Determination of Antenna Displacement from a Single Cut Quasi-Farfield Pattern for Cylindrical Mode Filtering Applications

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***Abstract*—In the quasi-far-field, the tangential orthogonal electric field components, *e.g.*, in the phi direction and z direction (in the cylindrical coordinate system), are decoupled, which means that only the co-polarized field component is sufficient to transform a single cut antenna pattern to the cylindrical mode domain. When the antenna pattern is measured with a displacement from the center of rotation, a phase coherent mathematical translation of the pattern to the center of rotation promotes mode separation between the modes of the antenna and those of the chamber reflections. A mode filter can then be applied to remove effects due to chamber multipath reflections. In this scheme, an accurate measurement of the displacement distance from the rotation center is essential. Conventionally, this is obtained by using a physical measure, *e.g.* ruler, laser tracker, *etc.* In this study, we investigate several techniques to automatically retrieve the requisite offset distance using the vector pattern data, including using: the unwrapped phase response, through time domain transformation, and by examining mode concentration within the spectrum domain. Each method is studied for its robustness, limitations and efficiency in accurately determining the displacement distance.**

***Index Terms*—cylindrical mode filtering, antenna pattern measurements, multipath effects reduction, spectrum domain analysis.**

I. Introduction

It is often desirable to measure single cut antenna patterns for antenna characterization. For example, antenna vendors often provide principle plane cut data in their datasheets. These pattern data are often collected in an indoor chamber where reflections from the chamber walls are of concern. To reduce the effect from extraneous reflections, the rotating antenna is usually placed as closely to the rotation center as possible to ensure a constant incident illuminating field. In the mode filtering scheme, the antenna is actually displaced with an intentional offset away from the rotation center [1, 2, 3, 4, 5]. This seems counterintuitive, as it exacerbates the reflection effects on the measured antenna pattern. However, with the aid of transforming the pattern to the mode spectrum domain and by mode filtering, it actually allows for a more accurate antenna pattern measurement through post processing. In the mode spectrum domain, the number of modes associated with a source is dictated by the Maximal Radial Extent (MRE) of the antenna under test (AUT), which is defined as the smallest radius which can encircle the rotating antenna and that is centered at the origin of the rotation axis [2, 3]. The bigger the MRE, the larger the number of modes needed to accurately represent the radiating field. Specifically, the number of modes required is proportional to the product of the MRE and the free space propagation constant. When the antenna is measured with a significant offset (compared to the size of the antenna), the number of modes required is much larger than if it were located in the rotation center. The antenna pattern, measured with an offset, can be then translated to the rotation center through a coordinate translation if the displacement is precisely known [4]. After the mathematical translation, the MRE is now confined to the size of the antenna, as though it were physically located in the center. Meanwhile, the chamber multipath effects are not phase coherently translated, so they remain in the higher order modes. This provides the opportunity to apply a filter to suppress the reflections [1, 2, 3, 4, 10].

In a related application, the cylindrical mode filtering method is proposed to measure the Site Voltage Standing Wave Ratio (SVSWR) in an EMC anechoic chamber to evaluate the quiet zone (QZ) performance [6, 7, 8, 9]. In this technique, an electrically small omnidirectional antenna is placed at the edge of the QZ (which is typical defined by a turntable on the floor), several single cut antenna patterns (with different antenna polarizations, orientations and heights) are measured with the antenna placed at the edge of the turntable. With the aid of the mode filtering described above, a reference pattern is obtained. The difference between the patterns before and after the filtering represents the standing wave pattern along the perimeter of the QZ. For the mode filtering method to work effectively, it is important to accurately know the offset distance. The conventional method is to measure it by using a ruler, tape measure, laser tracker, *etc*. Not only is this tedious, but is potentially inaccurate and prone to errors which can compromise the effectiveness of the mode filtering. The present work is motivated by the desire to obtain the offset distance automatically by taking advantage of the vector pattern data, which is already available within this measurement.

An obvious method to find the displacement is by inspecting the unwrapped phase as a function of rotation angle. The maximum phase differential in a revolution divided by the wavenumber should be twice the offset distance. This approach can work for "well-behaved" antennas, but proves to be far more challenging for complicated patterns with nulls and phase reversals. Phase changes across nulls can be ambiguous, and a taking a "wrong" branch phase value at a single step can upset the entire calculation. Instead, we propose to use an alternative method to compute the offset utilizing the entire pattern data. The optimal offset distance should be the one that yields the least phase variation, or provides the flattest phase response, in the translated pattern data. This aligns with one of the commonly used definitions for the antenna phase center [11].

Another option is to use time domain transformation. If the measurement data is broadband, the inverse Fourier transform of the frequency response provides time of arrival information, which can help solve for the offset distance. The drawback of this method is the bandwidth requirements, which limit the usefulness for many antennas.

Perhaps a more universal method is to examine the cylindrical mode distribution itself. The postulation is that if the offset distance is accurately applied in the coordinate translation, the antenna modes should be tightly concentrated about the lowest order mode, $n = 0$. Therefore, the distance which can bundle the modes best to the lowest order should be the sought-after offset distance. In [12], the authors show the relationship between N_{Max} (the maximum number of lowest order modes which contains a predetermined percentage of the total power (for example, 99.9995%) as a function of translation distance. The "optimal" offset is the one which yields the smallest $|N_{Max}|$. One of the considerations is the sensitivity of the N_{Max} value to the change of distance for various antennas. Note that for a given translation distance, finding N_{Max} at a given percentage of total power is an iterative calculation. In this study, we propose an alternative scheme. Since the size (and therefore the MRE) of the antenna is known, a filter can be applied to include only the modes which can be supported by the MRE (for example, using a filter width of $k_0 \cdot \text{MRE} + N_0$, where k_0 is the wavenumber, and N_0 is a safety factor). We may then find the offset distance which can yield the most power within the filter. This requires only one computation of CMC's per assumed distance, which is more computationally efficient. It also affords the user the flexibility to adjust the filter shape to promote certain power distribution profiles, *e.g.*, to match a known antenna modal distribution. We will show the results using both in this study.

II. Measurement and Data Processing

Measurements were taken in an EMC anechoic chamber, as seen in Fig. 1. The transmit antenna was a mini-biconical antenna, specified to operate from 18 to 40 GHz. The Remote Sensing Antenna (RSA) was a double ridged waveguide horn antenna operating in the same frequency range. The radius of the offset used was approximately 60 cm, and the RSA was placed 3.6 m from the center of the rotation. S_{21} data was collected at every 1° angular step for across the entire 18 to 40 GHz frequency range using 8001 points. Patterns for three antenna orientations were measured as shown in Fig. 2. In all cases, the RSA and the antenna under test (AUT) were co-polarized (*i.e.*, they were both horizontally, or both vertically polarized, in the same measurement).

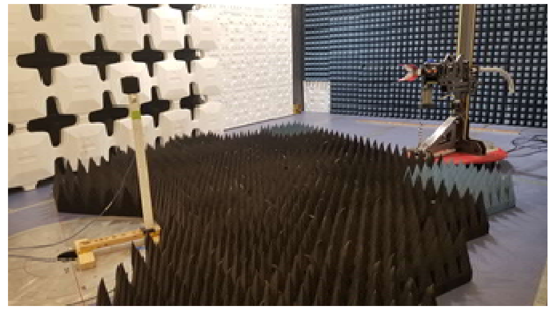

Fig. 1. Photo of the measurement setup, with an dipole-like biconical antenna placed at the edge of the turntable, and a double ridge waveguide horn antenna placed at 3m from the front edge of the QZ.

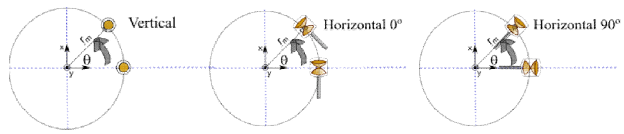

Fig. 2. Three pattern cuts used to qualify a EMC chamber.

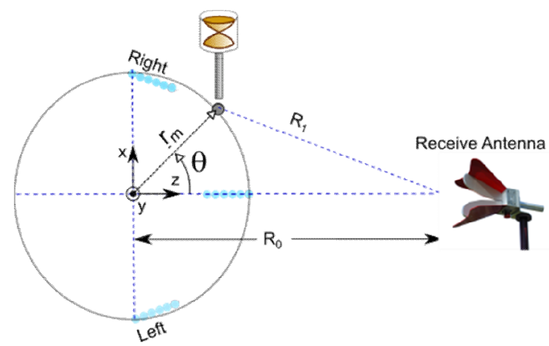

Fig. 3. Illustration of the measurement topology.

A. Minimum Phase Variation

The first method to find the offset distance is by inspecting the phase variation after the translation. Ideally, if the translation moves the antenna phase center to the center of rotation, there would be minimal phase variation versus. rotation angle. The translated phase angle of the electric field $\angle E_{\text{transl}}$ is given by,

$$\angle E_{\text{transl}}(\theta) = \text{unwrap}\{\text{mod}[k_0(R_1 - R_0) + \angle E_\theta, 2\pi]\} \quad (1)$$

where $\angle E_\theta$ is the phase angle before the translation, k_0 is the wavenumber, and R_0, R_1 are defined in Fig. 3. To find the minimum phase variation, we employ a L1 optimization to minimize $\Delta\alpha$. Compared to L2 optimization, L1 is less influenced by outliers,

$$\Delta\alpha = \sum_\theta \left|\angle E_{\text{transl}}(\theta) - \text{mean}\left(\angle E_{\text{transl}}(\theta)\right)\right| \quad (2)$$

The red line in Fig. 9 shows the results for vertical polarization. Figs. 10 and 11 show the results for the two horizontal cases. Note that for ease of comparison, the data from the different methods are plotted together in Figs. 7, 8, and 9, so upon first reading the references to them might appear out of order. In general, the resulting offset r_m for the vertical case was found to be very consistent across the entire frequency range. This is because the antenna pattern is mostly omnidirectional, and the feed cable has the least impact on the vertical polarization (the biconical antenna is end-fed, as can be seen in Fig. 2). For horizontal 0° case, the variation of r_m is noticeable larger as a function of frequency than both the vertical and horizontal 90° cases. This is likely cause by the feed cable, which is tangential to the rotation direction, and is co-polarized with the RSA. The cable was left draping freely down to the floor in the measurement. It can move more with respect to the antenna itself during the rotation than the horizontal 90° case where the feed cable is oriented radially toward the center. The result illustrates the sensitivity of the minimum phase variation method to cable perturbations, and highlights the importance of cable management. A more careful measurement setup, for example, by affixing the cable on the vertical stand with tape, would have likely yielded better test results. It is prudent to check the resulting r_m, for example, by inspecting the data as a function of frequency, or cross-checking against results obtained using another method discussed herein.

B. *Time domain method*

The time domain (TD) method is comparatively straightforward. Broadband data can be inversely transformed (via an inverse Fourier transform) to the TD domain, which provides the impulse response view. Similar to the minimum phase variation method, we use time of arrival for every angle in the rotation, and solve for r_m in a least square sense by minimizing the cost function below,

$$\text{cost} = \sum_{\theta}\{[\mathrm{c}\cdot t_p(\theta) - \mathrm{mean}(\mathrm{c}\cdot t_p(\theta))] - [R_1(\theta) - \mathrm{mean}(R_1(\theta))]\}^2 \quad (3)$$

where $t_p(\theta)$ is the antenna time domain response main peak at angle θ, in s;
c is the speed of light, approximately 3×10^8 m/s;
R_1 is the distance between antennas, as defined in Fig. 3.

Because r_m is solved from broadband data, the resulting r_m is constant as a function of frequency. The black curves in Figs. 9, 10 and 11 show the results.

C. *Mode Bundle – Minimal N_{Max}*

In this scheme, the goal is to find the value of r_m which would produce the smallest $|N_{Max}|$, where N_{Max} is defined as maximum mode order below which a certain percentage of the power resides. The percentage of power to apply is related to the total reflections in the chamber. Fig. 4 shows the resulting r_m for vertical polarization using 94%, 96% and 98% of the total power to calculate N_{Max}. Here, it can be seen that 96% produces the most stable results across the frequency range. Because this is an iterative process to find N_{Max}, it takes on average over 2000 iterations (using Matlab *fzero* function) to find the optimal r_m at each frequency. The green curves in Figs. 9, 10 and 11 are the resulting offset r_m obtained using this method.

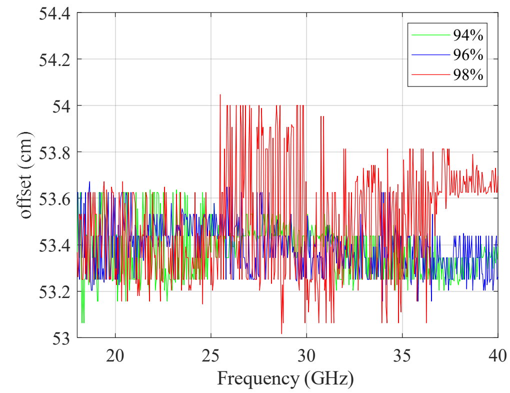

Fig. 4. Computed r_m for vertical polarization using mode bundle (minimal N_{Max}) and various percentage of power.

D. *Mode Bundle – filtered max power*

Instead of trying to find the N_{Max}, here a modal filter is applied to include the modes below $k_0 \cdot \mathrm{MRE} + N_0$, where N_0 is a safety factor and MRE includes the antenna only without any offset. In this application, $N_0 = 2$ works well. As seen in Fig. 5, the biconical antenna has a general modal distribution which is sharply biased toward the lowest order. The raised power cosine filter promotes the solution which can produce this behavior. The shape of the filter function can affect the results. Several filters have been investigated, as shown in Fig. 6. Fig. 7 shows the cost function using these filters. It is found that $\cos^{0.1}()$ filter provides a good compromise between preserving the total power and promoting the mode concentration toward the lower order for the three orientations used in this study, therefore, it is chosen for this application. As a comparison, Fig. 8 shows the cost function using the minimal N_{Max} mode bundling method. Since the mode numbers are integers, the number of modes does not change instantaneously with a varying r_m, which explains the stepped behavior in the cost function and jagged solution for r_m, for example, shown as the green curves in Figs 9, 10 and 11. Additionally, because only one calculation is needed to calculate the power within the filter per assumed offset, only 26 iterations on average are needed to solve r_m per frequency, so using the filtered power as the cost function is more stable and far more efficient than using the minimal N_{Max} method.

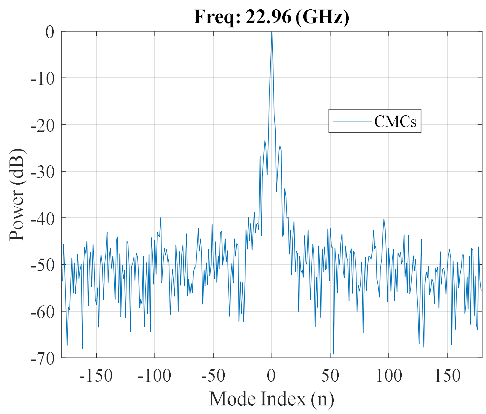

Fig. 5. Modal distribution of the vertical biconical antenna.

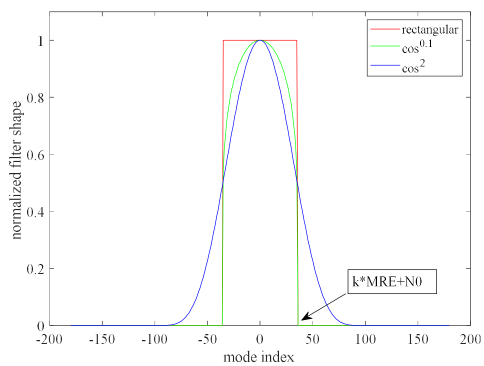

Fig. 6. Shape of the modal filter used in the mode bundle – filtered max power method.

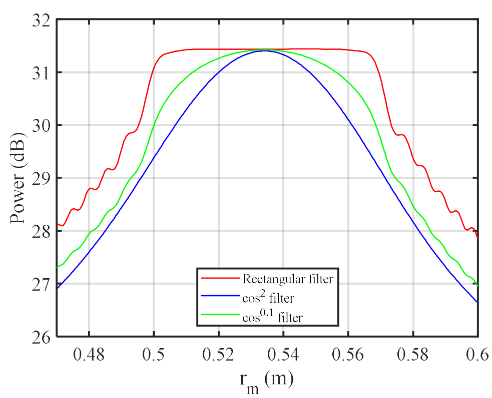

Fig. 7. Cost function of the mode bundle – maximum filtered power method (for vertical case at 37 GHz), showing the power after filtering as a fucntion of r_m.

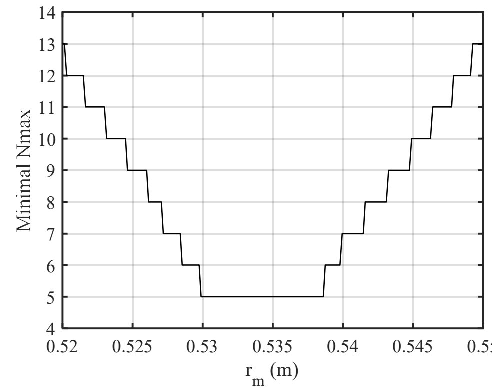

Fig. 8. Cost function of the mode bundle at – minmal N_{Max} method (for vertical case at 37 GHz), showing N_{Max} as a function of r_m.

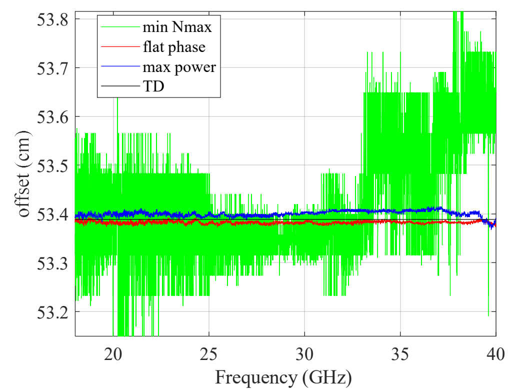

Fig. 9. Computed r_m for vertical polarization.

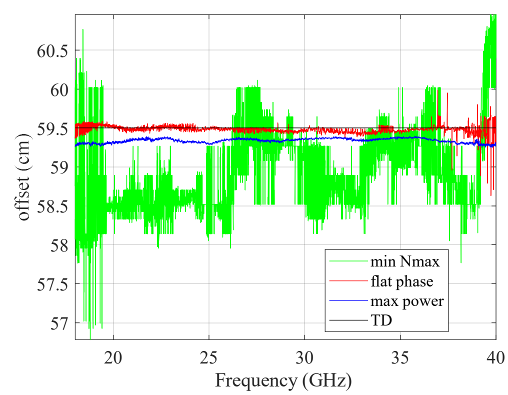

Fig. 10. Computed r_m for horizontal polarization (horizontal 90º case).

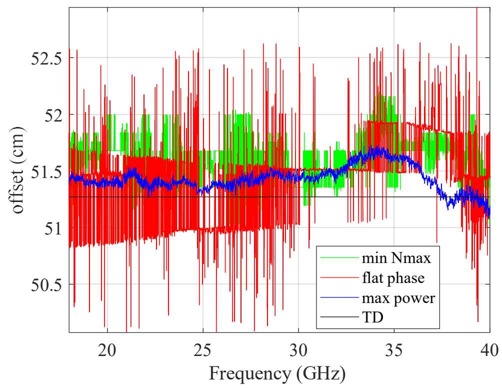

Fig. 11. Computed r_m for horizontal polarization (horizontal 0° case).

III. VALIDATION USING A DIFFERENT SETUP

As can be seen from the results presented above, the mode bundling method in general is a robust, efficient method to automatically determine the offset distance. For the purpose of measuring antenna pattern using the modal filtering technique, this is perhaps the more direct and relevant method as well. The mode bundling method, based on filtered maximum power, appears to be more robust and efficient. The minimal phase variation method in cases where the phase data is accurate and stable, can also work reasonably well but it is important to note that the two methods are seeking to solve for related, but slightly different properties of the antenna [11]. To further validate these processing techniques, the biconical antenna is moved closer to the rotation center with an approximate 10 cm offset. Fig. 12 shows the vertical results, and Figs. 13 and 14 show the two horizontal cases. They follow very similar trends as the larger offset cases. This further validates these processing methods.

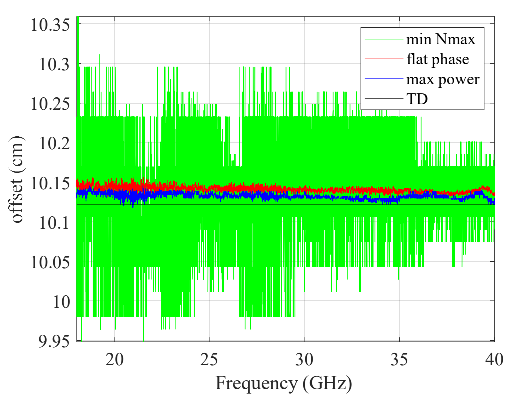

Fig. 12. Computed r_m for vertical polarization for a smaller offset.

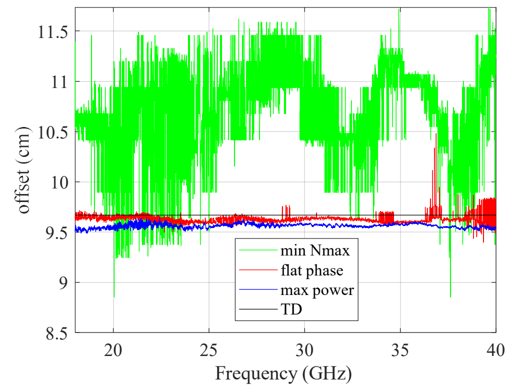

Fig. 13. Computed r_m for horizontal polarization (horizontal 90° case).

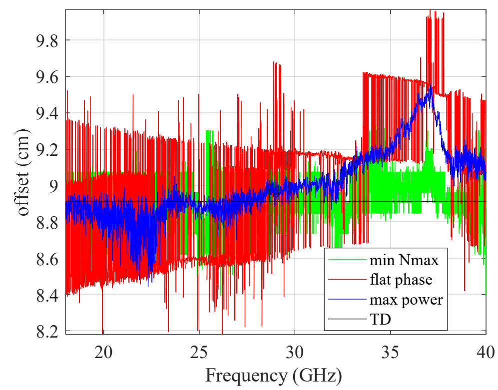

Fig. 14. Computed r_m for horizontal polarization (horizontal 0° case).

IV. CONCLUSIONS

In this study, we applied several techniques to find the antenna offset distance from the center of rotation using quasi-far-field single-cut pattern data. The study is motivated by the desire to find the displacement distance automatically in mode filtering applications, but these methods can be equally useful in finding the phase center of an antenna in other applications. The methods investigated include one based on minimizing the phase variation through the rotation, one using time domain time of arrival information, and two mode bundling techniques by transform the pattern data to the spectrum domain. The first mode bundling methods is to find the offset which can minimize the number of cylindrical modes containing a given percentage of total power. The second mode bunding method is to locate the offset which can maximize the total power within the modes supported by the MRE. Of these methods, for antennas with accurate phase measurements with minimal cable perturbations, the minimum phase method can work well, but can breakdown for complicated patterns, especially those perturbed by feed cable. The time domain method works well for broadband antennas, but it might be limited in narrow band applications. The second mode bundling method which seeks to maximize the power within the modes supported by the MRE is proven to be the more robust and universal method among these methods. In mode filtering applications, *e.g.*, to remove extraneous multipath reflections in antenna patterns, it is perhaps the most applicable and direct method. It is also advisable to use multiple methods to cross check the solution when applicable.

REFERENCES

[1] S.F. Gregson, A.C. Newell, G.E. Hindman, "Reflection Suppression In Cylindrical Near-Field Antenna Measurement Systems – Cylindrical MARS", Antenna Measurement Techniques Association Symposium (AMTA), 2009.

[2] S.F. Gregson, B.M. Williams, G.F. Masters, A.C. Newell, G.E. Hindman, "Application of Mathematical Absorber Reflection Suppression To Direct Far-Field Antenna Range Measurements", Antenna Measurement Techniques Association Symposium (AMTA), 2011.

[3] S.F. Gregson, J. Dupuy, C.G. Parini, A.C. Newell, G.E. Hindman, "Application of Mathematical Absorber Reflection Suppression to Far-Field Antenna Testing", LAPC, Loughborough, November, 2011.

[4] G.E. Hindman, A.C. Newell, "Reflection Suppression To Improve Anechoic Chamber Performance", AMTA Europe, Munich, Germany, March 2006.

[5] C.G. Parini, S.F. Gregson, J. McCormick, D. Janse van Rensburg "Theory and Practice of Modern Antenna Range Measurements", IET Press, 2014, ISBN 978-1-84919-560-7.

[6] Z. Chen and S. Gregson, "Examination of EMC Chamber Qualification Methodology for Applications above 1 GHz Using Frequency Domain Mode Filtering", in *Antenna Measurement Techniques Association Symposium (AMTA)*, 2020.

[7] Z. Chen and S. F. Gregson, "EMC Chamber Quiet Zone Qualification for Applications Above 1 GHz Using Frequency Domain Mode Filtering," in *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1-9, 2021, Art no. 6504909, doi: 10.1109/TIM.2021.3119143.

[8] Z. Chen and S. F. Gregson, "Intercomparisons of Site VSWR Measurement Methods using Mode Filtering, Time Domain and Spatial Sampling Techniques", in *Antenna Measurement Techniques Association Symposium (AMTA)*, 2021.

[9] Z. Chen and P. Miller, "Extending Site VSWR to Millimeter Wave Using Cylindrical Mode Filtering", International Symposium on Electromagnetic Compatibility (EMC Europe), Gothenburg, Sweden, 2022.

[10] S.F. Gregson and Z. Tian, "Verification of Generalized Far-Field Mode Filtering Based Reflection Suppression Through Computational Electromagnetic Simulation", IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, 5-10 July 2020, Montréal, Québec, Canada.

[11] A.W. Rudge, K. Milnw, A.D. Olver, P. Knight, "The Handbook of Antenna Dasign, Vol. 1", IEE Electromagnetic Waves Series 15, Peter Peregrinus Ltd., 1982, ISBN 0-906048-82-6.

[12] S. F. Gregson and Z. Tian, "Full-Wave Three-Dimensional EM Simulation of a Spherical Range to Examine and Optimise the Effectiveness of Mode Filtering Based Post Processing Techniques," *2021 15th European Conference on Antennas and Propagation (EuCAP)*, 2021, pp. 1-5.