accomplished (Ref. 1) and a quantitative measure can be established.

A comparison of large data sets can be accomplished using the techniques of image classification. The extraction of global statistical features from the data sets allows the direct comparison of the data sets in a dimensionally reduced feature space. This numerical comparison is utilised to determine how these errors propagation through the process and effects the final results.

1. INTRODUCTION

The recent measurement of a large active phased array antenna has resulted in the requirement for the development of diagnostic tools to assist in the final adjustment of the instrument, and to establish the extent to which the design specifications are satisfied. This has presented some specific measurement and analysis challenges, that are principally related to alignment, that are perhaps not encountered in other areas of application.

The normal aim of a range measurement process is to characterise the radiation pattern of the AUT at a very great, or infinite, distance with reference to an angular or other co-ordinate set with respect to a defined mechanical interface. This data can then be utilised to establish the extent to which the instrument fulfils it’s requirements. Typically the angular accuracy required is in the order of ±0.02°, particularly where the antenna is to be mounted on a spacecraft intended for low Earth, or geo-stationary orbit.

Typically, the intention of an antenna range test is to compare the instruments measured performance with that of a theoretical prediction or other similar criteria. In the case of synthetic aperture RADAR (SAR) antennas an additional objective is to identify defective or incorrectly adjusted radiating elements.

This is rendered less than transparent since a variation in any part of the near field will necessarily result in a change to every part of the corresponding far field, and vice-versa. This anti-reductionist nature of the pattern implies that localised malfunctions, associated within individual modules, will be characterised in the far field by variations over the entire pattern. This will mean that the identification of the effects associated with individual modules from the far field data will be demanding. The well-documented technique of microwave holographic metrology (MHM) is instantly recognisable as being especially well suited to such applications since it can be used to reconstruct the AUT’s vector aperture illumination function. Microwave holographic metrology can be thought of as a form of bi-static continuous wave inverse synthetic aperture imaging.

It is acknowledged that when MHM is deployed in its conventional form it may yield unreliable results when used to analyse instruments of large spatial extent. A misalignment of as little as half a degree in the azimuth, or elevation, plane can result in the calculation of an inaccurate aperture illumination.

2. MEASUREMENT METHODOLOGY

In principal it is possible for the AUT to be orientated in such a way as to be aligned perfectly to the principal axis of the range. However, due to the size of modern SAR instruments and their associated mechanical support equipment, there are considerable difficulties inherent with moving such an assembly with any degree of accuracy and precision. Clearly an alternative approach is necessary.

For the case of the planar near field to far field transformation the application of alignment correction data is handled rigorously by expanding the plane wave spectrum on an irregular grid in the range system. This irregular space corresponds to a regular angular domain in the antenna mechanical system. With the transformation of the measured Cartesian field components from the range polarisation basis into the antenna polarisation basis the required isometric rotation is complete.

The probe pattern can be thought of as spatially filtering the fields received from different parts of the AUT. In a planar range, the effects include something similar to a direct multiplication of the far field probe pattern with the far field antenna pattern. This can be seen to be a direct result of the nature of the convolution theorem (Ref. 2) and can be visualised directly from the mechanical operation of the scanner.

It is not usually possible to neglect these effects in the planar range because of the large angles of validity required and the short measurement distance employed. Considerable care has been taken over which co-ordinate system, and which field components, the probe convolution is understood to have taken place in so that a rigorous de-convolution can be applied. This has been extended so that an arbitrary, but known, probe orientation can be accommodated within the transformation process.

The reconstruction of near field data over a plane in space, other than the measurement plane, is accomplished by the application of a differential phase change. This can be seen to be analogous to a defocusing of the far field image. Near field data can then be readily reconstructed via the application of a two-dimensional discrete inverse Fourier transforms. On this occasion there is no requirement for any additional isometric transformations and as such all of the usual numerical techniques for improving the efficiency of the transformation can be utilised.

This reconstructed plane can be located at any of an infinite number of planes that are in the region of space at, or in front of the instruments phase centre. It is when the fields are reconstructed at a plane that is coincident with the AUT's *"aperture plane"* that this process is of most utility. The antenna aperture can be conveniently thought of as that surface in space, which represents the transition between the majority conduction current and displacement current regions defined by the presence of a charge distribution.

A near field measurement is typically constructed so that the field produced by the antenna is sampled over a region of space in which there is an absence of divergence contained within that field. Therefore, the plane to plane transform process results in a knowledge of only the radiating components and provides no knowledge as to the stored energy component.

Alignment errors manifest themselves in different ways in each domain. If the issues associated with polarisation are ignored then an error in the antenna to range alignment will correspond to an angular displacement of the far field pattern. The same error will correspond to a change in the nature of the near-field pattern that is not in general characterised simply by a corresponding linear phase taper.

The acquisition of alignment data in our planar facility is based upon the premise of being able to measure the Cartesian co-ordinates of four points on the antenna mechanical interface plane in the range co-ordinate system. From these four points we can construct four normals, the average angles between each can be used to indicate the degree of uncertainty in the measurement of these points. The projection of each Cartesian component of the first system onto each Cartesian component of the second system determines the antenna to range direction cosine matrix. For the case where there is a suitable datum available on the antenna the roll angle can be deduced from any of the edge vectors.

In principle the techniques outlined above are rigorous. However, in practice the integrity of the reconstructed near field data is not maintained. The source of this error that is propagated through the entire procedure is related to the truncation caused by the differences in the truncation of the measured data sets due to the misalignment of the AUT. Although the process is sufficiently robust to deal with a degree of variation in the truncation of the measured data sets, knowledge of the success of the correction at each stage of the process is crucial.

3. EXAMPLE RESULTS

In order that the validity of the alignment techniques employed in the planar range could be tested, an antenna was acquired at a variety of different orientations. The antenna to range alignment was measured as described above in each case and then the data transformed. The four antenna to range alignments used were:

- Set 1. AUT nominally aligned to the range,
- Set 2. AUT nominally aligned to the range but the scanning probe rotated around the range z axis,
- Set 3. AUT miss-aligned in azimuth to the range,
- Set 4. AUT grossly miss-aligned in azimuth, elevation and roll to the range.

A successful overlay of the transformed data would indicate that the alignment corrections do not contain mathematical errors. Figure 1 below illustrates the levels of accuracy that can be expected for the prediction of the far field from the different data sets and by inspection the correlation between the predicted patterns is good.

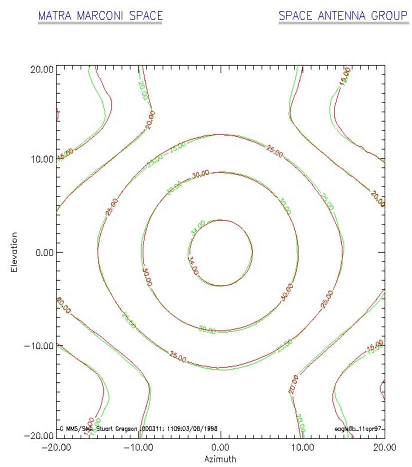

Figure 1.
Comparison of processed far field data, Set 1 and Set 4.

3. IMAGE ANALYSIS TECHNIQUE

The patterns illustrated above in figure 1 comprise a data set that contains more than six and a half thousand complex data elements and any direct numerical comparison, to confirm their similarities, is complicated by the large quantities of data inherent in the measurement process. However, the comparison of such large data sets can be significantly simplified by the techniques of statistical pattern recognition. This has the important advantage of reducing the dimensionally of the data set.

The application of such statistical techniques is particularly appropriate to antenna patterns if the nature of the pattern is not constrained to the conventional interpretation of a plane wave spectrum. A more fundamental view of the basic electromagnetic process illustrated within the measurements is that the pattern illustrates the probability of discrete photonic interactions occurring over given solid angles, relative to the AUT placed at the centre of an inertial frame of reference (Ref. 3). This frame of reference coincides with the fixed mechanical interface, relative to which the antenna pattern is usually calculated. The statistical approach has the advantage that it inherently considers the global features of the data set and distils the complexity of the pattern into a dimensionally reduced set of virtually unique features that can be utilised to describe the data set.

If the moments of the pattern that describe area, centroid, variance, kurtosis and skewness in two dimensions are calculated, they reduce the data sets to fifteen numerical values. These in turn can be used to construct a fifteen dimensional feature vector that can be used as a basis for a numerical discriminator function. With such large data sets comparison can be simplified by a reduction in the dimensionallity of the data.

The results shown are encouraging but a technique for determining how similar the results are is required. If the calculated moments are used to construct a feature vector for each pattern the definition of inner product, in any vector space, can be used to calculate a level of correlation between the set of vectors. In a vector space the concept of orthogonality can be used to construct the vectors **a** and **b** such that $\mathbf{a}\cdot\mathbf{b} = 0$, where $\mathbf{a} \neq \mathbf{0}$ and $\mathbf{b} \neq \mathbf{0}$. Thus, since the product of **a** and **b** is 0 the numerical product of **a** with another vector **c** is a direct comparison of the vectors **b** and **c**. Therefore the derivation of a second vector that is orthogonal to pattern vector produces a test vector that itself can be used to test the correlation of the pattern data with any other data set. Additionally the angles the vectors present to each other can be used as a measure of similarity thus the 6500 complex data points of the data sets can be condensed to 2 co-ordinates that can be plotted on a plane.

4. RESULTS

Figure 2 below illustrates the difference between the results obtained from the comparison technique, when used on the four measurements described above, when the data has been processed with and without the alignment correction.

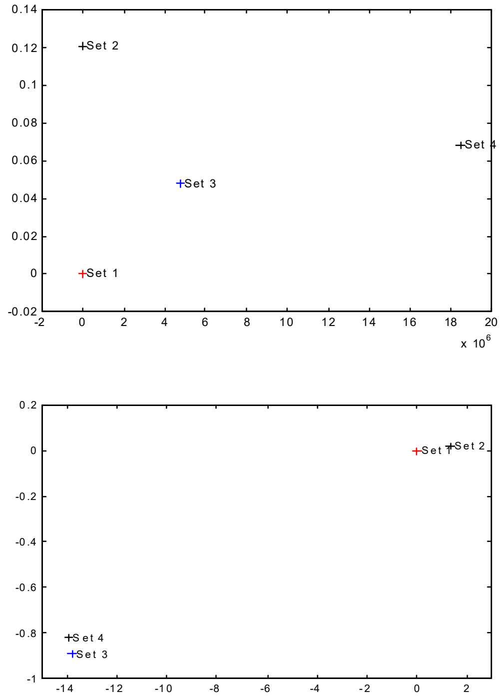

Figure 2.

Plot of far field antenna patterns plotted on a feature plane with no alignment correction (top), and with alignment correction (bottom). Please note the difference between the two scales.

The results of this comparison confirm the accuracy of the measurement technique and highlight the errors introduced by the differences in truncation associated with the original measurement conditions.

Figure 3 below illustrates the spatial transformation required to move from the co-ordinate system of a mis-aligned AUT to data set recorded for an aligned antenna.

Figure 4 and 5 below contain plots of recovered near field

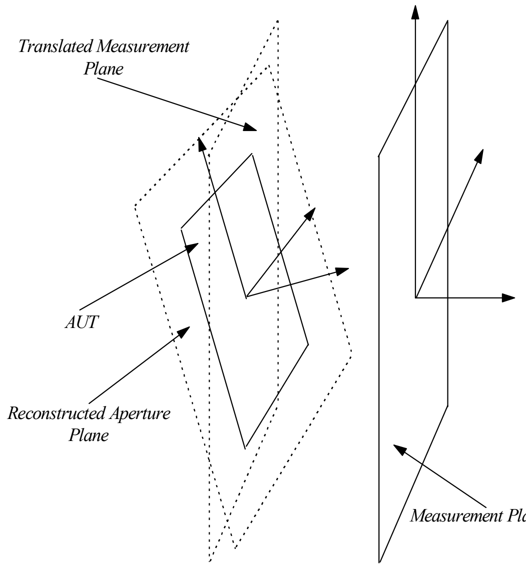

Figure 3.

Schematic representation of a plane to plane transform when performed with and without alignment correction.

planar illuminations derived from measurements when the AUT was aligned and mis-aligned with the range.

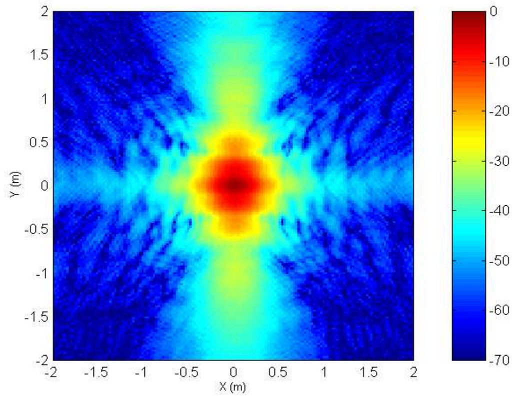

Figure 4.

Recovered near field plane illumination recovered from an acquisition where the AUT was nominally aligned with the measurement plane (Set 1).

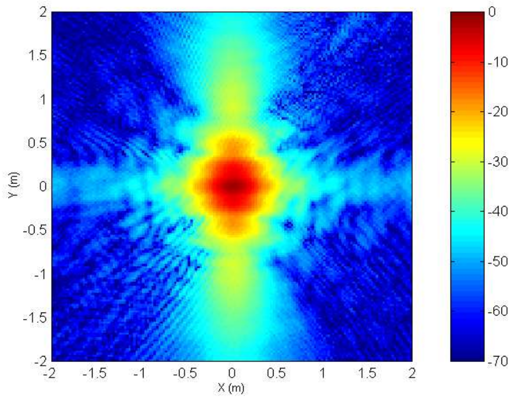

Figure 5.

Recovered near field plane illumination recovered from an acquisition where the AUT was grossly mis-aligned with the measurement plane (Set 4).

5. DISCUSSION OF THE RESULTS

Figure 2. Illustrates the action of the application of the AUT to range alignment correction in the feature space. In Figure 2 *(top)* no realignment has been attempted and the distribution of points on the graph is indicative of the difference between the computed far field patterns. However, Figure 2 *(bottom)* is consistent with the realignment process considerably improving the ability of the system to produce consistent results irrespective of the AUT's alignment.

However, although the realignment process improves the quality of the results this process cannot completely overcome the misalignment problem. This can be seen from the plots since Set 3 and 4 are displaced from Set 1 and 2, although overall there is considerable improvement in the agreement between the results.
The measured data sets, associated with the differently aligned antennas, in turn represent a partial knowledge of the field distribution over different finite planes in space. A consequence of the finite nature of these planes is that none of them contains sufficient data to compute precisely the far field pattern. The differences between these finite data sets will be manifest in differences in the computed patterns despite the realignment process.

Figure 4 and 5 constitute the holographic reconstruction of two equivalent planes from different measurement sets that were acquired over different planes. The high degree of similarity between the reconstructed illuminations is confirmation that the reduction in the displacement between data sets 1 and 4 on the feature plane before and after realignment is equally consistent in the near field.

The differences that are due principally to the finite nature of the acquisition plane could be minimised if the transformation process was extended to combine data that was acquired over more than a single planar near field data set.

In the past this has been successfully accomplished by employing coplanar data scans. However, the technique described above can be readily extend so that non-coplanar data sets can be utilised.

6. CONCLUSION

- The rigorous realignment process substantially increases the ability of the system to characterise antenna assemblies even in circumstances where gross misalignment is unavoidable or high degrees of angular precision are required.
- The rigorous holographic reconstruction of near field data from mis-aligned AUTs has been successfully demonstrated.
- The finite extent of the sampling plane is the principal limiting factor governing the applicability of the technique. This is illustrated by the displacement of the points that are associated with specific patterns when plotted on a feature space plane. The singularity on this plane can be removed by redefining the co-ordinate system as polar.
- These limitations could be overcome by extending the data set from which the pattern is derived. This can be readily achieved by combining multiple data sets, and possibly to the extent of covering a full sphere with a set of poly-hederials.

7. REFERENCES

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