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ANAMET-021: comparison of Type-N coaxial power splitter measurements from 1 GHz to 18 GHz

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ANAMET-021: comparison of Type-N coaxial power splitter measurements from 1 GHz to 18 GHz

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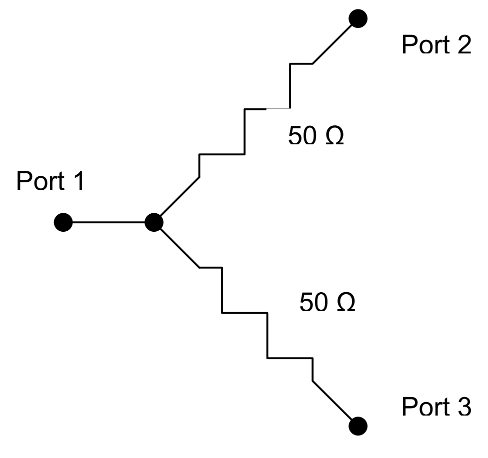
1. Introduction

This report describes a recent exercise to compare measurements of the electrical properties of a coaxial power splitter. The exercise formed part of ANAMET's long running programme of comparison exercises, further details of which can be found at www.npl.co.uk/anamet/comparisons. This exercise, numbered ANAMET-021 in the series, took place during 2002 and involved eight participants (all members of ANAMET) including NPL, which also acted as the pilot laboratory. The exercise was terminated prematurely when the device went missing in December 2002.

This report presents the results obtained by each participant, along with statistical summaries, but does not relate specific results with participants. The objective is to gain insight into an overall ability to make measurements of this kind.

2. Comparison details

The device chosen for the exercise was a Hewlett Packard 11667A, which is a two-resistor power splitter fitted with three female 50 Ω Type-N connectors, as shown in the schematic diagram below.



Schematic diagram of the power splitter used for the comparison exercise

The exercise compared the following four measurands:

1) Input VSWR at port 1;
2) Equivalent output VSWR at port 2;
3) Equivalent output VSWR at port 3;
4) Output tracking between ports 2 and 3.

A detailed description of the equivalent output VSWR of a power splitter (and indeed any arbitrary three-port device) has been given in [1]. The output tracking, *T*, measured in dB, is defined as:

$$T = 20\log_{10}\left(\frac{|S_{21}|}{|S_{31}|}\right)$$

Measurements were made at 1 GHz to 18 GHz in steps of 1 GHz. The participants were also invited to supply their pin-depth measurements of each of the splitter's coaxial connectors.

The eight organisations choosing to participate in the exercise were as follows:

i) Agilent Technologies, South Queensferry, UK;
ii) Celsius Metech AB, Arboga, Sweden;
iii) Czech Metrology Institute, Praha, Czech Republic;
iv) Dowding & Mills, Camberley, UK;
v) IFR Ltd, Dunfirmline, UK;
vi) METAS, Bern-Wabern, Switzerland;
vii) National Measurement Laboratory, CSIRO, Lindfield, Australia;
viii) National Physical Laboratory, Teddington, UK.

3. Measurement system details

As with other comparisons organised by ANAMET, no restrictions were placed on participants regarding the choice of measurement system or measurement technique used to obtain the results. In addition, participants were *not* required to supply uncertainties for their measurements[1]. Details are given below of the systems and techniques that were used by each participant for the measurements.

3.1 Agilent Technologies, South Queensferry, UK

Measurements were made using an 8510C VNA equipped with an 83650B synthesized sweeper and an 8515A test set. Components from an 85054B calibration kit were used to calibrate the VNA. A one-port sliding load calibration was used to measure input VSWR (at port 1) with the output ports terminated using broadband loads. Any corrections, where used, employed the 8510C firmware.

The equivalent output VSWRs (at ports 2 and 3) were measured using a 'ripple technique', as described by Orford [2], using the following procedure.

i) Perform a one-port VNA calibration and connect this to the power splitter output port under test.
ii) Terminate the power splitter input port with either a short-circuit (S/C) or open-circuit (O/C).

[1] This decision was taken at the outset of the comparison exercise, and is in line with all previous ANAMET comparisons. The intention is that laboratories that are not concerned primarily with assessing their uncertainties would not be excluded from participating in these exercises. (In any case, several of the laboratories did choose to supply uncertainties for their results.) Therefore, no consideration has been given to any uncertainty information during the subsequent analysis of the results of the comparison.

iii) Terminate the power splitter's remaining output port with a broadband load.
iv) Plot the trace obtained with the S/C connected then repeat the process with the O/C connected.
v) Repeat the above procedure using a total of four S/Cs and four O/Cs.
vi) Repeat the above procedure using different lengths of offset for the S/Cs and O/Cs, plotting all the traces obtained on the same axis.
vii) Interpolate the "lowest" plotted points to provide values at required frequencies.

The output tracking was measured without calibrating the VNA. The VNA test port connected to the power splitter output port was connected via a variety of very well matched 30 dB attenuators. The results were obtained from the mean of three measurements using three attenuators and reversing the device (e.g. use S_{21}, then S_{12}) for each power splitter port.

3.2 Celsius Metech AB, Arboga, Sweden

The measurements were made using an 8510C VNA with an 8515A test set and an 85054B calibration kit. The VNA was only used to extract raw data for the measurements using in-house-developed software to control the algorithms used to calibrate the measuring system and correct for systematic errors. The software also calculates the uncertainty of measurement in real time as the measurements are performed. The nine complex *S*-parameters of the power splitter were measured with the two-port VNA. This was done in three consecutive measurements:

i) Measure the *S*-parameters between port 1 and port 2 of the power splitter with a termination on port 3 of the power splitter.
ii) Measure the *S*-parameters between port 1 and port 3 of the power splitter with a termination on port 2 of the power splitter.
iii) Measure the *S*-parameters between port 3 and port 2 of the power splitter with a termination on port 1 of the power splitter.

The reflections from the imperfect termination of the third port in the measurements were not corrected for but were taken into account in the uncertainty of measurement. All measured parameters of the power splitter were calculated from the nine measured *S*-parameters of the power splitter.

3.3 Czech Metrology Institute, Praha, Czech Republic

Measurements were made using an 8510C VNA equipped with 83630B synthesized sweeper and an 8515A test set. Components from an 85054D calibration kit were used to calibrate the VNA and to terminate the third port of the measured device.

Two different procedures were used for determination of the power splitter parameters. The first one is based on measuring all the *S*-parameters of the device. Required parameters of the power splitter were calculated subsequently from the *S*-parameters. The second method used is described in [3]. This method yields only the values of equivalent output VSWR. An advantage with this method is that the VNA does not need to be calibrated.

The *S*-parameters were measured with the VNA calibrated using the OSLT method. Since the measured device is non-insertable, the "swap equal length adaptors" method was used. Measurement of the *S*-parameters was performed in two alternative ways. In the first case, the measurement process was the same as that described for Celsius Metech AB, shown above, involving the three consecutive measurements, with a broadband load connected to the third port. Reflections due to the imperfect termination (VSWR<1.02) on the third port were not corrected for.

Alternatively, the *S*-parameters were calculated from the three two-port measurements between ports 2 and 3 of the power splitter while port 1 was successively terminated with three standards (open, short, load).

Results obtained using both methods showed very good agreement. Therefore, the average values were submitted as the final laboratory results.

3.4 Dowding & Mills, Camberley, UK

The input VSWR at port 1 was measured by terminating ports 2 and 3 with well-matched loads having a VSWR of not greater than 1.05 at all frequencies of the comparison.

The equivalent output VSWRs at ports 2 and 3 were calculated from scalar measurements of the reflection coefficients of ports 2 and 3, and the transmission coefficients between ports 1 and 2, and between ports 1 and 3. On both occasions, the power splitter's unused port was terminated with a well-matched load having a VSWR of not greater than 1.05 at all frequencies.

The output tracking between ports 2 and 3 was calculated from measurements of the insertion loss between ports 1 and 2, and between ports 1 and 3.

3.5 IFR Ltd, Dunfirmline, UK

The measurements were made using an HP8510C VNA equipped with a HP8341A synthesized sweeper and a HP8514A *S*-parameter Test Set. A HP85054A calibration kit was used to calibrate the VNA.

The equivalent output VSWRs were measured using a "ripple technique" following an IFR in-house procedure (number Y043). The method measures the peak-to-peak ripple due to the interaction between the signals reflected from the power splitter output port and a monitoring power sensor assembly. This value, together with the input VRC of the monitor power sensor assembly, VRC_{sensor}, is used in the formula below to determine the output VSWR of the power splitter.

$$VRC_{splitter} = \frac{1}{VRC_{sensor}} \log_{10}\left(\frac{peak\ to\ peak\ ripple}{40} - 1 \right)$$

The output tracking and input VSWR were measured using the HP8510C.

3.6 METAS, Bern-Wabern, Switzerland

The *S*-parameters were measured with a 8510C VNA calibrated using a Short/Open/Sliding Load calibration scheme. Since the device is non-insertable, the "swap equal adaptors" method was also used. The measurement process was the same as that described for Celsius Metech AB, shown above, involving the three consecutive measurements, except a sliding load was used in place of the fixed termination. During all these two-port measurements, the "third" port of the splitter was terminated with the sliding load and measured at six sliding load positions. The subsequent calculation of the equivalent output VSWR (at ports 2 and 3) was made according to [4].

Raw data was extracted from the VNA and METAS software (called "VNA Tools") used to compute the calibration coefficients of the VNA, obtain the corrected *S*-parameters for the power splitter and calculate the circle fitting values from the six sliding load position measurements.

3.7 National Measurement Laboratory, CSIRO, Lindfield, Australia

The measurement process was the same as that described for Celsius Metech AB, shown above, involving the three consecutive measurements, made using an HP8510C VNA. The HP kit used to calibrate the VNA was validated using air gauging techniques. The "adaptor removal" scheme was used as part of the VNA measurement configuration.

The three-port *S*-parameters were then calculated, and the reflection coefficient of the termination corrected for, using a matrix renormalisation method [5]. Finally, the required measurement parameters for the comparison exercise were calculated from the three-port *S*-parameters.

3.8 National Physical Laboratory, Teddington, UK

The measurement process was the same as that described for Celsius Metech AB, shown above, involving the three consecutive measurements. The VRC of the terminating load was also measured on the calibrated VNA.

The *S*-parameters of the splitter were corrected for the mismatch of the terminating load using the method described in [5]. The four measurands of the comparison exercise were calculated from the corrected *S*-parameters.

The VNA was calibrated using an LRL scheme using non-insertable lines, fitted with female connectors, and a short-circuit. This allowed the *S*-parameters of the (female) non-insertable power splitter to be measured directly without the use of adaptors. In order to measure the VRC of the terminating load, a Type-N female-to-female adapter was used to change the sex of one of the VNA's male test ports. The *S*-parameters of the adapter were measured and used to de-embed the VRC of the terminating load from that of the combination of the load and the adaptor.

Raw data was extracted from the VNA and NPL software (called "PIMMS") was used to compute the calibration coefficients of the VNA and to obtain corrected *S*-parameters for the power splitter and corrected VRC values for the terminating load.

4. Statistical analysis

4.1 Comparison summaries

As with previous ANAMET measurement comparison exercises, statistics have been used to obtain summaries of the results achieved during this comparison exercise. In particular, a consensus value and a measure of the scatter in the participants' values are provided.

For each measurement parameter at each frequency, the consensus value has been chosen to be the median [6] of the results supplied by the participants. The median is simply the middle value of the results (having arranged the results in order of size). If the number of results is an even number, a unique middle value does not exist, so, by convention, the median is chosen to be the midpoint of the middle pair of values. Similarly, the median absolute deviation (MAD) is used as the basis of the measure of scatter in the participants' values[2]. The interval ±MAD is symmetric about the median and contains half the total number of values in a given sample of values.

These statistical estimators have been chosen since they are impervious to the effects of outlying values that may be present in the participants' values. This means that these statistical summaries continue to be useful despite the presence of any outlying values in the measurement samples.

4.2 Participant summaries

Having used statistics to obtain summaries for the data obtained by all participants, it is also possible subsequently to compare the results of each participant with respect to these summary values. In this report, two such measures have been used to make this comparison. These are, for each participant and each measurand:

i) "% inside MAD interval". This indicates the amount of data for a participant that is within the middle 50 % of (ordered) values. Therefore, a high percentage here indicates that a participant's values are in the middle of the scatter of data at a high proportion of the measurement frequencies. This is likely to indicate that the measurement data is well behaved.

ii) "% of outliers". These are values that lie outside a prescribed interval of acceptance for the data. The choice of the definition of this interval of acceptance is somewhat arbitrary. However, on this occasion, it has been chosen to be equivalent to a '95% confidence interval' for the data derived from a standard deviation, s, multiplied by two[3]. For normal distributions, a correction factor of approximately 1.5 can be used to obtain s from a MAD value, i.e.:

$$s \approx 1.5 \times \mathrm{MAD} \quad (1)$$

The 95 % confidence interval, U, for the data is therefore given by:

$$U = 2 \times s \approx 2 \times (1.5 \times \mathrm{MAD}) \approx 3 \times \mathrm{MAD} \quad (2)$$

A value, x_i, belonging to the ith participant, is therefore classified here as outlying if:

$$|x_i - x_{\mathrm{med}}| > U \quad (3)$$

where x_{med} is the median value for the data set.

[2] The MAD is defined here as the median of the absolute differences between each result and the median of all the participants' values [7].

[3] This is based on certain assumptions applying, e.g. that the data emanates from a normal distribution.

Therefore, a high percentage here indicates that a large proportion of a participant's values fall into the above 'outlier' category. This is likely to indicate that the data is poorly behaved.

5. Supplementary measurements

In addition to the electrical measurements described in section 2 of this report, each participant was also invited to supply mechanical pin-depth measurements for each of the power splitter's three coaxial connectors. This data has also been analysed using the techniques described in section 4 of this report.

6. Results

The results obtained by the participants, along with statistical summaries, are presented as Tables and graphs (i.e. Figures) for each measurand. The tables present the values supplied by each participant[4], along with median and MAD summary statistics, at each frequency. Participant summarises, in terms of "% inside MAD interval" and "% of outliers", are also given.

The anonymity of the participants' results has been preserved by using labels (i.e. LAB A, LAB B, etc) which have been applied arbitrarily.

For each measurand, two graphs are presented. The first graph shows the results obtained by each participant as a function of frequency. The second graph shows the same data normalised with respect to the sample median. This second graph also shows the ±MAD interval calculated from the participants' values. This graph can therefore be used to see the relative variation in each participant's values and assess that variation with respect to the MAD measure of scatter.

The results for each measurand are therefore given as follows:

- Figures 1 and 2, Table 1 – input VSWR at port 1;
- Figures 3 and 4, Table 2 – equivalent output VSWR at port 2;
- Figures 5 and 6, Table 3 – equivalent output VSWR at port 3;
- Figures 7 and 8, Table 4 – output tracking between ports 2 and 3.

In addition, the pin-depth measurements made by the participants are presented in Table 5, along with their statistical summaries.

[4] Participant results are shown in the tables to the same number of decimal places as supplied by the participants.

7. Discussion

7.1 Results for input VSWR at port 1

The results shown in Figures 1 and 2 indicate that the results supplied by most of the participants for the input VSWR at port 1 show relatively good agreement. This view is supported by the relatively low MAD values in Table 1 at all frequencies.

However, the results for LAB C exhibit noticeable departures from the majority of values at a significant number of frequencies. This observation is supported by only 6 % of values for LAB C being inside the MAD interval and 67 % of values being labelled as outliers. LAB B also shows some minor departures for the main grouping of values (with 28 % of values labelled as outliers). Finally, the results for LAB H show a serious departure from the majority of values at one frequency only (i.e. 16 GHz).

7.2 Results for equivalent output VSWR at port 2

As with the results for input VSWR at port 1, the results for equivalent output VSWR at port 2 (Figures 3 and 4) generally show good agreement and this is further supported by relatively low MAD values in Table 2 at all frequencies.

However, the notable exceptions are: LAB C exhibits significant departures from the majority of values (indicated also by only 6 % of values being inside the MAD interval and 72 % being labelled as outliers); and, LAB H shows minor discrepancies, compared to the majority of values, below approximately 7 GHz (indicated also by only 11 % of values being inside the MAD interval and 33 % being labelled as outliers).

7.3 Results for equivalent output VSWR at port 3

The results for equivalent output VSWR at port 3 (Figures 5 and 6) show relatively good agreement at low frequencies but tend to exhibit increased scatter at the higher frequencies (i.e. above approximately 14 GHz). This trend is reflected in the MAD values in Table 3, which show a marked increase at the higher frequencies[5].

As before, LAB C exhibits significant departures from the majority of values at a high proportion of frequencies (again, this being reflected by only 17 % of values being inside the MAD interval and 72 % being labelled as outliers). The results for LAB H show a similar behaviour to the equivalent output VSWR at port 2, with minor discrepancies observed below 7 GHz (indicated, on this occasion, by 39 % of values being labelled as outliers).

7.4 Results for output tracking between ports 2 and 3

The results for the output tracking between ports 2 and 3, shown in Figures 7 and 8, indicate reasonable agreement between the participants. This is further demonstrated by the relatively low MAD values in Table 4.

[5] It should be noted that LAB D chose not to supply measurements of the equivalent output VSWR at port 3 above 14 GHz. This was because of the poor repeatability observed by this participant in the determination of this measurand. Several other participants also reported observing similarly poor repeatability during their determination of this measurand at these frequencies.

However, there is an indication in the data that two distinct 'clusters' of values begin to form as the frequency increases above approximately 10 GHz (i.e. as the tracking becomes measurably non-zero) – one grouping consisting of LABs A, C, D, E and G, and the other of LABs B, F and H. Under these circumstances (i.e. with possibly more than one data grouping), the simple statistical techniques used here are likely to become ineffective at providing adequate summaries for all the data. Regardless of these reservations, it is clear that both LABs A and C have each produced one value which shows a significant departure from the majority of other values.

Finally, the reason for the participants' values becoming grouped into two distinct groups is unclear, but generally this may indicate that similar, dominant, systematic errors are present in the measurement set-ups used by some of the participants. However, it is also worth noting that the two groupings could be viewed as forming approximate mirror images of each other in the graph's *x*-axis (set at 0 dB) and that this might indicate an error in the calculation of this measurand derived from the measured *S*-parameters by some of the participants (i.e. by interchanging $|S_{21}|$ and $|S_{31}|$ in the equation defining the calculation of the tracking).

7.5 Pin-depth results

The results for the pin-depth measurements on the connectors of the power splitter, shown in Table 5, indicate no serious problems with any of the values supplied by the participants[6]. The only value identified as 'outlying' (using the criterion established in section 4.2), is likely to be due, in part, to the relatively poor resolution of the results supplied by this laboratory (i.e. LAB C) – bearing in mind that most modern pin-depth gauges found in network analyser calibration kits have scale graduations marked every 0.0001". Since the largest MAD value for these measurements is 0.0004", it would appear that supplying results to at least four decimal places (in inches) seems appropriate on this occasion.

Another interesting feature with this data is that the average (i.e. median) values for the recessions of all three connectors are relatively large (being approximately -0.004"). In contrast, and from experience, the pin-depth recession for Type-N General Precision Connectors (found on devices such as attenuators in network analyser verification kits) is often in the range -0.001" to -0.002", and that for Laboratory Precision Connectors (e.g. on verification kit air lines) within the range -0.0000" to -0.0005". This suggests that the connectors found on the power splitter used for this comparison were of a different specification than those found on these other devices.

8. Comparison with earlier ANAMET exercises

8.1 VSWR data

Since VSWR measurements at these frequencies have been the subject of an earlier ANAMET comparison (i.e. the first exercise, which took place in 1993, labelled ANAMET-931 [8, 9]) it is possible to compare the level of variability in the VSWR measurements during this current exercise with that found on the earlier occasion. The ANAMET-931 exercise compared VSWR measurements of six mismatched terminations fitted with Type-N connectors – three male and three female – with nominal VSWRs of 1.05, 1.2 and 1.5.

[6] LAB H chose not to supply their pin-depth measurements.

However, in order to compare the results obtained from these two exercises in a meaningful way, we can only really consider VSWR measurements of similar nominal values, since variability (or, more generally, uncertainty) in a VSWR measurement value will, to some extent, be a function of the VSWR value itself (as discussed in [10]). Therefore, only data from the 1.05 and 1.2 VSWR mismatches in the ANAMET-931 exercise are considered here for comparison with the data obtained during this current exercise, since they provide similar values of VSWR.

Also, for the ANAMET-931 exercise, variability was quantified in terms of standard deviation values. These need to be converted to equivalent MAD values (using equation (1), re-arranged) to enable easy comparison to be made between the two exercises. The data from both comparisons is further summarised in terms of the maximum observed MAD value, MAD_{max}, and these are shown for both comparison exercises, in Table 6, below.

Table 6: MAD_{max} values for the ANAMET-021 and -931 comparison exercises

Comparison identifier	**Device/connector description**	**MAD_{max} (VSWR)**
ANAMET-931 (1993)	VSWR = 1.05 (male)	0.006
	VSWR = 1.05 (female)	0.009
	VSWR = 1.2 (male)	0.009
	VSWR = 1.2 (female)	0.011
ANAMET-021 (2002)	Input VSWR at port 1	0.013
	Equivalent output VSWR at port 2	0.009
	Equivalent output VSWR at port 3	0.018

These MAD_{max} values indicate that the level of variation in the VSWR measurements made during this comparison exercise (ANAMET-021) is quite similar to that observed during the earlier comparison of mismatched terminations (ANAMET-931). A possible exception to this could be for the measurements made of the equivalent output VSWR at port 3 of the power splitter that shows the largest level of variability. This is consistent with observations made by some of the participants in this exercise who observed larger than expected variation in the determination of this measurand at the higher frequencies.

8.2 Pin-depth data

ANAMET has also been involved previously in comparisons of pin-depth measurements. One such exercise [11], which took place in 1996, compared measurements of seven different Type-N connectors, made during (!) an ANAMET meeting. On that occasion, the MAD values, derived from the eight participants' values, ranged from 0.00005" to 0.00020". This is significantly less than the MAD values obtained during this current comparison exercise, shown in Table 5.

This could be due, in part, to the greater nominal value of recession being measured during the current exercise (as noted in section 7.5). For example, an error due to non-linearity in the gauges' readings would thus be increased because of the larger values of recession being measured. In any case, the difference in variability observed between these two comparison exercises is not considered to be of great significance – rather, the overall level of agreement achieved by the majority of participants during both comparison exercises is generally encouraging.

9. Conclusions

The ANAMET-021 exercise has been successful in comparing measurements, made by eight leading measurement laboratories, of the electrical quantities of a coaxial power splitter. In general, the results obtained by the laboratories involved in the exercise showed good agreement. However, one or two laboratories produced results that were significantly different from the majority of values, at some of the measurement frequencies.

Looking at the general levels of variability within the results supplied, it is likely that the stability of the power splitter may have been suspect with regard to the measurement of the equivalent output VSWR at port 3 of the splitter, particularly at the higher frequencies of the comparison. This observation was made by several of the participants, and one participant (LAB D) chose not to supply results for this quantity at frequencies above 14 GHz because of the instability that was detected in this measurand. This instability is also likely to be the cause of the increased variability in the participants' results for this measurand at these frequencies, shown in Figures 5 and 6.

Despite the unreliability of one of the measurands, at some frequencies, useful data has been gathered regarding the overall variability that may be expected for measurements of power splitters of this type. The authors feel that, on this occasion, of particular interest has been the measurements of the equivalent output VSWR at ports 2 and 3 of the splitter, since these measurements are not straight forward to make, and this has led to a variety of methods being proposed in the literature (see, for example, [3] and [12]) for determining these quantities). Several of these methods have been used during this comparison exercise.

Finally, due to the premature termination of the exercise (due to the disappearance of the device), it was been decided to initiate a second power splitter comparison (which has since been labelled ANAMET-022, and is now in progress). Results from this second comparison will hopefully complement the information gathered here and further increase our understanding of measurements of these very important microwave quantities. It is hoped that the ANAMET-022 comparison will be completed early in 2004.

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Patrick Haggarty, IFR Ltd, Dunfirmline, UK
Alan Coster, Dowding & Mills, Camberley, UK
Karel Drazil, Czech Metrology Institute, Praha, Czech Republic
Juerg Ruefenacht, METAS, Bern-Wabern, Switzerland

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Input VSWR

Port 1

Figure 1: Input VSWR port 1

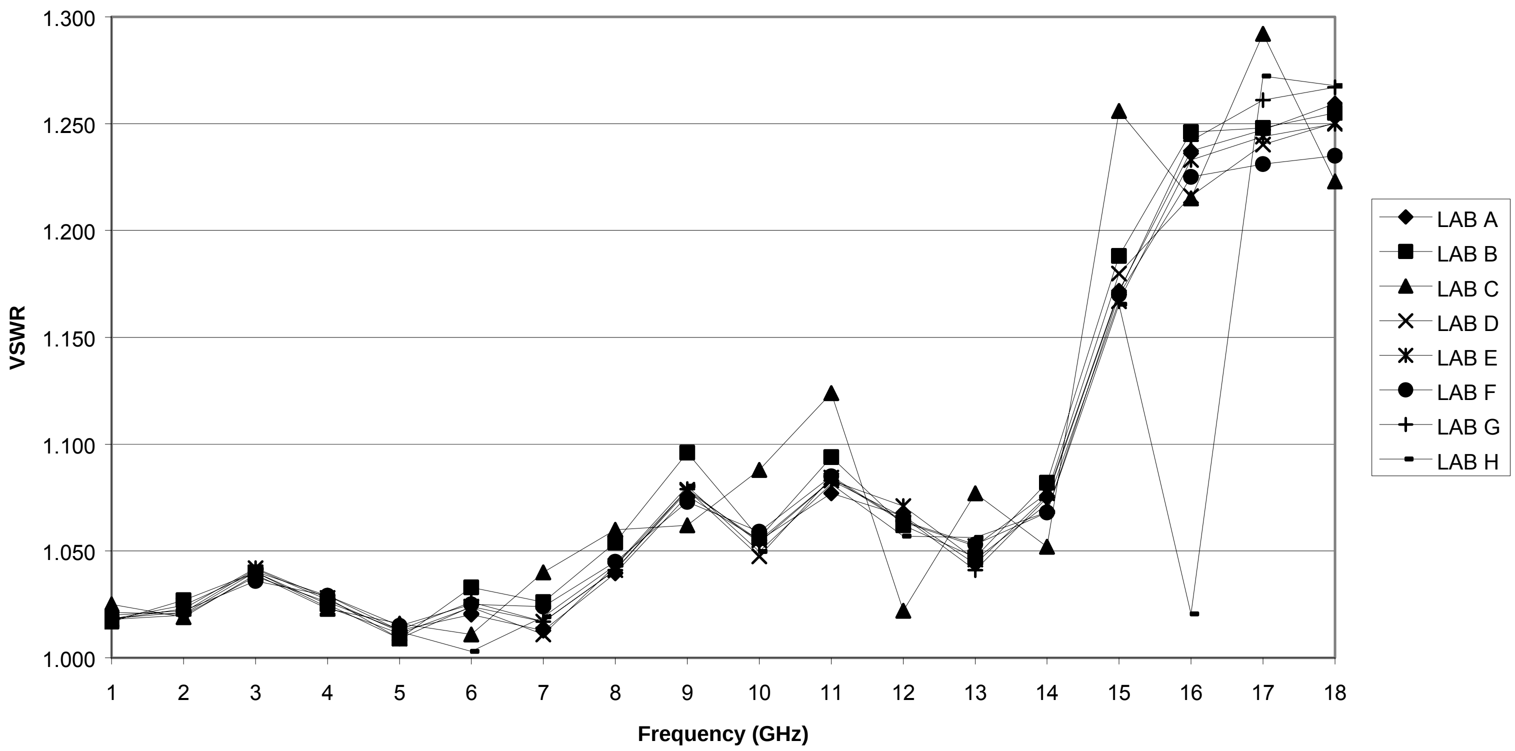

Figure 2: Normalised input VSWR port 1

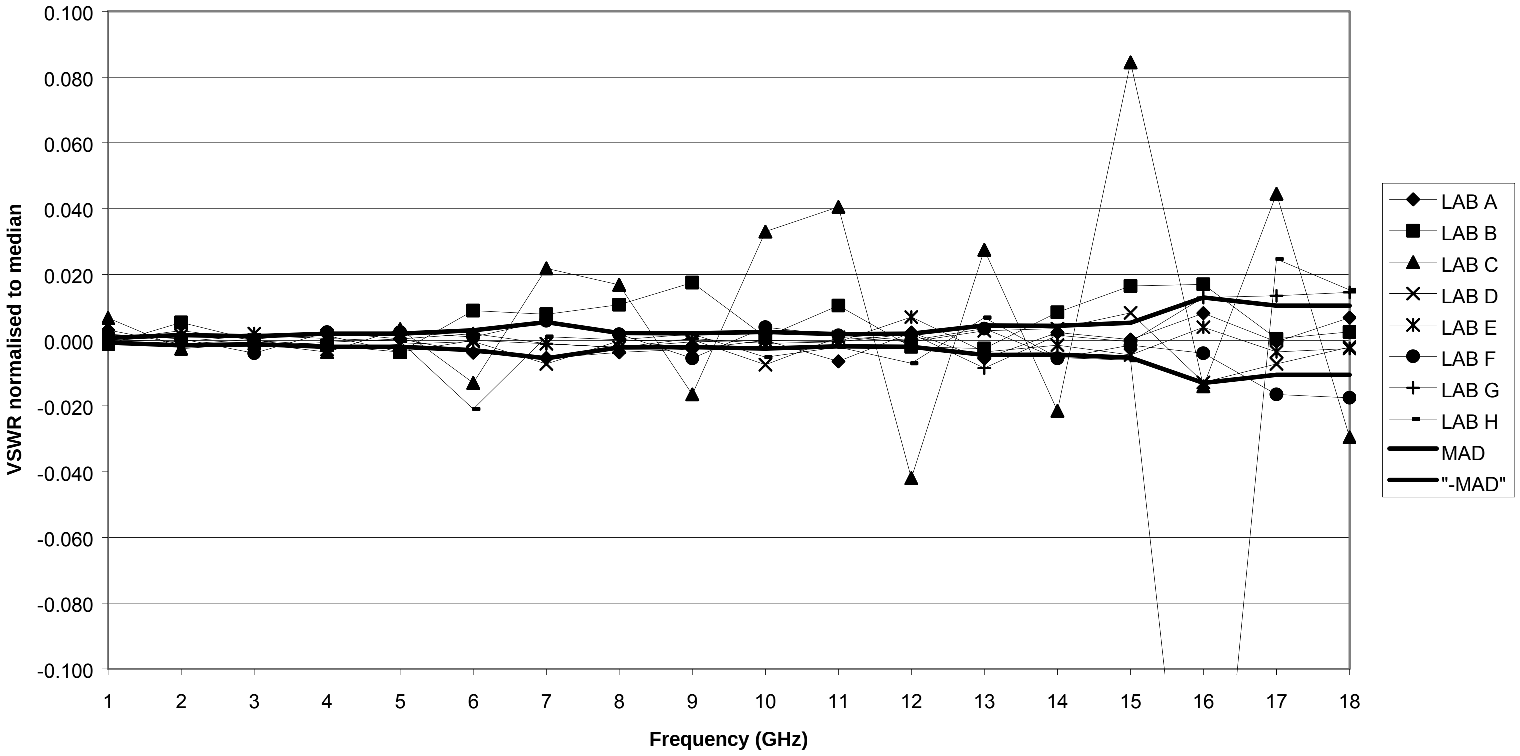

Table 1: Input VSWR at port 1

Frequency (GHz)	LAB A	LAB B	LAB C	LAB D	LAB E	LAB F	LAB G	LAB H	MEDIAN	MAD
1	1.021	1.017	1.025	1.018	1.018	1.020	1.018	1.01837	1.0182	0.0007
2	1.020	1.027	1.019	1.025	1.023	1.022	1.020	1.02122	1.0216	0.0016
3	1.040	1.040	1.039	1.040	1.042	1.036	1.038	1.04144	1.0400	0.0012
4	1.029	1.025	1.023	1.024	1.028	1.029	1.026	1.02716	1.0266	0.0020
5	1.013	1.009	1.016	1.011	1.009	1.015	1.013	1.01227	1.0126	0.0020
6	1.020	1.033	1.011	1.024	1.024	1.025	1.026	1.00304	1.0240	0.0030
7	1.013	1.026	1.040	1.011	1.017	1.024	1.017	1.01918	1.0181	0.0055
8	1.040	1.054	1.060	1.043	1.041	1.045	1.041	1.04332	1.0432	0.0022
9	1.076	1.096	1.062	1.079	1.078	1.073	1.079	1.08030	1.0785	0.0021
10	1.055	1.056	1.088	1.048	1.055	1.059	1.054	1.04981	1.0550	0.0025
11	1.077	1.094	1.124	1.084	1.083	1.085	1.083	1.08138	1.0835	0.0018
12	1.066	1.062	1.022	1.064	1.071	1.064	1.066	1.05698	1.0640	0.0020
13	1.044	1.047	1.077	1.052	1.046	1.053	1.041	1.05634	1.0495	0.0045
14	1.076	1.082	1.052	1.077	1.072	1.068	1.075	1.06825	1.0735	0.0044
15	1.172	1.188	1.256	1.180	1.167	1.170	1.171	1.16544	1.1715	0.0053
16	1.237	1.246	1.215	1.216	1.233	1.225	1.242	1.02055	1.2290	0.0130
17	1.247	1.248	1.292	1.240	1.244	1.231	1.261	1.27221	1.2475	0.0105
18	1.259	1.255	1.223	1.250	1.250	1.235	1.267	1.26783	1.2525	0.0105
% inside MAD interval	61	39	6	67	83	44	78	39		
% of outliers	11	28	67	0	6	6	0	17		

Equivalent output VSWR

Port 2

Figure 3: Equivalent output VSWR port 2

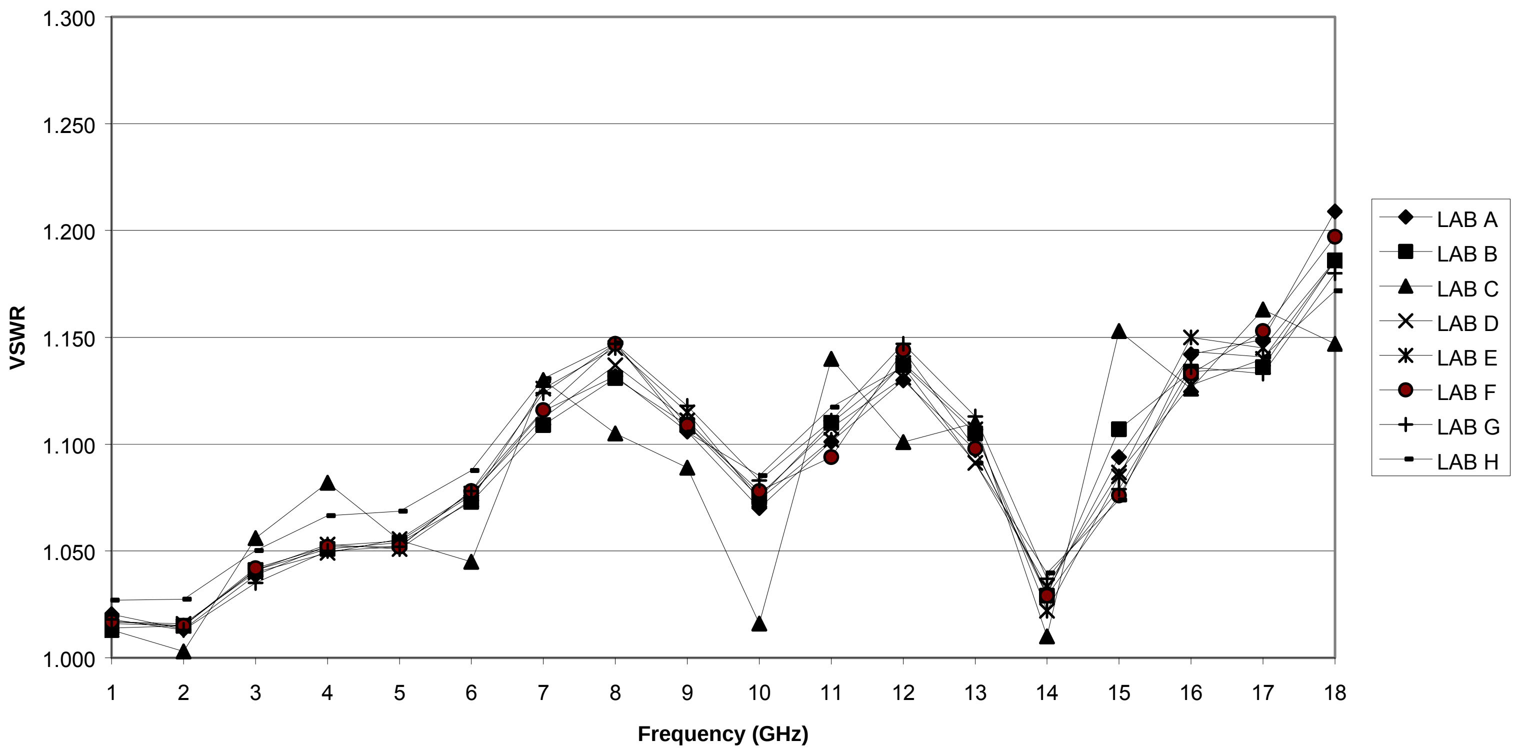

Figure 4: Normalised equivalent output VSWR port 2

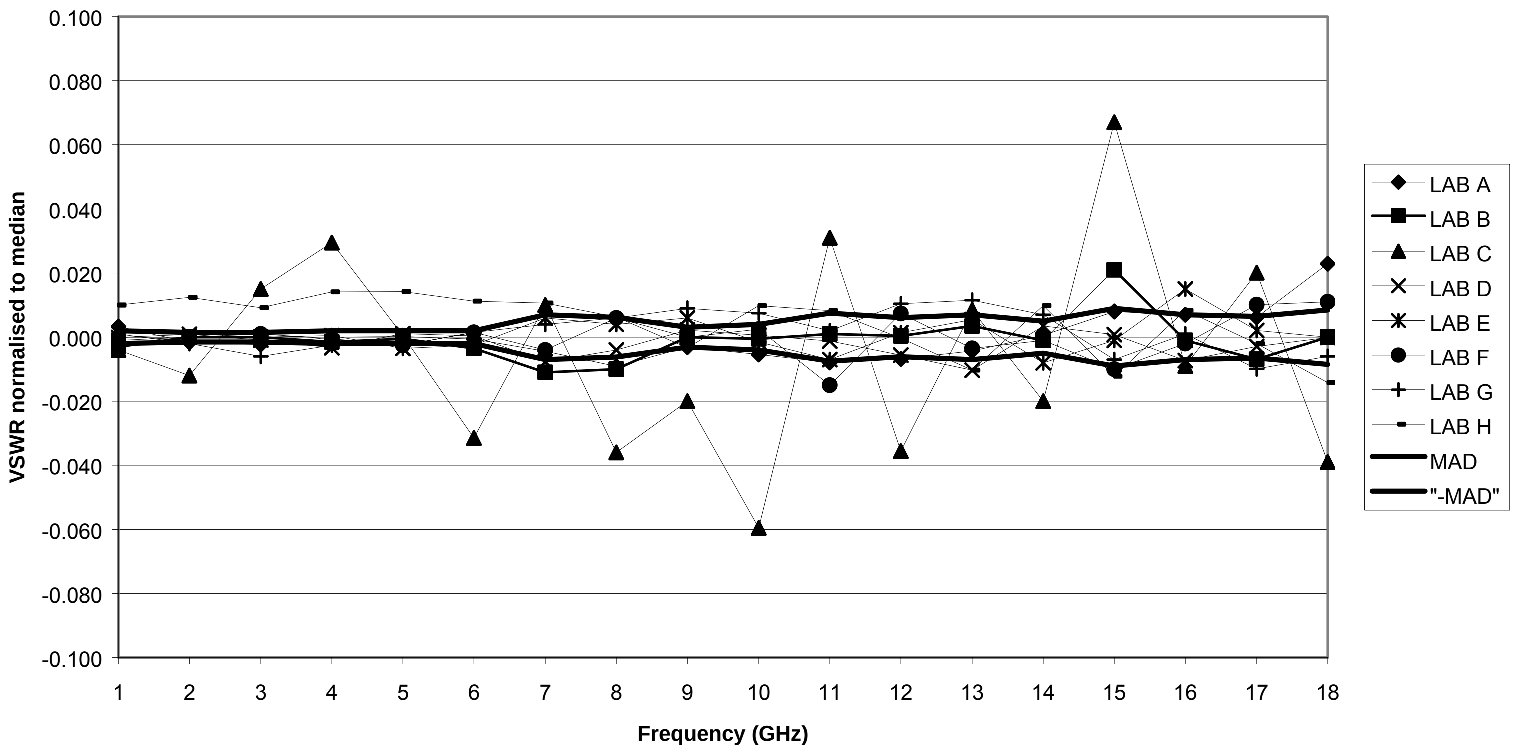

Table 2: Equivalent output VSWR port 2

Frequency (GHz)	LAB A	LAB B	LAB C	LAB D	LAB E	LAB F	LAB G	LAB H	MEDIAN	MAD
1	1.020	1.014	1.013	1.017	1.016	1.017	1.018	1.02696	1.0170	0.0020
2	1.013	1.015	1.003	1.016	1.015	1.015	1.013	1.02737	1.0150	0.0015
3	1.039	1.041	1.056	1.040	1.041	1.042	1.035	1.05023	1.0410	0.0015
4	1.053	1.051	1.082	1.049	1.053	1.052	1.050	1.06654	1.0525	0.0020
5	1.055	1.054	1.055	1.056	1.051	1.052	1.052	1.06868	1.0545	0.0020
6	1.076	1.073	1.045	1.077	1.074	1.078	1.078	1.08768	1.0765	0.0020
7	1.116	1.109	1.130	1.112	1.126	1.116	1.124	1.13061	1.1200	0.0070
8	1.132	1.131	1.105	1.137	1.145	1.147	1.147	1.14731	1.1410	0.0062
9	1.106	1.109	1.089	1.111	1.115	1.109	1.118	1.10571	1.1090	0.0031
10	1.070	1.075	1.016	1.076	1.074	1.078	1.083	1.08529	1.0755	0.0040
11	1.101	1.110	1.140	1.108	1.102	1.094	1.111	1.11730	1.1090	0.0075
12	1.130	1.137	1.101	1.131	1.138	1.144	1.147	1.13630	1.1366	0.0061
13	1.097	1.105	1.110	1.091	1.107	1.098	1.113	1.09118	1.1015	0.0070
14	1.031	1.029	1.010	1.033	1.022	1.029	1.037	1.03978	1.0300	0.0050
15	1.094	1.107	1.153	1.087	1.085	1.076	1.079	1.07383	1.0860	0.0090
16	1.142	1.134	1.126	1.128	1.150	1.133	1.136	1.14339	1.1350	0.0070
17	1.149	1.136	1.163	1.140	1.145	1.153	1.133	1.14087	1.1429	0.0065
18	1.209	1.186	1.147	1.186	1.186	1.197	1.180	1.17179	1.1860	0.0085
% inside MAD interval	50	67	6	83	72	67	44	11		
% of outliers	0	0	72	0	0	0	6	33		

Equivalent output VSWR

Port 3

Figure 5: Equivalent output VSWR port 3

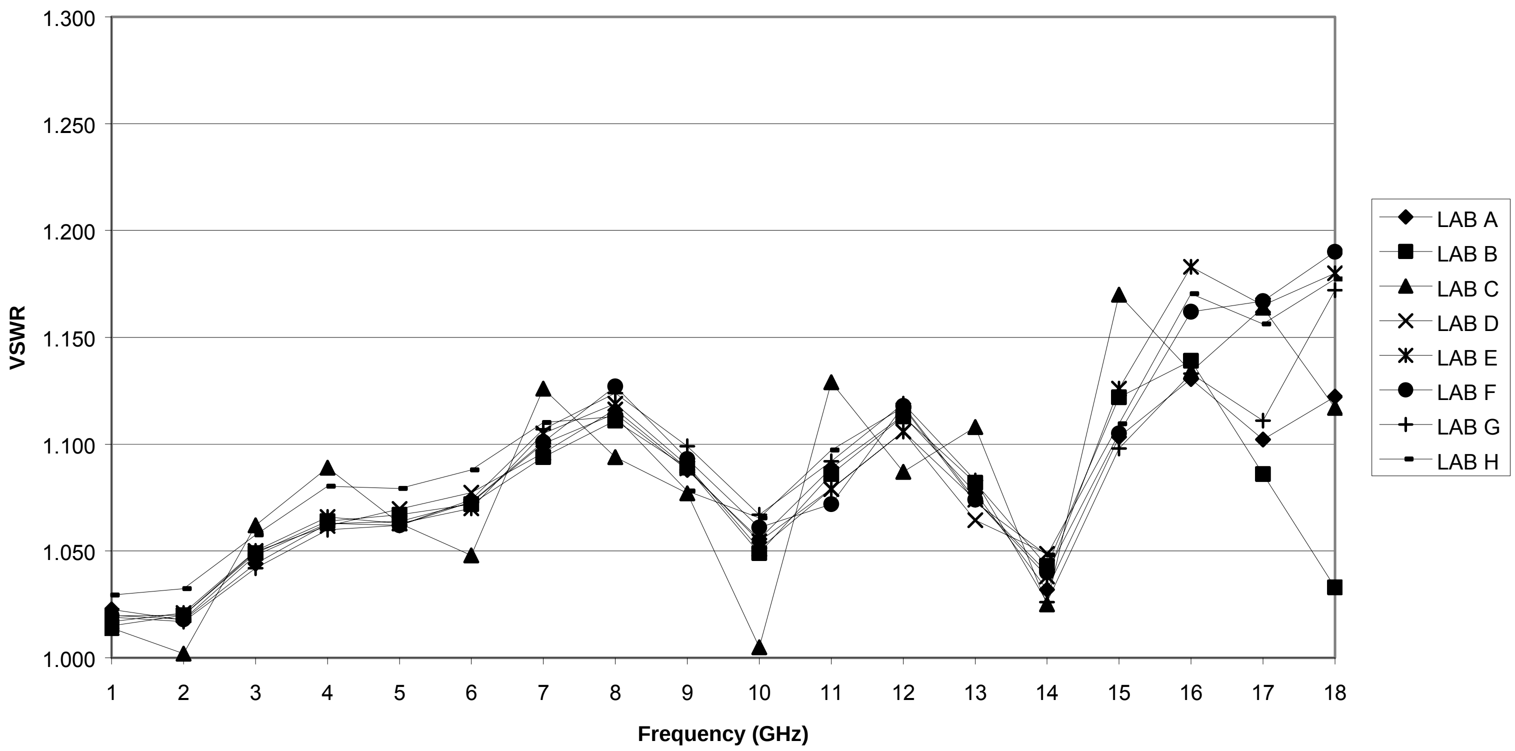

Figure 6: Normalised equivalent output VSWR port 3

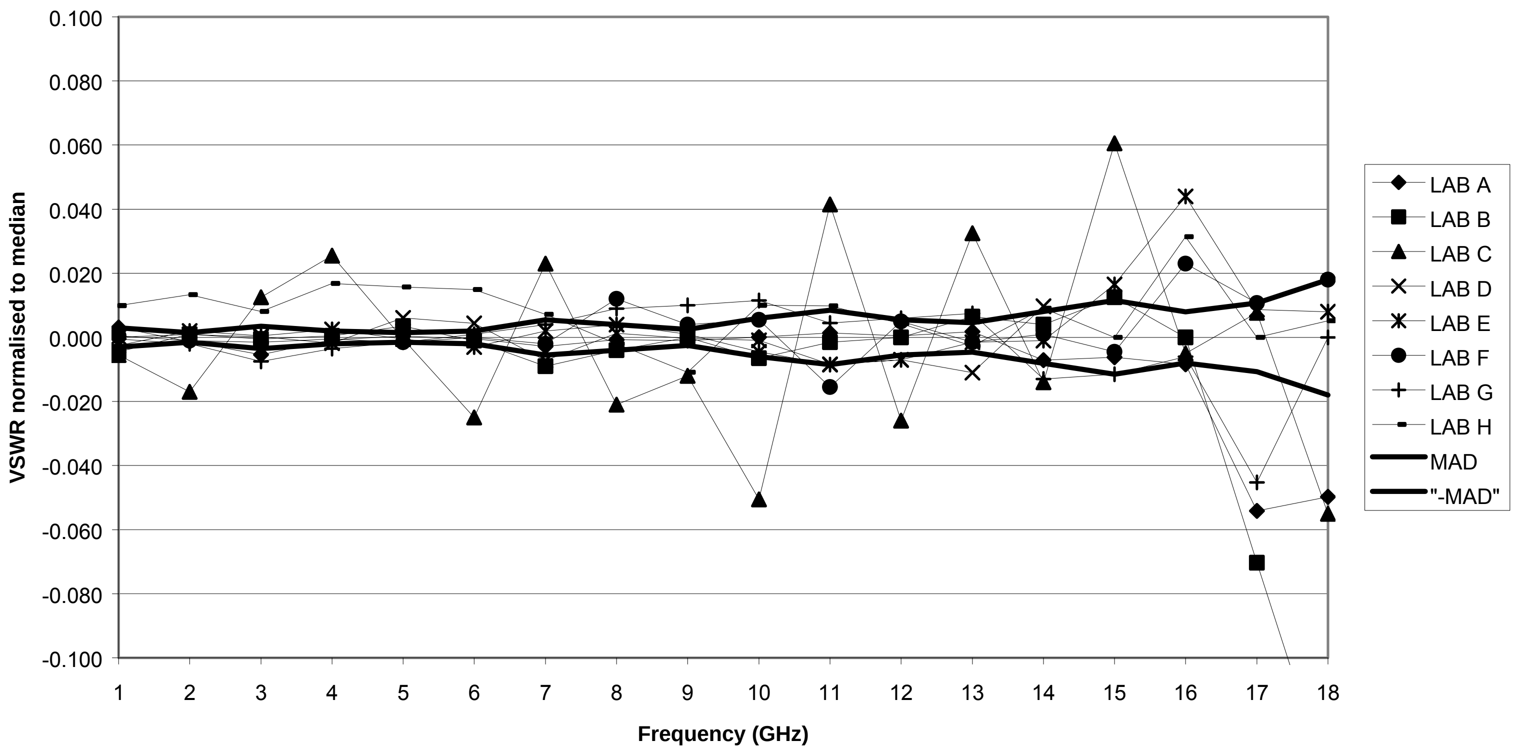

Table 3: Equivalent output VSWR port 3

Frequency (GHz)	LAB A	LAB B	LAB C	LAB D	LAB E	LAB F	LAB G	LAB H	MEDIAN	MAD
1	1.023	1.015	1.014	1.020	1.017	1.020	1.019	1.02943	1.0195	0.0030
2	1.018	1.020	1.002	1.020	1.021	1.018	1.017	1.03231	1.0190	0.0015
3	1.044	1.049	1.062	1.050	1.050	1.048	1.042	1.05761	1.0495	0.0035
4	1.063	1.064	1.089	1.062	1.066	1.063	1.060	1.08030	1.0635	0.0020
5	1.064	1.067	1.063	1.070	1.063	1.062	1.062	1.07922	1.0635	0.0015
6	1.073	1.072	1.048	1.077	1.070	1.073	1.074	1.08790	1.0730	0.0020
7	1.100	1.094	1.126	1.096	1.105	1.101	1.107	1.11015	1.1030	0.0055
8	1.114	1.111	1.094	1.116	1.119	1.127	1.124	1.11305	1.1150	0.0040
9	1.088	1.089	1.077	1.089	1.090	1.093	1.099	1.07814	1.0890	0.0025
10	1.056	1.049	1.005	1.055	1.051	1.061	1.067	1.06548	1.0555	0.0060
11	1.089	1.086	1.129	1.079	1.079	1.072	1.092	1.09732	1.0875	0.0085
12	1.113	1.113	1.087	1.106	1.106	1.118	1.119	1.11730	1.1130	0.0055
13	1.077	1.082	1.108	1.065	1.074	1.074	1.083	1.07275	1.0755	0.0046
14	1.032	1.043	1.025	1.049	1.038	1.040	1.026	1.04813	1.0390	0.0081
15	1.103	1.122	1.170	-	1.126	1.105	1.098	1.10948	1.1095	0.0115
16	1.131	1.139	1.134	-	1.183	1.162	1.133	1.17037	1.1390	0.0080
17	1.102	1.086	1.164	-	1.165	1.167	1.111	1.15633	1.1563	0.0107
18	1.122	1.033	1.117	-	1.180	1.190	1.172	1.17723	1.1720	0.0180
% inside MAD interval	78	50	17	57	67	78	44	33		
% of outliers	6	11	72	7	6	0	11	39		

Output tracking

Ports 2 and 3

Figure 7: Output tracking between ports 2 and 3 (dB)

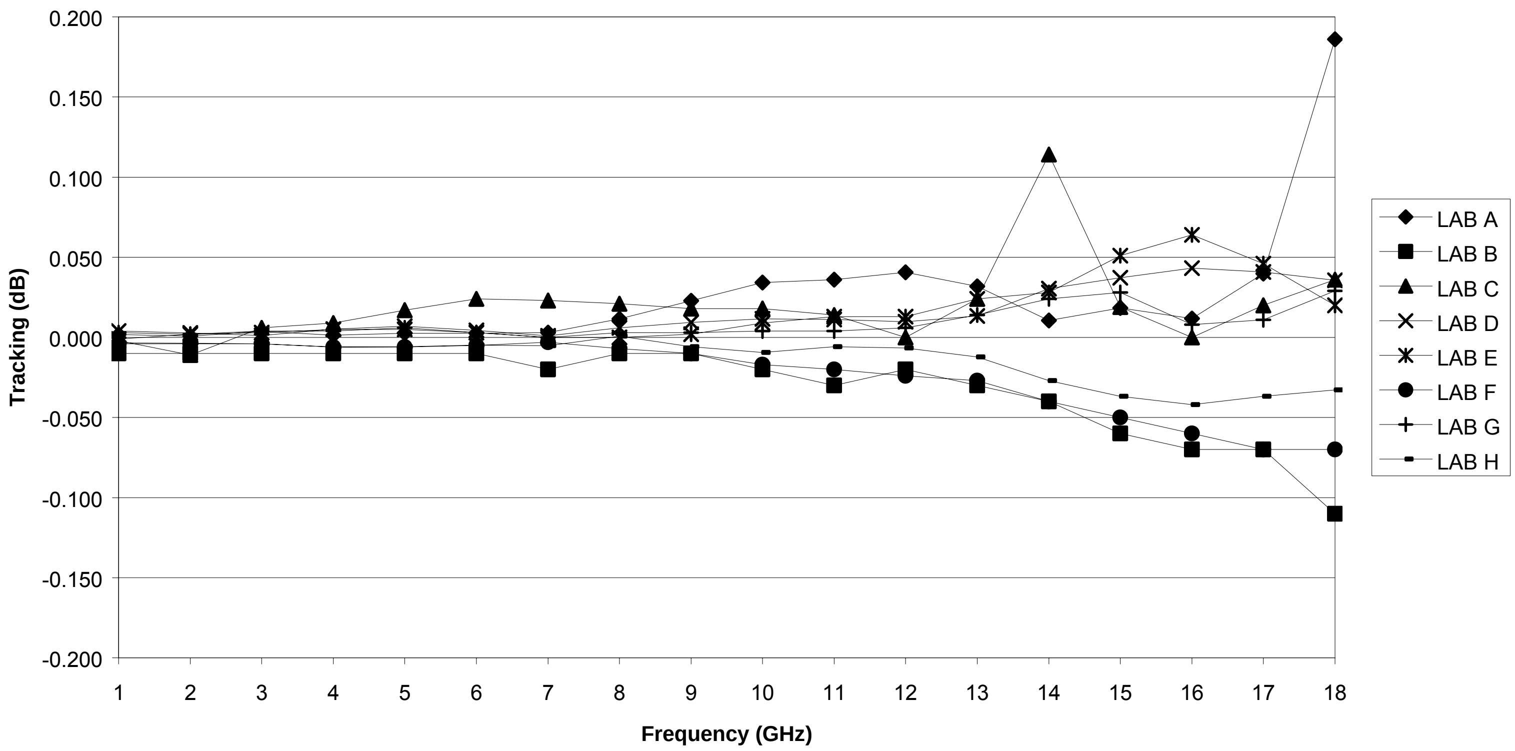

Figure 8: Normalised output tracking between ports 2 and 3 (dB)

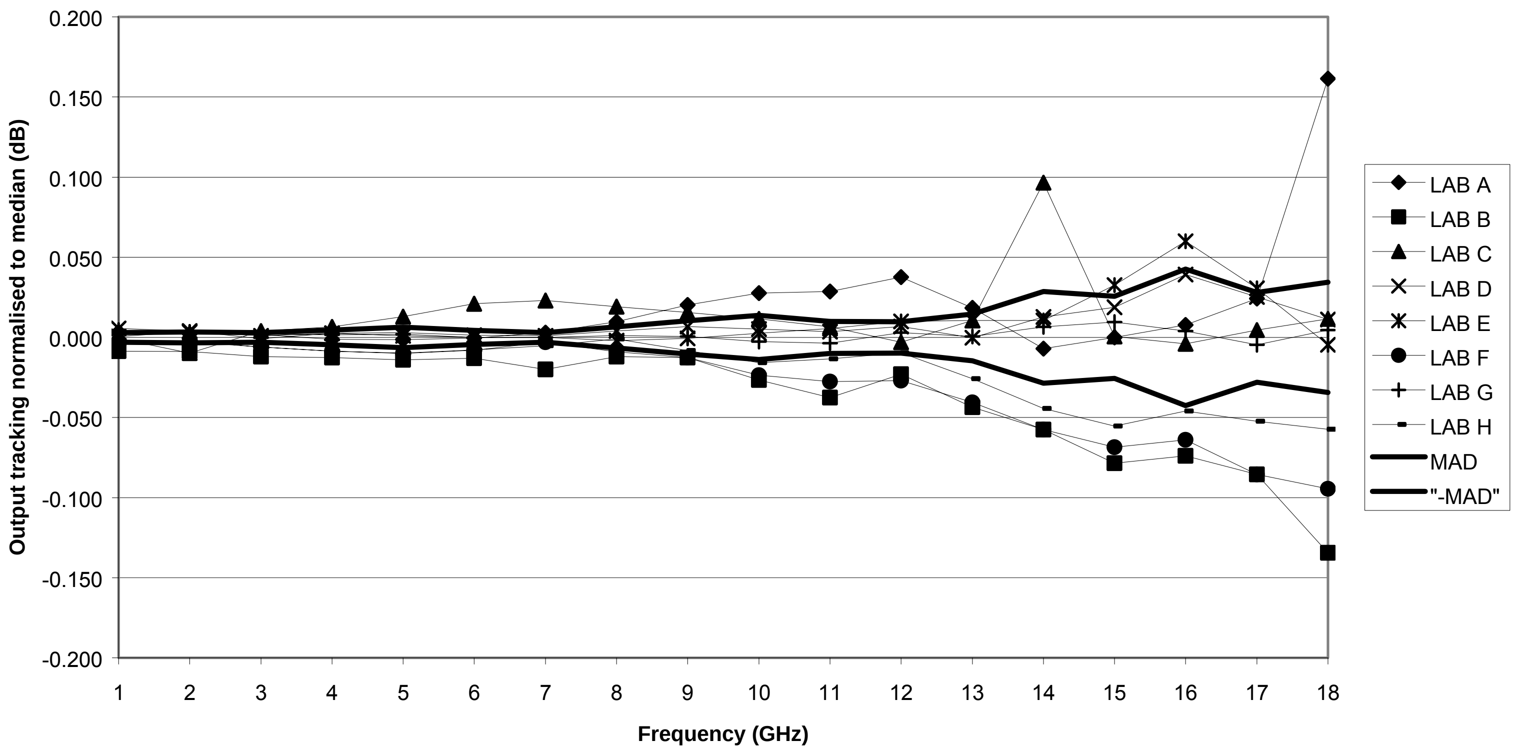

Table 4: Output tracking between ports 2 and 3 (dB)

Frequency (GHz)	LAB A	LAB B	LAB C	LAB D	LAB E	LAB F	LAB G	LAB H	MEDIAN	MAD
1	0.002	-0.01	-0.002	0.004	-0.001	-0.004	0.003	-0.00332	-0.0015	0.0030
2	0.001	-0.01	-0.011	0.003	0.002	-0.004	0.002	-0.00365	-0.0013	0.0033
3	0.004	-0.01	0.006	0.001	0.003	-0.004	0.004	-0.00396	0.0020	0.0030
4	0.001	-0.01	0.009	0.005	0.005	-0.006	0.004	-0.00609	0.0025	0.0045
5	0.003	-0.01	0.017	0.007	0.005	-0.006	0.006	-0.00577	0.0040	0.0064
6	0.003	-0.01	0.024	0.004	0.003	-0.005	0.003	-0.00475	0.0030	0.0044
7	0.003	-0.02	0.023	0.001	0.000	-0.003	0.000	-0.00512	0.0000	0.0030
8	0.012	-0.01	0.021	0.006	0.000	-0.007	0.003	0.00088	0.0019	0.0065
9	0.023	-0.01	0.018	0.009	0.002	-0.010	0.003	-0.00579	0.0025	0.0104
10	0.034	-0.02	0.018	0.012	0.009	-0.017	0.004	-0.00932	0.0065	0.0137
11	0.036	-0.03	0.014	0.011	0.013	-0.020	0.004	-0.00583	0.0075	0.0099
12	0.041	-0.02	0.000	0.010	0.013	-0.024	0.006	-0.00663	0.0030	0.0098
13	0.032	-0.03	0.024	0.013	0.024	-0.027	0.014	-0.01227	0.0135	0.0145
14	0.011	-0.04	0.114	0.030	0.028	-0.04	0.024	-0.02692	0.0175	0.0285
15	0.018	-0.06	0.019	0.037	0.051	-0.05	0.028	-0.03684	0.0185	0.0255
16	0.012	-0.07	0.000	0.043	0.064	-0.06	0.008	-0.04192	0.0040	0.0425
17	0.040	-0.07	0.020	0.041	0.046	-0.07	0.011	-0.03684	0.0155	0.0280
18	0.186	-0.11	0.036	0.036	0.020	-0.07	0.029	-0.03286	0.0245	0.0344
% inside MAD interval	56	0	50	89	78	17	94	28		
% of outliers	11	33	17	0	0	6	0	0		

Pin-depth measurements

Table 5: Pin depth (inches)

Port No	LAB A	LAB B	LAB C	LAB D	LAB E	LAB F	LAB G	LAB H	Median	MAD
1	-0.0040	-0.0040	-0.003	-0.00325	-0.00367	-0.00394	-0.0042	-	-0.00394	0.00026
2	-0.0044	-0.0050	-0.004	-0.00390	-0.00433	-0.00465	-0.0048	-	-0.00440	0.00040
3	-0.0044	-0.0035	-0.004	-0.00370	-0.00397	-0.00421	-0.0045	-	-0.00400	0.00030
% inside MAD interval	67	33	33	33	67	100	67	-		
% of outliers	0	0	33	0	0	0	0	-		