

1548

NPL REPORT CEM 6

REPORT

A comparison of complex scattering coefficient measurements of coaxial-to-waveguide adaptors

N M RIDLER

JANUARY 1999

NPL 
National Physical Laboratory

A comparison of complex scattering coefficient measurements of coaxial-to-waveguide adaptors

N M Rider
Centre for Electromagnetic Metrology
National Physical Laboratory
Teddington
Middlesex
United Kingdom, TW11 0LW

ABSTRACT

This report describes an exercise to compare complex scattering coefficient measurements of two coaxial-to-waveguide adaptors. The measurements were made at frequencies of 8.2 GHz, 10 GHz and 12.4 GHz. Results are presented in graphical form, together with a statistical summary of the measured values. The comparison exercise was organised by ANAMET, and the six participating organisations are members of ANAMET.

© Crown Copyright 1999
Reproduced by permission of the Controller HMSO

ISSN 1369-6742

National Physical Laboratory
Teddington, Middlesex, TW11 0LW

Extracts from this report may be reproduced provided the source is acknowledged and the extract is not taken out of context.

Approved on behalf of the Managing Director, NPL
by Dr S Pollitt, Head of the Centre for Electromagnetic Metrology

CONTENTS

	Page
1 INTRODUCTION	1
2 COMPARISON DETAILS	1
3 MEASUREMENT SYSTEMS DETAILS	2
4 STATISTICAL TECHNIQUES	2
5 RESULTS .	4
6 OBSERVATIONS ...	4
7 CONCLUSIONS	5
8 ACKNOWLEDGEMENTS	6
9 REFERENCES	6
Appendix ...	8

GRAPHS AND TABLES

page

Adaptor

Table 1: S_{11} summary statistics . . .	12
Table 2: S_{22} summary statistics . . .	12
Table 3: $S_{21}S_{12}$ summary statistics .	12
Figure 1: S_{11} at 8.2 GHz	13
Figure 2: S_{11} at 10 GHz	14
Figure 3: S_{11} at 12.4 GHz	15
Figure 4: S_{22} at 8.2 GHz	16
Figure 5: S_{22} at 10 GHz	17
Figure 6: S_{22} at 12.4 GHz	18
Figure 7: $S_{21}S_{12}$ at 8.2 GHz	19
Figure 8: $S_{21}S_{12}$ at 10 GHz	20
Figure 9: $S_{21}S_{12}$ at 12.4 GHz	21

Adaptor 2

Table 4: S_{11} summary statistics . . .	24
Table 5: S_{22} summary statistics . . .	24
Table 6: $S_{21}S_{12}$ summary statistics .	24
Figure 10: S_{11} at 8.2 GHz	25
Figure 11: S_{11} at 10 GHz	26
Figure 12: S_{11} at 12.4 GHz	27
Figure 13: S_{22} at 8.2 GHz	28
Figure 14: S_{22} at 10 GHz	29
Figure 15: S_{22} at 12.4 GHz	30
Figure 16: $S_{21}S_{12}$ at 8.2 GHz	31
Figure 17: $S_{21}S_{12}$ at 10 GHz	32
Figure 18: $S_{21}S_{12}$ at 12.4 GHz	33

Pin-depth gauge measurements

Table 7: Summary statistics	34
-----------------------------	----

1 INTRODUCTION

This report presents results obtained from a measurement comparison exercise which took place during 1996 and 1997. 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 analyser 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 six organisations who chose to participate in the exercise were as follows; (i) CMI, Prague, Czech Republic, (ii) CSIRO, West Lindfield, Australia, (iii) EEV Ltd, Chelmsford, UK, (iv) NMI, Delft, The Netherlands (v) NPL, Teddington¹, UK, and (vi) SESC, DERA Aquila, Bromley, UK.

The exercise compared the complex scattering coefficient measurements, S_{11} , S_{22} and the product $S_{21} \times S_{12}$, of two coaxial-to-waveguide adaptors at frequencies of 8.2 GHz, 10 GHz and 12.4 GHz. The results were expressed in terms of the linear magnitude and phase of each complex scattering coefficient.

Both adaptors were Hewlett Packard type HP X281C. The coaxial ports were fitted with 50 ohm Type-N coaxial connectors: a female connector on the adaptor labelled "Adaptor 1" and a male connector on the adaptor labelled "Adaptor 2". This labelling convention is used throughout this Report when referring to the adaptors. The waveguide ports were WG16/WR90/R100 (often referred to by microwave engineers as "X-band").

The coaxial port of each adaptor was designated as port 1, thus making port 2 the waveguide port. The orientation of the scattering parameters under investigation were therefore as follows: S_{11} , the reflection coefficient looking into the adaptor's coaxial connector; S_{22} , the reflection coefficient looking into the adaptor's waveguide port; and, the product $S_{21} \times S_{12}$ representing transmission through the adaptor in both directions.

¹ At the time the comparison took place, this part of NPL was based at DERA, Malvern

Since the adaptors were fitted with coaxial connectors, the participants were also invited to supply their connector pin-depth gauge measurements for each adaptor.

3 MEASUREMENT SYSTEMS DETAILS

No restrictions were placed on the measurement systems and calibration techniques to be used by the participants. Below are details of the systems that were used by each participant for the measurements.

CMI used an HP8510B with a 8350B sweep generator as the measuring instrument calibrated using the SOL method for the coaxial port and the SSL method for the waveguide port. The coaxial ports of both adaptors were measured whilst the waveguide ports were terminated successively with a short, offset short (of approximately quarter-wavelength), sliding load and 40 cm offset short-circuit. The S-parameters for the adaptors were calculated in a similar way to the error terms in a one-port ANA calibration.

CSIRO used a HP8510C network analyser, using its internal software (version 7.00) to control the measurements and for adaptor removal. The waveguide port was calibrated using the TRL technique referred to an in-house waveguide section. The type-N calibration used the standard "full two-port" method with a HP calibration kit. Measurements were subsequently corrected for known imperfections in the waveguide section.

EEV Ltd used a Wiltron 360 ANA as the measuring instrument calibrated using the SOLT technique. The adaptor removal calibration used software supplied by Wiltron called "ADAPTCAL" which has subsequently been modified to run on the EEV Ltd ATE system.

NMi used a Wiltron 360 ANA with a 3621A test set. Waveguide-to-coaxial adaptors from a Flann Microwave calibration kit were used during the exercise. Additional adaptors were also used to facilitate the measurements. Calibrations were performed in both waveguide and coaxial line and were combined using an in-house adaptor removal scheme.

NPL used a HP 8510C ANA as the measuring instrument calibrated using the SOLT technique for the coaxial calibrations and a SSLT (short, offset-short, load, through) technique for the waveguide calibrations. The ANA's proprietary software was used to perform the adaptor removal technique.

SESC, DERA Aquila used a Flann Microwave 16/3 slotted line, calibrated with the appropriate standards, to implement an in-house measurement technique. These measurements were verified using an HP 8510C ANA.

4 STATISTICAL TECHNIQUES

Statistical techniques are used to analyse and summarise the data obtained during ANAMET comparison exercises. In particular, a consensus value and a measure of spread of the participants' values are provided.

Experience from an earlier ANAMET comparison exercise [1, 2] showed that it is preferable to use methods which are resilient to the effects of occasional unusual measurement values² reported by some participants. This has led to the introduction of robust methods based on the median [3]. These methods were later extended to take account of the vector nature of the data [4] (since scattering coefficients are complex quantities). Subsequent comparisons of complex quantities organised by ANAMET have utilised these robust multivariate techniques [5-7]. This approach is similar to that employed by the Automatic RF Techniques Group (ARFTG) to analyse ANA measurement comparison data [8]. The main difference between the approaches is that the method used here analyses the data spatially (independent of the coordinate system used to express the vector, *i.e.* as either: magnitude and phase; or in terms of the real and imaginary components of the vector).

For each set of measurements from the six participants (of one scattering parameter at one frequency) the spatial median provided the consensus value and the median absolute deviation the measure of spread in the data.

Spatial median

The spatial median [9] of a set of measurements $X_1, \dots, X_n$, is the point μ that minimises the sum of the absolute deviations (distances) between μ and the n data points. *I.e.*:

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

is minimised when μ is the spatial median.

Median Absolute Deviation (MAD)

The MAD [10] is the median absolute deviation of a data set from a particular point – in this case, the magnitude or phase of the spatial median.

The MAD for the magnitude values was calculated as:

$$\text{MAD (Magnitude)} = \text{Median} \{ |DiffMag_i| ; i=1, \dots, n \}$$

where

$$DiffMag_i = |X_i| - \mu$$

where $DiffMag_i$ are the differences in the magnitude values.

The MAD for the phase values was calculated as:

$$\text{MAD (Phase)} = \text{Median} \{ |DiffPhase_i| ; i=1, \dots, n \}$$

A measurement value is said here to be unusual when it is significantly different from the majority of reported values.

where

$$DiffPhase_i = \phi_{xi} - \phi_{\mu}$$

DiffPhase_i are the differences in the phase values (where ϕ_{xi} and ϕ_{μ} are the phase values for a participant's result and the spatial median, respectively), except that whenever the calculated difference in phases lay outside the range $-180^{\circ} < DiffPhase_i \leq +180^{\circ}$, then 360° was either added to or subtracted from the result. This ensured that no point was described as being more than 180° away from the median. Using this method, the difference between -179° and $+180^{\circ}$ would be $+1^{\circ}$, rather than -359° .

As a measure of spread, the intervals $\{|\mu| \pm MAD \text{ (Magnitude)}\}$ and $\{\phi_{\mu} \pm MAD \text{ (Phase)}\}$ will contain half of the results in each case.

5 RESULTS

Results are presented at each frequency of the comparison in graphical and tabular form. Each participant's results are represented on the graphs as black dots. In some graphs the results for several participants are very close, causing dots to eclipse each other to some extent.

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 due to this rounding.

The figure and table numbers for the electrical measurements are shown in the box below.

	Figure numbers	Table numbers
Adaptor 1	1-9	1-3
Adaptor 2	10-18	4-6

The connector pin-depth results are summarised in Table 7.

6 OBSERVATIONS

Examining the summary statistics presented in the tables, the following observations can be made. Firstly, by examining the spatial median values for the magnitude of the reflection coefficients (S_{11} and S_{22}) for both adaptors at all frequencies, it is clear that these consensus values are all small (less than 0.01). Similarly, all consensus values (spatial medians) for the magnitude of the product $S_{21}S_{12}$ are close to unity (typically 0.98).

With this in mind, we can compare the measure of spread values (the MADs) for the magnitude reflection coefficients with values obtained in earlier exercises for similar connector types and frequency ranges. For example, an earlier exercise [1,2] which included low values of reflection coefficient for type-N terminations to 18 GHz was shown in [7] to produce MAD values of less than 0.005. This is slightly greater than values found during this exercise (less than 0.003). Similarly, another earlier exercise [5,6], which included low values of reflection for X-band

waveguide items, yielded MAD values of typically 0.0009. This is less than values found during this exercise (between 0.0017 and 0.0049). The same exercise also included a low insertion device (the Through connection of an X-band three-port directional coupler). The summary MAD value, when converted from dBs to linear units (see the appendix of this report for details of this transformation) for the coupler measurement in the earlier comparison was found to be 0.0035. This is slightly higher than the MAD values for the transmission measurements (product $S_{21}S_{12}$) found during the current comparison exercise (between 0.0014 and 0.0030).

The above observations might indicate that the data produced by this comparison exercise was generally well-behaved. However, by examining the data plots (figures 1-18) it can be seen that this was not so - see, for example, figures 5-10, figure 13, and figures 16-18, which contain one and sometimes two unusual values. In the case of the transmission measurements, these contain values which are rotated away from the cluster of values (indicating large phase errors in the measurements).

Also, the scatter in the reflection measurements is often erratic, producing unusually shaped data clusters. See, for example, figure 11, where the results appear to be aligned along a line at 45° with respect to the coordinate axes. This suggests the benefit in using spatial summary statistics since the scatter in the data appears not to be a function of the coordinate axes or the magnitude and phase of the data points.

The scatter in the phase values relates directly to the magnitude of the scattering parameter vector. When the magnitude of the vector is small, the scatter in the phase will be large, and when the magnitude of the vector is large, the scatter in the phase will be small. This is due to the location of the vectors in the complex plane. In particular, the proximity of the vector to the origin of the complex plane. The scatter in the phase values (their MAD values) found in this exercise generally agree with this prediction.

Finally, the connector pin-depth measurements, summarised in Table 7, show measure of spread values (the MADs) of $4.0\text{ }\mu\text{m}$ and $9.9\text{ }\mu\text{m}$ for the female and male type-N connectors, respectively. This variation is larger than that observed in an earlier ANAMET comparison exercise of GPC-3.5 coaxial components [3] where the equivalent largest MAD $\approx 2.9\text{ }\mu\text{m}$. (This value has been derived from the largest inter-quartile range (IQR) value for the exercise, since $\text{IQR} \approx 2 \times \text{MAD}$.) The larger variation in the type-N measurements could be because these measurements are made with respect to an offset (of approximately 5 mm) whereas the GPC-3.5 measurements are made with respect to a flush (or zero offset) reference. It is possible that the offset in the type-N connector may increase the likelihood of an additional systematic error leading to larger overall variation in the type-N pin-depth measurements.

7 CONCLUSIONS

This comparison, the seventh in ANAMET's on-going series of comparison 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 measurements of coaxial-to-waveguide adaptors used at microwave frequencies. It should be noted that traceability to primary national impedance standards is currently not available in the UK for these types of measurement (*i.e.* non-insertable devices).

The agreement between most participating laboratories was generally good, although a significant number of unusual values (gross errors) were observed - especially in the transmission measurements. This indicates potential avenues of research for the further improvement of the quality of this type of measurement.

8 ACKNOWLEDGEMENTS

The author would like to thank the following for participating in the exercise and for supplying details about their measurement systems: František Hejsek (CMI); Dr Tieren Zhang (CSIRO); David Hepworth (EEV Ltd); Dr Jan de Vreede (NMI); and, Steve Harter (SESC, DERA Aquila). The author is especially grateful to his former colleague, John Medley, who performed the data analysis for this comparison exercise.

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

9 REFERENCES

- [1] Ridler, N.M. and Jones, G.D. Comparison assesses the quality of network measurements. *Microwaves & RF*, January 1995, 34(1), 101-104.
- [2] 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.
- [3] Ridler, N.M. and Medley, J.C. A comparison of complex scattering coefficient measurements in 50 ohm coaxial line to 26.5 GHz. *NPL Report DES 138*, June 1995.
- [4] Medley, J.C. and Ridler, N.M. Analysing multidimensional measurement comparison data containing occasional erratic points, *Conference on Precision Electromagnetic Measurements (CPEM) Digest*, Braunschweig, Germany, 17-20 June 1996, 51-52.
- [5] Ridler, N.M. and Medley, J.C. A comparison of microwave reflection and transmission measurements in rectangular waveguide. In *Advances in Metrology and its Role in Quality Improvement and Global Trade*, edited by B S Mathur, V N Oja and P C Kothari, Narosa Publishing House, New Delhi, February 1996, 364-368.
- [6] Ridler, N.M. and Medley, J.C. Comparison of ANA *s*-parameter measurements in X-band waveguide. *24th ARMMS Conference Digest*, Beech Hill Hotel, Windermere, Cumbria, April 1996.
- [7] Ridler, N.M. and Medley, J.C. ANAMET comparison of reflection coefficient measurements at RF. *25th ARMMS Conference Digest*, The Limpley Stoke Hotel, Bath, 31st October and 1st November 1996.

- [8] Juroshek, J.R., Wang, C.M. and McCabe, G.P. Statistical analysis of network analyzer measurements. *Cal Lab - the international journal of metrology*, May/June 1998, **5** (3), 26-33.
- [9] Ridler, N.M. and Medley, J.C. Making a good estimate of a vector quantity. In *ANAMET. The collected ANALyse Notes. Volume 2 - Numbers 11 to 20*, edited by N M Ridler, *NPL Report CETM 8*, May 1997.
- [10] Ridler, N.M. and Medley, J.C. Assessing the quality of an estimated value - Part 2: the Median Absolute Deviation. *Ibid.*.

Appendix

This appendix examines the relationship between variation in attenuation and transmission coefficient. This enables previous measures of variation in attenuation measurements, found in an earlier ANAMET comparison exercise, to be converted into an equivalent variation in the transmission coefficients, $|S_{21}S_{12}|$, made during this comparison exercise.

For reciprocal two-port devices, the transformation relating attenuation, α , to the transmission coefficients, $|S_{21}S_{12}|$, is given by the following:

$$\alpha = 10 \times \log |S_{21}S_{12}| \quad (1)$$

The effect of uncertainty in attenuation on the transmission coefficients can be examined using the law of propagation of uncertainty³, which for this situation yields:

$$u(\alpha) = \frac{d\alpha}{d|S_{21}S_{12}|} u(|S_{21}S_{12}|) \quad (2)$$

where $u(\alpha)$ and $u(|S_{21}S_{12}|)$ are the standard uncertainties in the attenuation and transmission coefficient, respectively. Higher order terms in the Taylor series expansion used to obtain this expression have been neglected, while terms involving correlation coefficients vanish.

From equation (1):

$$\frac{d\alpha}{d|S_{21}S_{12}|} = 4.343 \times |S_{21}S_{12}|^{-1} \quad (3)$$

Since we are interested in the uncertainty in $|S_{21}S_{12}|$ as a function of the uncertainty in α , we substitute equation (3) into equation (2) and re-arrange as:

$$u(|S_{21}S_{12}|) = 0.23 \times |S_{21}S_{12}| u(\alpha)$$

For very low values of attenuation (such as the coupler Through path measurement in [5,6]), $|S_{21}S_{12}| \approx 1$, so that we have:

$$u(|S_{21}S_{12}|) \approx 0.23 \times u(\alpha)$$

BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, "Guide to the expression of uncertainty in measurement", International Organization for Standardization, Geneva, Switzerland. ISBN 92-67-10188-9, 1st edition 1993.

Since the functional relationship between standard uncertainty (derived from a standard deviation) and the MAD measure of spread is linear ($u \approx 1.5 \times \text{MAD}$), we can write:

$$\text{MAD}(|S_{21}S_{12}|) \approx 0.23 \times \text{MAD}(\alpha) \quad (4)$$

The earlier ANAMET comparison exercise [5,6] produced a summary MAD value for the spread in the attenuation measurements for the Through path of an X-band directional coupler of 0.015 dB. This can now be converted to an equivalent MAD value for $|S_{21}S_{12}|$ using equation (4):

$$\text{MAD}(|S_{21}S_{12}|) \approx 0.0035$$

This page is blank

ADAPTOR 1

Table 1: S_{11} summary statistics

Frequency (GHz)	Spatial Median		MAD		
	Magnitude	Phase (°)	Magnitude		Phase (°)
8.2	0.0084	+93.1	0.0022		21.2
10.0	0.0099	-60.7	0.0016		6.3
12.4	0.0045	+149.9	0.0021		47.1

Table 2: S_{22} summary statistics

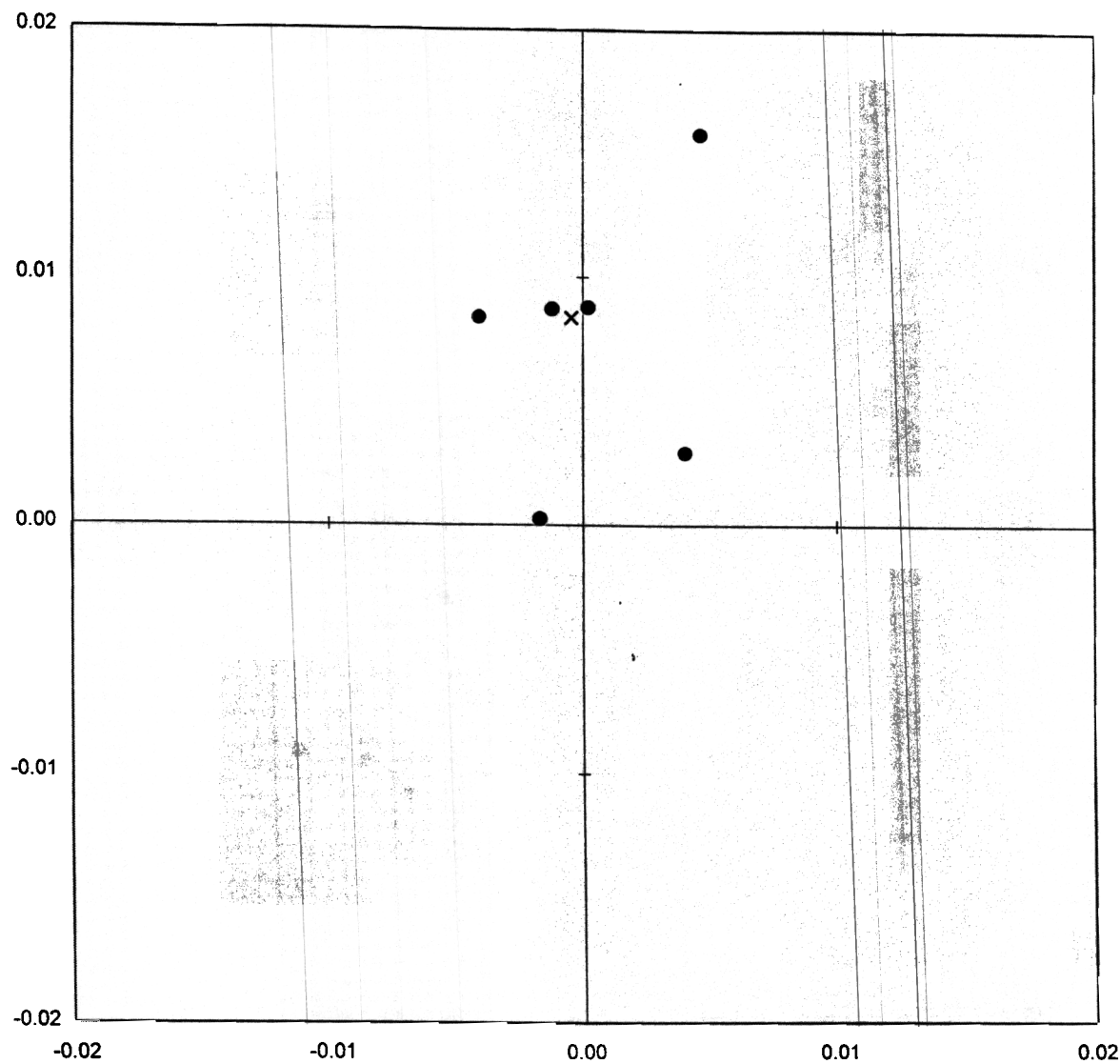
Frequency (GHz)	Spatial Median		MAD		
	Magnitude	Phase (°)	Magnitude		Phase (°)
8.2	0.0085	+28.3	0.0021		19.2
10.0	0.0076	+14.3	0.0024		22.4
12.4	0.0107	-149.6	0.0013		17.8

Table 3: $S_{21}S_{12}$ summary statistics

Frequency (GHz)	Spatial Median		MAD		
	Magnitude	Phase (°)	Magnitude		Phase (°)
8.2	0.9823	-57.9	0.0019		0.23
10.0	0.9856	+145.8	0.0017		0.23
12.4	0.9851	+151.1	0.0017		0.04

Figure 1

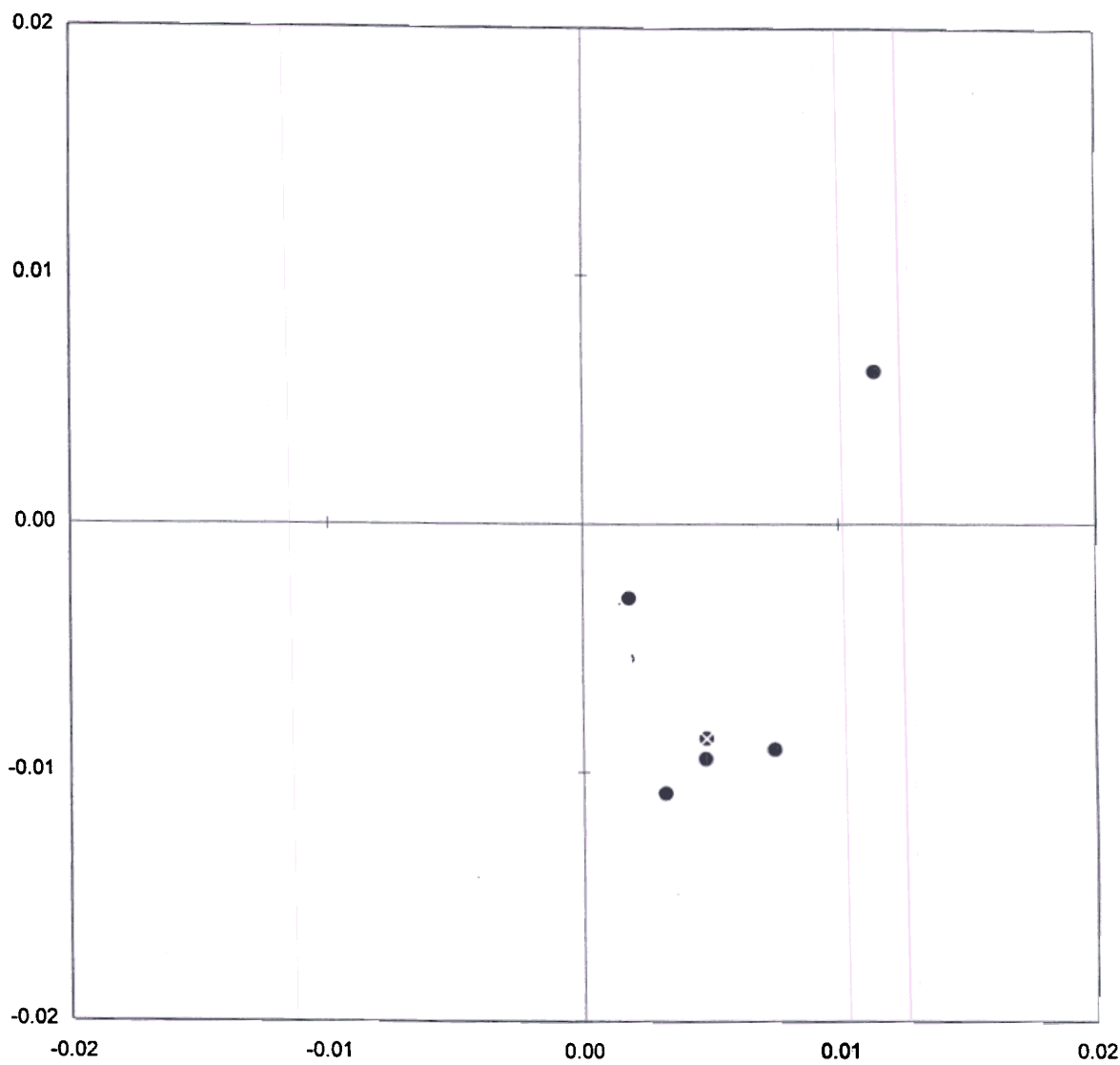
S11 of adaptor 1 (female)



Frequency: 8.2 GHz

Figure 2

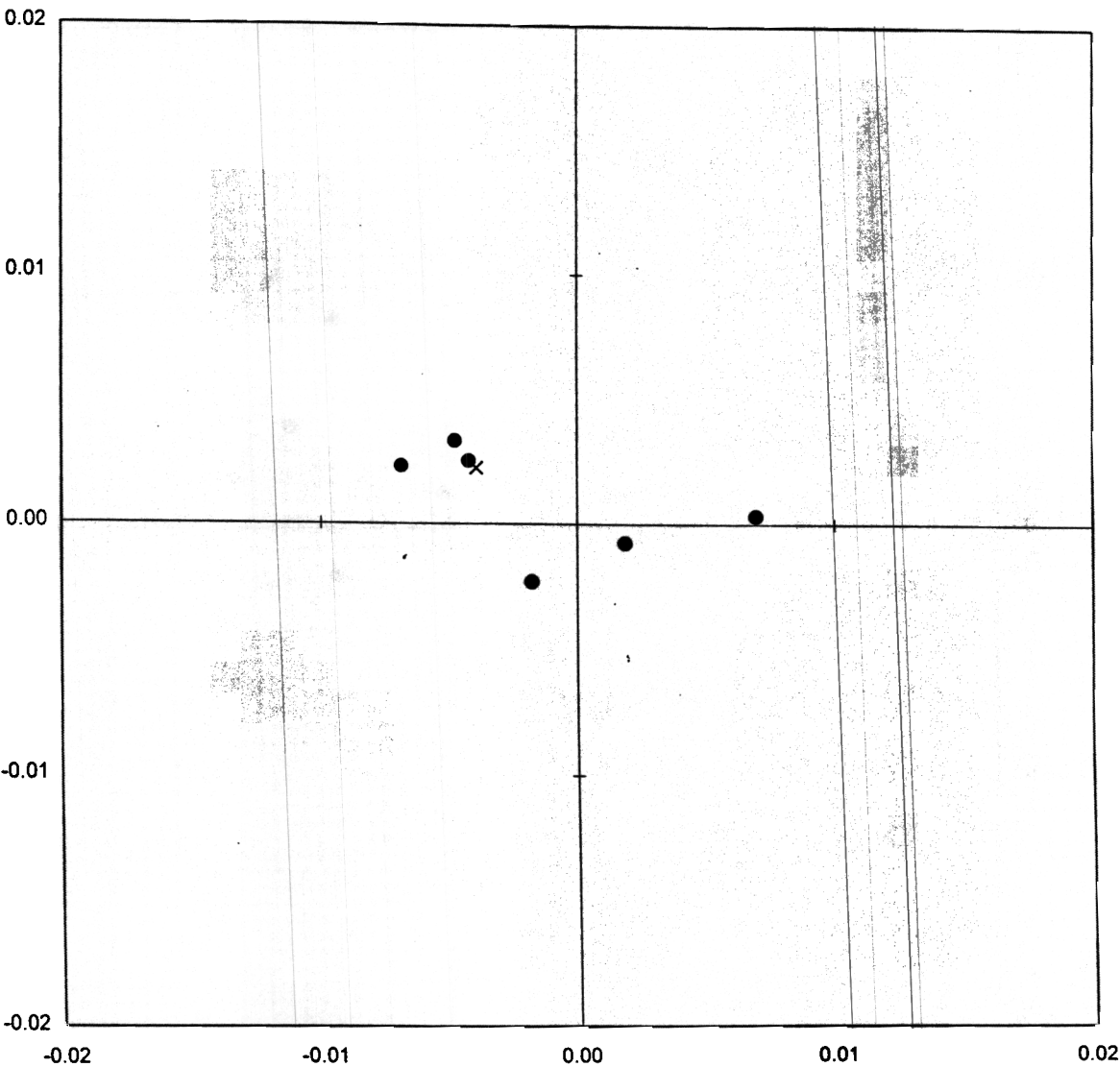
S11 of adaptor 1 (female)



Frequency: 10.0 GHz

Figure 3

S11 of adaptor 1 (female)



Frequency 12.4 GHz

Figure 4

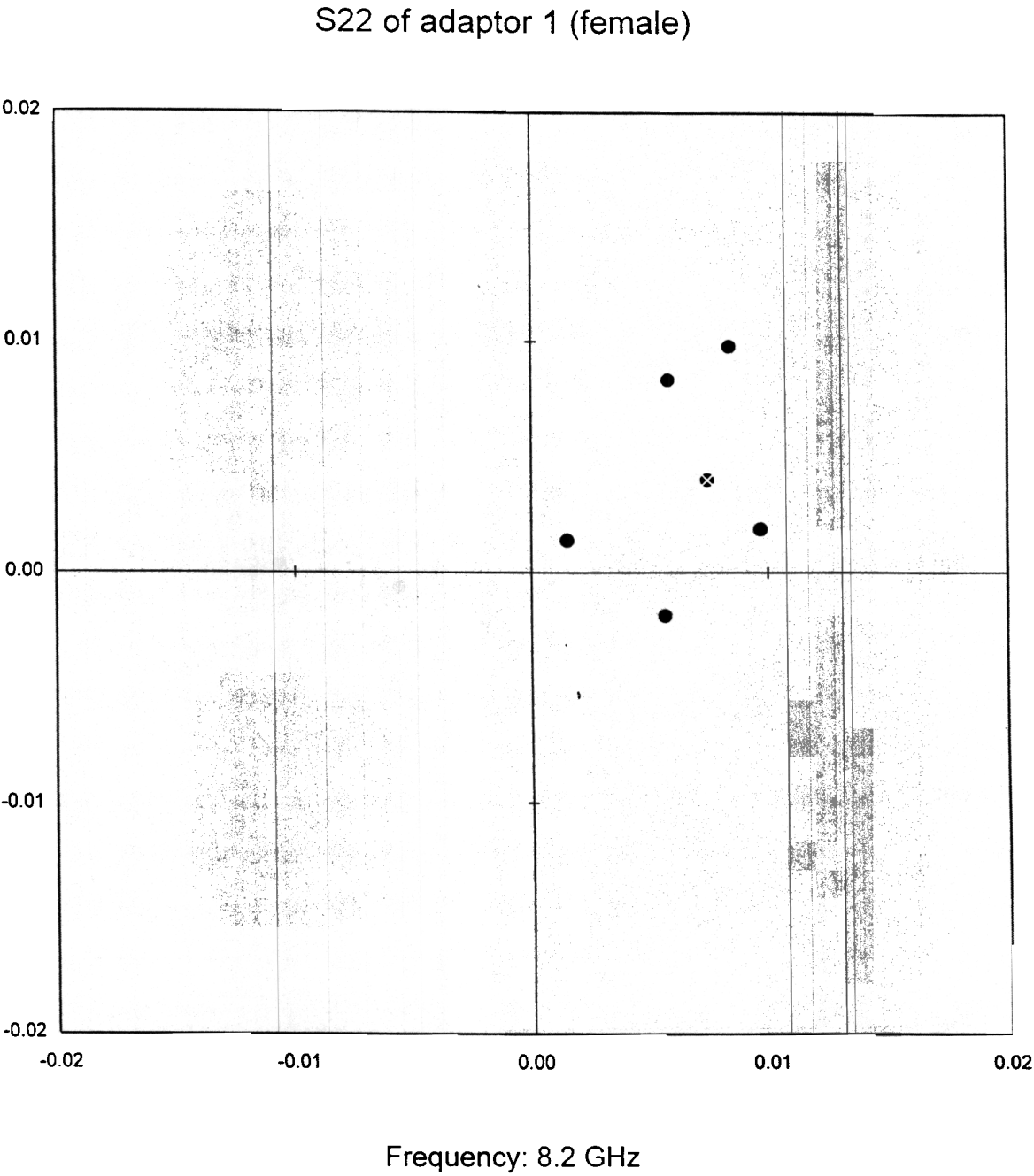


Figure 5

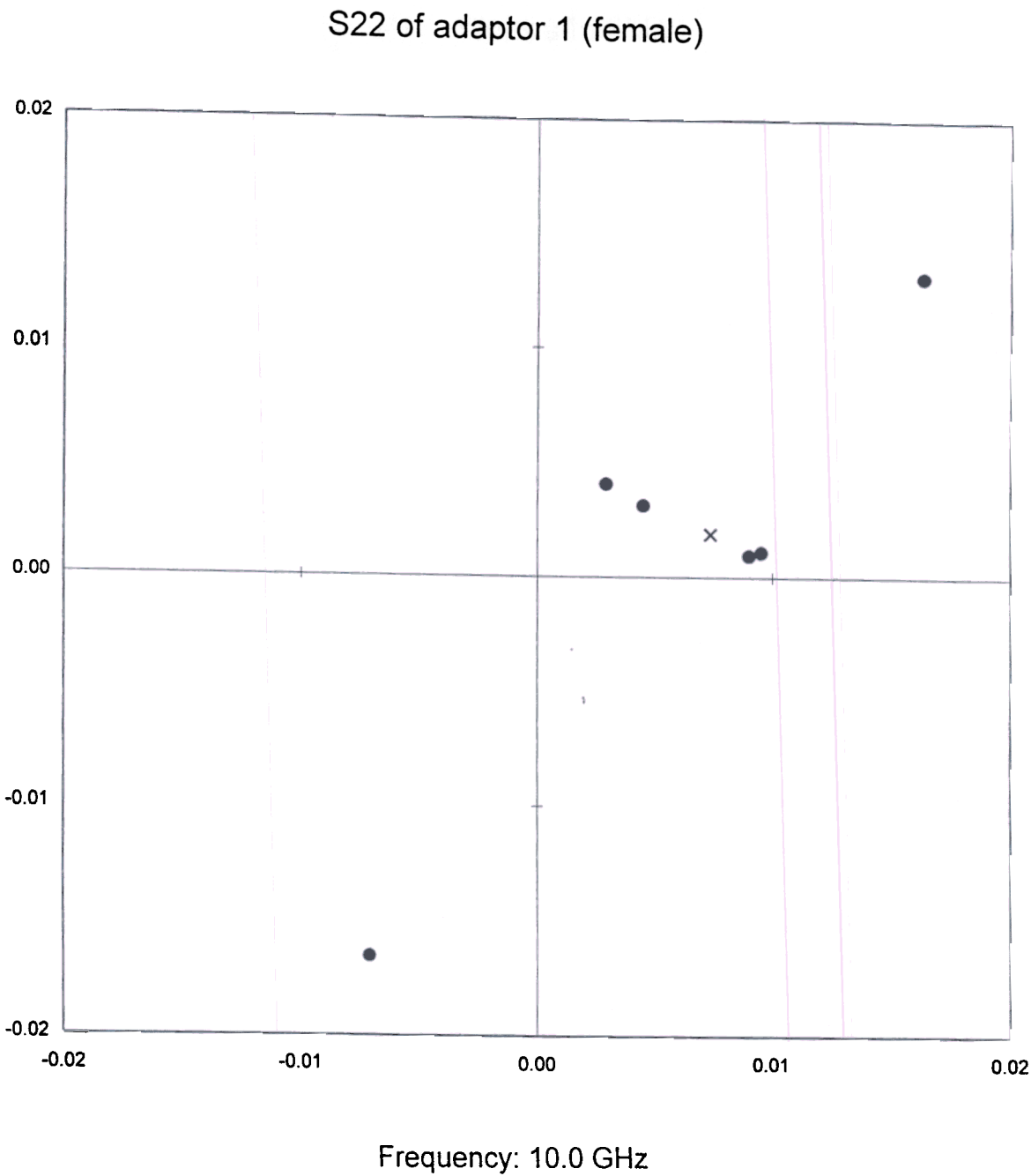
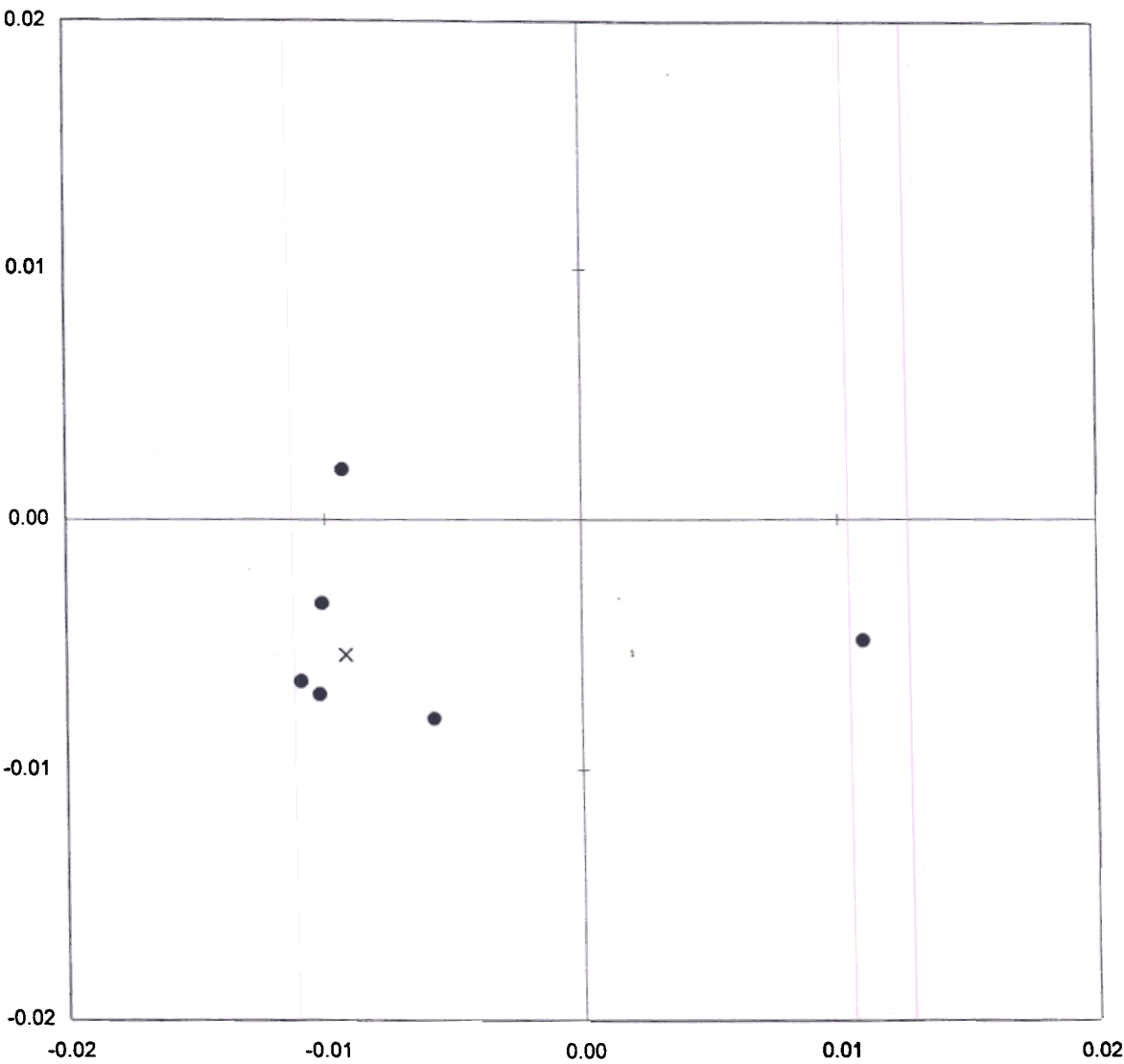


Figure 6

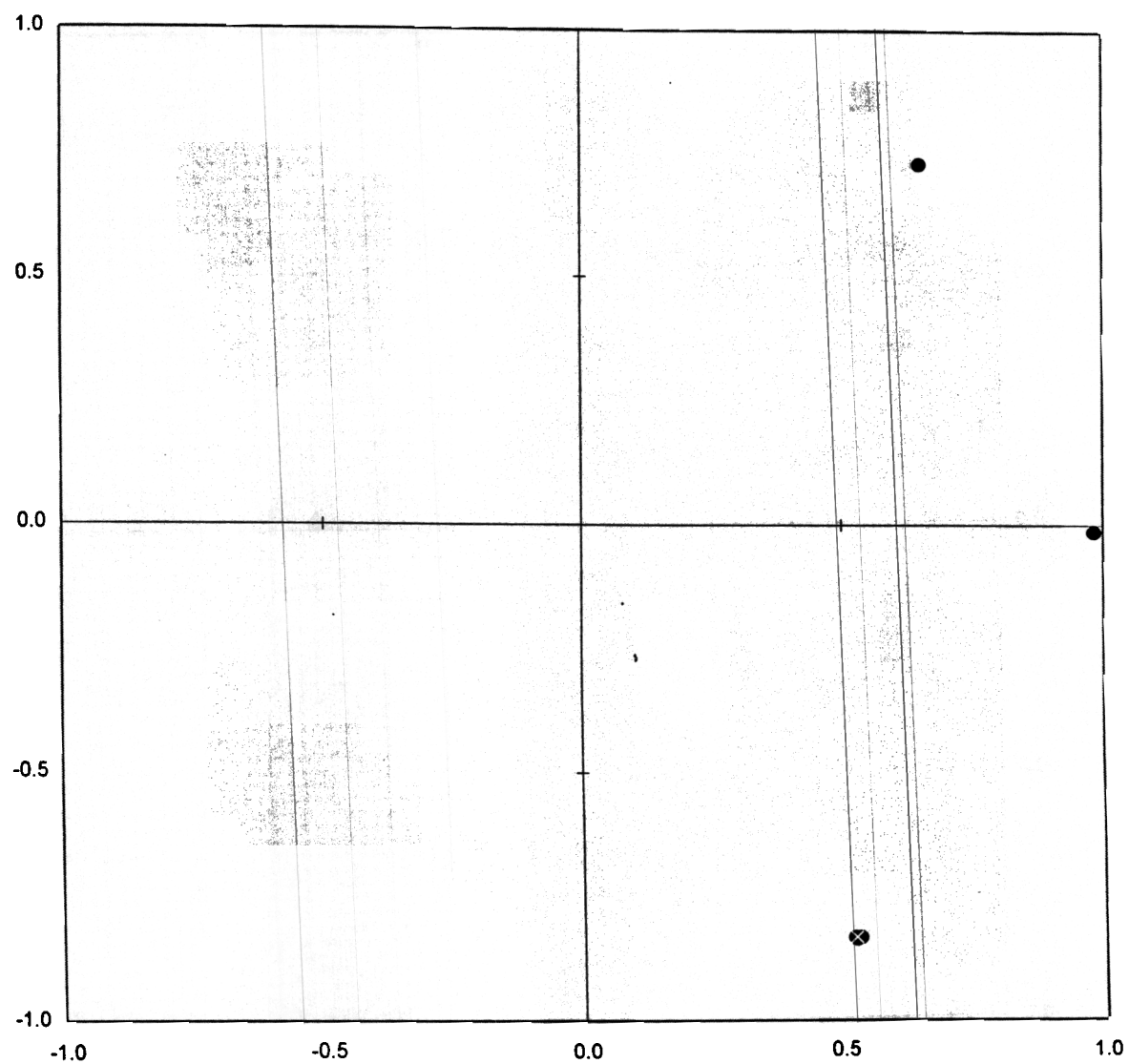
S22 of adaptor 1 (female)



Frequency 12.4 GHz

Figure 7

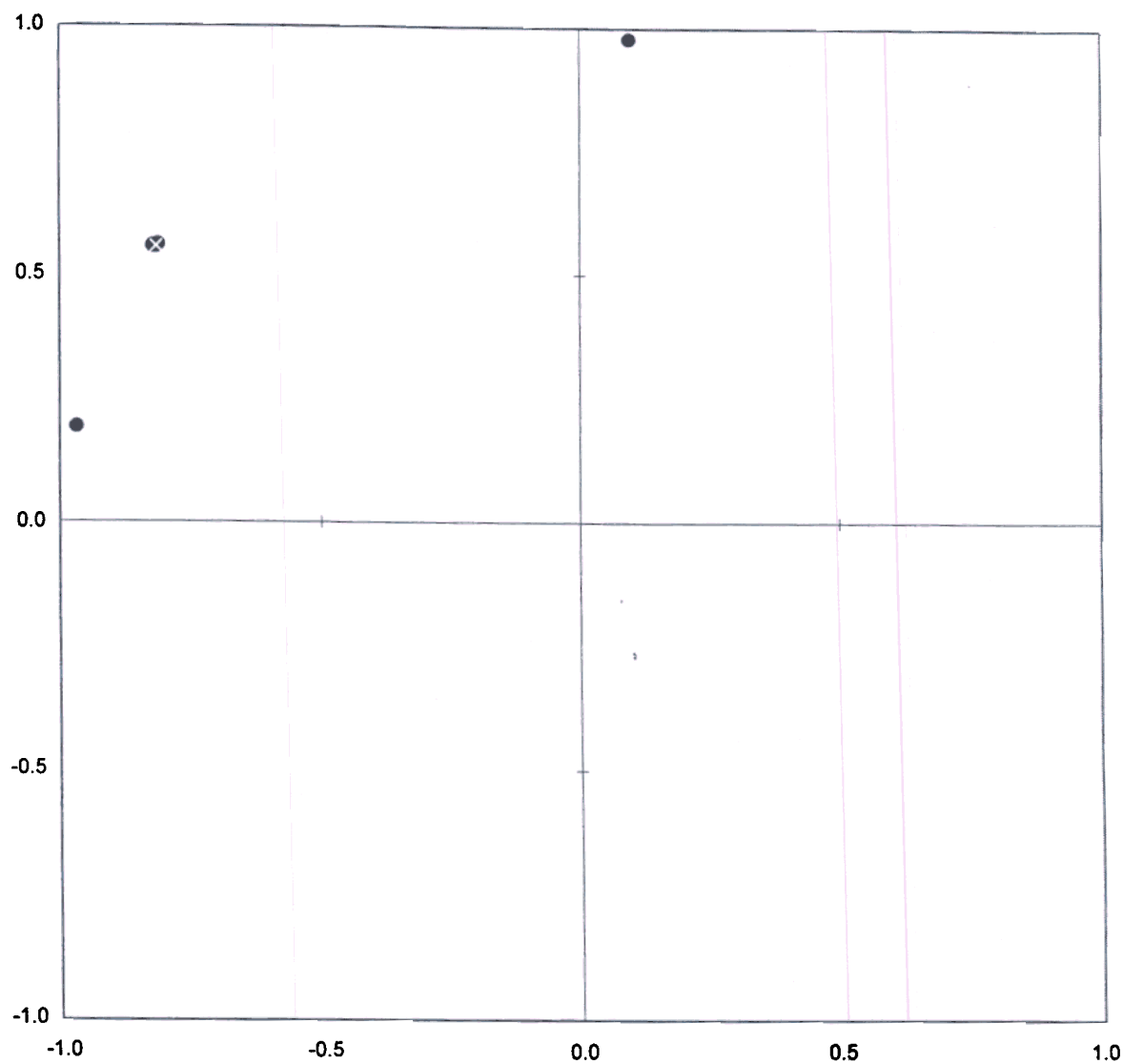
S21.S12 of adaptor 1 (female)



Frequency: 8.2 GHz

Figure 8

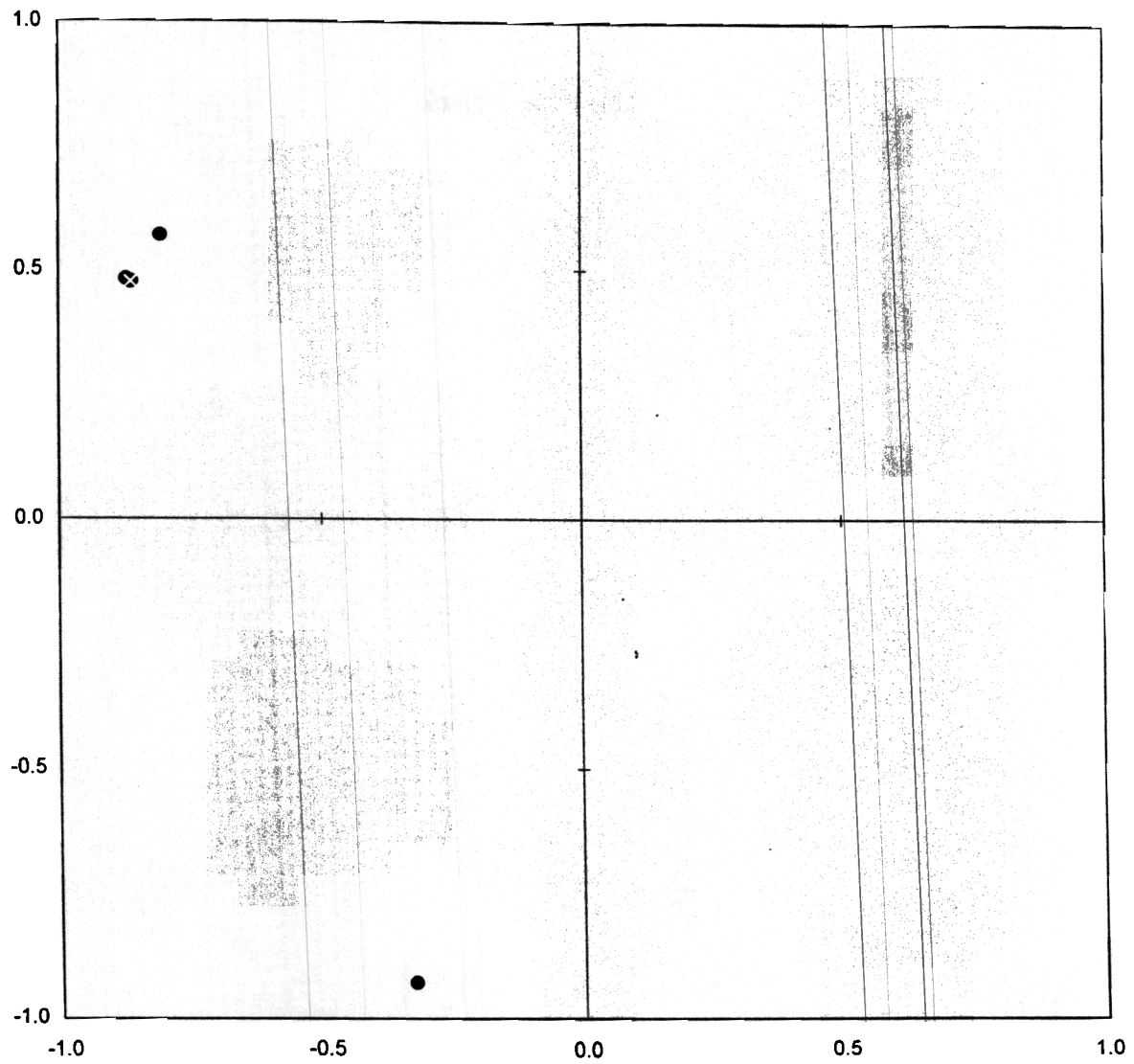
S21.S12 of adaptor 1 (female)



Frequency: 10.0 GHz

Figure 9

S21.S12 of adaptor 1 (female)



Frequency 12.4 GHz

This page is blank

ADAPTOR 2

Table 4: S_{11} summary statistics

Frequency (GHz)	Spatial Median		MAD	
	Magnitude	Phase (°)	Magnitude	Phase (°)
8.2	0.0076	-100.3	0.0029	24.8
10.0	0.0077	+15.8	0.0009	19.6
12.4	0.0070	-123.1	0.0021	19.0

Table 5 S_{22} summary statistics

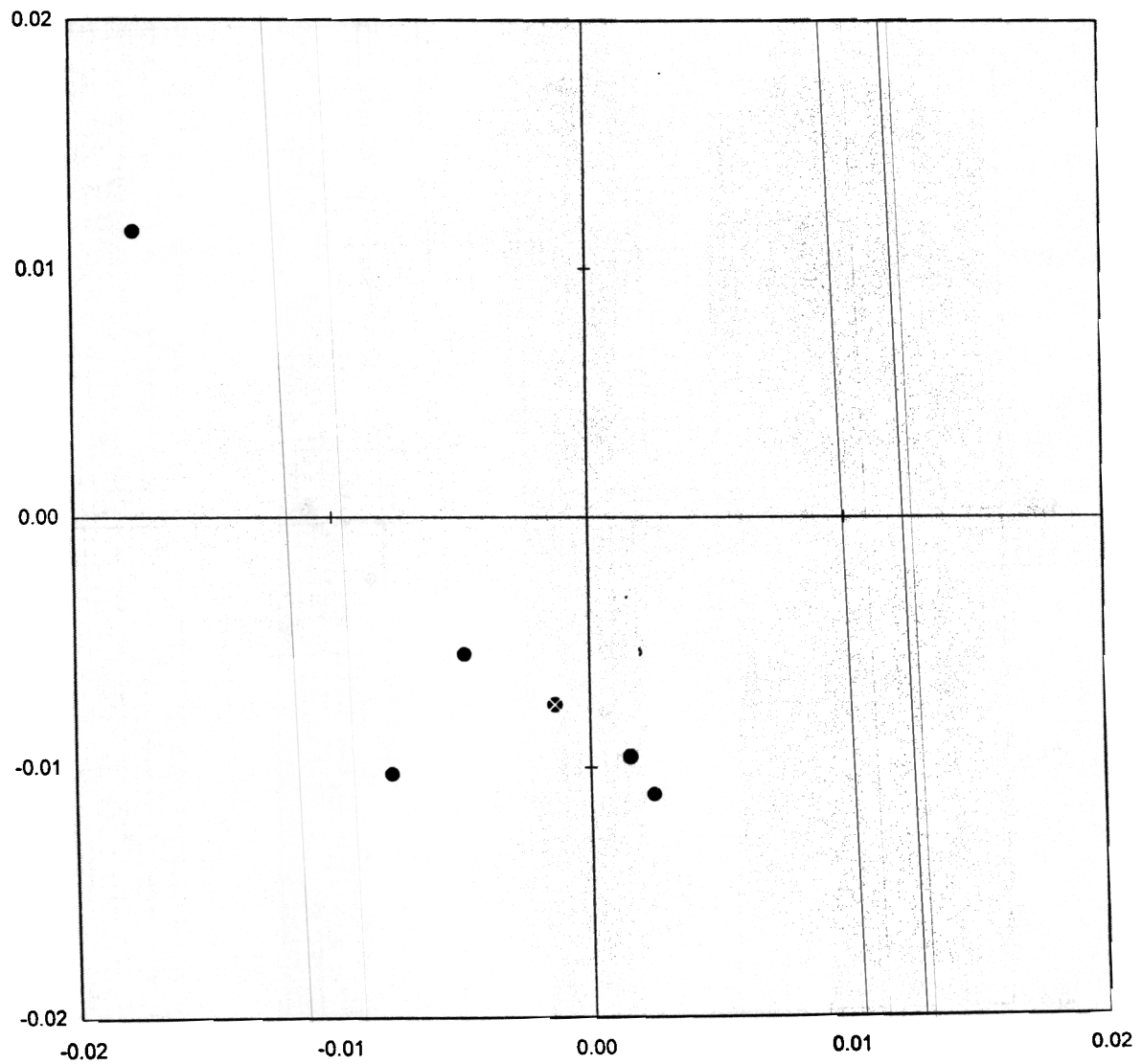
Frequency (GHz)	Spatial Median		MAD	
	Magnitude	Phase (°)	Magnitude	Phase (°)
8.2	0.0087	+18.4	0.0017	26.4
10.0	0.0047	+32.0	0.0049	37.8
12.4	0.0077	+155.0	0.0027	32.4

Table 6: $S_{21}S_{12}$ summary statistics

Frequency (GHz)	Spatial Median		MAD	
	Magnitude	Phase (°)	Magnitude	Phase (°)
8.2	0.9780	+109.1	0.0030	1.11
10.0	0.9808	-98.7	0.0014	1.35
12.4	0.9787	-158.7	0.0024	1.47

Figure 10

S11 of adaptor 2 (male)



Frequency: 8.2 GHz

Figure 1

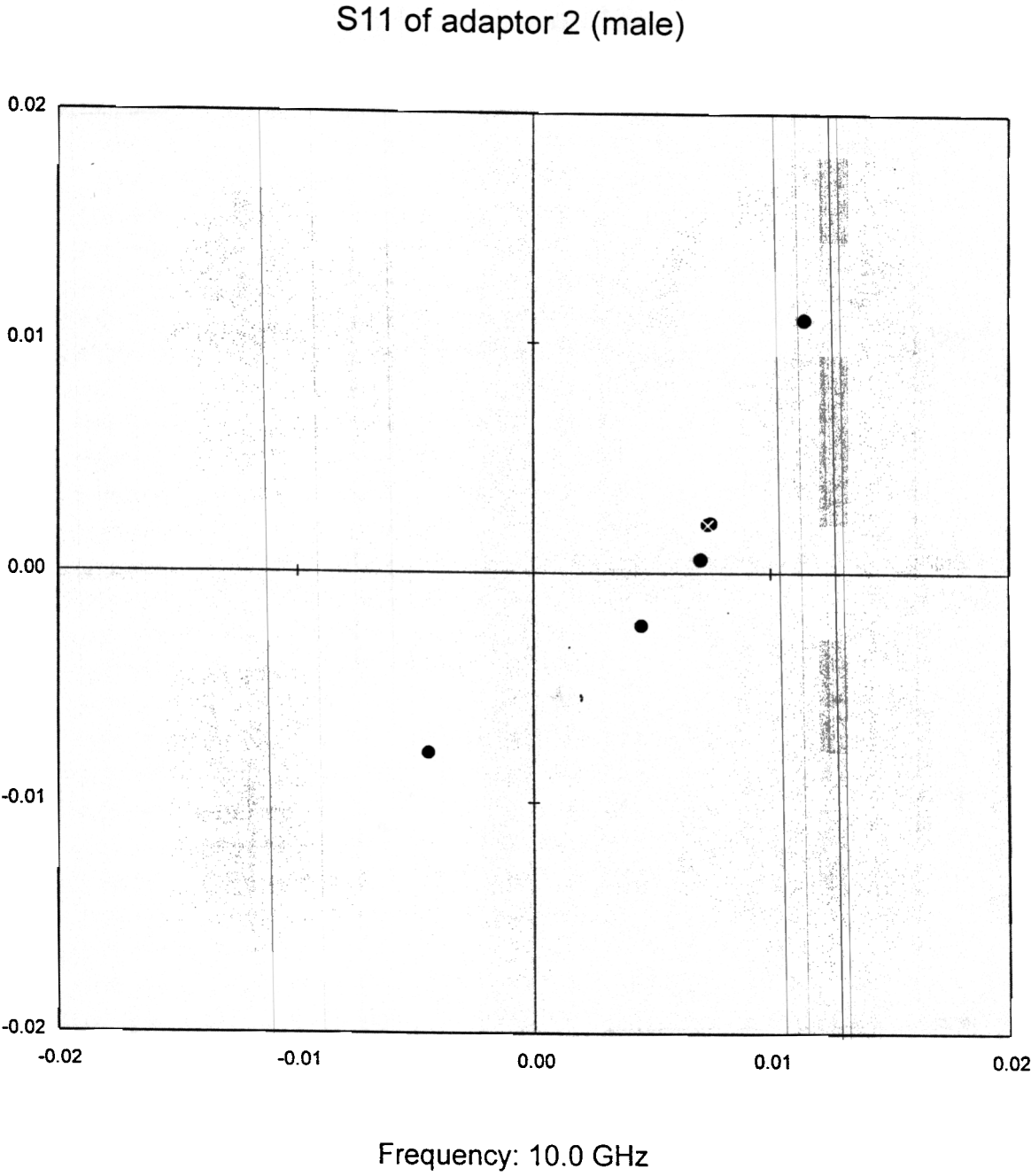


Figure 12

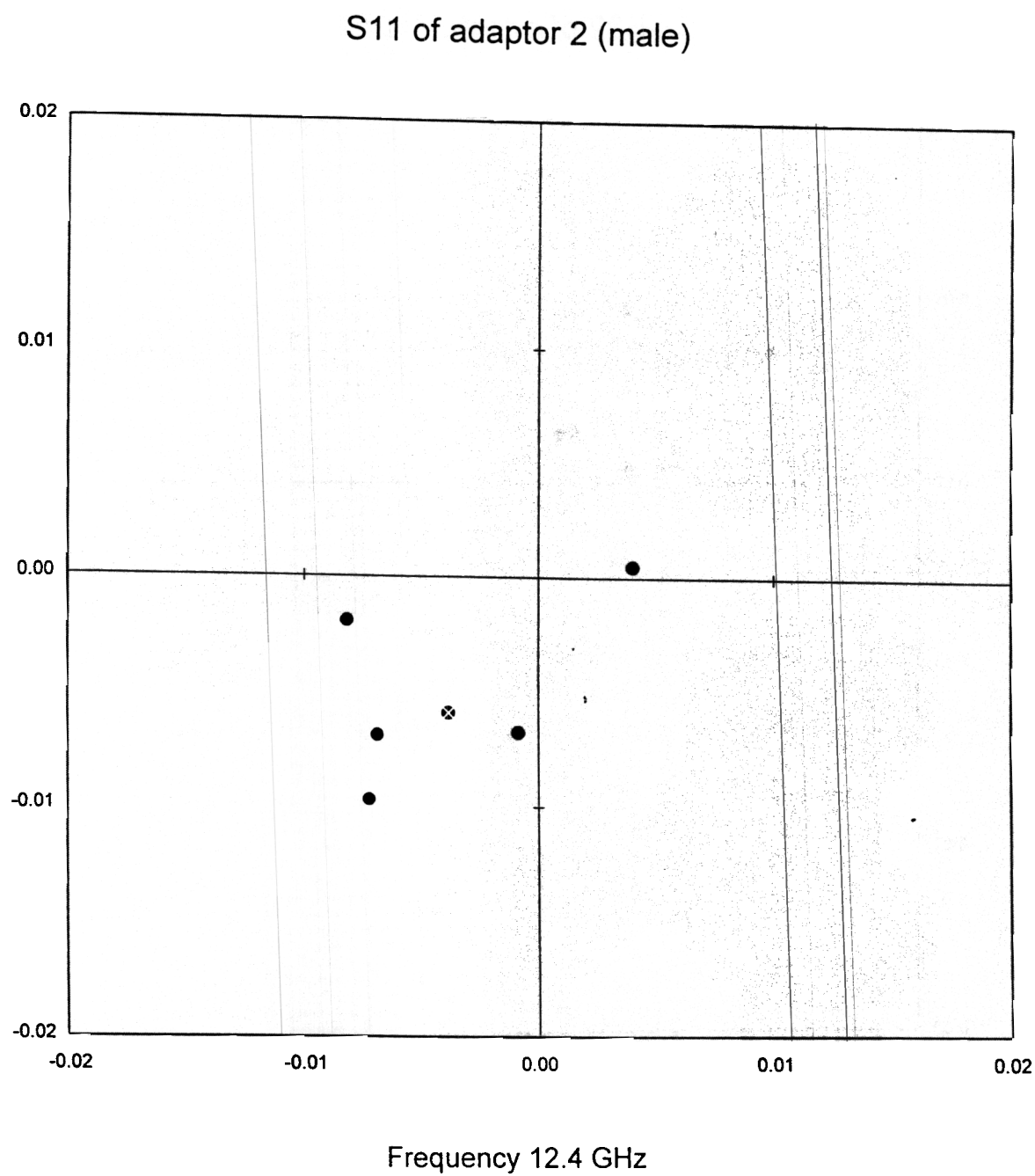


Figure 13

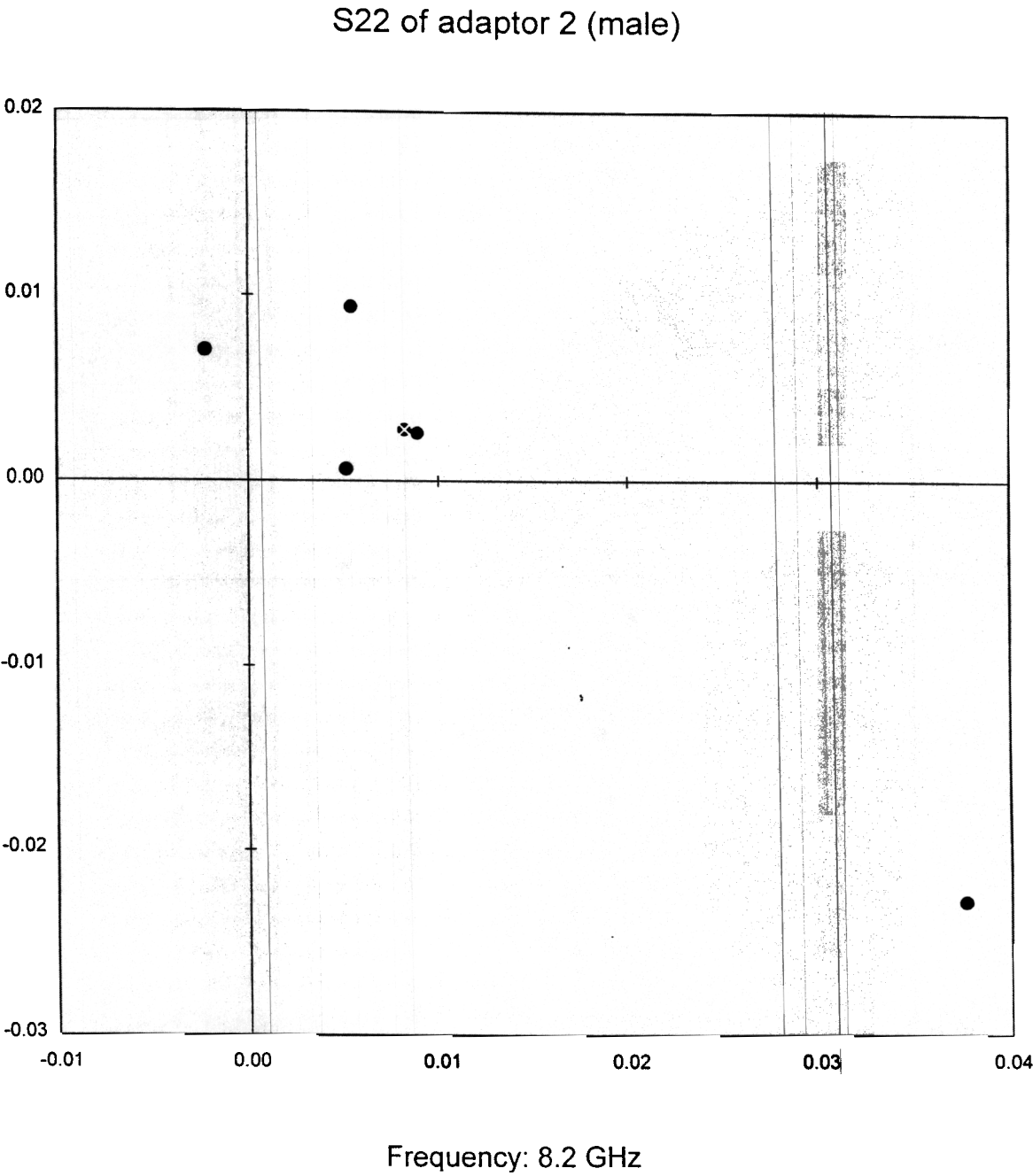
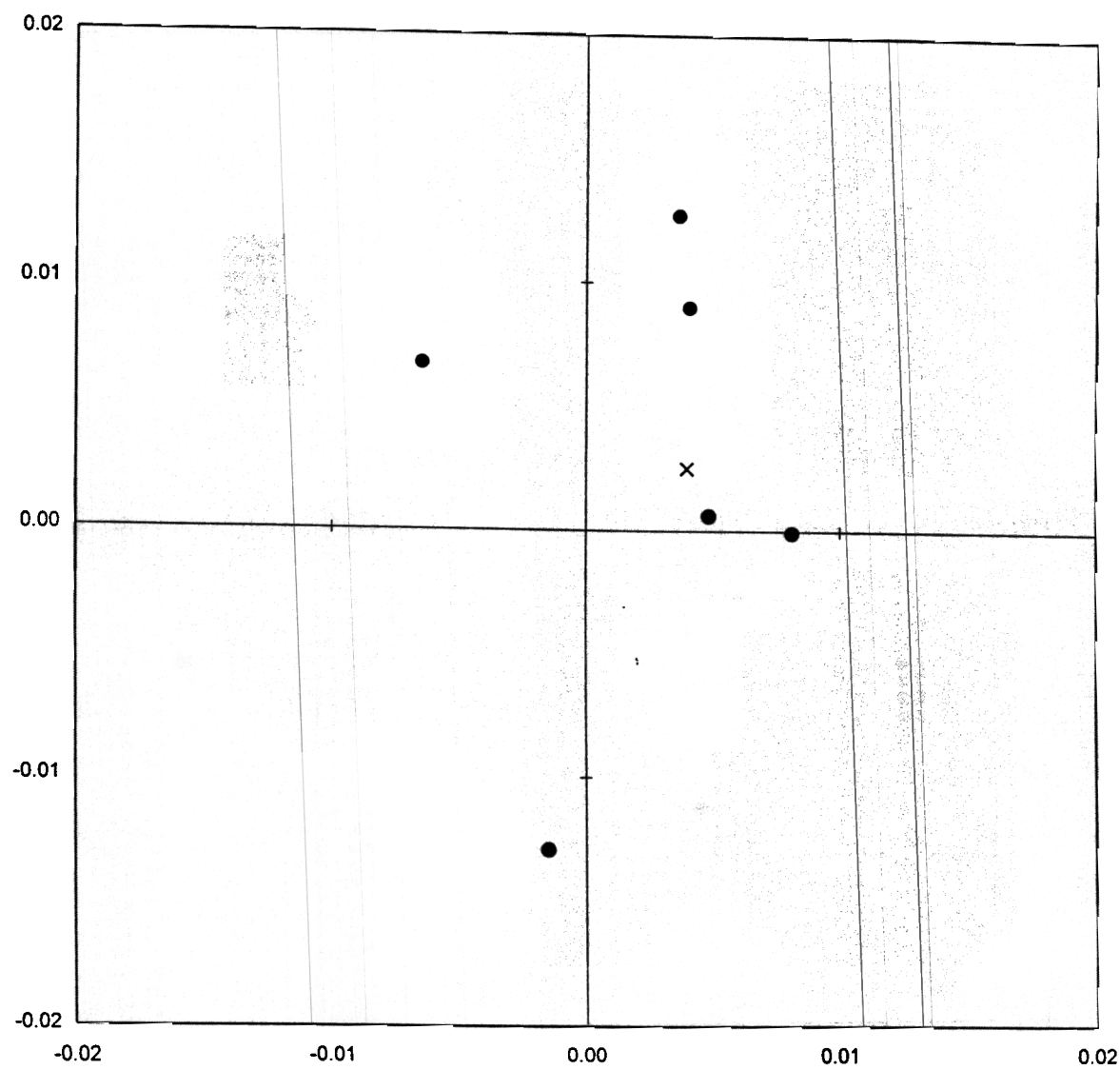


Figure 14

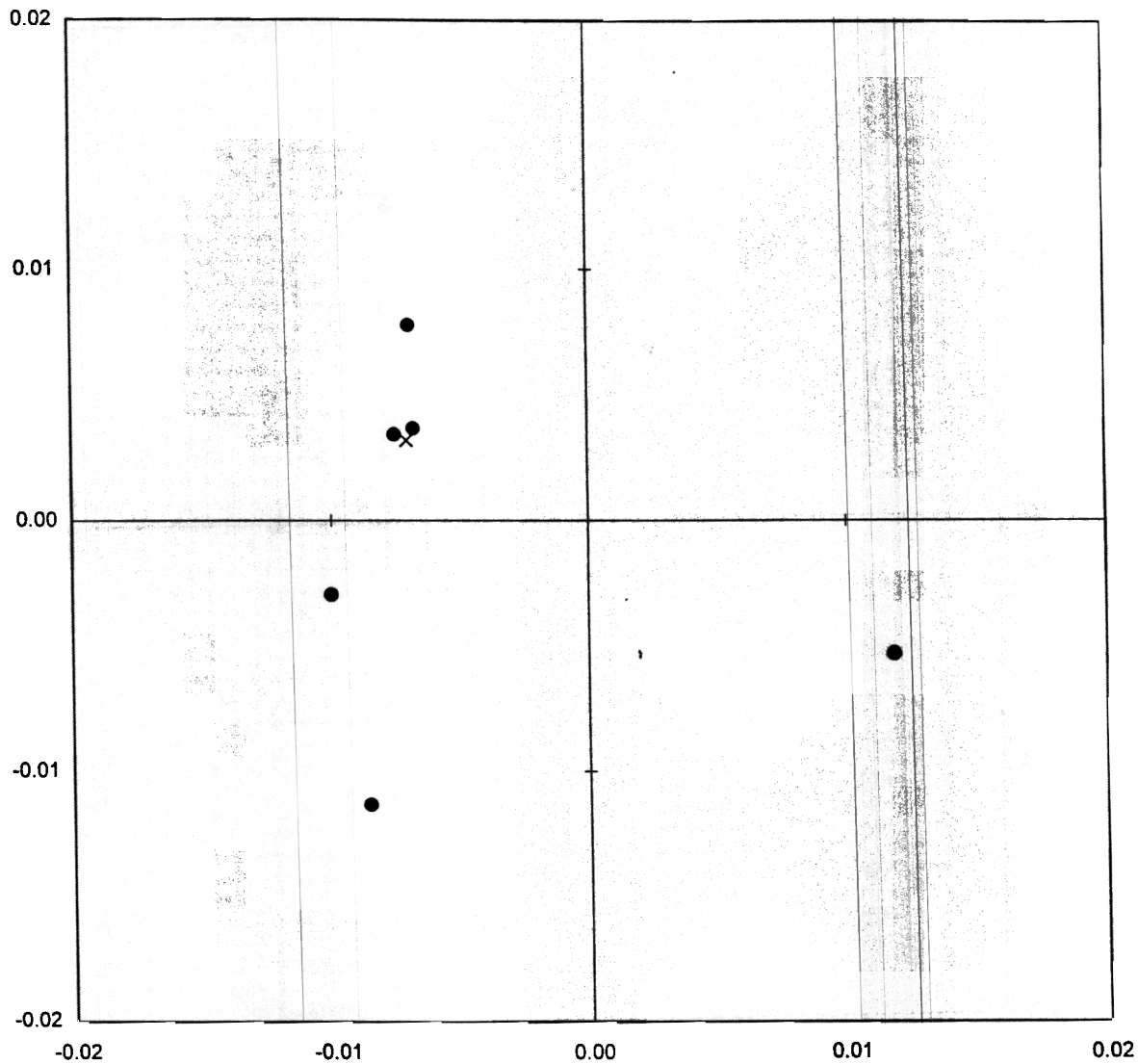
S22 of adaptor 2 (male)



Frequency: 10.0 GHz

Figure 15

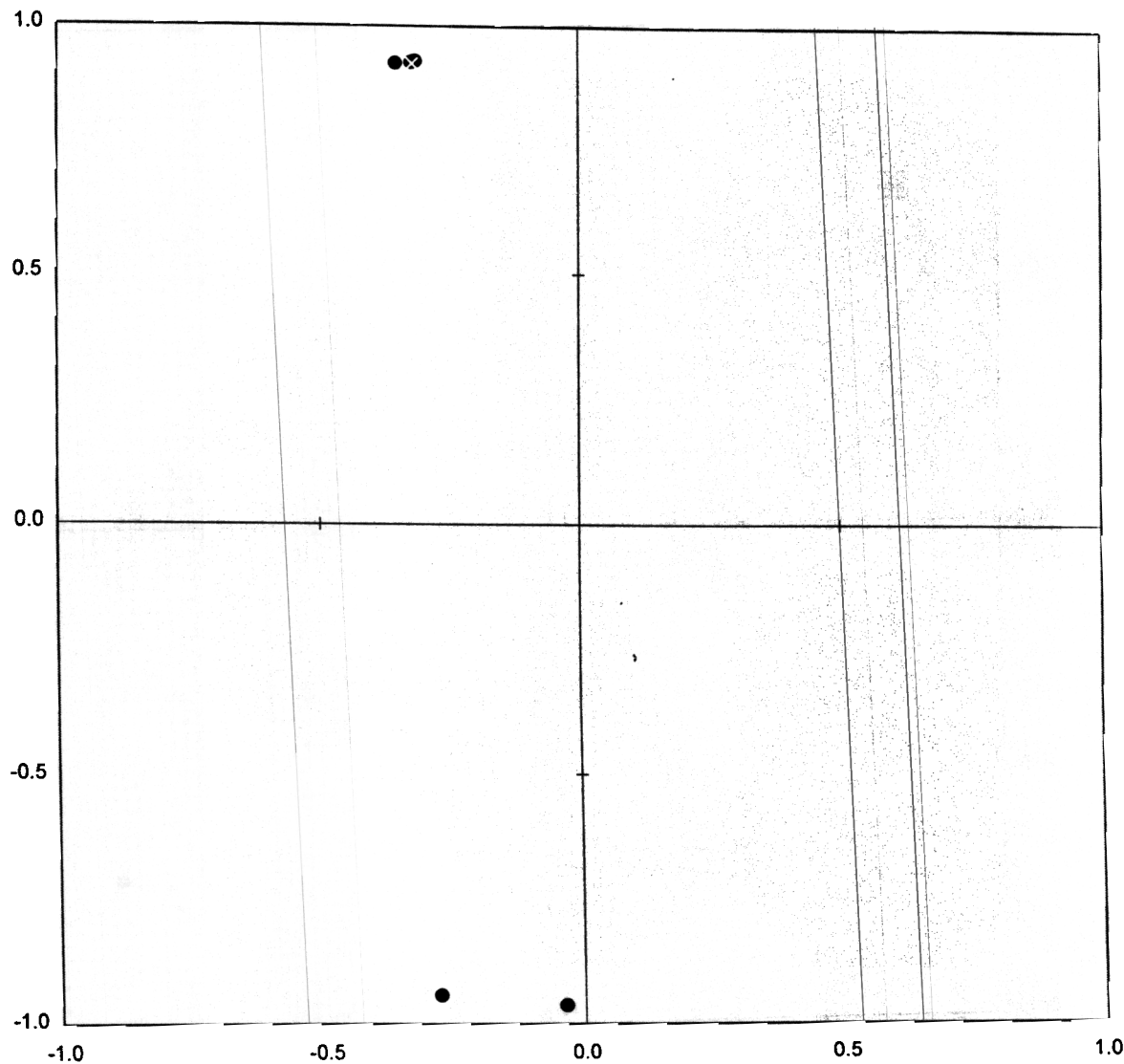
S22 of adaptor 2 (male)



Frequency 12.4 GHz

Figure 16

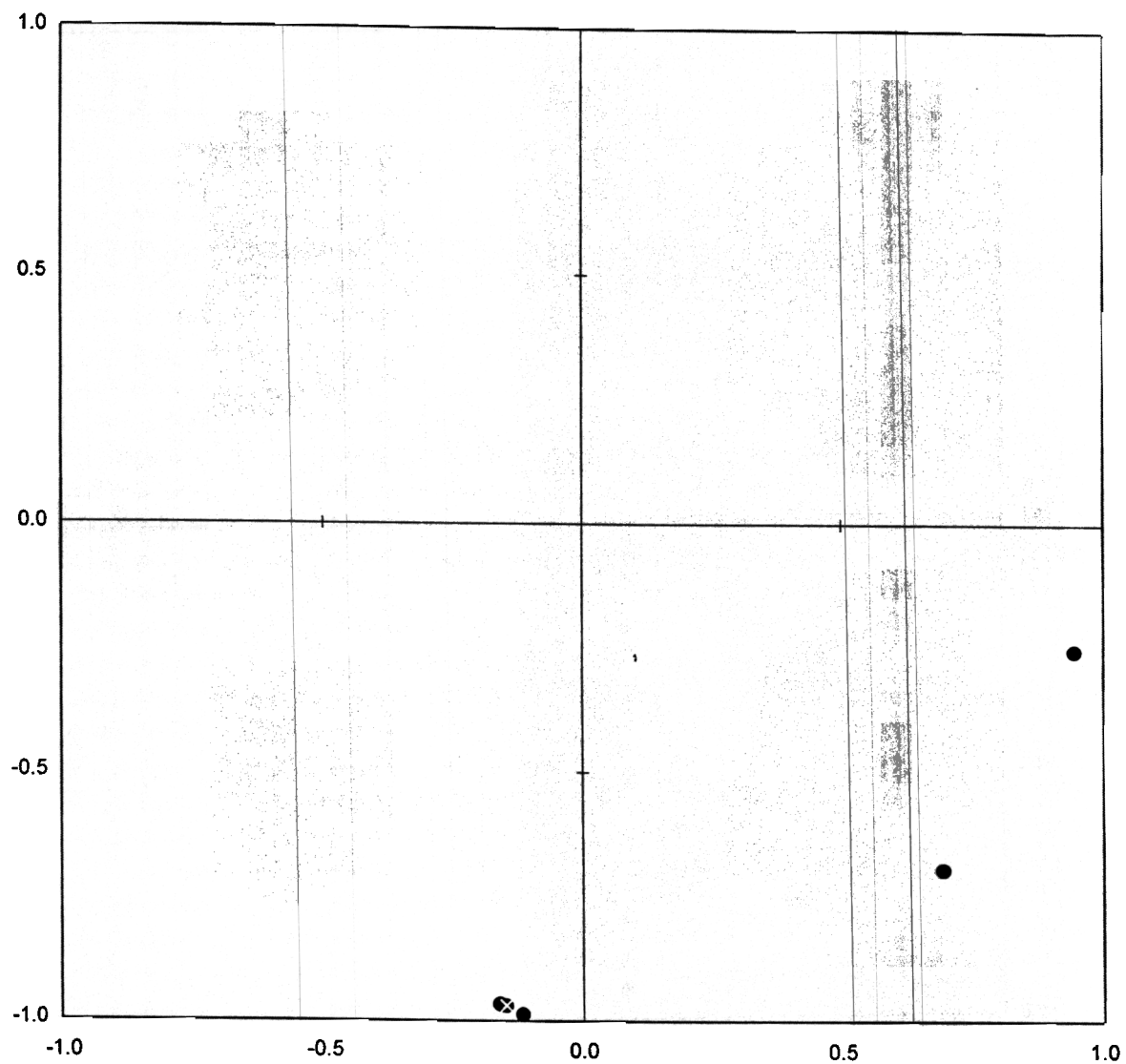
S21.S12 of adaptor 2 (male)



Frequency: 8.2 GHz

Figure 17

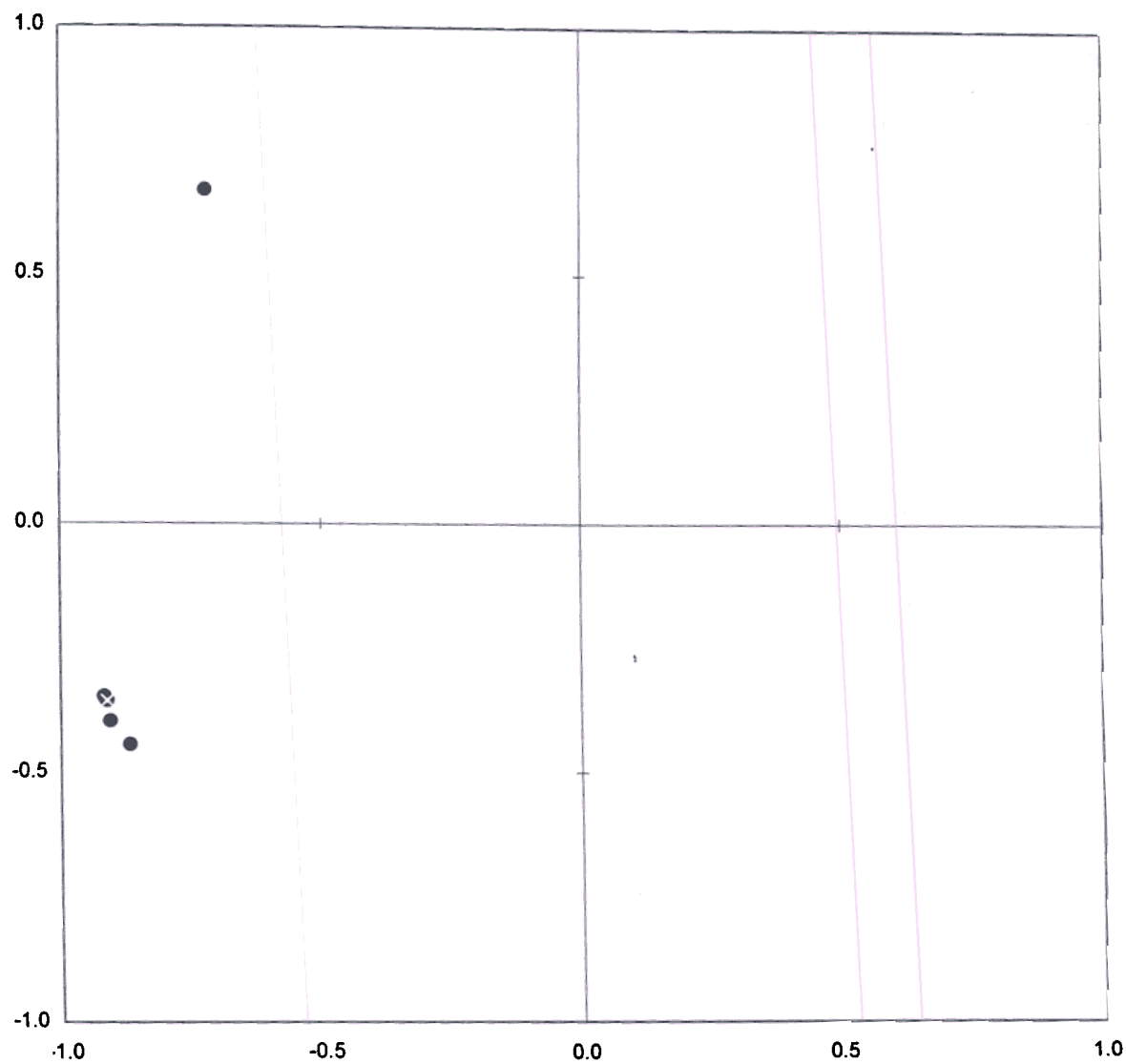
S21.S12 of adaptor 2 (male)



Frequency: 10.0 GHz

Figure 18

S21.S12 of adaptor 2 (male)



Frequency 12.4 GHz

PIN-DEPTH GAUGE MEASUREMENTS

Table 7: Summary statistics

Adaptor	Connector	Spatial median (μm)	MAD (μm)
1	Female	59.1	4.0
2	Male	60.7	9.9