EFFICIENT DESIGN OF A RADOME FOR MINIMISED TRANSMISSION LOSS

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Abstract

A radome has to be carefully designed to ensure it has minimum impact on the performance of the antenna. Traditional approaches involve equation approximations, complex ray tracing, iterative manufacturing process and or electrically large and lengthy Electromagnetic (EM) simulations. The novel approach described in this paper involves a 2D Ray Tracing Method (2DTRM) simulation in MATLAB and an electrically small unit cell simulation in HFSS. This new approach gives an optimal thickness result that is only 0.004mm different to that of a full EM simulation. The radome is manufactured and Radio Frequency (RF) tested in an Anechoic Chamber (AC), the calculated thickness is shown to be the optimal thickness.

I. INTRODUCTION

Radomes are structures that cover an antenna, providing environmental protection whilst by design have limited effect on the performance of the antenna. The introduction of a radome to an antenna system will increase transmission and receive losses, distort the pattern and polarisation of the antenna pattern and cause errors in boresight [1] [2]. To reduce impact radomes are carefully tuned to be a matched thickness for the frequency of EM radiation being used [3]. The matched thickness condition occurs when reflections are reduced and least power is lost through the radome and there is least phase disturbance. The external profile, robustness and material of the radome vary greatly depending on its purpose.

Often, due to the operational requirements of the system, the radome cannot be a hemisphere and has to be a shape such as a Von Kármán [4], meaning the refraction caused by the radome changes as a function of scan angle of the antenna. In radar systems this apparent movement of the source, caused by the aberration effects of the radome, has to be compensated for during measurement of the target [5]. Radomes can be made from a single electrically thin dielectric layer [6] or a sandwich, which has two dielectric layers with an alternative material between them as a core at its simplest [7].

This paper presents a novel and improved process to define the optimised thickness of a single walled radome. The antenna used for these simulations and measurements is a Twist Reflector Monopulse Antenna (TRMAS) [8]. Traditional radome design methods are time consuming and expensive often requiring iterations of hardware manufacture and are based around complex equation approximations [9], complex ray tracing [10] and or electrically large EM simulations. The approach described in this paper uses a 2DTRM written in MATLAB and a unit cell HFSS simulation which optimises the thickness of the radome without compromising on accuracy. Manufactured radomes are tested in an AC and the thickness verified.

II. TRADITIONAL RADOME DESIGN TECHNIQUES

The nominal matched thickness (RMT) for a radome can be calculated from Equations (1) and (2) where λ_m is the wavelength in the material, λ_o is the wavelength in free space of the Electromagnetic Radiation (EMR), ϵ_r is the relative permittivity, n is an integer and α_i, is the angle of incidence of the EMR. Before the common use of EM simulations to calculate the radome thickness a radome would be manufactured over-thick by several mm, RF tested, the thickness reduced, RF tested and iterated until the optimal thickness was found.

$$\lambda_m = \frac{\lambda_0}{\sqrt{\epsilon_r}} \tag{1}$$

$$RMT = \frac{n \, \lambda_m}{2} \, \cos \alpha_i \tag{2}$$

Ray tracing methods calculate the path of the RF wave through the radome system. It uses idealised narrow beams, rays, and calculates their propagation by known physical interactions at medium changes, in 2 or 3 dimensions. Snells Law is used to define the refraction of a wave at a medium boarder.

The radome under investigation in this paper is manufactured from BTCy-1, a pre-preg laminar composite material, with a $\epsilon_r = 3.6$ and $\tan \delta = 0.004$ at a frequency of 15 GHz. Using Equations (1) and (2) the nominal thickness of this radome can
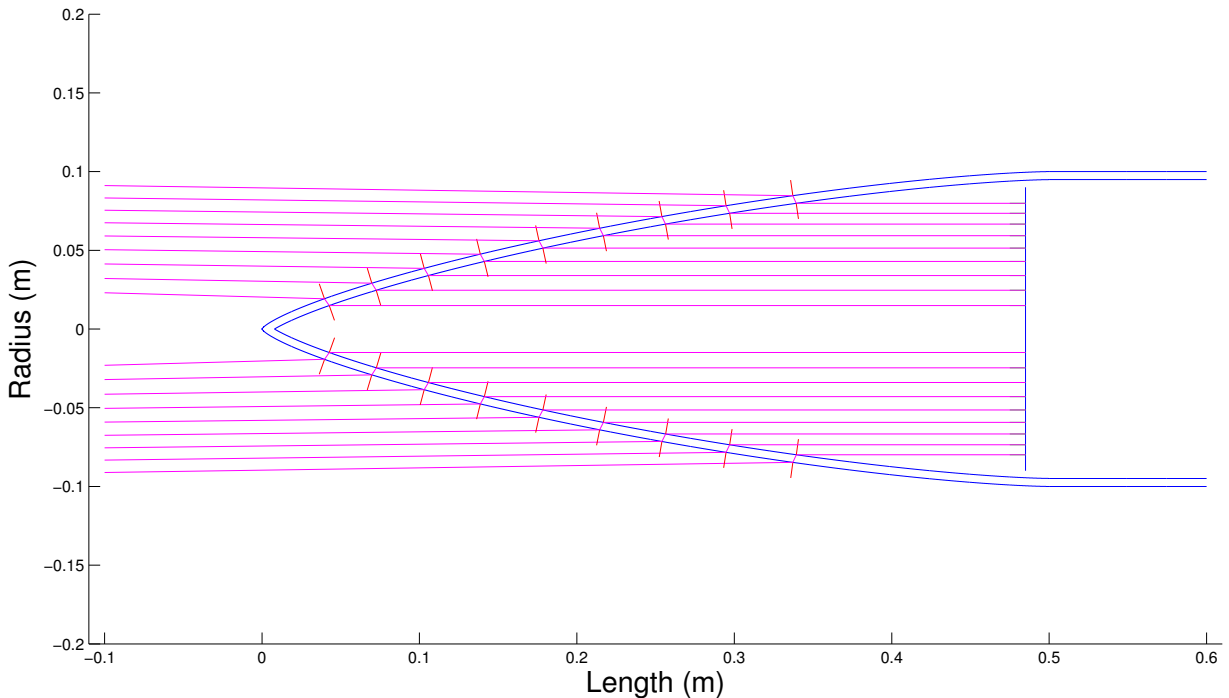
Fig. 1. 2DRTM plot of the range of rays at 0.1mm spacing and their path through the radome at a beam angle of 0 ^{o}.

be calculated to be 5.1 mm for normal incidences. As the centre frequency is low, n is set to 1 to keep the thickness of the radome to a minimum reducing transmission losses and maximising the antenna aperture.

III. COMBINED APPROACH FOR RADOME DESIGN

This paper presents a novel and improved process to define the optimised thickness of a radome. The approach described in this paper is a specifically written 2DRTM MATLAB code which is based on the geometry of a TRMAS. This outputs an average angle of refraction (α_r) which is used as the input to a unit cell HFSS simulation. The output of the optimisation in the HFSS simulation is the optimal thickness of the radome.

The radome shape to be optimised in this paper is a Von Kármán with C = 0. This is a shape that has very good aerodynamical properties, as it gives minimum drag for a given length and diameter, but is not particularly good for RF beam quality due to the sloped sides and pointed tip.

A. 2D RAY TRACING

The 2DRTM approach is valid for situations where diffraction is not a main effect. In summary the 2DRTM creates the required geometry for the TRMAS and radome under investigation and traces the path of a ray bundle from the twist plate and calculates the refraction at both radome and air boundaries; and determines the position where the ray travels to infinity.

Initially the 2DRTM programme sets up the external geometry of the radome, a Von Kármán Ogive followed by a parallel section of length 0.1 m, Fig. 1. The internal geometry of the radome is drawn to give a constant wall thickness using the external geometry as the defining surface. The thickness chosen is the nominal thickness of 5.1 mm as calculated previously. The twist plate radius is maximised in the available volume as 0.09 m and is set to an angle of 0 ^{o}.

A TRMAS geometry can be simplified to a band of parallel rays emerging from the twist plate, Fig. 1. The gap in the rays at the centre of the twist plate is due to the blockage caused by the feed. This 0.1 mm spacing clearly shows how the ray tracing works for a ray bundle. As the required parameter from this simulation is the refracted angle between the normal and the exit ray the ray spacing is reduced to 0.01 mm to give a high density of rays.

At the intersection of the ray with the radome, refraction will occur as the RF can travel through the radome. The refraction at the air to radome boundary is calculated using a form of Snell's law, Heckbert's method [11]. Heckbert's method, Equation (3), allows α_i and α_r to be calculated by using $\mathbf{I}$, the unit vector of the incident ray's direction and $\mathbf{N}$ the surface normal unit vector. $\mathbf{N}$ is calculated from the gradient of the surface where the ray intersects.

$$\begin{aligned} \cos\alpha_i &= -\mathbf{I}\cdot\mathbf{N} \\ \cos\alpha_r &= \sqrt{1 - n^2\left(1 - \cos\alpha_i^2\right)} \end{aligned} \tag{3}$$
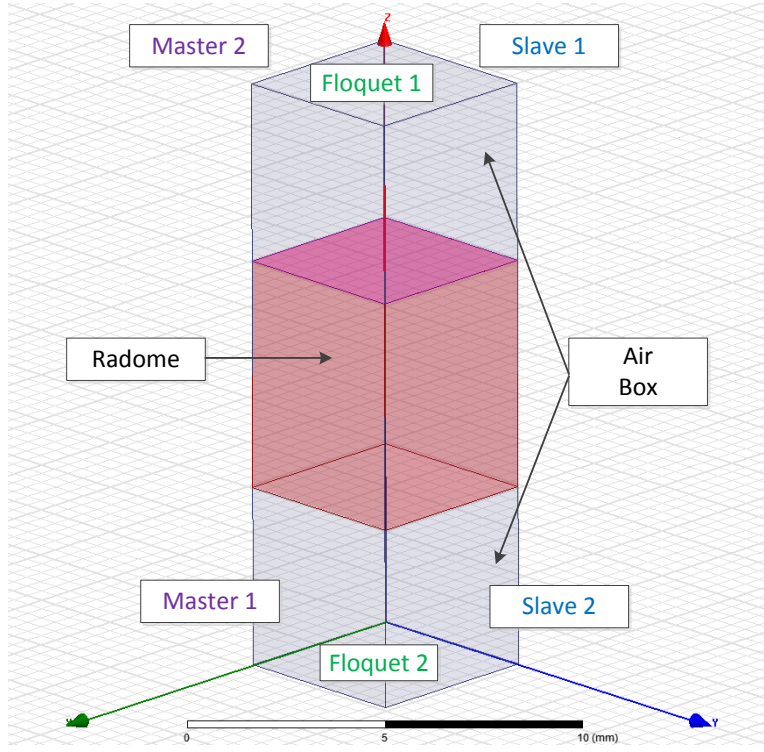
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Fig. 2. HFSS simulation set up for a radome and TRMAS model.

As defined by Equation (3) the ray then travels through the radome. At the radome air boundary refraction occurs again, as defined by Equation (3), and the ray then travels out of the radome and away from the antenna. Therefore the thickness of the radome can be optimised as a function of a single beam angle, as presented in this paper.

For this radome with look angle of 0° α_r ranges from 81.1 ^{o} to 68.8 ^{o}, with the average angle being 76.5 ^{o}. The symmetrical nature of this can be clearly seen in Fig. 1. This value will be used as an input to the unit cell model in HFSS to define the optimised radome thickness for maximum transmission at the required beam angle.

B. EM UNIT CELL MODEL

To optimise the thickness of the radome in the RF window a unit cell HFSS simulation was constructed, Fig. 2. The geometry is a flat sheet of radome material of parameterised thickness vertically in the centre, with an air box above and below it that is in excess of half the wavelength at 15GHz. The radome material is BTCy-1 and losses are included. Floquet ports are used so the model becomes a repeated structure infinite in size, but it remains electrically small so it remains quick to solve. α_i of the radiation is the same as to the calculated α_r in the ray tracing model, 76.5 ^{o}.

In HFSS the Quasi Newton optimization tool [12] was used to determine the optimal radome thickness for a given incident angle. For this investigation a single frequency of 15 GHz is used. The optimisation was set to optimise the thickness of the radome at α_i = 76.5 ^{o} with a target S_{11} value of - 32 dB and a convergence criteria of 1 e^{-6}, Equation (eqn:optimisation), these values are derived from experimentation and good engineering practice. Care must be taken to assign these values correctly, or the final result of the optimisation will be invalid. Results give a thickness of 6.136mm in 11 iterations.

$$RMT = \min_{S_{11}} (\alpha_i, RMT) \tag{4}$$

Now α_i has been calculated Equation (2) it can be used to calculate the thickness of the radome again. Using α_i = 76.5 ^{o} and n = 5 the thickness of the radome is calculated as 6.0 mm. This is close to the optimised value of 6.136 mm as calculated by the method presented in this paper.

Due to the difference between the starting thickness of the radome used as an input to the 2DRTM and the end thickness it is valuable to determine if an iteration of the design process is required before finalising the optimal thickness of the radome. After completing this investigation at an angle of 0 ^{o} the simulations do not have to be iterated. The matched thickness value of 6.136 mm will now be compared to the results of a full TRMAS and radome HFSS simulation.
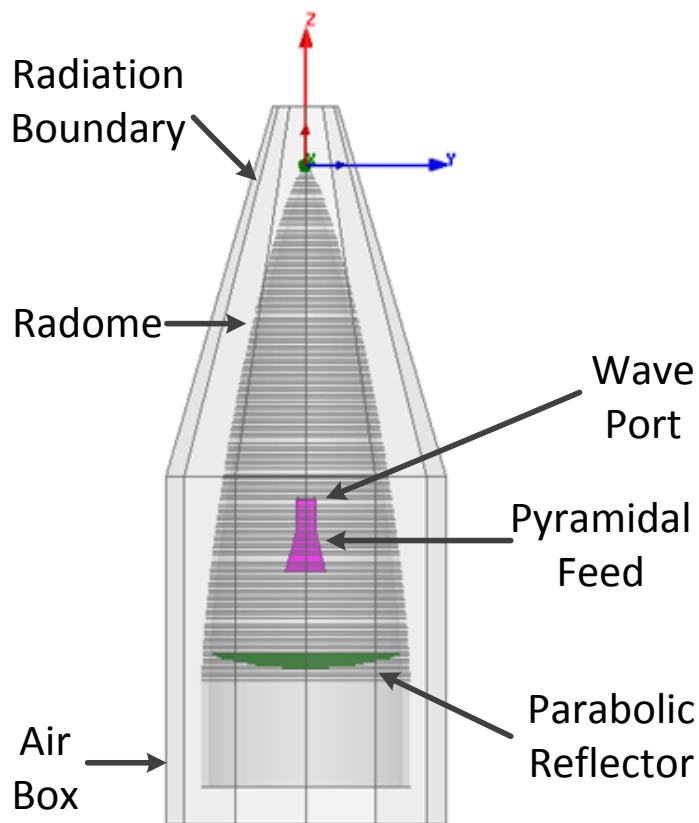
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Fig. 3. HFSS simulation set up for a radome and antenna model.

IV. RADOME AND ANTENNA FULL HFSS MODEL

A simplified TRMAS is to be simulated, Fig. 3. A set of parallel rays are to be projected from the twist plate. In this simulation this is achieved by using a front fed parabola. This simulation is detailed enough to calculate the gain as a function of thickness, whilst removing the full geometrical complexity. A single pyramidal horn feed is used as the feed which is situated at the focus of a metal paraboloid. An air box (vacuum) is constructed around radome with a radiation boundary set up at edge of this vacuum. A wave port is set up at the input end of the feed because it is inside the air box. To look at the gain of the system infinite radiation spheres are set. Conductor and dielectric losses are included in the simulation. The thickness of the radome is constructed as a parameter, and the gain of the system is simulated as a function of radome thickness. For a single frequency, beam angle and radome thickness this simulation takes 51:15 minutes to run on a distributive computing HPC with 96 cores and 576 GB total memory capacity. It was not possible to run this simulation as an optimisation, therefore it is run multiple times at difference thicknesses instead. The same simulation can be run on a 48 GB stand-alone machine, in 26 hours.

Fig. 4 shows the results for the gain as a function of radome thickness for the full radome with antenna HFSS model in 0.1 mm stages over the range of interest of 4.6 to 7 mm. The range of thickness covered has to start below the calculated value of thickness of 5.1 mm and continue until a definite peak is found at 6.1 mm.

From the peak gain found at 6.1 mm the next simulation range is chosen as 6.127 to 6.142 mm thickness in 0.001 mm stages. The maximum gain, i.e. the best tuned radome thickness, occurs at a thickness of 6.132 mm. The gain variation over this band width is only 0.14 dB, this level is below measurement tolerance and therefore is below measurement accuracy.

The overall optimisation of the radome thickness has taken 44 simulations and 41 hours of simulation time. If a mechanically accurate HFSS simulation had been run each simulation would have taken over 24 hours without improving the results.

V. COMPARISON OF APPROACHES

It can be seen that both approaches presented in this paper, 2DRTM with unit EM simulation and the full EM simulation, give a very similar value for the best matched thickness, therefore both methods are suitable for use. The difference between the methods in obtaining an optimal thickness is 0.004 mm. This difference in thickness leads to a drop in gain of 0.07 dB in
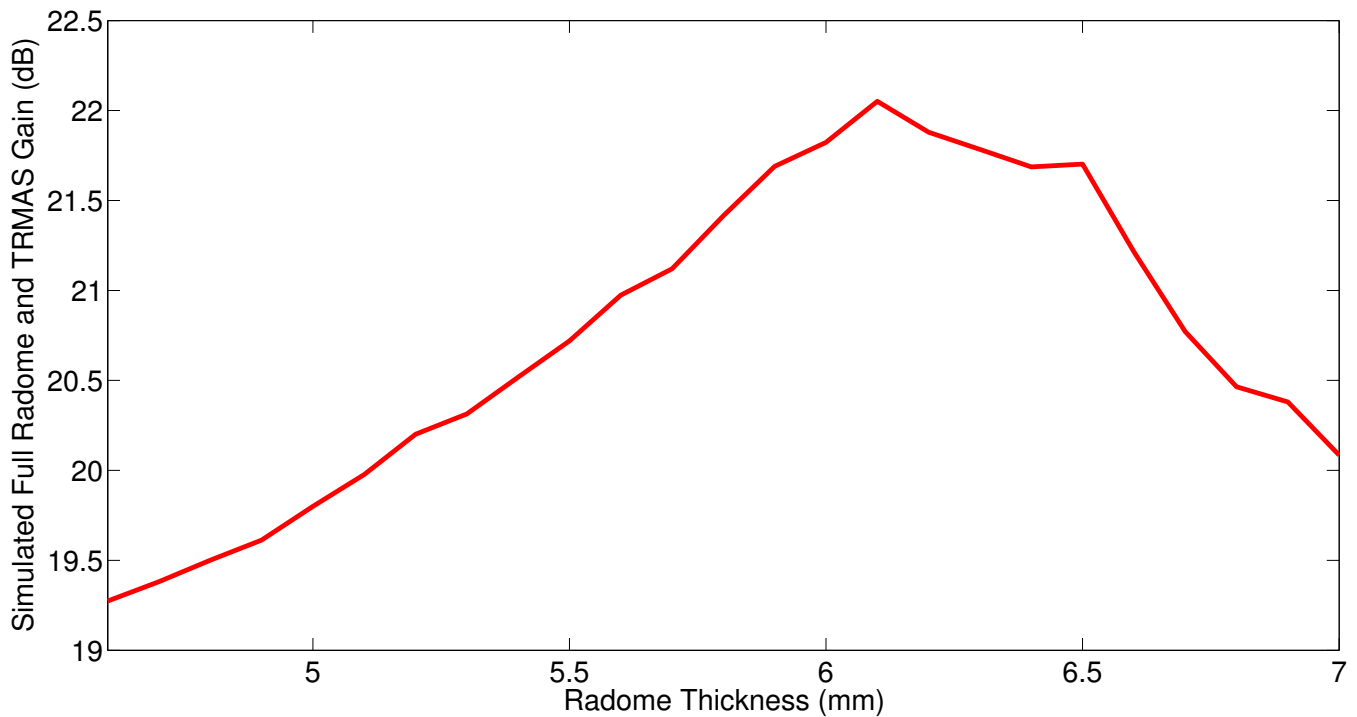
Fig. 4. Full radome with TRMAS HFSS simulated gain results.

SIMULATION	TIME TAKEN (MINUTES)	MEMORY (GB)	ITERATIONS
MATLAB RAY TRACING	0:12	4	~ 1
HFSS UNIT CELL	2:44	4	~ 1
HFSS	51:15	576	~ 44

TABLE I
COMPARISON OF SIMULATION TIMES AND CPU.

the full HFSS simulation, which is negligible in a real system. Indeed, in reality a standard machining tolerance is $\pm$ 0.1 mm, which means a thickness of 6.13 mm would be chosen in both cases as the manufacturable thickness.

As the two approaches give the same answer, the real difference between them is the time taken. The following analysis will not include the set up time of the models and will only consider the run times. Table I shows that the approach described in this paper sped up the simulation time by 984 times, and reduced the memory required by 144 times.

The new method presented in this paper is able to adjust to new geometry shapes easily as it requires a change to the 2DRTM geometry and the incident angle in the HFSS unit cell model. The full HFSS antenna and radome simulation will take several days to construct and successfully simulate. Therefore the approach reported in this paper will be quicker to set up the simulation for a new antenna and radome system.

A radome of thickness calculated from the 2DRTM and unit EM simulation will now be tested in hardware in an AC.

VI. RADOME PERFORMANCE AC TESTING

If the radome under test is a large structure that is made in several pieces it is possible to complete panel testing on each unit to measure the RF performance of the radome [13]. However, for monolithic radomes, the interaction of the radome with the antenna is greater and panel testing will therefore be useful for understanding the RF performance of the radome material [14]. AC testing of the antenna and radome system should be carried out to characterise the radome. The positioner in the chamber
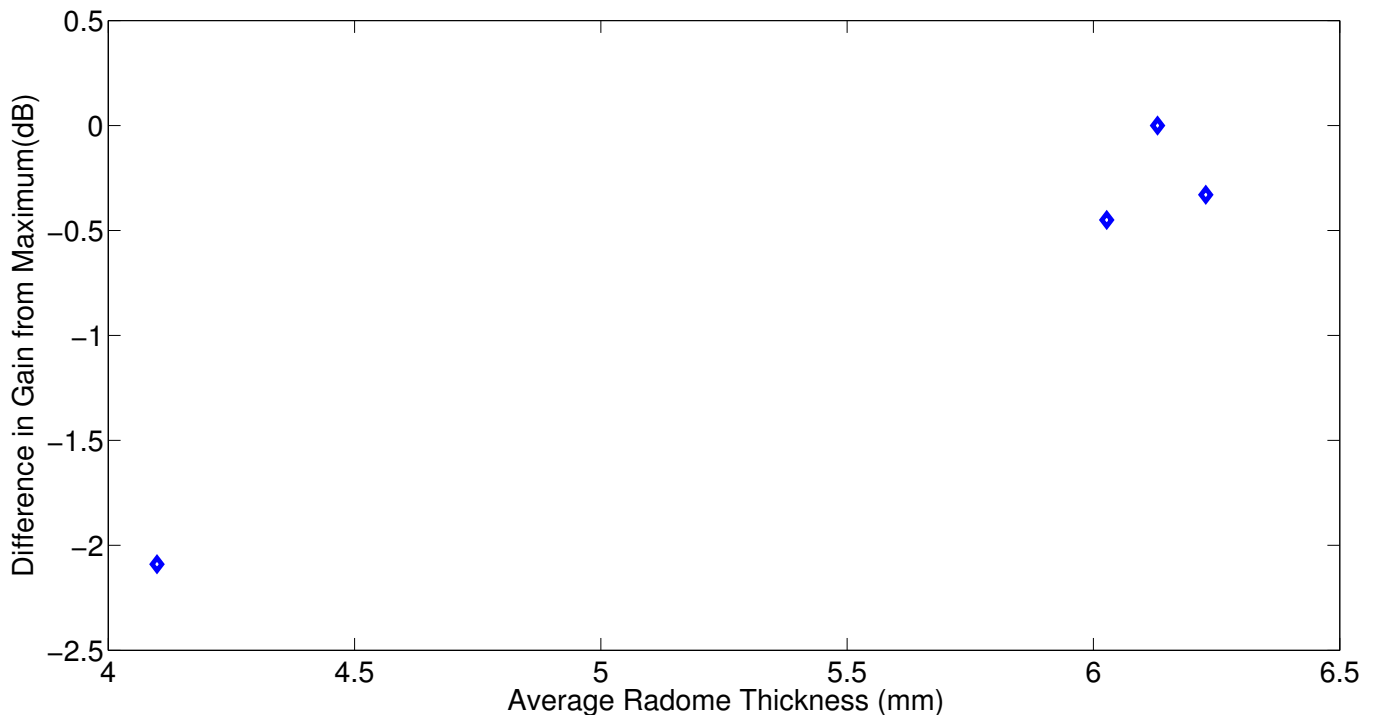
Fig. 5. AC testing of radome gain as a function of radome thickness.

should use axis transforms to correctly measure the antenna [15] and the hardware set up have minimal phase disturbance to the measurements during movement [16].

The thickness of the radome was determined as an average of 20 thickness measurement points across the RF window. Radomes of different thicknesses were tested with the same antenna at a beam angle of 0 ^{o}, the gain as a function of radome thickness is shown in Fig. 5, using the method described in [17] to create the Sum gain. Due to the cost of the units it was not possible to manufacture a large number of radomes that were known to be incorrect. However, one unit was manufactured 2.031mm under thickness, and bottom, middle and top of tolerance units have been used to show the range in gain performance.

Fig. 5 shows that the radome thickness has an impact on the gain. The highest gain is found from the calculated thickness of 6.13 mm thus validating the design process. The two points either side of the peak are at approximately $\pm$ 0.1 mm and are less than 0.5 dB down on the peak gain. This shows that the machining tolerances of the unit are valid. The one outlier at - 3 mm clearly shows a 2 dB drop in gain.

VII. CONCLUSIONS

This paper describes and validates a new method for the optimisation of the thickness of an antenna radome, 2DRTM and unit EM simulation. The presented method reduces the time to calculate the optimal thickness of a radome by 3 orders of magnitude and the required computer memory by 2 orders of magnitude over the full EM simulation without compromising accuracy. The presented approach is particularly useful as it removes the requirement to produce and validate the complex full EM simulation and it removes the need of a computer cluster to complete the design. As the timescales are reduced it allows for fast design iterations and fault finding during manufacture. The calculated thickness of the radome is then validated by anechoic chamber measurements of the full radome with antenna, showing that in a real system the thickness has been optimised by the simulation work.

In this approach the radome has been tuned specifically for a single frequency and a single look angle. Whilst systems will have a preferred frequency and look angle, it is likely that they will have to be able to work successfully over a specified range of angles as well as gien bandwidth. To optimise over a range of look angles the resultant average angle of refraction from a range of beam angles in the 2DRTM would have to be averaged to calculate the required input to the unit cell EM simulation. To run over a frequency range, the HFSS unit cell simulation will be altered to run over a range of frequencies and the results compared over the different frequency range required. When optimising over scan angle and frequency range the time saving of the method presented here is even more significant.

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The approach presented here can be used to determine the optimised thickness of a radome for any reflector antenna system with a simple alteration to the set up geometry in the MATLAB code. The alteration will require the band of parallel rays to be located at the correct position for the reflector antenna system. It is also possible to extend the method to optimise a radome with a variable thickness along its length. Instead of taking the average angle of refraction over the whole of the aperture it is spit into sections, corresponding to bands of equal height on the radome. For each band an average angle of refraction can be calculated, by making these bands small an optimised variable thickness radome can be constructed from the unit cell model.

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