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A comparison of complex scattering coefficient measurements in 50 ohm coaxial line to 26.5 GHz

N M Ridler and J C Medley

Division of Electrical Science
National Physical Laboratory
℅ DRA Malvern, St Andrews Road
Malvern, Worcs, WR14 3PS
United Kingdom

ABSTRACT

This report describes an exercise to compare complex scattering coefficient measurements of two-port items fitted with GPC-3.5 connectors in 50 ohm coaxial line. The measurements were made over the frequency range 1 GHz to 26.5 GHz. Results are presented in graphical form, together with a statistical summary of the measured values. Details of repeatability and drift assessments are also included. The eight participants are all members of ANAMET, which organised the administration and funding of the exercise.

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National Physical Laboratory
Teddington, Middlesex, UK, TW11 0LW

Approved on behalf of Chief Executive, NPL
by Dr T G Blaney, Head, Division of Electrical Science

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GRAPHS AND TABLES

1 INTRODUCTION

This report presents results obtained from a measurement comparison exercise which took place during 1994. The exercise was coordinated by ANAMET – the network analyser metrology club, set up in 1993 by NPL, for people and organisations interested in RF, microwave and millimetre-wave network measurements. One of the principle activities of the club is to organise measurement comparisons, the details of which are decided by the club membership.

Measurement comparisons, or inter-laboratory test programmes, are used in many scientific disciplines to evaluate the performance of measurement systems and techniques. For example, they are often used by accreditation bodies to evaluate the performance of laboratories, since a clear indication is given of each laboratory's ability to perform the measurements competently.

ANAMET measurement comparisons provide each participant with a confidential report highlighting their laboratory's results with respect to the other participants. (The participant's results are also compared with a statistical summary of the results.) This report presents the results of the exercise, with a statistical analysis, but does not relate specific results with participants. The objective is to gain an overall insight into the ability to make measurements of this kind.

2 COMPARISON DETAILS

The eight organisations who chose to participate in the exercise were as follows; (i) Assessment Services Ltd, Titchfield, UK, (ii) DRA Aquila, Bromley, UK, (iii) EEV Ltd, Chelmsford, UK, (iv) Hewlett-Packard Ltd, Wokingham, UK, (v) INTA, Madrid, Spain, (vi) NPL, Malvern, UK, (vii) NPL, Teddington, UK, and (viii) Swiss Telecom PTT, Bern, Switzerland.

2. ELECTRICAL MEASUREMENTS

The main objective of the exercise was to compare the complex scattering coefficient measurements, S_{11} and S_{21}, of two-port items in 50 ohm coaxial line. Values for S_{11} were measured as linear magnitude and phase, and values for S_{21} were given as the logarithmic magnitude (in dB) and phase. All phase data were given in degrees. The frequency range of the measurements was 1 GHz to 26.5 GHz in 1.5 GHz steps, providing 18 different frequency points.

The test items were passive attenuators fitted with GPC-3.5 connectors. Four attenuators with nominal values of 3 dB, 6 dB, 10 dB and 70 dB were chosen for the exercise. All the attenuators were made by the same manufacturer (Hewlett-Packard) and were of the same type (model number 8493C). This implies that the items would be of similar electrical and mechanical quality.

Each item was equipped with one female and one male connector. The female connector was designated as port 1, making the male connector port 2. The orientation of the scattering parameters under investigation were therefore as follows; S_{11}, the reflection coefficient looking into the item's female connector; S_{21}, the transmission coefficient from the item's female connector to the item's male connector.

2.2 MECHANICAL MEASUREMENTS

It was decided, during the formulation of the exercise, to also compare the measurements made by the participants of the items' connector pin-depths. These measurements, made prior to the electrical measurements, would provide valuable insight into the performance of the dial gauges used for this type of mechanical measurement.

3 MEASUREMENT SYSTEM DETAILS

No restrictions were placed on the measurement systems and calibration techniques to be used. The table below gives details of the systems that were used by each participant for the measurements.

Organisation	Instrumentation		Calibration details		
	ANA	Test Set	Kit type	Technique	Load details
Assessment Services Ltd	HP 8510A	HP 8514A	HP 85052A	SOLT	Fixed load at 1 GHz, sliding above
DRA Aquila	HP 8510C	HP 8515A	HP 85052C	TRL	N/A
EEV Ltd	Wiltron 360A	Wiltron 3621A	Wiltron 3650	SOLT	Sliding load at all frequencies
Hewlett-Packard Ltd (HP)	HP 8510B	HP 8515A[1]	HP 85052B[2]	SOLT	Fixed load below 3 GHz, sliding above
INTA Spain	HP 8510C	HP 8517A	HP 85052B	SOLT	Fixed load at 1 GHz, sliding above
NPL Malvern	Wiltron 360B	Wiltron 3612A	HP 85052B	SOLT	Fixed load at 1 GHz, sliding above
NPL Teddington	HP 8510C	HP 8515A	HP 85052C	TRL	N/A
Swiss Telecom PTT	HP 8510C	HP 8515A	HP 85052C	TRL	N/A

Details of the instrumentation, calibration type and technique, used by the participants.

Modified test set to give improved dynamic range

Kit specially selected by the manufacturer

All participants used Automatic Network Analysers (ANAs) as the measuring instruments. The calibrations were either of the Short-Open-Load-Thru (SOLT) type, or the Thru-Reflect-Line (TRL) type. Of the participants using the SOLT calibration technique, a sliding load was used at some, or all, the frequencies. All participants, except one, provided results at all the frequencies. Assessment Services Ltd provided results up to 17.5 GHz only.

4 SUPPLEMENTARY MEASUREMENTS

The comparison exercise was concluded by a series of supplementary measurements made by NPL, Malvern, on behalf of ANAMET. These measurements were made for two reasons; (i) to check that the characteristics of the items had not changed appreciably (*ie* drifted) during the course of the exercise, and (ii) to evaluate typical repeatability figures for these types of measurement. (Repeatability is defined, in [1], as "closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement".)

4. DRIFT ASSESSMENT

It is important to establish that an item's characteristics have remained essentially unchanged during the course of a measurement comparison exercise so that it can be assumed that all participants measure the same physical quantity. Such an assumption is fundamental to the legitimacy of this type of exercise. To do this, the items were measured a second time and compared with the first series of measurements made by NPL Malvern at the start of the exercise.

A visual inspection of the connector mating surfaces and general condition was also performed by NPL, Malvern. These inspections were made before sending the items to the participants.

4.2 REPEATABILITY ASSESSMENT

Repeatability figures give an indication of the minimum variation which can be achieved in a given type of measurement. Such figures can be useful when interpreting the between-laboratory variation achieved by the participants. For example, if the between-laboratory variation is considerably larger than the repeatability variation, for a given measurement, this suggests the presence of significant systematic differences between the participants' measuring instruments. Conversely, between-laboratory variations of a similar size as the repeatability variations suggest that the dominant errors in the measurement are more likely to be random in nature.

To assess repeatability, a series of measurements was performed under essentially the same conditions, *ie* using the same operator, measuring instrument, calibration data and measurement technique. However, the items were disconnected and reconnected between successive measurements since this represents the minimum variation which could happen between the measurements made by the participants.

Sufficient repeat measurements were made to provide the same number of measurements as were obtained from the participants (*ie* eight up to 17.5 GHz and seven above this frequency).

5 STATISTICAL TECHNIQUES

5 SUMMARY STATISTICS

It is conventional, when analysing data in an inter-laboratory test programme, to give a statistical summary of the measurement results. The summary usually gives an average value, based on the participants results, and a measure of the dispersion of the results about this average. Each participant can use the average value and measure of dispersion to assess the performance of their own result. For example, the difference between the average value and the value obtained by a participant gives an indication of the relative accuracy of the participant's result.

Similarly, the measure of dispersion can be used to judge whether this difference is significant – If the difference is small compared with the dispersion indicator, the participant's result is more likely to be considered of high quality than if the difference is large compared with the dispersion indicator. It is important, however, when making comparisons of this nature to consider the meaning of the dispersion indicator. For example the indicator may define an interval, about the average value, containing a specified proportion of the population, or sample under investigation. In this case, a measure of dispersion defining a low proportion of a population, or sample, will be a severe indicator of a measurement's quality.

It is appropriate to give summary statistics for each parameter measured in the comparison exercise, *ie* S_{11} magnitude, S_{11} phase, S_{21} magnitude, and S_{21} phase, at each frequency.

5.2 CHOICE OF ESTIMATORS

The most common estimators used to obtain an average value and a measure of dispersion, for a series of observations, are the arithmetic mean and the sample standard deviation, respectively. Confidence intervals for the mean can also be determined, from the standard deviation, if assumptions are made about the underlying distribution (*ie* Gaussian) from which the data have been obtained.

The main disadvantage in using the mean to provide a useful average (*ie* one that can be used to compare with the values obtained by the participants) and the standard deviation as a basis for a measure of dispersion is their sensitivity to contamination by outliers (values within the series of observations being analysed which appear not to conform to the pattern exhibited by the other data). The preliminary examination of the results of the comparison exercise revealed the presence of a significant number of such outliers in the data.

The rejection of outliers during the analysis of inter-laboratory test programme data is often recommended [2]. This procedure was applied in an earlier exercise organised by ANAMET [3,4] when it was clear that one participant had difficulties with all meaasurements of a certain type. There was no such pattern to the outliers in the current data and so it seemed unjustified to reject these data points from the analysis.

As an alternative to using outlier rejection, estimators can be used which exhibit some resistance to outlier contamination. Both the median and the inter-quartile range (referred to in this report as IQR), as an average value and a measure of dispersion respectively, exhibit such resistance and they have been applied to the measurement data in this comparison.

Both these estimators are evaluated by arranging the data to be analysed in ascending numerical order of value (*order statistics*). The lower quartile divides the order statistics so that 25% of the observations are below its value, the median has 50% below and 50% above, and the upper quartile has 25% above its value. The IQR is the difference between the values of the upper and lower quartiles.

However, the order statistics cannot always be split exactly into four equal parts. A more precise definition for these terms is given in terms of a calculated 'depth', *ie* how far to go through the data to find the required value. For n observations, the depth of the median is given by:

$$\textit{Depth of median} = \frac{n + 1}{2}$$

Thus when n is odd the median takes the value of the middle order statistic and when it is even it takes the value half way between the two middle order statistics.

Examples:	*n*	*ordered data*	*depth of median*	*median value*
	5	*-1,0,4,6,6*	*(5+1)/2 = 3*	*4*
	6	*-3,-1,0,4,6,6*	*(6+1)/2 = 3.5*	*(0+4)/2 = 2*

Similarly the depth of the quartiles is given by:

$$\textit{Depth of quartiles} = \frac{\textit{Depth of median} + 1}{2}$$

The lower quartile is found by entering the data, to the specified depth, from the low end (*ie* starting with the lowest value) and the upper quartile is found by entering from the high end (starting with the highest value).

Examples:	*n*	*ordered data*	*depth of median*	*depth of quartiles*	*lower quartile*	*upper quartile*	
	5	*-1,0,4,6,6*	*3*	*(3+1)/2 = 2*	*0*	*6*	*6*
	6	*-3,-1,0,4,6,6*	*3.5*	*(3.5+1)/2 = 2.25*	*-0.75*	*5.5*	

As a measure of dispersion, the IQR defines an interval which encompasses half the results – a quarter on either side of the median. As a guide, for data drawn from a Gaussian distribution, the IQR is approximately 1.3 times larger than the standard deviation.

5.3 FURTHER CONSIDERATIONS

The statistical analysis of phase data is not straightforward as phase is measured on a scale which is periodic in nature. This means that a single data point can be represented by more than one value. For example, if we measure phase in degrees then any of the values +45°, +405° (=45°+360°), -315° (45°-360°), +765° (45°+2×360°), ...etc, could be used to represent the same data point.

For phase measurements from an ANA it is conventional to quote the phase value, call it ϕ, in the interval $-180° < \phi \leq +180°$. However when performing calculations on phase data it can be convenient to use other intervals, such as $-360° < \phi \leq 0°$ or $0° \leq \phi < +360°$, although the results of the calculation will usually be quoted in the original $-180° < \phi \leq +180°$ interval.

Example *What is the mean of +179° and -177°?*

Using the interval $-180° < \phi \leq +180°$

$$mean = \frac{+179° - 177°}{2} = +1°.$$

Using the interval $0° \leq \phi < +360°$.

$$mean = \frac{+179° + 183°}{2} = +181°.$$

Re-expressing this result in terms of the conventional interval gives.

$$mean = -179°.$$

This second result seems a more sensible interpretation of the mean in this case.

There is a similar problem with the use of order statistics and assigning a median and quartiles. What interval should we use to get a sensible result?

5.3.1 'Well behaved' data. For phase data that is well behaved, *ie* is fairly tightly grouped with no outliers, the main difficulty in ordering the data is encountered if the range of data encompasses the discontinuity of the interval being used. For example, for data encompassing the point at ±180° it may make more sense to order the data using their values from the interval $0° \leq \phi < +360°$, rather than the conventional $-180° < \phi \leq +180°$ interval.

Example *What is the median of the data set +176°, +169°, -170°, +177°, -173° ?*

Using the interval $-180° < \phi \leq +180°$

Order statistics : -173°, -170°, +169°, +176°, +177°;
Median value = +169°.

Using the interval $0° \leq \phi < +360°$

Order statistics : +169°, +176°, +177°, +187°, +190°;
Median value = +177°.

This second result seems a more sensible interpretation of the median in this case.

5.3.2 Ordering outliers. Another difficulty with this numbering system occurs when trying to determine the order of outliers with respect to the majority of data values. With the well behaved data set of 5.3.1, it was quite straightforward to find an interval in which the order statistics led to a reasonable value for the median. However, as a data point becomes further removed from the main group it becomes less clear which interval is appropriate. In other words, does the data point belong at the top or at the bottom of the order statistics?

The approach adopted for the analysis of the results of this exercise was as follows:

(1) assign values to the phase data in the interval $-180° < \phi \leq +180°$, unless the data is grouped around the point ±180° in which case use the interval $0 \leq \phi < 360°$;
(2) order these values and calculate a median value;
(3) if: any phase value is more than 180° from the median value
then: (a) choose the phase value furthest from the median;
(b) if this value is less than the median then add 360° to the value, if it is greater than the median then subtract 360° from the value;
(c) reorder the values and calculate a new median value;
(d) perform step (3) again;
else: proceed to step (4);
calculate the quartiles of the data set in the current order.

When there are several values away from the main group, or if there is no clear indication of the presence of a group, the choice of interval in step (1) becomes more subjective. In this case the concept of a median value (and quartile values) is more difficult to interpret. For particularly pathological data sets, in which the scatter of data values is symmetric, there is no unique average value (median or mean). However the data produced by the current exercise was sufficiently well behaved for the above procedure to be adequate.

6 RESULTS

Results are presented at each frequency of the comparison in graphical and tabular forms. As one participant did not supply results above 18 GHz, there are eight data points at frequencies up to 17.5 GHz and seven data points at frequencies above this.

Each participant's results are represented on the graphs by black dots. In some graphs the results for several participants are very close, causing dots to eclipse one another to some extent. Where a result would not fit on the same scale as the other data points it is represented by an arrow and the value of the missing data point.

The results in the tables are rounded as follows: to four decimal places for the magnitude results; to two decimal places for the phase results; and to one decimal place for the connector pin-depth results (given in μm). Values given in the tables may have a marginal error component due to rounding.

The abbreviations "IQR - Repeat" and "IQR - Repro", used in the tables, represent "IQR repeatability" and "IQR reproducibility", respectively.

SUPPLEMENTARY MEASUREMENTS

6.1.1 Visual inspections. The visual inspections of the artefacts, made by NPL Malvern between each participant's measurements, revealed nothing that was likely to impair the performance of the items, although the coupling nut on the 6 dB attenuator required replacement during the course of the exercise. This change should not have affected the characteristics of the item.

6.1.2 Drift assessment. The two sets of measurements made by NPL Malvern at each end of the exercise were examined for differences which would indicate a possible change in the properties of one, or more, of the items. No such differences were observed, however it is always difficult to justify the absence of an effect especially without a full analysis of the measurement uncertainties.

6.1.3 Repeatability assessment. The measurements made to assess the repeatability of the measurements were analysed in the same way as the participants' results, *ie* by characterising the dispersion using the IQR. This gives a figure for repeatability which can be compared directly with the IQR for the between-laboratory variation (or reproducibility) achieved by the participants. The IQR repeatability figures, for each item and frequency, are given in tables 1 to 8, along with the statistical summaries of the participants' measurements (see below).

6.2 ELECTRICAL MEASUREMENTS

The results for each item are presented in six graphs and two tables. The graphs show the following parameters, plotted against frequency; (i) S_{11} magnitude, (ii) S_{21} magnitude, (iii) S_{11} phase, (iv) S_{21} phase, (v) S_{11} phase, difference from the median value, and (vi) S_{21} phase, difference from the median value. The two tables (one each for S_{11} and S_{21}) give, for both magnitude and phase; (i) the frequency, (ii) the median value, (iii) the repeatability IQR, and (iv) the reproducibility IQR. The figure and table numbers for each attenuator are shown in the box below.

Attenuator value	Figure numbers	Table numbers
3 dB	1-6	1 & 2
6 dB	7-12	3 & 4
10 dB	13-18	5 & 6
70 dB	19-24	7 & 8

The phase measurements show considerable variation with frequency which can make graphs of the phase data difficult to interpret. The graphs of differences from the median help to show more clearly how the results vary within each data set[3].

6.3 MECHANICAL MEASUREMENTS

The results of the pin-depth gauge measurements for all of the items are presented graphically in figure 25. Table 9 gives the summary statistics (median and reproducibility IQR) for the participants' measurements. The repeatability IQR is not given in the table since the repeatability for this type of measurement is very good (these values can be assumed to be close to zero).

The term "data set" is used here to indicate the set of values obtained for one of the measurement parameters, at a single frequency, for a specific item. Hence data sets in this comparison contain either seven or eight numbers, depending on the frequency.

7 OBSERVATIONS

7.1 GENERAL REMARKS

The visual inspections of the items, made during the exercise, and the drift assessment, made at the end of the exercise, indicated that the results obtained by the participants during the exercise could be meaningfully compared and analysed.

The exercise produced a large amount of data, with individual data sets exhibiting a number of interesting characteristics.

Bunching. In a "text-book" comparison exercise one might expect to obtain a relatively tightly grouped set of values, the small amount of variation between the results being indicative of a measurement parameter which can be determined reliably by the participants. The majority of data sets in the current comparison show such bunching. (See, for example, the graphs of S_{21} magnitude for the 3 dB (figure 2), 6 dB (figure 8) and 10 dB (figure 14) attenuators.)

Outliers. These are values which are far removed from the majority of values in the data set. 30 out of the 72 data sets of S_{11} phase results show obvious outliers. The difference from median graphs (figures 5, 11, 17 and 23) show these values up quite clearly – They appear as values at the top and bottom of the graphs (near the ±180° values). This indicates that the associated reflection coefficient values are on the *opposite side* of the complex plane to the majority of values. Some data sets contained *two* outlying values (see, for example, the data set at 14.5 GHz in figure 5, and the data sets at 11.5 GHz and 19 GHz in figure 17).

Unusual values. Some values are sufficiently removed from the majority of values in the data set to be noticeable and yet are not as extreme as outliers. Unusual values of this kind occur in both magnitude and phase data. For example, some of the data sets for the S_{21} magnitude measurements for the 70 dB attenuator clearly contain such values (see figure 20).

Bunching into more than one distinct group. Some data sets exhibited a tendency to form tight groupings around *two* notional average values. This tendency seems to occur over a range of frequencies, *eg* in the S_{21} phase measurements for the 3 dB and 6 dB attenuators (see figures 6 and 12). This suggests the presence of similar systematic errors in some of the systems.

The above descriptions of the data sets produced by the comparison exercise indicate clearly that this data is far from the "normal" data well-suited to traditional Gaussian statistical techniques. In fact the term "pathological" data could be a more appropriate description for some of these data sets. Under these circumstances, selecting more resistant statistical devices seems fully justified. The median and IQR have, in general, performed well as summary statistics aiding data analysis and interpretation. Occasionally however, for particularly pathological data sets, the IQR loses resistance and is subject to stretching due to two outliers on one side of the median (see, for example, the IQR reproducibility statistics for the S_{11} phase measurements for the 3 dB attenuator at 14.5 GHz and the 10 dB attenuator at 11.5 GHz).

7.2 THE FOUR MEASURED PARAMETERS

In this sub-section trends are examined in each of the four measurement parameters, S_{11} magnitude, S_{21} magnitude, S_{11} phase and S_{21} phase.

7.2.1 S_{11} magnitude results. The median values for the S_{11} magnitude results are similar for all four attenuators (less than 0.1). There is a slight increase in the reproducibilty IQR with frequency, but this relationship is not particularly marked.

Each S_{11} magnitude data set is tightly grouped in a single bunch with no obvious outliers. There are however a few unusual values, *eg* for the 3 dB attenuator at 17.5 GHz and 26.5 GHz. In each case the range of values in a data set is within 0.03 and is often considerably better.

7.2.2 S_{21} magnitude results. The spread of results for all the S_{21} magnitude data sets increases with frequency. The results in each data set are tightly grouped in a single bunch and their are no obvious outliers. However in a number of data sets for the 70 dB attenuator an unusual value appears to one side of the bunch (*eg* at 23.5 GHz and 26.5 GHz). Closer inspection of the data revealed that these values were from one participant whose results exhibited a periodic rippling with frequency. There are no such unusual values in the data sets for the other three attenuators.

For the 70 dB attenuator, the variations within each data set were all less than 4 dB. For the 3 dB, 6 dB and 10 dB attenuators, the variations within each data set were all less than 0.2 dB.

7.2.3 S_{11} phase results. For each attenuator, the median values for the S_{11} phase results vary considerably with frequency. This is to be expected as the reflected signal will be a composite of reflections from electrical discontinuities distributed throughout the device. Normalising the results to the median value removes this effect aiding subsequent interpretation of the data sets.

The spread of S_{11} phase results will depend on the magnitude of the reflected signal. As S_{11} magnitude gets smaller it becomes more difficult to discern the phase of the reflected signal and so the spread of S_{11} phase results will tend to increase. This should be taken into account when comparing the IQRs of S_{11} phase data sets in this exercise.

The S_{11} phase results represent the most erratic data obtained by this comparison exercise. All the characteristics discussed in the previous sub-section are to be found in these data sets. Bunching around the median value is exhibited by the majority of data sets. The range of these values is approximately 45°, with occasional unusual values just outside this range (*eg* at 2.5 GHz, 17.5 GHz and 25 GHz, for the 6 dB attenuator – figure 11), and an appreciable number of outliers near the ±180° boundaries. There is also some evidence of bunching into two distinct groups – see, for example, the data set at 22 GHz for the 3 dB attenuator, where there are two unusual values very close to each other. The data sets containing two outliers (at 14.5 GHz for the 3 dB attenuator and 11.5 GHz for the 10 dB attenuator) could also be considered candidates for this phenomenon.

7.2.4 S_{21} phase results. The S_{21} phase results of all the attenuators also vary considerably with frequency. However in this case, it is due primarily to the length of the item, introducing a frequency dependent phase change. Again, normalising the results to the median value removes this effect.

As with the S_{21} magnitude data, the variation in the results increases with frequency. For the 3 dB, 6 dB and 10 dB attenuators, the range of values in each data set (except one) is within 2.5°. The one unusual value occurs with the 10 dB attenuator at 8.5 GHz. This value is so unusual, viewed in context with the spread in the rest of the data, that it should probably be classed as an outlier. There is also a noticeable trend in the results for the 3 dB and 6 dB attenuators (and to a lesser extent, for the 10 dB attenuator) for results to bunch into two distinct groups. This can be seen clearly by looking sideways along the horizontal axis of the graphs. (This works best by viewing from the high frequency end.)

The values are more erratic for the 70 dB attenuator than the other attenuators. There are a number of unusual values (*eg* at 22 GHz, 23.5 GHz and 26.5 GHz) in the data, and even an outlier at 26.5 GHz (identified by the ↑+111 symbol). Ignoring these unusual values and outliers, the range of values in the data sets is less than 30°. The trend of bunching around two distinct values is not present in these data sets.

7.3 COMPARING REPEATABILITY AND REPRODUCIBILITY

This section examines trends in the values for the repeatability and reproducibility IQR statistics (these values are given in tables 1 to 8). The values can be further summarised using the median of each set of IQR values (one for the repeatability IQR and one for the reproducibility IQR) for each attenuator. The median of the IQR, M_{IQR}, represents an "average" for the spread, or scale, of values within all data sets for each attenuator. This makes it a good summary statistic for the data and allows repeatability and reproducibility to be compared directly. Values for M_{IQR} are given in the following tables.

Attenuator	S_{11} Magnitude (lin)		S_{11} Phase (degrees)	
	M_{IQR} Repeat	M_{IQR} Repro	M_{IQR} Repeat	M_{IQR} Repro
3 dB	0.0003	0.0021	1.23	9.84
6 dB	0.0002	0.0025	0.62	6.77
10 dB	0.0003	0.0021	0.92	8.49
70 dB	0.0003	0.0018	0.72	6.22

Summary statistics for S_{11} M_{IQR} values for repeatability and reproducibility for each attenuator.

Attenuator	S_{21} Magnitude (dB)		S_{21} Phase (degrees)	
	M_{IQR} Repeat	M_{IQR} Repro	M_{IQR} Repeat	M_{IQR} Repro
3 dB	0.0048	0.0077	0.17	0.63
6 dB	0.0035	0.0112	0.13	0.69
10 dB	0.0018	0.0077	0.16	0.66
70 dB	0.18	0.14	1.34	1.38

Summary statistics for S_{21} M_{IQR} values for repeatability and reproducibility for each attenuator.

Comparing the repeatability M_{IQR} with the reproducibility M_{IQR} reveals something about the types of errors likely to be present in the measuring systems. We will look first at the reflection measurements (S_{11}) then the transmission measurements (S_{21}).

7.3.1 Reflection measurements $- S_{11}$. The repeatability values for S_{11} magnitude and S_{11} phase are nominally an order of magnitude larger than the respective reproducibility values. This indicates that systematic errors (*eg* calibration errors) in the different measuring instruments dominate the random errors (*eg* due to connector repeatability and instrument noise) in the measurements. Systematic errors in calibration are often caused by invalid assumptions about the characteristics of the calibration artefacts. For example, it is common to assume that a "matched" load, used as a reflection standard, produces zero reflection, *ie* is perfect.

The assumption that systematic errors dominate random errors in the reflection measurements agrees with observations made during the first ANAMET measurement comparison exercise [3,4]. This could indicate that systematic errors are likely to dominate in other similar types of measurement. (For example, reflection measurements of items fitted with other connectors, such as GPC-7, GPC-2.4, K- and V-connectors.)

7.3.2 Transmission measurements $- S_{21}$. 3 dB, 6 dB and 10 dB attenuators: The reproducibility M_{IQR} values are approximately 4 times larger than the repeatability values for these items. (The reproducibility M_{IQR} values are actually between 1.6 and 5.3 times larger than the repeatability values, but 4 times is a realistic summary value for the comparison.) This indicates that, although systematic errors are still likely to be larger than the random errors, the random errors are no longer insignificant and would need to be considered when estimating the uncertainties in this type of measurement.

70 dB attenuator: the reproducibility M_{IQR} values are of the same order as the repeatability values. This indicates that random errors dominate the measurements at this level of attenuation. We can make this deduction by noting that the dispersion in the reproducibility measurements is due to the presence of both random and systematic errors whereas the dispersion in the repeatability measurements is due solely to random errors. Comparable values for the repeatability and reproducibility therefore indicates that any contribution due to systematic effects must be small in relation to contributions due to random effects.

Another indication that the dispersion at 70 dB is predominantly due to random errors is that there is no real reason to suspect that the size of systematic errors will be a function of the attenuation level being measured. In other words, we would expect systematic errors to be of a similar size (on a linear scale) for all four values of attenuation measured.

The most significant sources of random errors in the measuring instruments are likely to be due to connector repeatability (no two connections are ever identical) and electrical noise. As with the systematic errors, the connector repeatability errors are not expected to vary as a function of attenuation level so could not account for the sudden dominance of the random errors. However, the contribution due to electrical noise *will* vary with attenuation level and will increase as the value of attenuation increases. (As a signal descends into the noise floor of a measuring instrument it becomes difficult to detect and ultimately only the "random" noise is detected.)

7.4 PIN-DEPTH MEASUREMENTS

The pin-depth gauge measurements, presented graphically in figure 25 and summarised in table 9, provide useful information about this type of measurement:

(i) The graph shows that, for each connector gauged, one value was consistently far-removed from the majority of values. Closer inspection of the participants results revealed that these values were all supplied by one laboratory. Following a subsequent investigation, the laboratory discovered that their gauge had been consistently misread producing values nominally an order of magnitude higher than the other participants. Such a mistake is easily made and might indicate the need for clearer labelling of the scales on such gauges.

Examination of the median values for pin-depth measurements given in the table shows that the values for the male connectors are consistently higher than the values for the female connectors. This might be a consequence of the manufacturing process for this type of attenuator.

The IQR values for male and female connectors are similar, indicating that the ability to measure the different sexes of connector are similar.

The range of values within each of the data sets, excluding the values obviously in error, for all connectors gauged in this exercise is within 15μm.

8 CONCLUSIONS

The measurement comparison exercise detailed in this report has produced some very interesting results which give an increased awareness of the difficulties in making measurements of this kind. Generally, the spread of values produced by the participants' results were small indicating that the measurement parameters can usually be determined reliably – this is encouraging. However, the tendency for these systems to produce results containing gross errors will be of concern to *all* users of such instruments. (Subsequent diagnostics performed by the participants have resolved some, but by no means all, of the problems which may have been responsible for these errors.) Clearly, further comparisons are required to improve the understanding of the mechanisms of these highly automated measurement systems.

The comparison of repeatability and reproducibility statistics has gained further insight into the likely sources of significant errors present in the measurements. It has indicated that for the reflection measurements, systematic errors dominate, whereas for transmission measurements, both random and systematic errors are significant. The random component of error in the transmission measurements was found to be a function of the value of attenuation being measured and becomes the dominant contribution at high levels of attenuation (*ie* 70 dB). Random errors at these levels of attenuation are likely to be caused by the small size of the signals, relative to the electrical noise, that require detection by the network analysers.

It cannot be claimed that the above deductions on the relative contributions of random and systematic errors have been proven categorically by the results of this exercise. However, they do add to the growing catalogue of knowledge which increases understanding of the modern measuring instruments used for RF and microwave network analysis.

9 ACKNOWLEDGEMENTS

The authors would like to thank the following for participating in the exercise and for supplying details about their measurement systems; Mr A Edwards (Assessment Services Ltd), Mr A P Gregory (NPL Teddington), Mr S J Harter (DRA Aquila), Mr D J Hepworth (EEV Ltd), Mr I Instone (Hewlett-Packard Ltd), Mr V Lopez-Fernandez (INTA), Dr P R Merki (Swiss Telecom PTT).

The ANAMET club is part-funded by the National Measurement System Policy Unit of the Department of Trade and Industry, UK.

10 REFERENCES

[1] International vocabulary of basic and general terms in metrology, Geneva, Switzerland, International Organization for Standardization, 1993 (2nd edition).

[2] International Organization for Standardization Standard, ISO 5725-2:1994(E), *Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic methods for the determination of repeatability and reproducibility of a standard measurement method.*

[3] Ridler, N.M. and Jones, G.D. Comparison assesses the quality of network measurements. *Microwaves & RF*, January 1995, 101-104.

[4] Jones, G.D., Ridler, N.M., Gentle, D.G., Hepworth, D.J., James, S., Medley, J.C., Potter, C.M. and Williams, B. ANAMET comparison of type-N VSWR measurements. *20th Automated RF & Microwave Measurement Society (ARMMS) Conference*, University of Nottingham, March 1994, paper No 6.

GRAPHS AND TABLES

The graphs and tables presenting the results of the comparison exercise follow on pages 15 to 40.

3 dB ATTENUATOR

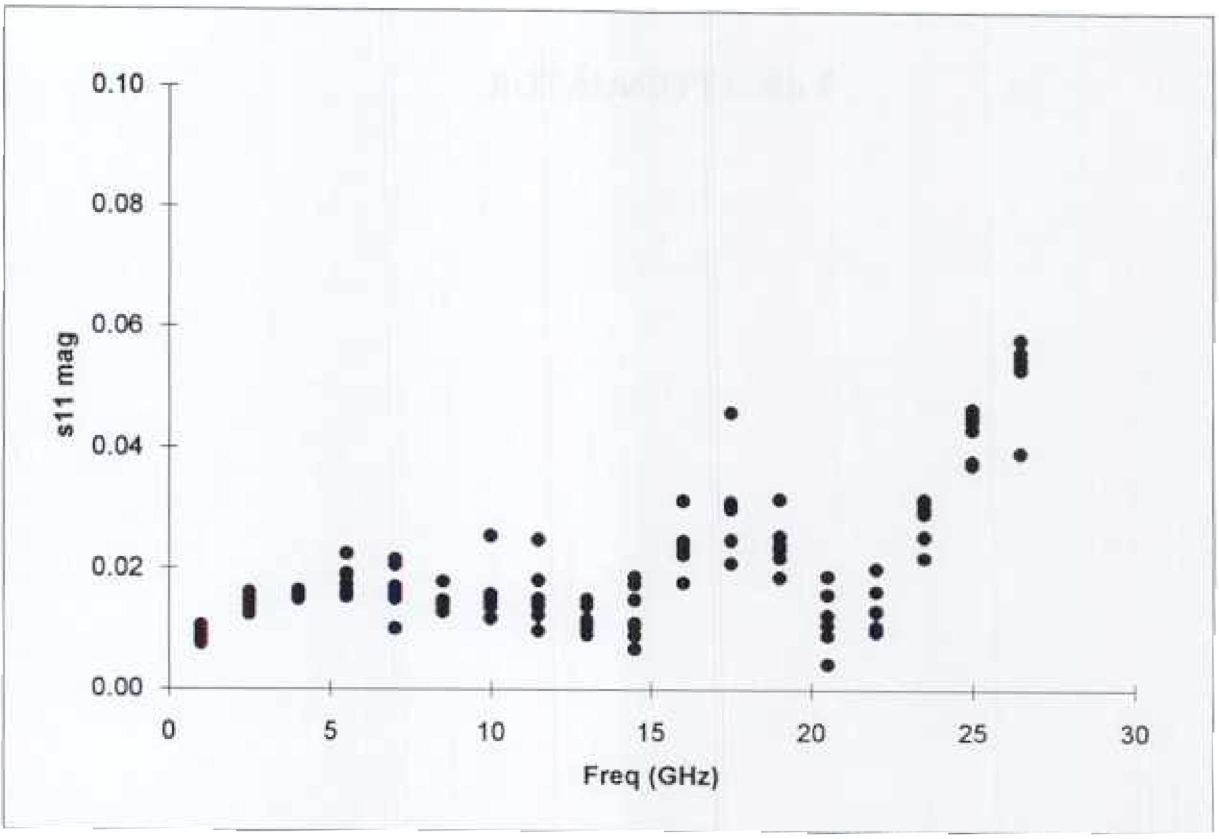
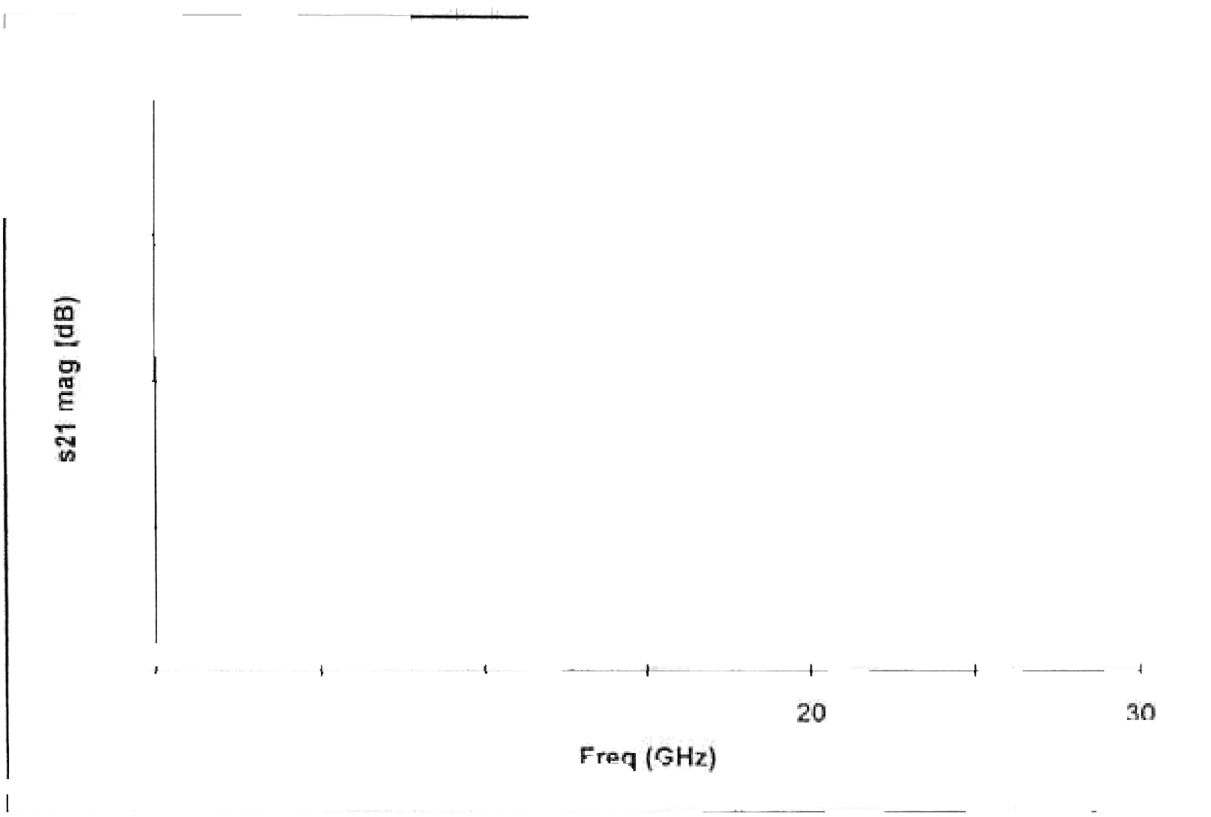


Figure 3dB attenuator magnitude



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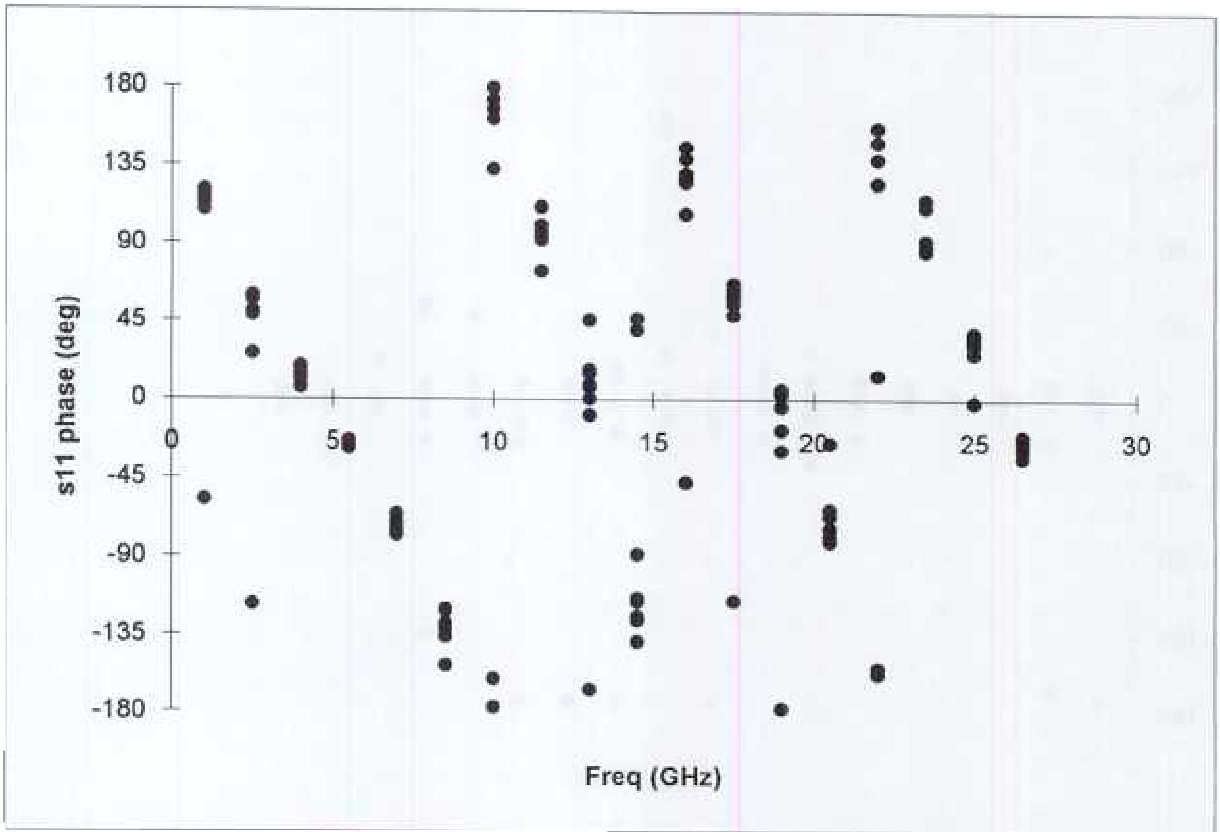
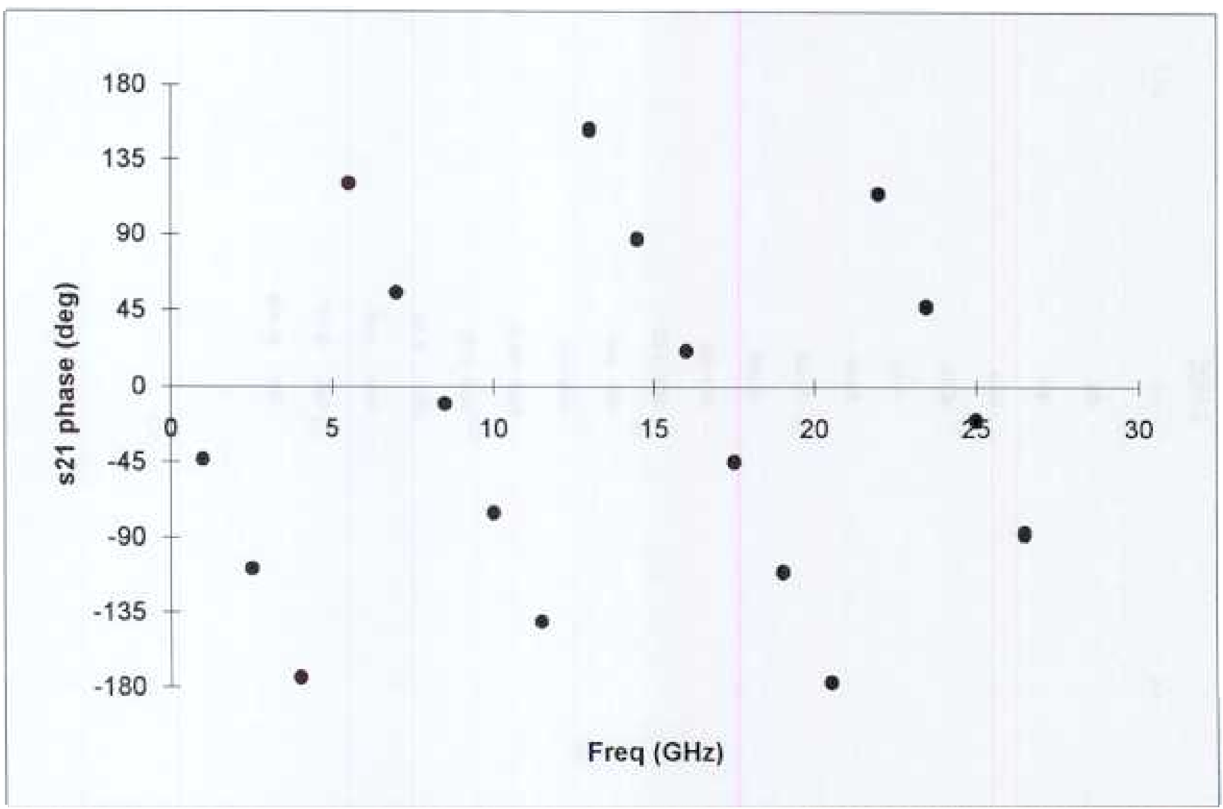


igı 3dB attenuator phase



igı 3dB attenuator s2 phase

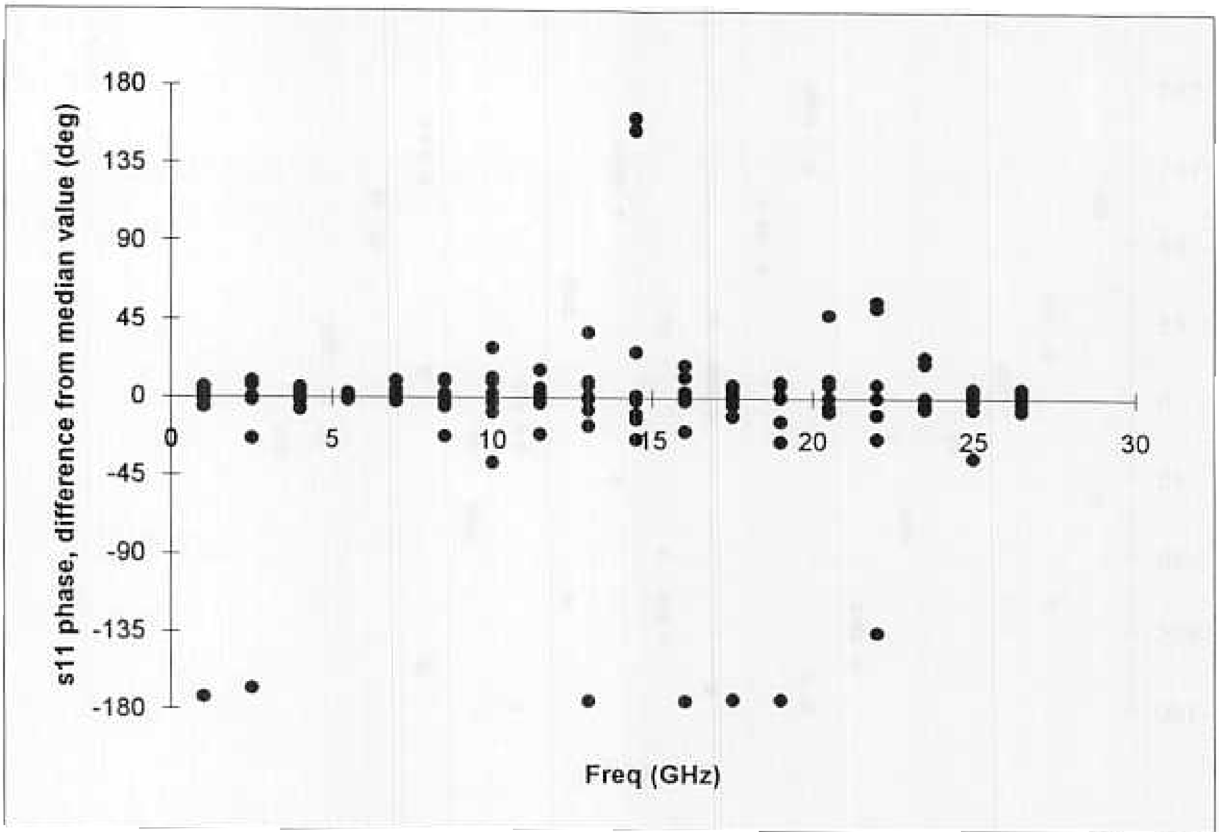


Figure 5 : 3dB attenuator, s11 phase, difference from median value

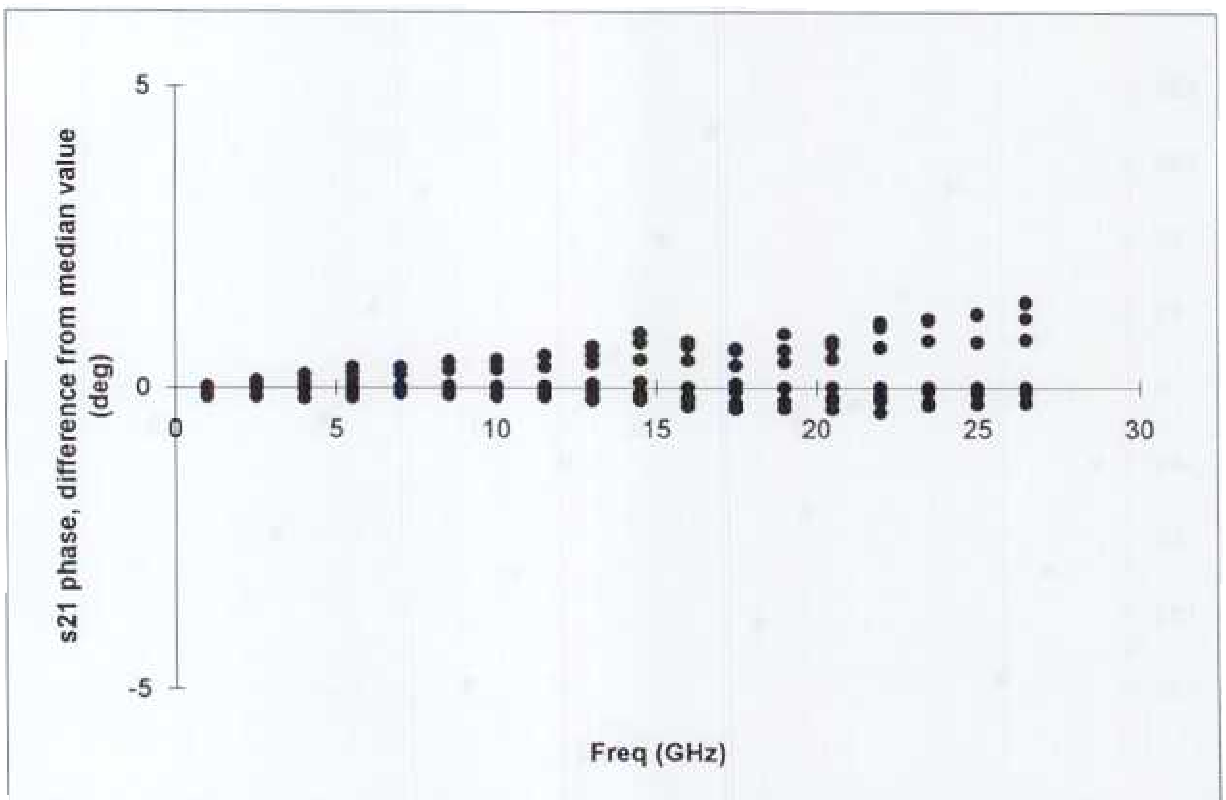


Figure 6 : 3dB attenuator, s21 phase, difference from median value

Table 1 : 3dB attenuator, s11

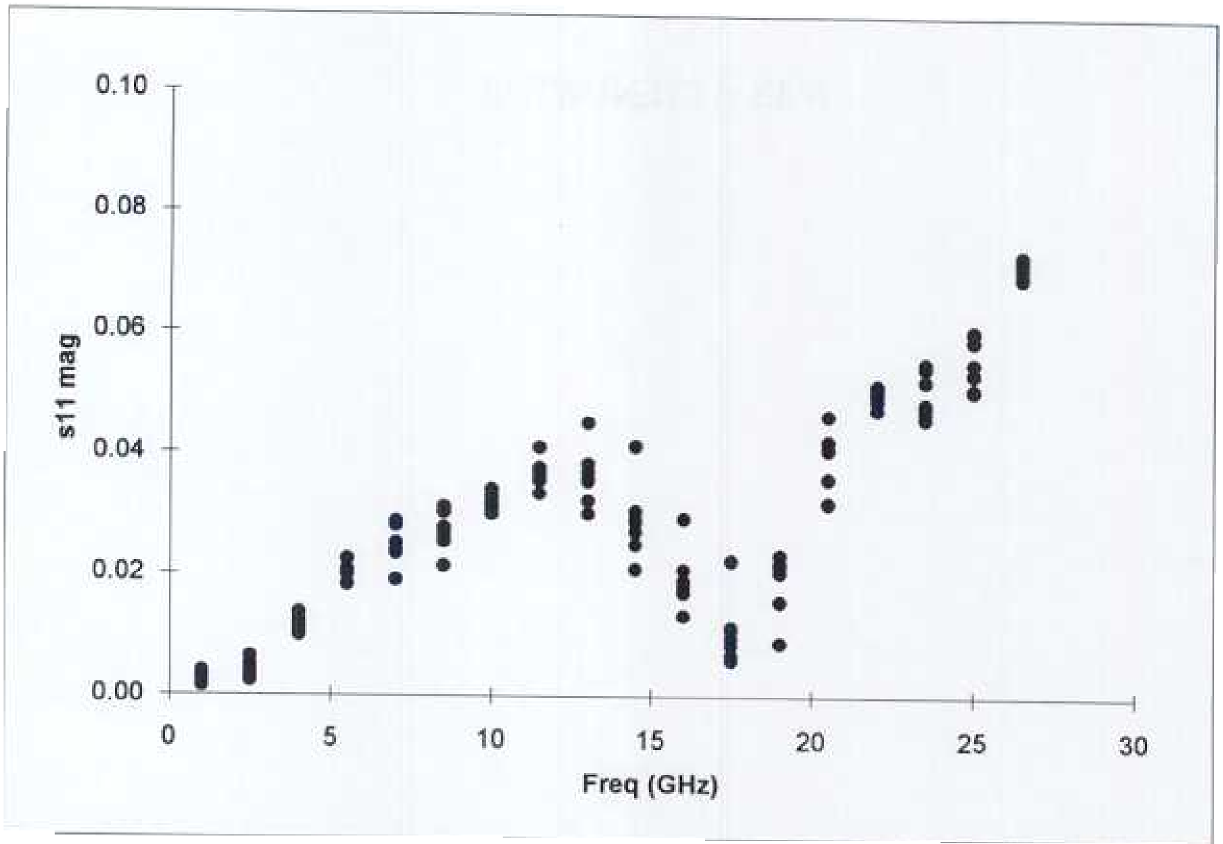
Frequency (GHz)	Linear magnitude			Phase (degrees)		
	Median	IQR - Repeat	IQR - Repro	Median	IQR - Repeat	IQR - Repro
1.0	0.0085	0.0001	0.0017	+114.61	0.67	4.81
2.5	0.0140	0.0002	0.0011	+50.18	0.45	14.46
4.0	0.0157	0.0002	0.0004	+13.56	0.33	5.42
5.5	0.0181	0.0001	0.0030	-26.62	0.33	1.08
7.0	0.0161	0.0003	0.0025	-75.82	0.39	3.55
8.5	0.0144	0.0002	0.0007	-131.00	0.75	6.64
10.0	0.0147	0.0002	0.0020	+170.38	1.47	14.17
11.5	0.0140	0.0003	0.0024	+95.37	0.93	4.72
13.0	0.0111	0.0003	0.0019	+7.68	2.00	16.97
14.5	0.0108	0.0004	0.0054	-115.14	2.71	68.63
16.0	0.0236	0.0007	0.0016	+127.44	1.21	11.43
17.5	0.0304	0.0007	0.0021	+59.02	1.05	8.53
19.0	0.0237	0.0004	0.0021	-4.12	2.60	23.46
20.5	0.0107	0.0011	0.0042	-73.87	4.34	11.15
22.0	0.0130	0.0010	0.0043	+149.00	5.67	46.48
23.5	0.0293	0.0003	0.0051	+92.19	2.07	13.60
25.0	0.0446	0.0007	0.0051	+32.59	1.96	6.73
26.5	0.0548	0.0004	0.0021	-26.39	1.24	7.80

Table 2 : 3dB attenuator, s21

Frequency (GHz)	Log magnitude (dB)			Phase (degrees)		
	Median	IQR - Repeat	IQR - Repro	Median	IQR - Repeat	IQR - Repro
1.0	2.6453	0.0005	0.0050	-43.62	0.04	0.06
2.5	2.6688	0.0016	0.0015	-108.92	0.06	0.11
4.0	2.6968	0.0016	0.0034	-174.22	0.06	0.19
5.5	2.7296	0.0009	0.0048	+120.46	0.09	0.25
7.0	2.7639	0.0013	0.0043	+55.07	0.10	0.30
8.5	2.8069	0.0022	0.0041	-10.34	0.12	0.40
10.0	2.8519	0.0027	0.0047	-75.82	0.14	0.46
11.5	2.9059	0.0046	0.0088	-141.43	0.15	0.52
13.0	2.9612	0.0051	0.0097	+152.83	0.16	0.62
14.5	3.0290	0.0041	0.0058	+86.91	0.17	0.67
16.0	3.0985	0.0063	0.0140	+20.90	0.18	0.69
17.5	3.1792	0.0067	0.0209	-45.23	0.18	0.72
19.0	3.2520	0.0075	0.0067	-111.68	0.24	0.65
20.5	3.3483	0.0057	0.0120	-178.40	0.26	0.79
22.0	3.4337	0.0057	0.0106	+114.40	0.28	1.01
23.5	3.5394	0.0072	0.0144	+47.00	0.32	1.12
25.0	3.6457	0.0108	0.0236	-20.70	0.34	1.09
26.5	3.7450	0.0148	0.0309	-88.80	0.37	1.15

NB: IQR - Repeat is Inter-Quartile Range for repeatability data
IQR - Repro is Inter-Quartile Range for reproducibility data

6 dB ATTENUATOR



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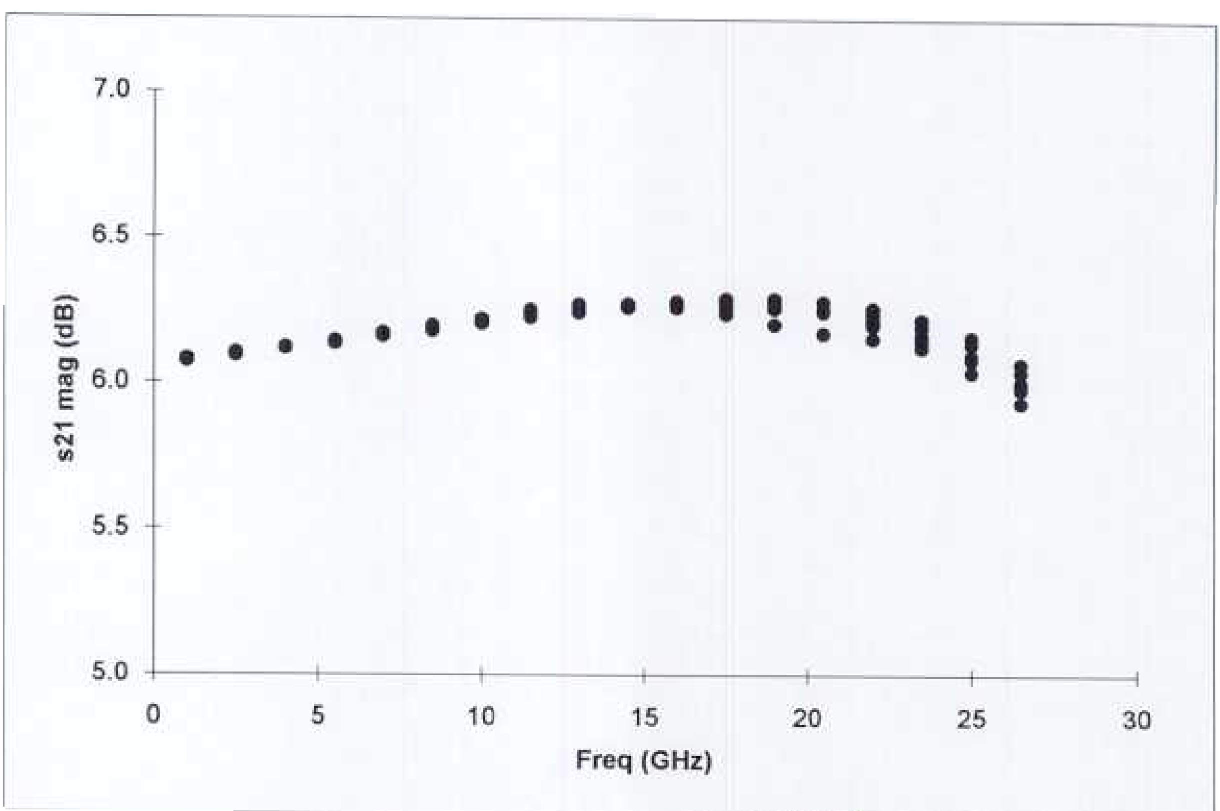

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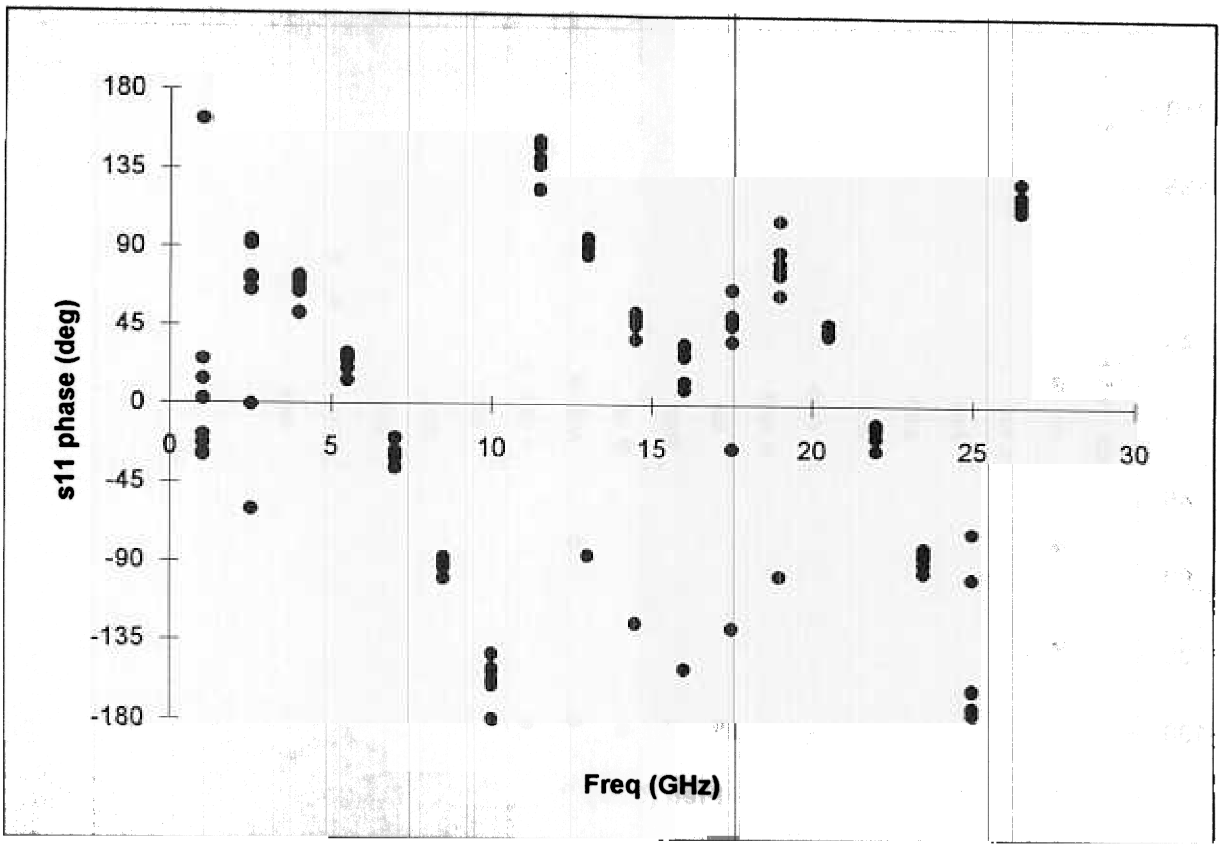

Figure 9 : 6dB attenuator, s11 phase

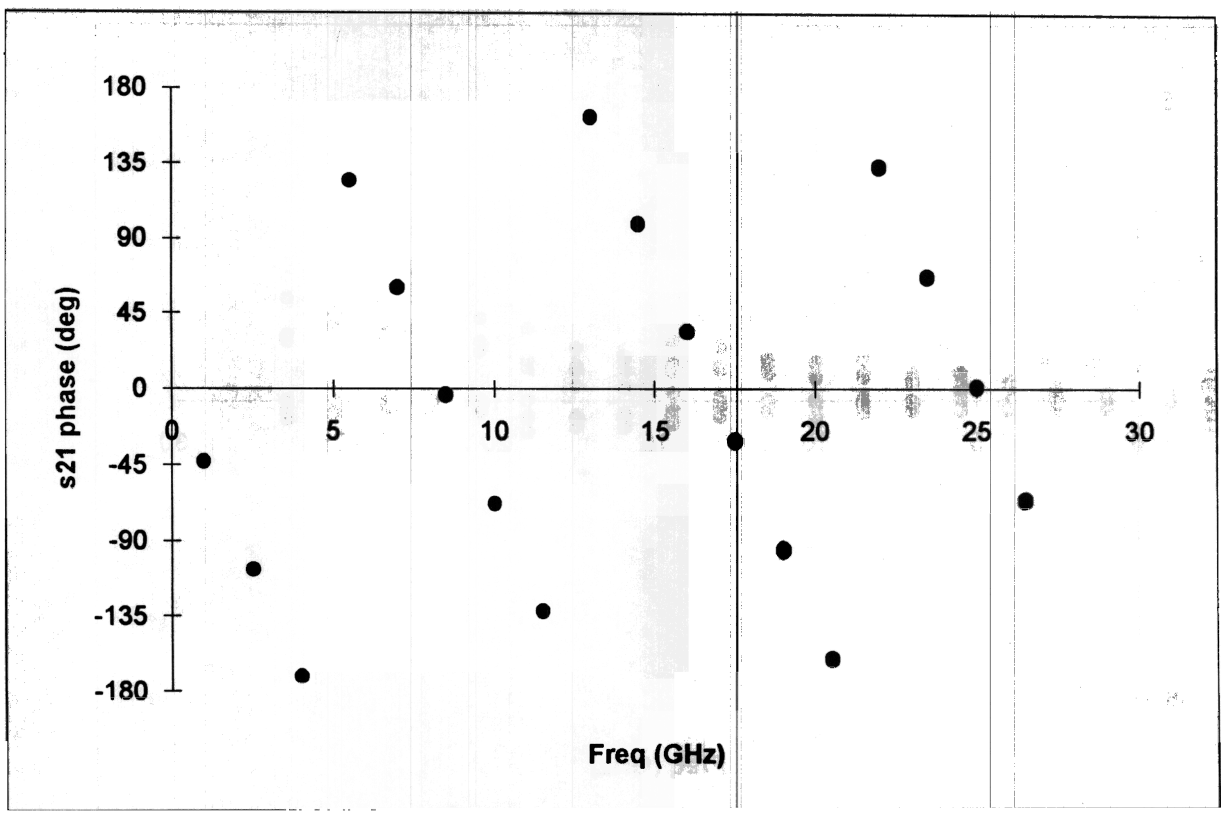

Figure 10 : 6dB attenuator, s21 phase

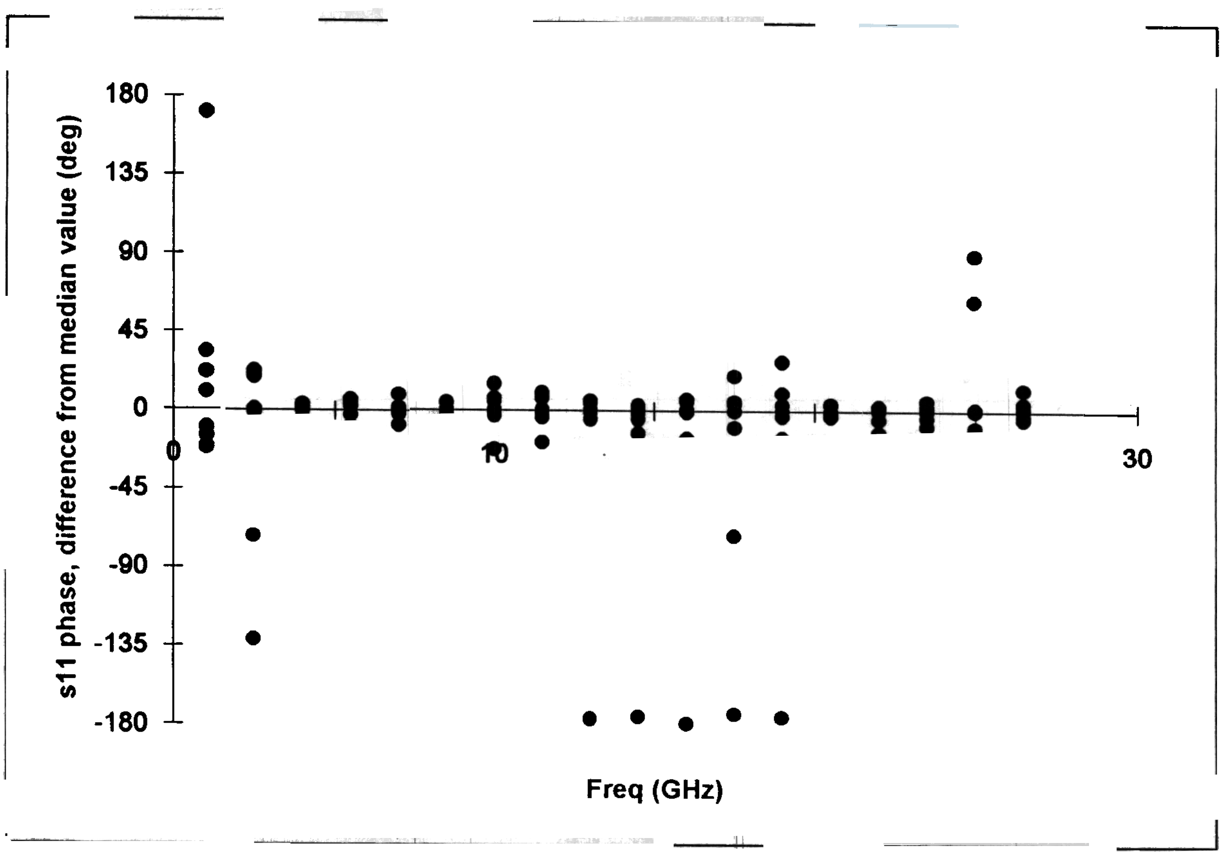

Figure 11 : 6dB attenuator, s11 phase, difference from median value

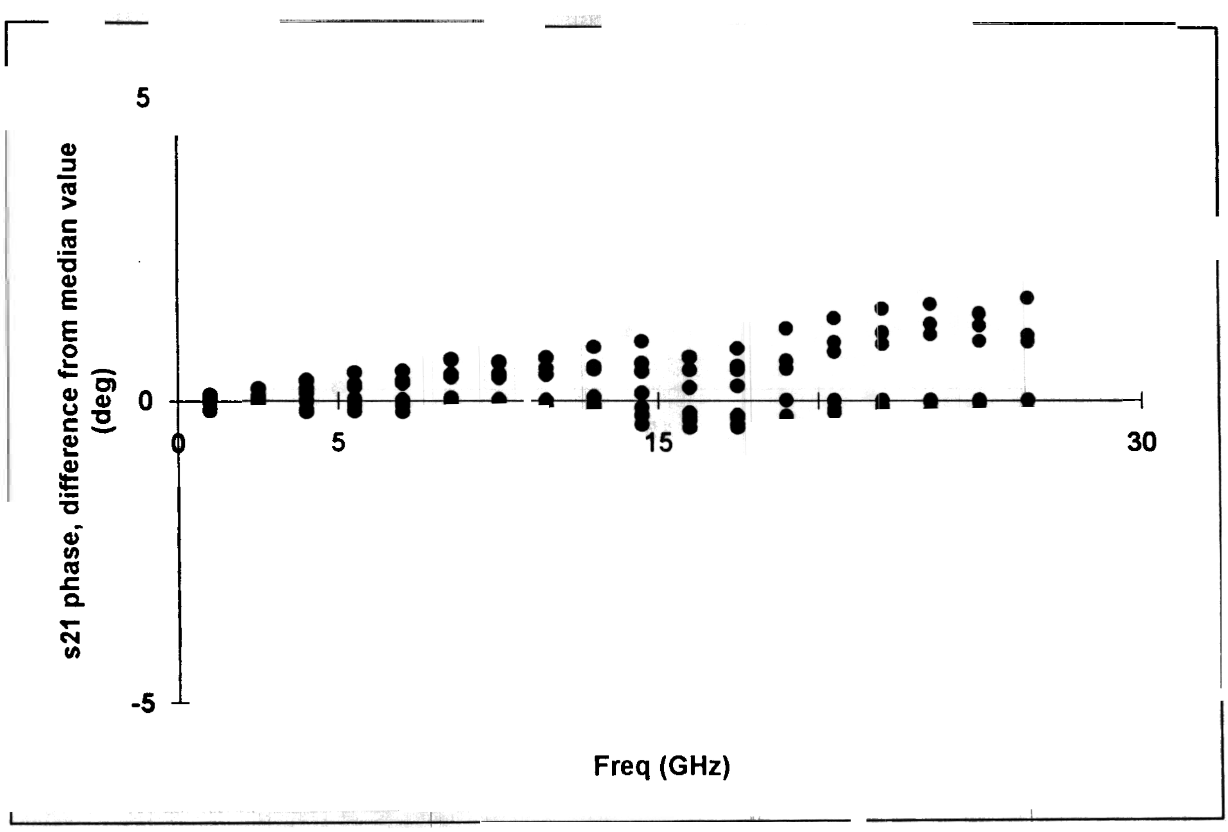

Figure 12 : 6dB attenuator, s21 phase, difference from median value

Table 3 : 6dB attenuator, s11

Frequency (GHz)	Linear magnitude			Phase (degrees)		
	Median	IQR - Repeat	IQR - Repro	Median	IQR - Repeat	IQR - Repro
1.0	0.0025	0.0001	0.0013	-7.81	2.71	40.76
2.5	0.0038	0.0001	0.0010	+71.62	0.99	42.84
4.0	0.0116	0.0001	0.0015	+69.93	0.48	5.97
5.5	0.0201	0.0001	0.0007	+22.39	0.52	6.43
7.0	0.0250	0.0002	0.0020	-28.75	0.15	2.42
8.5	0.0265	0.0001	0.0027	-91.58	0.30	2.19
10.0	0.0316	0.0001	0.0010	-158.02	0.48	7.70
11.5	0.0363	0.0002	0.0023	+141.84	0.69	3.71
13.0	0.0359	0.0002	0.0027	+90.75	0.43	3.32
14.5	0.0288	0.0002	0.0029	+50.30	0.73	8.91
16.0	0.0187	0.0002	0.0032	+28.51	1.41	21.75
17.5	0.0091	0.0002	0.0045	+46.61	1.14	28.93
19.0	0.0214	0.0002	0.0038	+78.38	1.66	15.68
20.5	0.0410	0.0005	0.0038	+43.60	0.47	2.29
22.0	0.0501	0.0005	0.0014	-13.28	1.44	5.68
23.5	0.0484	0.0003	0.0060	-87.00	0.44	4.00
25.0	0.0551	0.0010	0.0073	-163.40	0.90	42.17
26.5	0.0717	0.0006	0.0018	+117.22	0.56	7.11

Table 4 : 6dB attenuator, s21

Frequency (GHz)	Log magnitude (dB)			Phase (degrees)		
	Median	IQR - Repeat	IQR - Repro	Median	IQR - Repeat	IQR - Repro
1.0	6.0745	0.0009	0.0069	-42.89	0.04	0.09
2.5	6.0938	0.0012	0.0072	-107.09	0.05	0.12
4.0	6.1173	0.0008	0.0047	-171.31	0.06	0.20
5.5	6.1402	0.0015	0.0045	+124.45	0.07	0.28
7.0	6.1638	0.0021	0.0064	+60.22	0.07	0.36
8.5	6.1882	0.0020	0.0052	-4.06	0.08	0.46
10.0	6.2125	0.0025	0.0066	-68.32	0.10	0.51
11.5	6.2365	0.0030	0.0107	-132.70	0.10	0.56
13.0	6.2535	0.0029	0.0180	+162.82	0.12	0.64
14.5	6.2665	0.0040	0.0090	+98.32	0.14	0.74
16.0	6.2688	0.0046	0.0116	+33.59	0.15	0.85
17.5	6.2705	0.0057	0.0134	-31.26	0.17	0.84
19.0	6.2650	0.0062	0.0155	-96.39	0.23	0.88
20.5	6.2569	0.0071	0.0171	-161.96	0.25	0.97
22.0	6.2200	0.0061	0.0231	+132.39	0.26	1.15
23.5	6.1680	0.0063	0.0310	+66.30	0.28	1.20
25.0	6.0911	0.0115	0.0328	-0.04	0.27	1.23
26.5	5.9943	0.0125	0.0347	-67.00	0.25	1.25

NB: IQR - Repeat is Inter-Quartile Range for repeatability data
IQR - Repro is Inter-Quartile Range for reproducibility data

10 dB ATTENUATOR

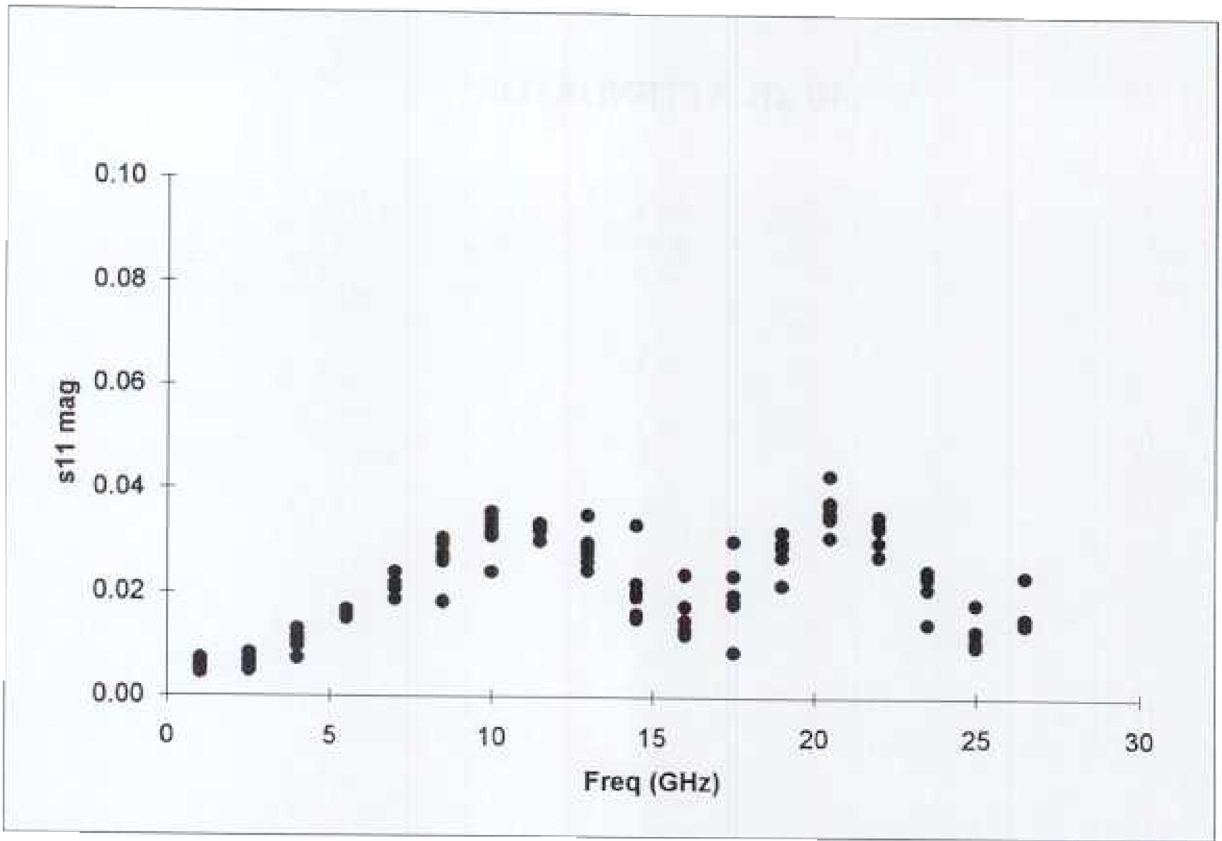

Figure 13 : 10dB attenuator, s11 magnitude

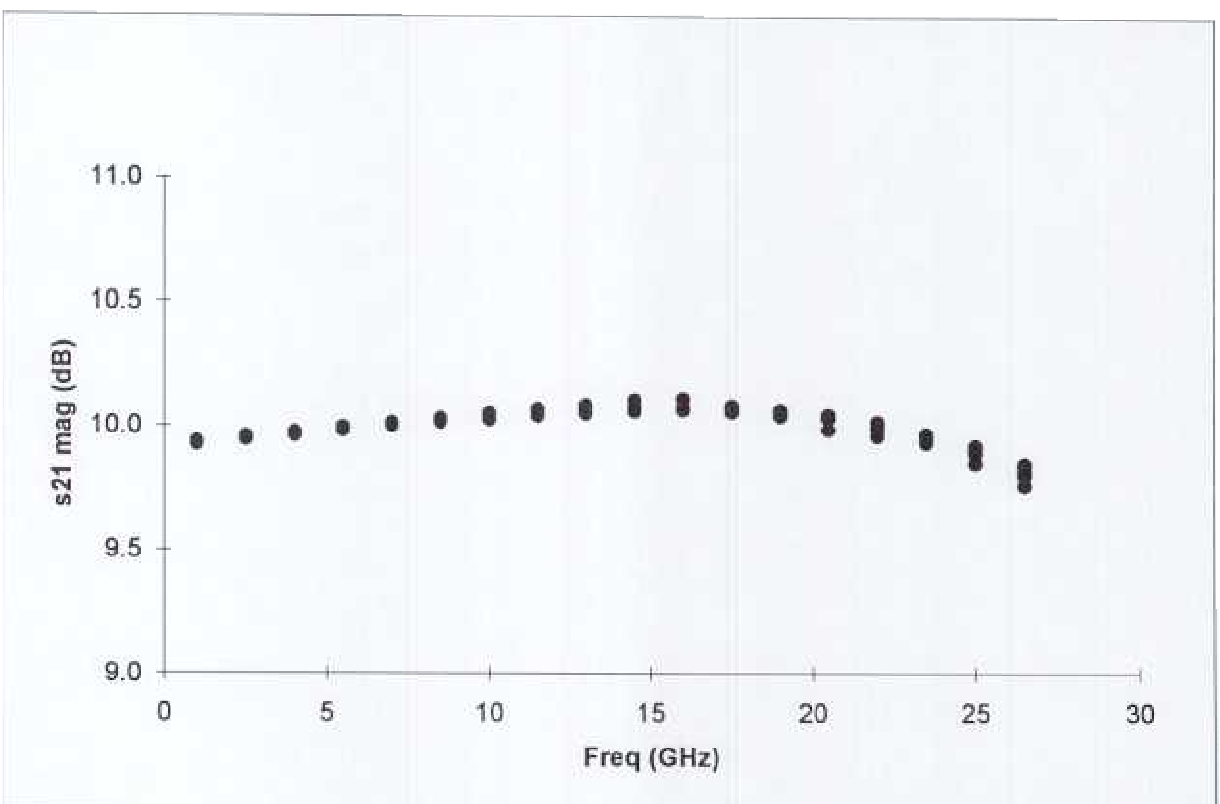

Figure 14 : 10dB attenuator, s21 magnitude (dB)

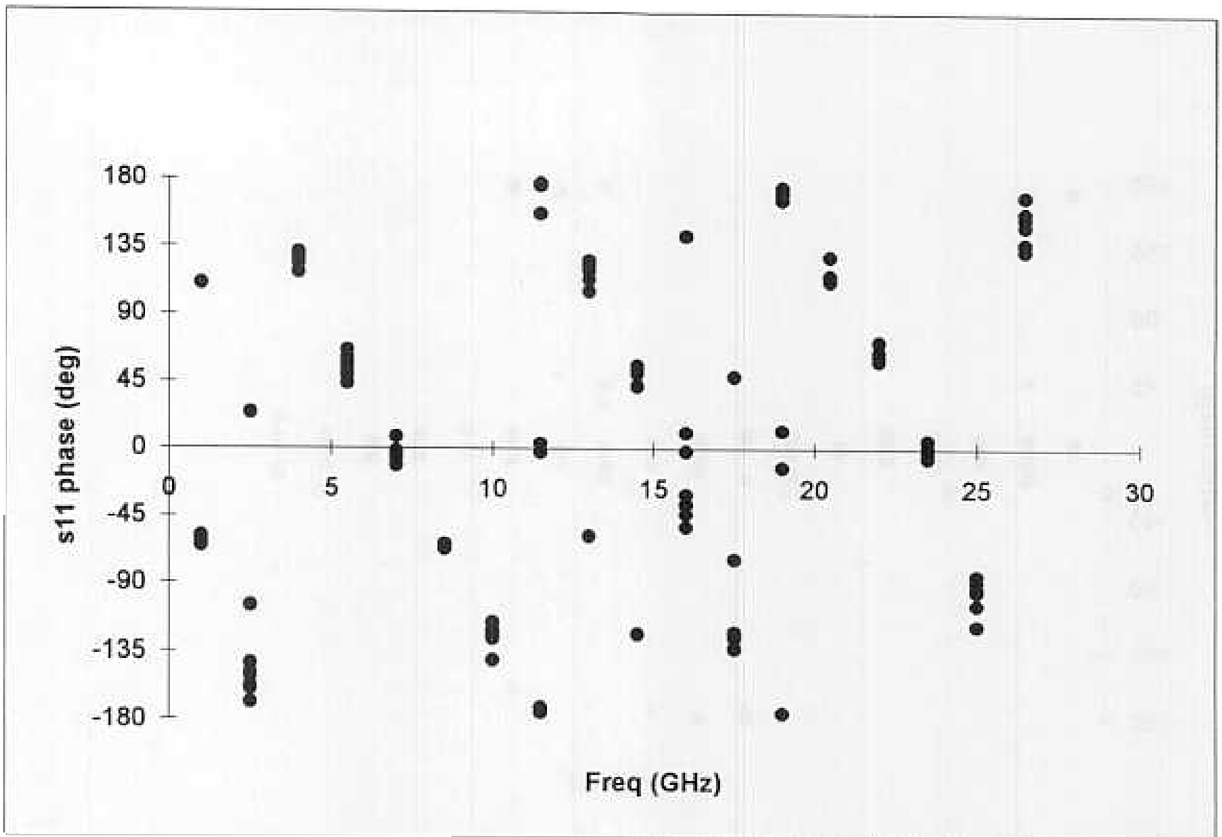

Figure 15 : 10dB .ator, s11 phase

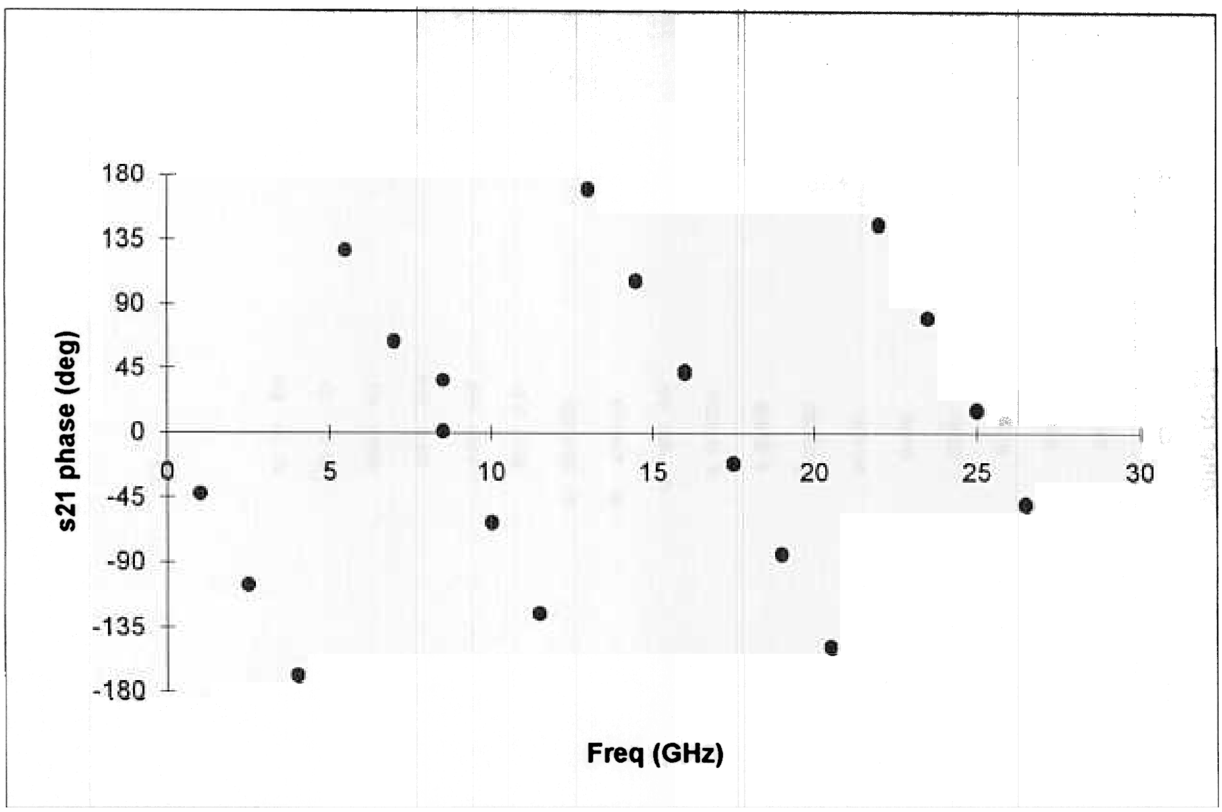

Figure 16 : 10dB attenuator, s21 phase

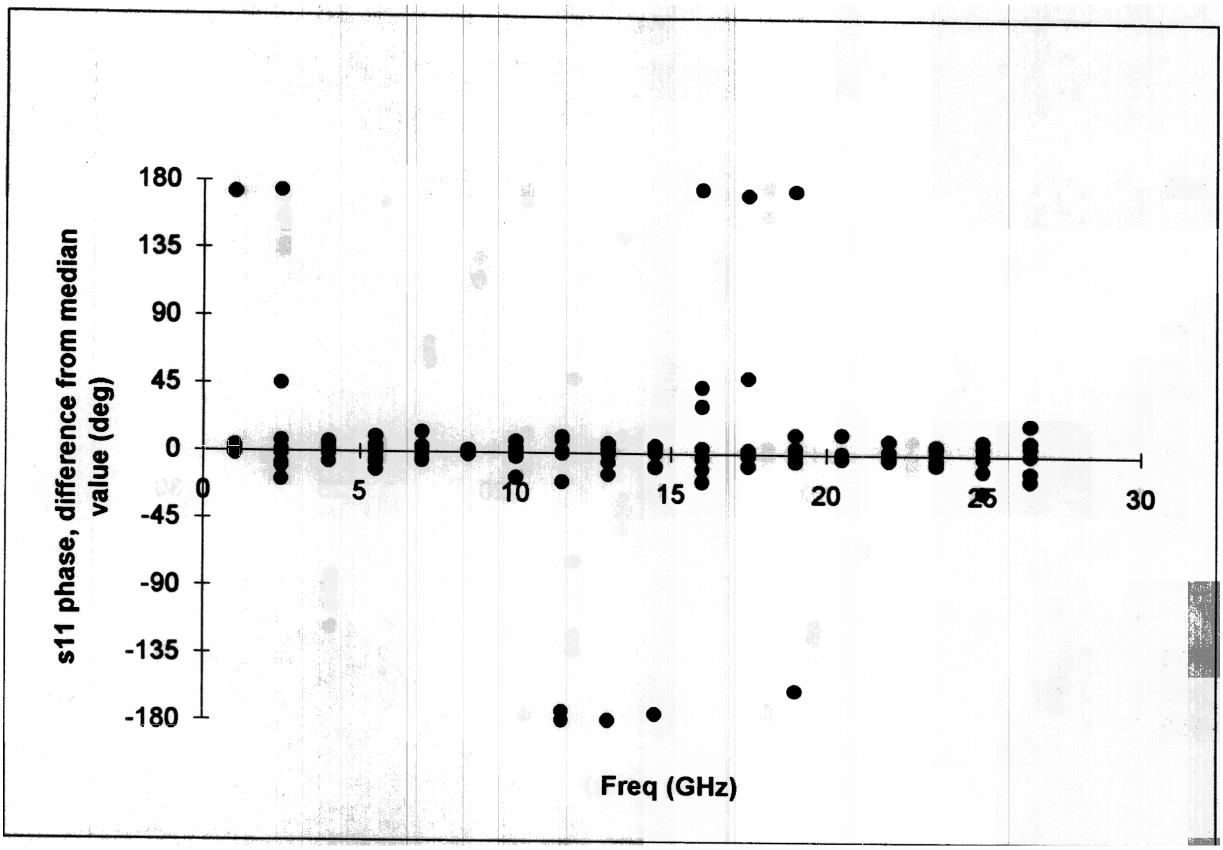

Figure 17 : 10dB attenuator, s11 phase, difference from median value

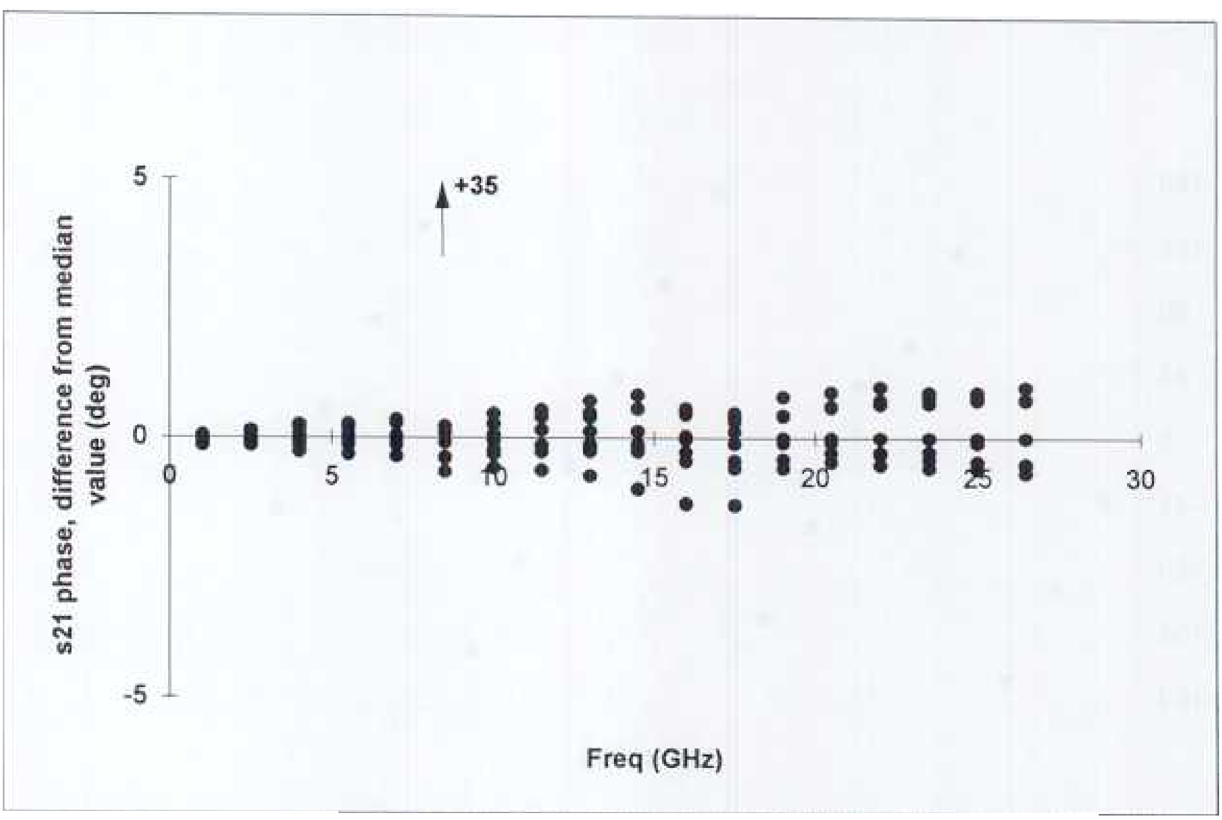

Figure 18 : 10dB attenuator, s21 phase, difference from median value

Table 5 : 10dB attenuator, s11

Frequency (GHz)	Linear magnitude Median	Linear magnitude IQR - Repeat	Linear magnitude IQR - Repro	Phase (degrees) Median	Phase (degrees) IQR - Repeat	Phase (degrees) IQR - Repro
1.0	0.0059	0.0001	0.0015	-62.45	1.02	2.67
2.5	0.0067	0.0002	0.0008	-150.24	1.99	24.78
4.0	0.0107	0.0001	0.0013	+124.39	0.75	5.06
5.5	0.0161	0.0001	0.0008	+55.92	0.31	8.18
7.0	0.0216	0.0002	0.0014	-5.79	0.34	4.32
8.5	0.0268	0.0002	0.0017	-65.68	0.11	1.53
10.0	0.0318	0.0003	0.0020	-123.90	0.10	4.36
11.5	0.0325	0.0001	0.0006	+176.35	0.37	60.80
13.0	0.0288	0.0003	0.0023	+119.60	0.42	11.30
14.5	0.0198	0.0006	0.0021	+51.00	0.82	11.03
16.0	0.0133	0.0007	0.0026	-34.13	2.24	40.36
17.5	0.0186	0.0004	0.0024	-124.87	1.10	22.38
19.0	0.0290	0.0003	0.0028	+171.11	0.69	11.53
20.5	0.0357	0.0009	0.0024	+115.11	1.30	7.28
22.0	0.0327	0.0009	0.0054	+62.60	1.22	2.62
23.5	0.0233	0.0006	0.0022	+0.43	1.35	6.81
25.0	0.0125	0.0004	0.0024	-93.94	4.56	8.80
26.5	0.0150	0.0010	0.0007	+148.70	1.32	18.86

Table 6 : 10dB attenuator, s21

Frequency (GHz)	Log magnitude (dB) Median	Log magnitude (dB) IQR - Repeat	Log magnitude (dB) IQR - Repro	Phase (degrees) Median	Phase (degrees) IQR - Repeat	Phase (degrees) IQR - Repro
1.0	9.9305	0.0012	0.0036	-42.32	0.02	0.09
2.5	9.9497	0.0017	0.0032	-105.71	0.06	0.16
4.0	9.9695	0.0010	0.0037	-169.04	0.04	0.29
5.5	9.9910	0.0018	0.0076	+127.64	0.05	0.33
7.0	10.0038	0.0013	0.0063	+64.25	0.07	0.40
8.5	10.0257	0.0013	0.0077	+1.09	0.09	0.53
10.0	10.0426	0.0018	0.0053	-62.46	0.09	0.52
11.5	10.0596	0.0012	0.0081	-126.04	0.12	0.60
13.0	10.0695	0.0015	0.0227	+170.38	0.15	0.64
14.5	10.0730	0.0016	0.0067	+106.68	0.17	0.79
16.0	10.0741	0.0025	0.0067	+42.97	0.18	0.81
17.5	10.0667	0.0024	0.0092	-20.88	0.19	0.81
19.0	10.0575	0.0031	0.0072	-85.09	0.25	0.69
20.5	10.0431	0.0025	0.0123	-149.60	0.27	0.81
22.0	10.0060	0.0059	0.0199	+145.70	0.28	1.00
23.5	9.9620	0.0038	0.0219	+80.70	0.30	1.08
25.0	9.9010	0.0056	0.0203	+15.30	0.33	1.05
26.5	9.8092	0.0105	0.0268	-50.50	0.34	1.26

NB: IQR - Repeat is Inter-Quartile Range for repeatability data
IQR - Repro is Inter-Quartile Range for reproducibility data

70 dB ATTENUATOR

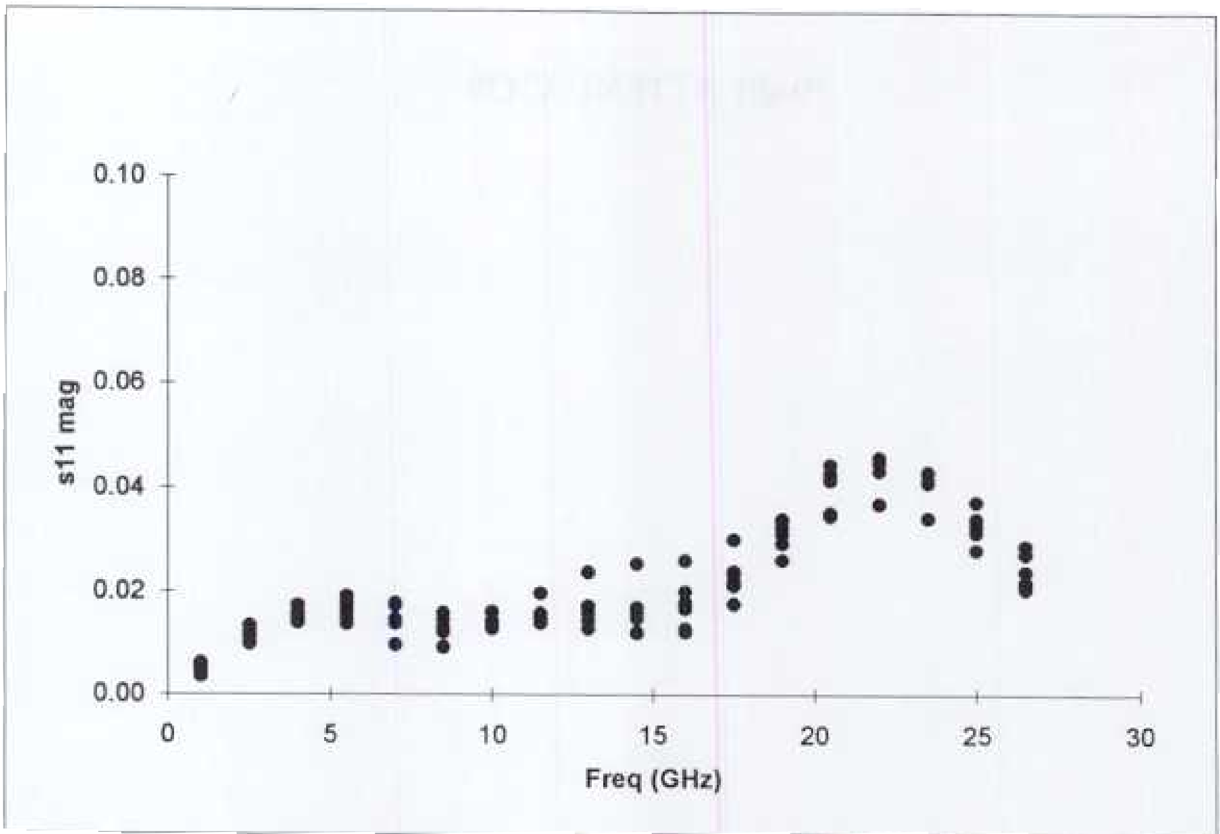

Figure 70dB attenuator magnitude

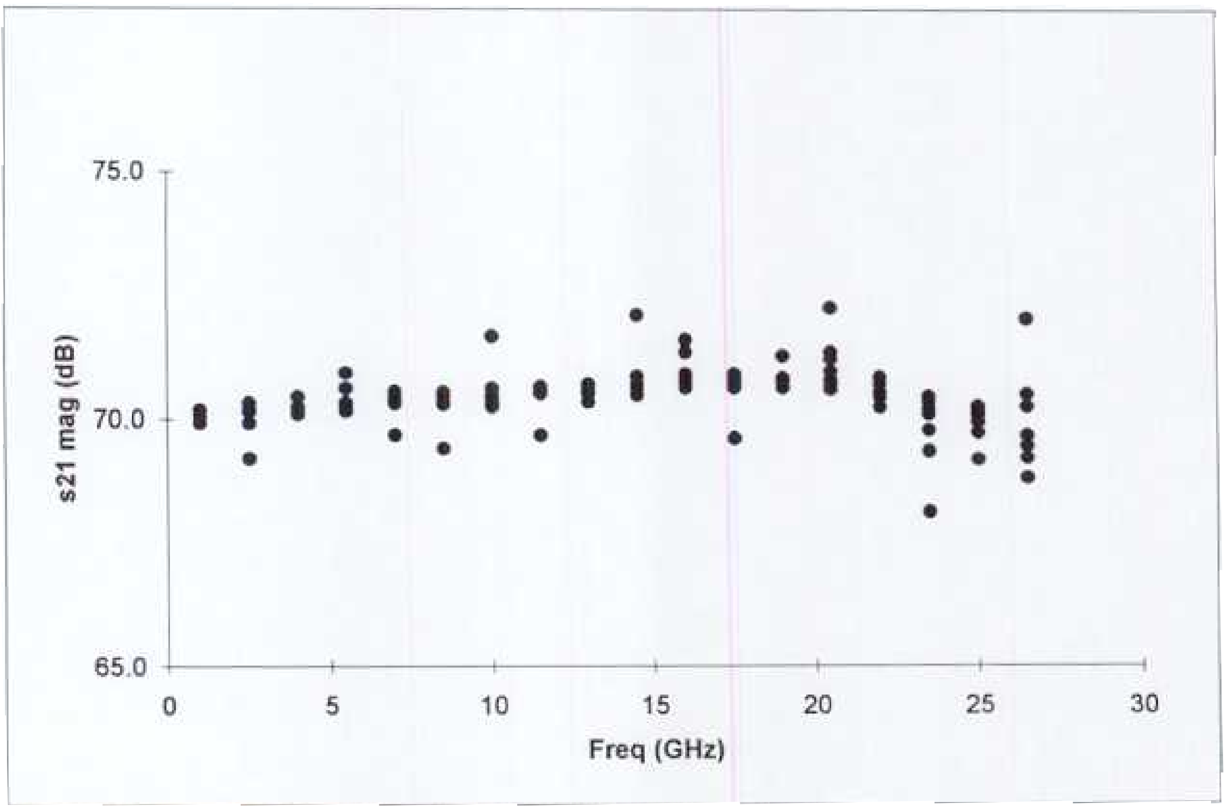

Figure 20 70dB attenuator s2 magnitude (dB)

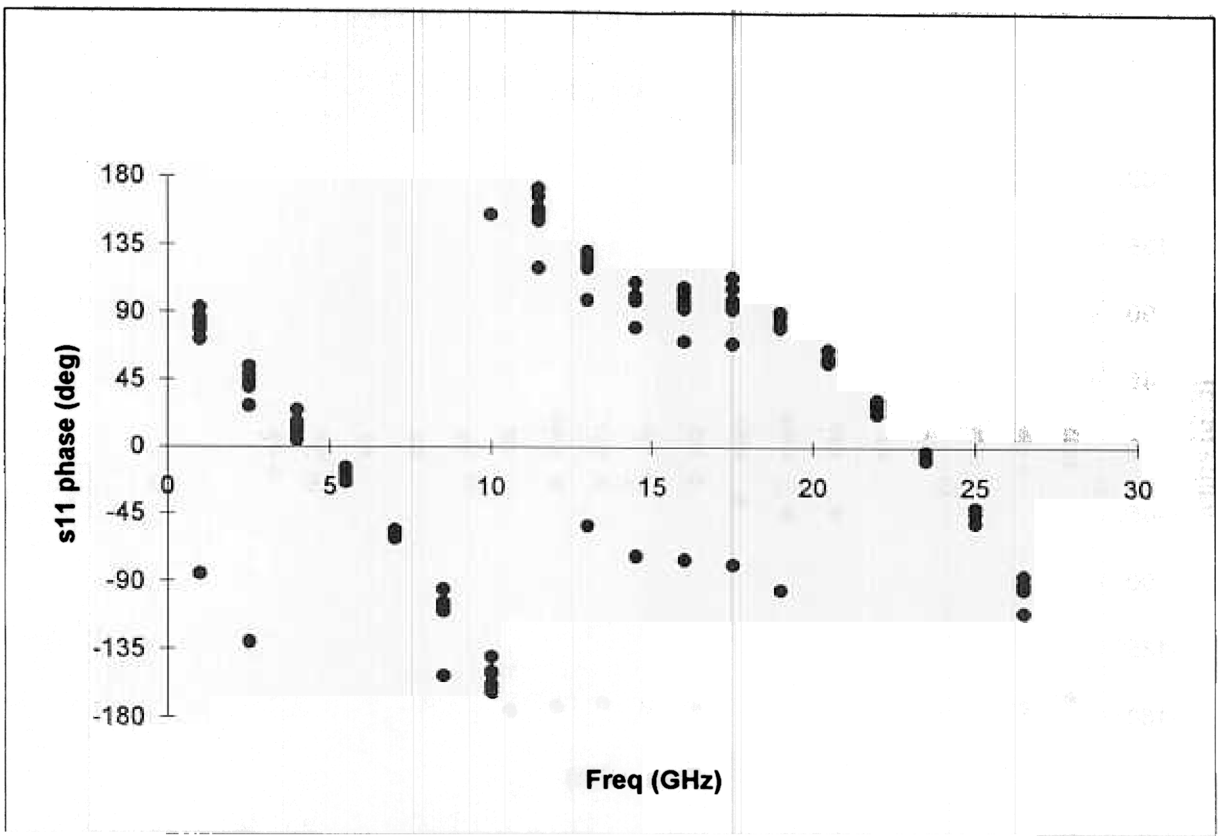

Figure 21 : 70dB attenuator, s11 phase

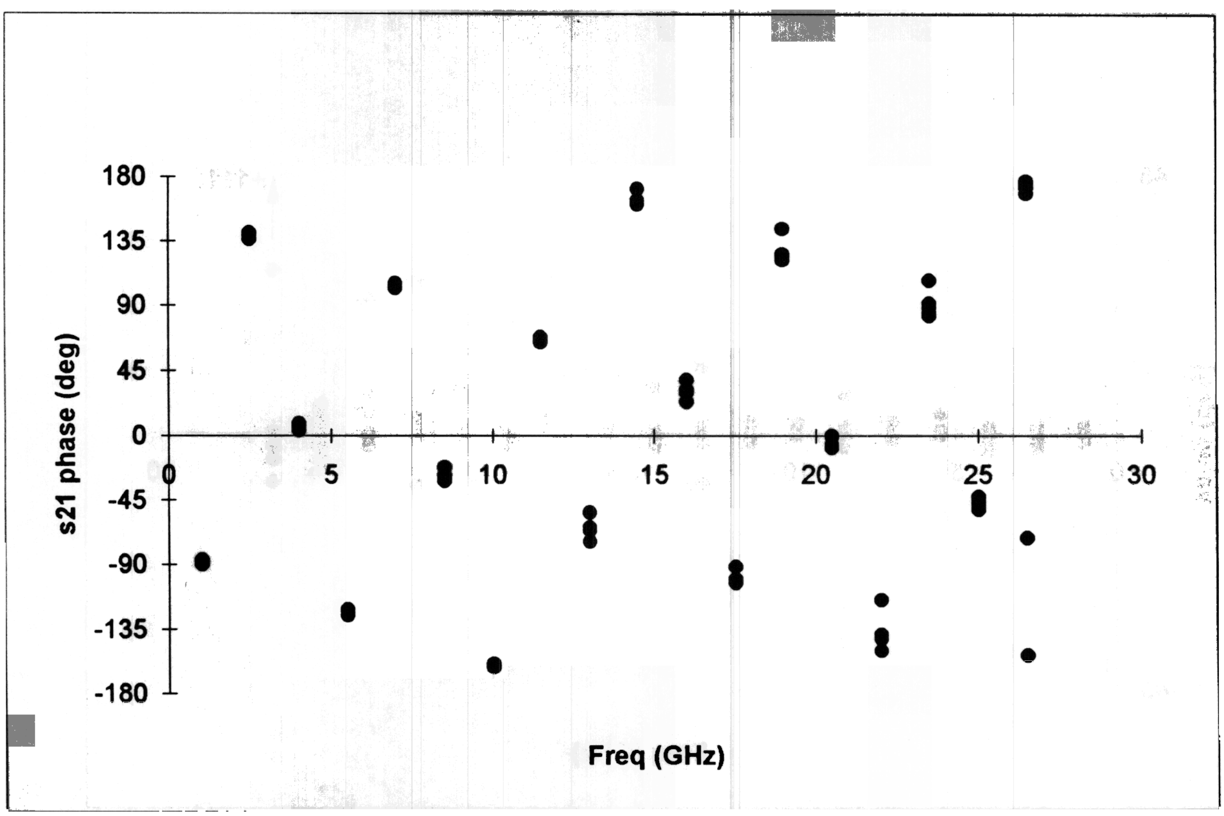

Figure 22 : 70dB attenuator, s21 phase

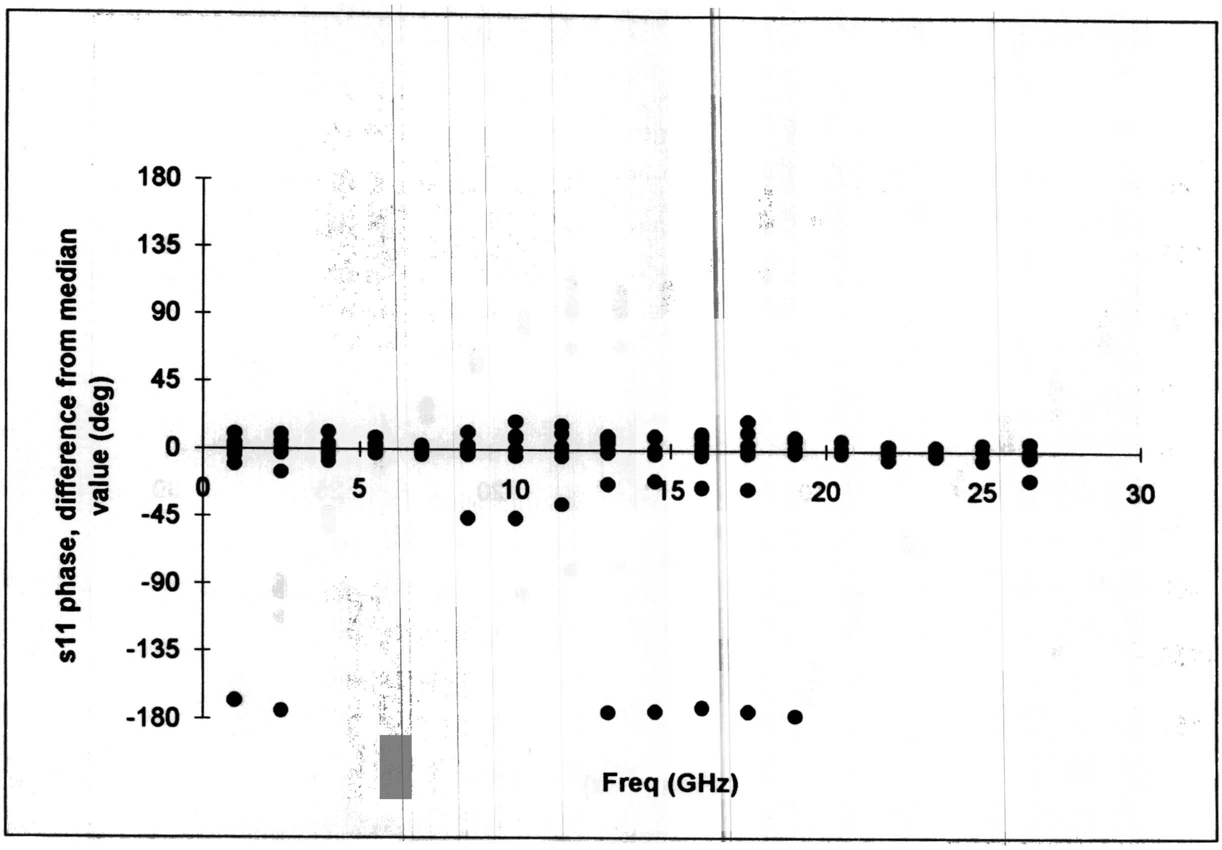

Figure 23 : 70dB attenuator, s11 phase, difference from median value

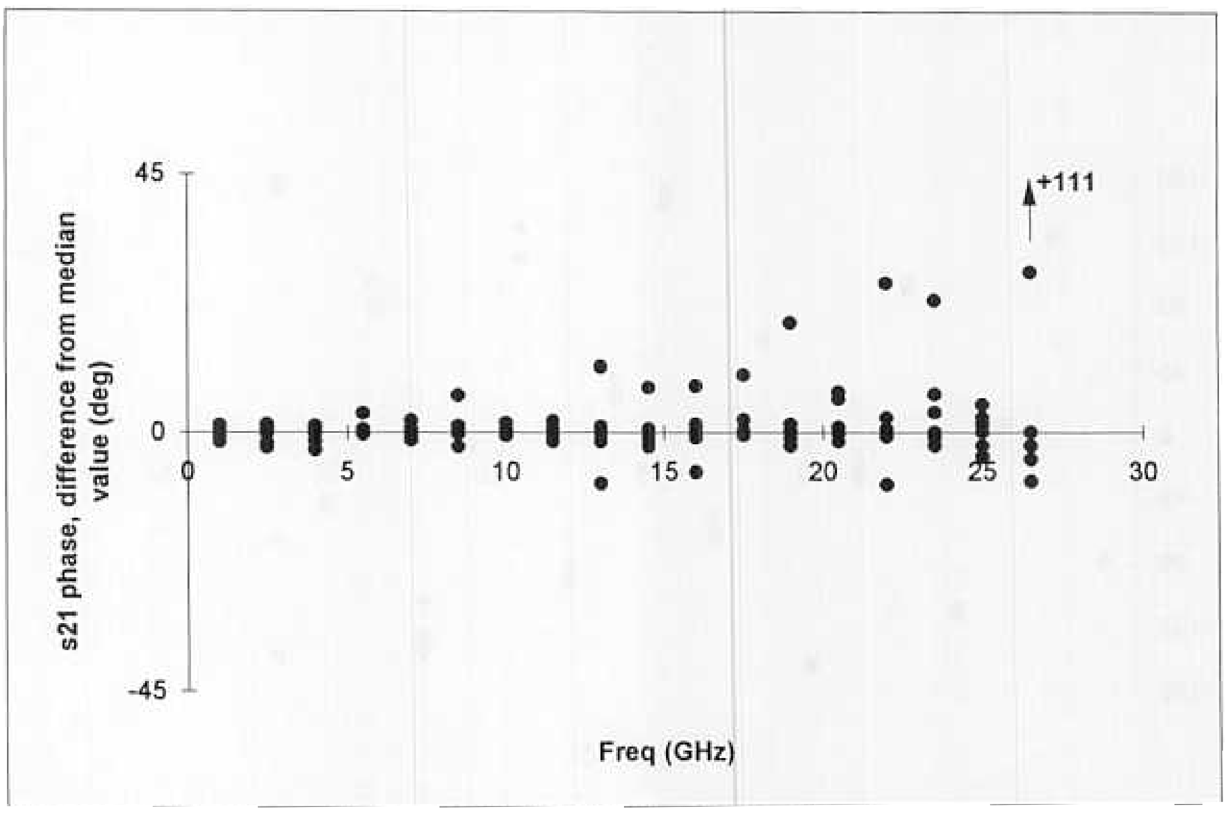

Figure 24 : 70dB attenuator, s21 phase, difference from median value

Table 7 : 70dB attenuator, s11

Frequency (GHz)	Linear magnitude			Phase (degrees)		
	Median	IQR - Repeat	IQR - Repro	Median	IQR - Repeat	IQR - Repro
1.0	0.0044	0.0001	0.0014	+82.34	0.96	9.33
2.5	0.0115	0.0001	0.0007	+43.56	0.21	10.80
4.0	0.0147	0.0001	0.0013	+13.56	0.24	6.42
5.5	0.0161	0.0000	0.0025	-21.09	0.48	4.30
7.0	0.0144	0.0002	0.0014	-58.32	0.29	2.39
8.5	0.0130	0.0001	0.0009	-106.53	0.34	4.00
10.0	0.0140	0.0002	0.0013	-158.34	1.03	9.62
11.5	0.0151	0.0001	0.0008	+156.75	0.67	9.17
13.0	0.0168	0.0001	0.0017	+121.97	0.96	11.59
14.5	0.0161	0.0004	0.0026	+101.51	1.49	10.28
16.0	0.0173	0.0007	0.0028	+96.71	2.02	14.30
17.5	0.0221	0.0003	0.0019	+95.35	1.53	14.30
19.0	0.0323	0.0004	0.0028	+81.49	0.71	5.09
20.5	0.0418	0.0008	0.0043	+58.61	0.72	1.64
22.0	0.0453	0.0006	0.0013	+28.82	0.73	2.06
23.5	0.0416	0.0007	0.0020	-5.68	0.54	2.15
25.0	0.0338	0.0010	0.0020	-45.30	1.70	6.03
26.5	0.0220	0.0011	0.0039	-91.21	1.33	3.07

Table 8 : 70dB attenuator, s21

Frequency (GHz)	Log magnitude (dB)			Phase (degrees)		
	Median	IQR - Repeat	IQR - Repro	Median	IQR - Repeat	IQR - Repro
1.0	70.097	0.161	0.041	-88.29	1.00	1.05
2.5	70.166	0.184	0.098	+139.10	1.26	1.04
4.0	70.212	0.271	0.073	+7.12	1.62	1.02
5.5	70.312	0.171	0.132	-124.90	0.59	0.58
7.0	70.370	0.085	0.098	+103.09	0.99	0.93
8.5	70.423	0.255	0.143	-28.98	1.43	1.34
10.0	70.465	0.119	0.185	-161.55	1.34	0.50
11.5	70.553	0.121	0.060	+66.19	1.44	0.90
13.0	70.593	0.255	0.105	-65.15	2.19	2.10
14.5	70.658	0.314	0.218	+163.63	1.70	1.97
16.0	70.826	0.354	0.275	+30.85	2.04	1.25
17.5	70.744	0.126	0.114	-102.46	2.25	2.53
19.0	70.793	0.267	0.103	+124.82	1.66	1.42
20.5	70.986	0.179	0.551	-7.00	1.19	3.41
22.0	70.497	0.185	0.174	-141.48	1.35	1.98
23.5	70.111	0.083	0.717	+85.03	0.87	5.96
25.0	70.102	0.168	0.318	-47.59	1.10	5.30
26.5	69.693	0.172	1.051	+177.40	0.64	17.56

NB: IQR - Repeat is Inter-Quartile Range for repeatability data
IQR - Repro is Inter-Quartile Range for reproducibility data

PIN-DEPTH GAUGE MEASUREMENTS

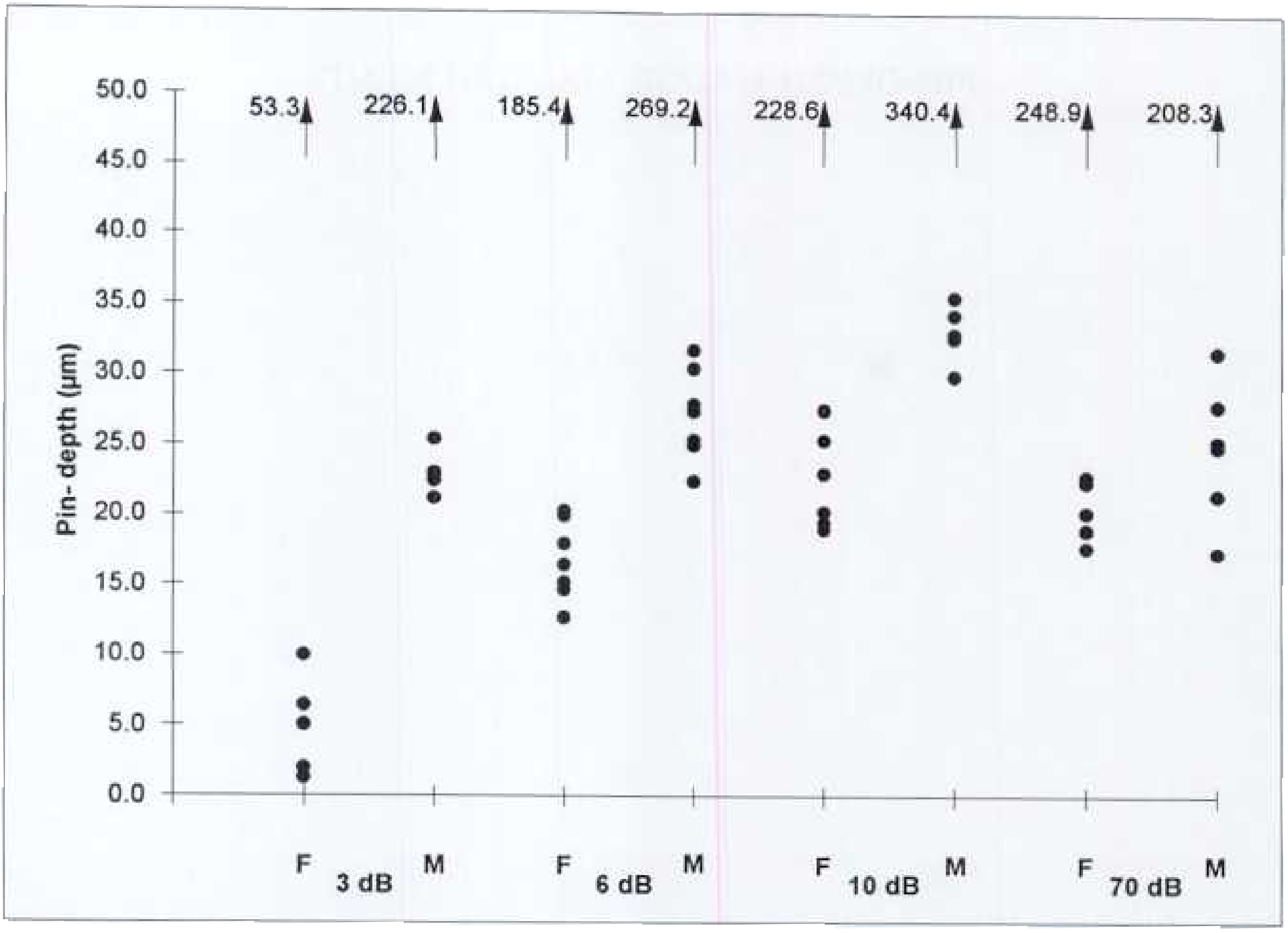

Figure 25 : Pin-depth gauge measurements

Table 9 : Summary statistics for pin-depth gauge measurements

Attenuator	Pin-depth (µm)			
	Female connector		Male connector	
	Median	IQR	Median	IQR
3 dB	5.1	3.1	22.9	0.8
6 dB	17.3	5.0	27.7	5.5
10 dB	21.7	5.8	33.7	1.7
70 dB	19.7	3.6	25.4	4.8

NB: IQR is Inter-Quartile Range