ANOVA-Based Assessment of Electromagnetic Performance in Submarine X-Band Radomes

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Abstract— **This paper presents a statistical analysis of the electromagnetic performance of submarine X-band radomes using the Analysis of Variance (ANOVA) method. The study evaluates the influence of three design factors — composite material type, thickness, and mesh type — on the scattering parameters (S-parameters) obtained from waveguide measurements. Results indicate that thickness has the most significant effect on both reflection and transmission coefficients. The proposed approach serves as an effective screening tool for radome design optimization, particularly in the early stages of development.**

Keywords— **Radome, S-parameters, ANOVA, Submarine, Statistical Analysis**

I. Introduction

A radome (a term derived from the combination of words *radar* and *dome*) is an enclosure intended to shield antennas from environmental hazards—such as wind, rain, dust, and extreme temperatures—while allowing radio frequency (RF) signals to pass through with minimal attenuation [1]. Constructed from low-loss dielectric materials, radomes are critical in aerospace, maritime, and military applications, where antennas must operate reliably in harsh conditions without performance degradation.

For X-band radar systems, which operate from 8.2 to 12.4 GHz frequencies, the radome's material composition, shape, and structural design significantly influence electromagnetic wave propagation and overall antenna system performance, making its optimization essential for mission-critical operation. These same design factors also critically determine the platform's overall radar cross section (RCS) [2]-[3]. Thus, improving radome construction parameters is key to enhancing stealth, durability, and operational efficiency in military applications.

Particularly for submarines, radomes play a vital role in ensuring signal integrity for communication, navigation, electronic warfare (EW) and radar systems. Since submarines operate in highly corrosive and high-pressure underwater environments, the radome must withstand mechanical stress while maintaining electromagnetic transparency [4].

In recent years, several studies on the influence of radomes on the RF parameters have been proposed, with focus in both materials properties and electromagnetic properties [4]–[6]. These works can be further divided into simulated analysis and experimental analysis. However, little of this research is directed toward undersea environments.

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Furthermore, due to the nature of military applications and restricted industry data, submarine radome development remains an understudied field. The lack of open-source information increases the challenge of optimizing radome performance for RF transparency and structural integrity. This knowledge gap makes independent research vital for national defense autonomy, reducing reliance on foreign technology while advancing domestic expertise in this strategic defense component.

The objective of this work is to apply the Analysis of Variance (ANOVA) method to verify design elements that influence the radome's electromagnetic properties in the X-band range. Specifically, it aims to identify which of three construction factors—*composite material type*, *thickness*, and *composite mesh type*—has a greater impact the mean magnitude of the *scattering parameters* (S-parameters) for submarine radomes.

The study presented here differs from the previously cited references by employing a purely statistical approach to assess the effects of design factors on the output variable. Although it does not provide a thorough characterization of electromagnetic parameters across the entire frequency band of interest, the analysis was conceived to reuse data from other experimental characterizations and serve primarily as a screening tool to help expedite conclusions during the early stages of the project. Furthermore, it can be easily extended to output variables beyond the scattering matrix and used as a validation tool for other analyses.

II. Materials and Methods

A. ANOVA Overview

Analysis of Variance (ANOVA) is a statistical technique introduced by Ronald Fisher in the early 20th century [7]. The core idea of ANOVA is to partition the total variability into components attributable to different sources of variation, namely the variation between groups and the variation within groups (error). By comparing these variances through an F-test, ANOVA assesses whether the observed differences among group means are likely to have occurred by chance.

The classical framework of ANOVA assumes normally distributed residuals, homogeneity of variances, and independent observations. It is widely used in engineering and experimental design for testing factor effects and their interactions in factorial experiments. The method has been further formalized and expanded in modern statistical literature, such as [8], which provides detailed procedures for one-way, two-way, and mixed-factor ANOVA.

In the ANOVA, the null hypothesis states that the means of all groups under comparison are equal, meaning that the factor or interaction has no significant effect on the response variable. The *p-value* quantifies the probability of obtaining the observed data assuming the null hypothesis is true. A significance level of 5% is commonly adopted; therefore, a p-value below 0.05 provides sufficient evidence to reject the null hypothesis, indicating that the factor or interaction has a statistically significant effect. The degrees of freedom (Df) in ANOVA indicate the number of independent values that are free to vary in estimating statistical parameters. For a factor, the degrees of freedom typically correspond to the number of levels minus one, while the residual degrees of freedom relate to the variability within groups.

It is important to emphasize that ANOVA only reveals whether there is a significant difference among groups but does not indicate which specific treatments are different. Additional post-hoc analyses are necessary to pinpoint the source of these differences.

B. Experimental Setup

The data used in the present analysis were produced by a experimental setup developed as part of an ongoing research. That investigation aims at utilizing the Transmission Line Method (TLM) to determine the influence of fiber alignment on the properties of layered composite materials for submarine radomes. The measurement setup consisted of laminated composite material samples, a Vector Network Analyzer (VNA), and its companion tools.

For each combination of composite, thickness, and mesh, the sample was inserted into a WR-90 rectangular waveguide connected to a Keysight two-port VNA (model *N5232A*) using a calibration kit. Four replicates per composite-thickness-mesh configuration were considered, with sample order randomly selected. The *N1500A Materials Measurement Suite* software was used to operate the VNA [9], taking 1,024 frequency steps from 8.2 to 12.4 GHz and saving the S-parameters to a standardized s2p file.

Details regarding the specific choices for composite formulation, thickness, and mesh configuration used to fabricate the test bodies are part of the aforementioned study; thus, the input factors are treated as qualitative in the present work. Table I summarizes the factors, levels (also known as treatments), and total number of samples.

TABLE I. EXPERIMENTAL DESIGN FACTORS AND LEVELS.

Factor	Levels	Count
Composite	C1, C2	2
Thickness	T1, T2, T3	3
Mesh Types	M1, M2, M3	3
Replicates		4
Total Combinations		**18**
Total Samples (with replicates)		**72**

C. Data Preprocessing

The setup explained in Subsection II-B can be seen as a $2 \cdot 3^2$ mixed-level factorial design, as described in [8], except that each run produces a 1,024-point array measurement for each S-parameter instead of a single value. In other words, an individual s2p file contains 1,024 rows corresponding to frequency points and four columns representing the complex values for the outputs S_{11}, S_{12}, S_{21}, S_{22}. Therefore, to conduct classical univariate ANOVA analysis, a representative function must be selected to condense the 1,024 S-parameter measurements of a given S-parameter output into a scalar value.

The work reported in [10] extensively employs the mean absolute values of S-parameters over the frequency range to evaluate the performance of WM-380 rectangular waveguides. Additionally, the study developed in [11] models the stochastic behavior of patch antennas in the Ka band using the mean and standard deviation of their reflection coefficient. Accordingly, the mean magnitude appears to be a reasonable aggregation function to support the application of ANOVA in the present work.

Consequently, the preprocessing phase consists of a MATLAB script that iteratively reads the 72 .s2p files using RF Toolbox functions, calculates the mean of the magnitude for each element of the S-matrix, and saves the results in the *long format* required for the ANOVA analysis. In the long format, each row corresponds to a single observation, with columns indicating factors and outputs. The head and tail of the dataset used in this work are shown in Table II.

TABLE II. EXCERPT OF LONG FORMAT ($\overline{|S|}$ in dB)

Id	C	T	M	R	s11	s12	s21	s22
1	C1	T1	M1	1	-2.832	-3.530	-3.545	-2.829
2	C1	T1	M1	2	-2.838	-3.518	-3.533	-2.841
3	C1	T1	M1	3	-2.847	-3.514	-3.529	-2.849
4	C1	T1	M1	4	-2.837	-3.527	-3.542	-2.841
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
69	C2	T3	M3	1	-3.806	-3.112	-3.126	-3.851
70	C2	T3	M3	2	-3.673	-3.180	-3.192	-3.723
71	C2	T3	M3	3	-3.618	-3.217	-3.231	-3.680
72	C2	T3	M3	4	-3.785	-3.119	-3.132	-3.826

III. ANOVA FULL MODEL

This section describes the ANOVA analysis of the preprocessed data. The initial approach is to identify the key factors and interactions influencing the mean $|S_{11}|$ and $|S_{21}|$. For a EW passive antenna enclosed within the radome, these values are related to the reflection transmission coefficient, respectively. Tables III and IV summarize the ANOVA results for these outputs. The columns labeled *Df*, *SS*, *%SS*, and *Pr(>F)* represent, respectively, the degrees of freedom, the sum of squares, the percentage contribution of each factor to the total sum of squares, and the p-value.

TABLE III. ANOVA $\overline{|S_{11}|}$.

Factor	Df	SS	%SS	Pr(> F)
Composite	1	4.3	0.846	$< 2 \times 10^{-16}$
Thickness	2	500.5	98.70	$< 2 \times 10^{-16}$
Mesh	2	0.0	0.003	0.127
Composite:Thickness	2	1.3	0.254	$< 2 \times 10^{-16}$
Composite:Mesh	2	0.1	0.011	0.00144
Thickness:Mesh	4	0.4	0.088	7.96×10^{-13}
Composite:Thickness:Mesh	4	0.3	0.056	1.53×10^{-9}
Residuals	54	0.2	0.041	

At the default 5% significance level, all main factors and interactions demonstrate statistical significance, with the exception of the mesh factor for $\overline{|S_{11}|}$. The ANOVA summaries for the outputs $\overline{|S_{12}|}$ and $\overline{|S_{22}|}$ are omitted for brevity. Nonetheless, the results are similar in that all factors

TABLE IV. ANOVA $\overline{|S_{21}|}$.

Factor	Df	SS	%SS	Pr(> F)
Composite	1	1.04	1.436	$< 2 \times 10^{-16}$
Thickness	2	70.61	97.674	$< 2 \times 10^{-16}$
Mesh	2	0.02	0.033	1.76×10^{-6}
Composite:Thickness	2	0.37	0.512	$< 2 \times 10^{-16}$
Composite:Mesh	2	0.04	0.050	1.28×10^{-8}
Thickness:Mesh	4	0.11	0.154	1.77×10^{-15}
Composite:Thickness:Mesh	4	0.06	0.089	4.13×10^{-11}
Residuals	54	0.04	0.052	

exhibit statistical significance, with p-values of 2.17×10^{-6} and 6.87×10^{-3}, respectively.

Notably, the sum of squares associated with the thickness factor is substantially larger than that of the other factors in all cases, indicating that its contribution to the overall variance is dominant. This implies that variations in thickness induce proportionally larger changes in the output compared to changes in the other factors.

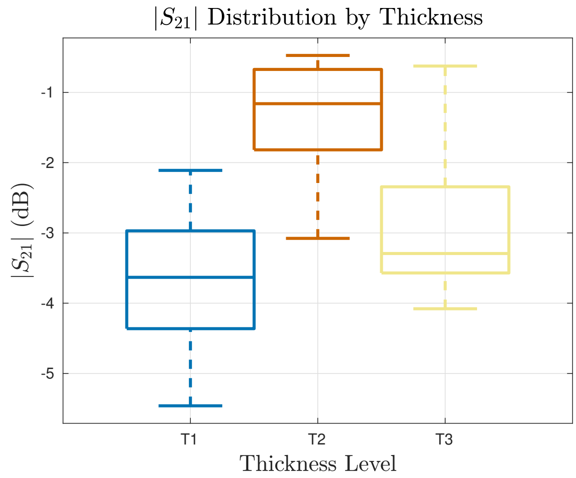

Fig. 2. Boxplot of $|S_{21}|$ demonstrating thickness-dependence.

IV. Reduced ANOVA Model

This section presents a reduced model analysis, aiming to simplify the factorial design by removing factors and levels with limited influence. This simplification facilitates the development of a mathematical model that describes the system behavior and provides insights into how the radome construction parameters affect electromagnetic performance.

Firstly, based on the results presented in Section III, the *mesh* factor is removed from the model. Although it is statistically significant for most of the S-parameters, it is the main factor with the least contribution to the total variance. From a practical standpoint, varying the mesh configuration may not be justified, as it could increase manufacturing complexity and costs while offering only marginal improvements to the output.

Secondly, based on the plots in Figure 1, which display the averaged replicates for each composite-mesh combination grouped by thickness, it is evident that the thickness level T1 consistently yields the lowest values of $|S_{21}|$ over the frequency range, potentially leading to a greater reduction in the amount of energy transmitted through the structure. This observation is reinforced by the boxplot in Figure 2. For this reason, the *T1 level* is removed from the analysis.

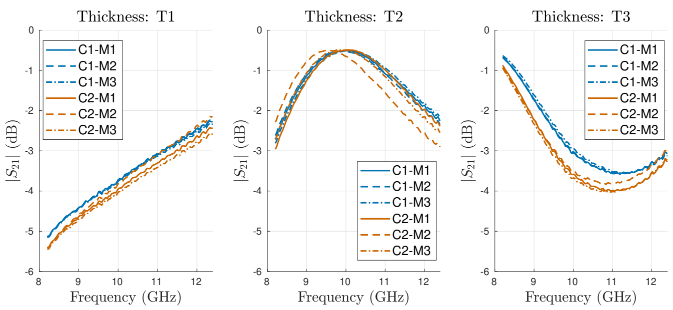

Fig. 1. $|S_{21}|$ across different thickness configurations. Colors represent composite type, while line styles indicate mesh variation.

Therefore, the reduced experimental dataset can now be regarded as a 2^2 factorial design, as described in [8]. The ANOVA summary for $\overline{|S_{21}|}$ based on this simplified model is presented in Table V. Results for other outputs are omitted, as they exhibit a similar behavior in terms of factor significance and variance contribution.

Moreover, the factors are now coded using standardized levels -1 and 1. This approach enhances the understanding of the model coefficients as they can be directly interpreted as effects [8], [12]. Based on the ANOVA results for the reduced model, regression techniques can be used to obtain an estimation equation for each S-parameter. Equation (1) presents the model to estimate $\overline{|S_{21}|}$,

$$\widehat{\overline{|S_{21}|}} = -2.072 - 0.133 \cdot X_{\mathrm{C}} - 0.808 \cdot X_{\mathrm{T}} - 0.085 \cdot X_{\mathrm{C}} \cdot X_{\mathrm{T}} \quad (1)$$

where X_{C} represents the coded level of composite (-1 for C1, +1 for C2) and X_{T} represents the coded level of thickness (-1 for T2, +1 for T3).

TABLE V. ANOVA $\overline{|S_{21}|}$ Reduced Model.

Factor	Df	SS	%SS	Pr(> F)
Composite	1	0.85	2.6	$< 2 \times 10^{-16}$
Thickness	1	31.37	95.92	$< 2 \times 10^{-16}$
Composite:Thickness	1	0.35	1.05	9.79×10^{-14}
Residuals	44	0.13	0.41	

Finally, validity of the proposed model is assessed by examining its residuals, ensuring that the assumptions of normality and homogeneity of variances are satisfied. The Shapiro-Wilk test for normality [13] was performed yielding a p-value greater than 0.05, indicating no violation of normality. Additionally, the histogram and the normal quantile plot in Figure 3 support the normality assumption, as the points in the Q-Q plot (bottom left) align closely with the reference line, and the histogram (right), despite not being perfectly symmetric, exhibits an approximately bell-shaped distribution. However, the residuals versus fitted values plot (top left) indicates potential issues with the constant variance assumption, as certain composite-thickness combinations exhibit lower dispersion, with residuals clustering more tightly around the reference line. A more in-depth analysis would be advisable to address this heteroscedasticity; nonetheless, it is considered that this limitation does not compromise the objectives of the present work.

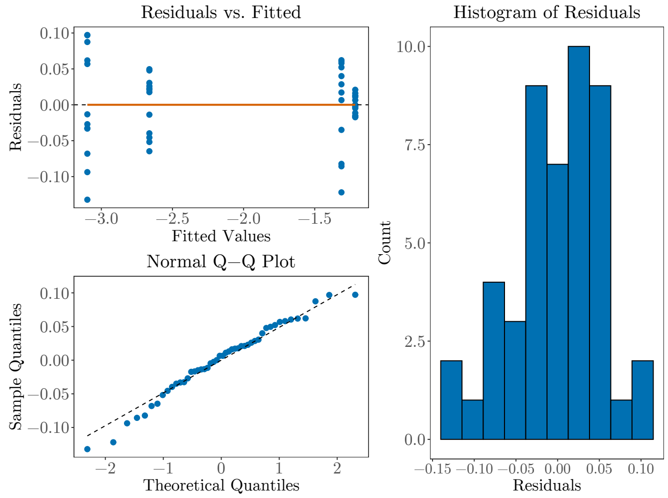

Fig. 3. Residual plots: Normal Q-Q (bottom left), Residuals vs. Fitted Values (top left) and Histogram (right).

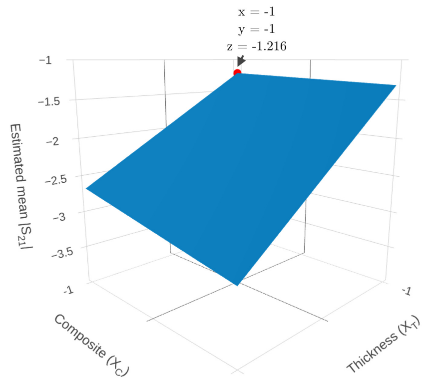

Fig. 4. Surface Plot: Composite-thickness combinations vs. $|S_{21}|$

V. Conclusions and Discussion

The objective of applying the ANOVA method to verify the design elements that influence the radome's electromagnetic properties in the X-band range was successfully achieved. The analysis revealed that the thickness factor has the greatest impact on the mean magnitude of the S-parameters. Furthermore, according to the ANOVA results, all factors and their interactions are statistically significant. Nevertheless, for the purpose of developing a simplified linear model to describe the system's behavior, as the mesh parameter exhibited the smallest contribution to the total variance, it was no longer treated as a factor in the reduced model. Additionally, the thickness level T1 was removed, as it caused a pronounced degradation in $\overline{|S_{21}|}$.

Although the model was validated only for $\overline{|S_{21}|}$, the proposed framework is directly applicable to other S-parameters. The model equation provides insights for early-stage design. For instance, the negative coefficients for composite and thickness indicate that increasing their coded levels (from -1 to +1) substantially reduces $|S_{21}|$. This behavior suggests that moving from the low to the high level of thickness—likely corresponding to a transition from thinner to thicker material—results in increased attenuation, which aligns with physical expectations. Additionally, the negative interaction term implies that the combined effect of composite and thickness further amplifies this reduction, highlight the importance of considering interactions when evaluating radome design elements.

Another way to interpret the reduced model is by considering the factors as quantitative variables. Even though detailed information about the actual thickness and composite configuration is not available, this example demonstrates the usability of the model. Suppose that the thickness varies linearly from t mm (thin, coded level -1) to $t+5$ mm (thick, coded level $+1$); similarly, one component of the composite formulation could vary in concentration from $c\%$ to $c+10\%$. Assuming that these changes produce a linear variation in $|S_{21}|$, the model can serve as an interpolation tool to estimate the effect of intermediate values of composite formulation and thickness on $|S_{21}|$. The surface plot in Figure 4 helps visualize this concept.

In summary, the proposed model offers a practical tool to support radome design decisions within the studied parameter space. While it simplifies the system's behavior, it effectively captures the main trends and interactions between thickness and composite combinations. Future work may extend this approach by incorporating additional factors or nonlinear effects to further enhance the model's predictive capability.

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