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INTERLABORATORY COMPARISON OF S-PARAMETER MEASUREMENTS IN WM-380 WAVEGUIDE AT FREQUENCIES FROM 500 GHz TO 750 GHz

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ABSTRACT

A recent measurement comparison exercise involving four participating laboratories was undertaken to establish understanding of the current state of the art of WM-380 rectangular metallic waveguide S-parameter measurement capabilities. This report details the comparison in which each participant measured four WM-380 waveguide devices operating from 500 GHz to 750 GHz. A summary of the results obtained is given, along with some observations and analysis.

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CONTENTS

GLOSSARY/ABBREVIATIONS

WM-380	Rectangular waveguide with broad wall dimension of 380 μm supporting frequencies from 500 GHz to 750 GHz
S-parameters	Scattering parameters of a device or component
SOLT	Short-Offset Short-Load-Through method of VNA calibration
TRL	Through-Reflect-Line method of VNA calibration
IF	Intermediate frequency
VNA	Vector Network Analyser
S_{11}	Reflection S-parameter measured at port 1
S_{22}	Reflection S-parameter measured at port 2
S_{21}	Transmission S-parameter measured between ports 1 and 2 with stimulus applied at port 1
S_{12}	Transmission S-parameter measured between ports 1 and 2 with stimulus applied at port 2

1 INTRODUCTION

The TEMMT[1] European metrology project [1], which ran from 2019 to 2022, involved the development of state-of-the-art high frequency S-parameter measurement facilities. One of these developments was based around the WM-380 waveguide band, which operates at frequencies from 500 GHz to 750 GHz. Following the development of these new facilities, an intercomparison of measurements was undertaken to establish the level of equivalence between these measurement facilities. The participants in the intercomparison were the four institutes involved in developing the new measurement facilities: Chalmers University of Technology, Sweden; National Physical Laboratory, UK; University of Birmingham, UK; Virginia Diodes, Inc (VDI), USA.

This report provides details about this intercomparison in which the participants each measured four WM-380 devices. The devices were selected to provide a broad range of responses which would indicate the extent of the performance of each measurement facility. The results from the four participants are presented in an anonymised fashion, using labels A, B, C and D. This is so that the results can be judged independently from the knowledge of who contributed them.

2 PARTICIPANT DETAILS

Table 1 lists the participants' details, i.e. the dates of the measurements, the method used for calibrating the VNA, and other related information. In terms of hardware, all four participants used Keysight PNA-X Vector Network Analysers (VNAs) in conjunction with VDI frequency extender heads to achieve the WM-380 setup.

Table 1. Details of the Comparison Participants

Participant	**Date of measurements**	**Calibration technique used**	**Other information**
A	June 2020	¾-wave TRL	IF bandwidth: 100 Hz Measured every 0.5 GHz
B	September 2020	¼-wave TRL	IF bandwidth: 100 Hz Measured every 1 GHz
C	November 2020	SOLT	IF bandwidth: 300 Hz Measured every 1 GHz
D	January 2021	SOLT	IF bandwidth: 300 Hz Measured every 1 GHz

The pilot laboratory measured the items twice: first, at the beginning of the comparison, and again at the end of the comparison. The two sets of measurements were used to determine whether the characteristics of the devices had changed significantly during the comparison exercise. It was found that the differences between these two sets of measurements were insignificant when compared with the differences seen between the participants' results in the comparison, and therefore the devices are expected to have remained stable throughout the duration of the comparison.

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[1] TEMMT – "Traceability for Electrical Measurements at Millimetre-wave and Terahertz frequencies for communications and electronics technologies".

3 COMPARISON DEVICES

Table 2 lists the comparison device details along with the measurement parameters being compared in this comparison.

Table 2. Comparison Device Details

Type	Model Number	Serial Number	Parameters
10 dB attenuator	WM380SWGMDIR7	1-02	S_{11}, S_{22}, S_{21}, S_{12}
¼-wave cross-guide	-	QW-016	S_{21}, S_{12}
Offset short-circuit	QD R2	1-18	S_{11}
1” straight waveguide	WM380SWGMDIR7	1-20	S_{11}, S_{22}, S_{21}, S_{12}, Magnitude reciprocity, Phase reciprocity

4 MEASUREMENT CONDITIONS

The comparison exercise involved comparing the measurement results from each participant at frequencies from 500 GHz to 750 GHz in 1 GHz steps. The results at extra frequencies (i.e. down to 495 GHz and up to 755 GHz), which were included to avoid any problems that might occur at the beginning or end of the measurement sweep, were not compared.

The measurands were the complex-valued S-parameters listed in Table 2 together with ‘magnitude reciprocity’ and ‘phase reciprocity’ of the 1” straight waveguide, i.e. the difference between a participant’s S_{21} and S_{12} magnitude and phase results at each frequency. Results are presented in logarithmic magnitude (dB) and phase format with phase in the range -180° to +180°.

Separate S-parameter measurements were made in order to account for the four possible orientations of each device:

1) Device port 1 connected to VNA port 1—DUT in “up” position
2) Device port 1 connected to VNA port 1—DUT in “down” position
3) Device port 1 connected to VNA port 2—DUT in “up” position
4) Device port 1 connected to VNA port 2—DUT in “down” position

The serial number on the flange of each device was used to identify the device orientation (i.e. “up” is when the serial number is facing upwards during connection).

5 ANALYSIS TECHNIQUES

Statistics summarising the S-parameter measurements made in the comparison in terms of logarithmic magnitude (dB) and phase (degrees) are plotted in figures 1 to 11. Figure 12 summarises the magnitude and phase reciprocity measurements for the 1” straight waveguide. Table 3 lists the contents of the figures.

Table 3. Figures summarising the measurements made in the comparison

Figure	Section	Device	Parameter
1	6.1	10 dB Attenuator	S_{11}
2			S_{22}
3			S_{21}
4			S_{12}
5	6.2	¼-wave cross-guide	S_{21}
6			S_{12}
7	6.3	Offset short-circuit	S_{11}
8	6.4	1” Straight Waveguide	S_{11}
9			S_{22}
10			S_{21}
11			S_{12}
12			Reciprocity

For S-parameters with small magnitude (i.e. with linear magnitude close to zero), the phase of the S-parameter is not well defined since a small change in the complex-valued S-parameter (such as that caused by noise in the VNA or lack of repeatability in the device connection) can result in a very large change in its phase. In addition, the phases of S_{21} and S_{12} of the cross-guide are not considered to be of primary interest. Therefore, phase is only presented for the S-parameters listed in Table 4 which are considered to have a sufficiently large magnitude to ensure that the phase is well defined, in addition to the phase being a direct characteristic of the device’s performance.

Table 4. S-parameters for which phase was considered

Device	S-parameter phase included in the comparison
10 dB attenuator	None
Cross-guide	None
Offset short-circuit	S_{11}
1” straight waveguide	S_{12} and S_{21}

The participants made up to four repeat measurements of each device with the device in a different orientation for each repeat measurement. The four orientations are defined in Section 4. In some instances, certain participants made fewer than four repeat measurements of certain S-parameters.

For each S-parameter of interest, $S = |S|\angle\phi$, the following summary statistics are plotted as functions of frequency:

- The mean S-parameter magnitude (dB) for participant i (where $i = 1, \ldots, 4$ for the four participants), $\overline{|S|}_i(dB)$. This is an average of the repeat measurements made by participant i.
- The mean S-parameter magnitude (dB) for all four participants, $\overline{|S|}(\mathrm{dB})$. This is an average of the mean measurements made by all four participants.
- The standard deviation in S-parameter magnitude (dB) for participant i (where $i = 1, \ldots, 4$ for the four participants), $\mathrm{SD}(|S|_i)(\mathrm{dB})$. This measures the amount of variability between the repeat measurements made by participant i. It can only be computed for those participants who made at least two repeat measurements of the S-parameter.

- The standard deviation in S-parameter magnitude (dB) for all four participants, SD($|S|$)(dB). This measures the amount of variability between the mean measurements made by the four participants.

In addition, for those S-parameters for which phase is being considered, the following summary statistics are also plotted:

- The mean S-parameter phase for participant i (where $i = 1, \ldots, 4$ for the four participants), $\bar{\phi}_i$.
- The mean S-parameter phase for all four participants, $\bar{\phi}$.
- The standard deviation in S-parameter phase for participant i (where $i = 1, \ldots, 4$ for the four participants), SD(ϕ_i).
- The standard deviation in S-parameter phase for all four participants, SD(ϕ).

Finally, for the 1" straight waveguide, the following additional parameters are also plotted:

- Magnitude (dB) reciprocity for participant i (where $i = 1, \ldots, 4$ for the four participants), $R_i(\mathrm{dB})$. This is the difference between the mean S_{21} (dB) and the mean S_{12} (dB) for participant i.
- Phase reciprocity for participant i (where $i = 1, \ldots, 4$ for the four participants), ψ_i. This is the difference between the mean S_{21} phase and the mean S_{12} phase for participant i.

The calculation of these summary statistics is now described.

5.1. CALCULATION OF SUMMARY STATISTICS

Let M be the number of participants in the comparison ($M = 4$), let S be a complex-valued S-parameter of interest and let N_i be the number of repeat measurements of S made by the *i*th participant. Let the jth repeat measurement of S made by the ith participant at a particular frequency be:

$$S_{ij} = |S|_{ij} \angle \phi_{ij}$$

for $i = 1, \cdots, M$ and $j = 1, \cdots, N_i$ where $|S|_{ij}$ is the measured linear magnitude and ϕ_{ij} is the measured phase. The following summary statistics are calculated at each frequency.

5.1.1. Summary statistics for magnitude values

5.1.1.1. Summary of repeat magnitude measurements made by the ith participant

The mean S-parameter magnitude (expressed in dB) for participant i, $\overline{|S|}_i(dB)$, is given by equation (1):

$$\overline{|S|}_i(\mathrm{dB}) = 20\log_{10}\left(\frac{1}{N_i}\sum_{j=1}^{N_i}|S|_{ij}\right) \quad (1)$$

The standard deviation in S-parameter magnitude for participant i (expressed in dB), $\mathrm{SD}(|S|_i)(\mathrm{dB})$, is given by equation (2) [2]:

$$\mathrm{SD}(|S|_i)(\mathrm{dB}) = \frac{8.686}{\overline{|S|}_i}\sqrt{\frac{1}{N_i - 1}\sum_{j=1}^{N_i}\left(|S|_{ij} - \overline{|S|}_i\right)^2} \quad (2)$$

where $\overline{|S|}_i = \frac{1}{N_i}\sum_{j=1}^{N_i}|S|_{ij}$. Note that the standard deviation can only be calculated if the number of repeat measurements is at least two.

5.1.1.2. Summary of magnitude measurements made by all four participants

The mean S-parameter magnitude (expressed in dB) for all four participants, $\overline{|S|}(\mathrm{dB})$, is given by equation (3) (with $M = 4$):

$$\overline{|S|}(\mathrm{dB}) = 20\log_{10}\left(\frac{1}{M}\sum_{i=1}^{M}\overline{|S|}_i\right) \quad (3)$$

The standard deviation in S-parameter magnitude (expressed in dB) for all four participants, $u(|S|)(\mathrm{dB})$, is given by equation (4) (with $M = 4$) [2]:

$$\mathrm{SD}(|S|)(\mathrm{dB}) = \frac{8.686}{\overline{|S|}}\sqrt{\frac{1}{M - 1}\sum_{i=1}^{M}\left(\overline{|S|}_i - \overline{|S|}\right)^2} \quad (4)$$

where $\overline{|S|} = \frac{1}{M}\sum_{i=1}^{M}\overline{|S|}_i$.

5.1.2. Summary statistics for phase values

In order to avoid difficulties arising from phase wrapping, measured phase values are ‘unwrapped’ (i.e. numerical discontinuities at +180° and -180° are removed by subtracting multiples of 360°) prior to the calculation of mean and standard deviation phase statistics.

5.1.2.1. Summary of repeat phase measurements made by the ith participant

The mean S-parameter phase for participant i, $\bar{\phi}_i$, is given by equation (5):

$$\bar{\phi}_i = \frac{1}{N_i}\sum_{j=1}^{N_i}\phi_{ij} \quad (5)$$

The standard deviation in S-parameter phase for participant i, $\mathrm{SD}(\phi_i)$, is given by equation (6):

$$\mathrm{SD}(\phi_i) = \sqrt{\frac{1}{N_i - 1}\sum_{j=1}^{N_i}\left(\phi_{ij} - \bar{\phi}_i\right)^2} \quad (6)$$

Note that the standard deviation can only be calculated if the number of repeat measurements is at least two.

5.1.2.2. Summary of phase measurements made by all four participants

The mean S-parameter phase for all four participants, $\bar{\phi}$, is given by equation (7):

$$\bar{\phi} = \frac{1}{M}\sum_{i=1}^{M}\bar{\phi}_i \tag{7}$$

The standard deviation in S-parameter phase for all four participants, SD(ϕ), is given by equation (8):

$$\mathrm{SD}(\phi) = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}(\bar{\phi}_i - \bar{\phi})^2} \tag{8}$$

5.1.2.3. Summary of normalised phase measurements made by all four participants

The normalised mean S-parameter phase for participant *i*, $Norm(\bar{\phi_\iota})$, is given by equation (9):

$$Norm(\bar{\phi_\iota}) = \bar{\phi_\iota} - \bar{\phi} \tag{9}$$

i.e. it is the difference between the mean S-parameter phase for participant *i* and the mean S-parameter phase for all four participants. The normalised mean phase for S_{12} and S_{21} of the straight waveguide section is plotted in Figures 10d and 11d respectively. The standard deviation in the normalised mean phase for S_{12} and S_{21} is plotted in Figures 10e and 11e respectively.

5.1.3. Reciprocity for the 1” straight waveguide section

Let *A* and *B* represent S_{21} and S_{12} of the 1” waveguide, respectively, where

$$A = S_{21} = |A|\angle\alpha$$

and

$$B = S_{12} = |B|\angle\beta$$

Let the mean magnitude and phase quantities measured by participant i be $|\bar{A}|_i$, $|\bar{B}|_i$, $\bar{\alpha}_i$ and $\bar{\beta}_i$. The magnitude reciprocity for participant i (expressed in dB), $R_i(dB)$, is given by equation (10):

$$R_i(dB) = 20\log_{10}\left(\frac{|\bar{A}|_i}{|\bar{B}|_i}\right) = 20\log_{10}|\bar{A}|_i - 20\log_{10}|\bar{B}|_i \tag{10}$$

The phase reciprocity for participant i, ψ_i, is given by equation (11):

$$\psi_i = \bar{\alpha}_i - \bar{\beta}_i \tag{11}$$

6 RESULTS

For all figures, each participant’s result is presented by a coloured trace as given in Table 5.

Table 5. Legend for Participants’ Traces

Participant	**Colour of trace**
A	Blue
B	Yellow
C	Grey
D	Orange
All Participants	Green

6.1. 10 dB ATTENUATOR

6.1.1. Reflection coefficients (S_{11} and S_{22})

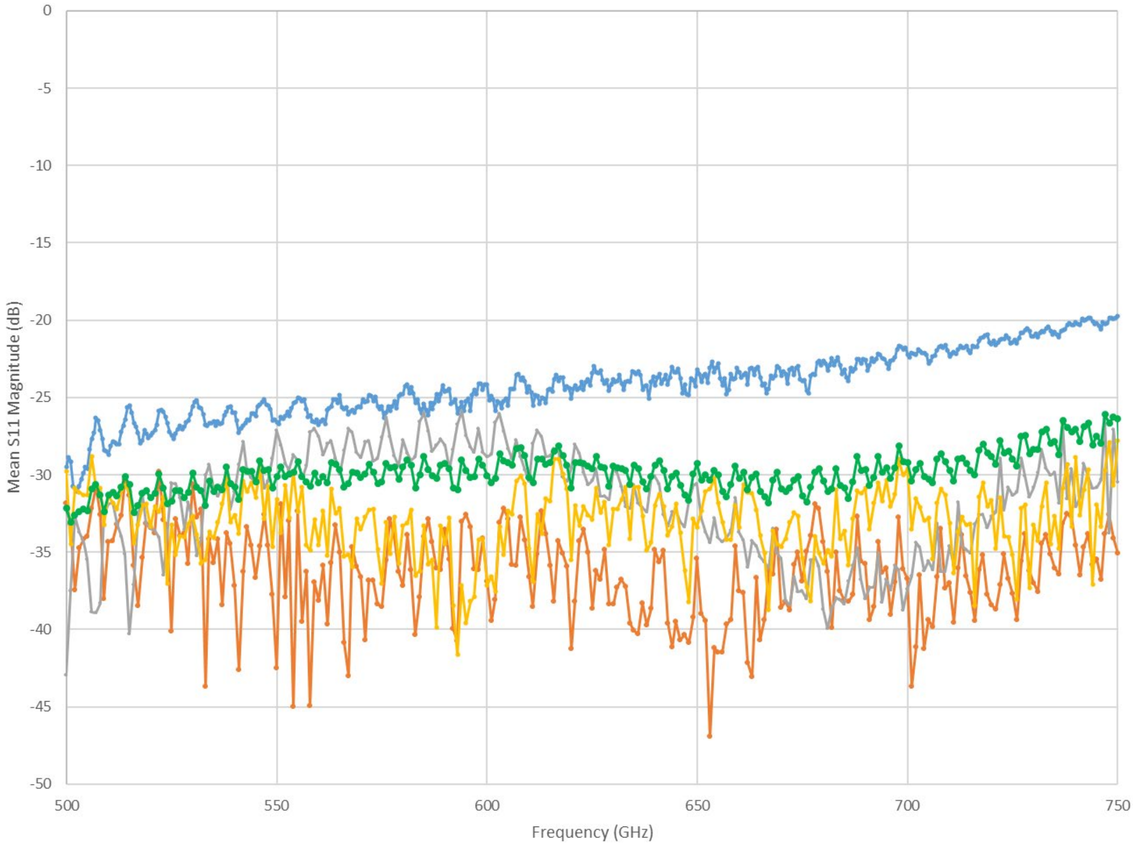

Figure 1a. 10 dB attenuator - S_{11} mean magnitude (dB)

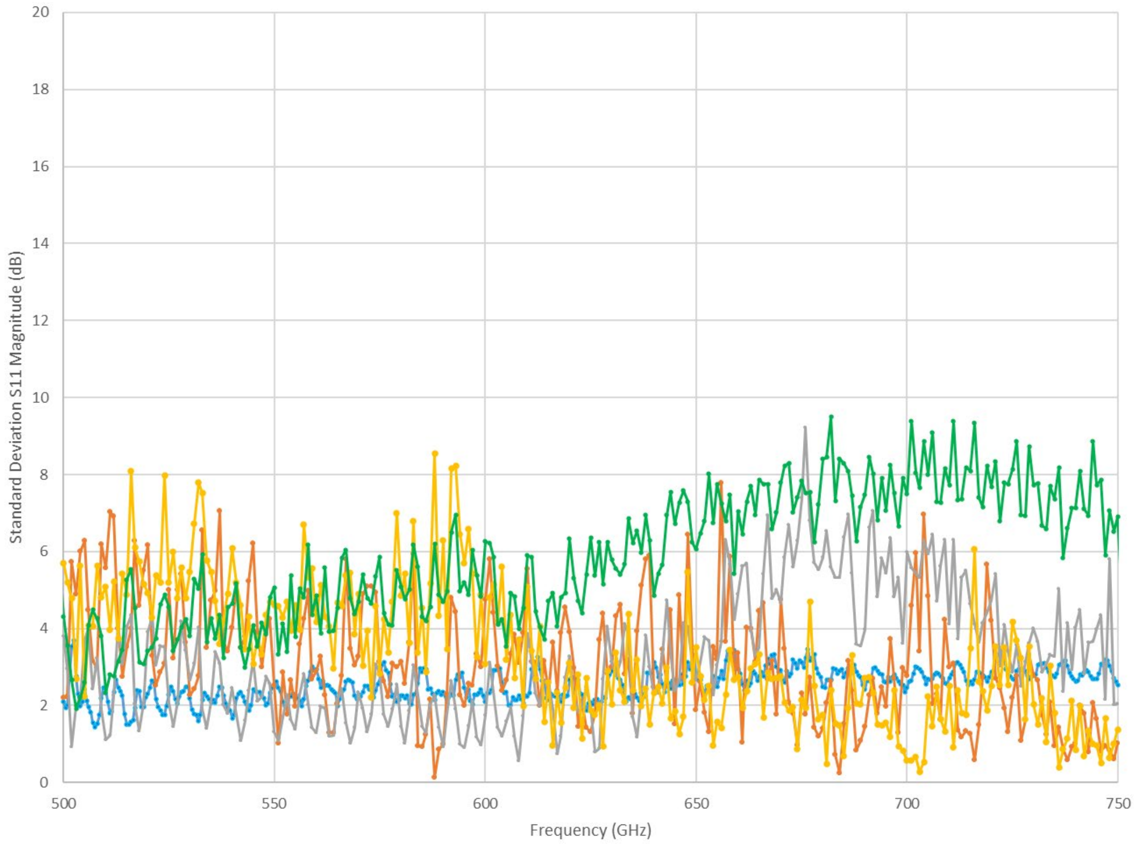

Figure 1b. 10 dB attenuator - S_{11} standard deviation magnitude (dB)

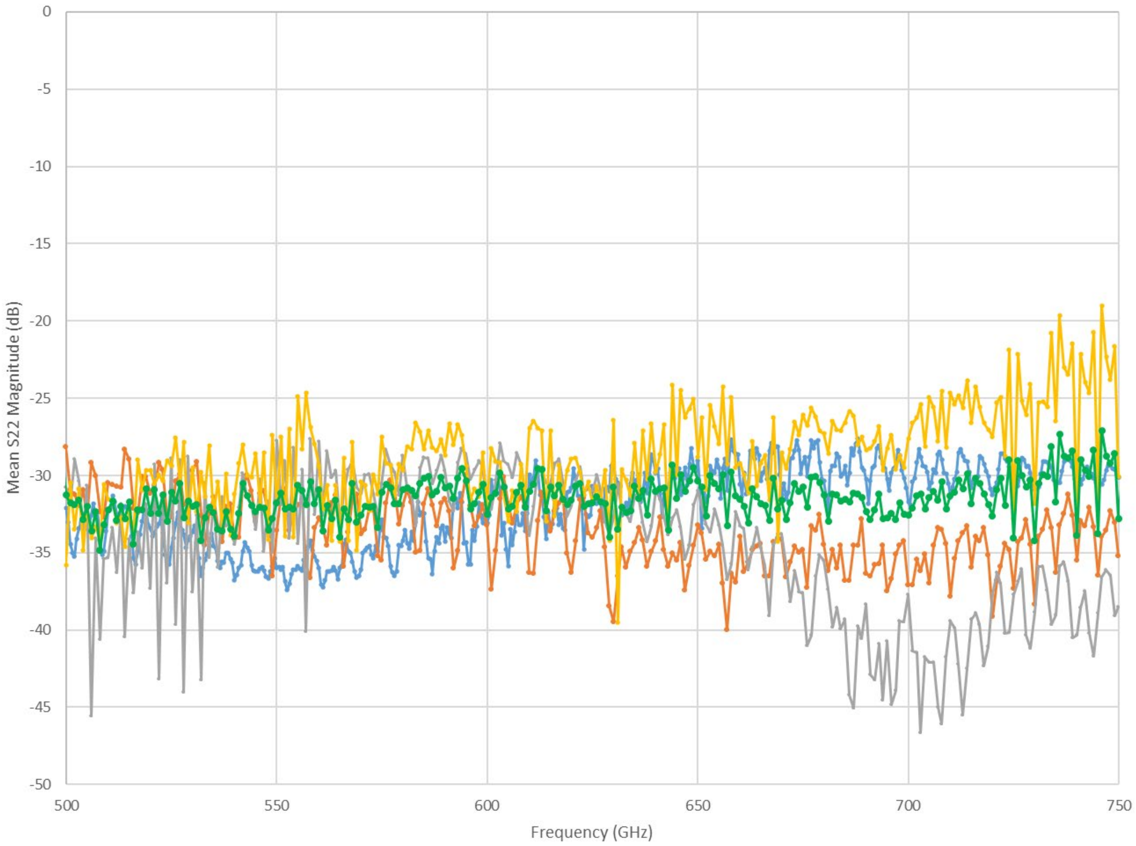

Figure 2a. 10 dB Attenuator - S_{22} Mean Magnitude (dB)

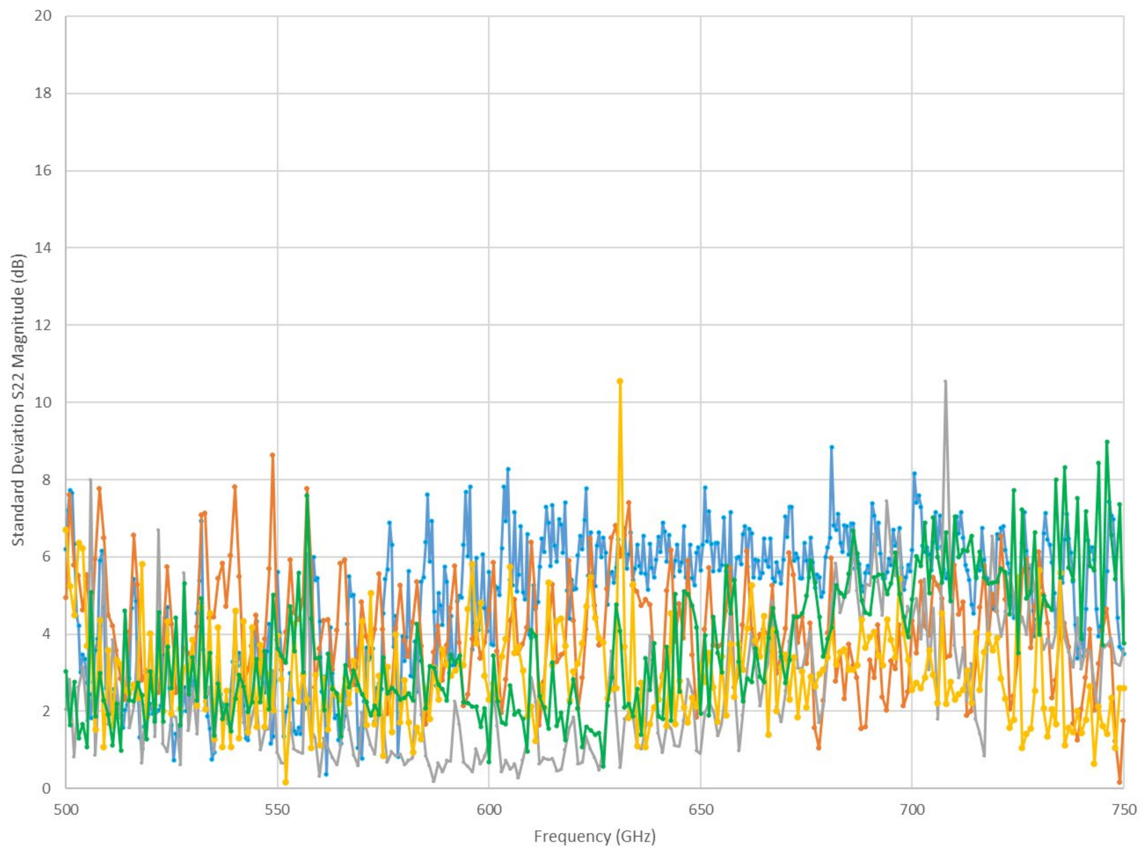

Figure 2b. 10 dB Attenuator - S_{22} Standard Deviation Magnitude (dB)

6.1.2. Transmission coefficients (S_{21} and S_{12})

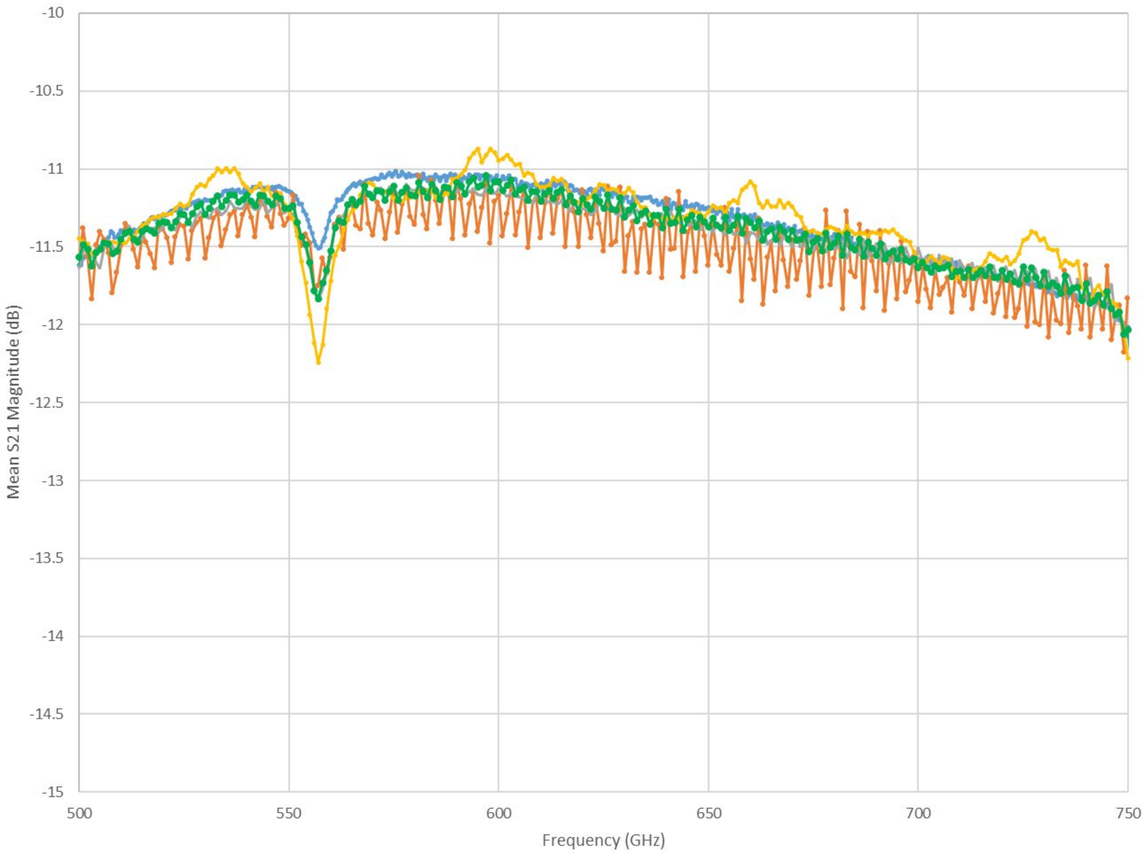

Figure 3a. 10 dB Attenuator - S_{21} Mean Magnitude (dB)

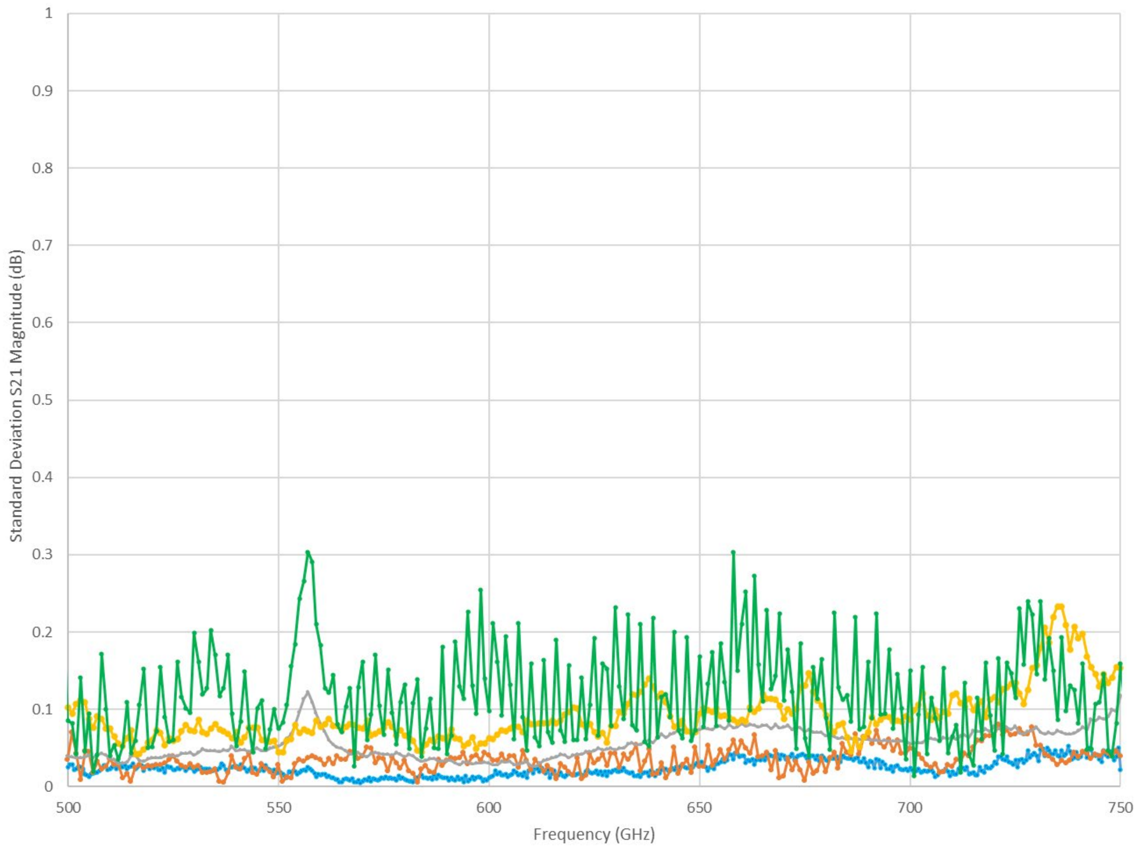

Figure 3b. 10 dB Attenuator - S_{21} Standard Deviation Magnitude (dB)

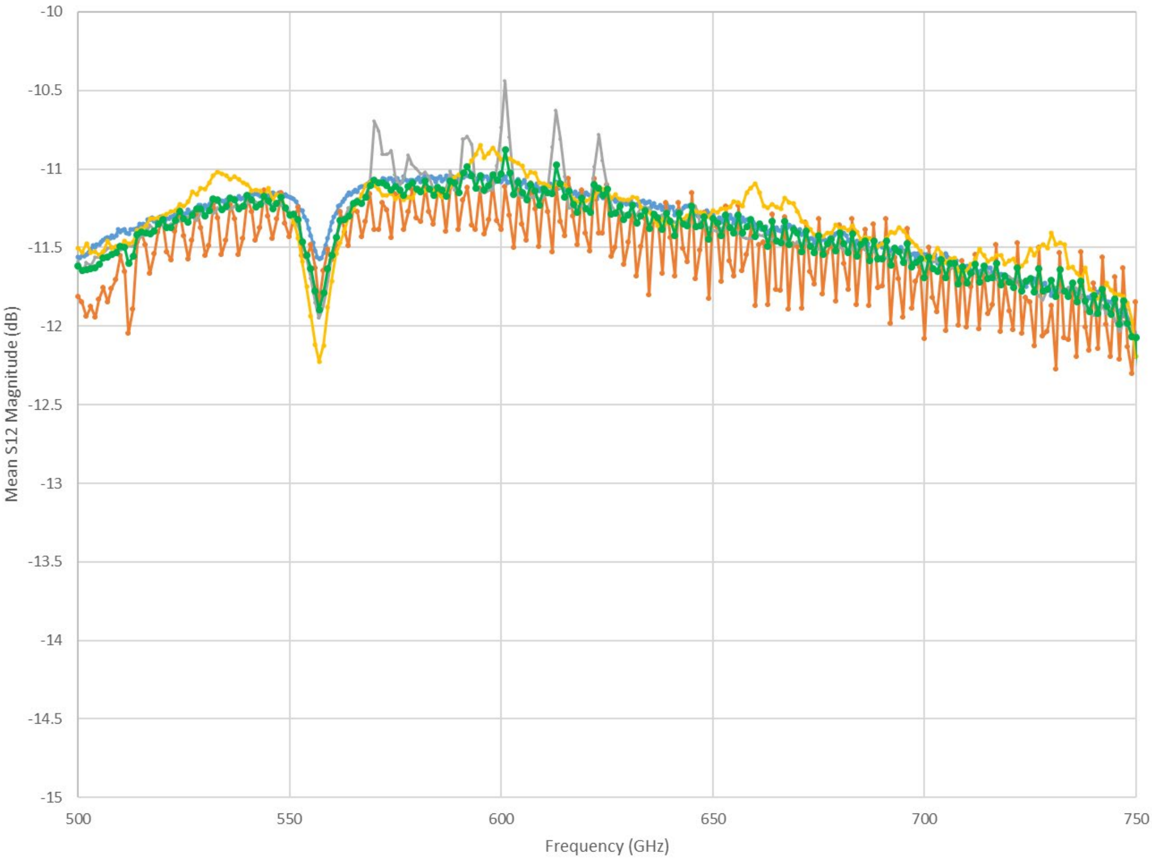

Figure 4a. 10 dB Attenuator – S_{12} Mean Magnitude (dB)

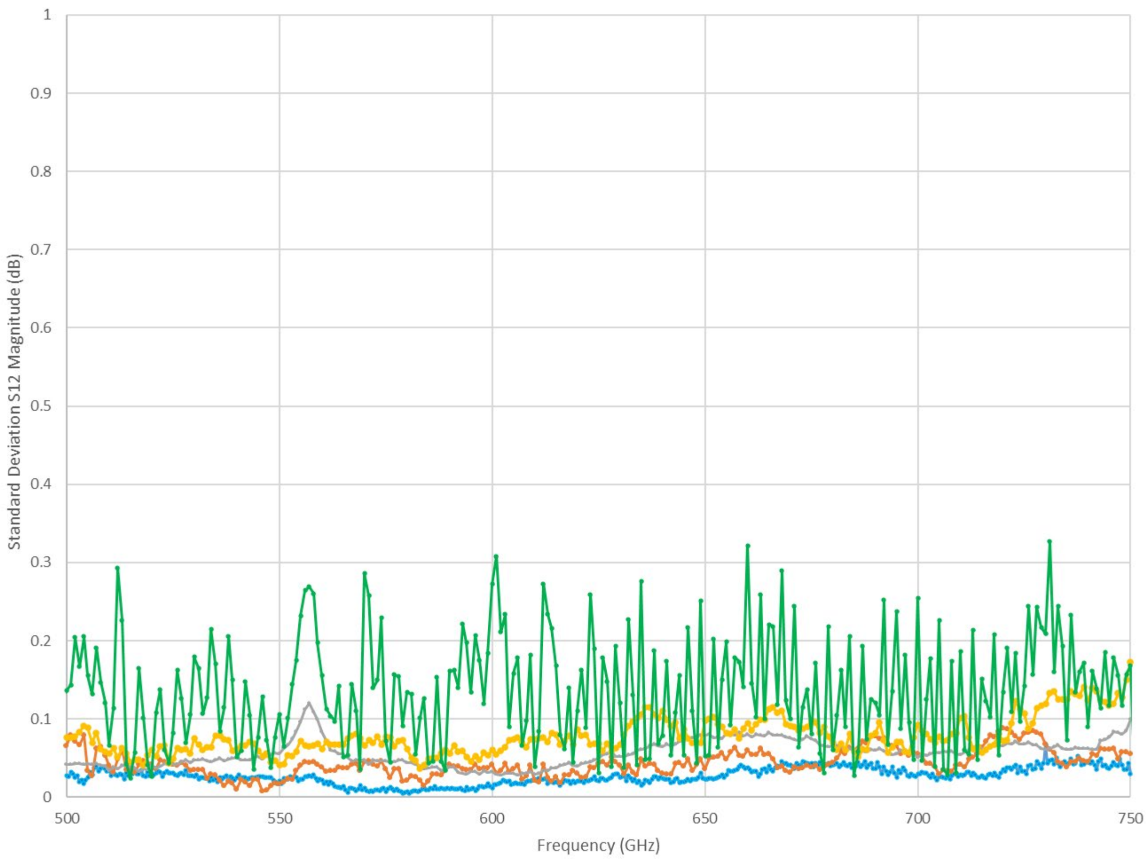

Figure 4b. 10 dB Attenuator - S_{12} Standard Deviation Magnitude (dB)

6.2. ¼-WAVE CROSS-GUIDE

6.2.1. Transmission coefficients (S_{21} and S_{12})

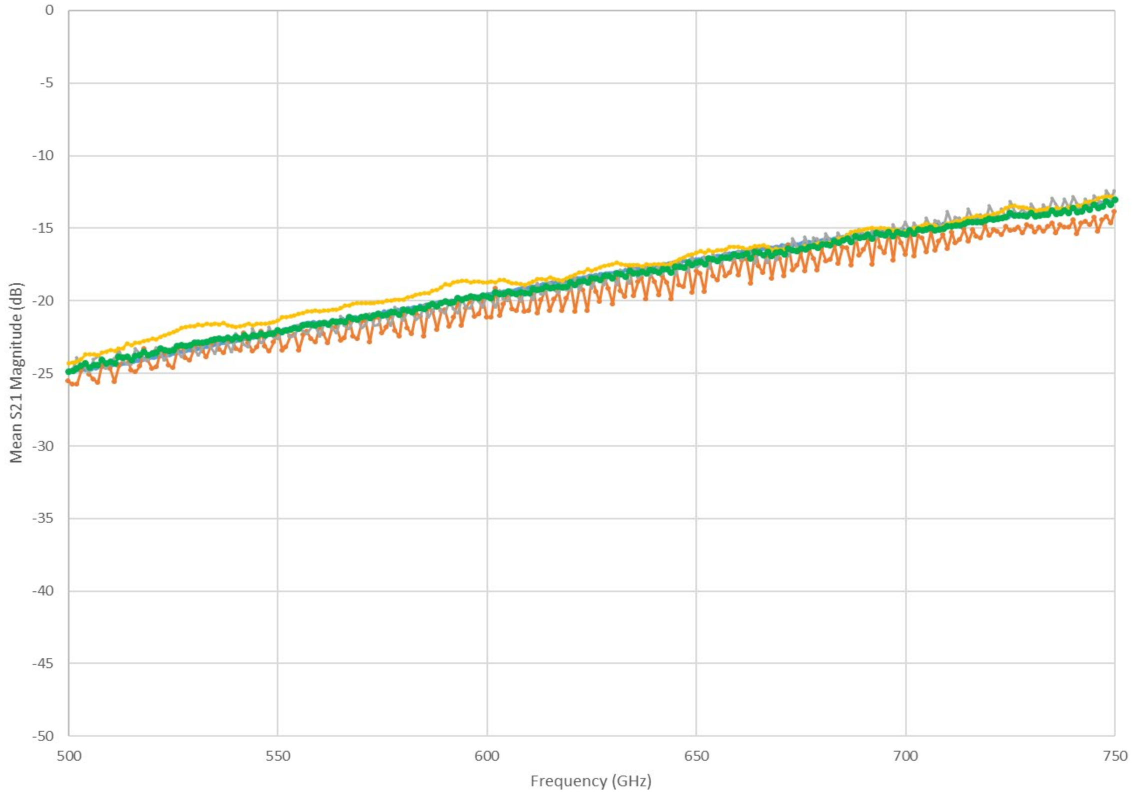

Figure 5a. 1/4-Wave Cross-Guide Line – S_{21} Mean Magnitude (dB)

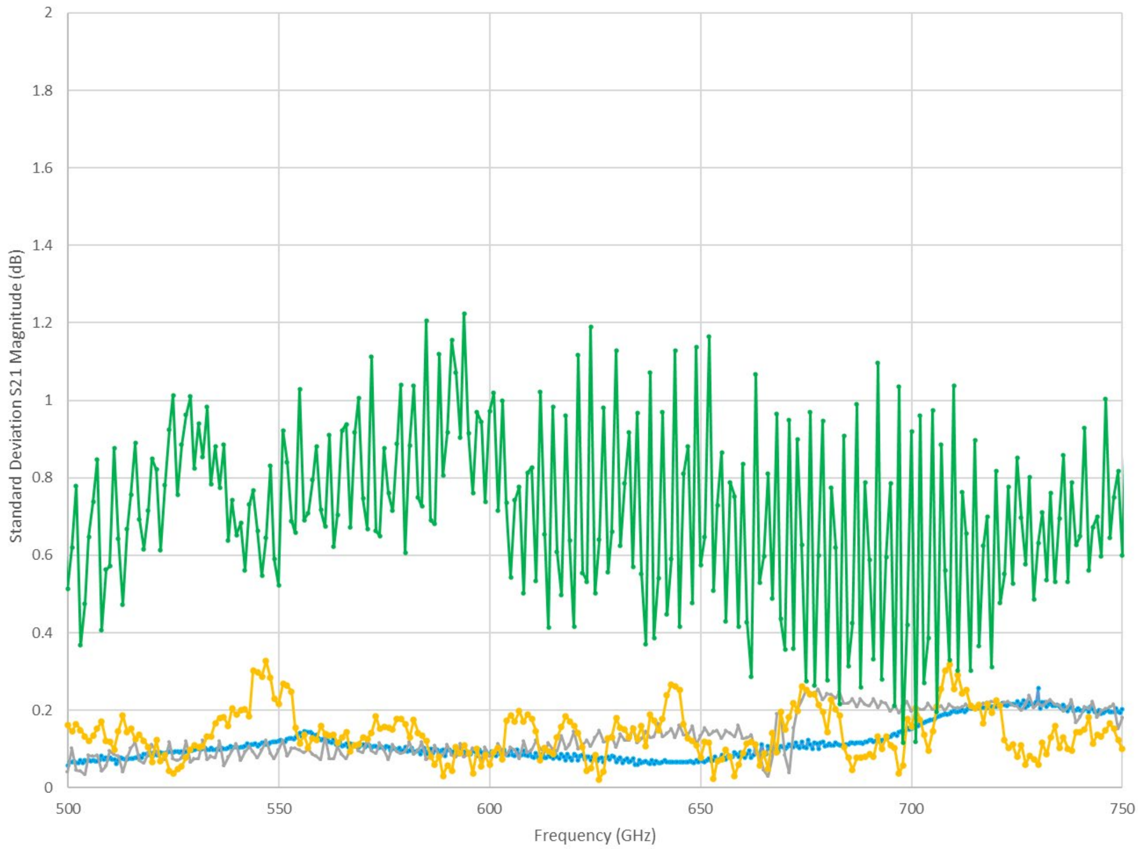

Figure 5b. 1/4-Wave Cross-Guide Line - S_{21} Standard Deviation Magnitude (dB)

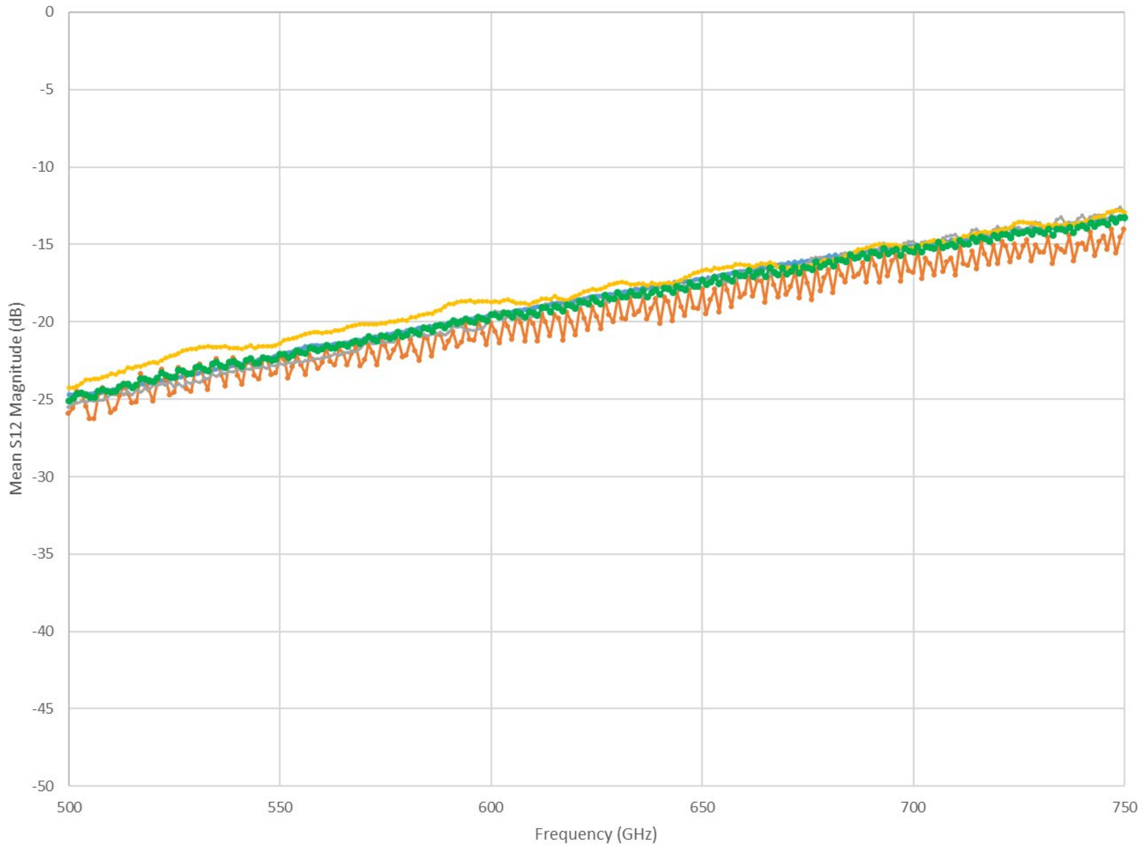

Figure 6a. 1/4 -Wave Cross-Guide Line - S_{12} Mean Magnitude (dB)

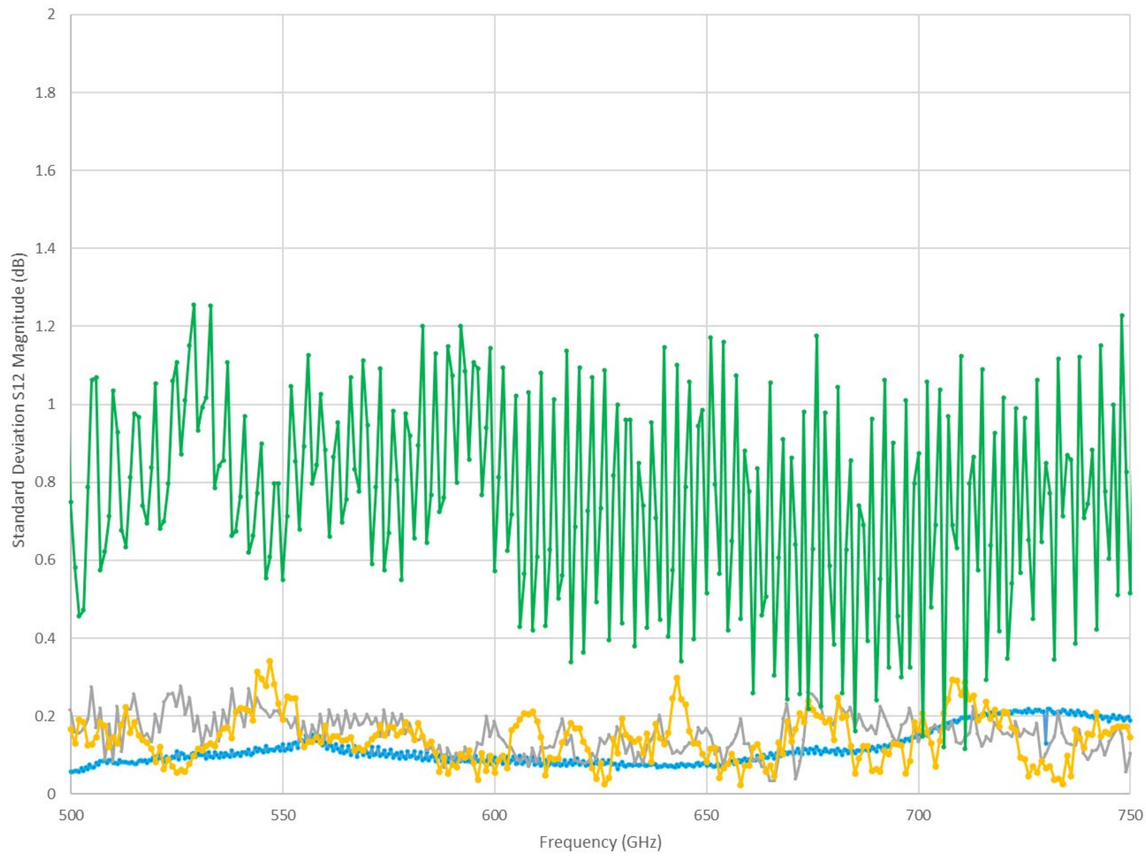

Figure 6b. ¼-Wave Cross-Guide Line - S_{12} Standard Deviation Magnitude (dB)

6.3. OFFSET SHORT-CIRCUIT

6.3.1. Reflection coefficient (S_{11})

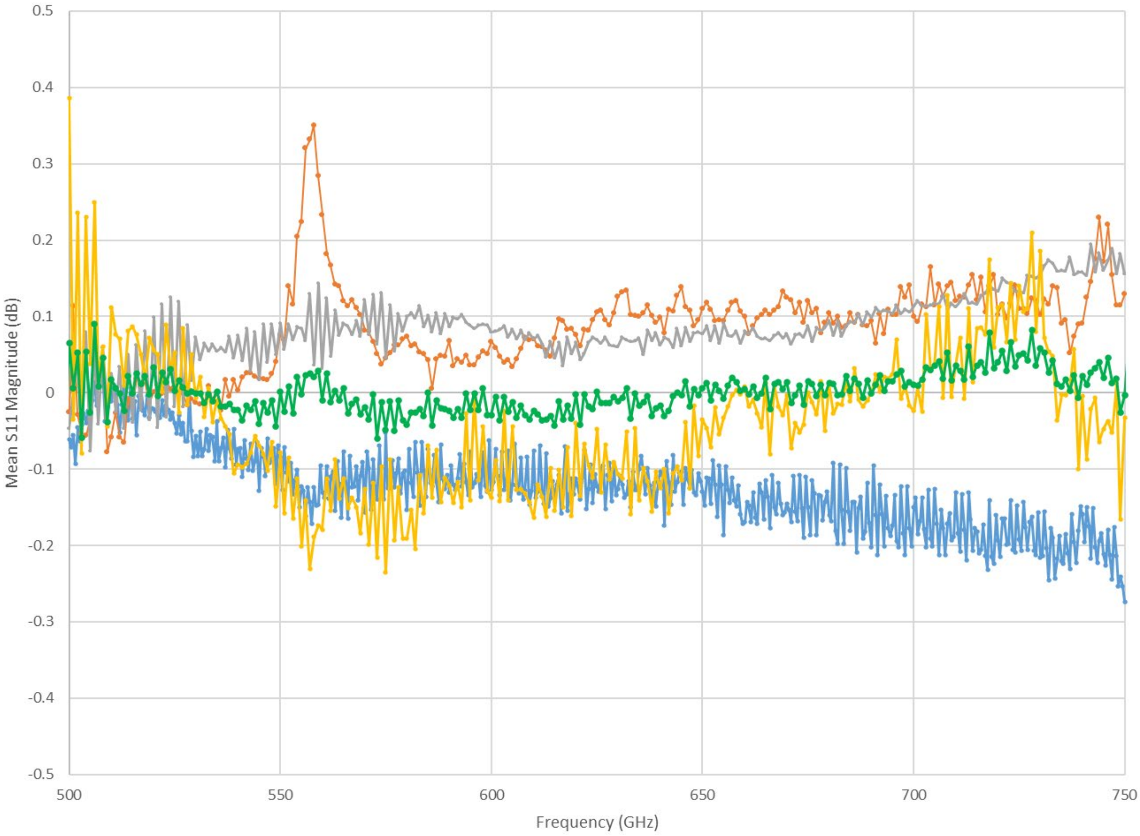

Figure 7a. Offset Short-Circuit - S_{11} Mean Magnitude (dB)

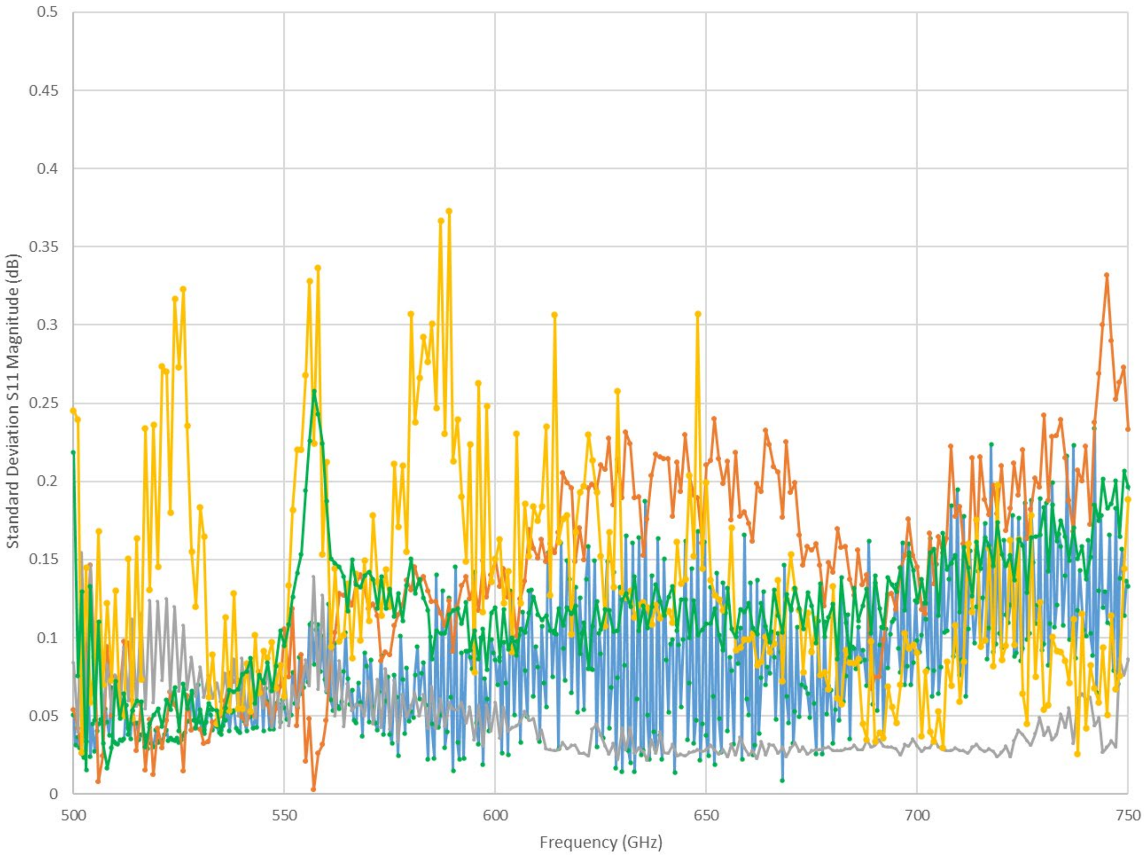

Figure 7b. Offset Short-Circuit - S_{11} Standard Deviation Magnitude (dB)

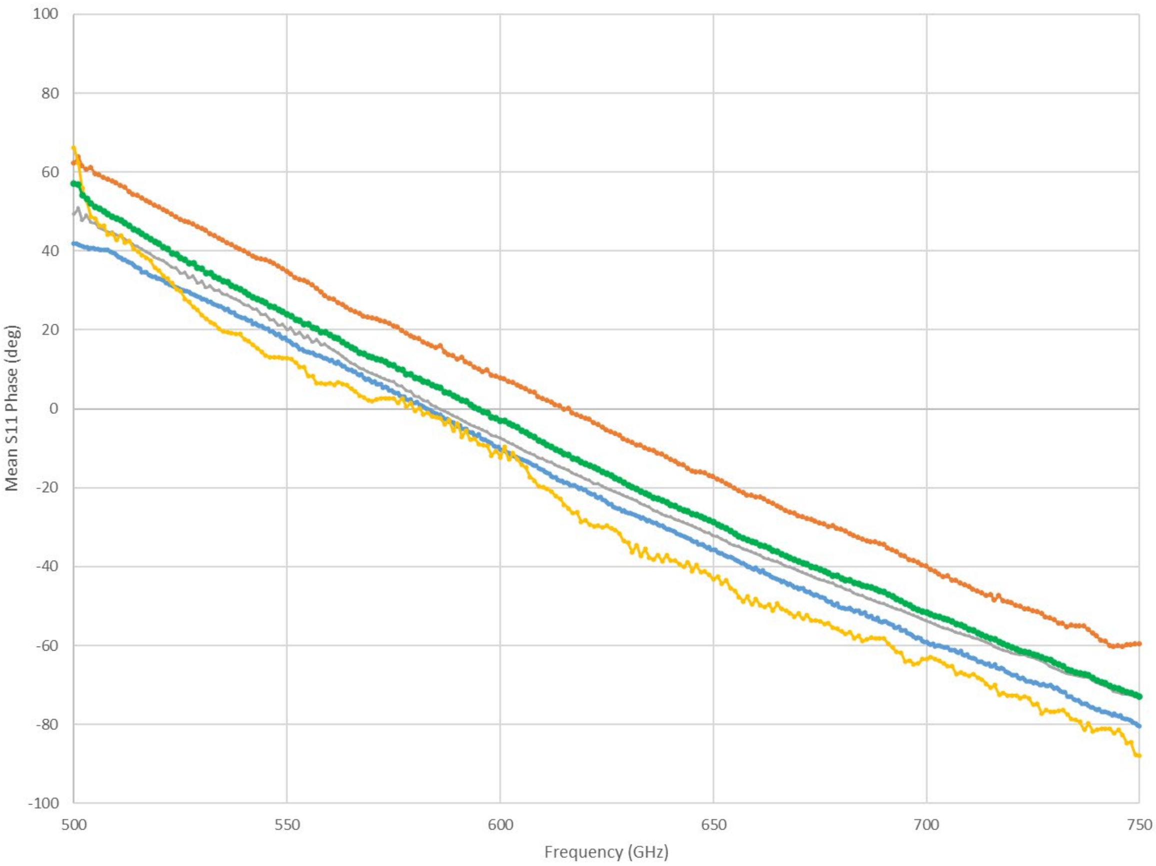

Figure 7c. Offset Short-Circuit - S_{11} Mean Phase

Figure 7d. Offset Short-Circuit - S_{11} Standard Deviation Phase

6.4. 1" STRAIGHT WAVEGUIDE SECTION

6.4.1. Reflection coefficients (S_{11} and S_{22})

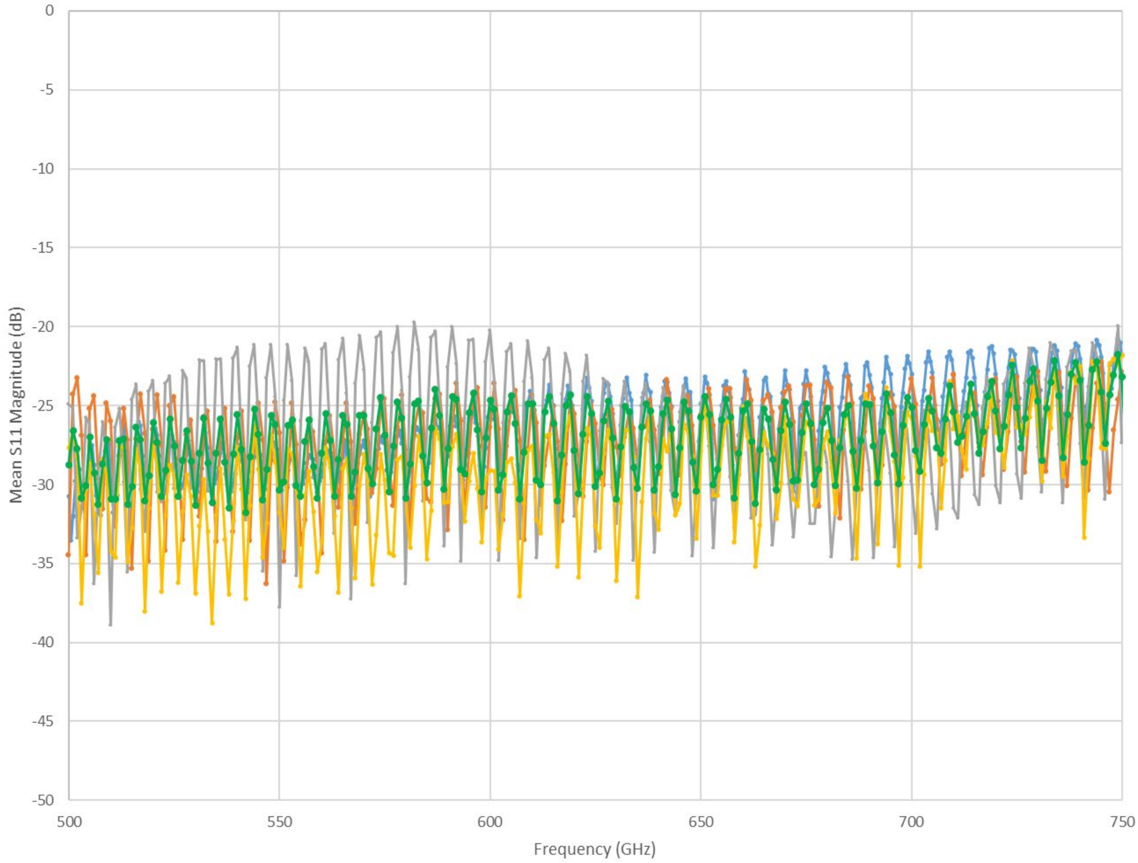

Figure 8a. 1" Straight Waveguide - S_{11} Mean Magnitude (dB)

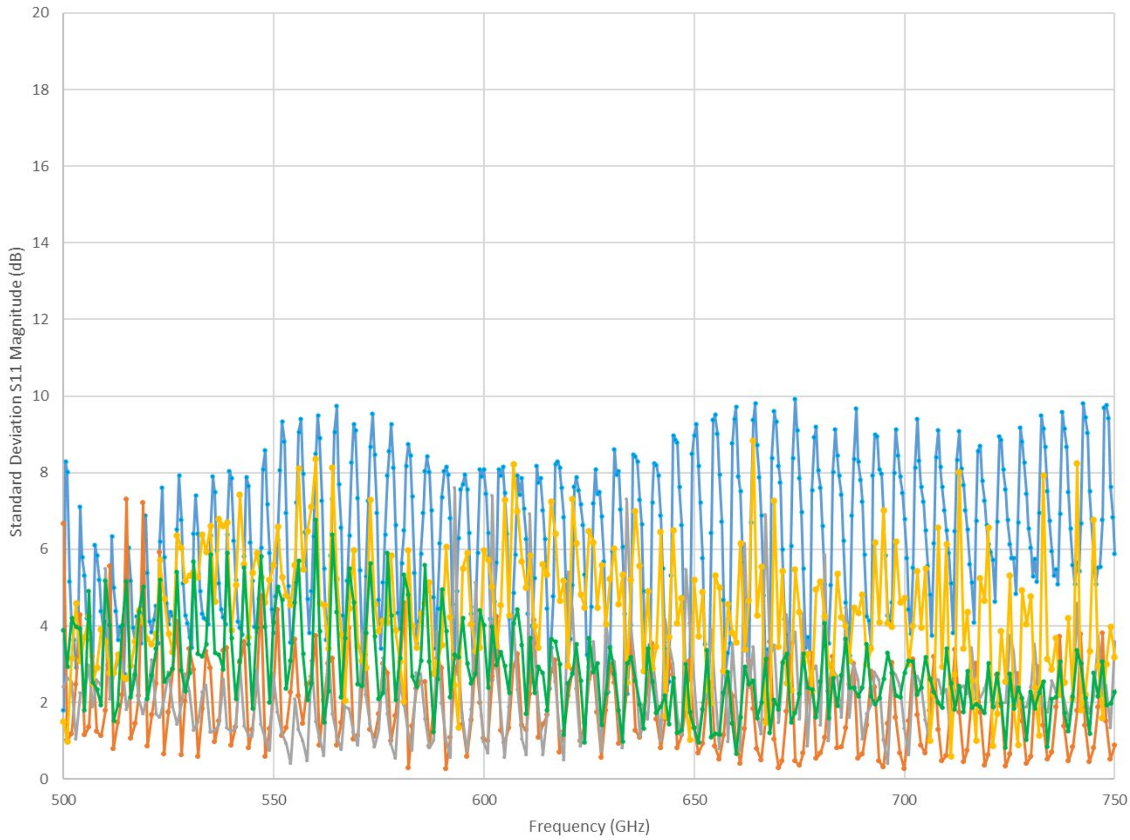

Figure 8b. 1" Straight Waveguide - S_{11} Standard Deviation Magnitude (dB)

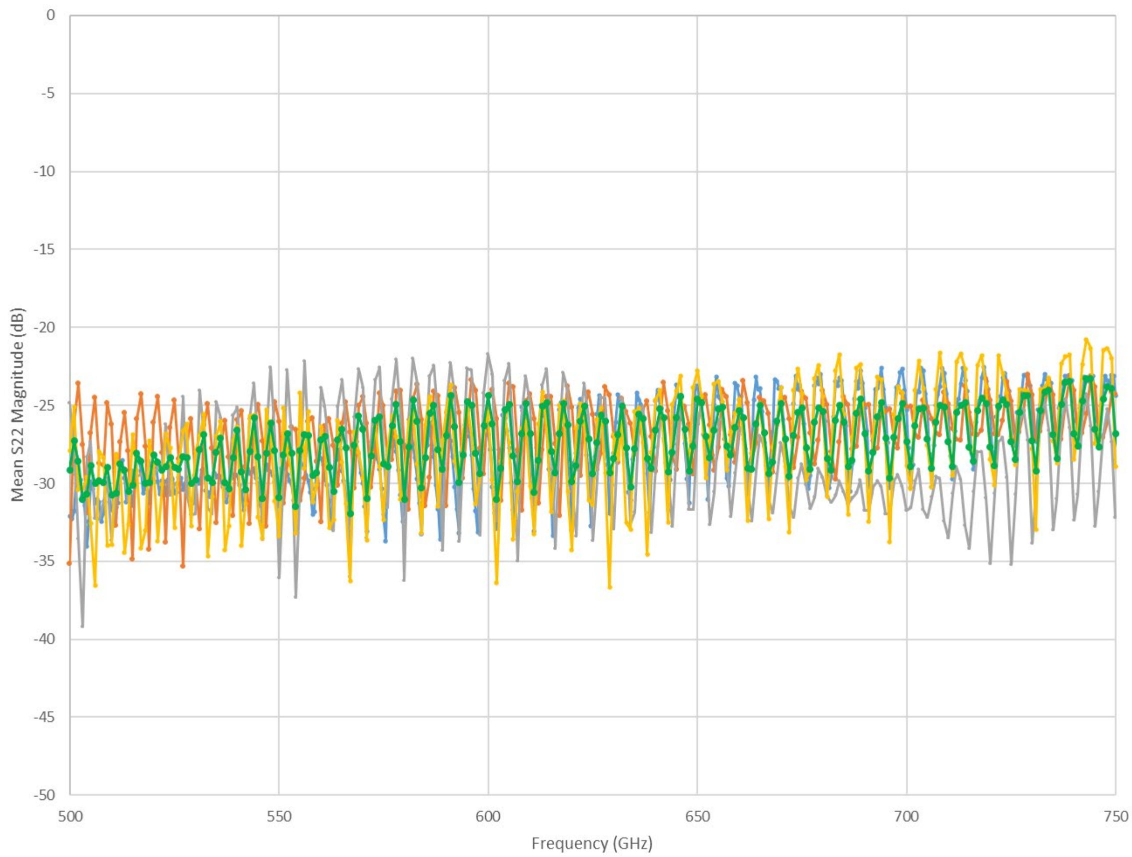

Figure 9a. 1” Straight Waveguide - S_{22} Mean Magnitude (dB)

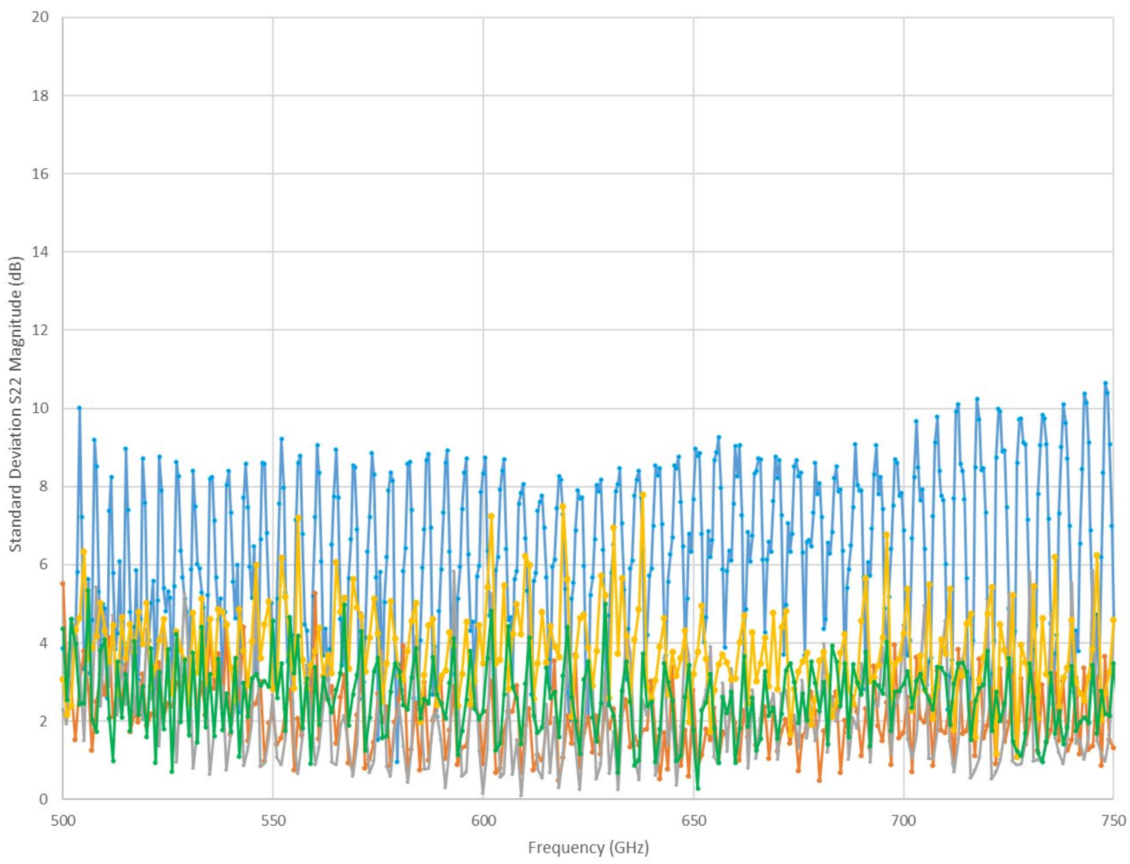

Figure 9b. 1” Straight Waveguide - S_{22} Standard Deviation Magnitude (dB)

6.4.2. Transmission coefficients (S_{21} and S_{12})

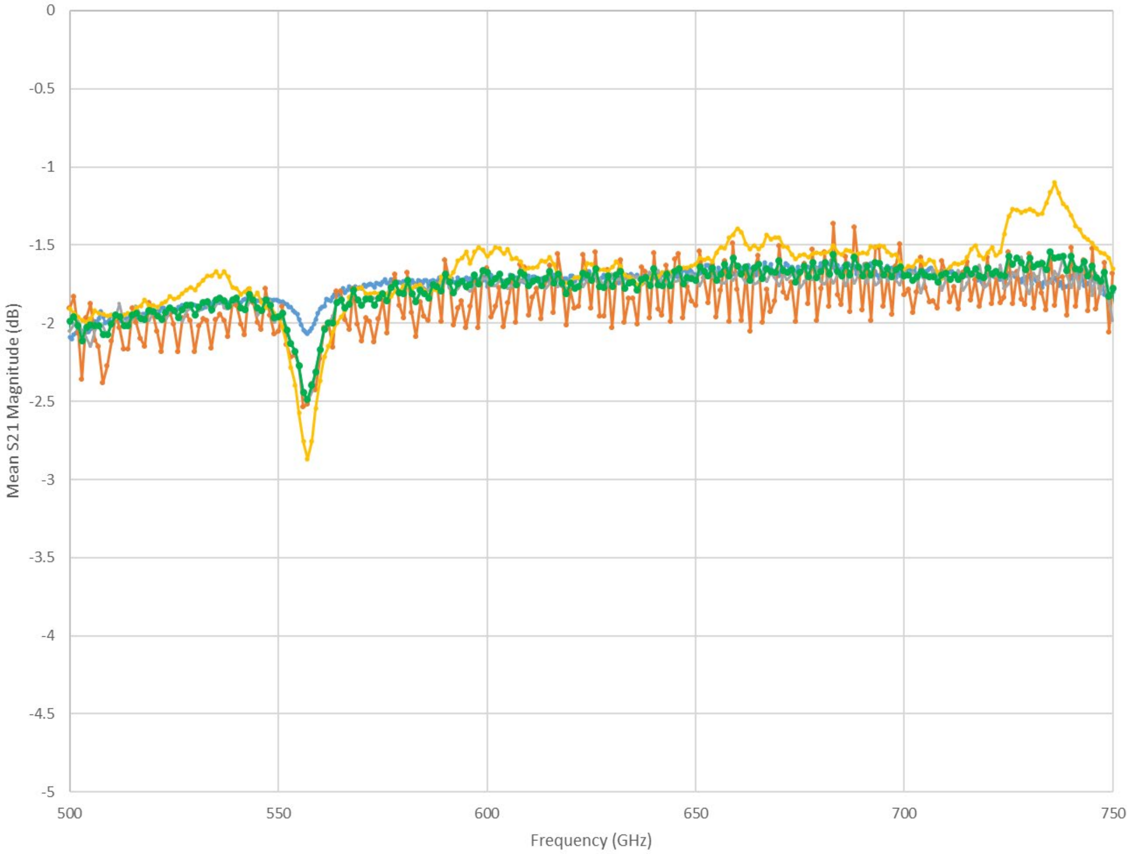

Figure 10a. 1” Straight Waveguide - S_{21} Mean Magnitude (dB)

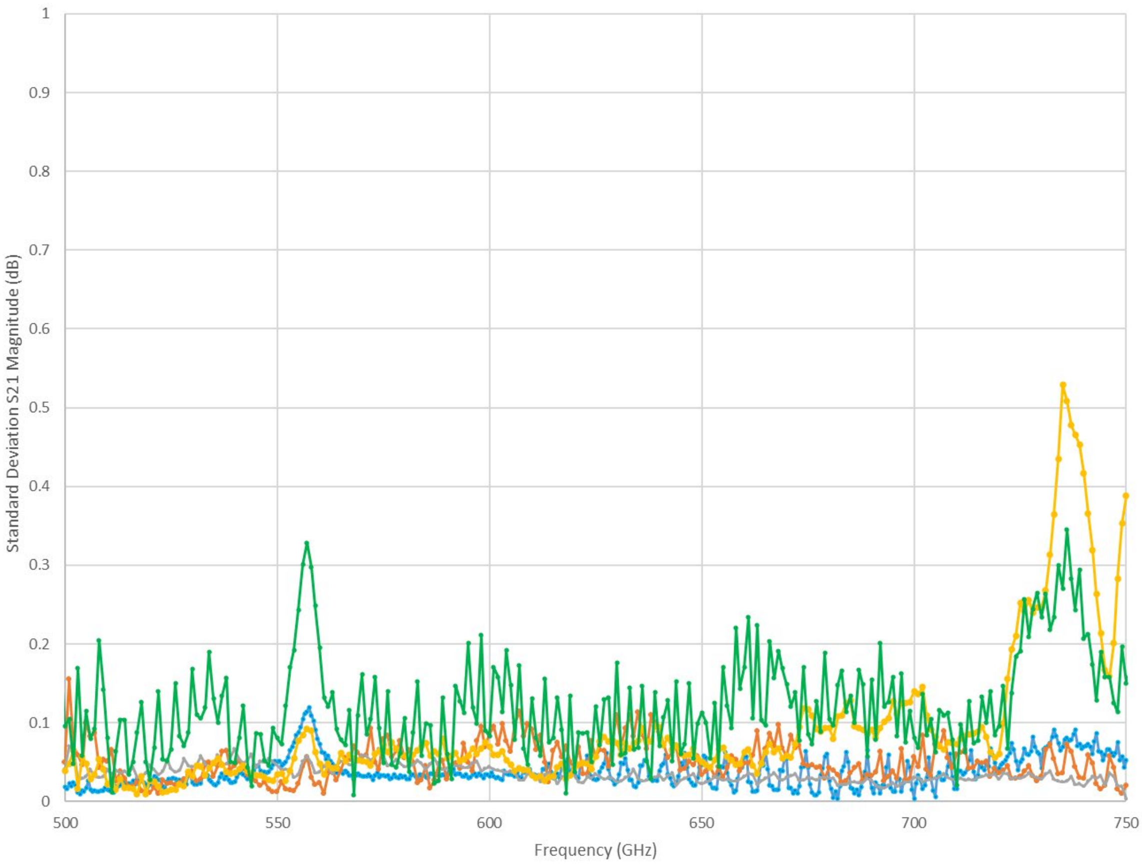

Figure 10b. 1” Straight Waveguide - S_{21} Standard Deviation Magnitude (dB)

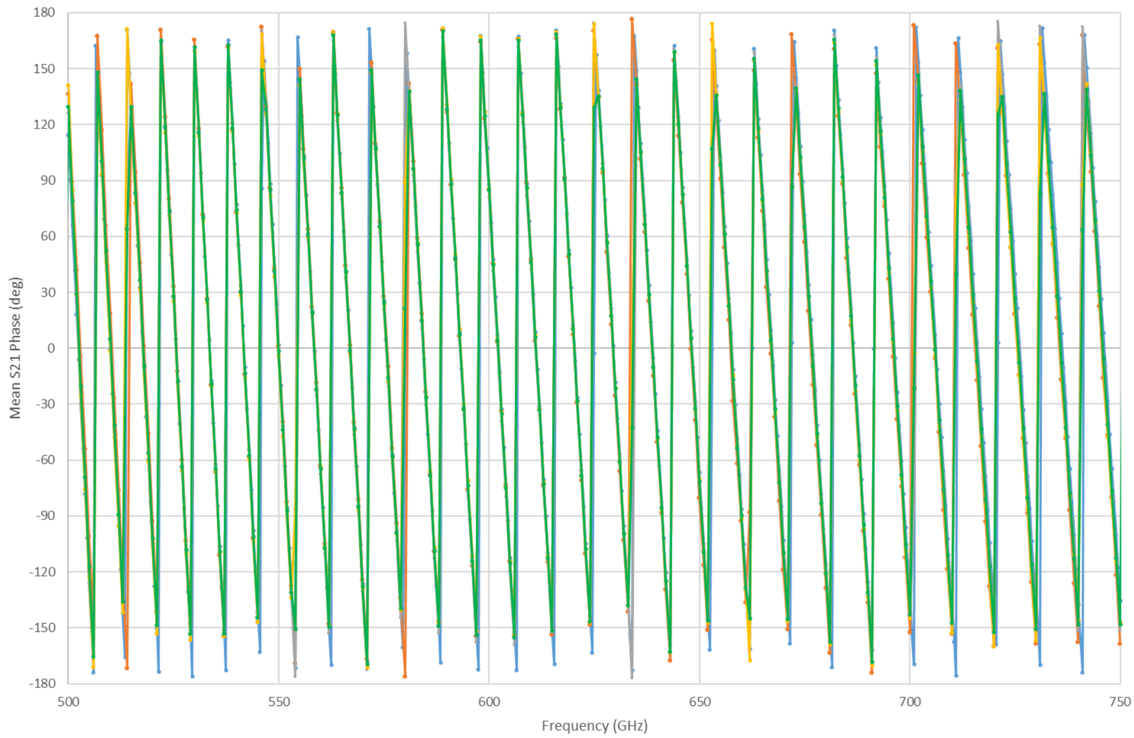

Figure 10c. 1" Straight Waveguide - S_{21} Mean Phase

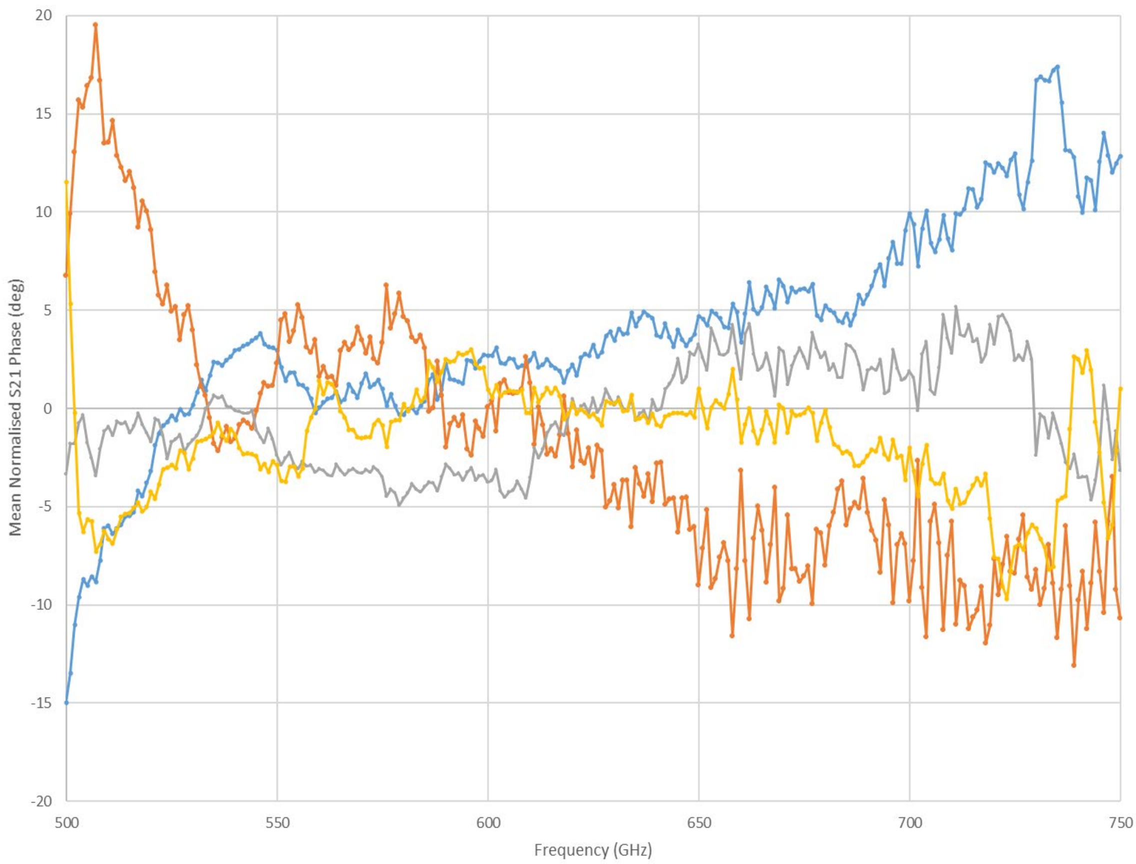

Figure 10d. 1" Straight Waveguide - S_{21} Mean Phase (Normalised)

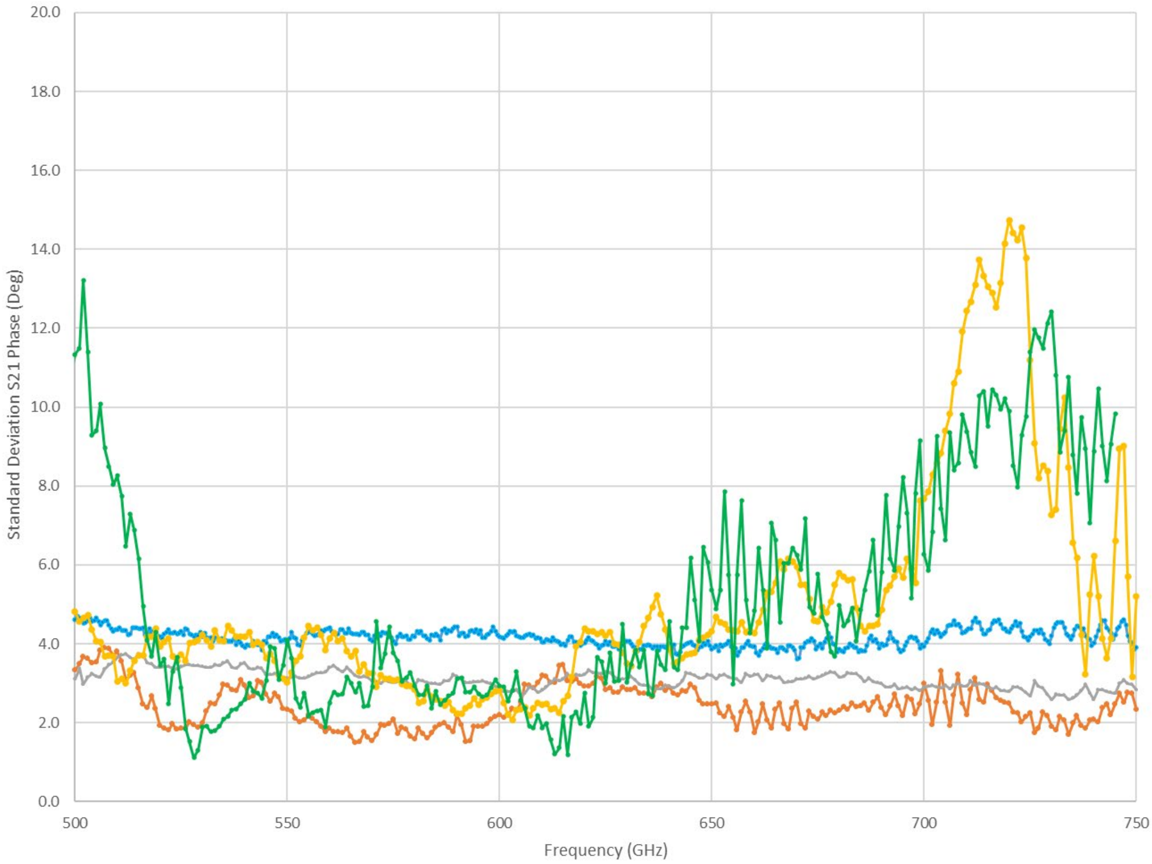

Figure 10e. 1" Straight Waveguide - S_{21} Standard Deviation Phase

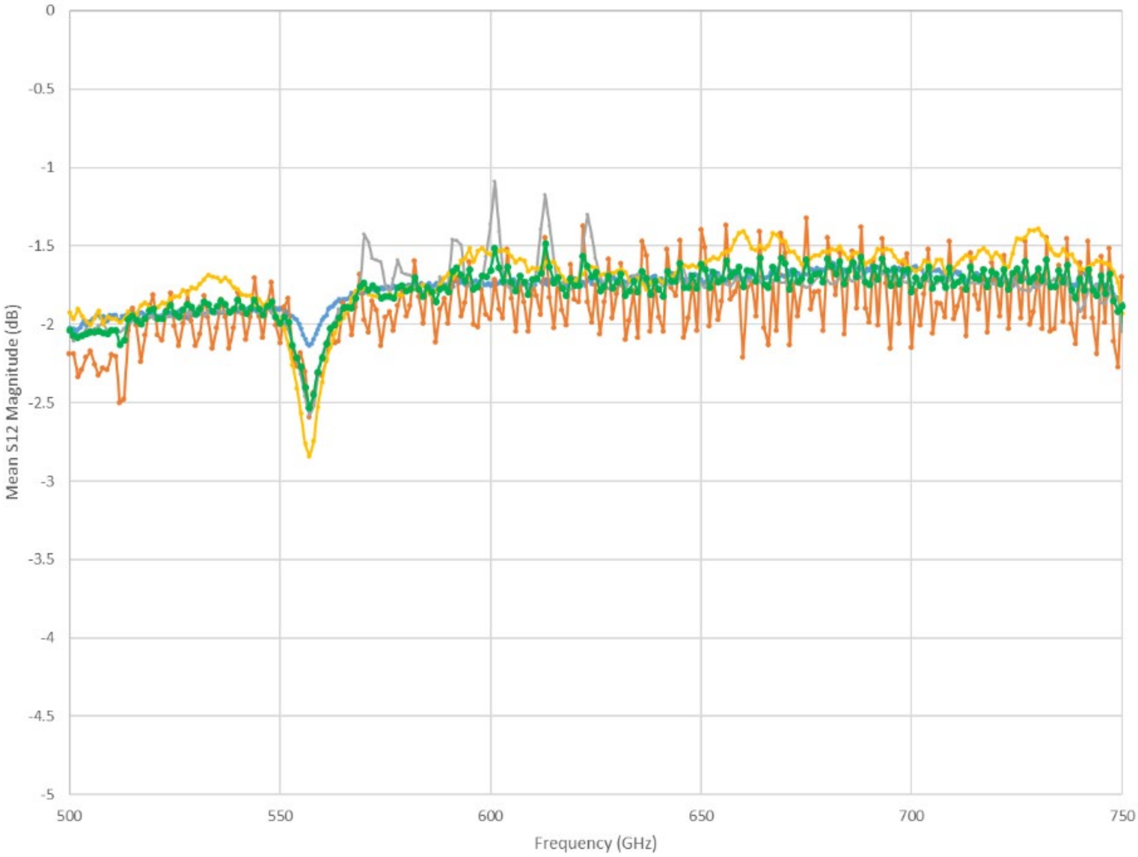

Figure 11a. 1" Straight Waveguide - S_{12} Mean Magnitude (dB)

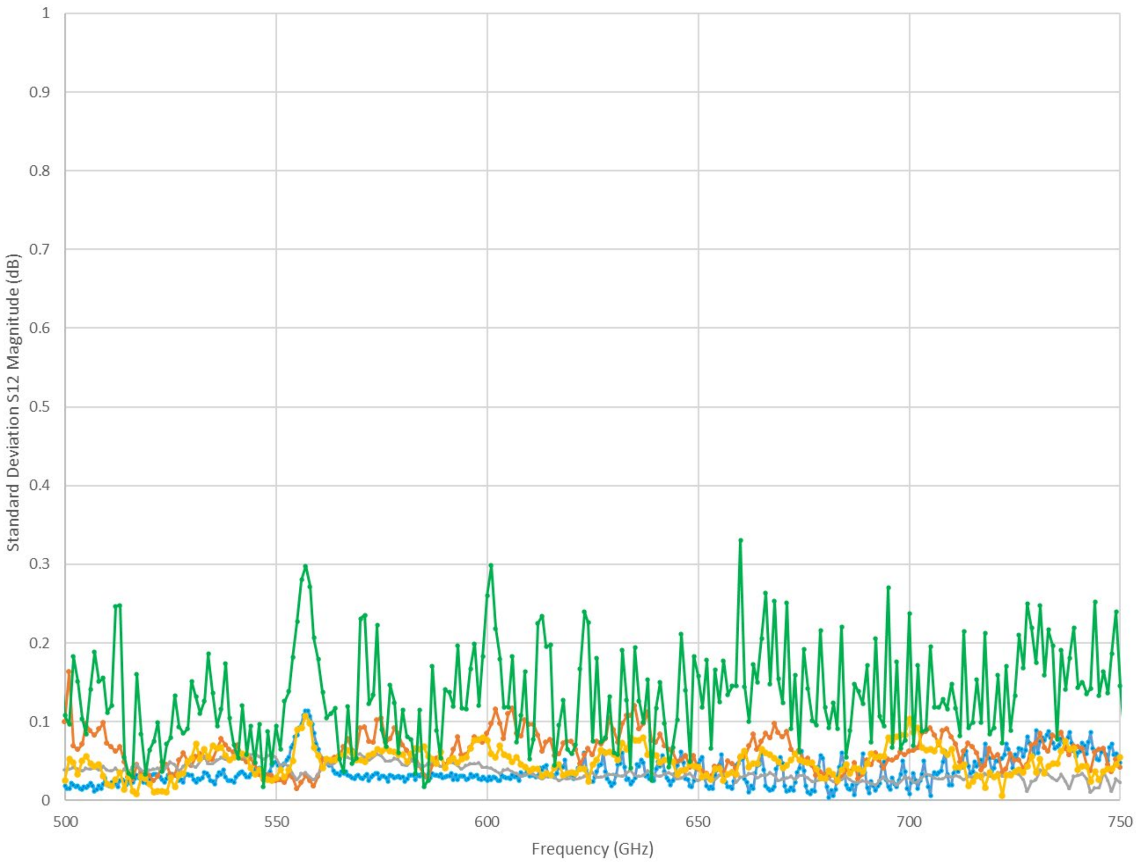

Figure 11b. 1" Straight Waveguide - S_{12} Standard Deviation Magnitude (dB)

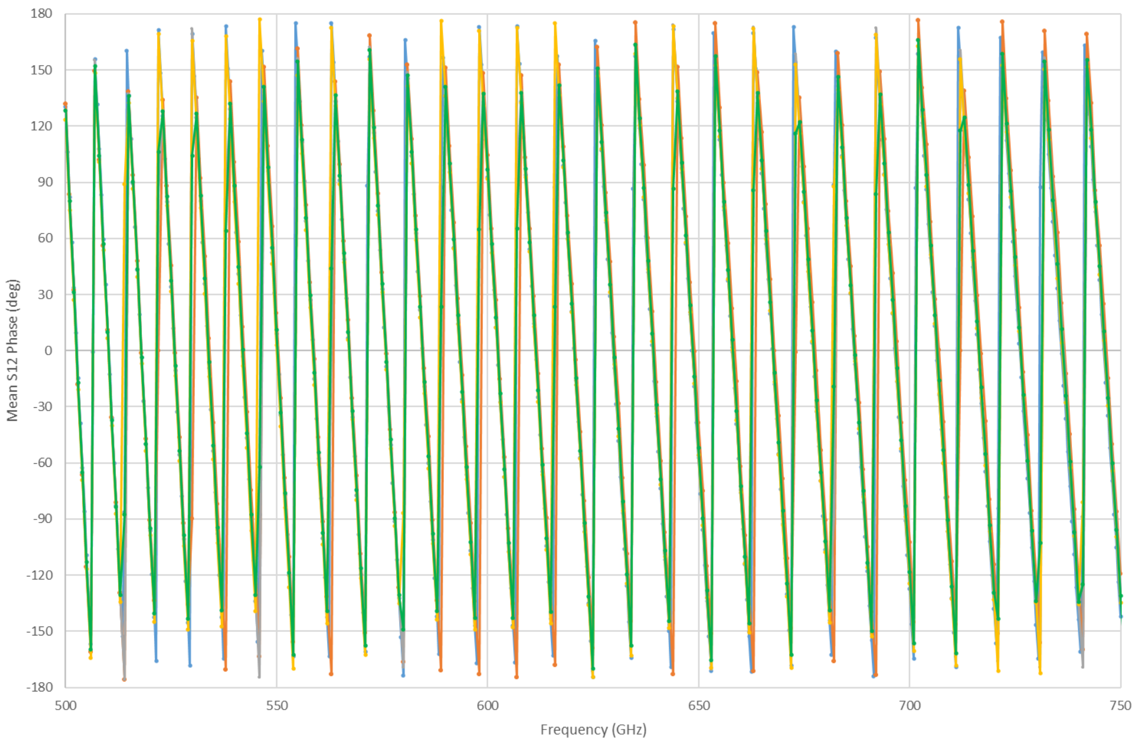

Figure 11c. 1" Straight Waveguide - S_{12} Mean Phase

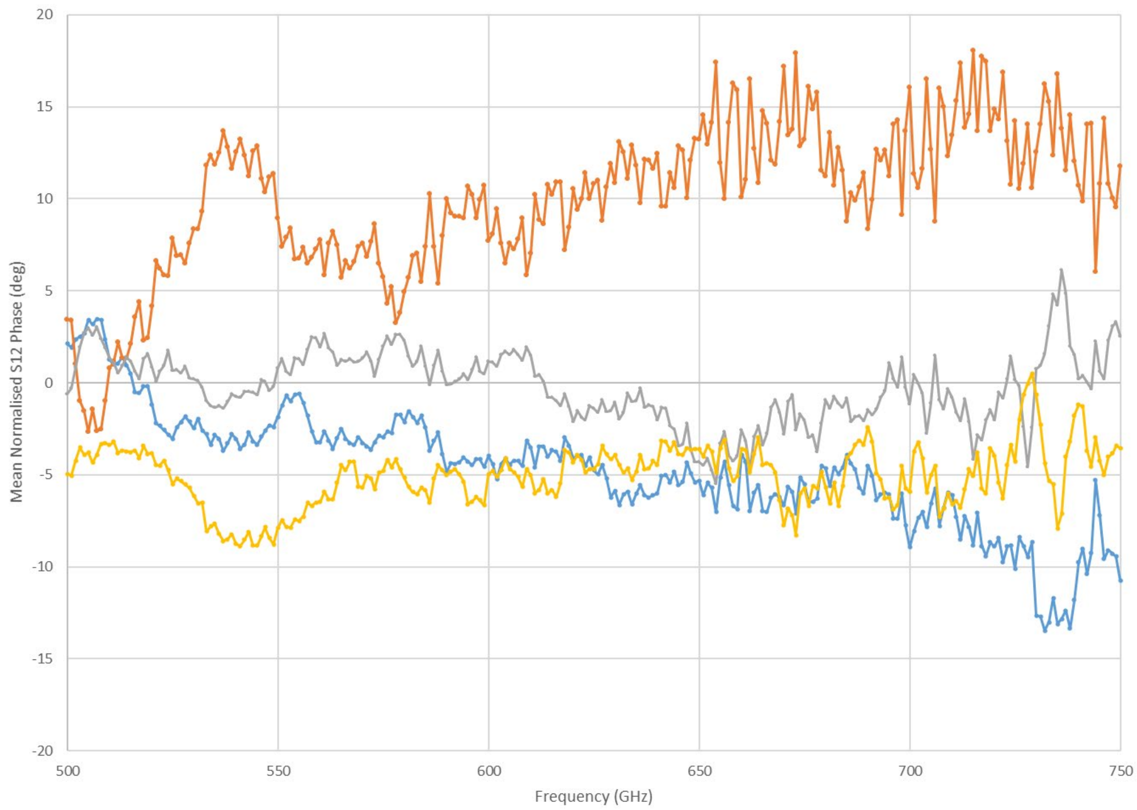

Figure 11d. 1" Straight Waveguide - S_{12} Mean Phase (Normalised)

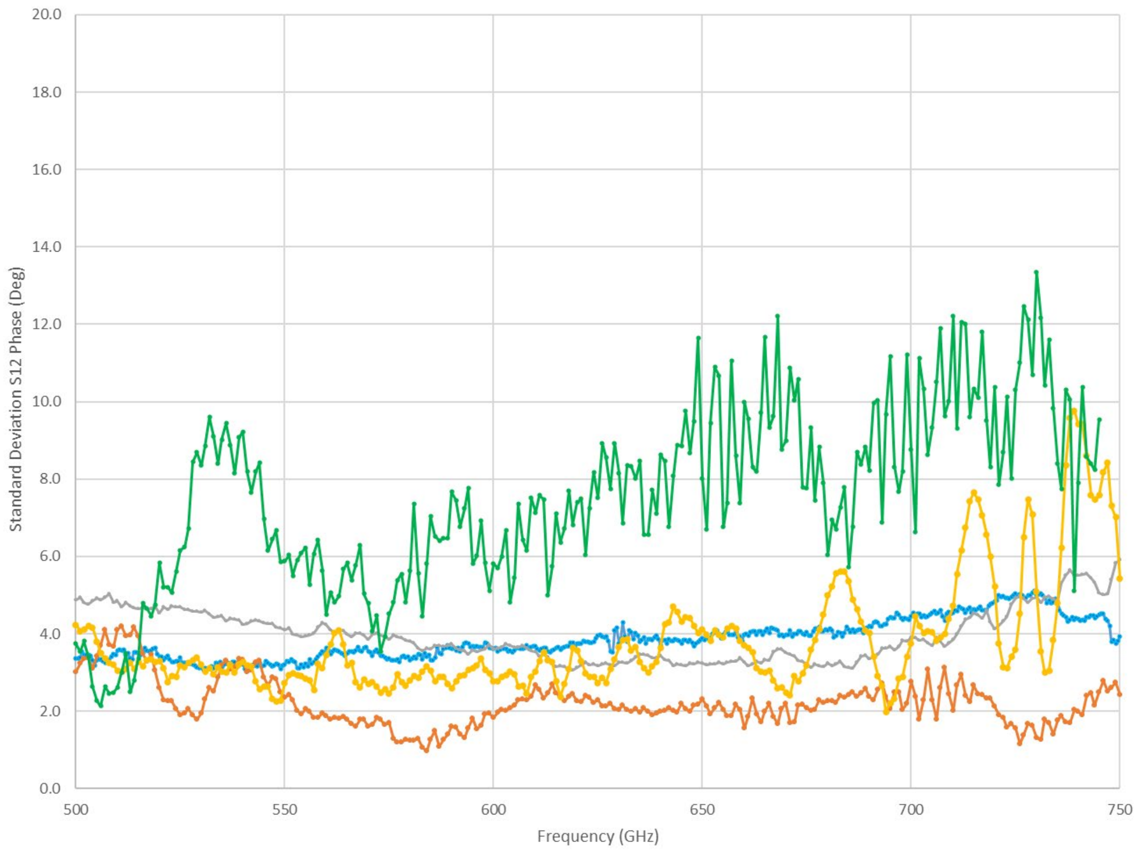

Figure 11e. 1" Straight Waveguide - S_{12} Standard Deviation Phase

6.4.3. Reciprocity

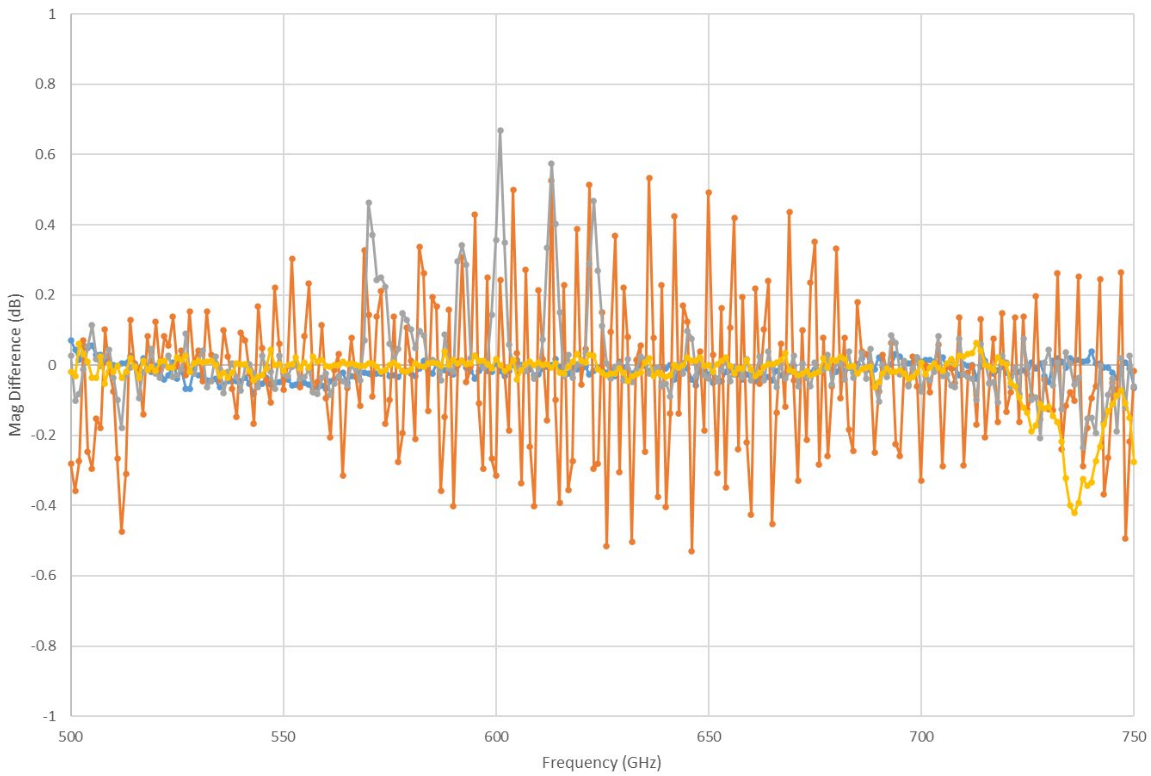

Figure 12a. 1” Straight Waveguide - Magnitude Reciprocity

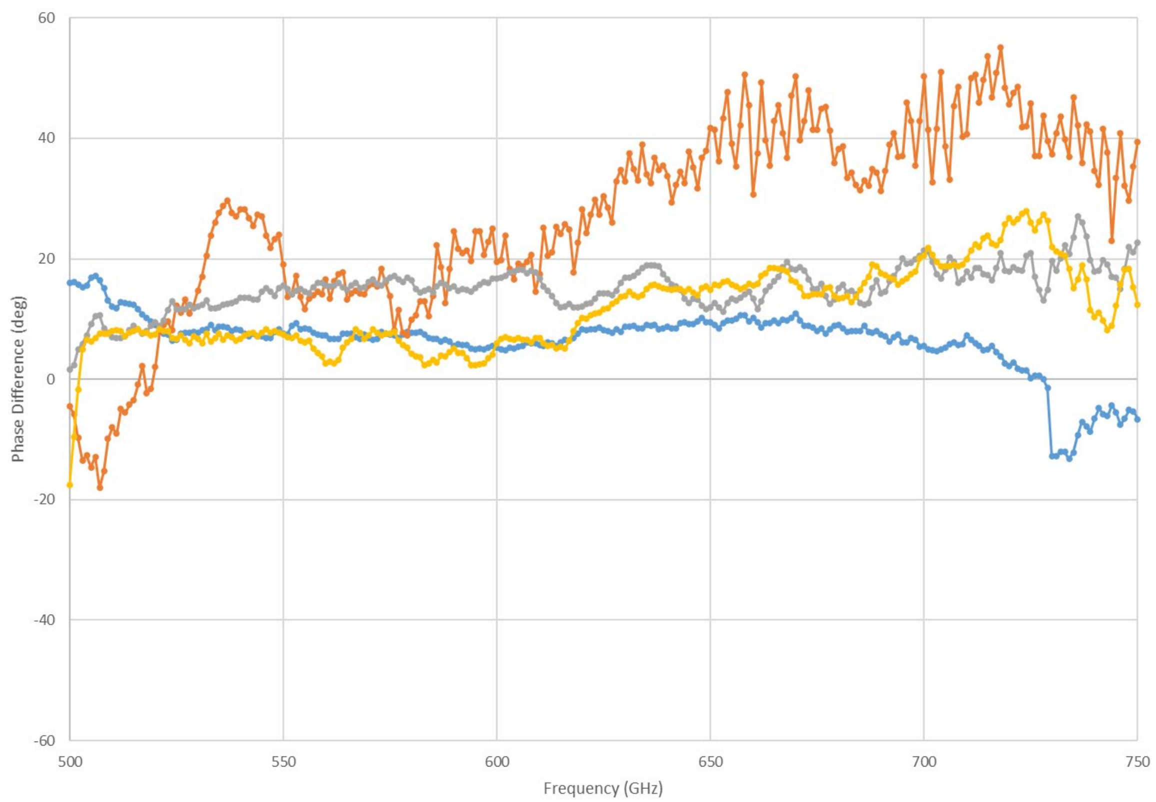

Figure 12b. 1” Straight Waveguide - Phase Reciprocity

7 OBSERVATIONS

- The participants' ability to achieve repeatable S-parameter results varied from device to device and from S-parameter to S-parameter.
- No single participant achieved the lowest standard deviation amongst the four participants for the measurement of all S-parameters. In other words, no one participant consistently showed better repeatability in their measurements than the other participants.
- Figures 5b and 6b do not include a trace for participant D as they only provided a single measurement of the cross-guide, and so it is not possible to calculate a standard deviation for this participant for this device. However, their result was included in the 'All Participants' trace in figure 6b.
- Resonances can be observed at around 560 GHz in the transmission results for the 10 dB attenuator and the 1" straight waveguide, see figures 3a, 4a, 10a and 11a. It is suspected that these are caused by signal absorption by water molecules present in the atmosphere under normal operating conditions [3].
- It is assumed that the 1" straight waveguide is reciprocal and so ideally the transmission magnitude and phase reciprocity plotted in figure 12 should be zero. Any observed deviations of these quantities from zero are indicative of errors in the S-parameter measurements.
- For a given S-parameter, the standard deviation for a single participant indicates the measurement repeatability achieved by the participant. The standard deviation for all participants indicates the measurement reproducibility between all participants. The standard deviations for the individual participants are smaller than the standard deviation for all participants for: the 10 dB attenuator s_{11} magnitude (figure 1b), S_{21} magnitude (figure 3b) and S_{12} magnitude (figure 4b); the ¼ wave cross-guide S_{21} magnitude (figure 5b) and S_{12} magnitude (figure 6b); the 1" straight waveguide S_{21} magnitude (figure 10b), S_{21} phase (figure 10e), S_{12} magnitude (figure 11b) and S_{12} phase (figure 11e). This indicates that the measurement repeatability of the individual participants is significantly better than the overall between participant reproducibility.[2]

8 SUMMARY

This report has presented an analysis of the results obtained from a recent S-parameter measurement comparison exercise in WM-380 waveguide. In general, the results obtained by individual participants have shown good agreement.

9 ACKNOWLEDGEMENTS

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[2] This situation is common for many high frequency measurements. It indicates that the size of random errors (e.g. due to connection repeatability) is significantly less than systematic errors (e.g. due to different participants' measurement systems).

10 REFERENCES

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[3] T Schneider, *et al*, "Link budget analysis for terahertz fixed wireless links", in IEEE Transactions on THz Science and Technology, vol 2, no. 2, pp. 250-256, March 2012.