Modeling and Analysis of Anechoic Chamber Using CEM Tools

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***Abstract*—** Advances in computational resources facilitate anechoic chamber modeling and analysis at VHF/UHF frequencies using full-wave solvers available in commercial software such as FEKO. The measurement community has a substantial and increasing interest in utilizing computational electromagnetic (CEM) tools to minimize the financial and real estate resources required to design and construct a custom anechoic chamber without sacrificing performance. A full-wave simulation analysis such as the finite element method (FEM) provides a more accurate solution than the approximations inherent to asymptotic ray-tracing techniques such as physical optics (PO), which have traditionally been exploited to overcome computational resource limitations. An anechoic chamber is simulated with a rectangular down-range cross-section (in contrast with the traditional square cross-section) to utilize the software's capability to assess polarization performance. The absorber layout within the anechoic chamber can be optimized using FEKO for minimal reflections and an acceptable axial ratio in the quiet zone. Numerical results of quiet zone disturbances and axial ratios are included for both low- and medium-gain source antennas over a broad frequency range.

Index Terms - Anechoic chamber, axial ratio, computational electromagnetics, FEKO, finite element method, and physicaloptics.

I. INTRODUCTION

The optimum choice of anechoic chamber dimensions is crucial to ensure the minimum performance level of the quiet zone and to minimize the system cost. In many cases, however, the dimensions are predetermined (e.g., rectangular rather than square cross-section). The chamber geometry is not the only parameter limiting quiet zone performance. The quiet zone behavior depends on several factors such as absorbing material performance, layout and grades, source antenna/device under test (DUT) separation, source antenna beamwidth, DUT positioning equipment geometry and material, *etc*. A full 3D electromagnetic analysis must be performed to correctly account for all of these parameters.

To date, the industry most often analyzes anechoic chambers with a method similar to "ray tracing", which suffers from poor accuracy. The inaccuracy is especially prevalent in scenarios where the room characteristic dimensions are only a few wavelengths (i.e., a typical situation at VHF/UHF frequency bands). A few components contributing to the inaccuracy are detailed below:

- Limited data is available on the reflectivity of absorbing materials at VHF/UHF, especially at off-normal incidence.Historically, the reflection coefficient is only described by magnitude and the phase is not provided. As a result, only approximate information can be extracted from the RMS fields in the quiet zone. In some cases, assumptions were made on the reflectivity at off-normal incidence

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angles at VHF/UHF frequencies based on similarities to better established reflectivity curves at higher frequencies (e.g.,>2.0GHz). However, the extrapolation has been proven inaccurate for a number of VHF/UHF chambers.In other cases, the off-normal incidence data is retrieved from normal incidence reflectivity using Fresnel formulas, which are accurate for planar absorbing multi-layered structures only.

- Specular area characteristic dimensions include a few wavelengths of surface covered by absorbing material (e.g., pyramids, wedges, *etc*.), which at VHF/UHF may exceed side wall characteristic dimensions and may, therefore, span a large range of incidence angles of the illuminating rays on the specular area. Choosing the correct incidence angle and corresponding reflection coefficient at each consecutive specular point then becomes a difficult process. Upgrading the "ray-tracing" method to the "aperture integration" method is a better fit for the analysis. However, accuracy is limited by the data available for the reflectivity of absorbing materials.

Thus, the need for a more rigorous and comprehensive analysis such as a full 3D electromagnetic simulation is obvious, especially at VHF/UHF bands [1, 2].Insufficient accuracy in the chamber design has resulted in some poor chamber implementations in the past. Even identifying improper chamber performance with the VSWR test procedure is a difficult process at VHF/UHF bands. The test may show uniform field distribution in the quiet zone, while the overall chamber performance is far from optimal.

Some factors limiting the effectiveness and accuracy of the VSWR tests for chamber certification at the VHF/UHF bands are:

- Often the test zone dimensions are comparable to or less than 1λ at the lowest operating frequency. Thus, visually retrieving and/or distinguishing the ripples (period and ripple amplitude) associated with multiple reflections in the chamber interior to the fullest extent from the measured data are part of a difficult process. The chamber may even appear to achieve acceptable performance in scenarios where the reflected signal is stronger than the direct (desired) one.
- Due to geometry constraints the field probe antenna used in the free-space, VSWR procedure is typically a low- or medium-gain antenna. In cases with relatively high reflections in the shielded room, the reference measurement results may be in error. An uncertainty is then added through the entire VSWR data processing. Consequently, there could be a situation at VHF/UHF bands where the VSWR tests optimistically report the quiet zone reflectivity performance.
- The VSWR procedure is often inapplicable without modifications (e.g.,transversal cuts in elongated chambers such as tapered ones). As a result, the procedure is frequently "engineered" to exclude conflicting/confusing measurement data.

The primary manifestation of a poor elongated chamber performance includes:

- Inconsistent longitudinal trace behavior in the quiet zone over a broad frequency range.
- Significant signal level variation over a broad frequency range with the source and probe antennas rotated simultaneously (clocked) around their boresight (the chamber line of sight).

In order to assure that the chamber performs well, a significant amount of extra testing is required to be performed on the quiet zone, which might be costly or often impossible to execute. Effort has previously demonstrated an efficient method for modeling the reflectivity of absorber, while saving computational resources as compared to a full 3D EM solver [3].

A full 3D anechoic chamber simulation at VHF/UHF frequencies is a helpful tool that may be used to predict/estimate some test results and assure optimal performance. In particular, 3D anechoic chamber simulations can estimate the axial ratio accuracy, which can be achieved in the chamber with a non-square cross-section.

II. NUMERICAL METHODS

As computational resources such as memory and processors continue to experience reductions in price, state of the art CEM techniques available in commercial software packages such as FEKO [4] are becoming a more attractive option for engineers during the design phase of anechoic chambers. Full-wave techniques, such as finite-

difference time-domain (FDTD), method of moments (MoM), multi-level fast multipole method (MLFMM), and finite element method (FEM) accurately solve Maxwell's equations without approximations and are therefore becoming a popular choice with the availability of cheaper memory and CPU power. To demonstrate feasibility of anechoic chamber design at VHF/UHF frequencies using a full-wavetechnique such as FEM, we chose the commercial EM simulation tool FEKO.

FEKO is a comprehensive electromagnetic software suite that includes asymptotic solvers such as physical optics (PO), geometrical optics (GO), and uniform theory of diffraction (UTD) together with the full-wave solvers including MoM, MLFMM, and FEM. The asymptotic methods and FEM have been hybridized with MoM to assist with solving large and complex problems [5-7]. Asymptotic methods are well suited for the analysis of electrically large anechoic chambers. Apart from providing a solution with limited resources, asymptotic methods operate with underlying approximations wherein vigilance is required to model the problem well within those approximations.

In this paper, the analysis and design process for an anechoic chamber is presented. The design process utilizes both the full-wave FEM and asymptotic PO techniques, which are ideal for this electrically large, non-radiating dielectric model. FEM utilizes a volume meshing technique that employs tetrahedral elements to accurately mesh arbitrarily shaped volumes where the dielectric properties may vary between neighboring tetrahedral elements. The outer shell is meshed with triangular elements and does not require a radiation boundary. In contrast, PO utilizes a surface meshing technique that employs triangular elements to accurately mesh arbitrarily shaped surfaces where the dielectric properties are homogeneous.

III. CHAMBER AND ANTENNA MODELING

A custom anechoic chamber with a rectangular down-range cross-section (i.e., W × H) is modeled to fit within a physically limited volume. FEM was used to analyze an anechoic chamber model with a perfectly conducting outer shell. The chamber dimensions are 17″ H × 24″ W × 32.5″ L as shown in Fig. 1, where the orange color represents the outer shell modeled as PEC and the blue represents the inner absorbing material.

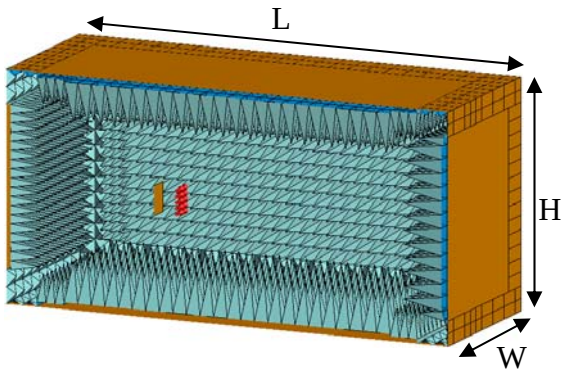

Fig. 1. Anechoic chamber model dimensions.

The center of the quiet zone is 10″ from the receiving wall and measures 6″ H × 6″ W × 6″ L. The source antenna is modeled at a 10″ separation from the center of the quiet zone (i.e., 20″ from the receiving wall) and visible left of center in Fig. 1. PO was employed to analyze an anechoic chamber model with a dielectric shell as shown in Fig. 2, because FEKO limits the analysis with PO to a single material within a given model.

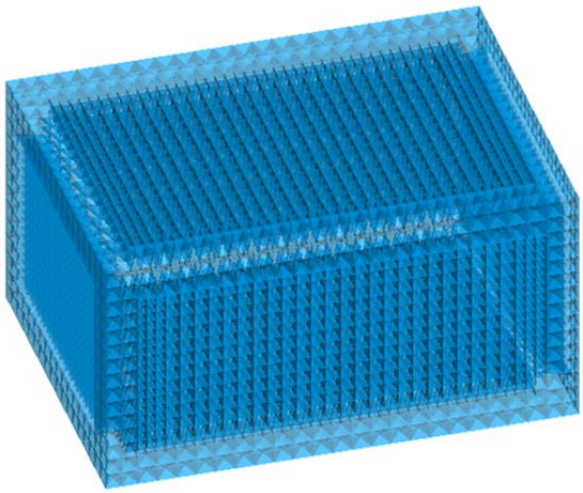

Fig. 2. Anechoic chamber analyzed with PO.

Both low- and medium-gain source antennas are modeled for vertical and horizontal polarizations with a directive gain of ~6 and 10 dBi, respectively. Any type of source antenna can be included in the model. For practical reasons, we

have chosen to generate a source antenna, similar to Fig. 3, with 25 current sources measuring λ/15 in length and arranged on a plane to achieve the desired beam widths in both the E- and H-planes, where λ is the operating wavelength. A realistic pattern is emulated by minimizing the energy radiating toward the rear of the chamber with a PEC reflector separated by λ/4 (represented by orange).

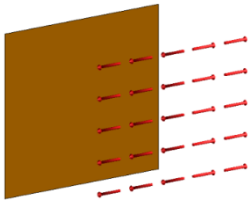

Fig. 3. Source antenna model used for analysis.

The 3dB beam widths (BW) of the source antennas are summarized below in Table II.

Table I: Source antenna of 3 dB BW.

Gain	E-Plane 3dB BW	H-Plane 3dB BW
Low	68º	111º
Medium	65º	67º

A center patch region of the two side walls, the receiving wall, the floor and ceiling were modeled with large pyramidal absorber and surrounded by small pyramidal absorber as illustrated in Fig. 4.

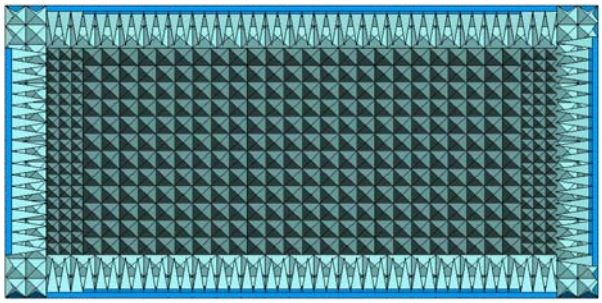

Fig. 4. Large absorber was used in center patch region of several walls.

The large pyramidal absorber is modeled with a 12″ H × 12″ W × 6″ L cuboid base below a 36″ long pyramid. The small pyramidal absorber in the surrounding area is modeled with an 8″ H × 8″ W × 4″ L cuboid base below a 24″ long pyramid as shown in Fig. 5.

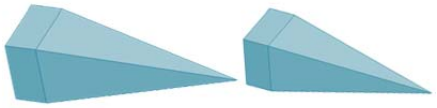

Fig. 5. Large and small pyramidal absorber models.

The real and imaginary dielectric constant for the absorbing material is illustrated in Fig. 6 and 7, respectively. The upper line indicates the maximum value, the lower line indicates the minimum value and the middle solid line indicates the average dielectric constant resulting from the manufacturing tolerances.

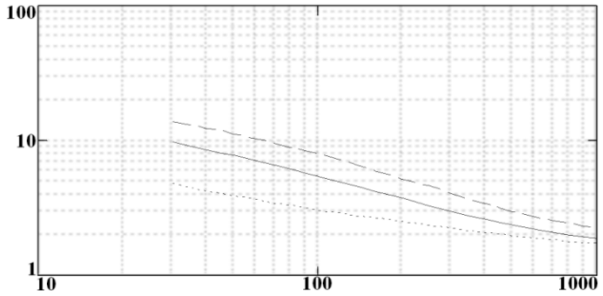

Fig. 6. Real dielectric constant for the absorber.

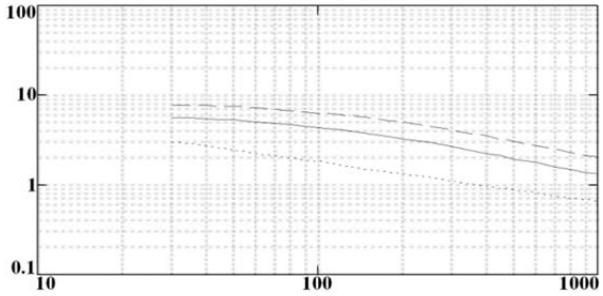

Fig. 7. Imaginary dielectric constant for the absorber.

We have elected to use the average dielectric constant and loss tangent for the absorber as summarized below in Table II for the frequencies analyzed.

Table II: Absorber material properties.

Frequency	ε'_r	ε''_r	Tan δ
150 MHz	4.758	4.467	0.93884
250 MHz	3.5	3.0	0.85714
500 MHz	2.4	1.95	0.81250
1000 MHz	1.95	1.4	0.71795
2000 MHz	1.95	1.4	0.71795

The computer memory required depends on the size of the mesh (i.e., number of tetrahedra and/or triangles), dielectric constant, and frequency as summarized in Table III and IV.

Table III: FEM mesh characterization.

Frequency	Tetrahedra	Triangles	Memory
150 MHz	1181640	43508	14 GB
250 MHz	3265760	86404	43 GB
500 MHz	12 583 444	234 684	196 GB

Table IV: PO mesh characterization.

Frequency	Triangles	Memory
500 MHz	2 364 916	10 GB
1000 MHz	7 615 698	31 GB
2000 MHz	30 035 292	123 GB

The respective run times required for this model are listed inTableV.

Table V: Simulation runtime.

Frequency	Method	Run Time
150 MHz	FEM	3 min
250 MHz	FEM	12 min
500 MHz	FEM	81 min
500 MHz	PO	27 min
1000 MHz	PO	77 min
2000 MHz	PO	271 min

Simulations were performed on a workstation with an Intel Xeon E5-2650 CPU with a total of 8 processors operating at 2.0 GHz. The workstation had 256 GB of shared memory available.

IV. ERROR ANALYSIS

Numerical results are computed for both the down-range cross-section of the fields in the center of the quiet zone and the down-range axial ratio. The quiet zone fields were then normalized with fields produced by an identical antenna radiating into free space. This process was repeated for two distinct frequencies (i.e., 150 MHz and 250 MHz). The normalized fields represent an error termproduced by energy reflecting off of the absorber,

$$\varepsilon = \left| 20 \log \sqrt{\frac{\sum |Chamber\ Field\ Components|^2}{\sum |Clear\ Site\ Field\ Components|^2}} \right|. \quad (1)$$

The down-range axial ratio,quantifies the polarization performance of an anechoic chamber by comparing the results from a simulation using a horizontally polarized antenna to the results from a simulation using a vertically polarized antenna,

$$AR = \left| 20 \log \sqrt{\frac{\sum |H\ Pol\ Field\ Components|^2}{\sum |V\ Pol\ Field\ Components|^2}} \right|. \quad (2)$$

These two equations help quantitatively validate the performance of a custom anechoic chamber configuration.

V. RESULTS

The errors produced in the central cross-section of the quiet zone have been analyzed with equation (1) for both low- and medium-gain source antennas for horizontal and vertical polarizations.

Fig. 8, 9, and 10 illustrate the results for a horizontally polarized, low-gain source antenna operating at 150 MHz, 250 MHz,and 500 MHz, respectively. The vertically polarized data sets were omitted for brevity. Fig. 11 and 12 depict the error produced when operating at 150 MHz and 250 MHz, respectively, for a vertically polarized, medium-gain source antenna. The horizontally polarized data sets were omitted for brevity.

Note the collection of plots in Fig. 8 through Fig. 12 illustrates a quiet zone error generally below 1 dB. Fig. 13 illustrates the axial ratio error from equation (2) along the length of the anechoic chamber through the center of the quiet zone for low- and medium-gain source antennas operating at 150 MHz and 250 MHz.

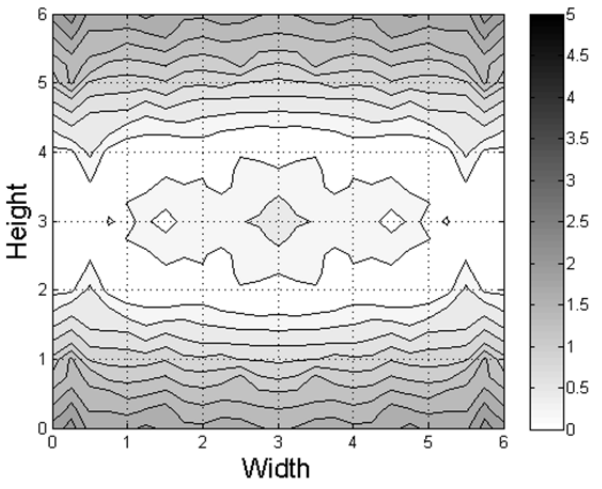

Fig. 8. Error when operating an H-polarizedlow-gain source antenna at 150 MHz.

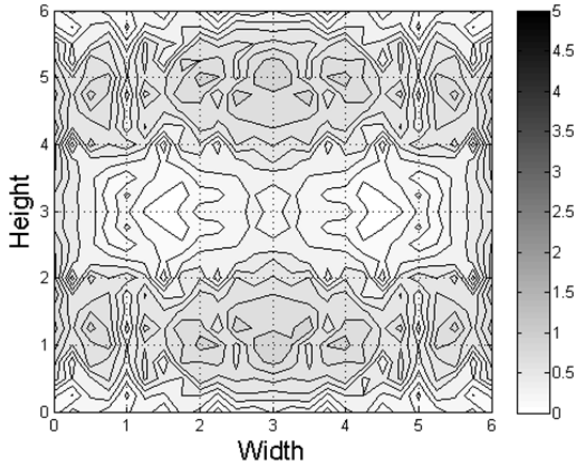

Fig. 9. Error when operating an H-polarizedlow-gain source antenna at 250 MHz.

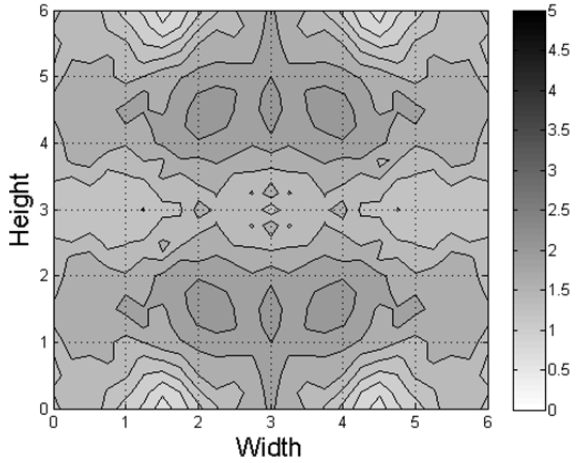

Fig. 10. Error when operating an H-polarized low-gain source antenna at 500 MHz.

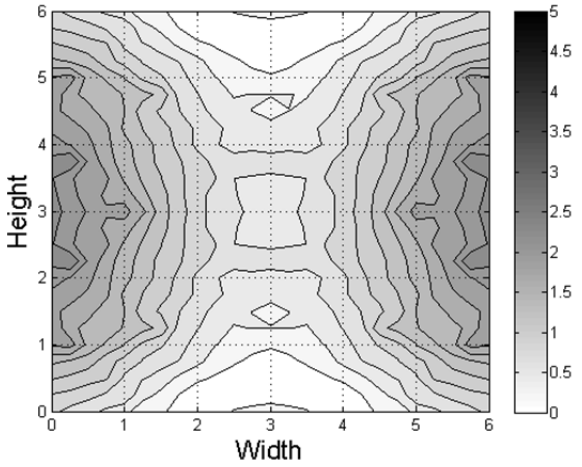

Fig. 11. Error when operating a V-polarized medium-gain source antenna at 150 MHz.

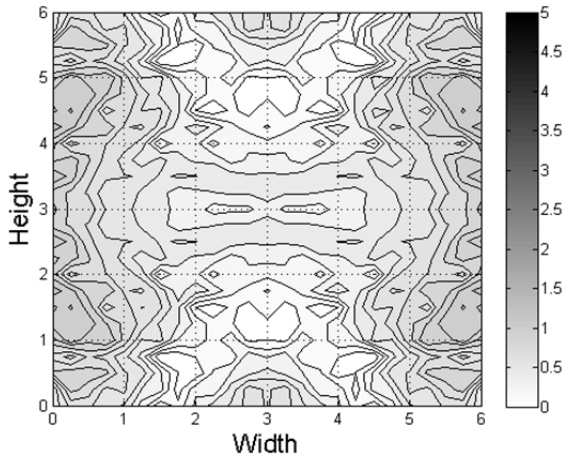

Fig. 12. Error when operating a V-polarizedmedium-gain source antenna at 250 MHz.

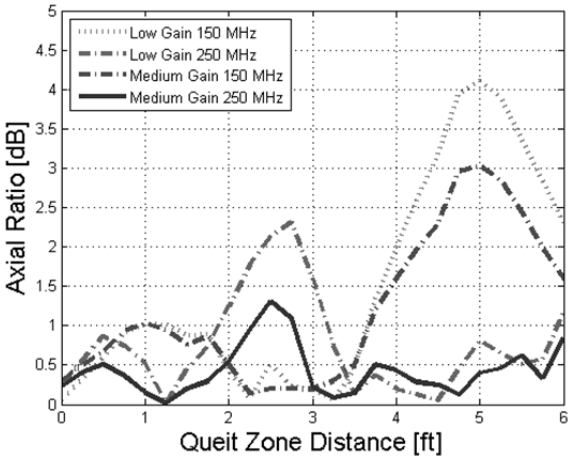

Fig. 13. Axial ratio for low- and medium-gain source antennas operating at 150 and 250 MHz.

Note the behavior of the curves in Fig. 13 is largely explained by the rectangular cross-section of the chamber resulting in:

- Different reflectivity exhibited by the side walls, the floor, and the ceiling.
- Different free space attenuation associated with different propagation distance of the reflected waves from the side walls and the floor and ceiling to the center of the quiet zone.

In theory, the axial ratio does not exist in a symmetrical chamber with a squared cross-section. If detected in a practical squared cross-section chamber, the axial ratio error is associated only with the manufacturing tolerances contributing to the error.

In addition to analyzing the anechoic chamber with FEM, the PO technique was also validated by comparing near fields in the quiet zone when operating at 500 MHz. The difference between the FEM and PO results is illustrated in Fig.14.

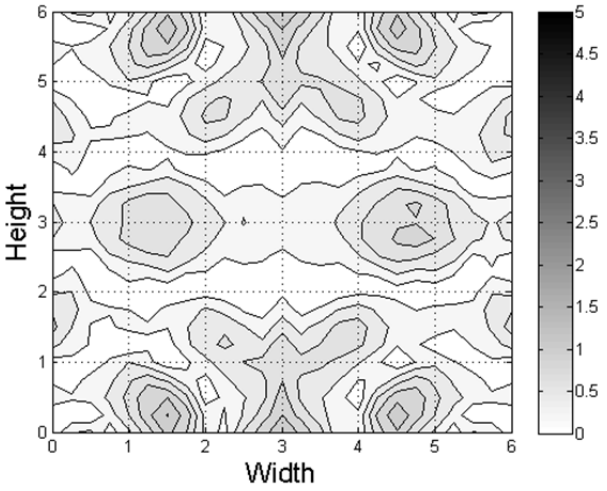

Fig.14. The difference between FEM and PO analysis results when operating at 500 MHz.

The PO technique is shown to have a maximum error of 1.0 dB when computing near fields in the quiet zone of an anechoic chamber. The additional error introduced by the physical optics method is limited, which facilitates simulating the anechoic chamber at much higher frequencies. As shown in Table IV and V, we simulated the anechoic chamber up to 2 GHz. Further increases in frequency are possible.

VI. CONCLUSION

Both full-wave and asymptotic analyses have been performed on the quiet zone of a rectangular cross-section anechoic chamber at VHF/UHF frequencies using a 3D solver within the FEKO simulation software. The results demonstrate meaningful and expected performance in the chamber with rectangular cross-section, which indicate that:

- Quiet zone performance (reflectivity) is improving as operating frequency increases.
- Quiet zone performance degrades with the increasing separation between the source antenna and quiet zone.
- A higher gain source antenna provides better quiet zone performance.
- The linear rotating polarization axial ratio is getting worse with longer separation between the source antenna and the quiet zone.
- Axial ratio is improving at higher frequencies.
- Axial ratio is improving for a higher gain source antenna.

FEKO is an effective tool for performing computational analyses of anechoic chambers at VHF/UHF frequency bands. Of particular value is the fact that one can switch from a rigorous method like FEM to an asymptotic method like PO within the same environment. Future applications of the FEKO simulation software to assist with analyzing anechoic chambers are expected.

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