ANAMET REPORT

ANAMET measurement
comparisons 931, 942 and 951

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ANAMET MEASUREMENT COMPARISONS; 931, 942 AND 951

Foreword

This Report contains a compilation of papers reporting on a selection of ANAMET measurement comparison exercises. The papers were originally presented to the Automated RF & Microwave Measurements Society (ARMMS) at its biannual meetings and published in the Digests accompanying the meetings. Each paper presents the results obtained in one comparison exercise. The papers in this Report are as follows:

- "ANAMET comparison of type-N VSWR measurements", presented at the 20th ARMMS meeting, University of Nottingham, 28th and 29th March 1994, describes the first comparison exercise (ANAMET-931);

- "Comparison of ANA s-parameter measurements in X-band waveguide", presented at the 24th ARMMS meeting, The Beech Hill Hotel, Windemere, Cumbria, 18th and 19th April 1996, describes the third exercise (ANAMET-942);

- "ANAMET comparison of reflection coefficient measurements at RF", presented at the 25th ARMMS meeting, The Limpley Stoke Hotel, Bath, 31st October and 1st November 1996, describes the fourth exercise (ANAMET-951).

This report, taken with NPL Report DES 138, "A comparison of complex scattering coefficient measurements in 50 ohm coaxial line to 26.5 GHz" and ANAMET Report 001, "ANAMET-962 dial gauge comparison exercise", produces a complete record of the results obtained in all the ANAMET comparison exercises to date.

Future comparison exercises will be written up and issued in the ANAMET Report series, thus ensuring that the knowledge and experience gained from the comparison exercises is shared by all the ANAMET membership.

Nick Ridler
ANAMET Technical Advisor

ANAMET COMPARISON OF TYPE-N VSWR MEASUREMENTS

by

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and

participants;   D G Gentle (NPL, Teddington)
D J Hepworth (EEV Ltd, Chelmsford),
S James (Assessment Services Ltd, Titchfield),
J C Medley (NPL, Malvern),
C M Potter (Marconi Instruments Ltd, Stevenage), and
B Williams (DRA Aquila, Bromley).

Abstract

This paper reports on a measurement comparison exercise of VSWR in 50 ohm coaxial line for items with type-N connectors. There were six participants in the comparison, which was organised by ANAMET - the network analyser metrology club. NPL Malvern acted as the pilot laboratory, and included repeatability and drift assessments as part of their measurements. These results are given along with the results achieved by the participants using their own measurement systems.

1 INTRODUCTION

In 1993, NPL launched ANAMET - a metrology club and interest group for people and organisations interested in RF and microwave network measurements. Since its launch, ANAMET has issued regular newsletters disseminating up-to-date information about network measurements to its members. ANAMET has also started a series of Technical Notes giving detailed information about specific aspects of network measurements. One of the core activities of ANAMET is the organisation of measurement comparison exercises. The purpose of these exercises is to increase the confidence in the measurement instrumentation and the participants' ability to perform measurements. The type of comparison exercise is decided by the club membership, and participation in the exercise is only available to club members.

The first comparison exercise ran from July 1993 to December 1993. Six member organisations participated in the exercise which was of Voltage Standing Wave Ratio (VSWR) measurements in 50 ohm coaxial line for items with type-N connectors. The frequency range of 1 GHz to 18 GHz in 1 GHz steps provided 18 different frequency values for the comparison. All six participants supplied measurement data at all these frequencies.

Each participant received a detailed, confidential, report on the results of the exercise, highlighting their own results against a statistical analysis of the other participants' results. This paper presents

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[1]   Glyn Jones is a private consultant working under contract to NPL.

[2]   Nick Ridler is employed by Assessment Services Limited and works under contract to NPL.

overall observations of the exercise, thus ensuring the commercial confidentiality of each participant's results.

2 THE TEST ITEMS

Three pairs of terminations with nominal VSWRs of 1.05, 1.2 and 1.5 were chosen as the test items for the comparison. Each pair of items had one fitted with a male and one fitted with a female type-N connector. All the terminations were of the same manufacturer and type, *i.e.*, expected to be of similar electrical and mechanical quality. Figure 1 shows a photograph of the items, and Figure 2 shows the case used to transport the items between the participating organisations during the exercise.

3 THE SYSTEMS

3.1 Measuring instruments

All participants used automatic analysers measuring reflection for the comparison. Assessment Services Ltd used an HP 8510A ANA fitted with an 8514A test set. DRA Aquila and NPL Malvern used similar types of ANA - HP 8510Cs fitted with 8515A test sets. EEV Ltd used a Wiltron 360A ANA fitted with a 3621A test set. Marconi Instruments Ltd used a Marconi Instruments 6210 Reflection Analyzer fitted to a 6203 Microwave Test Set. NPL Teddington used an HP 8510B ANA fitted with an 8514A test set.

3.2 Calibration

All participants used the SOL (short-open-load) technique to calibrate the analysers. EEV Ltd used a fixed load at all 18 frequencies. The other participants used a fixed load for the 1 GHz measurement and a sliding load for the 2 GHz to 18 GHz measurements. Assessment Services Ltd used an HP 85054A calibration kit to realise the SOL standards. DRA Aquila, NPL Malvern and NPL Teddington used similar types of calibration kit - the HP 85054B. EEV Ltd used a Wiltron 3653 calibration kit. The Marconi Instruments Reflection Analyzer uses the six-port principle [1], but a novel internal calibration technique [2] allows a conventional calibration kit to be used, with a Rosenberger 05 CK 100-150 kit.

4 THE RESULTS

4.1 Repeatability results

Six successive measurements were made by NPL Malvern for the repeatability analysis. Table 1 gives the repeatability standard deviation, s_r, for each item at selected frequencies, calculated using the following formula;

$$s_r = \sqrt{\frac{1}{m-1} \sum_{i=1}^{m} (\alpha_i - \bar{\alpha})^2}$$

where α_i are the individual m observations ($m = 6$) and $\bar{\alpha}$ is the arithmetic mean of these observations. All standard deviations are in terms of VSWR.

Freq. (GHz)	Male terminations			Female terminations		
	1.05	1.2	1.5	1.05	1.2	1.5
3	0.0002	0.0003	0.0002	0.0001	0.0004	0.0004
7	0.0004	0.0004	0.0004	0.0001	0.0004	0.0005
10	0.0004	0.0004	0.0005	0.0001	0.0007	0.0007
14	0.0005	0.0004	0.0007	0.0001	0.0011	0.0008
18	0.0005	0.0008	0.0016	0.0009	0.0017	0.0023

Table 1:   A selection of the repeatability standard deviations for the six test artefacts.

4.2 Reproducibility results

Figures 3 to 8 present graphs of the VSWR measurements made by the participants, as a function of frequency, for the six test artefacts. Table 2 gives the corresponding between-participant standard deviation, s_B, for each item at each frequency, calculated using the following formula;

$$s_B = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (\beta_j - \overline{\beta})^2}$$

where β_j are the individual n participant observations ($n = 6$) and $\overline{\beta}$ is the arithmetic mean of the observations. As with Table 1, all standard deviations are in terms of VSWR.

The spread of results displayed in Figures 3, 5 and 7, indicate a problem with one participant's measurements of the artefacts fitted with male type-N connectors. Further investigation by the participant revealed a problem with the adaptor used to provide the female type-N test port for the measurement system. With this in mind, it seems reasonable therefore to classify this data as outlying, and re-compute the between-participant standard deviation using only the remaining five participant's data. A selection of these new values of s_B are given in Table 3 for the three male terminations after outlier rejection has been applied.

4.3 Drift results

To assess any one-way shift in the characteristics of any of the items during the exercise, a final measurement was performed by NPL Malvern and compared with the initial one, *i.e.*, the measurement sequence for the comparison exercise took the form;

(i)   measurements by NPL Malvern,
(ii)   measurements by the other participants,
(iii)   repeat measurements by NPL Malvern.

A detailed visual inspection of the connectors mating surfaces and general condition was performed between measurements made by each participant. These inspections revealed nothing that was likely to impair the performance of the items.

Freq. (GHz)	Male terminations			Female terminations		
	1.05	1.2	1.5	1.05	1.2	1.5
1	0.0022	0.0024	0.0035	0.0005	0.0013	0.0012
2	0.0023	0.0024	0.0046	0.0010	0.0023	0.0024
3	0.0042	0.0057	0.0092	0.0038	0.0045	0.0068
4	0.0040	0.0043	0.0061	0.0031	0.0045	0.0049
5	0.0048	0.0053	0.0073	0.0035	0.0058	0.0074
6	0.0049	0.0039	0.0062	0.0042	0.0053	0.0041
7	0.0084	0.0188	0.0262	0.0053	0.0046	0.0075
8	0.0166	0.0210	0.0291	0.0072	0.0084	0.0107
9	0.0104	0.0077	0.0109	0.0086	0.0023	0.0096
10	0.0132	0.0113	0.0138	0.0048	0.0074	0.0117
11	0.0050	0.0061	0.0075	0.0059	0.0096	0.0096
12	0.0083	0.0089	0.0106	0.0033	0.0063	0.0064
13	0.0053	0.0209	0.0272	0.0053	0.0073	0.0114
14	0.0173	0.0403	0.0499	0.0027	0.0072	0.0196
15	0.0177	0.0166	0.0272	0.0079	0.0134	0.0237
16	0.0109	0.0054	0.0092	0.0133	0.0047	0.0151
17	0.0050	0.0120	0.0184	0.0036	0.0100	0.0196
18	0.0106	0.0114	0.0211	0.0064	0.0154	0.0199

Table 2: Between-participant standard deviation for the six test artefacts.

Freq. (GHz)	Male terminations		
	1.05	1.2	1.5
3	0.0017	0.0016	0.0034
7	0.0034	0.0049	0.0097
10	0.0052	0.0052	0.0073
14	0.0089	0.0073	0.0127
18	0.0057	0.0067	0.0207

Table 3: A selection of the estimated between-participant standard deviation for the three male artefacts after removing outlying data.

Table 4 gives a selection of the differences, in VSWR, between the two NPL Malvern measurements, for each item at each frequency.

Freq. (GHz)	Male terminations			Female terminations		
	1.05	1.2	1.5	1.05	1.2	1.5
3	+0.0006	+0.0003	+0.0022	-0.0013	-0.0022	-0.0021
7	-0.0028	+0.0015	+0.0016	+0.0002	+0.0009	-0.0001
10	-0.0037	+0.0011	-0.0093	-0.0026	+0.0002	+0.0004
14	-0.0014	+0.0016	-0.0037	+0.0003	+0.0047	+0.0059
18	-0.0039	-0.0048	-0.0110	+0.0033	+0.0023	-0.0003

Table 4:   *A selection of differences between the two NPL Malvern measurements, in terms of VSWR, for the six test artefacts.*

5 OBSERVATIONS AND DISCUSSION

5.1 General

In general, the lack of repeatability and reproducibility increases as the nominal value of the VSWR increases. This can be explained by examining the propagation of errors (or more generally, uncertainties) through the transformation relating VSWR to voltage reflection coefficient, Γ, as in Appendix A, which gives;

$$ s = \frac{2}{(1 - |\Gamma|)^2} \gamma $$

where s and γ are the VSWR and voltage reflection coefficient standard uncertainties, respectively.

This expression indicates that $s = 2\gamma$ when $|\Gamma| = 0$, and increases with increasing $|\Gamma|$, becoming infinite at $|\Gamma| = 1$.

5.2 Repeatability

The largest repeatability standard deviations (see sub-section 4.1) for the NPL Malvern measurements, and the repeatabilities at the 95% confidence probability derived from them (see Appendix B.1), are summarised in Table 5.

5.3 Reproducibility

The largest between-participant standard deviations for the female items (six participants) and the male items (five participants), and the reproducibilities at the 95% confidence probability derived from them (see Appendix B.2), are summarised in Table 6.

Nominal VSWR	Connector sex	s_r	r
1.05	male	0.0007	0.0025
1.05	female	0.0010	0.0036
1.2	male	0.0010	0.0036
1.2	female	0.0018	0.0065
1.5	male	0.0017	0.0062
1.5	female	0.0024	0.0087

Table 5: Summary values for the repeatability standard deviation, s_r, and the repeatability at a 95% confidence probability, r, for the items.

Nominal VSWR	Connector sex	s_B	R
1.05	male	0.009	0.035
1.05	female	0.014	0.051
1.2	male	0.013	0.051
1.2	female	0.016	0.058
1.5	male	0.021	0.083
1.5	female	0.024	0.088

Table 6: Summary values for the between-participant standard deviation, s_B, and the reproducibility at a 95% confidence probability, R, for the items.

5.4 Drift

The differences between the NPL Malvern measurements made at the start and the finish of the exercise given in Table 4 do not indicate the presence of significant drift in the characteristics of the artefacts. However it is always more difficult to justify the absence of an effect especially without a full analysis of the measurement uncertainties.

5.5 Summary

The drift assessment revealed no appreciable change in the characteristics of the items, indicating that results obtained by the participants during the exercise could be compared meaningfully using statistical techniques.

The values for repeatability and reproducibility are summarised in Table 7. These values are arithmetic means of the two values given earlier for each VSWR.

VSWR	Repeatability	Reproducibility
1.05	0.003	0.043
1.2	0.005	0.055
1.5	0.007	0.086

Table 7:   *Summary values, at a 95% confidence probability, for repeatability and reproducibility for the comparison.*

Table 7 indicates that the reproducibility, for each nominal value, is poorer than the repeatability by approximately an order of magnitude. Both repeatability and reproducibility increase by approximately a factor of two as the nominal value of VSWR varies between 1.05 and 1.5. This is consistent with the predictions given in sub-section 5.1.

6 CONCLUSIONS

The first ANAMET measurement comparison exercise has been a success for a number of reasons. Firstly, the reproducibility (being an order of magnitude larger than the repeatability) would suggest that care must be taken when estimating measurement uncertainties for this type of measurement since any one measurement system is only capable of assessing repeatability, which might give an optimistic impression of a system's uncertainty. This indicates that systematic errors probably dominate the majority of the measurement systems participating in the exercise.

Secondly, the exercise has detected a faulty adaptor belonging to one participant which produced hitherto undetected measurement errors. Any problem with the adaptor was not apparent from a visual inspection. The adaptor has since been returned to the manufacturer for repair. The participant will be given the opportunity to re-measure the comparison items, when the adaptor has been repaired, to verify subsequent system performance.

Thirdly, the exercise provides clear, documented, evidence of the capability of some key UK measurement laboratories to perform microwave network measurements in a connector type used extensively by UK industry. The evidence has been encouraging.

Finally, it has shown ANAMET to be well-equipped to deal with the organisation of such comparison exercises, which it will continue to do so in the future. The next measurement exercise is for complex scattering coefficients to 26.5 GHz in GPC-3.5 and is already underway.

7 ACKNOWLEDGEMENT

8 REFERENCES

[1]   C Potter, "The principles behind the six-port reflection analyzer", 19th ARMMS Conference Digest, Paper No 3, University of Leeds, September 1993.

[2]   G Hjipieris, "Design of the six-port reflection analyzer", 19th ARMMS Conference Digest, Paper No 4, University of Leeds, September 1993.

APPENDIX A: VRC TO VSWR TRANSFORMATION - PROPAGATION OF ERRORS

The bilinear transformation relating voltage reflection coefficient (VRC) to VSWR is given by;

$$S = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

where S denotes the VSWR and $|\Gamma|$ the magnitude of the VRC.

The effect of uncertainties in $|\Gamma|$ on S can be examined using the law of propagation of uncertainty [A1], which, for this situation gives;

$$s = \frac{dS}{d|\Gamma|}\gamma$$

where s is the standard uncertainty in VSWR and γ the standard uncertainty in $|\Gamma|$. (Higher order terms in the Taylor series expansion used to obtain this expression have been neglected and terms involving correlation coefficients vanish.)

Now;

$$\frac{dS}{d|\Gamma|} = \frac{2}{(1 - |\Gamma|)^2}$$

therefore;

$$s = \frac{2}{(1 - |\Gamma|)^2}\gamma$$

This expression indicates that $s = 2\gamma$ when $|\Gamma| = 0$, and increases with increasing $|\Gamma|$, becoming infinite at $|\Gamma| = 1$.

Reference

[A1]   ISO, "Guide to the expression of uncertainty in measurement", International Organization for Standardization, ISBN 92-67-10188-9, First Edition, 1993, Printed in Switzerland.

APPENDIX B: REPEATABILITY AND REPRODUCIBILITY

B.1 Repeatability

It is useful to summarise values of repeatability at a specified confidence probability. In this exercise, the repeatability, r, at a given confidence probability, p, has been calculated using the following formula [B1];

$$r = t_p(v) \sqrt{2} \, s_r$$

where $t_p(v)$ is the t-factor from the t-distribution for v degrees of freedom corresponding to a given probability p.

For this exercise, $v = m - 1$, so the factor $t_{0.95}(v)\sqrt{2} = 3.63$, for a 95% confidence probability. This figure is used with the standard deviation statistics to give repeatabilities at a 95% confidence probability. These values are given in Table 5.

B.2 Reproducibility

As with the repeatability values, reproducibility is often quoted at a specific confidence probability (usually 95%). For the purpose of this exercise the reproducibility, R, at a given confidence probability has been calculated using the following formula [B1];

$$R = t_p(v) \sqrt{2} \, s_R$$

where s_R is the estimated reproducibility standard deviation given by;

$$s_R = \sqrt{s_B^2 + s_r^2}$$

Note:- Strictly speaking, the repeatability standard deviation, s_r, should be evaluated by each participant and this value used with each respective value of s_B. However, variations in s_r are expected to be of second-order compared with s_B.

For this exercise, $v = n - 1$, so the factor $t_{0.95}(v)\sqrt{2}$ has a value of 3.63 for the female terminations (since n = 6), and 3.93 for the male items (since n = 5). These figure are used with the standard deviation statistics to give reproducibilities at a 95% confidence probability. These values are given in Table 6.

Reference

[B1]   ISO 5725:1986, "Precision of test methods - Determination of repeatability and reproducibility for a standard test method by inter-laboratory tests", International Organization for Standardization, Geneva, Switzerland.
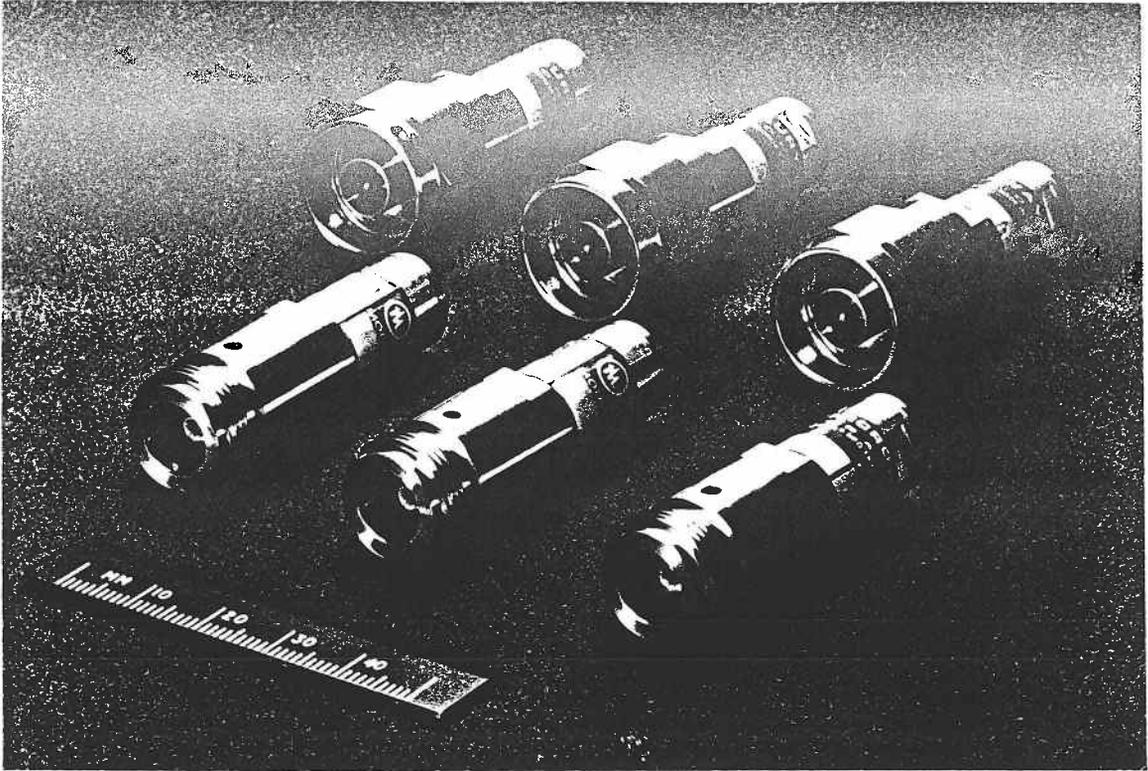
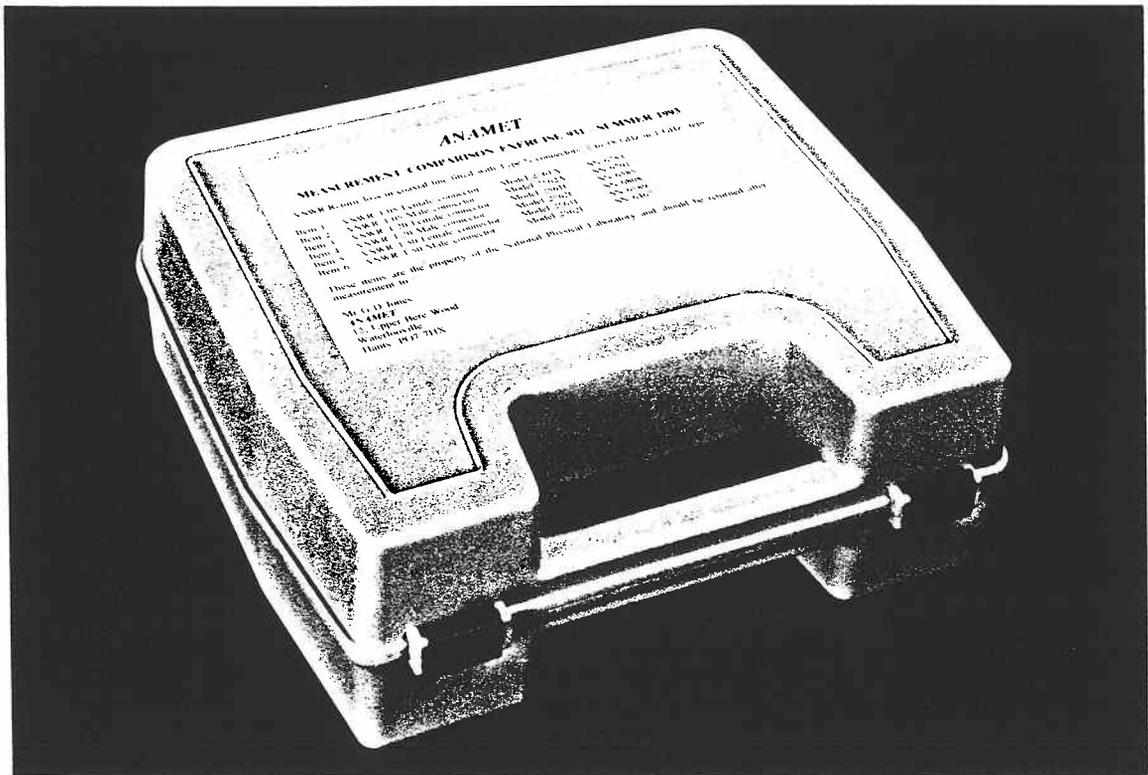*Figure 1:* *photograph showing the terminations used for the comparison exercise.*

Figure 2: *photograph showing the carrying case used to transport the items between the organisations during the exercise.*
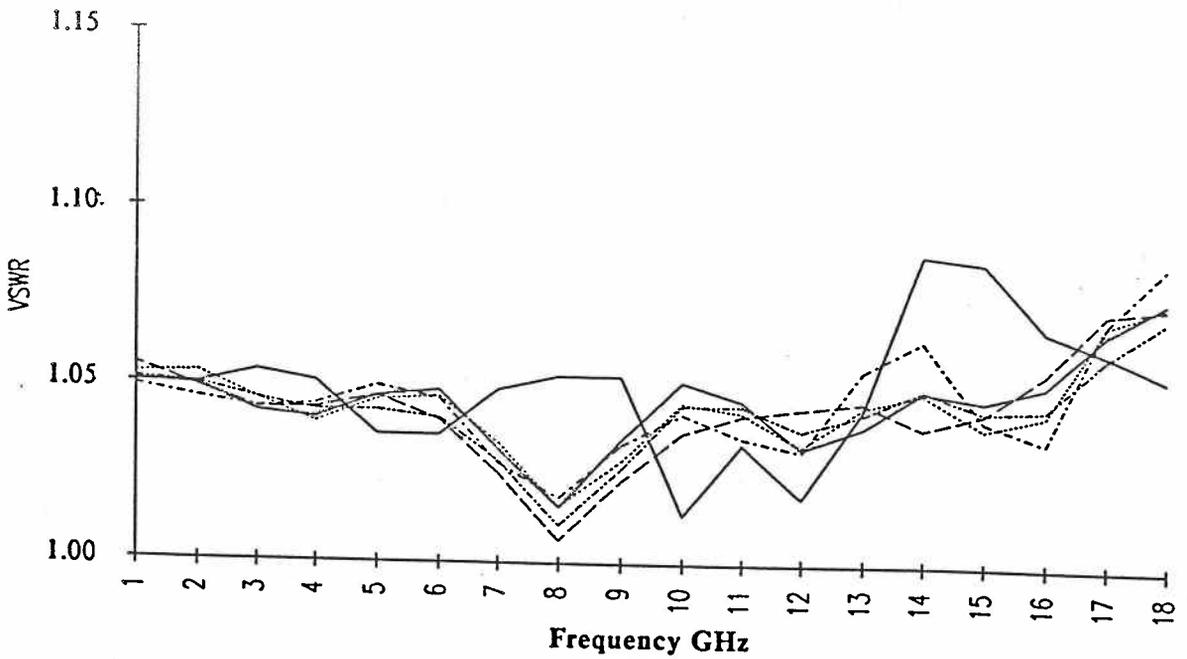
Figure 3: graph showing the participant's VSWR measurements, as a function of frequency, for the nominal 1.05 VSWR item fitted with a male connector.
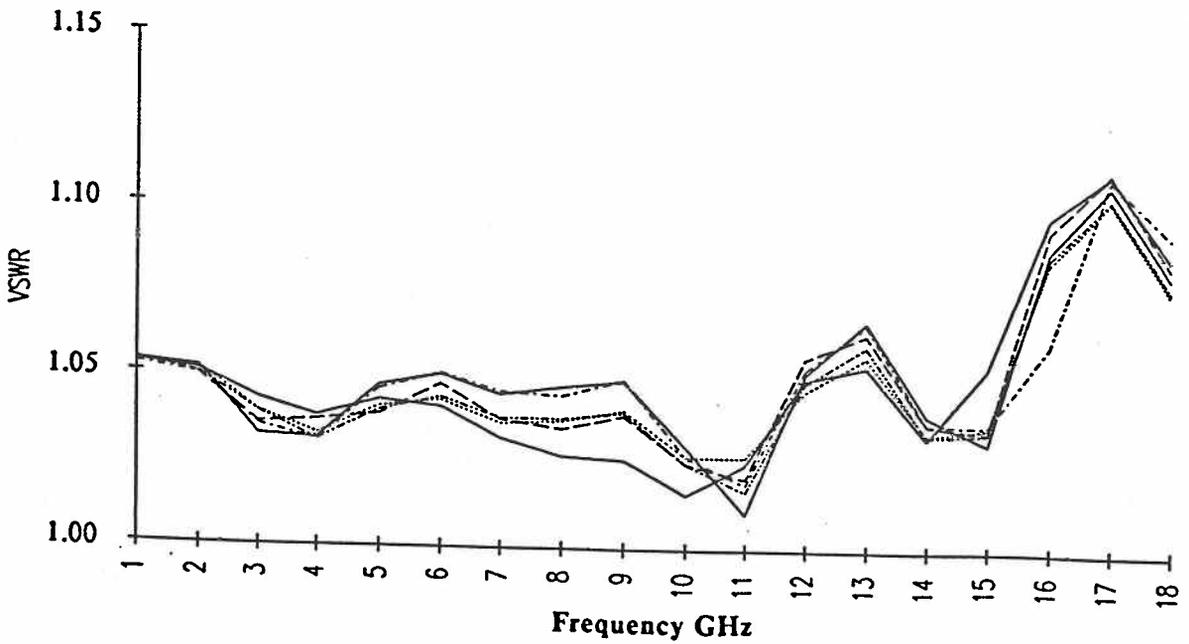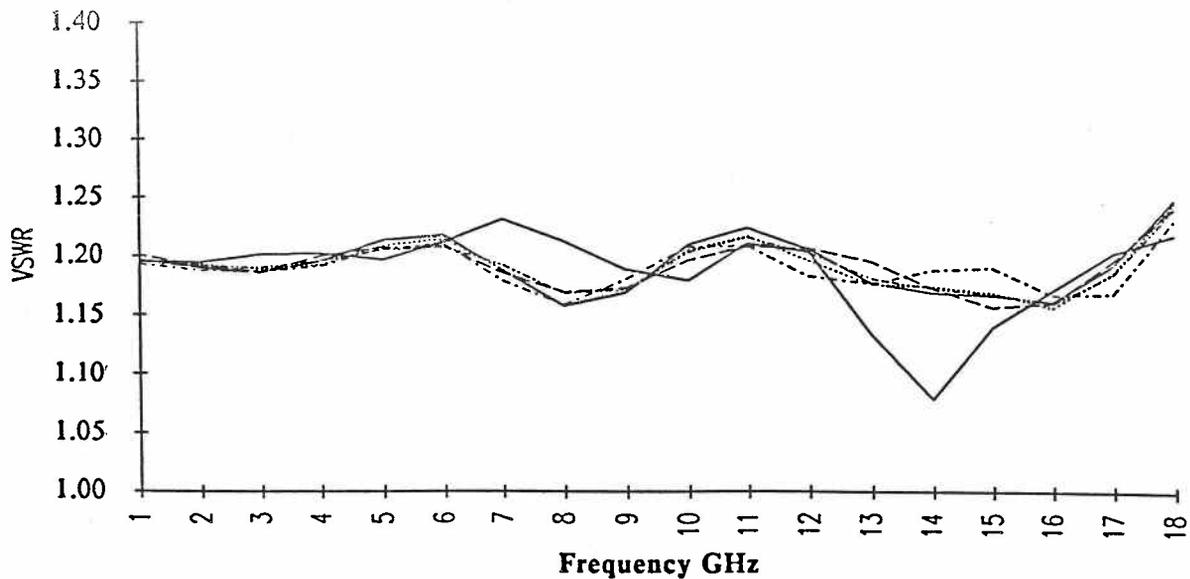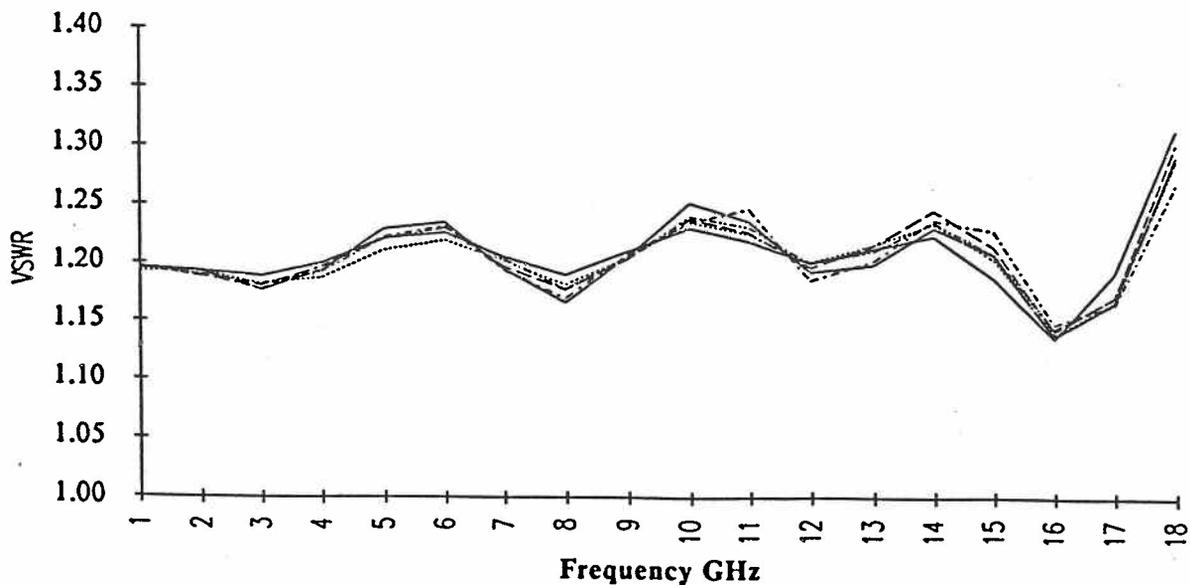

Figure 4: graph showing the participant's VSWR measurements, as a function of frequency, for the nominal 1.05 VSWR item fitted with a female connector.

Figure 5:   graph showing the participant's VSWR measurements, as a function of frequency, for the nominal 1.2 VSWR item fitted with a male connector.

Figure 6:   graph showing the participant's VSWR measurements, as a function of frequency, for the nominal 1.2 VSWR item fitted with a female connector.
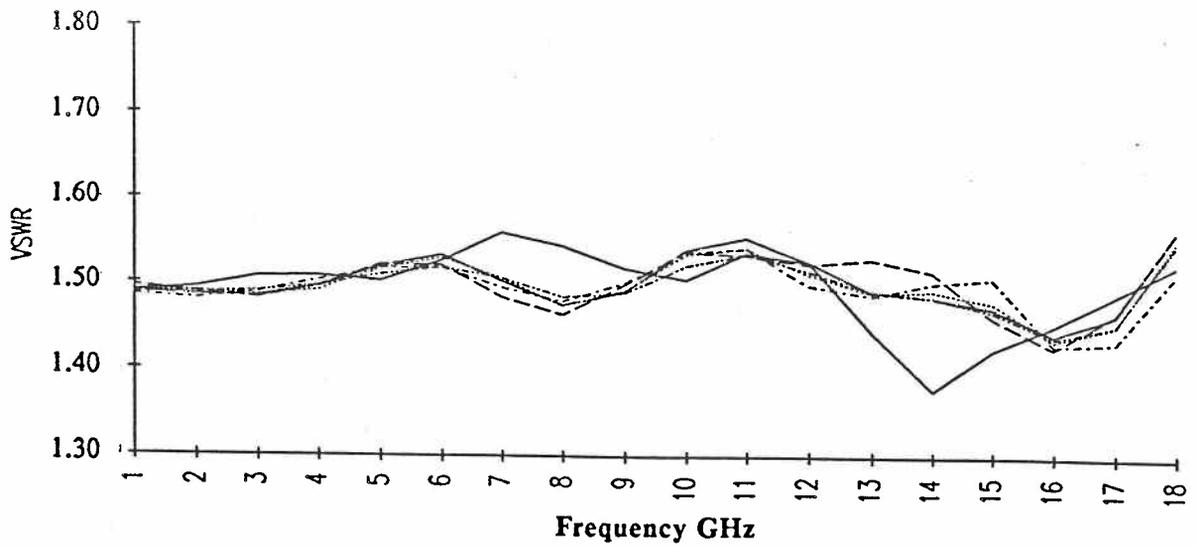
Figure 7:   graph showing the participant's VSWR measurements, as a function of frequency, for the nominal 1.5 VSWR item fitted with a male connector.
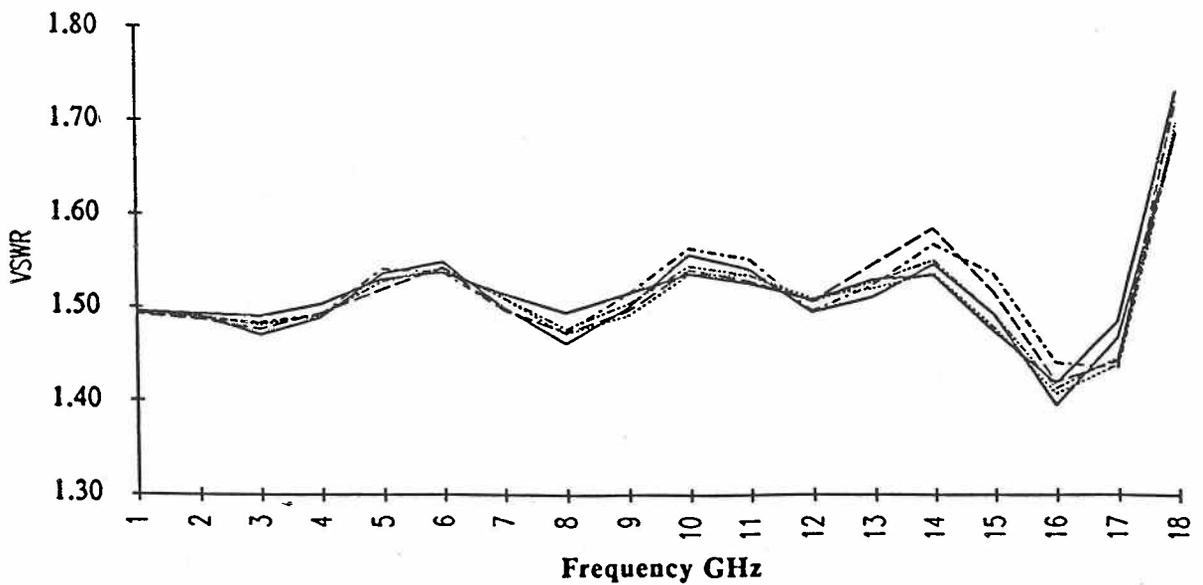

Figure 8:   graph showing the participant's VSWR measurements, as a function of frequency, for the nominal 1.5 VSWR item fitted with a female connector.

Comparison of ANA *s*-parameter measurements in X-band waveguide

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ABSTRACT

This paper reports on an exercise to compare measurements of reflection and transmission parameters (*s*-parameters) in rectangular waveguide at microwave frequencies. The results obtained by the eight laboratories participating in the exercise are summarised in terms of the between-laboratory reproducibility. These values are compared with a within-laboratory repeatability assessment made by the pilot laboratory for the exercise. Multivariate robust statistical techniques have been used to obtain the summary statistics for the complex data.

1 INTRODUCTION

At the present time, the preferred measuring instrument for characterising microwave circuit parameters is the automatic network analyser (ANA). This multi-function measuring instrument finds application in almost every microwave measurement situation. The operating principles of these instruments are highly complex and an in-depth knowledge of these principles often eludes the practitioner. This brings into question an operator's reliance on these instruments to produce measurements of the required calibre.

In 1993, NPL set up ANAMET, the ANA METrology club for people and organisations interested in RF and microwave network measurements. One of the principle activities of the club is to organise measurement comparisons, to increase participants' confidence in making ANA measurements. The details of the comparisons are decided by the club membership and reflect areas in which they have most interest.

This paper reports on a comparison of reflection and transmission measurements (*s*-parameters) in X-band waveguide (R100, WG16, WR090), organised by ANAMET. This waveguide size was chosen due to its popularity in microwave engineering applications. X-band waveguide has approximate internal dimensions 23 mm × 10 mm and propagates frequencies in the range 8.2 GHz to 12.4 GHz.

2 COMPARISON DETAILS

Three items were chosen for the comparison; a matched load, a mismatched load, and a 20 dB 3-port directional coupler. The participants were invited to supply measurements of the following five complex parameters:

(i)   reflection coefficient of the matched load, nominally 0.0;

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[1]   Mr Ridler is employed by Assessment Services Ltd and works under contract to NPL.

(ii)   reflection coefficient of the mismatched load, nominally 0.2;
(iii)   transmission coefficient of the through path of the coupler, nominally 0 dB;
(iv)   transmission coefficient of the coupled path of the coupler, nominally 20 dB;
(v)   transmission coefficient of the isolation path of the coupler, nominally 70 dB.

For each of the transmission measurements the remaining port was terminated with the matched load.

Eight organisations participated in the comparison exercise and supplied results for the above five configurations at 0.5 GHz intervals starting from 8.5 GHz and going up to 12.0 GHz. Results were also supplied at the waveguide band-edge frequencies, 8.2 GHz and 12.4 GHz, making a total of 10 frequencies for the comparison.

3 STATISTICAL ANALYSIS TECHNIQUES

Results were analysed, in accordance with international recommendations [1], in terms of the between-laboratory reproducibility of values and compared with a within-laboratory repeatability assessment made by the pilot laboratory, NPL Malvern. The reproducibility values indicate the level of variation found in the results supplied by the participating laboratories whereas the repeatability values indicate a typical variation made by one participant performing repeat measurements under essentially the same conditions. Therefore, the repeatability values provide a useful base-line to assess the variability in the participants' measurements.

3.1 Robust estimators

It is conventional, when summarising data in a measurement comparison exercise, to give an average value and a measure of the dispersion of the data about that average. Usually the arithmetic mean and the standard deviation are used, however they provide a less useful summary for data sets containing unusual, or outlying, values — as was the case with this exercise. Under these circumstances, estimators exhibiting resilience (or, robustness) to outliers are preferable. For example, the median provides a robust average and the median absolute deviation (or its close relative, the inter-quartile range) provides a robust dispersion indicator. (These estimators were discussed at the last ARMMS meeting [2] and were also used to summarise data obtained in an earlier comparison exercise [3].)

The median, x_{med}, of a set of results, x_i, supplied by n participants, is simply the middle value of the results after they have been arranged in ascending order of size, i.e., $x_1 \leq x_2 ... \leq x_n$. If the number of results is an even number, a unique middle value does not exist, so the median is taken as the midpoint of the middle pair of values.

The median absolute deviation (MAD) is defined as follows;

$$MAD = median\left\{ |x_i - x_{med}| \; ; \; i = 1,..,n \right\}$$

A useful equivalence relationship between MAD and the more common standard deviation, $s(x)$, for large samples drawn from a normal distribution, is:

$$s(x) \approx 1.483 \times MAD$$

This could be used to compare intervals produced by each statistic.

3.2 Bivariate considerations

Since all measured values in the exercise were complex (vector) quantities, further consideration was given to the statistical analysis of this type of data, i.e., bivariate data. In particular, a bivariate version of the median — the spatial median — was used to establish an average value for each data set.

The spatial median is defined as the point in the complex plane which minimises the sum of the absolute differences (distances) between the individual participants' values and its value. In other words, for participant values $\{ x_i ; i = 1, .., n \}$, the expression :

$$\sum_{i=1}^{n} |x_i - \mu|$$

is a minimum (over all possible choices of point μ) when μ is the spatial median.

The spatial median provides an average value which is relatively unaffected by the presence of outliers in complex data. (This is analogous with the resilience exhibited by the conventional median for univariate data.)

3.3 MAD calculations

When assessing the variability in the complex reflection and transmission measurements, the participants are mainly concerned with the variation in the magnitude and phase components of the measurement parameters. The MAD calculation has therefore been applied separately to the magnitude and phase components of each data set (with respect to the magnitude or phase of the spatial median, respectively). *I.e.*

$$\text{MAD (Magnitude)} = median \left\{ \left| |X_i| - |\mu| \right| ; i = 1,..,n \right\}$$

$$\text{MAD (Phase)} = median \left\{ \left| \phi_{X_i} - \phi_{\mu} \right| ; i = 1,..,n \right\}$$

where ϕ_{X_i} and ϕ_{μ} are the phase values for the ith result and the spatial median, respectively. (Arithmetic performed on phase data requires special consideration as values are usually represented on a scale which is periodic in nature, *i.e.*, either 0° to 360°, or ±180°. This requires a form of clock arithmetic.)

As a measure of dispersion, ± MAD (Magnitude) and ± MAD (Phase) produce intervals about the median value which are expected to contain half the results, in each case.

4 RESULTS SUMMARIES

The results summaries supplied to the participants in the exercise included the following information, at each frequency; (i) the value of the spatial median, (ii) the difference between the participants value and the spatial median value, and (iii) the MAD values. However, for the purposes of this paper, a more concise summary is adequate concentrating on the variations between the participants values (the reproducibility) and comparing with the variations recorded during the repeatability assessment made by the pilot laboratory.

Since no frequency dependence was discernable with the reported values, a single MAD value for each measurement configuration provides an adequate summary. The summary statistics for the reflection and transmission measurements are given in tables 1 and 2. (MAD Repeat summarises the repeatability variations and MAD Repro the reproducibility variations.)

Reflection coefficient	Linear magnitude		Phase (degrees)	
	MAD Repeat	MAD Repro	MAD Repeat	MAD Repro
Matched load	0.0005	0.0009	9	43
Mismatched load	0.0002	0.0015	0.07	0.39

Table 1:   *Repeatability and reproducibility summary statistics for the reflection measurements of the terminations.*

Transmission coefficient	Log magnitude (dB)		Phase (degrees)	
	MAD Repeat	MAD Repro	MAD Repeat	MAD Repro
Through path	0.004	0.015	0.20	0.33
Coupled path	0.004	0.023	0.13	0.45
Isolation path	0.1	2.6	1	20

Table 2:   *Repeatability and reproducibility summary statistics for the transmission measurements of the coupler.*

5 DISCUSSION

5.1 Sources of error

As a rule of thumb, repeatability figures indicate variations due to the effects of random errors in the measurements. Similarly, the reproducibility figures indicate variations due to the combined effects of random and systematic errors.

Since the reproducibility statistics are generally between two and eight times larger than the repeatability statistics this indicates that systematic errors are significant (and can dominate) for these types of measurements. (The summary statistics for the measurements of the transmission of the isolation path are discussed separately, below.)

5.2 Problems in analysing the isolation path values

The measurement data supplied by the participants for the isolation path of the coupler has caused some analysis problems. In each data set there appear to be two distinct groups of data points, whereas the data sets for the other measured parameters form single groups in each case.

Figure 1 shows the positions of the eight participants' measurements of transmission of the coupled path, represented by black dots in the complex plane. The data set forms a single,

quite compact group (although there is an outlier to the top left of the main group). In contrast, Figure 2 shows the eight measurements of transmission for the isolation path. There are two distinct groups of data points, with similar magnitudes but with a phase difference of nominally 180°. Under these circumstances, the use of the MAD alone as an indication of variation in the data sets is inadequate. Further work is needed to provide an acceptable summary for data sets of this kind.

6 CONCLUSIONS

The comparison exercise produced some interesting results which have raised the awareness of the difficulties in making measurements of this kind. In particular, the indication of significant (and potentially dominant) systematic errors means that careful consideration should be given to the assessment of measurement uncertainty for such measurements.

The comparison has also demonstrated a problem with measuring the phase of waveguide transmission measurements using ANAs (the isolation path measurements). It has been shown elsewhere [4,5] that a 180° phase ambiguity can occur with this type of measurement.

Finally, the knowledge gained by the participants in this comparison exercise should provide valuable insight when quantifying uncertainty and assessing the ability of these instruments to perform measurements of this kind over this very important frequency range.

7 ACKNOWLEDGEMENTS

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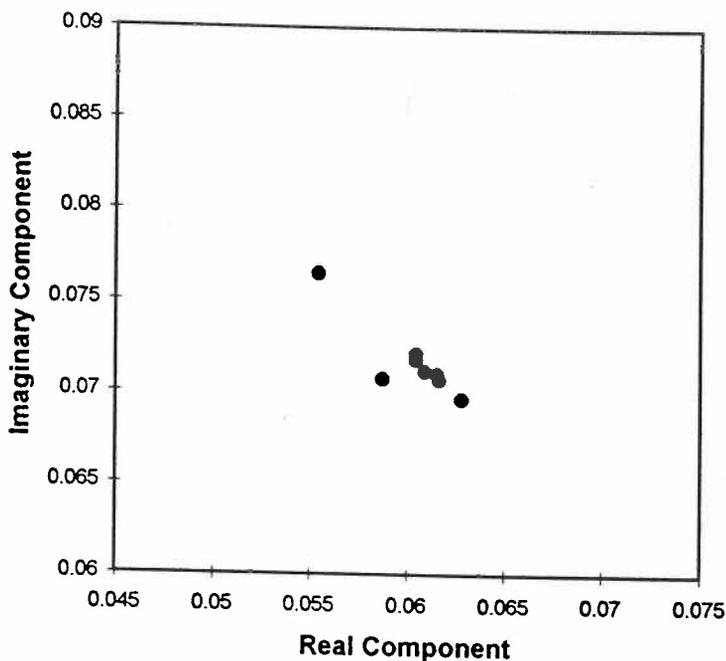
Figure 1:   *The eight measurements of the transmission coefficient of the coupled path of the coupler at 11 GHz.*
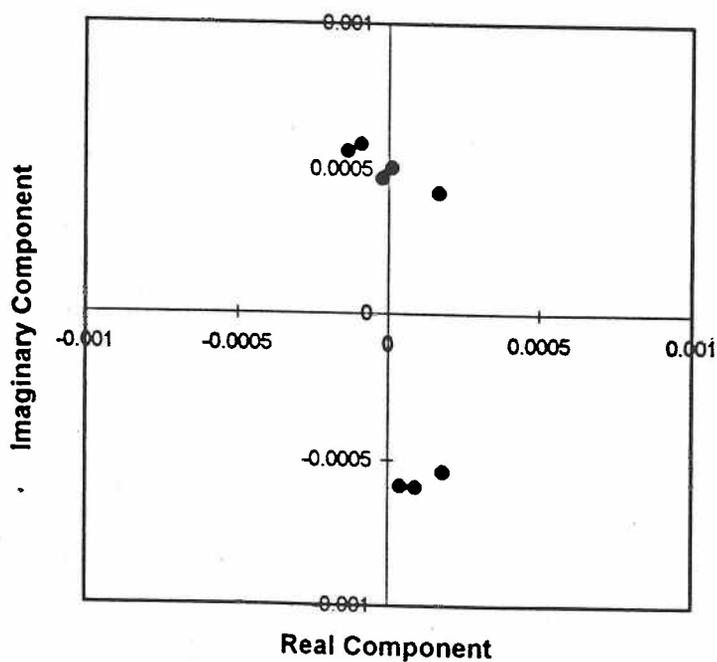

Figure 2:   *The eight measurements of the transmission coefficient of the isolation path of the coupler at 11 GHz.*

ANAMET comparison of reflection coefficient measurements at RF

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ABSTRACT

This paper reports on an exercise to compare measurements of the complex reflection coefficient of coaxial terminations at RF (100 kHz to 1 GHz). The results obtained by the eleven laboratories participating in the exercise are summarised in terms of the between-laboratory reproducibility. These values are compared with a within-laboratory repeatability assessment made by the pilot laboratory for the exercise. The exercise was coordinated by ANAMET - the Automatic Network Analyser METrology club operated by NPL.

1 INTRODUCTION

This paper reports on a recent comparison exercise of complex voltage reflection coefficient (VRC) measurements made in 7 mm 50 ohm coaxial line. Six terminations fitted with type N connectors (three male and three female) were used as the test artefacts for the exercise (see Figure 1) which consisted of measurements at 16 frequencies from 100 kHz to 1 GHz. (The microwave properties of these terminations have been investigated in an earlier ANAMET comparison exercise [1,2] over the frequency range 1 GHz to 18 GHz.)

The exercise was coordinated by ANAMET – the Automatic Network Analyser METrology club operated by NPL. Eleven member organisations of ANAMET chose to participate in the exercise, including six national metrology institutes from around the world. The pilot laboratory was NPL Malvern.

This paper presents general observations about the exercise consistent with earlier reports on ANAMET comparison exercises [1-5]. These include: comparing the between-laboratory variation (*i.e.*, reproducibility) with a within-laboratory variation (*i.e.*, repeatability); predicting the likely significant sources of error in the VRC measurements; assessing any variability trends (*e.g.*, due to frequency, VRC value, etc); and, estimating the number of measurements far-removed from the majority of values (*i.e.*, statistical outliers). Finally, the variability of the data in this exercise is compared with that obtained in the earlier ANAMET comparison exercise from 1 GHz to 18 GHz.

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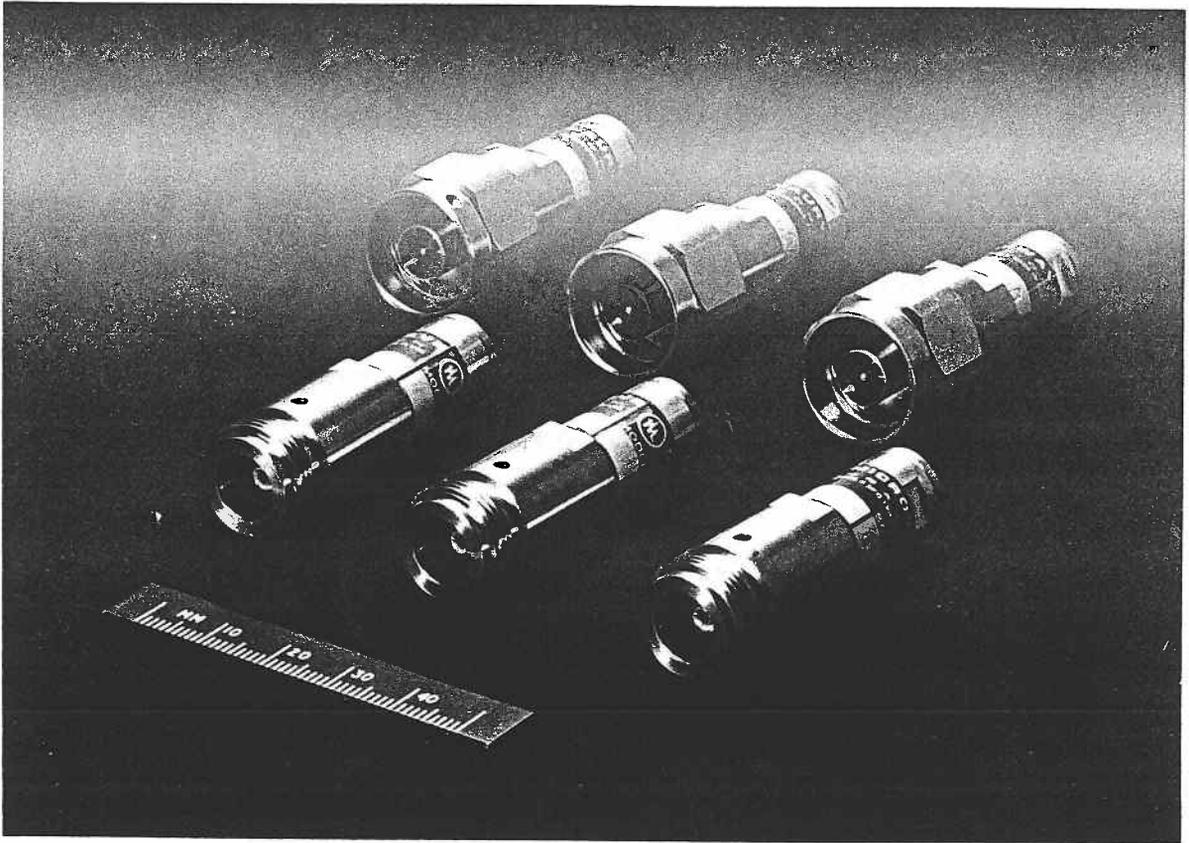
Figure 1: photograph showing the terminations used for the exercise

2 COMPARISON DETAILS

The terminations provided nominal values of VSWR of 1.05, 1.2 and 1.5 for both the male and female connectors. (*I.e.*, VRC magnitudes of nominally 0.024, 0.091 and 0.200.) The participants were invited to submit measurements of complex VRC, magnitude and phase, at the following frequencies; 100 kHz, 300 kHz, 1 MHz, 3 MHz, 10 MHz, 30 MHz, 100 MHz and in steps of 100 MHz to 1 GHz, making a total of 16 frequencies.

Eight of the participants supplied results at all the frequencies. Two participants supplied results at all frequencies except 100 kHz and one participant at all frequencies from 100 MHz to 1 GHz.

3 MEASUREMENT SYSTEM DETAILS

For the purposes of this paper, the participants supplied details of the systems they used for the measurements.

- The Hong Kong Government Standards and Calibration Laboratory, Hong Kong, used a HP 8752A ANA calibrated using a HP 85032B kit.

- The National Metrology Laboratory, CSIR, South Africa, used a HP 8510C ANA with a HP 8515A Test Set calibrated using a HP 85054A kit.

- Assessment Services, Titchfield, used a HP 4192A LF Impedance Analyser, for the measurements at 100 kHz, and a HP 8753A ANA with a HP 85046A Test Set for all other frequencies. Both instruments were calibrated using a HP 85032B kit.

- SESC, DRA Aquila, Bromley, used a HP 8751A ANA with a HP 87511A Test Set for the measurements up to 100 MHz and a HP 8753B ANA with a 85047A Test Set above 100 MHz. Both systems were calibrated using a HP 85032B kit.

- Hewlett Packard, Winnersh, used a HP 8753B ANA with a HP 85047A Test Set calibrated using a HP 85054B kit.

- Hewlett Packard, Queensferry, used a HP 3577A ANA with a HP 35677A Test Set for the measurements to 200 MHz and a HP 8510B ANA with a HP 8515A Test Set above 200 MHz. The 8510B was calibrated using a HP 85054B kit.

- INTA, Spain, used a HP 8751A ANA with a HP 87511A Test Set and a HP 8510C ANA with a HP 8517A Test Set.

- Swiss Telecom PTT, Switzerland, used a HP 8753D ANA calibrated using a HP 85032B kit.

- Marconi Instruments, Stevenage, used a HP 3577A ANA with a HP 35677A Test Set up to 200 MHz and the MI 6210 reflection analyzer from 250 MHz. Both systems were calibrated using a Wiltron kit and Marconi Instrument's own standards.

- NMi, The Netherlands, used a Quadtech 7600 Precision RLC Meter at 100 kHz and a HP 8753B ANA with a HP 85046A Test Set for all other frequencies. The calibration kit was a HP 85032B.

- NPL, Malvern, used a HP 8751A ANA with a HP 87511A Test Set for the measurements up to 500 MHz and a HP 8753B ANA with a 85046A Test Set above 500 MHz. Both systems were calibrated using a HP 85054B kit.

All participants who supplied details concerning the method used to calibrate the ANAs used the short-open-load technique, where the load was a fixed near-matched termination. Assessment Services used a S/C and O/C to calibrate their LF Impedance Analyser.

4 STATISTICAL ANALYSIS

4.1 Variability assessment

As with previous ANAMET comparison exercises, the variation in the results was assessed using the concepts given in [6] — specifically, in terms of the between-laboratory reproducibility of values and compared with a within-laboratory repeatability assessment made by the pilot laboratory.

The reproducibility values indicate the level of variation found in the results supplied by the participants whereas the repeatability values indicate a typical variation experienced by one participant performing repeat measurements under essentially the same measurement conditions. Therefore, the repeatability values provide a useful base-line to assess the variability in the participants' measurements.

4.2 Summary statistics

It is conventional, when summarising data in a measurement comparison exercise, to give an average value and a measure of the dispersion of the data about that average. As with the previous ANAMET comparison exercise [4,5], multivariate robust statistical techniques have been used to obtain the summary statistics for this exercise. These techniques produce summary values which remain unaffected by the occasional unusual value which may appear in the measurement data sets, and are applicable to measurement results which are complex numbers.

The average is given by the spatial median of each measurement data set and the measure of dispersion by the median absolute deviation (MAD). ±MAD produces an interval, symmetric about the spatial median, which contains 50% of the data points. For more detailed information on these estimators, see [7].

5 RESULTS SUMMARIES

The results summaries supplied to the participants in the exercise included the following information, at each frequency; (i) the value of the spatial median, (ii) the difference between the participants value and the spatial median value, and (iii) the MAD values. However, for the purposes of this paper, a more concise summary is adequate concentrating on the variations between the participants values (the reproducibility) and comparing with the variations recorded during the repeatability assessment made by the pilot laboratory.

The MAD values for each termination are different at different frequencies. For conciseness, only the largest MAD value obtained for each termination is given here (see Table 1). MAD statistics are given for both the magnitude and phase components of the complex voltage reflection coefficients. MAD Repeat summarises the repeatability variations and MAD Repro the reproducibility variations.

Test item	VRC linear magnitude (mU)		VRC phase (°)	
	MAD Repeat	MAD Repro	MAD Repeat	MAD Repro
1.05 (male)	0.07	0.7	0.10	1.6
1.05 (female)	0.04	0.6	0.12	1.2
1.2 (male)	0.07	0.7	0.05	0.3
1.2 (female)	0.05	0.6	0.03	0.4
1.5 (male)	0.10	0.7	0.01	0.3
1.5 (female)	0.06	0.8	0.01	0.3

Table 1: MAD values for the repeatability and reproducibility summary statistics for the magnitude and phase of the VRC measurements.

6 DISCUSSION

6.1 Sources of error

Measurement errors can be classified as either random or systematic in nature — the classification depending on the physical process causing the error to occur. For example, random errors in VRC measurements are caused by the inevitable electrical noise present on all detected signals and by imperfect connections of artefacts (both calibration and measurement) to the instrument test port. Systematic errors are caused by departures from the assumed characteristics of the calibration items. (Detector non-linearities will also produce systematic errors. However, for a well designed system, non-linearity effects are expected to be a small compared with the effects due to the calibration items.)

Comparing the repeatability values with the reproducibility values enables an estimate to be made for the two types of error affecting the measurements. In general, repeatability figures indicate typical variations due to the effects of random errors in the measurements. In contrast, reproducibility figures indicate typical variations due to the combined effects of random and systematic errors.

Since the reproducibility values in Table 1 are between 6 and 30 times larger than the repeatability values this indicates that systematic errors dominate random errors for these measurements. This suggests the major source of errors in the systems is due to departures from the assumed characteristics of the calibration items.

Participants who stated their method of ANA calibration generally used the Short/Open/Load technique, using a fixed near-matched termination as the load standard. It is anticipated that departures from the assumed characteristics of the short-circuit and open-circuit will be small, as these items are of simple geometry and relatively easy to model. (Generally, short-circuits are assumed to have $|VRC| \approx 1$ and phase $\pm 180°$. Open-circuits are assumed to have $|VRC| \approx 1$ and a negative phase angle due to the frequency-dependent capacitance inherent in the item.) However, the load standard *will* generally introduce a significant error into the measurements if it is assumed to have $|VRC| = 0$, as is usually the case for commercial ANA calibration routines. The authors predict that the systematic errors in the load standard are the most likely cause of the relatively large reproducibility values (as compared with the repeatability values) and as such, expect the load standard to be the limiting factor for the accuracy for many of the measurement systems.

6.2 Other features of the data

(i)   Two trends often present in comparison data of this type are for the size of the MAD reproducibility values to be dependent on the nominal value of the $|VRC|$ of the termination and/or the measurement frequency. A closer examination of the data revealed that the MAD reproducibility values for $|VRC|$ did not exhibit any significant dependence on the nominal value of the $|VRC|$ of the termination (see Table 1) or on the measurement frequency (see Table 2). This is in contrast to the MAD phase values which showed both dependence on the nominal value of the $|VRC|$ (see Table 1) - MAD values decreased as the nominal value of the $|VRC|$ increased - and frequency dependence (see Table 2) - MAD values increased with increasing frequency.

Frequency	VRC MAD Repro	
	Linear magnitude (mU)	Phase (°)
100 kHz	0.6	0.002
1 MHz	0.4	0.019
10 MHz	0.3	0.035
100 MHz	0.3	0.04
1 GHz	0.7	0.21

Table 2:   A selection of VRC MAD values, at different frequencies, produced by the 1.5 VSWR female termination.

Both of the effects observed in the MAD phase values are to be expected. Firstly, phase becomes generally more difficult to measure at higher frequencies as it relates directly to the ability to discriminate length, or distance. For example, a 1° phase change at 100 kHz equates to a distance of 8 m whereas the same phase change at 1 GHz is equivalent to a distance of 0.8 mm. Secondly, for a given (fixed) scatter in a set of VRC values, the subsequent scatter in the phase parameter increases as the set of values move towards the origin (i.e., zero VRC) of the complex plane describing the VRC. (This effect is described in more detail in [8].)

(ii)   Previous comparison exercises [1-5] have produced a significant number of unusual values (statistical outliers). This led to the introduction of the robust statistical techniques which have been used here to summarise the data. The robust techniques are relatively unaffected by outlying values making them a very useful mechanism for dealing with outliers when summarising the data sets. However, as an objective assessment of the overall calibre of the exercise, the identification of outlying data is a valuable part of the data analysis.

A visual inspection of all the |VRC| results in the exercise showed that none were obvious candidates to be classified as outlying. Similarly, the VRC phase values did not suffer from the extreme 180° problems encountered in the previous two ANAMET exercises [3-5]. However, some phase values were clearly well-removed from the main cluster of values suggesting potential measurement problems.

6.3 Comparison with microwave measurement comparison

The microwave properties of the items in this exercise have been compared in an earlier ANAMET exercise [1,2]. The VSWRs of the items were compared from 1 GHz to 18 GHz and the variability (between-laboratory reproducibility) reported using the standard deviation of each data set.

In order to compare meaningfully the variations found in both exercises it is necessary to convert the values in the earlier exercise from VSWR standard deviations to |VRC| MADs. In [2] it was shown that, for small |VRC|s, the standard uncertainty (or standard deviation) in |VRC|, $s(|VRC|)$, is approximately equal to half the standard uncertainty in VSWR, $s(VSWR)$. I.e.;

$$s(|VRC|) \approx s(VSWR)/2$$

Another useful relationship relates the standard deviation, $s(x)$, to the MAD;

$$MAD \approx 0.674 \times s(x)$$

(Strictly speaking, this is only true for large sample sizes drawn from a normal distribution.)

These two expressions have been used to convert the repeatability and reproducibility VSWR standard deviations from the earlier exercise (Tables 5 and 6 in [1]) into equivalent |VRC| MAD values. These values are presented in Table 3.

Comparing MAD values in Tables 1 and 3 shows that, in general, the variability is consistently larger with the measurements made at microwave frequencies in the earlier comparison exercise. This observation is consistent with engineering folk-lore which says that "microwave measurements are more difficult to make than low frequency ones".

Test item	VRC linear magnitude (mU)	
	MAD Repeat	MAD Repro
1.05 (male)	0.24	3.0
1.05 (female)	0.34	4.7
1.2 (male)	0.34	4.4
1.2 (female)	0.61	5.4
1.5 (male)	0.57	7.1
1.5 (female)	0.81	8.1

Table 3:   Equivalent MAD values for the repeatability and reproducibility for |VRC| measurements obtained in the earlier ANAMET comparison.

7 CONCLUSIONS

This comparison, the fourth in ANAMET's on-going series of exercises, has further contributed to the catalogue of information which is emerging on network measurements and the performance of network measuring instruments in the 1990s. This body of data is providing vital information on actual performance figures for these systems over a wide range of applications.

The comparison focused on the lower RF region of the electromagnetic spectrum including frequencies where traceability is currently not available in the UK for this type of measurement (i.e., below 50 MHz). The agreement between the participating laboratories was encouragingly good with none of the measurement anomalies (180° phase errors) which contaminated the data sets in the two previous comparison exercises [3-5]. Systematic errors appear to be dominating these measurements. This indicates potential avenues of research for the further improvement of the quality of these measurements.

ANAMET will continue to conduct measurement comparison exercises on behalf of its membership, with the focus likely to move towards some of the less well understood areas of RF, microwave and millimetre-wave metrology.

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