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Statistical Preprocessing and Boxplot-Based Analysis of Multiband Microwave Absorption Performance in Single-Slot Pyramidal Microwave Absorbers

Yaakub Omar[1,3, a *], Ilya Ismail[1,3, b], Nur Athirah Syafiqah Noramli[1,c], Nurlaila Ismail[1,d], Hasnain Abdullah[2,e], Mohd Nasir Taib[1,f]

[1]Faculty of Electrical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[2]School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Penang, Malaysia
[3]Politeknik Sultan Salahuddin Abdul Aziz Shah, Persiaran Usahawan, 40150 Shah Alam, Selangor, Malaysia

[a]aminyaakub47@gmail.com, [b]ilyaismail86@gmail.com, [c]athirah.noramli1@gmail.com, [d]nurlaila0583@uitm.edu.my, [e]hasnain@uitm.edu.my, [f]dr.nasir@uitm.edu.my

Abstract. This paper presents a statistical preprocessing and boxplot analysis of microwave absorption performance for single-slot pyramidal microwave absorbers operating in L-band, S-band, C-band, and X-band frequency ranges. The absorbers were fabricated using biomass-derived carbon coating material as part of a sustainable microwave absorber design and configured with three slot sizes, namely big, medium, and small. More than 1200 experimental absorption data points were collected from multiple frequency measurements for each band to enable statistical evaluation of multiband absorption behaviour. Boxplot analysis was performed to visualize the distribution of absorption values for different slot sizes and frequency bands. The initial dataset contained 29, 57, 114, and 201 data points for L, S, C, and X band respectively for each slot configuration. The analysis revealed the presence of extreme values that could affect the reliability of interpretation. Therefore, outlier removal was applied using the interquartile range (IQR) method with a multiplier of 1.5. After preprocessing, the number of data points was reduced to 25 for L-band, 54 for S-band, 103 for C-band, and 194 for X-band depending on slot size. The results show that lower frequency bands produce more stable absorption performance, while higher frequency bands, especially C-band and X-band, exhibit larger variation with absorption values below −40 dB. Slot size also influences stability, where the small slot shows wider distribution compared to the big slot. The study confirms that boxplot analysis with IQR-based outlier removal provides a reliable and effective approach for evaluating multiband microwave absorption data obtained from experimental measurements of sustainable pyramidal microwave absorbers.

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Keywords: microwave absorber, multiband, boxplot analysis, pyramidal absorber, outlier removal, IQR method.

1 Introduction

Microwave absorbers are widely used in electromagnetic compatibility (EMC), antenna measurement systems, radar cross-section reduction, and radio frequency applications due to their ability to attenuate unwanted electromagnetic reflections over a wide frequency range. The performance of microwave absorbers is influenced by several factors including material composition, structural geometry, and operating frequency band. Among various absorber structures, pyramidal microwave absorbers are commonly used because they provide broadband absorption characteristics and stable performance over multiple frequency bands [14–18].

In experimental microwave absorber studies, absorption performance is normally evaluated across several radio frequency ranges such as L-band, S-band, C-band, and X-band. These measurements generate a large amount of experimental data that must be analysed carefully in order to obtain reliable conclusions. Experimental datasets obtained from real measurements may contain noise, measurement uncertainty, and abnormal values caused by fabrication tolerance, impedance mismatch, and environmental interference. Therefore, statistical preprocessing is required before further analysis to ensure that the dataset accurately represents the actual behaviour of the absorber [9–13].

Statistical data visualization techniques are commonly used in the early stage of data analysis to understand the distribution characteristics of experimental data. One of the most widely used techniques is boxplot analysis, which summarizes the distribution of data using quartiles, median values, and extreme observations. Boxplot visualization allows fast comparison between multiple datasets and helps identify abnormal values that may affect the interpretation of experimental results [2, 5, 6]. In addition, the interquartile range (IQR) method is commonly applied together with boxplot analysis to detect outliers without assuming normal data distribution [3, 4].

Several studies have applied statistical preprocessing techniques such as boxplot visualization and interquartile range (IQR) methods in data analysis, particularly in spectral data processing and signal analysis applications [2–6]. In addition, previous research in microwave absorber design has mainly focused on material development and electromagnetic performance evaluation across different frequency bands [14–18]. However, the integration of statistical preprocessing techniques to enhance the reliability of experimental microwave absorber datasets remains limited. This highlights the need for systematic data preprocessing approaches prior to further analysis.

Although statistical analysis methods have been widely applied in signal processing and material characterization, the application of boxplot-based preprocessing specifically for multiband microwave absorber experimental datasets remains underexplored [2, 5, 6]. Existing studies have not sufficiently addressed the need for systematic statistical preprocessing in evaluating absorption performance across multiple frequency bands and slot configurations. Therefore, this study aims to address this gap by applying boxplot analysis combined with interquartile range (IQR)-based outlier removal to evaluate the multiband absorption performance of single-slot pyramidal microwave absorbers operating in L-band, S-band, C-band, and X-band.

2 Methodology

2.1 Boxplot Analysis

Boxplot analysis was used as an exploratory statistical technique to visualize the distribution characteristics of microwave absorption measurements. A boxplot summarizes a dataset using five descriptive statistics consisting of the minimum value, first quartile Q1, median Q2, third quartile Q3, and maximum value [2, 5, 6]. The central box represents the interquartile range, which contains the middle fifty percent of the observations. The median line inside the box indicates the central tendency of the dataset, while the whiskers extend to values within the acceptable statistical limits[3, 4].

Observations that fall outside the whiskers are considered potential outliers and are represented as individual points in the boxplot. This visualization technique allows efficient comparison of the distribution of absorption measurements across different slot sizes and frequency bands. By observing the median values, interquartile ranges, and the presence of extreme observations, the stability and variability of microwave absorption performance can be evaluated. The general structure of the boxplot used in this study is illustrated in Fig. 1 [9–13].

2.2 Outlier Detection Using Interquartile Range

Outlier detection was performed using the interquartile range method in order to identify extreme observations that may influence the reliability of the dataset. The interquartile range measures the spread of the central portion of the data and is defined as the difference between the third quartile and the first quartile [26]. The interquartile range and the statistical limits used to detect outliers are defined in Eq. (1)–(3).

$$\text{IQR} = \text{Q3} - \text{Q1} \tag{1}$$
$$\text{Lower Limit} = \text{Q1} - 1.5 \times \text{IQR} \tag{2}$$
$$\text{Upper Limit} = \text{Q3} + 1.5 \times \text{IQR} \tag{3}$$

Observations that fall below the lower limit or exceed the upper limit are classified as outliers. These observations may occur due to measurement noise, temporary experimental disturbances, or fabrication variability. Removing these extreme observations reduces the influence of abnormal values that could distort the interpretation of the experimental dataset.

The selection of the 1.5×IQR threshold follows a widely accepted convention in statistical analysis for detecting moderate outliers. This threshold is commonly used because it provides a balance between sensitivity and robustness, allowing extreme values caused by measurement noise or experimental uncertainty to be identified while pre-

serving the natural variability of the dataset. Therefore, the 1.5×IQR criterion is considered suitable for preprocessing experimental microwave absorber data in this study [2, 4].
After the removal of outliers, the processed dataset is analysed again using boxplot visualization to examine the distribution characteristics of the cleaned data. This preprocessing procedure allows a more reliable evaluation of microwave absorption performance across different slot configurations and frequency bands [24-25].

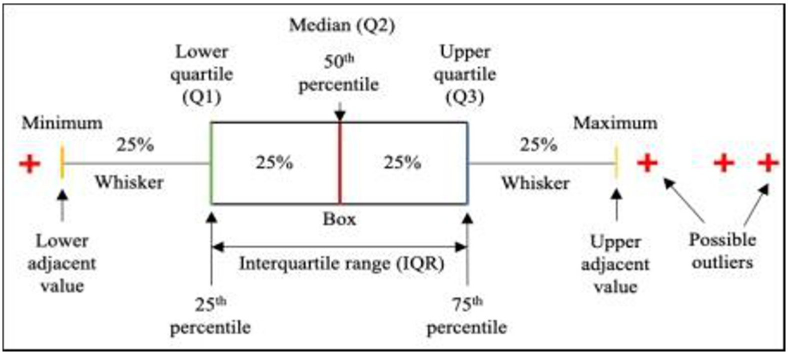


Fig. 1. Shows the basic structure of a boxplot, including quartiles, whiskers, and outlier points used in statistical data visualization.

3 Methodology

3.1 Boxplot Distribution Before Outlier Removal

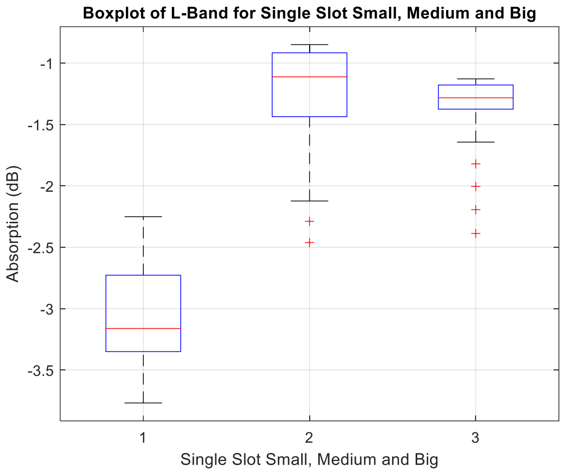
Boxplot analysis was first performed on the original dataset to evaluate the distribution of microwave absorption measurements before applying the outlier removal procedure. The boxplot visualization allows observation of median values, quartile ranges, and extreme observations for each slot configuration across the L-band, S-band, C-band, and X-band frequency ranges. The boxplots for the original dataset are presented in Fig. 2.

The results indicate noticeable differences in the statistical distribution of absorption measurements across the four frequency bands. The L-band dataset exhibits the narrowest interquartile range among the frequency bands, indicating that the absorption measurements are relatively concentrated around the median value. This narrow distribution suggests that the absorber exhibits stable absorption behaviour in the lower frequency region.

The S-band dataset shows slightly wider distributions compared with the L-band. Although the measurements remain relatively concentrated, the increased spread indicates moderate variability in the absorption values. This behaviour suggests that the absorber maintains relatively stable performance within the mid-frequency range.

In contrast, the C-band dataset demonstrates a significantly wider interquartile range along with several extreme observations. The broader distribution indicates greater variability in absorption measurements. This behaviour can be associated with the shorter electromagnetic wavelength at higher frequencies, which increases the sensitivity of the absorber performance to structural variations and fabrication tolerances.

The X-band dataset exhibits the largest spread among all frequency bands. The wide interquartile range and the presence of multiple extreme observations indicate that absorption measurements at higher frequencies show greater variability. Table 1 summarizes the statistical parameters of the original dataset, including the number of observations, minimum values, maximum values, and quartile statistics for each slot configuration.



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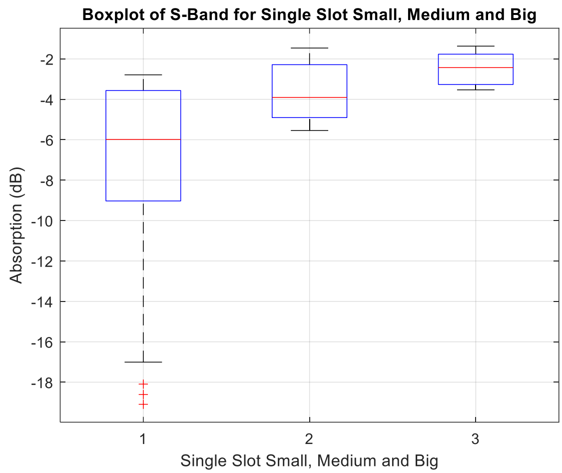

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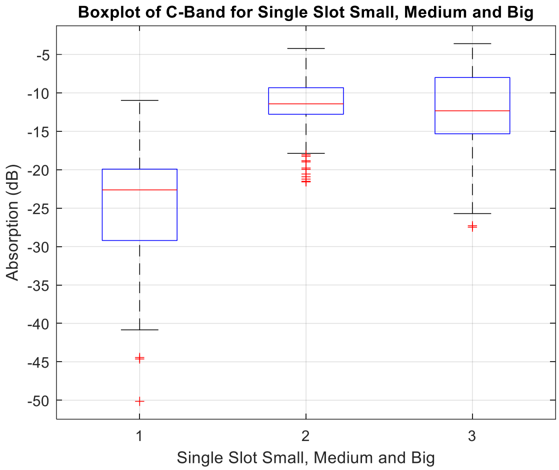

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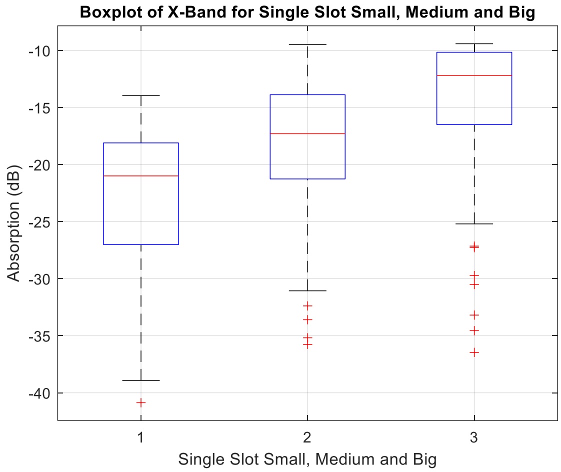


(d)

Fig. 2. Boxplot of absorption performance for different slot sizes using the original dataset (a) L-band, (b) S-band, (c) C-band, (d) X-band

The comparison between slot sizes also reveals differences in the distribution of absorption measurements. The big slot configuration generally produces a wider range of absorption values, indicating greater variability in electromagnetic interaction within the absorber structure. In contrast, the small slot configuration tends to produce more concentrated distributions in several frequency bands, suggesting more stable absorption behaviour.

Table 1. Statistical summary of boxplot analysis for the original dataset of L-, S-, C-, and X-band absorption performance according to slot size

Band	Parameter	Big Slot	Medium Slot	Small Slot
L-Band	Number of Data Points	29	29	29
	Min	-2.3881	-2.4619	-3.7689
	Max	-1.1285	-0.8498	-2.2514
	Q1 (25th percentile)	-1.3752	-1.4367	-3.3504
	Q2 (Median)	-1.283	-1.112	-3.1624
	Q3 (75th percentile)	-1.1783	-0.9165	-2.7277
S-Band	Number of Data Points	57	57	57
	Min	-3.5302	-3.5302	-19.0936
	Max	-1.3681	-1.3681	-2.7878
	Q1 (25th percentile)	-3.2657	-3.2657	-9.0291
	Q2 (Median)	-2.4309	-2.4309	-5.9847
	Q3 (75th percentile)	-1.7658	-1.7658	-3.5648
C-Band	Number of Data Points	114	114	114
	Min	-27.4774	-21.5891	-50.1436
	Max	-3.5954	-4.2258	-10.9841
	Q1 (25th percentile)	-15.3222	-12.7815	-29.211
	Q2 (Median)	-12.3305	-11.4261	-22.6285
	Q3 (75th percentile)	-7.9999	-9.3256	-19.923
X-Band	Number of Data Points	201	201	201
	Min	-36.462	-35.76	-40.871
	Max	-9.413	-9.486	-13.96
	Q1 (25th percentile)	-16.509	-21.264	-27.02
	Q2 (Median)	-12.16	-17.347	-20.926
	Q3 (75th percentile)	-10.156	-13.899	-18.097

3.2 Dataset After Outlier Removal

The interquartile range method was applied to detect and remove outliers from the dataset. This preprocessing step aims to improve the reliability of the statistical analysis by reducing the influence of extreme observations that may arise from measurement noise or experimental inconsistencies.

The reduction in the number of data points after preprocessing can be quantitatively observed across all frequency bands. The L-band dataset decreased from 29 to 25 data points, corresponding to an approximate reduction of 13.8%. The S-band dataset was reduced from 57 to 54 data points (5.3%), while the C-band dataset decreased from 114 to 103 data points (9.6%). Similarly, the X-band dataset was reduced from 201 to 194 data points (3.5%). These results indicate that lower frequency bands contain a relatively higher proportion of extreme values compared to higher frequency bands, reflecting the influence of measurement variability and noise in the dataset.

After the removal of outliers, the number of data points is slightly reduced across several frequency bands and slot configurations. Table 2 presents the statistical summary of the dataset after the preprocessing procedure. The table includes the updated number of observations together with the corresponding minimum values, maximum values, and quartile statistics for each slot configuration across the four frequency bands.

The processed dataset maintains the central distribution characteristics of the original measurements while eliminating abnormal observations. The median values remain relatively consistent after preprocessing, indicating that the central tendency of the dataset is not significantly affected by the removal of extreme values. However, the overall range between minimum and maximum values becomes narrower, reflecting the improved stability of the dataset.

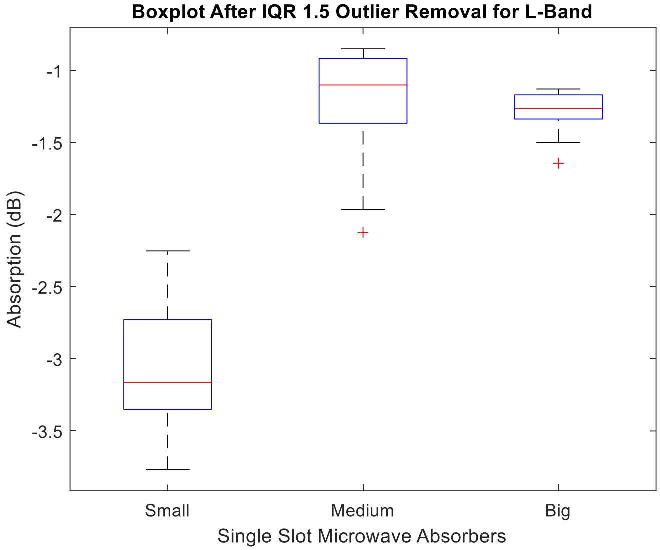
Table 2. Statistical summary of boxplot analysis for the original dataset of L-, S-, C-, and X-band absorption performance according to slot size

Band	Parameter	Big Slot	Medium Slot	Small Slot
L-Band	Number of Data Points	25	27	29
	Min	-1.6437	-2.1234	-3.7689
	Max	-1.1285	-0.8498	-2.2514
	Q1 (25th percentile)	-1.3367	-1.3660	-3.3504
	Q2 (Median)	-1.2630	-1.1005	-3.1624
	Q3 (75th percentile)	-1.1690	-0.9164	-2.7277
S-Band	Number of Data Points	57	57	54
	Min	-3.5302	-3.5302	-17.0070
	Max	-1.3681	-1.4618	-2.7878
	Q1 (25th percentile)	-3.2657	-4.9040	-8.1338
	Q2 (Median)	-2.4309	-3.9049	-5.7413
	Q3 (75th percentile)	-1.7658	-2.2848	-3.5607
C-Band	Number of Data Points	112	103	111
	Min	-25.7062	-17.8733	-40.8398
	Max	-3.5954	-4.2258	-10.9841
	Q1 (25th percentile)	-15.2730	-12.5020	-28.0958
	Q2 (Median)	-12.2557	-11.1324	-22.4420
	Q3 (75th percentile)	-7.9165	-9.0859	-19.4734
X-Band	Number of Data Points	194	197	200
	Min	-25.1990	-31.0643	-38.9198
	Max	-9.4127	-9.4855	-13.9602
	Q1 (25th percentile)	-16.0306	-21.2344	-26.9965
	Q2 (Median)	-11.8094	-20.9237	-20.9237
	Q3 (75th percentile)	-10.1292	-18.0911	-18.0911

3.3 Boxplot Distribution After Preprocessing

The interquartile range method was applied to detect and remove outliers from the dataset. This preprocessing step aims to improve the reliability of the statistical anal-ysis by reducing the influence of extreme observations that may arise from measure-ment noise or experimental inconsistencies.

The reduction in the number of data points after preprocessing can be quantita-tively observed across all frequency bands. The L-band dataset decreased from 29 to 25 data points, corresponding to an approximate reduction of 13.8%. The S-band dataset was reduced from 57 to 54 data points (5.3%), while the C-band dataset de-creased from 114 to 103 data points (9.6%). Similarly, the X-band dataset was re-duced from 201 to 194 data points (3.5%). These results indicate that lower frequen-cy bands contain a relatively higher proportion of extreme values compared to higher frequency bands, reflecting the influence of measurement variability and noise in the dataset.



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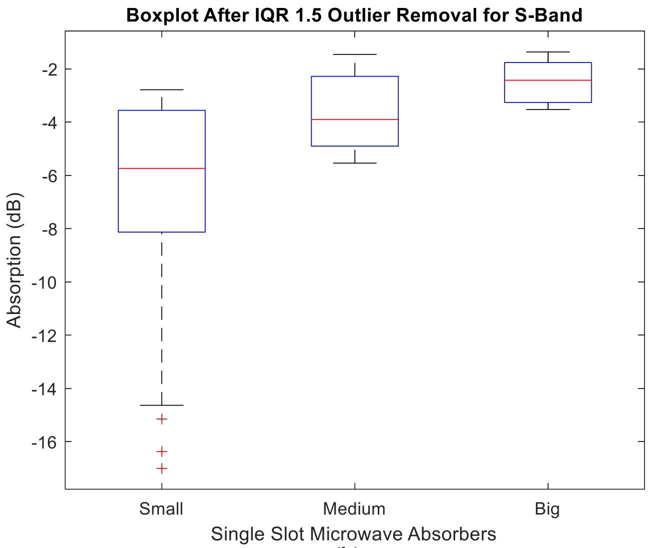

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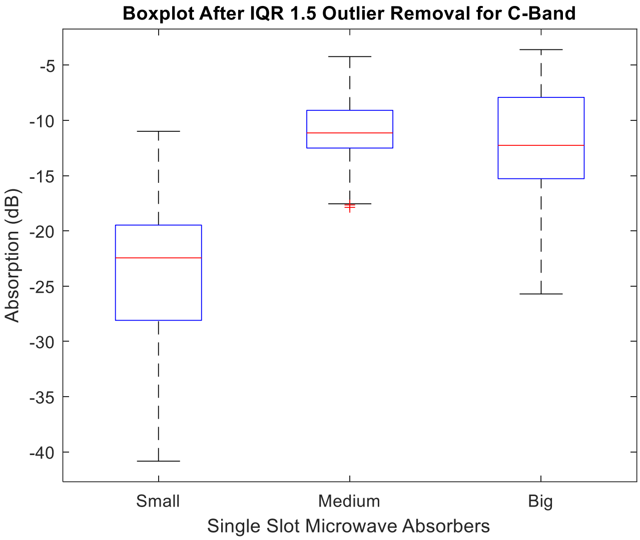

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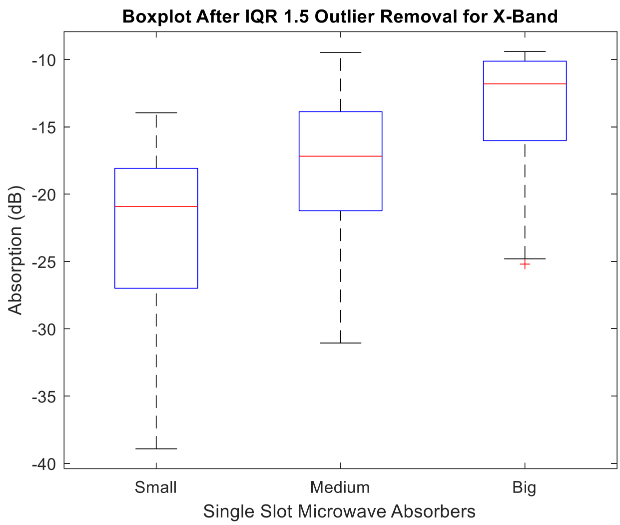

(d)

Fig. 3. Boxplot of microwave absorption performance after outlier removal for different slot configurations across (a) L-band, (b) S-band, (c) C-band, and (d) X-band.

Boxplot analysis was performed again after the outlier removal procedure to examine the distribution characteristics of the processed dataset. The boxplots for the cleaned dataset are shown in Fig. 3. Compared with the original dataset, the distributions appear more consistent and contain fewer extreme observations.

The L-band dataset continues to exhibit the most stable distribution with a narrow interquartile range and concentrated absorption values around the median. The S-band dataset also demonstrates relatively stable behaviour after preprocessing. The removal of extreme observations produces a more uniform distribution of absorption measurements.

The C-band and X-band datasets still show wider interquartile ranges compared with the lower frequency bands. Although the removal of outliers reduces the number of extreme observations, the datasets continue to display larger variability in absorption measurements. This observation indicates that the variability observed at higher frequencies is not solely caused by abnormal measurements but is also influenced by the inherent characteristics of the absorber structure.

The comparison between slot configurations further confirms that slot geometry influences the statistical distribution of microwave absorption measurements. Larger slot configurations tend to produce wider spreads of absorption values, while smaller slot configurations show more concentrated distributions in certain frequency bands. This behaviour suggests that slot size affects the interaction between electromagnetic waves and the absorber structure.

Overall, the results demonstrate that boxplot visualization combined with interquartile range-based preprocessing provides a useful approach for evaluating experimental microwave absorber datasets. The preprocessing procedure improves the clarity of data distribution and supports a more reliable interpretation of absorption characteristics across different frequency bands and slot configurations.

Although formal statistical hypothesis testing is not included in this study, the observed reduction in data spread and the improved consistency in boxplot distributions indicate a meaningful enhancement in dataset reliability after preprocessing.

4 Conclusion

This study presented the application of boxplot-based exploratory data analysis and interquartile range preprocessing for evaluating the statistical distribution of microwave absorption measurements obtained from single slot pyramidal microwave absorbers operating across L-band, S-band, C-band, and X-band frequency ranges. Boxplot visualisation allows efficient representation of median values, quartile ranges, and extreme observations within the experimental dataset.

The analysis revealed that absorption measurements in the L-band and S-band exhibit relatively stable distributions with narrower interquartile ranges, while the C-band and X-band datasets show larger variability in absorption values. This increased variability at higher frequencies is associated with the shorter electromagnetic wavelength, which increases the sensitivity of the absorber performance to structural variations and measurement conditions.

The interquartile range-based outlier detection method successfully identifies and removes extreme observations from the dataset. After preprocessing, the statistical distribution of the absorption measurements becomes more consistent while maintaining the central characteristics of the original data. The comparison between slot configurations also indicates that slot geometry influences the distribution of absorption measurements across different frequency bands.

Overall, the results demonstrate that statistical preprocessing using boxplot visualisation and interquartile range filtering is an effective approach for analysing experimental microwave absorber datasets. The preprocessing procedure improves dataset reliability and provides a clearer basis for further analysis, such as normalization, regression modelling, or machine learning based prediction of microwave absorber performance.

Future work will focus on extending the proposed preprocessing approach by integrating machine learning techniques such as K-Nearest Neighbour (KNN) and regression models to predict microwave absorption performance based on the processed dataset. This will enable more advanced modelling and improve the accuracy of absorption performance prediction across multiple frequency bands.In experimental microwave absorber studies, absorption performance is normally

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