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Anamet-022 Comparison of Type-N coaxial power splitter measurements from 1 GHz to 18 GHz

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ANAMET-022: 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 forms part of ANAMET's long running programme of comparison exercises.[1] This exercise, numbered ANAMET-022 in the series, began in August 2002 and involved 17 participants (all members of ANAMET) including NPL, which also acted as the pilot laboratory. The exercise was completed in August 2004.

This exercise followed on from a previous ANAMET comparison exercise [1], which also involved measuring a coaxial power splitter (of a different manufacturer). The earlier comparison exercise ended prematurely when the device went missing in December 2002. This comparison exercise therefore provided the opportunity for a much larger number of participants to be involved – only 8 participants were involved in the previous comparison whereas 17 were involved in the comparison reported here.

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 Weinschel 93459 Model 1870A two-resistor power splitter (serial number 6684) fitted with three female 50 Ω Type-N connectors, as shown in Figure 1, below.

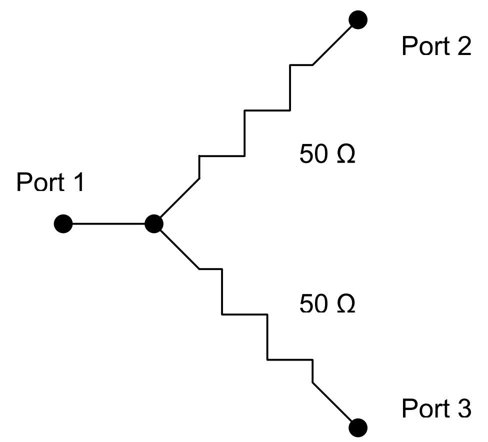

Figure 1: schematic diagram of the power splitter used for the comparison exercise

[1] Further details of all ANAMET comparison exercises can be found at www.npl.co.uk/anamet/comparisons.

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.

These measurands can be defined in terms of the *S*-parameters of the power splitter, as follows. The input VSWR at port 1 is given by:

$$(VSWR)_1 = \frac{1+|S_{11}|}{1-|S_{11}|}$$

Similarly, the effective output VSWRs at ports 2 and 3 are given by:

$$(VSWR)_2 = \frac{1+|\Gamma_2|}{1-|\Gamma_2|}$$

$$(VSWR)_3 = \frac{1+|\Gamma_3|}{1-|\Gamma_3|}$$

where the effective output reflection coefficients, Γ_2 and Γ_3, are given by:

$$\Gamma_2 = S_{22} - \frac{S_{12}S_{23}}{S_{13}}$$

and

$$\Gamma_3 = S_{33} - \frac{S_{13}S_{32}}{S_{12}}.$$

The equivalent output VSWR is the VSWR that is obtained when the splitter is used in a levelling or ratio system and is usually expected to be less than 1.15 for this particular splitter (based on the manufacturer's specification [2]). A detailed description of the equivalent output VSWR of a power splitter has been given in [3].

Finally, the output tracking, *T*, expressed in dB, is given by:

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

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 17 organisations choosing to participate in the exercise, listed alphabetically, are as follows:

- i) Agilent Technologies, South Queensferry, UK;
- ii) Agilent Technologies, Winnersh, UK;
- iii) ANACOM, Barcarena, Portugal;
- iv) ASAP Calibration Services, Bromley, UK;
- v) CSIR National Metrology Laboratory of South Africa, Pretoria, South Africa;
- vi) Czech Metrology Institute, Praha, Czech Republic;
- vii) Dowding & Mills, Camberley, UK;
- viii) Finnish Defence Forces, Riihimaki, Finland;
- ix) Government of the Hong Kong Special Administrative Region Standards and Calibration Laboratory, Wanchai, Hong Kong;
- x) IFR Ltd, Dunfirmline, UK;
- xi) INTA, Madrid, Spain;
- xii) METAS, Bern-Wabern, Switzerland;
- xiii) NMi-VSL, Delft, Netherlands;
- xiv) NPL, Teddington, UK;
- xv) Rohde & Schwarz GmbH, Munich, Germany;
- xvi) Saab Metech AB[2], Arboga, Sweden;
- xvii) UME, Kocaeli, Turkey.

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.[3] Some general information is given below concerning the systems and techniques that were used by the participants for the measurements.

3.1 Measuring instruments

15 of the 17 participants used Vector Network Analysers (VNAs) as the measuring instrument. The other two participants used scalar measurement systems comprising combinations of VSWR bridges and receiver-based attenuation systems. 14 of the VNAs were Agilent (formerly HP) 8510 series instruments with the remaining system being a Rohde & Schwarz ZVK.

The large number of 8510s used in the comparison indicates the key role that this instrument still plays in many measurement laboratories. This is despite the fact that this instrument is no longer available from the manufacturer.

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[2] Formerly known as Celsius Metech AB.

[3] 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.

3.2 Calibration techniques

The most popular method used to calibrate the VNAs was SOLT (Short-Open-Load-Thru), either with or without the use of sliding loads. Adaptor removal (or swap equal adaptors) was often incorporated within the calibration scheme. One participant used the LRL (Line-Reflect-Line) technique.

3.3 Measurement techniques

Several different methods were used to perform the measurements in this comparison. The most popular method was to directly measure the *S*-parameters of the splitter and compute the measurands accordingly [3, 4]. During these measurements, any unused ports on the power splitter were terminated with well-matched loads.[4]

Two alternative methods were also used to obtain the equivalent output VSWRs at ports 2 and 3. These were the Direct Calibration Method of Juroshek [5] and methods derived from a technique proposed originally by Engen [6] and later re-evaluated by Moyer [7] where it was called the Passive Open-Circuit method. This method utilises variable high reflects (e.g. using a sliding short-circuit or a range of different offset short- and open-circuits) attached to port 1 of the splitter to establish a null condition in the transmission between, or the reflection coefficients at, ports 2 and 3.

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 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 [8] 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.[5] 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.

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[4] The match of these loads was either assumed to be perfect or a correction was applied to take account of the reflection coefficient.

[5] The MAD is defined here as the median of the absolute differences between each result and the median of all the participants' values [9].

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 (as in [1]), 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 are in good agreement with those belonging to the other participants.

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 2.[6] For normal distributions, a correction factor of approximately 1.5 can be used to obtain s from a MAD value, i.e.:

$$s \approx 1.5 \times \mathrm{MAD}$$

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

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

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

$$|x_i - x_{\mathrm{med}}| > U$$

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

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 do not show good agreement with those belonging to the other participants.

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

6. Results

The results obtained by the participants, along with statistical summaries, are presented in the appendices to this report as tables and graphs (i.e. Figures) for each measurand. The tables present the values supplied by each participant,[7] along with median and MAD summary statistics, at each frequency. Participant summaries, in terms of "% inside MAD interval" and "% of outliers", are also given. Each table is presented in two parts on separate pages. This is to accommodate the significant size of each table (i.e. comprising 20 columns).

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, at least two graphs are presented. The first graph shows the results obtained by each participant as a function of frequency. In the case of the output VSWRs, one participant supplied values that were very different from the other values.[8] This causes the vertical scale on these graphs to have a low sensitivity so that examining the variability of the other participants' values becomes difficult. Therefore an additional graph has been included with this participant's values removed. This allows a more sensitive vertical scale to be used to display the remaining participants' values. For all four measurands, a further graph shows the same data normalised with respect to the sample median.

The graph showing the data normalised to the median also includes 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:

- Input VSWR at port 1 – Appendix A; Figures A1 and A2, Tables A1a and A1b;
- Equivalent output VSWR at port 2 – Appendix B; Figures B1, B2 and B3, Tables B1a and B1b;
- Equivalent output VSWR at port 3 – Appendix C; Figures C1, C2 and C3, Tables C1a and C1b;
- Output tracking between ports 2 and 3 – Appendix D; Figures D1 and D2, Tables D1a and D1b.

In addition, the pin-depth measurements made by the participants are presented in Tables E1a and E1b of Appendix E, along with their statistical summaries. As is common practice in the industry, all values have been expressed in inches. Therefore, values supplied by participants expressed in millimetres have been converted to inches by dividing by 25.4.

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[7] For the electrical measurements, participant results are shown in the tables to the same number of decimal places as supplied by the participants. For the mechanical pin-depth measurements, these are expressed to four decimal places (for consistency). These pin-depth values may therefore contain small errors due to rounding.

[8] After discussions with this participant, it became clear that they had measured a different measurand – namely, VSWRs at ports 2 and 3 derived from just the S_{22} and S_{33} of the splitter, respectively, when measured as a simple passive device. These VSWRs are expected to be of the order of 1.7 [7] (compared with values of less than 1.15 for the equivalent output VSWRs [2]).

A further complication exists when quoting pin-depth values for Type-N connectors. This relates to the fact that the position of the centre conductor of the connector is offset from the connector's reference plane (as defined by the position of the outer conductor) by a specified amount.[9] Some participants supplied pin-depth values that referred to the absolute position of the centre conductor with respect to the outer conductor reference plane. However, the majority of participants supplied pin-depth values relative to an assumed offset value. Therefore, in order to analyse all values simultaneously, values representing the absolute position of the centre conductor with respect to the reference plane were converted to values relative to an offset of 0.207 inches [10].

Appendix E also contains graphs (Figures E1, E2 and E3) showing the participants' pin-depth measurements for each connector along with the median and the ±MAD interval.

7. Discussion

7.1 Results for input VSWR at port 1

Figures A1 and A2 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 (≤ 0.008) in Table A1 at all frequencies.

However, the results for Labs C and O do, at some frequencies, exhibit a noticeable departure from the majority of values. This observation is supported by 28 % and 33 % of values, respectively, being labelled as outliers. These were the participants that used the scalar measurement systems.

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 B1, B2 and B3) generally show good agreement and this is further supported by relatively low MAD values (≤ 0.013) at all frequencies in Table B1.

However, the notable exception to this is Lab O who, it has already been stated, measured a different measurand (i.e. S_{22} of the device). This explains why this participant's results differ so greatly from the other participants' values.

Another interesting feature in these Figures is that a second grouping of values begins to emerge from the main grouping of values at frequencies above approximately 11 GHz. This grouping consists of Labs B, H and Q. This observation is supported by these participants obtaining the highest percentage of values that have been labelled as outliers (i.e. 61 %, 56 % and 44 %, respectively). These participants used measurement methods derived from the high reflect 'nulling' technique described earlier (and presented in [6, 7]) to determine this measurand.

To examine the possible significance of the difference between these two groupings of results, Figure 2, below, shows the same results along with a line representing the

[9] These days, it is generally recognised that for precision Type-N connectors this offset is specified to be 0.207 inches [10]. However, care should be taken when applying this offset value to all Type-N connectors since several other specifications for Type-N connectors exist that give different values for this offset (as discussed in [11]).

specification limit for equivalent output VSWR for this type of power splitter. This Figure shows that two of the participants in this secondary grouping (i.e. Labs B and H) have measured the power splitter to be outside the specification at 17 GHz. This could mean that, if testing this device to its specification, these laboratories would reject the device as non-compliant. This is interesting when one considers that the majority of participants (i.e. those using other measurement methods) would accept the device as compliant with the specification.

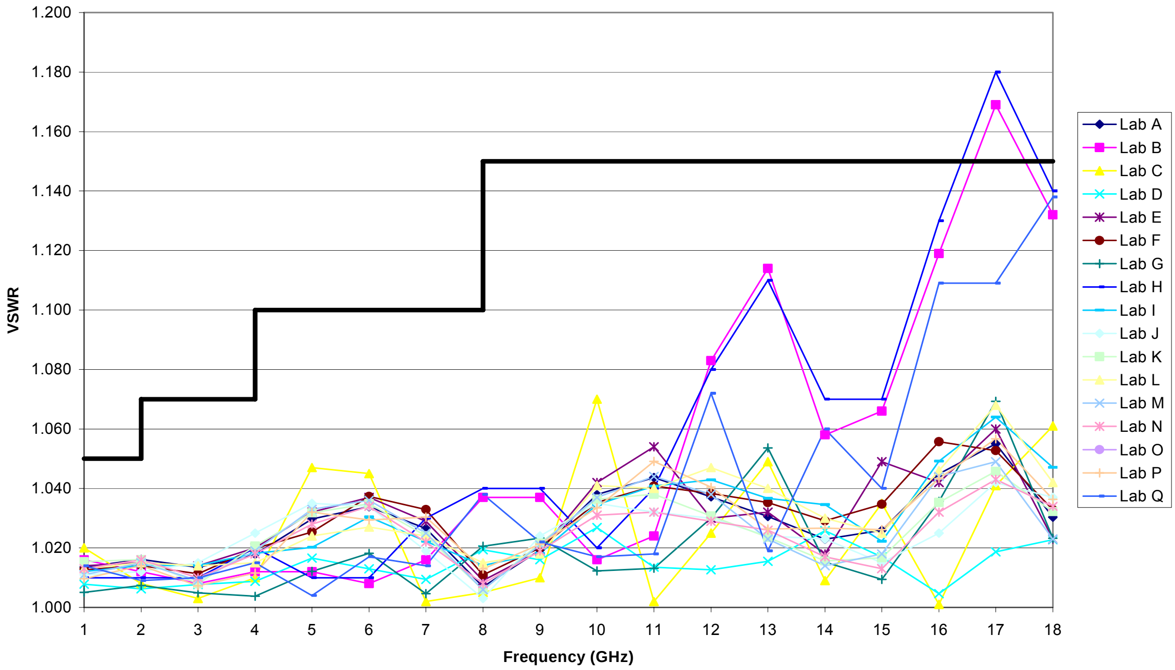

Figure 2: Equivalent output VSWR at port 2 showing manufacturer's specification limit (as a thick black line).

7.3 Results for equivalent output VSWR at port 3

The results for equivalent output VSWR at port 3 (Figures C1, C2 and C3) show good agreement and this is further supported by relatively low MAD values (≤ 0.015) at all frequencies in Table C1.

As with the equivalent output VSWR at port 2, the notable exception to this is Lab O, which measured a different measurand (i.e. S_{33} of the device), and so this explains why this participant's results differ so greatly from the other participants' values. There is also evidence of the same secondary grouping of values (from Labs B, H and Q) emerging from the main grouping of values at high frequencies (i.e. above 15 GHz). Once again, these participants used measurement methods derived from the high reflect 'nulling' technique.

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 D1 and D2, indicate reasonable agreement between all participants. This is further demonstrated by the relatively low MAD values (≤ 0.027 dB) in Table D1.

However, the results for Labs C, I, N and O do, at some frequencies, exhibit noticeable departures from the majority of values. This observation is supported by 44 %, 33 %, 89 %

and 94 % of values, respectively, being labelled as outliers. These included the participants that used the scalar measurement systems.

7.5 Pin-depth results

The results for the pin-depth measurements, shown in Table E1, generally show good agreement between the values supplied by the participants.[10] However, there are a few values that have been identified as 'outlying' (using the criterion established in section 4.2) – i.e. one of the three values for each of Labs A, E and F. These correspond to the measurements made on port 3 (as can be seen in Figure E3).

An interesting feature with the pin-depth measurements supplied for port 1 is that there appears to be a step change in values between Lab F and Lab H (Lab G did not supply pin-depth data). In particular, values supplied by Labs A to F range from 0.0000 inches to -0.0005 inches, whereas those supplied by Labs H to Q range from -0.0008 inches to -0.0017 inches. These two ranges do not overlap and so this suggests that the value for this measurand may have changed during the comparison exercise. This effect can also been seen in Figure E1.

To investigate this further, we can examine the pin-depth measurements that were made by the pilot laboratory throughout the comparison after the device was returned from each participant. (These measurements were made as part of the checks performed on the device throughout the comparison exercise.) These values are shown in Figure 3.

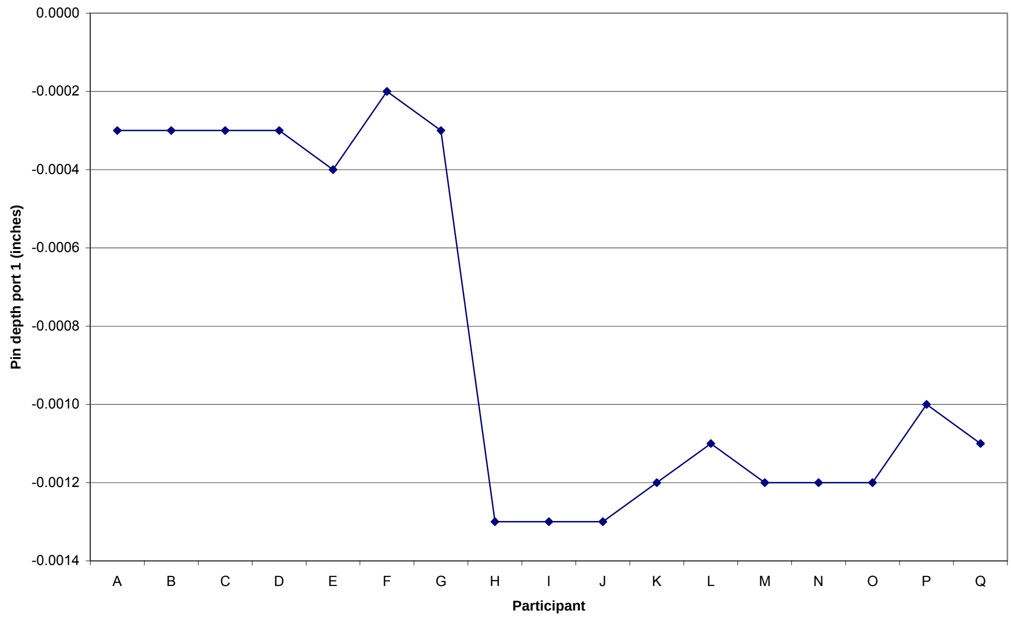

Figure 3: Pin-depth values for port 1 measured by the pilot laboratory after the power splitter was returned from each participant

This Figure clearly shows that a step change in the value of this measurand did indeed occur, and that it actually occurred between the measurements made by Lab G and Lab H. Under these circumstances, the simple statistical techniques used in this report to provide summaries for this data become less effective.

[10] Labs B and G chose not to supply pin-depth measurements.

Having identified this step change in the value for this measurand, no corresponding effect can be seen in the electrical measurements for Labs A to G. For example, the measurements of the input VSWR for port 1 do not show any separate grouping for these participants' values.

Finally, the process used to convert values supplied by some participants that measured the absolute position of the centre conductor with respect to the reference plane to values relative to an offset of 0.207 inches (so that the data could be analysed simultaneously) appears not to have introduced any serious discrepancies in the data. This therefore supports the use of this conversion process on this occasion.

8. Comparison with ANAMET-021 exercise

Since the ANAMET-021 comparison exercise [1] compared the same measurands as were measured during this exercise, it is possible to compare the levels of variability found on both occasions.[11] (Note that the ANAMET-021 exercise used a power splitter supplied by a different manufacturer - Hewlett Packard.)

8.1 Electrical data

Table 1 summarises the electrical measurement data obtained during both comparison exercises in terms of the maximum achieved MAD values for each measurand. It is clear that, for all three VSWR measurands, the levels of variability are similar on both occasions. They can be further summarised by stating that all MAD values are less than 0.02. Similarly the levels of variability for the output tracking measurand are also similar on both occasions, being less than 0.05 dB. It is encouraging that similar levels of variability have been found on both occasions.

Table 1: Maximum MAD values for both ANAMET power splitter comparisons

Measurand	Maximum MAD values	
	ANAMET-021	ANAMET-022
Input VSWR at port 1	0.013	0.008
Equivalent output VSWR at port 2	0.009	0.013
Equivalent output VSWR at port 3	0.018	0.015
Output tracking between ports 2 and 3 (dB)	0.043	0.027

8.2 Pin-depth data

Table 2 summarises the pin-depth measurement data obtained during both comparison exercises in terms of the maximum achieved MAD values. As with the electrical data, it is clear that the levels of variability are similar on both occasions.

Table 2: Maximum MAD pin-depth values for both ANAMET power splitter comparisons

ANAMET-021	ANAMET-022
0.0003 to 0.0004 inches	0.0001 to 0.0004 inches

[11] Seven of the eight laboratories that participated in the earlier ANAMET-021 exercise also participated in this current exercise (ANAMET-022).

9. Conclusions

The ANAMET-022 exercise has been successful in comparing measurements, made by 17 leading measurement laboratories, of the electrical quantities of a coaxial power splitter. The results obtained by the laboratories involved in the exercise have generally shown good overall agreement. However, the measurements made by Lab O of the effective output VSWRs at ports 2 and 3 were very different from the other laboratories. This was found to be due to this laboratory measuring different measurands (i.e. S_{22} and S_{33}) and therefore this explains the lack of agreement on this occasion.

Several interesting features in the data have been identified concerning relating the results supplied by the participants to either the choice of measuring instrument or measurement technique. For example, for measurements of the input VSWR at port 1 and output tracking between ports 2 and 3, the scalar measuring instruments produced greater variability in the values obtained. This could be due to different sources of error in these systems compared with the VNAs. Also, for the output VSWRs at ports 2 and 3, participants using the high reflect 'nulling' measurement technique [6, 7] obtained values that were similar with each other, but different from the other participants' values at the higher frequencies. It was further shown that this difference in value could cause a dispute over whether the power splitter was inside or outside its specification.

The mechanical pin-depth data showed good agreement although it became clear that the value for one of the measurands (pin-depth on port 1) actually changed during the lifetime of the comparison. This may need to be taken into account when participants examine the results for their own pin-depth measurements.

Finally a comparison with the earlier ANAMET-021 exercise (involving a different manufacturer's power splitter) has also been presented. This has shown that the level of variability found during both exercises was in fact quite similar.[12] This suggests that this level of variability may be indicative of what is to be expected for these types of measurements. If this is indeed the case, then this sets a benchmark for the expected level of agreement between laboratories performing such measurements.

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Steve Harter and Peter Constable, ASAP Calibration Services, Bromley, UK;
Erik Dressler and MJ Prinsloo, CSIR-NML, South Africa, Pretoria, South Africa;
Karel Drazil, Czech Metrology Institute, Praha, Czech Republic;
Alan Coster, Dowding & Mills, Camberley, UK;
Pertti Saarinen and Tuomas Haitto, Finnish Defence Forces, Riihimaki, Finland;
Michael Chow, Hong Kong Standards and Calibration Laboratory, Wanchai, Hong Kong;
Patrick Haggarty, IFR Ltd, Dunfirmline, UK;

[12] The fact that seven laboratories participated in both comparison exercises may have an impact on this observation.

Manuel Rodriguez, INTA, Madrid, Spain;
Juerg Ruefenacht, METAS, Bern-Wabern, Switzerland;
Jan de Vreede, NMi-VSL, Delft, Netherlands;
Joachim Schubert and Harald Jaeger, Rohde & Schwarz GmbH, Munich, Germany;
Patrik Persson, Saab Metech AB, Arboga, Sweden;
Senel Yaran, UME, Kocaeli, Turkey.

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11. References

[1] N M Ridler, M J Salter and S H Fletcher, "ANAMET-021: comparison of Type-N coaxial power splitter measurements from 1 GHz to 18 GHz", *ANAMET Report 039*, September 2003.

[2] The specification for this splitter can be found at: www.weinschel.com.

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[8] N M Ridler, "Making a good estimate of a measurand", *ANAMET ANAlyse Note 7*, January 1995.

[9] N M Ridler and J C Medley, "Assessing the quality of an estimated value – Part 2: the Median Absolute Deviation", *ANAMET ANAlyse Note 16*, April 1996.

[10] IEEE P287/D1, "Draft standard for precision coaxial connectors (DC to 110 GHz", *IEEE Instrumentation and Measurement Society*, August 2001. (This is, at present, an unpublished draft document and therefore not always easy to obtain.)

[11] A D Skinner, "ANAMET connector guide", 2nd edition, May 2004. (Available for download, free, from www.npl.co.uk/anamet.)

Appendix A:

Input VSWR at port 1

Figure A1: Input VSWR port 1

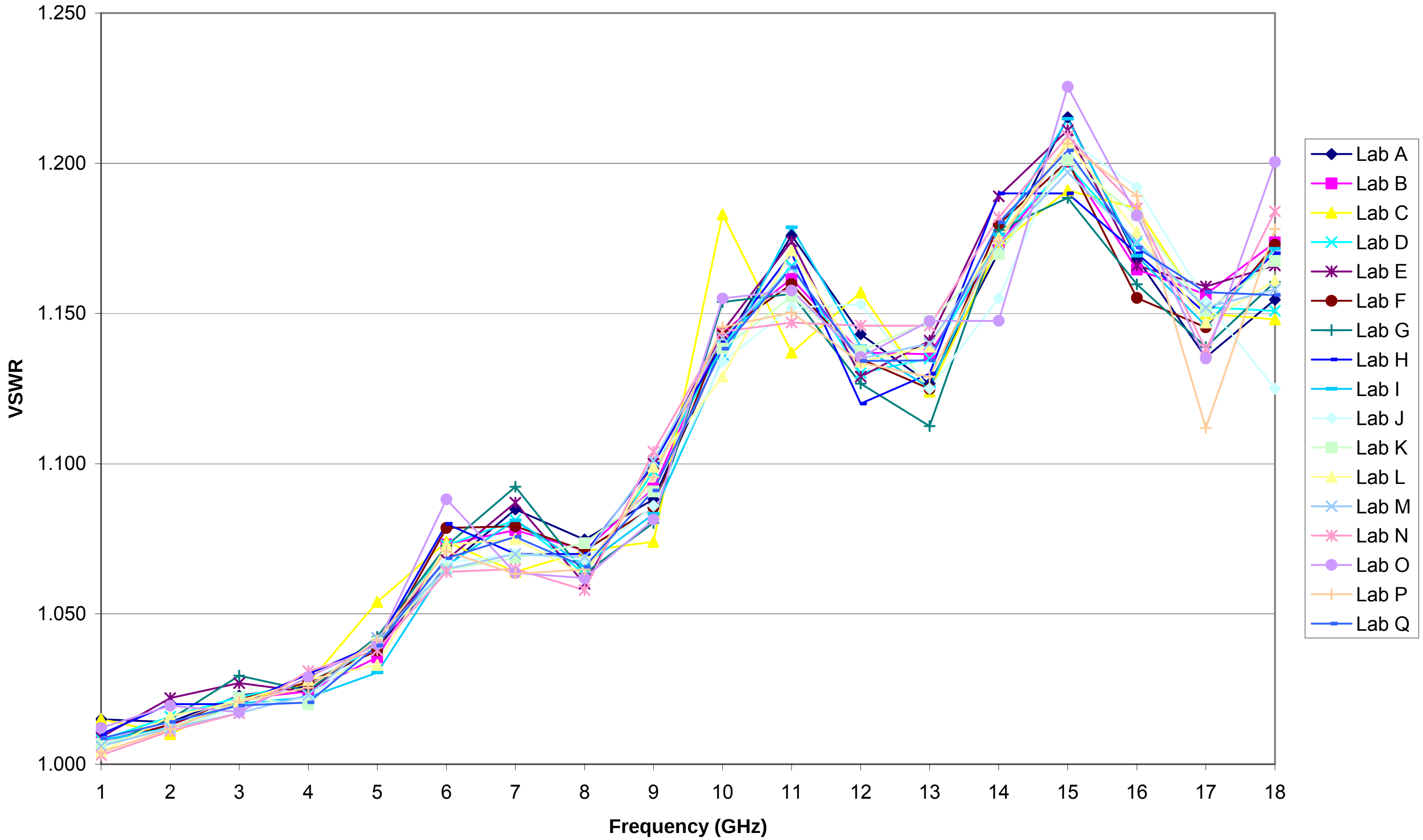


Figure A2: Normalised input VSWR port 1

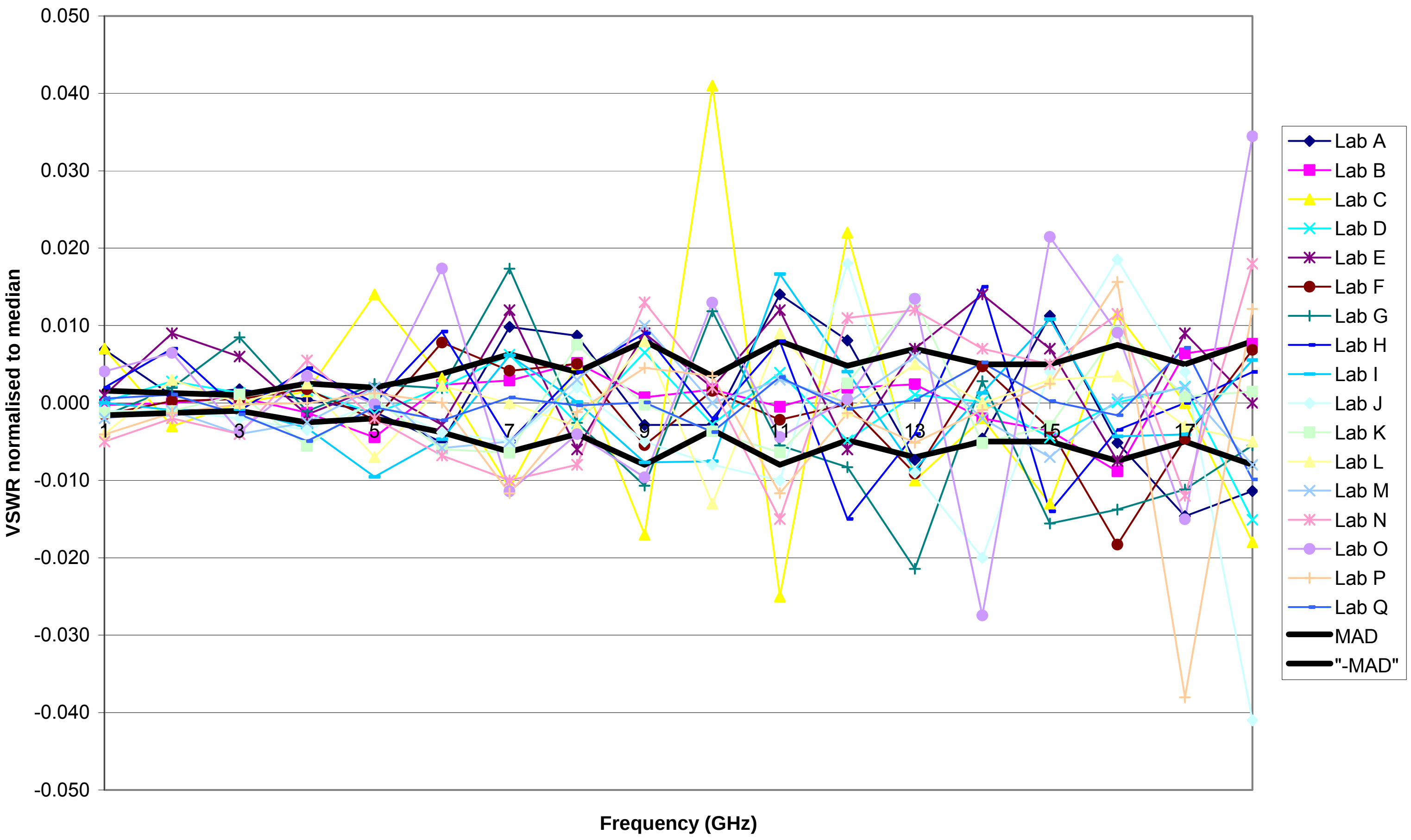


Table A1a: Input VSWR port 1

Frequency GHz	Lab A	Lab B	Lab C	Lab D	Lab E	Lab F	Lab G	Lab H	Lab I
1	1.015	1.008	1.015	1.0082	1.009	1.007	1.0064	1.01	1.008
2	1.014	1.013	1.010	1.0158	1.022	1.013	1.0150	1.02	1.012
3	1.023	1.022	1.021	1.0223	1.027	1.022	1.0295	1.02	1.020
4	1.026	1.024	1.027	1.0271	1.024	1.027	1.0244	1.03	1.022
5	1.039	1.036	1.054	1.0386	1.042	1.038	1.0424	1.04	1.030
6	1.066	1.073	1.074	1.0728	1.068	1.079	1.0727	1.08	1.066
7	1.085	1.078	1.064	1.0813	1.087	1.079	1.0923	1.07	1.081
8	1.075	1.071	1.071	1.0634	1.060	1.071	1.0634	1.07	1.066
9	1.088	1.092	1.074	1.0975	1.100	1.086	1.0803	1.10	1.083
10	1.139	1.144	1.183	1.1392	1.144	1.144	1.1538	1.14	1.134
11	1.176	1.162	1.137	1.1659	1.174	1.160	1.1565	1.17	1.179
12	1.143	1.137	1.157	1.1302	1.129	1.135	1.1267	1.12	1.139
13	1.127	1.136	1.124	1.1351	1.141	1.125	1.1126	1.13	1.125
14	1.170	1.173	1.173	1.1751	1.189	1.180	1.1778	1.19	1.176
15	1.215	1.200	1.191	1.1995	1.211	1.201	1.1884	1.19	1.215
16	1.168	1.165	1.185	1.1735	1.166	1.155	1.1597	1.17	1.169
17	1.135	1.156	1.150	1.1521	1.159	1.145	1.1388	1.15	1.146
18	1.155	1.174	1.148	1.1509	1.166	1.173	1.1605	1.17	1.172
% inside MAD Interval	39	78	28	83	44	78	39	56	61
% of outliers	11	0	28	0	11	0	22	17	6

Table A1b: Input VSWR port 1

Frequency GHz	Lab J	Lab K	Lab L	Lab M	Lab N	Lab O	Lab P	Lab Q	MEDIAN	MAD
1	1.007	1.0067	1.004	1.006	1.003	1.01	1.0039	1.009	1.0080	0.0016
2	1.012	1.0120	1.016	1.012	1.011	1.02	1.0117	1.014	1.0130	0.0013
3	1.019	1.0221	1.021	1.017	1.017	1.02	1.0208	1.020	1.0210	0.0010
4	1.022	1.0200	1.028	1.023	1.031	1.03	1.0255	1.021	1.0255	0.0025
5	1.040	1.0405	1.033	1.042	1.038	1.04	1.0413	1.039	1.0400	0.0020
6	1.067	1.0648	1.073	1.065	1.064	1.09	1.0708	1.069	1.0708	0.0038
7	1.070	1.0686	1.075	1.070	1.065	1.06	1.0633	1.076	1.0750	0.0063
8	1.068	1.0735	1.063	1.069	1.058	1.06	1.0648	1.066	1.0660	0.0040
9	1.086	1.0908	1.099	1.101	1.104	1.08	1.0955	1.091	1.0910	0.0080
10	1.134	1.1383	1.129	1.142	1.144	1.15	1.1455	1.138	1.1420	0.0035
11	1.152	1.1556	1.171	1.165	1.147	1.16	1.1503	1.165	1.1620	0.0080
12	1.153	1.1375	1.134	1.135	1.146	1.14	1.1337	1.134	1.1350	0.0048
13	1.125	1.1474	1.139	1.140	1.146	1.15	1.1289	1.134	1.1340	0.0070
14	1.155	1.1698	1.175	1.173	1.182	1.15	1.1741	1.180	1.1750	0.0050
15	1.208	1.2010	1.207	1.197	1.209	1.23	1.2065	1.204	1.2040	0.0050
16	1.192	1.1827	1.177	1.174	1.185	1.18	1.1891	1.172	1.1735	0.0075
17	1.154	1.1508	1.147	1.152	1.138	1.13	1.1120	1.157	1.1500	0.0050
18	1.125	1.1675	1.161	1.158	1.184	1.20	1.1781	1.156	1.1660	0.0080
% inside MAD Interval	50	50	72	67	17	22	67	78		
% of outliers	17	0	11	6	11	33	6	0		

Appendix B:

Equivalent output VSWR at port 2

Figure B1: Equivalent output VSWR port 2

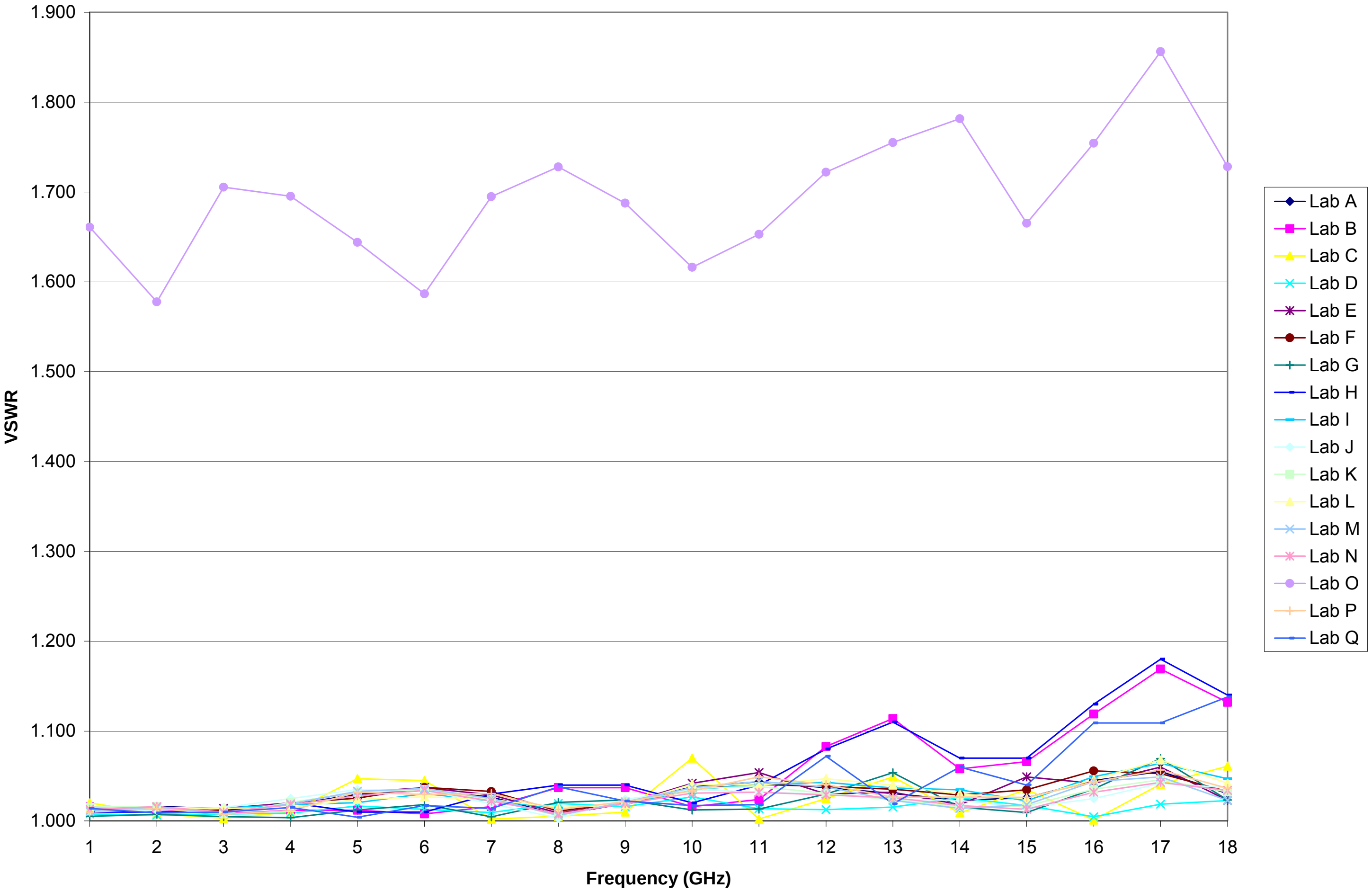


Figure B2: Equivalent output VSWR port 2

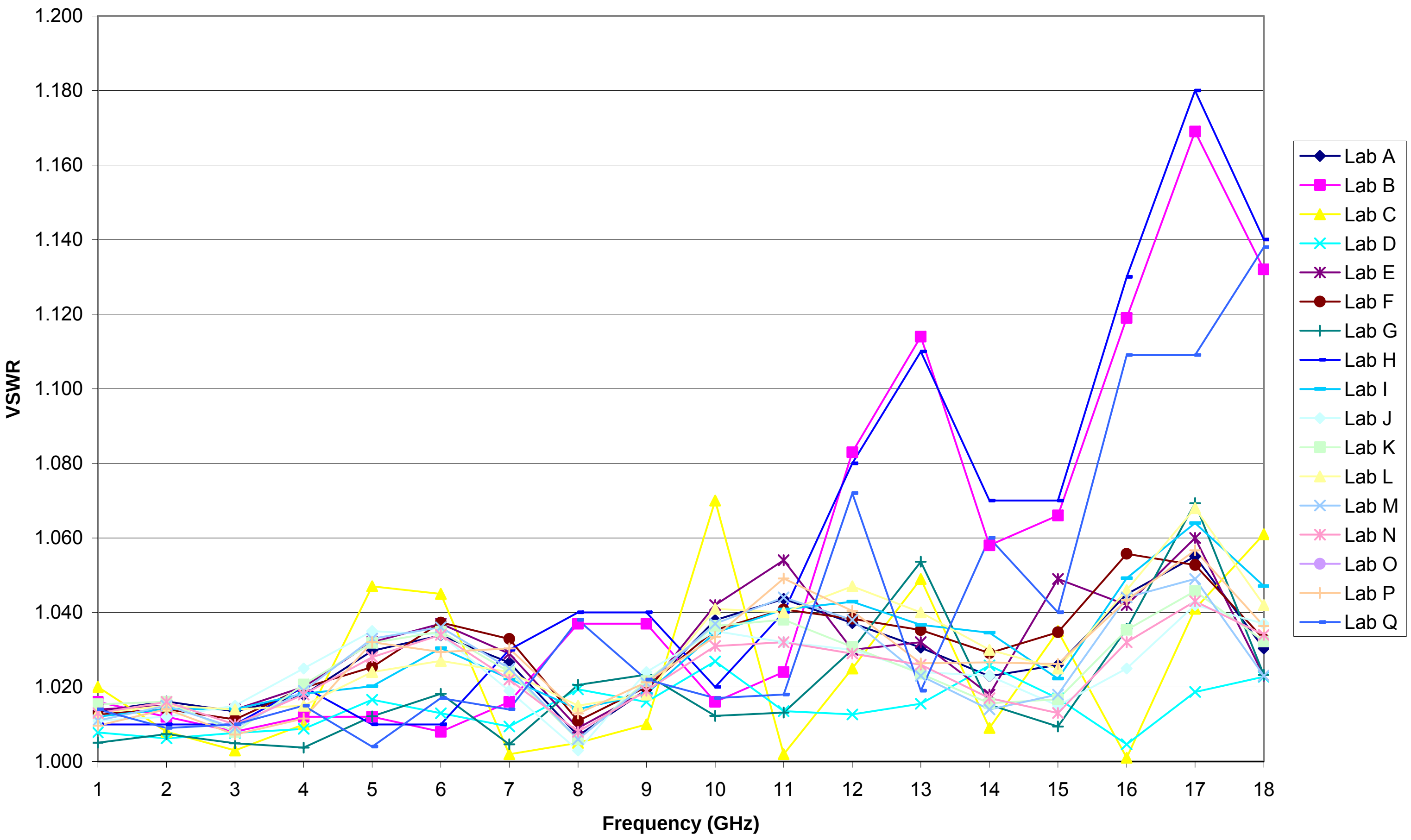


Figure B3: Normalised equivalent output VSWR port 2

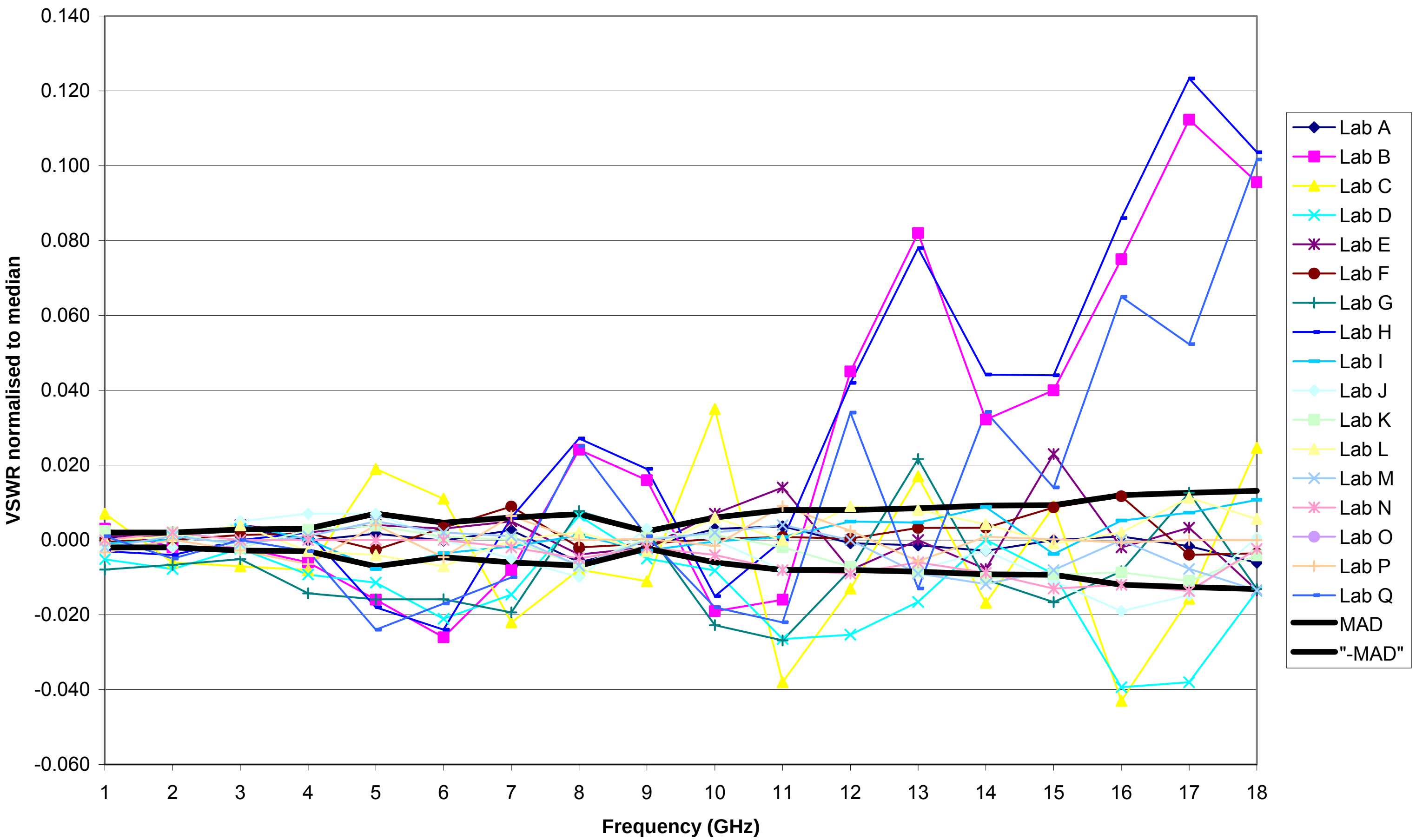


Table B1a: Equivalent output VSWR port 2

Frequency GHz	Lab A	Lab B	Lab C	Lab D	Lab E	Lab F	Lab G	Lab H	Lab I
1	1.014	1.016	1.020	1.0078	1.014	1.013	1.0051	1.01	1.012
2	1.016	1.012	1.008	1.0062	1.015	1.014	1.0074	1.01	1.014
3	1.013	1.008	1.003	1.0077	1.014	1.011	1.0049	1.01	1.014
4	1.018	1.012	1.010	1.0087	1.020	1.020	1.0037	1.02	1.018
5	1.030	1.012	1.047	1.0166	1.032	1.025	1.0121	1.01	1.020
6	1.034	1.008	1.045	1.0130	1.037	1.037	1.0181	1.01	1.030
7	1.027	1.016	1.002	1.0094	1.029	1.033	1.0046	1.03	1.022
8	1.007	1.037	1.005	1.0194	1.009	1.011	1.0206	1.04	1.014
9	1.019	1.037	1.010	1.0160	1.019	1.020	1.0233	1.04	1.018
10	1.038	1.016	1.070	1.0269	1.042	1.035	1.0122	1.02	1.035
11	1.044	1.024	1.002	1.0135	1.054	1.041	1.0132	1.04	1.041
12	1.037	1.083	1.025	1.0127	1.030	1.038	1.0300	1.08	1.043
13	1.031	1.114	1.049	1.0155	1.032	1.035	1.0536	1.11	1.037
14	1.023	1.058	1.009	1.0258	1.018	1.029	1.0152	1.07	1.035
15	1.026	1.066	1.035	1.0170	1.049	1.035	1.0094	1.07	1.022
16	1.045	1.119	1.001	1.0047	1.042	1.056	1.0356	1.13	1.049
17	1.055	1.169	1.041	1.0187	1.060	1.053	1.0693	1.18	1.064
18	1.030	1.132	1.061	1.0228	1.023	1.033	1.0233	1.14	1.047
% inside MAD Interval	94	11	6	22	72	94	28	22	83
% of outliers	0	61	33	39	0	0	39	56	0

Table B1b: Equivalent output VSWR port 2

Frequency GHz	Lab J	Lab K	Lab L	Lab M	Lab N	Lab O	Lab P	Lab Q	MEDIAN	MAD
1	1.011	1.0154	1.013	1.011	1.013	1.66	1.0097	1.014	1.0130	0.0020
2	1.012	1.0161	1.015	1.015	1.016	1.58	1.0140	1.009	1.0140	0.0020
3	1.015	1.0079	1.014	1.009	1.010	1.71	1.0072	1.010	1.0100	0.0028
4	1.025	1.0206	1.015	1.019	1.018	1.70	1.0116	1.015	1.0180	0.0030
5	1.035	1.0318	1.024	1.033	1.028	1.64	1.0320	1.004	1.0280	0.0070
6	1.034	1.0349	1.027	1.036	1.034	1.59	1.0294	1.017	1.0340	0.0046
7	1.019	1.0241	1.024	1.025	1.022	1.69	1.0304	1.014	1.0240	0.0060
8	1.003	1.0059	1.015	1.006	1.008	1.73	1.0129	1.038	1.0129	0.0069
9	1.024	1.0216	1.018	1.021	1.019	1.69	1.0213	1.022	1.0210	0.0023
10	1.035	1.0364	1.041	1.037	1.031	1.62	1.0335	1.017	1.0350	0.0060
11	1.032	1.0381	1.040	1.044	1.032	1.65	1.0491	1.018	1.0400	0.0080
12	1.030	1.0308	1.047	1.038	1.029	1.72	1.0404	1.072	1.0380	0.0080
13	1.024	1.0235	1.040	1.023	1.026	1.76	1.0263	1.019	1.0320	0.0085
14	1.023	1.0156	1.030	1.014	1.017	1.78	1.0266	1.060	1.0258	0.0092
15	1.015	1.0167	1.025	1.018	1.013	1.67	1.0262	1.040	1.0260	0.0093
16	1.025	1.0354	1.046	1.044	1.032	1.75	1.0433	1.109	1.0440	0.0120
17	1.042	1.0457	1.068	1.049	1.043	1.86	1.0567	1.109	1.0567	0.0126
18	1.037	1.0322	1.042	1.023	1.034	1.73	1.0364	1.138	1.0364	0.0131
% inside MAD Interval	61	78	78	83	83	0	78	22		
% of outliers	0	0	0	0	0	100	0	44		

Appendix C:

Equivalent output VSWR at port 3

Figure C1: Equivalent output VSWR port 3

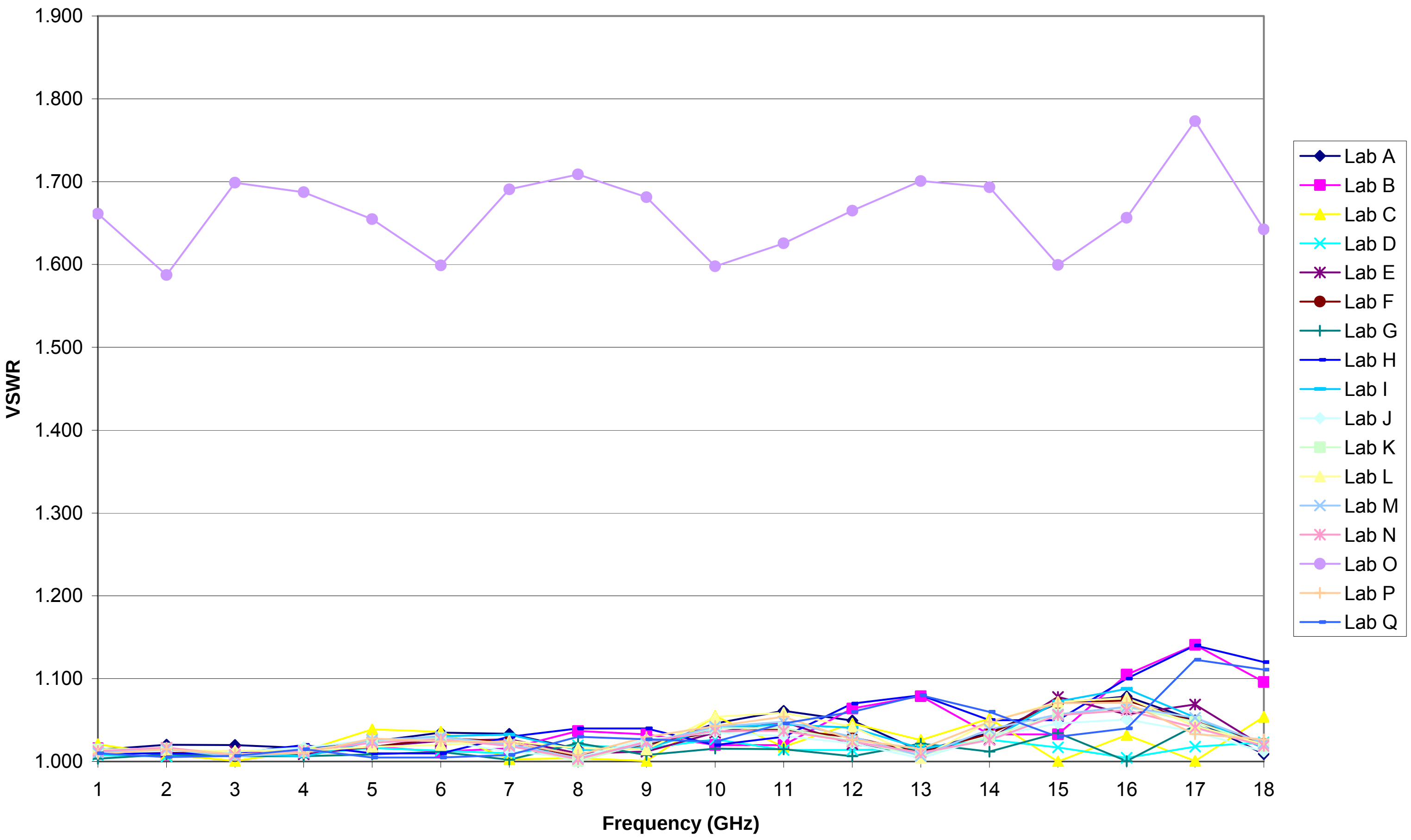
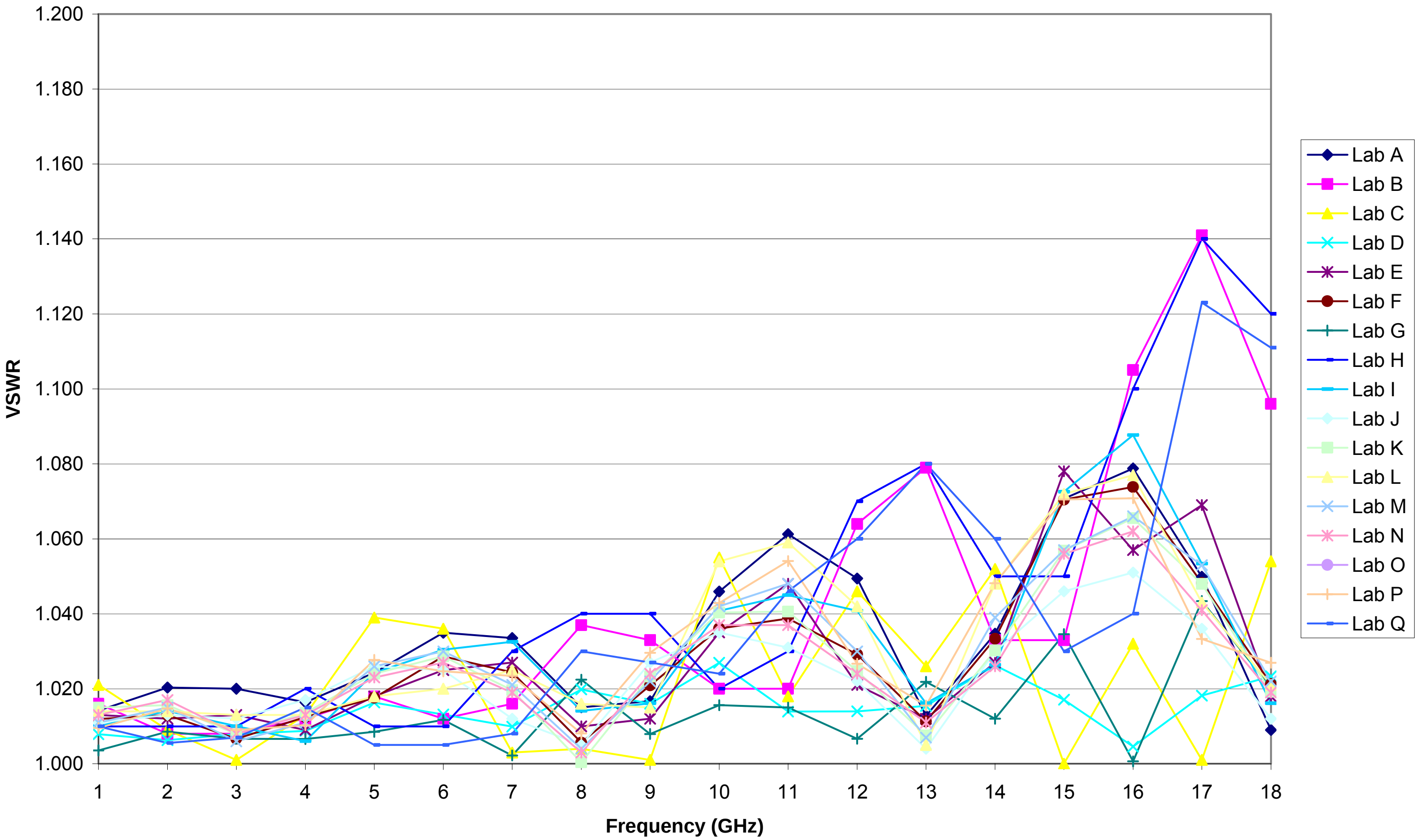


Figure C2: Equivalent output VSWR port 3



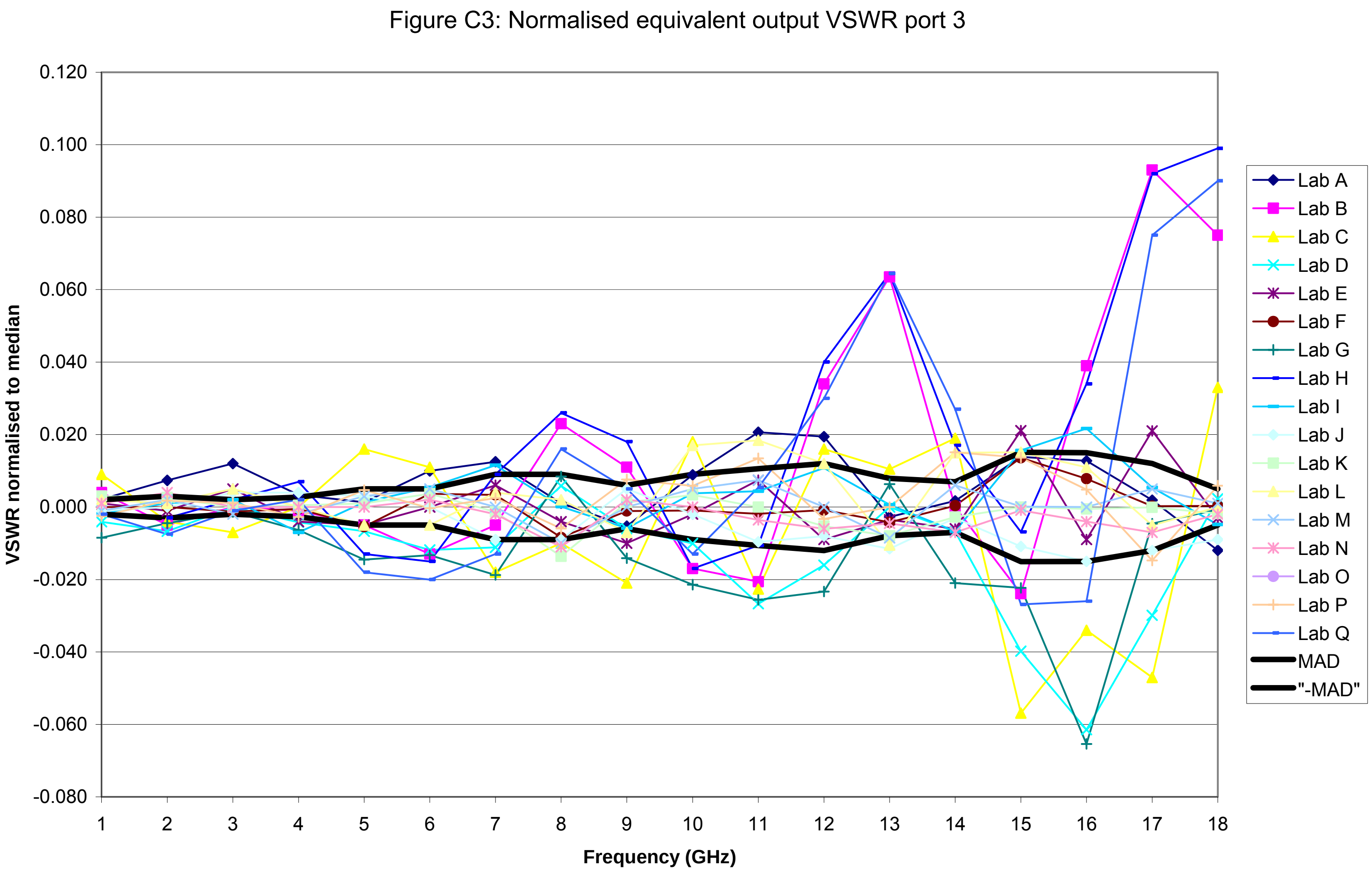


Figure C3: Normalised equivalent output VSWR port 3
VSWR normalised to median
0.120
0.100
0.080
0.060
0.040
0.020
0.000
-0.020
-0.040
-0.060
-0.080
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Frequency (GHz)
Lab A
Lab B
Lab C
Lab D
Lab E
Lab F
Lab G
Lab H
Lab I
Lab J
Lab K
Lab L
Lab M
Lab N
Lab O
Lab P
Lab Q
MAD
"-MAD"

Table C1a: Equivalent output VSWR port 3

Frequency GHz	Lab A	Lab B	Lab C	Lab D	Lab E	Lab F	Lab G	Lab H	Lab I
1	1.014	1.016	1.021	1.0079	1.013	1.012	1.0035	1.01	1.010
2	1.020	1.008	1.009	1.0063	1.012	1.013	1.0085	1.01	1.014
3	1.020	1.008	1.001	1.0079	1.013	1.007	1.0067	1.01	1.010
4	1.016	1.012	1.013	1.0088	1.009	1.012	1.0066	1.02	1.006
5	1.024	1.018	1.039	1.0163	1.018	1.018	1.0085	1.01	1.024
6	1.035	1.012	1.036	1.0132	1.025	1.029	1.0117	1.01	1.030
7	1.034	1.016	1.003	1.0099	1.027	1.024	1.0022	1.03	1.033
8	1.015	1.037	1.004	1.0198	1.010	1.006	1.0224	1.04	1.014
9	1.017	1.033	1.001	1.0160	1.012	1.021	1.0079	1.04	1.016
10	1.046	1.020	1.055	1.0270	1.035	1.036	1.0156	1.02	1.041
11	1.061	1.020	1.018	1.0139	1.048	1.039	1.0150	1.03	1.045
12	1.049	1.064	1.046	1.0140	1.021	1.029	1.0067	1.07	1.041
13	1.013	1.079	1.026	1.0155	1.012	1.011	1.0218	1.08	1.016
14	1.035	1.033	1.052	1.0262	1.027	1.033	1.0120	1.05	1.026
15	1.071	1.033	1.000	1.0171	1.078	1.070	1.0346	1.05	1.073
16	1.079	1.105	1.032	1.0045	1.057	1.074	1.0006	1.10	1.088
17	1.050	1.141	1.001	1.0182	1.069	1.048	1.0434	1.14	1.053
18	1.009	1.096	1.054	1.0233	1.018	1.021	1.0203	1.12	1.016
% inside MAD Interval	56	28	6	43	72	100	28	28	78
% of outliers	6	17	39	7	0	0	17	22	0

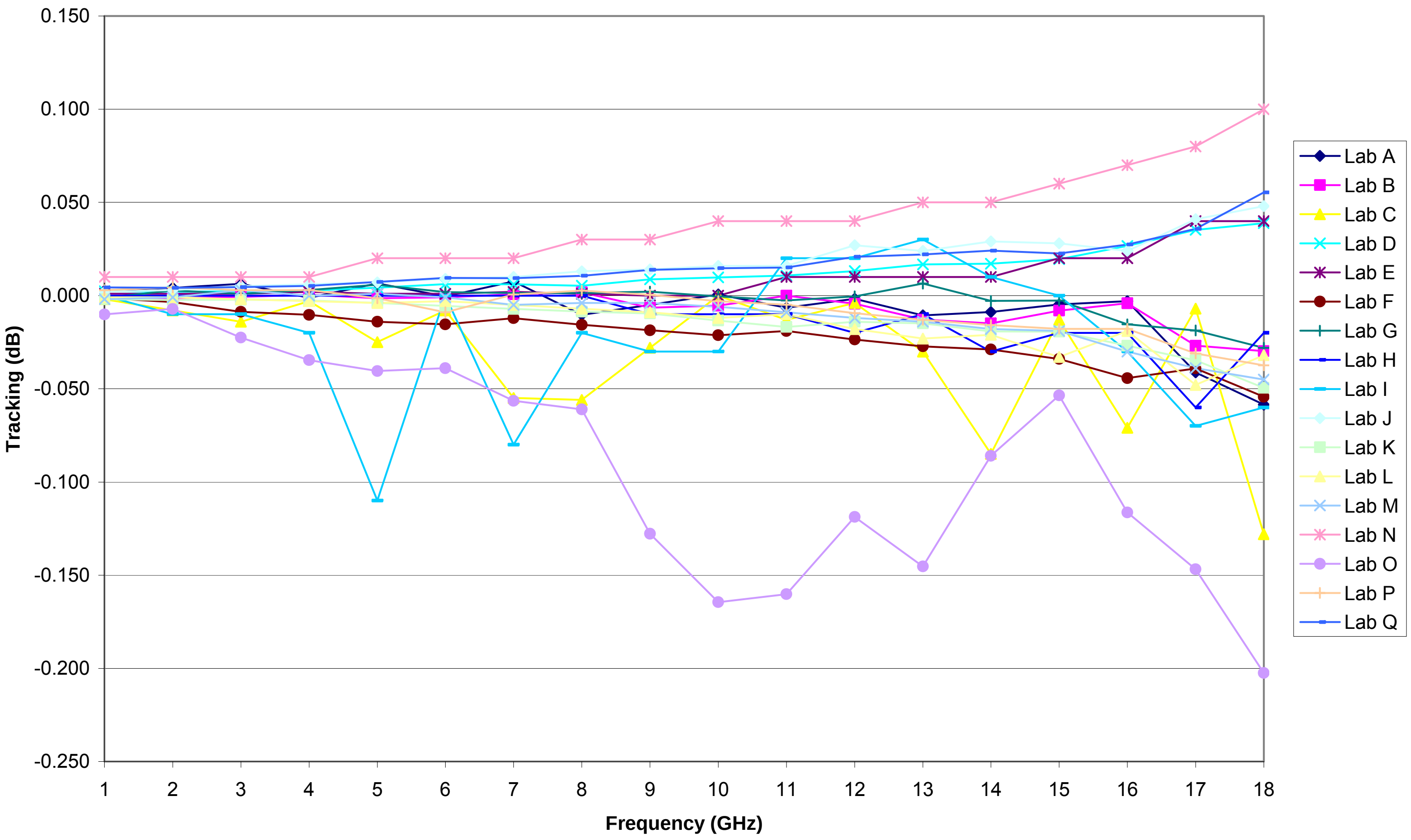
Table C1b: Equivalent output VSWR port 3

Frequency GHz	Lab J	Lab K	Lab L	Lab M	Lab N	Lab O	Lab P	Lab Q	MEDIAN	MAD
1	1.011	1.0150	1.014	1.011	1.013	1.66	1.0095	1.010	1.0120	0.0020
2	1.013	1.0156	1.014	1.015	1.017	1.59	1.0148	1.006	1.0130	0.0030
3	1.012	1.0079	1.013	1.006	1.008	1.70	1.0090	1.007	1.0080	0.0020
4	1.017	1.0135	1.013	1.011	1.013	1.69	1.0103	1.015	1.0130	0.0027
5	1.026	1.0240	1.018	1.026	1.023	1.65	1.0277	1.005	1.0230	0.0050
6	1.025	1.0287	1.020	1.030	1.027	1.60	1.0247	1.005	1.0250	0.0050
7	1.012	1.0196	1.025	1.021	1.019	1.69	1.0234	1.008	1.0210	0.0090
8	1.005	1.0004	1.016	1.004	1.003	1.71	1.0081	1.030	1.0140	0.0090
9	1.027	1.0233	1.015	1.022	1.024	1.68	1.0296	1.027	1.0220	0.0060
10	1.035	1.0404	1.054	1.042	1.037	1.60	1.0429	1.024	1.0370	0.0090
11	1.031	1.0406	1.059	1.048	1.037	1.63	1.0541	1.046	1.0406	0.0106
12	1.022	1.0247	1.042	1.030	1.024	1.66	1.0267	1.060	1.0300	0.0120
13	1.004	1.0076	1.005	1.007	1.011	1.70	1.0155	1.080	1.0155	0.0079
14	1.030	1.0302	1.048	1.039	1.026	1.69	1.0481	1.060	1.0330	0.0070
15	1.046	1.0569	1.072	1.057	1.056	1.60	1.0705	1.030	1.0569	0.0151
16	1.051	1.0655	1.077	1.066	1.062	1.66	1.0708	1.040	1.0660	0.0150
17	1.036	1.0479	1.043	1.053	1.041	1.77	1.0333	1.123	1.0480	0.0120
18	1.012	1.0192	1.021	1.022	1.019	1.64	1.0269	1.111	1.0210	0.0050
% inside MAD Interval	78	89	67	89	89	0	67	28		
% of outliers	0	0	0	0	0	100	0	33		

Appendix D:

Output tracking between ports 2 and 3

Figure D1: Output tracking between ports 2 and 3 (dB)



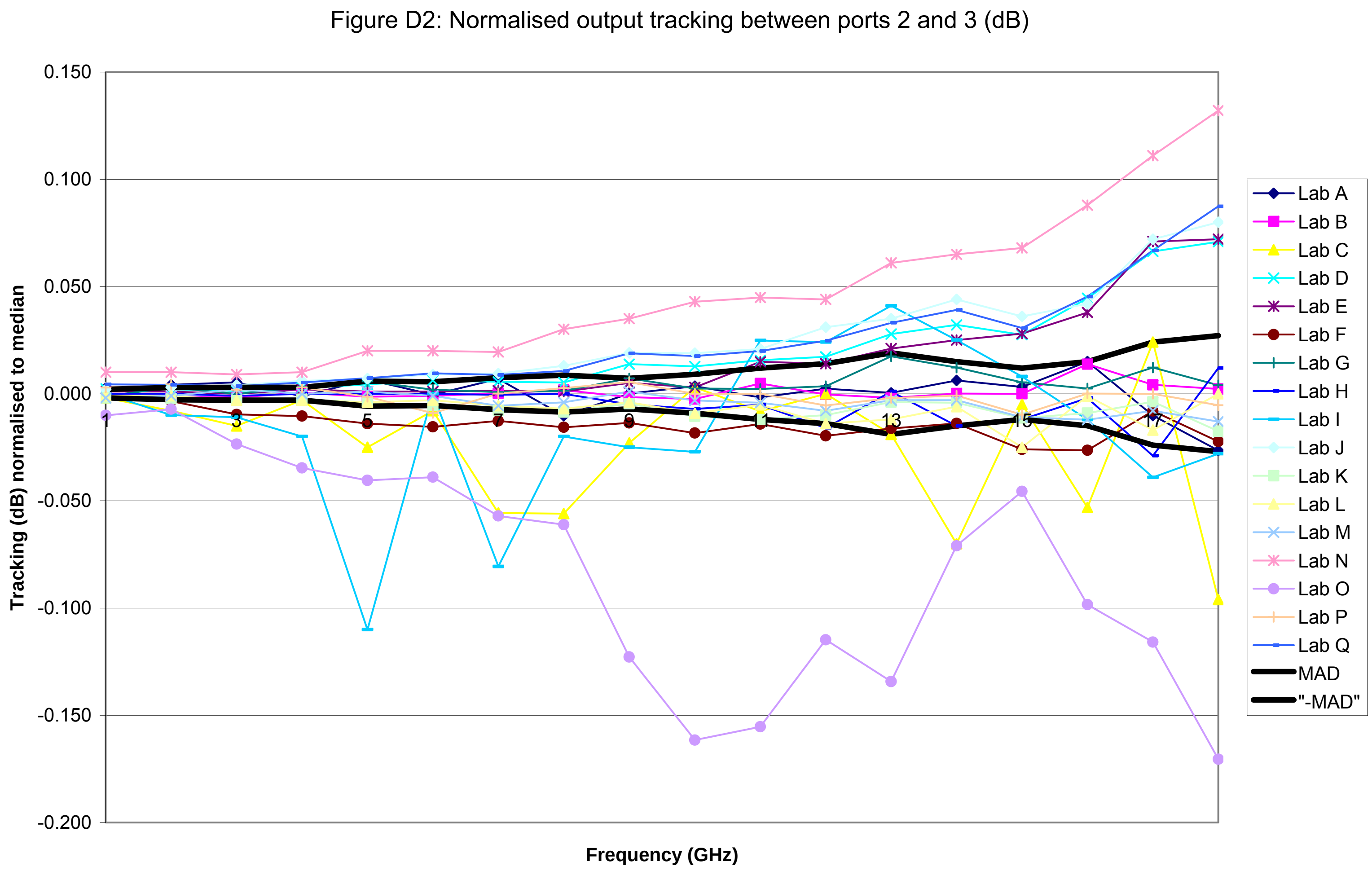


Figure D2: Normalised output tracking between ports 2 and 3 (dB)
0.150
0.100
0.050
0.000
-0.050
-0.100
-0.150
-0.200
Tracking (dB) normalised to median
1
3
5
7
9
11
13
15
17
Frequency (GHz)
Lab A
Lab B
Lab C
Lab D
Lab E
Lab F
Lab G
Lab H
Lab I
Lab J
Lab K
Lab L
Lab M
Lab N
Lab O
Lab P
Lab Q
MAD
"-MAD"

Table D1a: 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	Lab I
1	0.003	-0.002	-0.002	0.002	0.001	0.00	-0.0012	0.00	0.00
2	0.004	-0.001	-0.008	0.002	0.001	0.00	0.0028	0.00	-0.01
3	0.006	-0.001	-0.014	0.002	0.001	-0.01	0.0010	0.00	-0.01
4	-0.001	0.000	-0.003	0.003	0.002	-0.01	0.0030	0.00	-0.02
5	0.007	-0.001	-0.025	0.004	0.001	-0.01	0.0058	0.00	-0.11
6	0.000	-0.001	-0.008	0.006	0.001	-0.02	0.0018	0.00	0.00
7	0.008	0.001	-0.055	0.006	0.002	-0.01	0.0013	0.00	-0.08
8	-0.010	0.002	-0.056	0.005	0.001	-0.02	0.0014	0.00	-0.02
9	-0.005	-0.007	-0.028	0.009	0.00	-0.02	0.0021	-0.01	-0.03
10	0.001	-0.005	0.000	0.010	0.00	-0.02	-0.0004	-0.01	-0.03
11	-0.007	0.000	-0.013	0.011	0.01	-0.02	-0.0025	-0.01	0.02
12	-0.002	-0.004	-0.004	0.013	0.01	-0.02	-0.0005	-0.02	0.02
13	-0.011	-0.013	-0.030	0.017	0.01	-0.03	0.0064	-0.01	0.03
14	-0.009	-0.015	-0.085	0.017	0.01	-0.03	-0.0029	-0.03	0.01
15	-0.005	-0.008	-0.013	0.020	0.02	-0.03	-0.0027	-0.02	0.00
16	-0.003	-0.004	-0.071	0.027	0.02	-0.04	-0.0155	-0.02	-0.03
17	-0.041	-0.027	-0.007	0.035	0.04	-0.04	-0.0188	-0.06	-0.07
18	-0.059	-0.030	-0.128	0.039	0.04	-0.05	-0.0281	-0.02	-0.06
% inside MAD Interval	72	100	44	39	61	33	100	89	22
% of outliers	0	0	44	6	0	17	0	0	33

Table D1b: Output tracking between ports 2 and 3 (dB)

Frequency GHz	Lab J	Lab K	Lab L	Lab M	Lab N	Lab O	Lab P	Lab Q	MEDIAN	MAD
1	0.002	-0.0020	-0.001	-0.002	0.01	-0.0101	0.0029	0.004	0.0000	0.0020
2	0.003	-0.0023	-0.001	-0.001	0.01	-0.0072	0.0043	0.004	0.0000	0.0028
3	0.005	-0.0022	-0.002	0.003	0.01	-0.0225	0.0029	0.004	0.0010	0.0030
4	0.006	-0.0026	-0.003	0.000	0.01	-0.0346	0.0030	0.005	0.0000	0.0030
5	0.007	-0.0040	-0.004	0.001	0.02	-0.0405	-0.0014	0.007	0.0000	0.0058
6	0.009	-0.0055	-0.003	-0.001	0.02	-0.0389	-0.0090	0.010	0.0000	0.0055
7	0.010	-0.0072	-0.005	-0.005	0.02	-0.0565	0.0006	0.009	0.0006	0.0074
8	0.013	-0.0086	-0.007	-0.004	0.03	-0.0611	0.0026	0.011	0.0000	0.0086
9	0.014	-0.0096	-0.009	-0.004	0.03	-0.1277	0.0004	0.014	-0.0050	0.0071
10	0.016	-0.0134	-0.012	-0.006	0.04	-0.1645	-0.0029	0.015	-0.0029	0.0091
11	0.016	-0.0168	-0.010	-0.009	0.04	-0.1601	-0.0048	0.015	-0.0048	0.0120
12	0.027	-0.0140	-0.018	-0.012	0.04	-0.1188	-0.0095	0.021	-0.0040	0.0140
13	0.024	-0.0149	-0.023	-0.014	0.05	-0.1453	-0.0131	0.022	-0.0110	0.0190
14	0.029	-0.0193	-0.021	-0.018	0.05	-0.0859	-0.0159	0.024	-0.0150	0.0150
15	0.028	-0.0194	-0.033	-0.019	0.06	-0.0535	-0.0178	0.023	-0.0080	0.0120
16	0.024	-0.0269	-0.019	-0.030	0.07	-0.1163	-0.0179	0.027	-0.0179	0.0149
17	0.041	-0.0348	-0.048	-0.039	0.08	-0.1469	-0.0310	0.036	-0.0310	0.0240
18	0.048	-0.0495	-0.032	-0.045	0.10	-0.2025	-0.0374	0.055	-0.0320	0.0270
% inside MAD Interval	6	83	94	100	0	0	83	6		
% of outliers	0	0	0	0	89	94	0	11		

Appendix E:

Pin-depth measurements

Table E1a: Pin depth (inches)

Port No	LAB A	LAB B	LAB C	LAB D	LAB E	LAB F	LAB G	LAB H	LAB I
1	-0.0003	-	0.0000	-0.0005	-0.0005	-0.0003	-	-0.0015	-0.0010
2	-0.0008	-	-0.0006	-0.0010	-0.0012	-0.0012	-	-0.0015	-0.0010
3	0.0001	-	-0.0015	-0.0018	-0.0020	-0.0022	-	-0.0019	-0.0016
% inside MAD Interval	0	-	33	33	33	33	-	0	100
% of outliers	33	-	0	0	33	33	-	0	0

Table E1b: Pin depth (inches)

Port No	LAB J	LAB K	LAB L	LAB M	LAB N	LAB O	LAB P	LAB Q	Median	MAD
1	-0.0011	-0.0014	-0.0017	-0.0009	-0.0012	-0.0010	-0.0010	-0.0008	-0.0010	0.0004
2	-0.0012	-0.0014	-0.0014	-0.0011	-0.0012	-0.0010	-0.0012	-0.0010	-0.0012	0.0002
3	-0.0016	-0.0017	-0.0019	-0.0015	-0.0017	-0.0015	-0.0015	-0.0014	-0.0016	0.0001
% inside MAD Interval	100	100	33	100	100	100	100	67		
% of outliers	0	0	0	0	0	0	0	0		

Figure E1: port 1 pin-depth (inches)

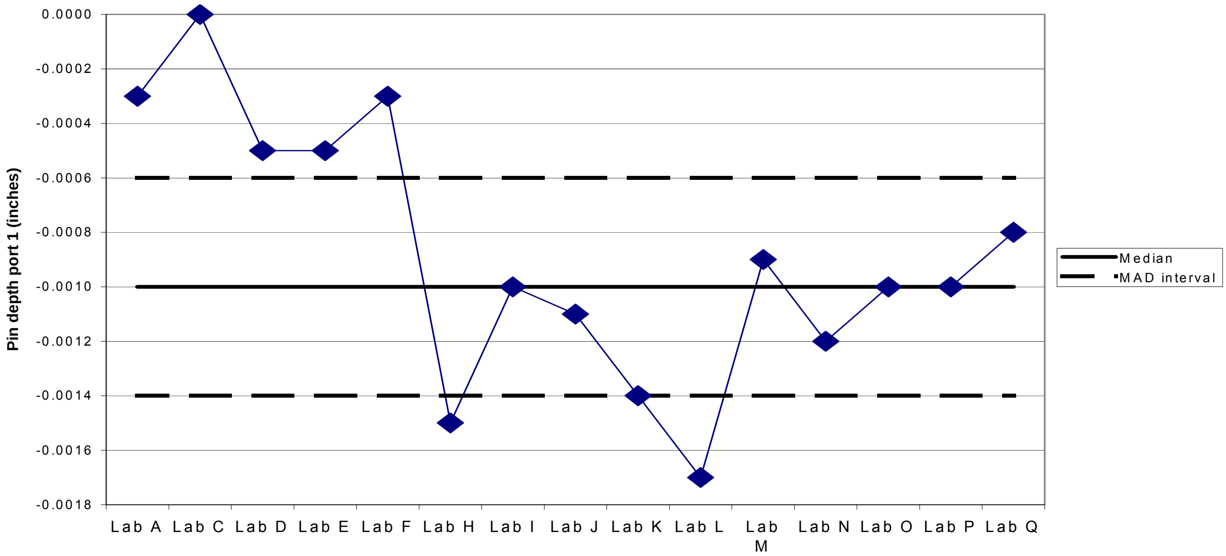


Figure E2: port 2 pin-depth (inches)

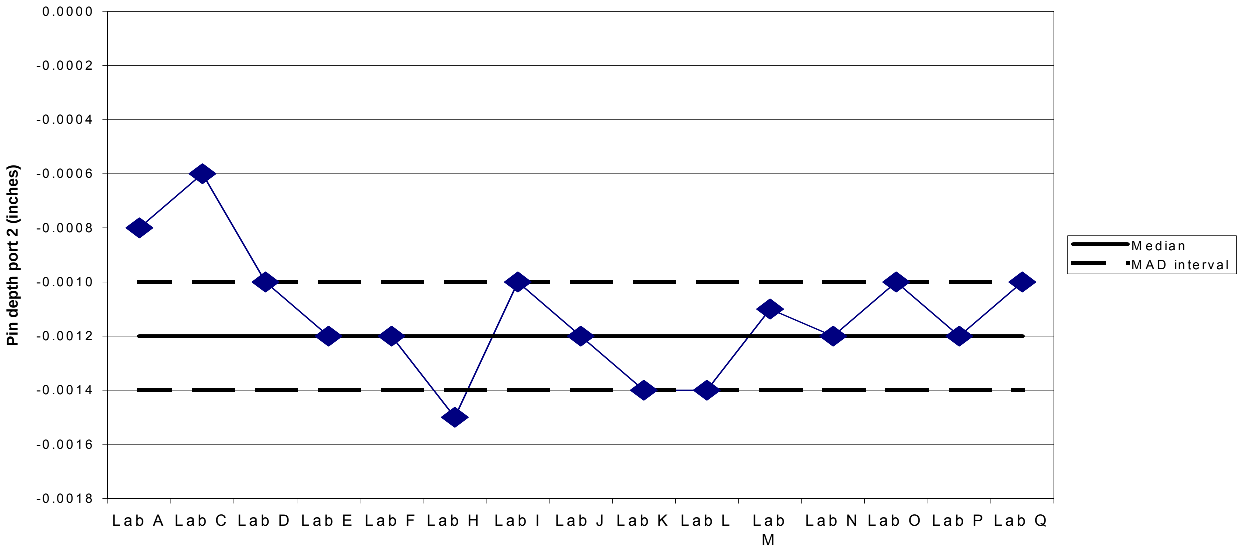


Figure E3: port 3 pin-depth (inches)