

REPORT

International Comparison GT-RF/83-4: Measurement of Scattering Coefficients Over the Band 2 - 18 GHz

J P Ide

July 1999

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1 ABSTRACT

This is a detailed report of a international comparison of one of the most important microwave parameters, namely impedance. The comparison was actually of one of the manifestations of impedance called scattering coefficients and was given the title "Measurements of scattering coefficients over the band 2 - 18 GHz" and the reference number GT-RF/83-4 by the relevant CCE working group. The following institutes participated: PTT (Switzerland), VSL (the Netherlands), NIST (United States of America), FFV (Sweden), LCIE (France), IEN (Italy), PTB (Germany), CSIRO (Australia) and NPL (United Kingdom), the latter as pilot laboratory. The items to be compared were all fitted with precision GPC-7 sexless 50 ohm coaxial 7 mm connectors so that they were both reversible and insertable. Six items, consisting of four two-port devices and two one-port devices, were circulated to the participants who were asked to supply measurements of the scattering coefficients (referred to 50 ohms) of each of the items at 65 frequencies, covering the range 2 to 18 GHz in steps of 0.25 GHz. Because of the vast amount of data generated, traditional methods of evaluating the comparison were not necessarily appropriate and this report explores some of those issues as well as presenting a selection of the results. It is intended that material drawn from this report will be submitted to BIPM for publication as the final report.

2. INTRODUCTION

The Radiofrequency Working Group (GT-RF) of the Comité International des Poids et Mesures' (CIPM) Comité Consultatif d'Electricité agreed to run an international comparison of scattering coefficients at RF and microwave frequencies and allocated the number 83-4 to this comparison. The following national institutes indicated their wish to participate:

- a) National Physical Laboratory (NPL), represented by the RF and microwave standards division at Great Malvern, Worcestershire, UK, which also acted as pilot laboratory.
- b) Swiss Telecom (PTT), Bern, Switzerland.
- c) NMi Van Swinden Laboratorium (VSL), Delft, The Netherlands.
- d) National Institute of Standards and Technology (NIST), Boulder, Colorado, USA
- e) FFV Aerotech AB (FFV), Arboga, Sweden.
- f) Laboratoire Central des Industries Electriques (LCIE), Fontenay-aux-Roses, France.
- g) IEN Galileo Ferraris (IEN), Torino, Italy.
- h) Physikalisch Technische Bundesanstalt (PTB), Braunschweig, Germany.
- i) Commonwealth Scientific and Industrial Research Organisation (CSIRO), Sydney, Australia.

A rosette arrangement for the transportation of the items to and from the various laboratories was used as shown in Diagram 1. This arrangement enabled NPL to monitor the stability of the items and to take remedial action when required.

The parameter to be compared was the scattering coefficient or S-parameter. A two-port device has four S-parameters (S11, S21, S12 and S22) where the suffixes describe the port at which the signal is detected and the port from which it is launched. Thus S11 refers to the ratio of the signal detected at port 1 to that launched at the same port, which is more usually called the voltage reflection coefficient. In the same way S21 is the voltage transmission coefficient from port 1 to port 2. These coefficients are complex i.e. have two components, because both signals have magnitude and phase and thus the ratio between them has both magnitude and phase. A one-port device has only a single S-parameter, S11, but this is still complex. It is implicit in the definition of scattering coefficients that the impedance of the line is known. In this case the reference impedance for all the measurements was 50 ohms.

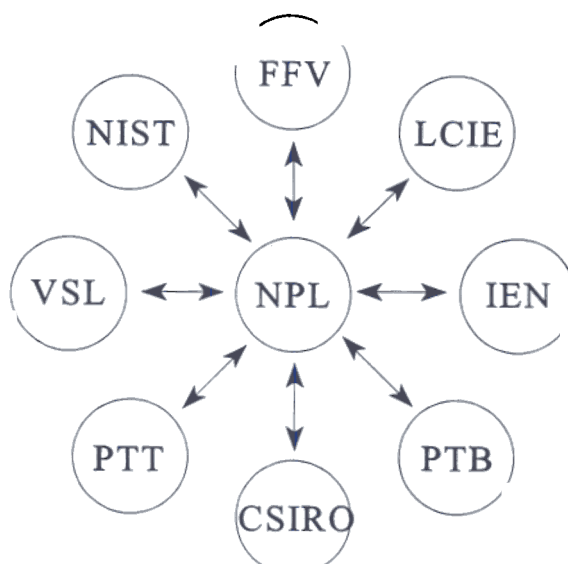


Diagram 1: The Rosette arrangement for the transportation of items.

3. THE MEASUREMENT ITEMS.

- 3.1 Six devices, all fitted with GPC-7 connectors, were circulated to each of the participants in the order given above. Measurements were requested of all four scattering coefficients of four two-port devices, and the reflection coefficient of two one-port devices. Included in the items were a pair of unsupported coaxial lines. These items consist of an outer conductor made to very tight dimensional tolerances so that the bore is circular and uniform along its length, and an inner conductor of the same length fitted with special 'bullets' that enable it to be supported by the collets of the test ports. This means that the dielectric between the inner and outer conductor is air, thus the name - air line. The characteristic impedance of this type of coaxial line is well-defined and readily calculated from the dimensions. One air line had a uniform 50 ohm impedance and the other a stepped 25 ohm impedance. This consisted of an air line with a inner conductor whose diameter changed for part of its length giving a device with a section of 25 ohm characteristic impedance sandwiched between two sections of 50 ohm impedance. The purpose of this design is to separate the effects of the change in impedance for 50 to 25 ohm from those occurring at the junctions of the line and test ports. A more detailed description of the bullets, collets and air lines is given in appendix A.
- 3.2 To determine any differences between the measurement ports on the measuring systems, the participants were asked to reverse two of the devices so that differences in the ports would be exposed. The full list of items was as given below:

Item 1.	Nominal 10 dB attenuator
Item 2.	Nominal 40 dB attenuator
Item 3.	50 ohm air line
Item 4.	50 ohm air line reversed
Item 5.	25 ohm air line
Item 6.	25 ohm air line reversed
Item 7.	Nominal short-circuit
Item 8.	Nominal well-matched termination.

- 3.3 Participants were asked to supply measurements of the real and imaginary components of each S-parameter, with uncertainties in each component, at 65 frequencies, covering 2 to 18 GHz in steps of 0.25 GHz.

4. MEASUREMENT SYSTEMS AND CALIBRATION METHODS OF THE VARIOUS LABORATORIES

4.1

- 4.1 The system used an HP8510B automatic network analyser (ANA) fitted with an HP8515A test set. The type of calibration performed was a TRL (THROUGH-REFLECT-LINE) using items from a HP85050C TRL 7 mm precision calibration kit. A calibration was performed before each of the 10 measurement runs. A precision ruggedised 3.5/GPC-7 adaptor was used as port 1 of the measurement system and the special TRL adaptor from the calibration kit on the end of a 3.5 mm flexible test port cable made up port 2.

- 4.2 The use of the TRL adaptor meant that the ports were not identical and special precautions had to be taken to overcome this potential problem. The special TRL adaptor has a screw thread to support the short air line that comprised the LINE part of the TRL calibration and this meant that it could not support a conventional GPC-7 collet. Thus during the REFLECT part of the calibration, in which the two test ports are terminated with items having nominally identical reflection coefficients, a pair of special short-circuits were used. One was plain, i.e. completely flat and one included a collet as part of its structure. This meant that each junction contained only one collet.

- 4.1.3 During the measurements a special support pin with integral collet was used to support the end of the unsupported air lines at the TRL adaptor end. Under these conditions all the junctions contained a single collet for maximum repeatability.

- 4.4 The data was gathered for a single measurement run by collecting the data on the calibration items and measurement items in turn and presenting the combined data to a suite of proprietary NPL software which produced the measurement data for each item, corrected for the errors in the ANA with the data on the calibration items. This process was repeated 10 times, giving 10 separate measurements of the real and imaginary components of each S-parameter at every frequency. The results at each frequency were processed to produce a mean value for the Real component and a mean value for the Imaginary component. The standard deviations of the measurements of the two components were combined with uncertainties in the TRL procedure to produce a single figure for uncertainty, appropriate to both components.

- 4.1.5 The laboratory conditions were reported as 23 ± 1 °C and 40 ± 10 % rel. humidity.

4.2

- 4.2.1 The equipment used was an HP8510B ANA fitted with an HP8515A test set. The calibration of the ANA was performed using a TRL calibration with items from an HP85050C TRL 7 mm precision calibration kit. A calibration was performed before each of the 10 measurement runs. A pair of 7 mm cables were used to connect the measurement items to the test ports, with one cable between each end of the measurement items and the test set so that the system was symmetrical. A TRL adaptor was attached to make up one of the test ports.

The system was controlled under HP85161 NWA measurement software running under BASIC 5.11 on a HP320 computer. The ANA was set up so that each measurement value was the average of 1024 readings. The results were presented as the mean Magnitude and mean Phase of each S-parameter with a value representing the repeatability at each frequency for each parameter and for each item. This value was calculated using the formula

$$s(z) = \sqrt{\frac{\sum_{i=1}^n |z_i - \bar{z}|^2}{(n-1)}}$$

where $s(z)$ is the value representing the repeatability derived from n measurements of the complex S-parameter with a mean value of $\bar{z}$.

Values representing full uncertainties instead of the repeatability were supplied later for three frequencies.

The laboratory conditions were reported as 23.5 ± 0.5 °C and 45 ± 5 % rel. humidity.

4.3 VSL

The equipment used was a Wiltron 360B ANA. The calibration of the ANA was performed using the SOLT method which uses a Short-circuit, an Open-circuit and a Load as reflection standards on each port and a Through connection to complete the calibration. The load used was a fixed 50 ohm termination.

A calibration was performed before each of the 10 measurement runs and the results were presented as the mean values of each of the Real and Imaginary components of each S-parameter with a single value representing the repeatability at each frequency and for each item. Values representing the full uncertainties were supplied later for three frequencies.

4.4 NIST

4.4 The equipment used was a dual 6-port automatic network analyser. This was calibrated using an LRL (LINE-REFLECT-LINE) technique which incorporates the following calibration devices: two air lines of different lengths, a flat short-circuit, a dielectrically loaded open-circuit, two 1-port devices and a 10 dB attenuator. The type-N female bulkheads on the 6-port heads were adapted to GPC-7 using precision type-N male to GPC-7 adaptors.

4.4.2 After the dual 6-port was calibrated six measurements were made on each of the devices. For the 1-port devices, three connections were made to each test port. For the 2-port items, three connections were made in both the forward and reverse orientations and the results averaged. Thus the results presented for Item 4 were identical to those presented for Item 3 and similarly for Items 5 and 6. The results were presented as values for the mean magnitude and mean phase with separate uncertainties in both magnitude and phase, for each S-parameter at each frequency and for each item.

4.4.3 The laboratory conditions were reported as 23 ± 1 °C and 40 ± 5 % rel. humidity.

4.5

- 4.5.1 The equipment used was an HP8510B ANA fitted with an HP8516A Option 003 test set and a HP85050C TRL calibration kit. Option 003 on the test set enhances the dynamic range for the measurement of S21 at the expense of the S12 measurements. Measurements of S11 and S22 are not affected by this option. However when using TRL calibration techniques on a test set fitted with option 003, problems can occur due to an unpadded diode sampler at port 2. To overcome these problems, an internal 10 dB attenuator was used in the port 2 path. Under these circumstances the performance of S12 and S22 are degraded by approximately 10 dB while S11 and S21 are almost unaffected.
- 4.5.2 Adaptors were required to change the 2.4 mm connectors on the test set to the 7 mm connectors required for the 7 mm cables. The TRL adaptor was connected to the end of the cable making up port 2.
- 4.5.3 The ANA was set up so that each measurement value was the average of 1024 readings. The results were presented as the values of the mean and standard deviation of the magnitude and phase of each S-parameter at each frequency and for each item. Values representing the full uncertainties were later supplied at 3 frequencies.
- 4.5.4 The laboratory conditions were reported as 23 ± 1 °C and 45 ± 5 % rel. humidity.

4.6 LCIE

- 4.6.1 The measurement system was a dual 6-port type with an HP85050C TRL calibration kit. Special adaptors were used to convert the Narda 3.9 mm test ports to the required GPC-7 ports. The special TRL adaptor was connected to port 2.
- 4.6.2 The results were presented as values of the mean of the magnitude and phase of each S-parameter at each frequency and for each item. Values for the uncertainties did not accompany the results and were not supplied until some time after the exercise had been completed.
- 4.6.3 The laboratory conditions were reported as 23 ± 1 °C and <60% rel. humidity.

4.7

- 4.7.1 The equipment used was an HP8510C ANA fitted with an HP8517A test set. The calibration of the ANA was performed using a TRL calibration with items from an HP85050C TRL 7 mm precision calibration kit. A calibration was performed before each of the 7 measurement runs. A pair of cables were used to connect the measurement items to the test ports, with one cable between each end of the measurement items and the test set so that the system was symmetrical. A TRL adaptor was attached to make up one of the test ports.
- 4.7.2 The ANA was set up so that each measurement value was the average of 1024 readings. The results were presented as the values of the mean and standard deviation of the real and imaginary components of each S-parameter at each frequency and for each item. The estimates of the full uncertainties were obtained by combining the type A components of uncertainty i.e. the standard deviations, with the value for the type B component supplied to cover both reflection parameters or both transmission parameters, as appropriate, for each item.

The laboratory conditions were reported as 21.5 ± 0.5 °C and $50 \pm 5\%$ rel. humidity.

4.8 PTB

The equipment used was a HP8510B ANA fitted with an HP8515A test set. The type of calibration performed was a SOLT using a short-circuit and open-circuit from an HP85050C 7mm precision calibration kit. The load was generated using a Maury 2608C sliding termination.

Each item was measured in two sets. Each set consisted of a calibration followed by 10 single measurements of the same item, with the item being rotated through an angle of some 10 degrees between each single measurement. For further evaluation, five single measurements values from the first set and five from the second were taken.

The ANA was set up so that each measurement value was the average of 1024 readings. The results were presented as the values of the mean and standard deviation of the magnitude and the phase of each S-parameter at each frequency and for each item. A single Type B uncertainty was supplied for each S-parameter for each item.

4.8.4 The laboratory conditions were reported as 23.0 ± 0.2 °C and $50 \pm 15\%$ rel. humidity.

4.9 CSIRO

4.9.1 The equipment used was an HP8510C ANA. The type of calibration performed was TRL using items from an HP85050C TRL 7 mm precision calibration kit. A calibration was performed before each of the 10 measurement runs. An extended test cable was used on port 2 of the instrument to reduce cable flexing. To this the TRL adaptor was attached to form the measurement port 2.

4.9.2 The ANA was set up so that each measurement value was the average of 1024 readings. The results were presented as the values of the real and imaginary components and an uncertainty that applied to both components of each S-parameter at each frequency and for each item.

4.9.3 The laboratory conditions were reported as 22.0 ± 0.5 °C

5. PROBLEMS ENCOUNTERED DURING THE MEASUREMENT CYCLE

5 There were several problems encountered during the circulation of the items, some of them more severe than others.

5.2 The characteristics of the two attenuators changed during the measurement cycle. Item 2, the 40 dB attenuator, consists of a pair of connectors attached to a central barrel section containing the resistive element. Connection to the resistive element was made by a sprung contact to the end of the glass slide on which the resistive material is deposited. The junction between one of the connectors and the central barrel section became loose and the measurements became very unrepeatable. For this reason FFV were not able to supply measurements of this item. This was investigated at NPL and it was observed that the connection was sufficiently unrepeatable that retightening would not reproduce the original figures. Accordingly the attenuator was substituted with another from the same manufacturer. The label of the old attenuator, giving its type and serial number was attached to the new attenuator, so that the customs carnets that had been previously acquired were still valid.

- 5.3 The characteristics of item 1, the 10 dB attenuator, also underwent a step change in its values. This change appeared to be stable and so the original device continued to circulate.
- 5.4 The loss of continuity of two of the devices has damaged the purpose of the intercomparison but some benefit can still be gained through the NPL measurements of both states of the devices. This allows some conclusions to be drawn.
- 5.5 There were the usual problems relating to customs carnets to allow the items to pass through customs at the various national borders. Some of the laboratories were unable to accept the items for measurement at the agreed time and so the carnets which had a fixed time period lapsed. Rescheduling the order of the laboratories to accomodate their own measurement schedules was a perennial problem, especially when the time scale became so extended that it was difficult to give a sense of urgency.

Some of the participants were still in the process of assessing their facilities and capabilities and were therefore unable to supply a full set of uncertainty figures. These participants originally supplied only figures for the repeatability of their values without including systematic errors and uncertainties. Due to the considerable delay in the production of the final report all these participants were eventually able to produce full uncertainty estimates at three frequencies.

- 5.7 A considerable debate was held about the benefits of giving participants an idea of the values that they should expect to get before they perform the measurements. It was suggested that each item should be treated as a black box, i.e. a complete unknown, as this was the only way to ensure that the participants couldn't 'cheat' and adjust their values either consciously or unconsciously. It was claimed that this would reinforce the confidence that others would have in the individual laboratories, rather like passing an examination. However, it was felt that the purpose of the exercise was primarily one of research rather than enforcement of any standards of proficiency and that any results that were dramatically different from the rest, e.g., due to different interpretations of the instructions, would undermine the whole exercise. It was hoped that giving the participants 'nominal' figures would raise their confidence in their results which would reduce the amount of time for which each participant required the items, and reduce the risk of outliers.

A copy of the instructions sent to the participants including a small sample of the 'nominal' figures is given in appendix B.

6. COMMENTS ON THE PRESENTATION OF THE RESULTS

- 6.1 The data comprising the results submitted by the participants including the uncertainties comes to a staggering 45000 individual numbers. Processing this amount of data and presenting it in a clear, sensible and useful manner has been a logistical nightmare.
- 6.2 For clarity, two families of graphs are presented in this report. The first figures (Figures 1 to 14) show the data submitted by the participants for S11 and S21 of each of the items without uncertainties. The second set of figures (Figure 15 to 36) show the data for selected parameters and items at three selected frequencies only; 2, 10 and 18 GHz. This data is presented in logarithmic or linear format as appropriate to the parameter. In these figures the standard uncertainty associated with each data point is represented by the

length of the uncertainty bars attached to that data point. It should be noted that although the lengths of the uncertainty bars above and below the point are equal when displayed in a linear format, they are unequal when displayed in a logarithmic (e.g. decibels) format. The results for S22 and S12 are not plotted as they are so similar to the results for S11 and S21 that nothing would be gained by presenting them.

- 6.3 The purpose of presenting the two sets of figures in this way is to enable trends and overall agreement to be estimated from the first set and a detailed analysis to be derived from the second set. The first set allows a picture to be built up of the spread of the data and its relationship to frequency. The second set shows the level of agreement within the uncertainty bounds. The presentation of the two sets together enables a judgement to be made of an individual participant's performance over the entire frequency range.
- 6.4 The phases of the transfer standards change quickly with frequency and the effect of the 'clock' arithmetic (i.e. limited to ± 180 degrees) is to produce sawtooth effects on such a scale as to make the traces largely indistinguishable. These effects could be reduced by using a frequency-related offset calculated from the electrical length of the item but this would imply prior knowledge of the electrical length. It was felt by the author of this report that using any offset would impose such a bias as to the 'rightness' of the offset value as to render the exercise misleading. Using some form of average value as an offset was also rejected for the first set of figures because the change in value with frequency is more useful than the level of disagreement.
- 6.5 The phase of an S-parameter becomes less meaningful as the magnitude reduces to zero. This can be most simply demonstrated by using the words 'length' and 'direction' in place of magnitude and phase. It is impossible to talk of the direction of a zero length line. Thus the phase of a reflection too close to zero will also be meaningless.
- 6.6 The uncertainty of the position of a point in the complex plane can be described by the radius of a circle around that point. Under these circumstances, it is easy to convert between the uncertainties in the real and imaginary components and the uncertainties in the magnitude and phase. The uncertainty in the real component is, by this definition, numerically equal to the uncertainty in the imaginary component *and* the uncertainty in the magnitude, i.e. a circle of uncertainty. Conventionally, the uncertainty in the magnitude might be expected to be the root-mean-square value of the two components but this would not result in a circle.
- 6.7 The uncertainty in the phase is calculated from the radius of the circle of uncertainty and the magnitude of the reflection coefficient using the inverse sin relationship i.e.

$$\text{phase uncertainty} = \arcsin(\text{radius of circle of uncertainty} / \text{reflection coefficient magnitude})$$

This is shown in Diagram 2 below. It can be seen from this diagram that when the magnitude of the VRC is smaller than the uncertainty, the origin is contained within the uncertainty circle, making all phases possible. Under these circumstances the phase is indeterminate and the uncertainty is specified as ± 180 degrees.

- 6.8 Some participants presented their results as real and imaginary components. These results were processed as above to enable them to be presented with the others in magnitude and phase format.

Imaginary axis

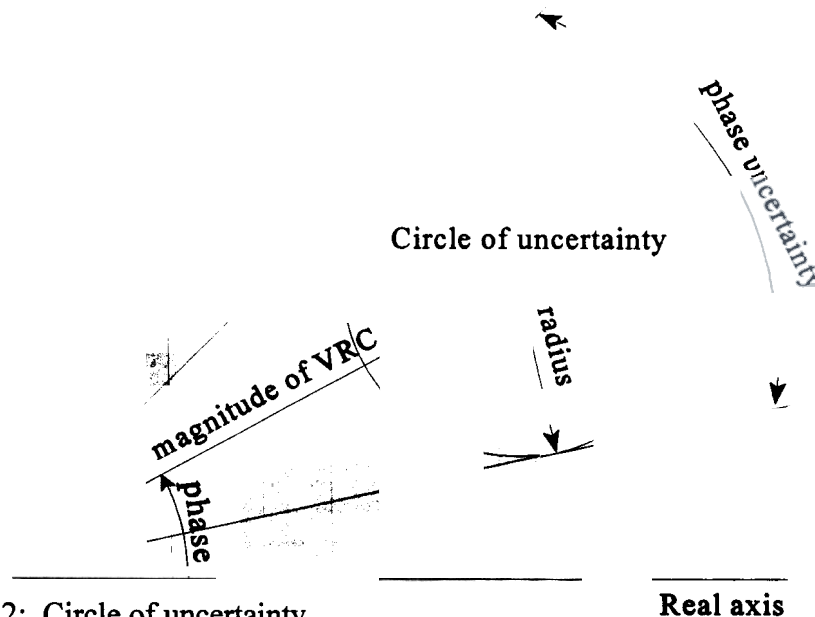


Diagram 2: Circle of uncertainty

7. DISCUSSION OF THE OVERALL RESULTS.

7.1 Overall results for item 1 (10 dB attenuator) as displayed in Figures 1A, 1B, 2A & 2B

The magnitude of S11 shows that all participants bar one agree well from 2 GHz to 8 GHz. From about 8 GHz, the spread in the results becomes more significant until at 14 GHz the separate traces for the two different states of the attenuator become apparent. The results from LCIE show considerable scatter about the notional average of the other participants values.

The phase of S11 shows the typical sawtooth effect of clock arithmetic with large scatter where the magnitude of S11 is small i.e. around 2 GHz and 16 GHz. These comments are also appropriate to the results of the measurement of S21 with LCIE displaying considerable scatter. It is apparent that the IEN measurements of the magnitude of S21 differ significantly from the rest but in a systematic way. The measurements of phase of S21 show excellent agreement between the participants on that scale. The results at the three frequencies selected, i.e. 2, 10 and 18 GHz, for more detailed comparison in Figures 15, 16 and 17 are typical.

7.2 Overall results for item 2 (40 dB attenuator) as displayed in Figures 3A, 3B, 4A & 4B

The magnitude of S11 shows the differences between the two items that masquerade as a single item due to the failure of the first item, and the trace is confusing as a consequence. LCIE results show considerable scatter around the values presented by the other participants. VSL results differ dramatically from the rest at 17.75 and 18 GHz.

The phase of S11 shows good agreement of the participants in measuring whichever of the items they were given with the exception of VSL whose values show a systematic deviation from the other participants from 12 GHz upwards.

The magnitude of S21 shows not only the difference between the first item and its replacement but also the effect of insufficient resolution in the results presented. Some of the participants presented their results with 4 decimal places. For this item that truncation leads to the staircase effect present in this figure. Again LCIE and VSL differ from the other participants but in different ways. The phase of S21 is related to the length of the measurement item and because the two items were of the same type, supplied by the same manufacturer at the same time, the item and its replacement should have similar electrical length and this figure confirms it. The results at the three frequencies selected, i.e. 2, 10 and 18 GHz, for more detailed comparison in Figures 18, 19 and 20 are typical.

- 7.3 Overall results for item 3 (50 ohm air line) as displayed in Figures 5A, 5B, 6A & 6B
- 7.3 The magnitude of S11 shows how well the participants agree at measuring a nominal 50 ohm impedance. An air line is used because it is the closest to a calculable standard that is currently available. All the participants show good agreement apart from LCIE. Just perceptible through the confusion of points is a cyclical variation in the results presented by NIST. This sort of variation is typical of a 'Beatty' standard in which reflections from an impedance transition from 50 ohms beat with reflections from an impedance transition back to 50 ohms, reinforcing or cancelling their effects depending on their phase relationship which varies as a function of frequency. It is also noticeable that NIST systematically deviates from the other participants at the lowest frequencies. The results at the three frequencies selected, i.e. 2, 10 and 18 GHz, for more detailed comparison in Figures 21A, 21B and 21C are typical.
 - 7.3.2 The phase of S11 is indeterminate although the presence of loosely defined periodic areas of white on Figures 5B and 7B indicate that the results are not completely random. Because the phase is nominally indeterminate results are not presented in section 8 at the three selected frequencies for this parameter.
 - 7.3.3 The magnitude of S21 shows good agreement between the participants with the exception of LCIE and IEN. The plot taken in conjunction with Figure 2A suggests a systematic nature to the difference between the IEN results and the rest. The phase of S21 shows complete agreement within the resolution of the figure.
- 7.4 Overall results for item 4 (50 ohm air line reversed) as displayed in Figures 7A, 7B, 8A & 8B
 - 7.4.1 The magnitude of S11 shows that the participants agree that this item is symmetrical and that the results for each end are comparable. The results from NIST still systematically deviate from the other participants at the lowest frequencies confirming the results shown in Figure 5A. The phase of S11 still shows structure relating to individual participants but is effectively indeterminate.

The results for S21 magnitude and phase confirm those shown in Figures 6A and 6B.

7.5 Overall results for item 5 (25 ohm air line) as displayed in Figures 9A, 9B, 10A & 10B

The magnitude and phase of S11 for this item show that the participants all apparently agree on this scale. However, the wide range of values makes this particular form of presentation almost worthless. The same is also true for S21. These figures are included to demonstrate the difficulty of displaying such data usefully.

7.6 Overall results for item 6 (25 ohm air line reversed) as displayed in Figures 11A, 11B, 12A & 12B

7.6.1 The plots for S11 and S21 are indistinguishable from those of Figures 9 and 10 except a very small variation in the phase of S11 by PTB at 9.75 GHz has resulted in it being plotted at +180 instead of -180. The difference is trivial but the clock arithmetic makes it appear to be dramatic.

7.7 Overall results for item 7 (short-circuit) as displayed in Figures 13A & 13B

7.7.1 The figures showing the results for items 7 and 8 are labelled as S11 and S22 respectively. This is because the participants were asked to measure them as a pair, simulating a two-port item with a short-circuit as its input reflection coefficient and zero transmission between the input and output port. Accordingly the short-circuit is labelled S11 and the termination S22. It was important that the measurements were performed in this fashion for the participants using a special TRL adaptor as the short-circuit did not contain a collet and would have made a very poor join with the uncolletted TRL adaptor.

7.7.2 The spread of results for S11 magnitude show good agreement for most of the participants. The spread indicates that most of the calibration schemes do not rely on a short-circuit as a defined standard with a VRC of 1 @ 180°.

7.7.3 The spread of the results for S11 phase confirm the comments made in section 7.7.2 above. Because the phase differences from 180° increase monotonically with frequency, it is probable that this could be traced back to errors in the specification of the length of the TRL line, where TRL has been used, as this is commonly used to set the position of the reference planes at the test ports. The results for both magnitude and phase at the three frequencies selected, i.e. 2, 10 and 18 GHz, for more detailed comparison in Figures 31, 32 and 33 are typical of the overall results.

7.8 Overall results for item 8 (termination) as displayed in Figures 14A & 14B

7.8.1 The spread of results for S22 magnitude show good agreement for most of the participants. It is interesting that the difference between NIST and the rest of the participants at the lower frequencies that appeared for items 3 and 4 is also apparent here. Another point of interest is that the spread is not directly related to the frequency but has regions of good and bad agreement indicated by the amount of scatter about a nominal average. The regions around 7 and 12 GHz are particularly good, i.e. low scatter, while those around 10 and 16.5 GHz are particularly poor.

- 7.8.2 The variation in phase with frequency swamps the results so that one can only say that all the participants except LCIE agree well and that the results for both magnitude and phase at the three frequencies selected, i.e. 2, 10 and 18 GHz, for more detailed comparison in Figures 34, 35 and 36 are typical of the overall results.

8. DETAILED COMPARISON AT 2, 10 AND 18 GHz

- 8.1 Figures 15 to 36 show the results for the measurement of reflection in linear units or the measurement of transmission in dB. The phase is always presented in degrees, however whether the results are presented in the range 0 - 360° or $\pm 180^\circ$ depends on the values and the most useful form for display purposes. Each result has error bars whose lengths indicate the standard uncertainty in that measurement in appropriate units.

- 8.2 Additional measurements were made at NPL after each participant returned the items and they show that no drift (step changes excluded) occurred during the comparison. For clarity these additional results have not been shown in any of the plots.

In the results for items 1 and 2, the vertical dotted line shows when the step change in the performance of the item occurred, or when the item was replaced. For these items there is an additional NPL measured value, annotated as NPL(B), which attempts to establish continuity.

- 8.4 Comparison of transmission results at 2, 10 and 18 GHz for item 1 (10 dB attenuator). Figures 15, 16 & 17.

- 8.4 For this item there is excellent agreement between most of the participants. The results for both the magnitude and phase show that the uncertainties are consistent with the level of agreement between the participants, even though there is a wide range in the uncertainties presented. These results indicate that all the systems are capable of making good transmission measurements of a nominal 10 dB attenuator. The good agreement in the mean values compared with the uncertainties implies that PTT and FFV are being unduly pessimistic in their uncertainties. The reverse may be true for LCIE, especially for measurement of the magnitude.

- 8.5 Comparison of transmission results at 2, 10 and 18 GHz for item 2 (40 dB attenuator). Figures 18, 19 & 20.

For this item, too, there is generally excellent agreement between the participants. The results for both the magnitude and phase show that the uncertainties are consistent with the level of agreement between the participants, even though there is a wide range in the uncertainties presented. These results indicate that all the systems are capable of making good transmission measurements of a nominal 40 dB attenuator. One possible exception is the measurement of phase at 18 GHz by LCIE.

The good agreement between the values presented compared with the uncertainties suggest that PTT, IEN and NPL are being unduly pessimistic in their uncertainties. The poor agreement, relative to their uncertainties, between the values for phase at 18 GHz

supplied by PTB and CSIRO suggests that one or both of the uncertainties are optimistic.

8.6 Comparison of reflection results at 2, 10 and 18 GHz for item 3 (50 ohm air line). Figure 21.

For this item there are no phase measurements to compare because the value of the reflection coefficient is so close to zero that the phase has little, if any, meaning. These plots also show another of the dilemmas facing anyone tasked with presenting this type of data. Whether the errors bars should be shown as being symmetrical about the point or should be shown as limited by any physical impossibilities. It is impossible, by definition, to have a negative magnitude. However the uncertainties were quoted as $x \pm y$, and in this case it happens that y is bigger than x . A compromise has been chosen here in which the error bars are not displayed for values below zero.

The results show excellent agreement between the participants, except LCIE, and show that none of the uncertainties claimed are optimistic. An interesting exception is NIST at 2 GHz where the value is significantly different. One can speculate that this relates to the method of normalising the measurement to 50 ohms from the characteristic impedance of the calibration standards. Where lines are used the impedance will deviate from 50 ohms at the lower frequencies and the greater the resistivity of the material, the greater the deviation. However there is insufficient evidence to confirm this speculation.

Detailed analysis of the individual NPL results (not presented here) indicated that a large proportion of the uncertainty comes from the poor repeatability of the item. This is not surprising because the inner conductor is entirely supported at its ends by the collets (see Appendix A) and these will settle into different relative positions for each re-connection. The actual position of the line will depend on the relative strengths of the two collets. For participants using TRL calibrations the effect may be more pronounced as one collet is of the conventional variety and one of the pin/collet variety.

8.7 Comparison of transmission results at 2, 10 and 18 GHz for item 3 (50 ohm air line). Figures 22, 23 & 24.

8.7.1 These plots show a wide variation in the size of the uncertainties claimed by the participants. The measurement of a small loss is dominated by the uncertainties in the mismatch factors at either end, especially as the errors produced at the junction of the line and the test ports at each end go in and out of phase, thereby adding or subtracting, as the frequency changes. Under the circumstances the agreement between the participants (excepting LCIE and IEN) is very good. The phase measurements are more worrying. Not only is there considerable variation in the size of the uncertainties but in many cases the differences between the mean values provided by the participants are larger than the combined uncertainties. Several of the participants may wish to revisit their uncertainties in the light of these results.

8.8 Comparison of reflection results at 2, 10 and 18 GHz for item 5 (25 ohm air line). Figures 25, 26 & 27

8.8 One of the strengths of the 'Beatty' standard is that cancellation of errors occurs at

specific frequencies. This can also be one of the weaknesses. The three frequencies chosen are all at or near peaks in the response. This means that measurements near the troughs have not been compared but it allows the three frequencies to be compared in a reasonable manner.

These plots show wide variation in the size of the uncertainties between the participants with the differences in the mean values presented by the participants generally being smaller than the combined uncertainties. It is interesting to note that the difference between NIST and the other participants in the measurement of the magnitude of reflection coefficient at 2 GHz, seen in earlier plots, is still present. The large phase uncertainties are a consequence of the small magnitudes but the values have meaning and agree well within the uncertainties.

8.9 Comparison of transmission results at 2, 10 and 18 GHz for item 5 (25 ohm air line). Figures 28, 29 & 30

These results echo those of the 50 ohm air line. It is interesting to note that although, in the case of an item with small losses such as a short coaxial transmission line, the uncertainties in the reflection measurements dominate the uncertainties in the transmission measurement, the difference between NIST and the other participants at 2 GHz for the measurement of reflection coefficient does not appear as a difference in values of transmission coefficient.

There is again a wide variation in the uncertainty of the measurement of phase with some of the uncertainties looking optimistic if the differences in the values presented are used as a guide.

Examination of the individual NPL results suggested that the uncertainties are again dominated by the poor repeatability of the lines. This poor repeatability limits the usefulness of unsupported air lines as transfer standards.

8.10 Comparison of reflection results at 2, 10 and 18 GHz for item 7 (short-circuit). Figures 31, 32 & 33

8.10 The short-circuit is a difficult device to measure because of the high current density at the reference plane and this is confirmed by the generally higher proportion of the uncertainty attributable to repeatability in the NPL results. It is interesting to note that the agreement in the value of phase of the item appears better than the agreement in the value for the magnitude, presumably because the high current density will result in a variable loss but the phase of the discontinuity will be less affected.

8.10.2 The phase results at 18 GHz show a variation in the values that is difficult to reconcile with the quoted uncertainties. Some of the laboratories may wish to revisit aspects of their uncertainty assessments in the light of these results.

8 Comparison of reflection results at 2, 10 and 18 GHz for item 8 (termination). Figures 34, 35 & 36

- 8.11.1 A termination should, in principle, be one of the easiest items to measure. The uncertainties should be dominated by those incurred during calibration as the repeatability of connection should be excellent. For participants that used TRL calibrations with the special TRL adaptor on port 2, there was a single collet between the measurement item and the reference plane, while for calibrations without the adaptor there was a pair of collets. There is some evidence to suggest that a single collet gives better reproducibility than a pair of collets, even though this moves the connector outside the definition of a 'precision sexless connector'.
- 8.11.2 The participants all agree well at all three frequencies. However the NIST value at 2 GHz confirms the discrepancy disclosed by the air lines (Figures 5A, 21A and 25A). The good agreement between the participants extends to the measurement of phase. Although the size of the uncertainties quoted vary significantly with frequency, this is related to the value for the magnitude of the reflection coefficient as expected from the arcsin relationship (see section 6.7). Thus the larger the magnitude, the smaller the phase uncertainty.
- 8.11.3 Examination of the individual NPL measurements indicated that the major proportion of the uncertainties relate to the type B uncertainty confirming the suitability of such fixed items as transfer standards.

9. CONCLUSIONS

- 9.1 An international comparison of impedance at microwave frequencies has been carried out. The actual parameter compared were scattering coefficients relative to 50 ohms for items fitted with GPC-7 precision sexless connectors. The frequency range of the comparison was 2-18 GHz.
- 9.2 Six items, consisting of two fixed attenuators, two air lines, a short-circuit and a fixed load were circulated to nine standards laboratories around the world.
- 9.3 Neither of the attenuators survived the exercise unscathed. One was damaged beyond repair and was replaced; the characteristics of the other underwent a step change.
- 9.4 The repeatability of the fixed items was significantly better than the repeatability of the air lines. It is suggested that this is because the inner conductor floats between the test ports and settles in a different position each time.
- 9.5 Some laboratories used TRL calibration algorithms which require a special adaptor and the use of a special pin/collet to support the air lines. Although it is arguable if these participants were actually measuring the 'same items' as the participants who used traditional collets, the differences are, almost certainly, not significant.

Measurements made of an item whose characteristics change rapidly with frequency such as the 25 ohm air line are likely to be affected by variations in both temperature and frequency. This makes them poor transfer standards as the cause of any disagreement cannot be uniquely identified.

Measurements of the rapidly varying non-linear characteristics of the 25 ohm air line can

also be subject to sampling errors which change the apparent agreement between participants.

- 9.8 Bearing in mind the above comments, it is still possible to draw some valuable conclusions from the values and uncertainties provided by the participants. The comments and conclusions are all based on the relationships between the values presented and the uncertainties given.

Although the variation in the size of the uncertainties in the measurement of transmission coefficients of the 10 dB and 40 dB attenuators is very large, the agreement in the values is consistent within those uncertainties and thus it can be concluded that almost all the participants agree for these measurements of magnitude and phase of transmission of nominal 10 dB and 40 dB attenuators.

For the measurement of the reflection coefficient of a nominal 50 ohm device, the assessments of the uncertainties are much more consistent. The values supplied by the participants all agree within the uncertainties with the exception of NIST (at 2 GHz) and LCIE.

For the measurement of the transmission coefficient of the nominal 50 ohm air line which is a low loss device, the assessments of the uncertainties become more consistent for both magnitude and phase as the frequency increases. The values for the measurement of magnitude all agree well in terms of the uncertainties with the exception of IEN, whose uncertainties at 10 GHz and 15 GHz are not sufficiently large to encompass the differences in values between it and the majority of the other participants. For the phase measurement the range in the size of the uncertainties is much greater than for the magnitude and as the uncertainties become more consistent, it becomes increasingly difficult to reconcile some of the differences in value within the uncertainties given. Thus it can be concluded that generally the participants agree well on the measurement of the magnitude of the loss of a low loss device but less well on the phase.

For the measurement of the magnitude of reflection coefficient of a nominal 25 ohm device, the assessments of the uncertainties are very similar to those of the 50 ohm device, and the values supplied by the participants all agree within the uncertainties with the exception of NIST at 2 GHz. Although the size of the phase uncertainties varies with frequency, the values supplied by the participants agree very well relative to those uncertainties.

- 9.8.5 The relationships between the uncertainties and the values supplied by the participants for the magnitude and phase of the transmission coefficient of the 25 ohm air line are very similar to that of the 50 ohm air line except that the differences in the phase values are smaller compared to the uncertainties. However these differences are still not sufficiently small to make a convincing argument that the participants agree for these particular measurements.
- 9.8.6 For the measurement of the magnitude and phase of the reflection coefficient of a short-circuit at 2 GHz and 10 GHz, the uncertainties generally encompass the values supplied by the participants. However for the phase measurement at 18 GHz there are several participants that do not agree.
- 9.8.7 The measurement of the magnitude and phase of the reflection coefficient of the

termination produces the best agreement between the values submitted by the participants and their uncertainties. In particular the phase uncertainties, although large, look realistic for all the participants.

- 9.9 In general the intercomparison showed that measurements were made by the various participants with a wide range of uncertainties but in most cases the participants agreed within those uncertainties.

10. RECOMMENDATIONS

The objectives of the comparison were not sufficiently tightly defined. It should have been decided right from the start what exactly would be compared rather than allowing the obvious abilities of ANAs to drive the comparison. This particular area is one in which there is rapid development going on and this affected the ambitions and capabilities of the participants. It would have been better to perform a comparison among participants who had achieved a similar level of maturity.

- 10.2 Future comparisons should use only items in which the inner and outer conductors have a permanently fixed relationship. This would exclude unsupported lines but would allow lines supported at one or both ends.

Fixed items such as attenuators and terminations should be made as robust as possible by changing the method of attaching the connectors to the body of the item to one which is less vulnerable.

The number of data points requested from the participants should be limited to a few essential points. This would be of benefit both to the participants and the pilot laboratory.

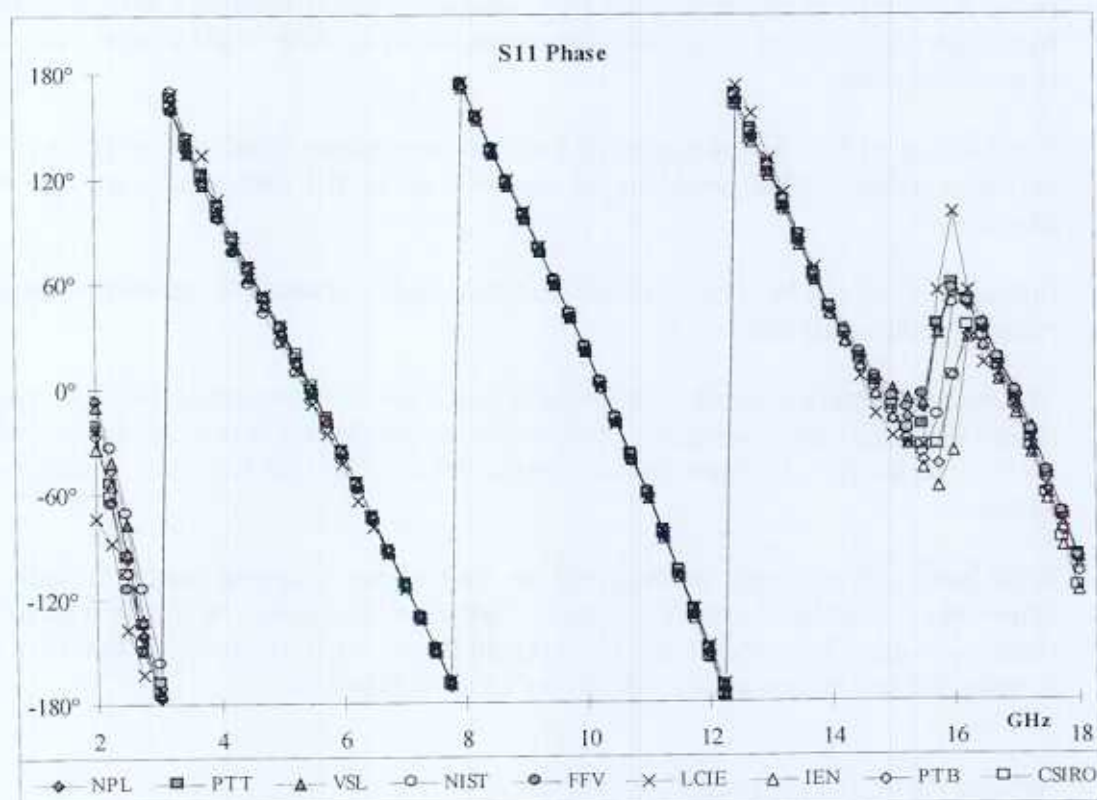
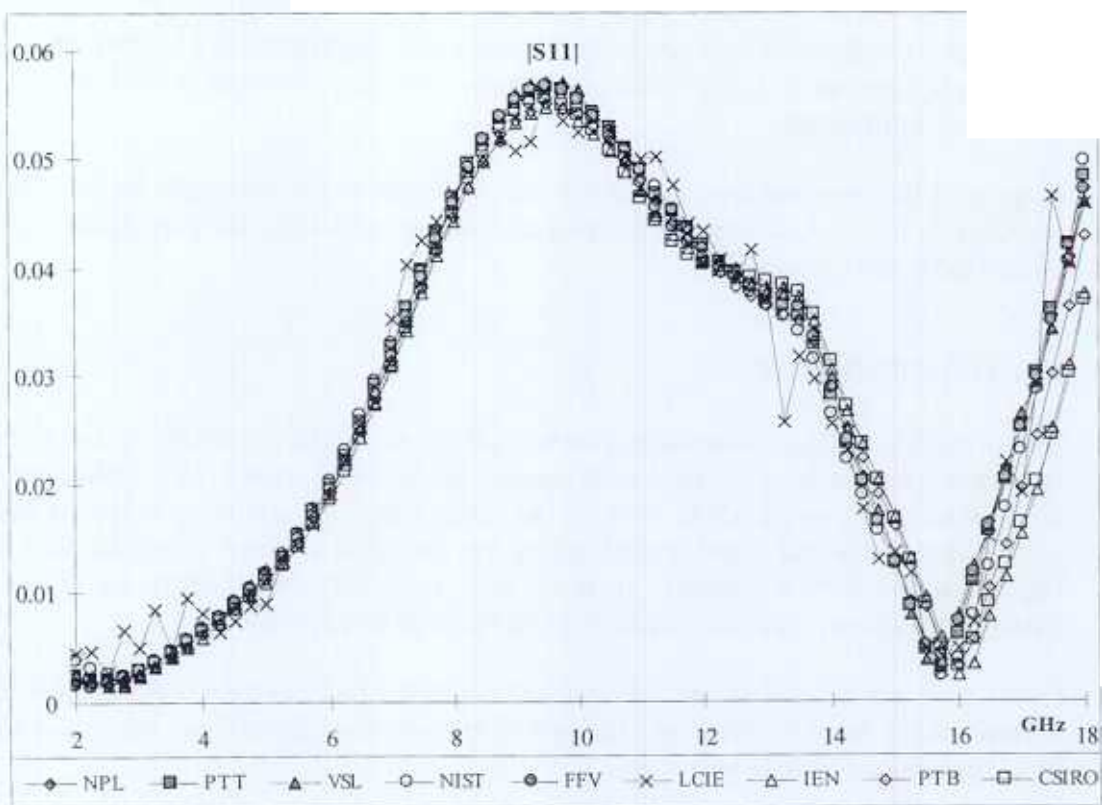
Frequencies should be chosen so that cancellation due to multiple reflections does not mask significant effects.

- 10.6 The measurements requested from the participants should be chosen to focus on specific objectives of the intercomparison. Items where the parameters at one port are dependent on those at another, i.e. the reflection coefficient of a low loss two-port, should not be included.

- 10.7 Participants should only be accepted as part of an intercomparison if they can demonstrate, at the start of the comparison, that uncertainties can be supplied for all the measurements. They should not be accepted on the basis of assuming that they will develop the techniques during the lifetime of the comparison.

11. ACKNOWLEDGEMENTS

The author would like to take this opportunity to express his gratitude to the other participants in this intercomparison: Kurt Hilty of PTT; Jan de Vreede of VSL; Bob Judish of NIST; Anders Ekland of FFV; Joseph Achkar of LCIE; Luciano Brunetti of IEN; Ulrich Stumper of PTB; John Peters of CSIRO and to the UK Department of Trade and Industry's National Measurement System Policy Unit who funded the production of this report.



Figures 1A & 1B

Magnitude and Phase of the Reflection Coefficient of Item
(10 dB Attenuator).

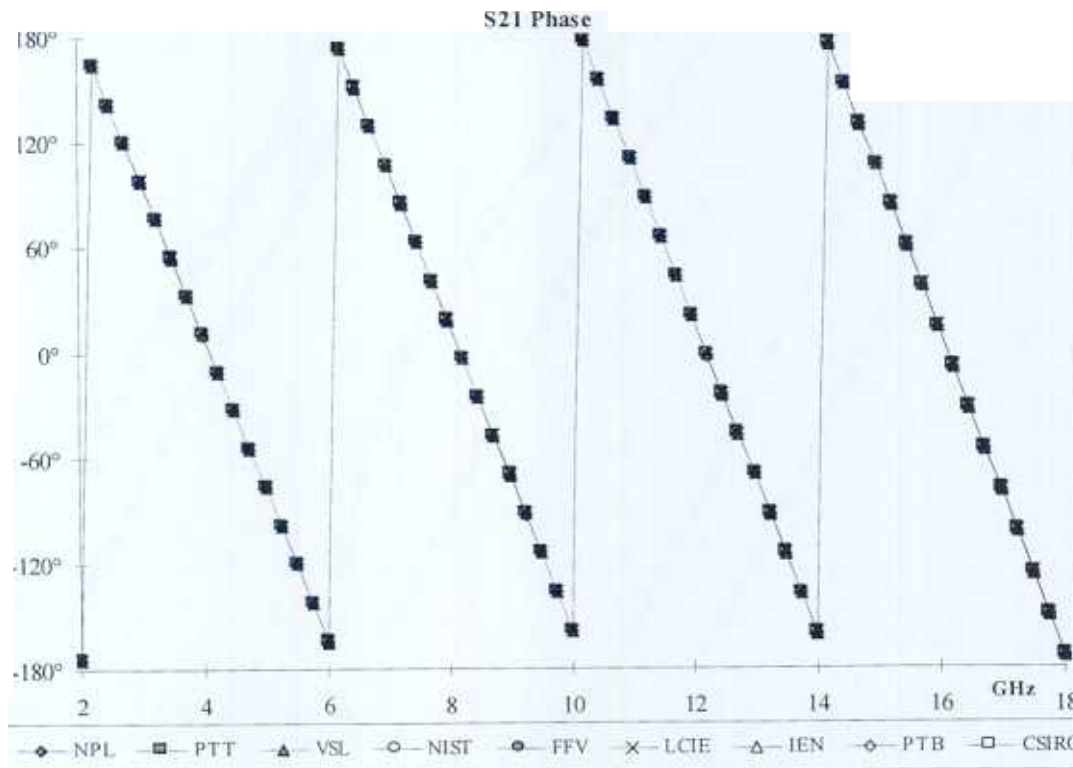
|0.320

|S21|



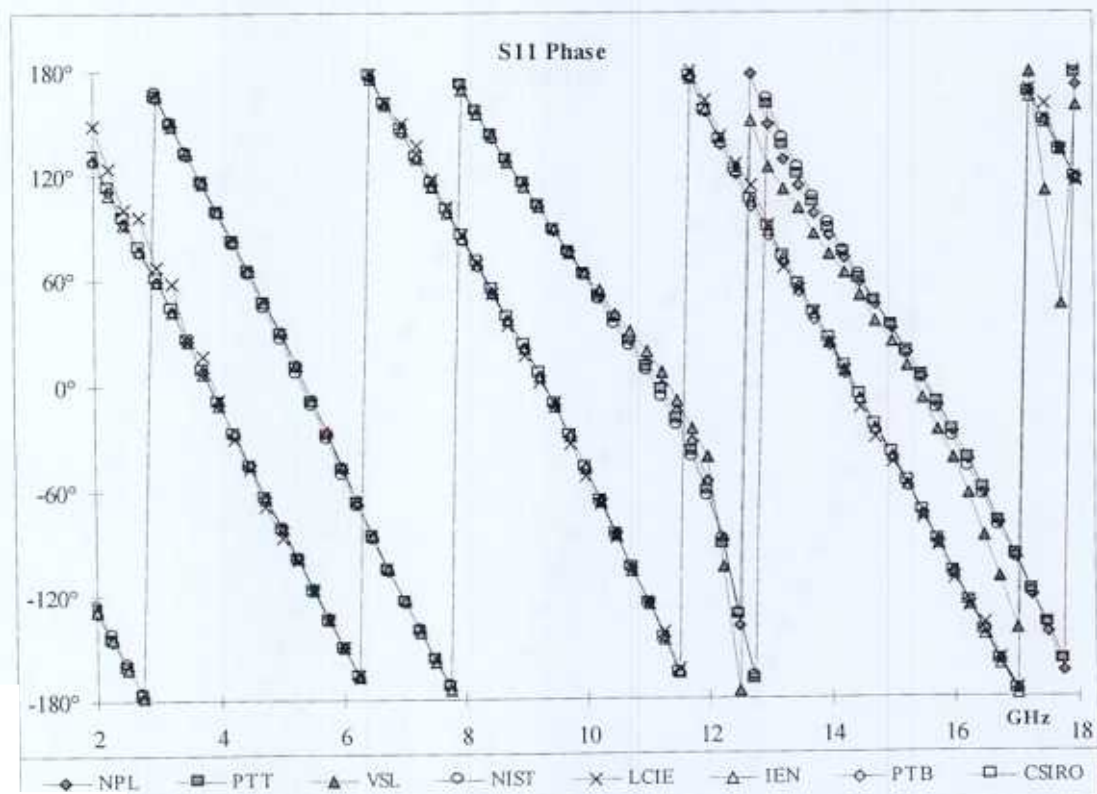
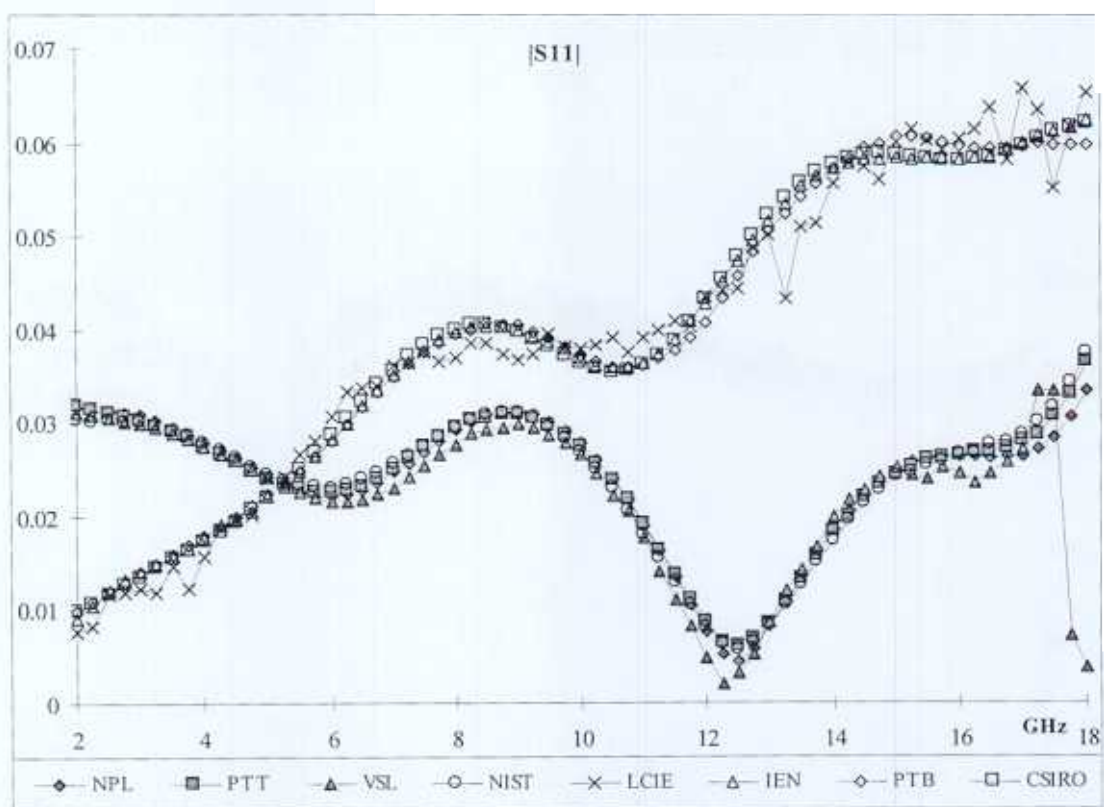
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0.308



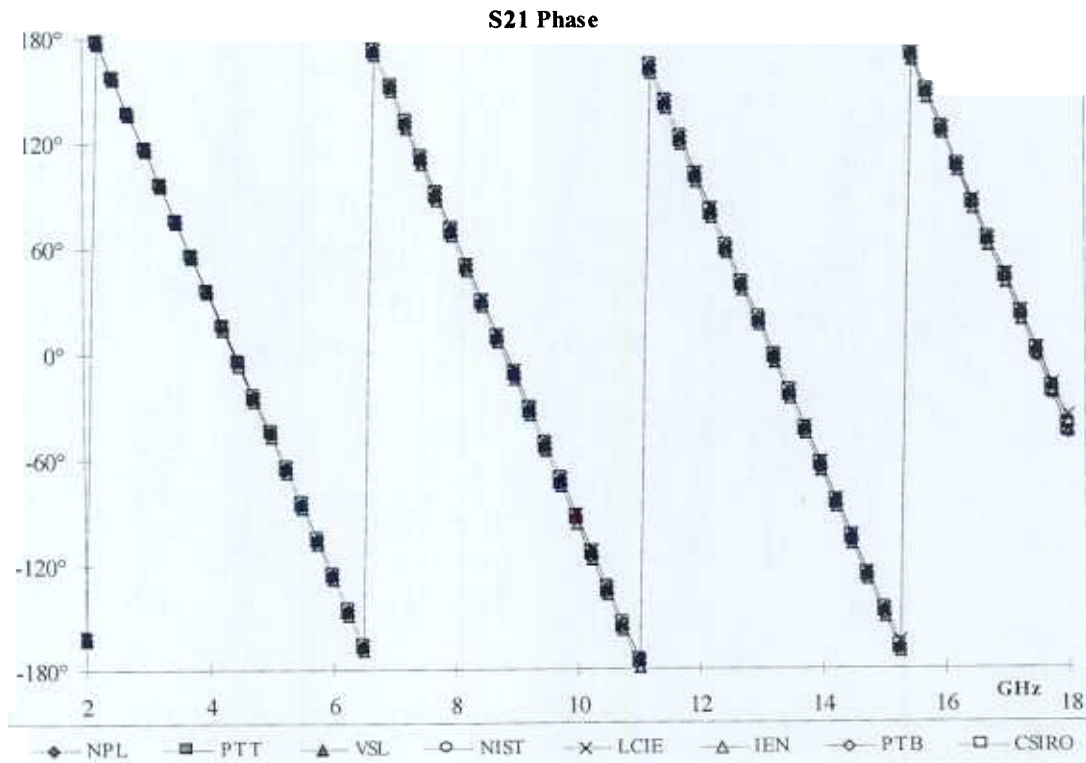
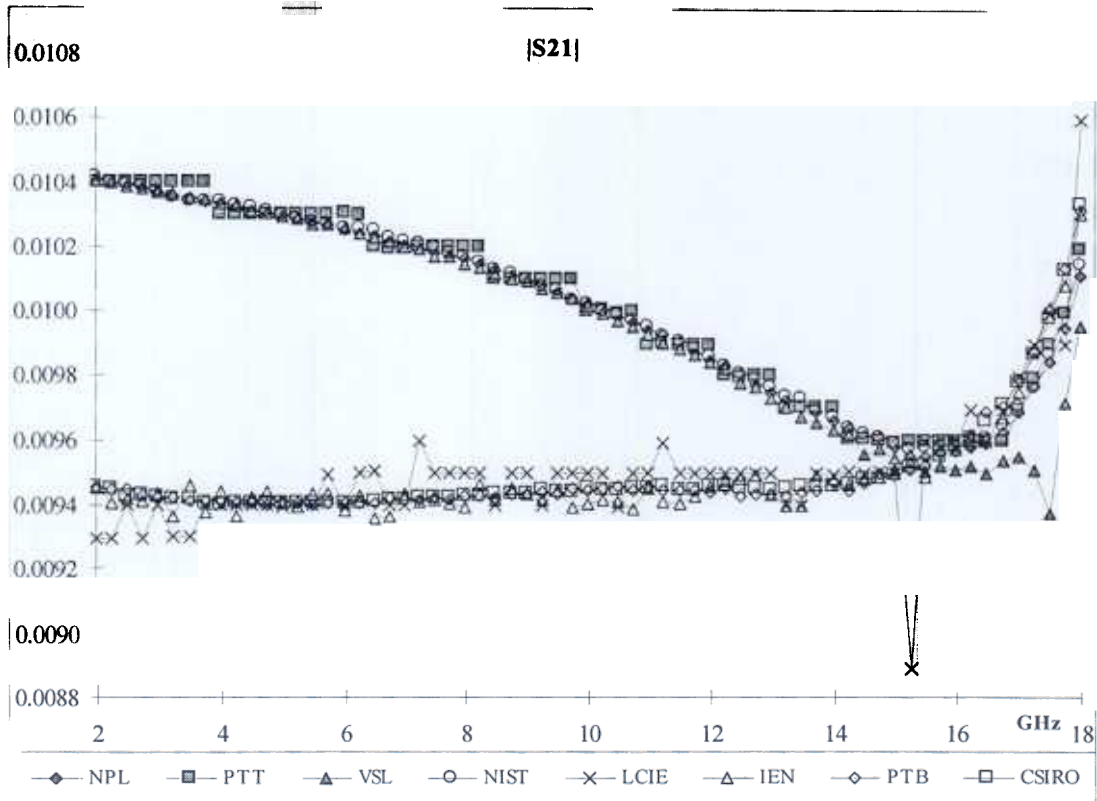
Figures 2A & 2B

Magnitude and Phase of the Transmission Coefficient of Item 1
(10 dB Attenuator).



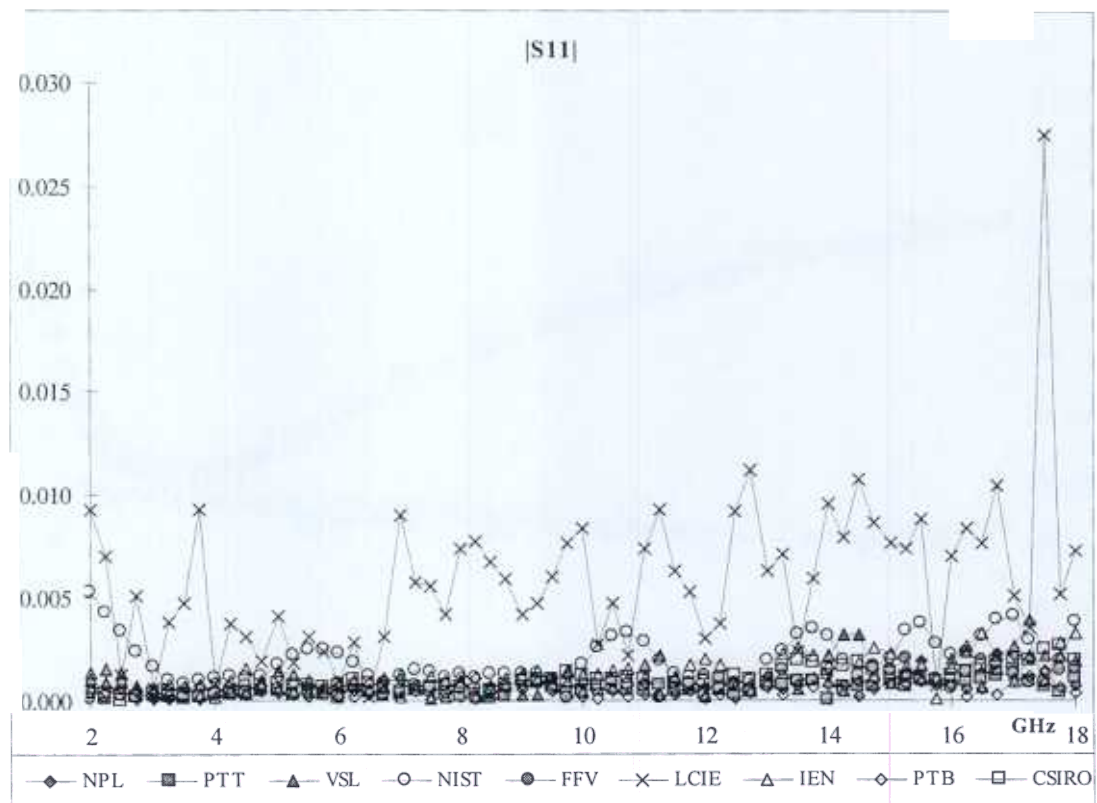
Figures 3A & 3B

Magnitude and Phase of the Reflection Coefficient of Item 2
(40 dB Attenuator).

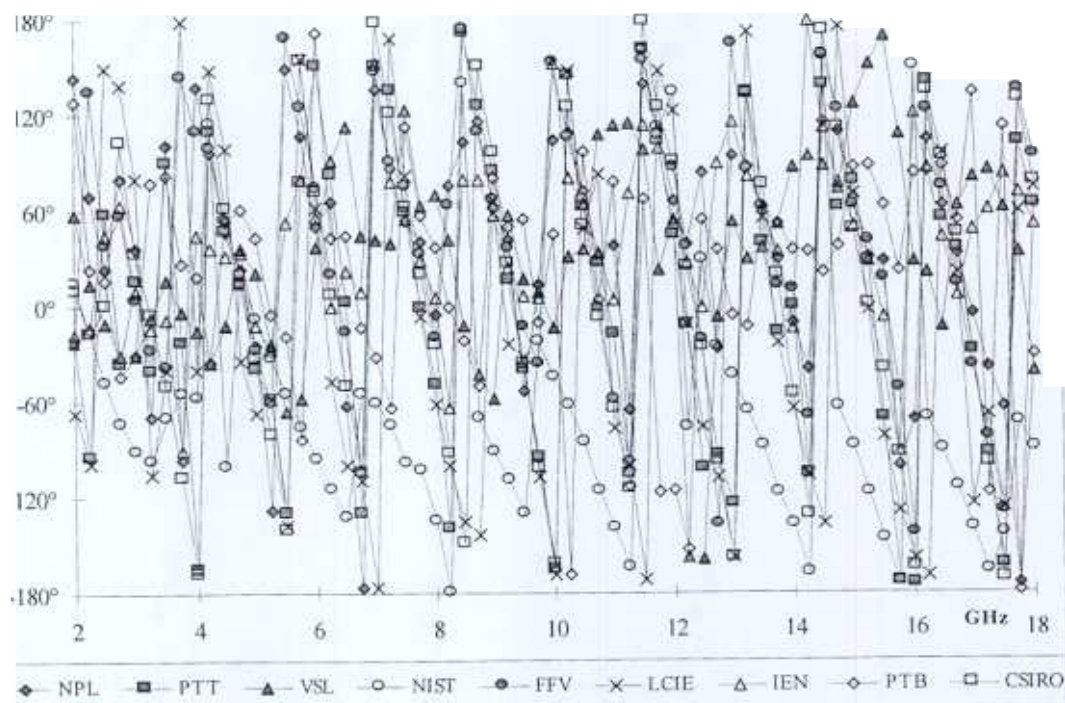


Figures 4A & 4B

Magnitude and Phase of the Transmission Coefficient of Item 2
(40 dB Attenuator).

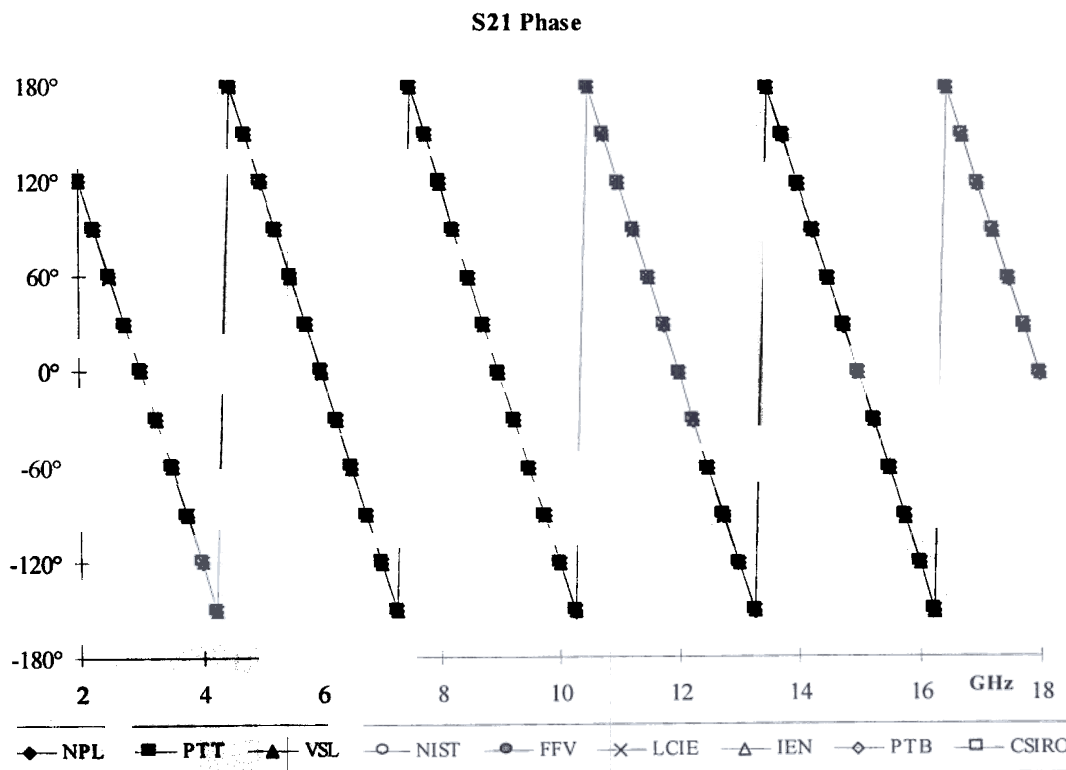
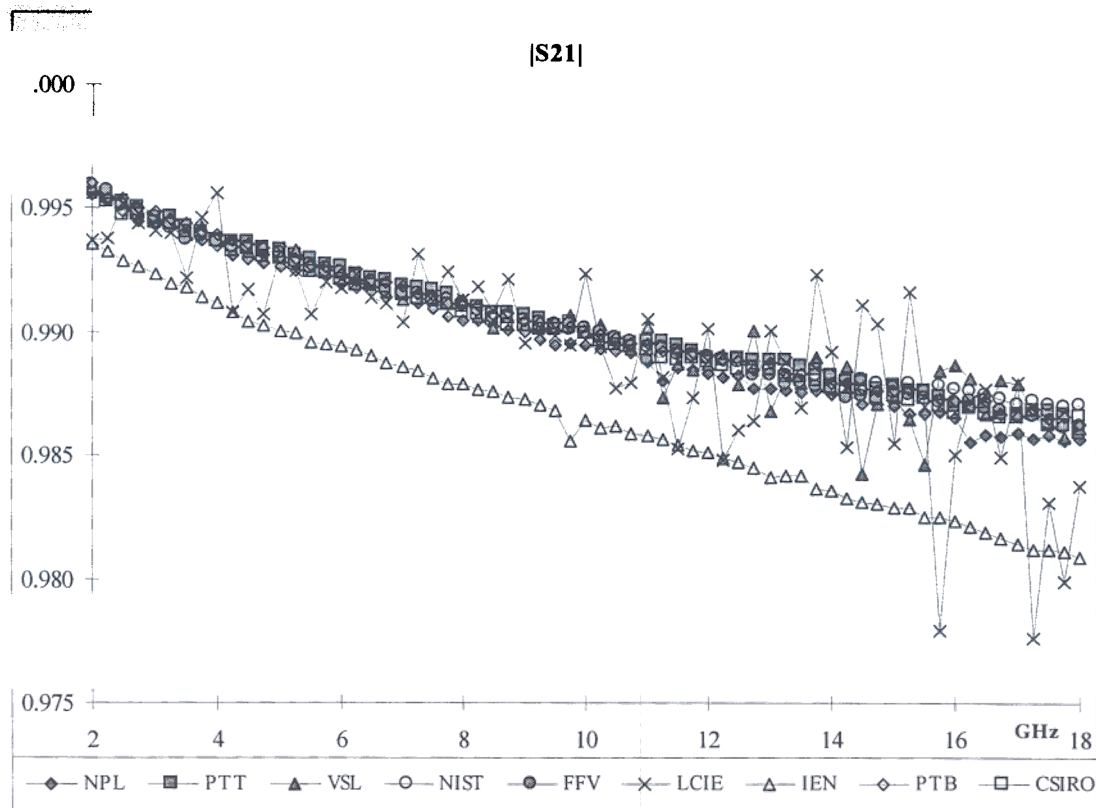


S11 Phase



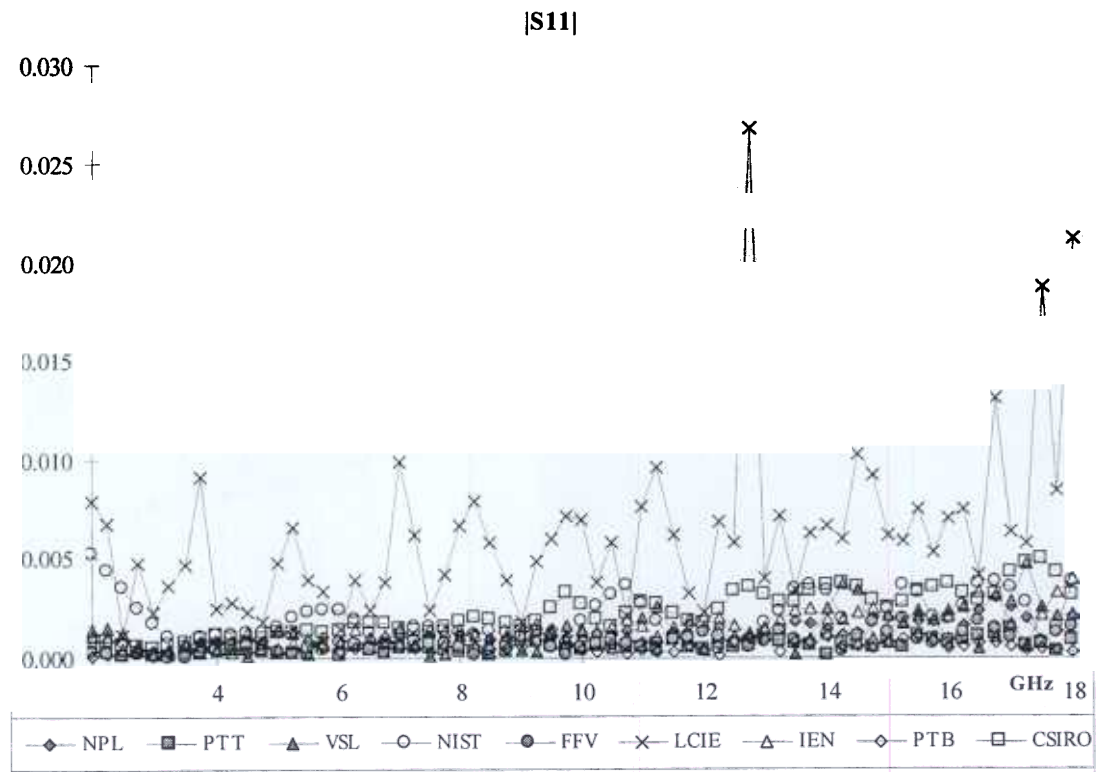
Figures 5A & 5B

Magnitude and Phase of the Reflection Coefficient of Item 3
(50 ohm air line).

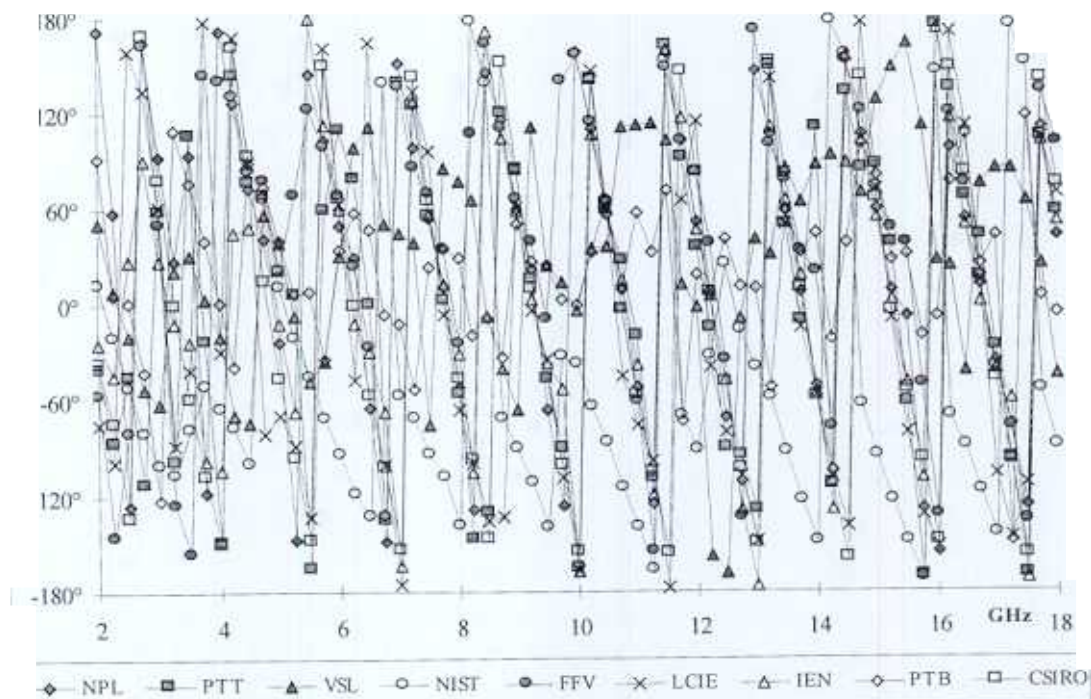


Figures 6A & 6B

Magnitude and Phase of the Transmission Coefficient of Item 3
(50 ohm air line).



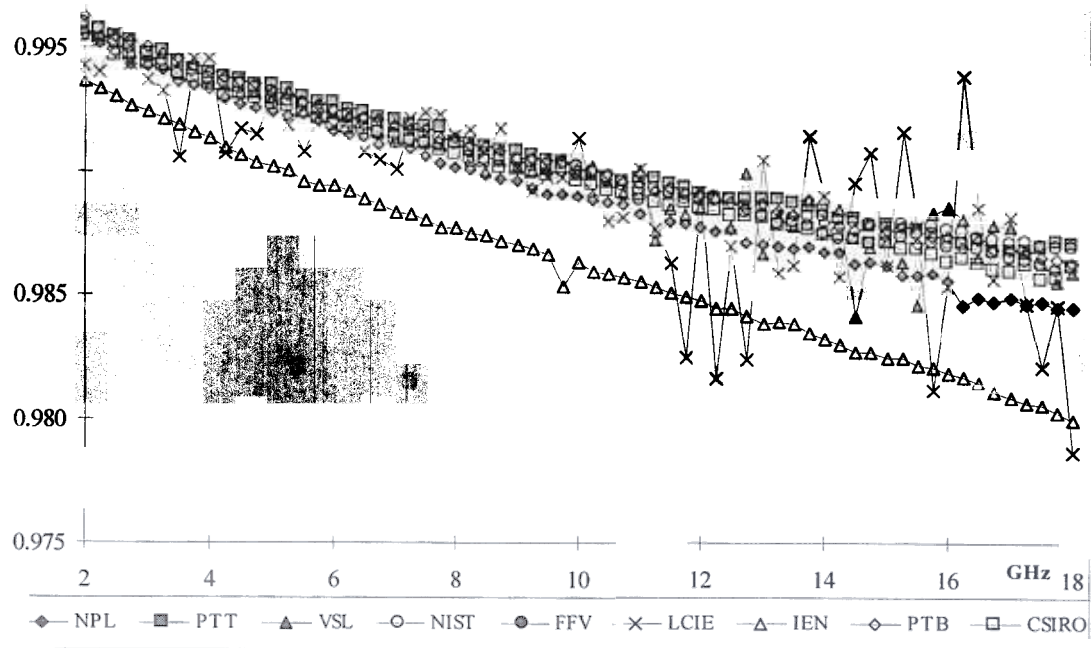
S11 Phase



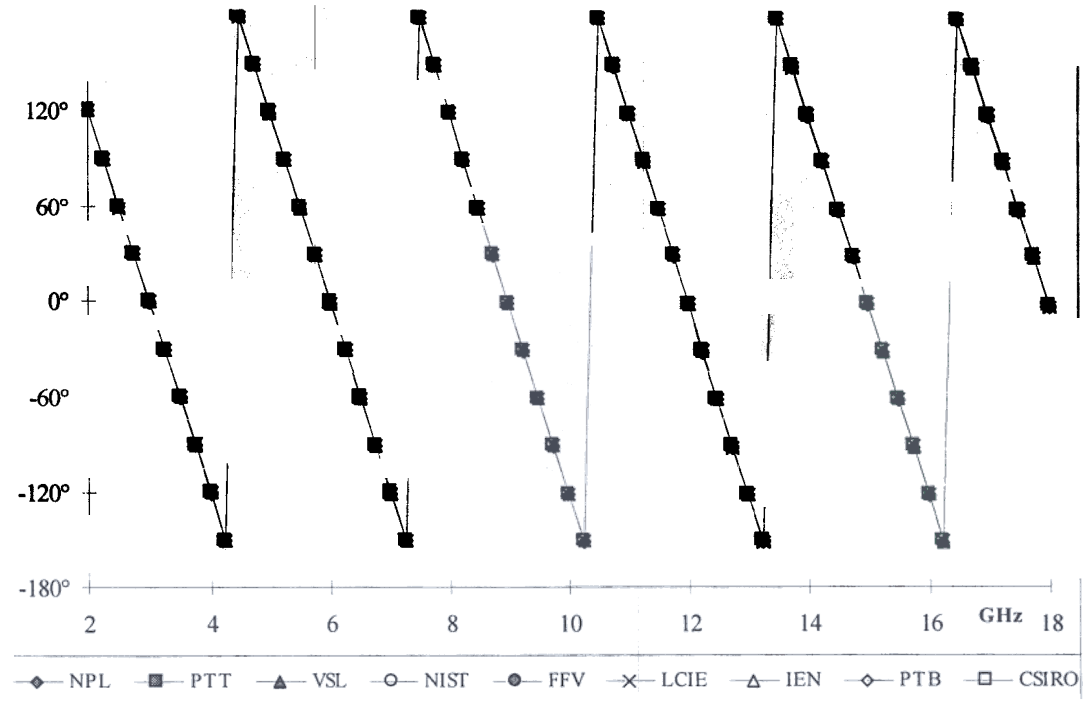
Figures 7A & 7B

Magnitude and Phase of the Reflection Coefficient of Item 4
(50 ohm air line reversed).

|S21|

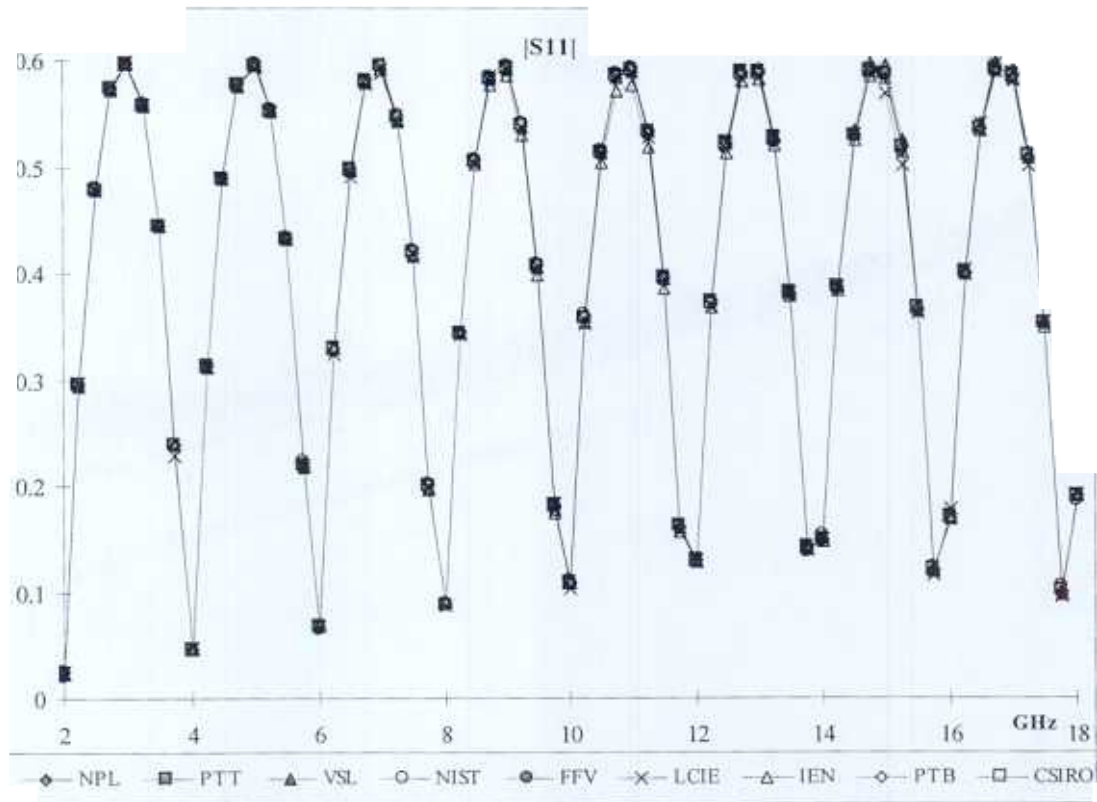


S21 Phase

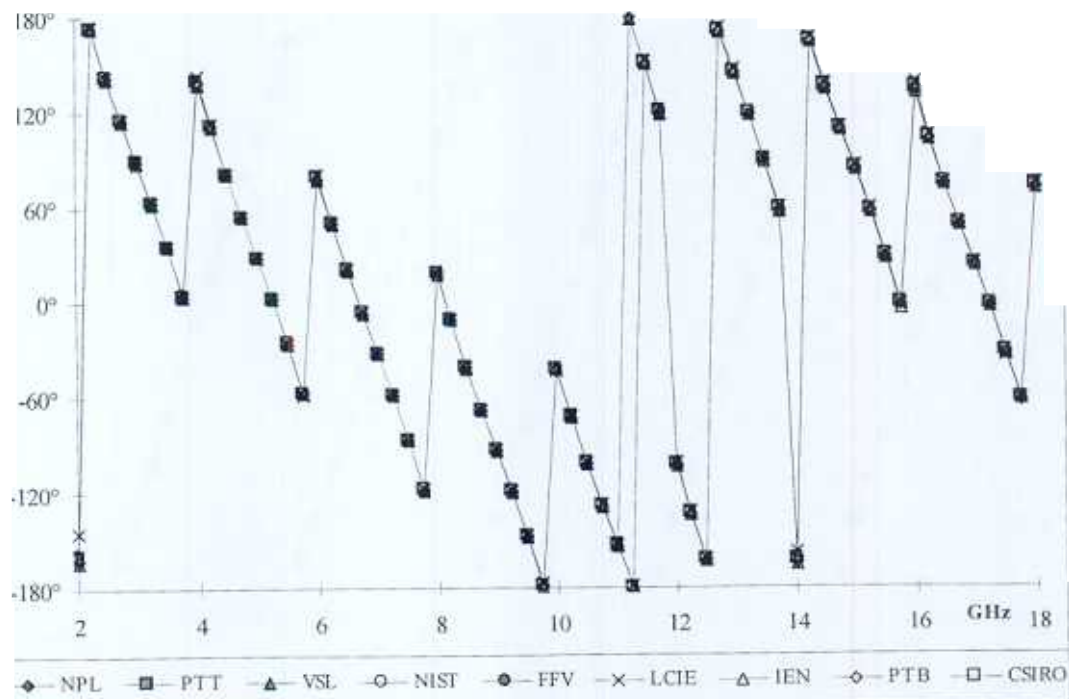


Figures 8A & 8B

Magnitude and Phase of the Transmission Coefficient of Item 4
(50 ohm air line reversed).

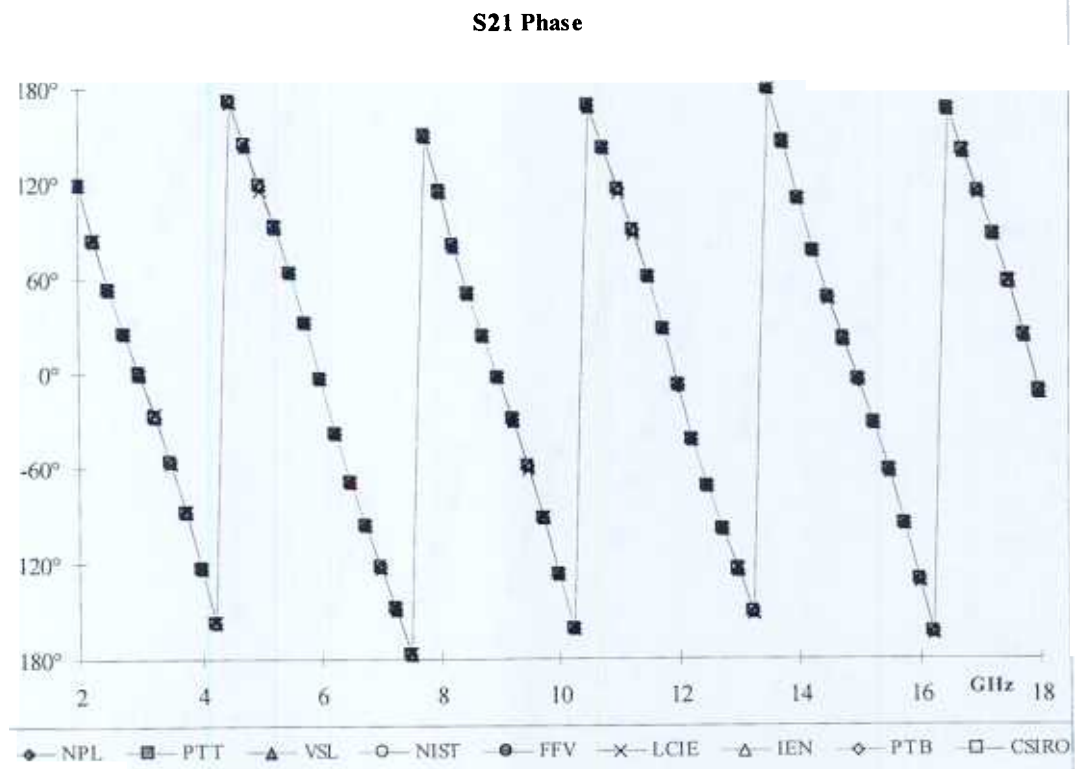
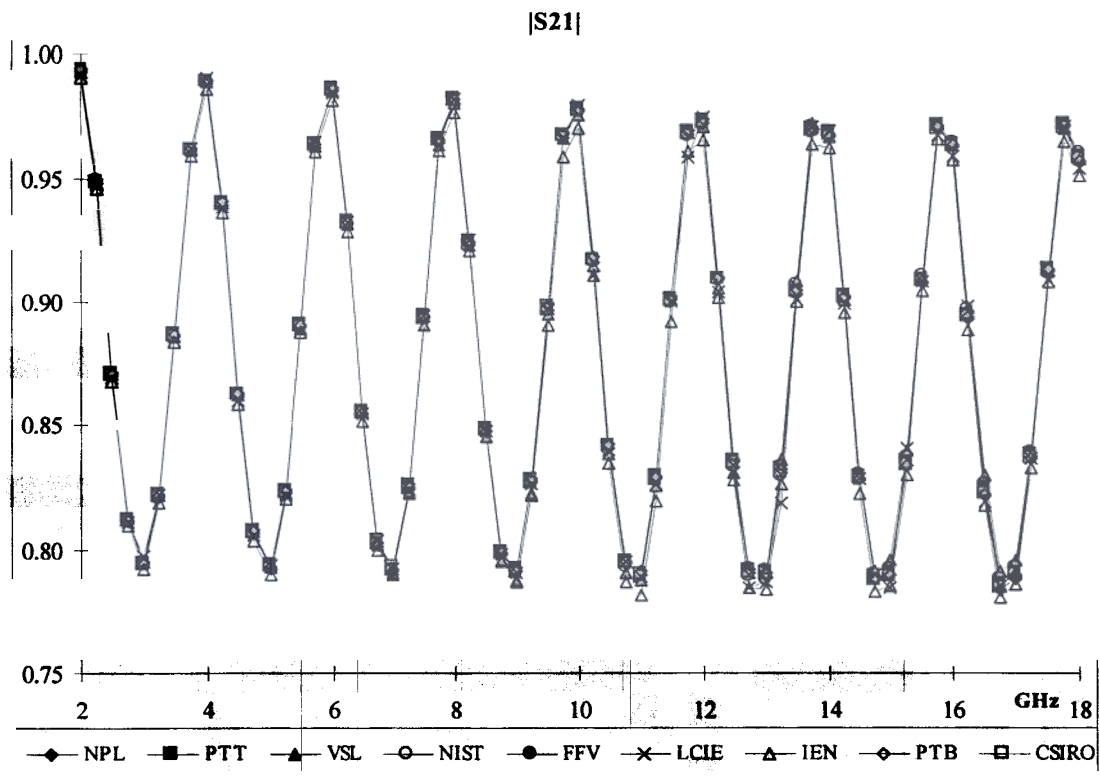


S11 Phase



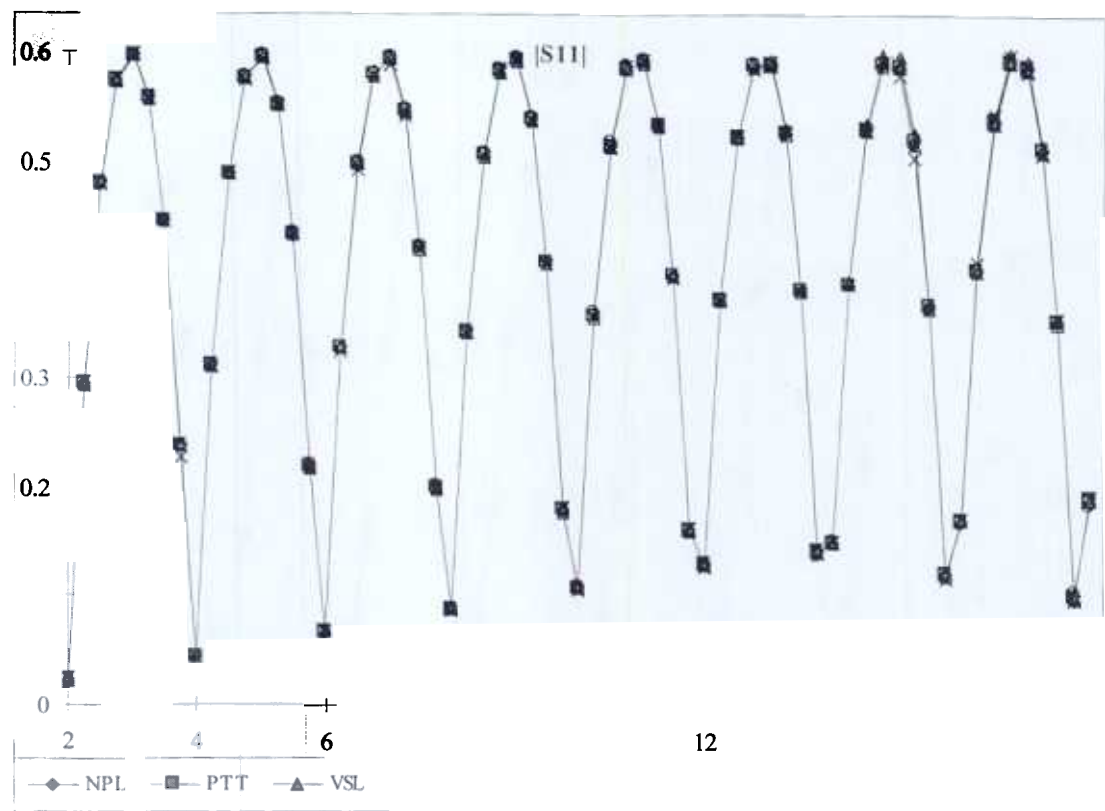
Figures 9A & 9B

Magnitude and Phase of the Reflection Coefficient of Item 5
(25 ohm air line).

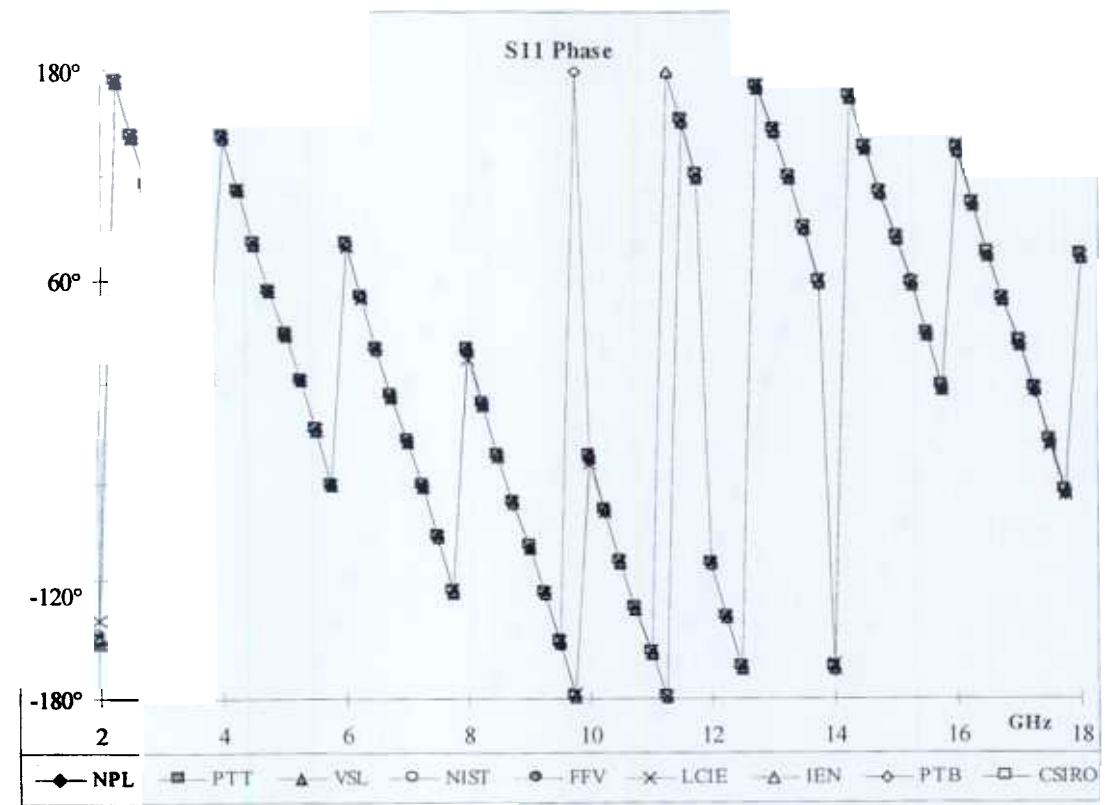


Figures 10A & 10B

Magnitude and Phase of the Transmission Coefficient of Item 5
(25 ohm air line).

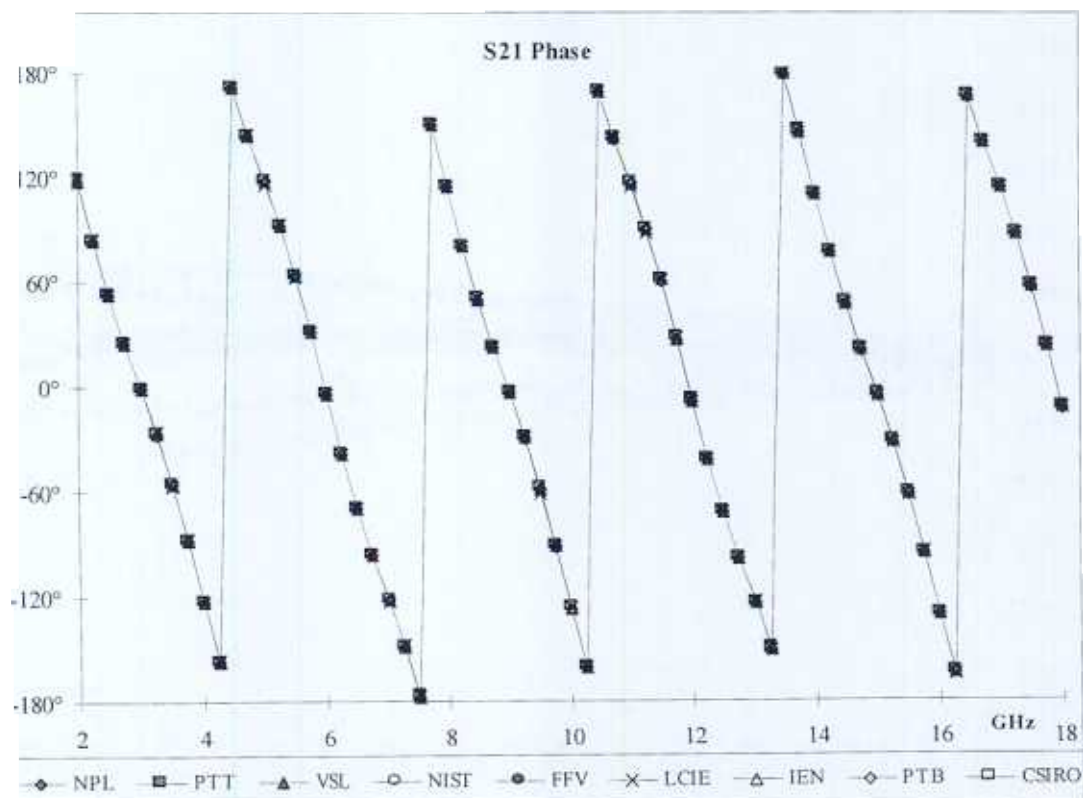
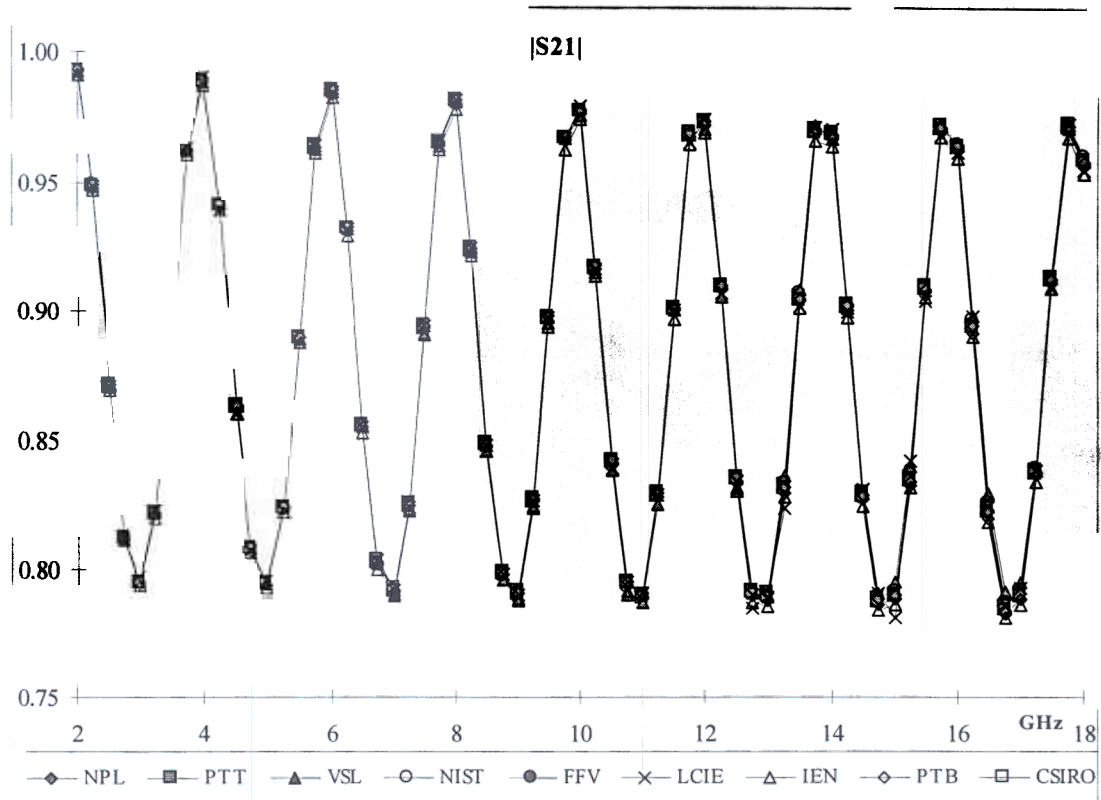


12



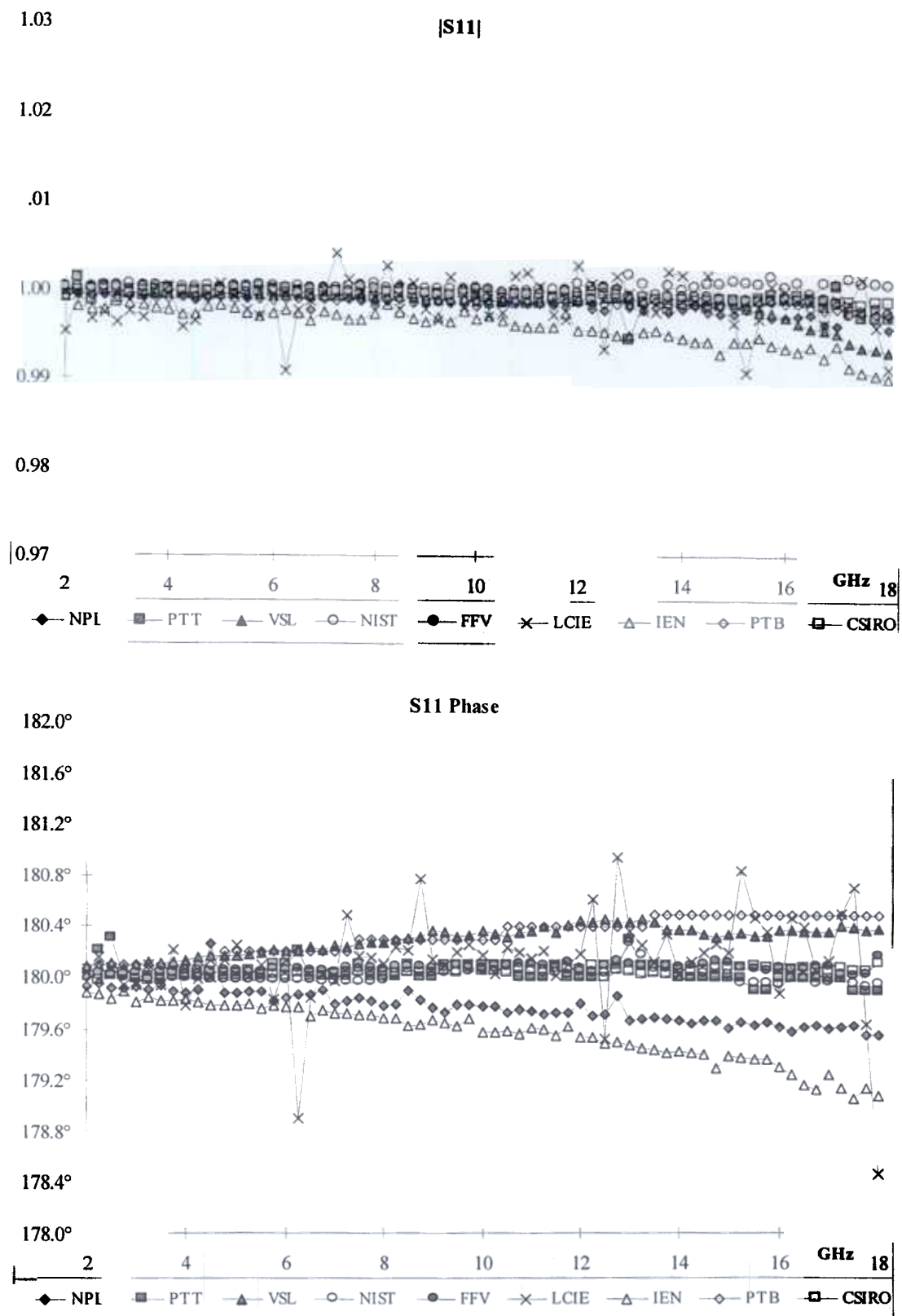
Figures 11A & 11B

Magnitude and Phase of the Reflection Coefficient of Item 6
(25 ohm air line reversed).



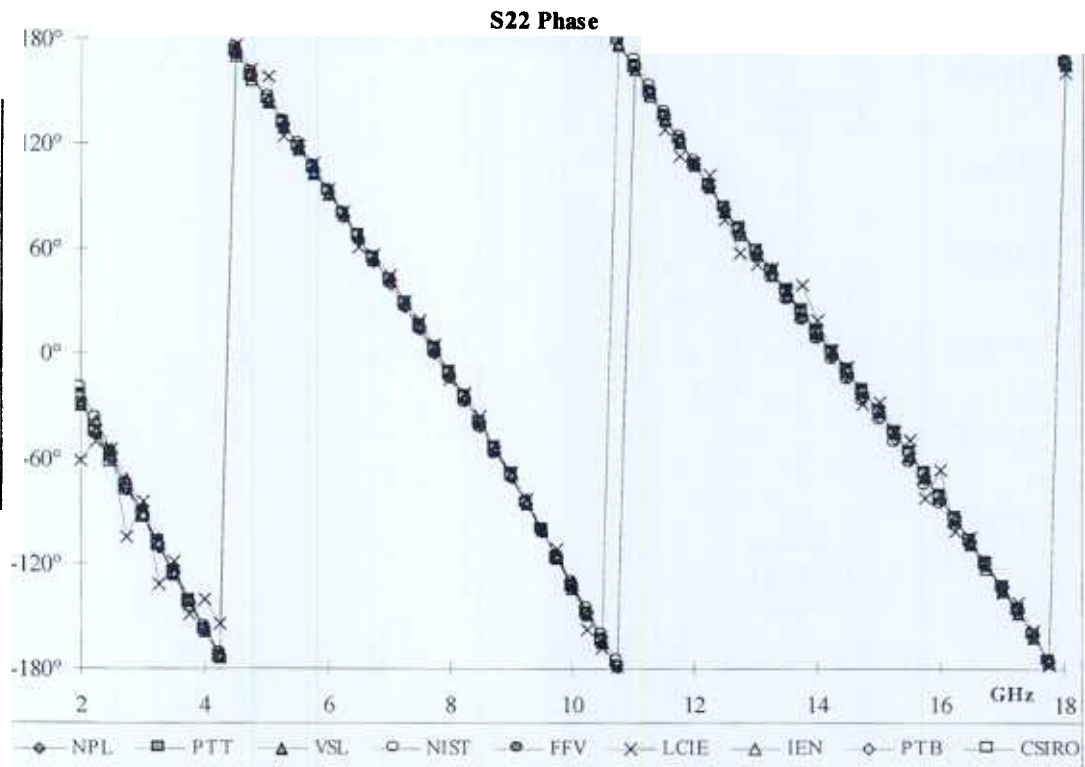
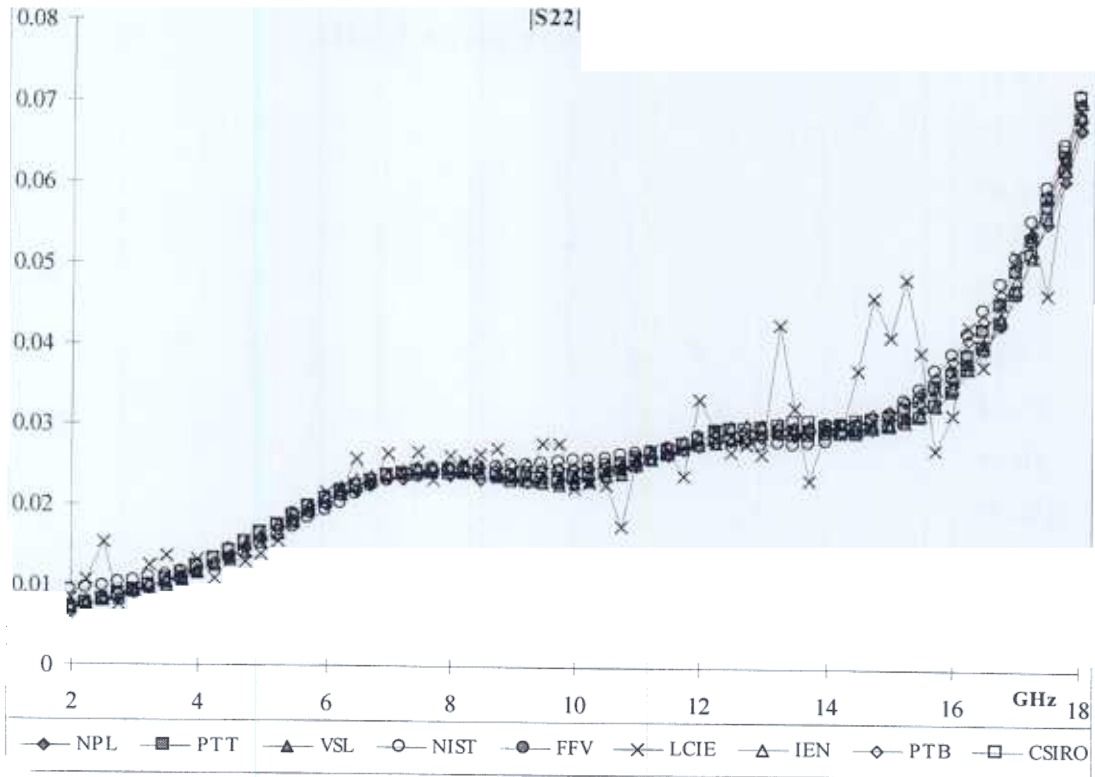
Figures 12A & 12B

Magnitude and Phase of the Transmission Coefficient of Item 6
(25 ohm air line reversed).



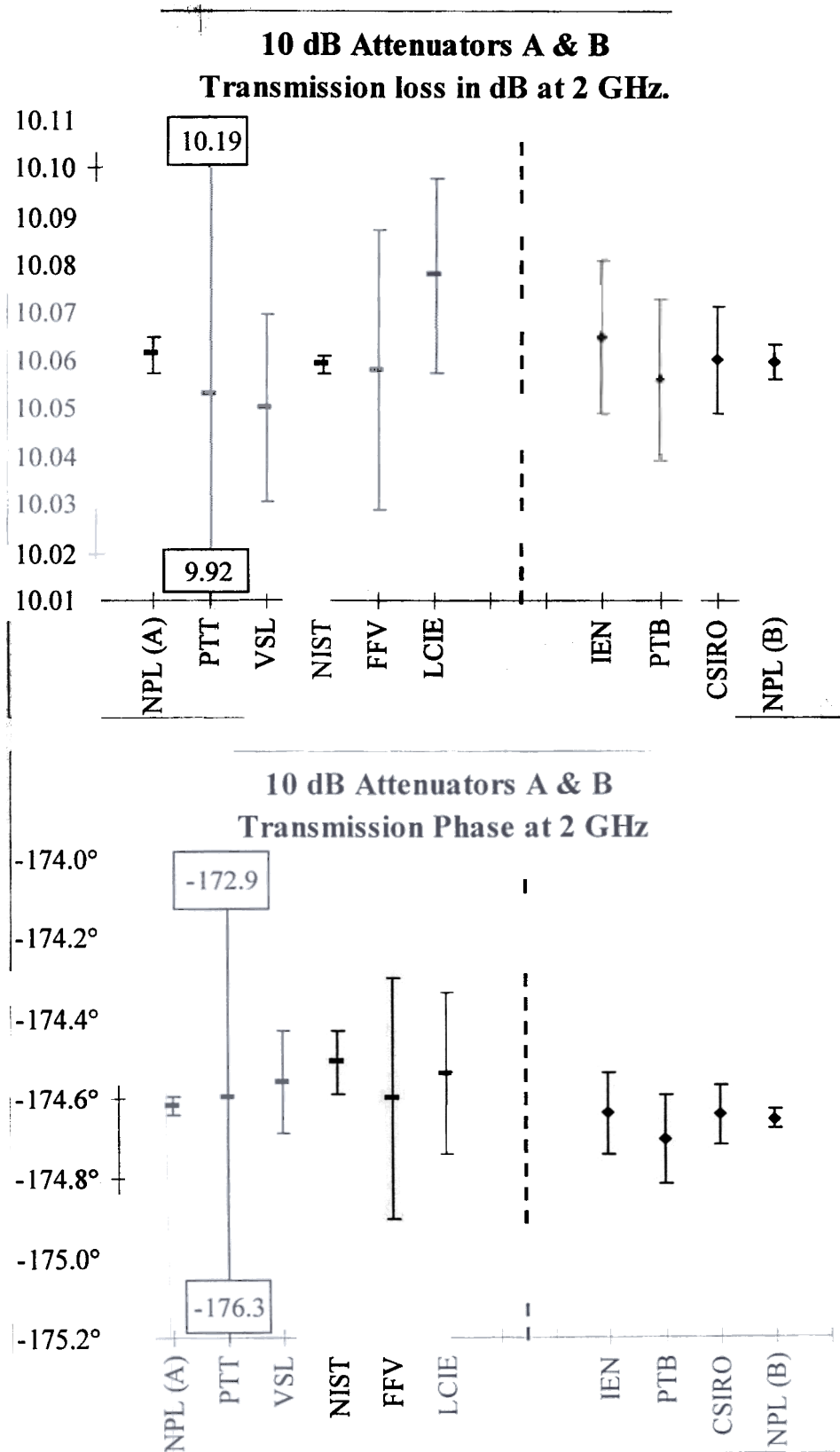
Figures 13A & 13B

Magnitude and Phase of the Reflection Coefficient of Item 7
(Short-circuit).



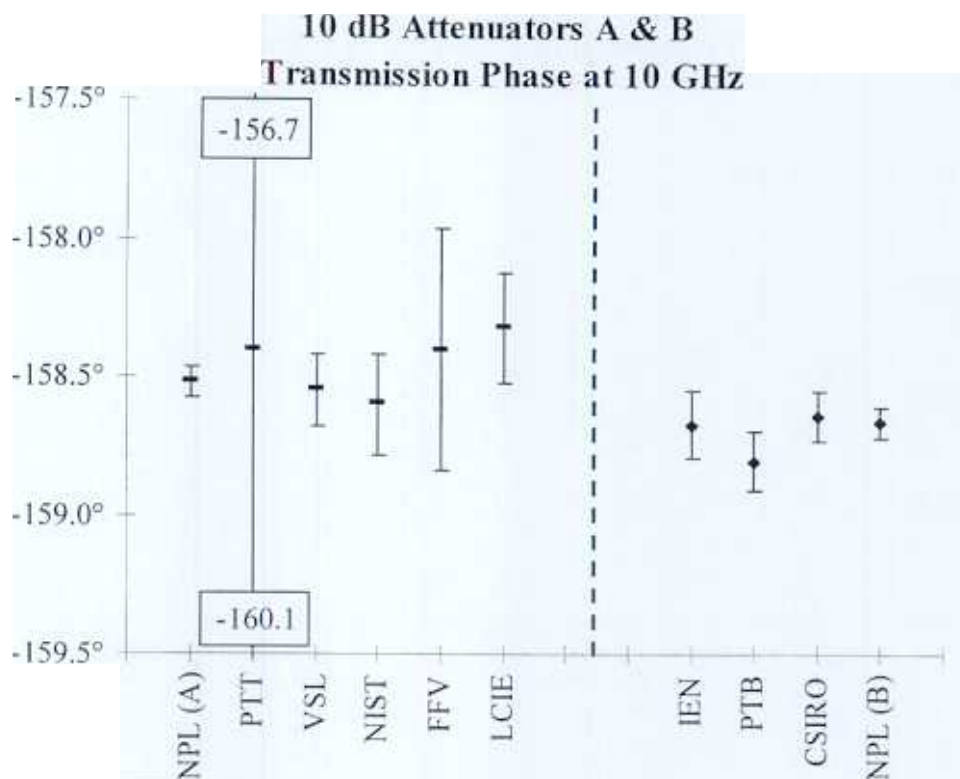
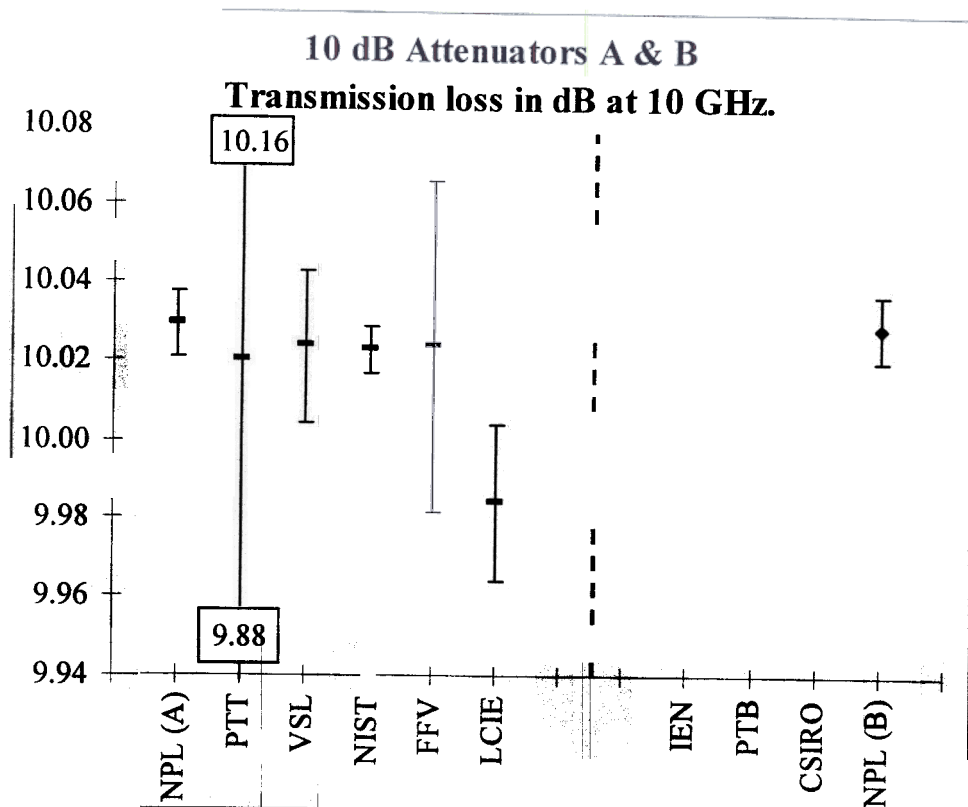
Figures 14A & 14B

Magnitude and Phase of the Reflection Coefficient of Item 8
(Termination).



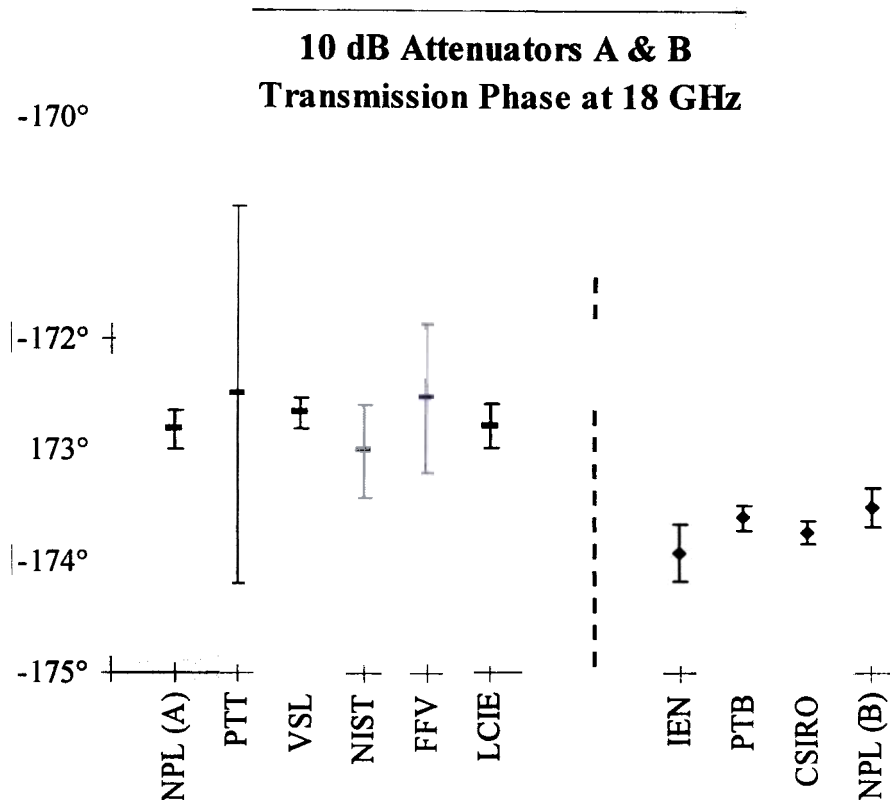
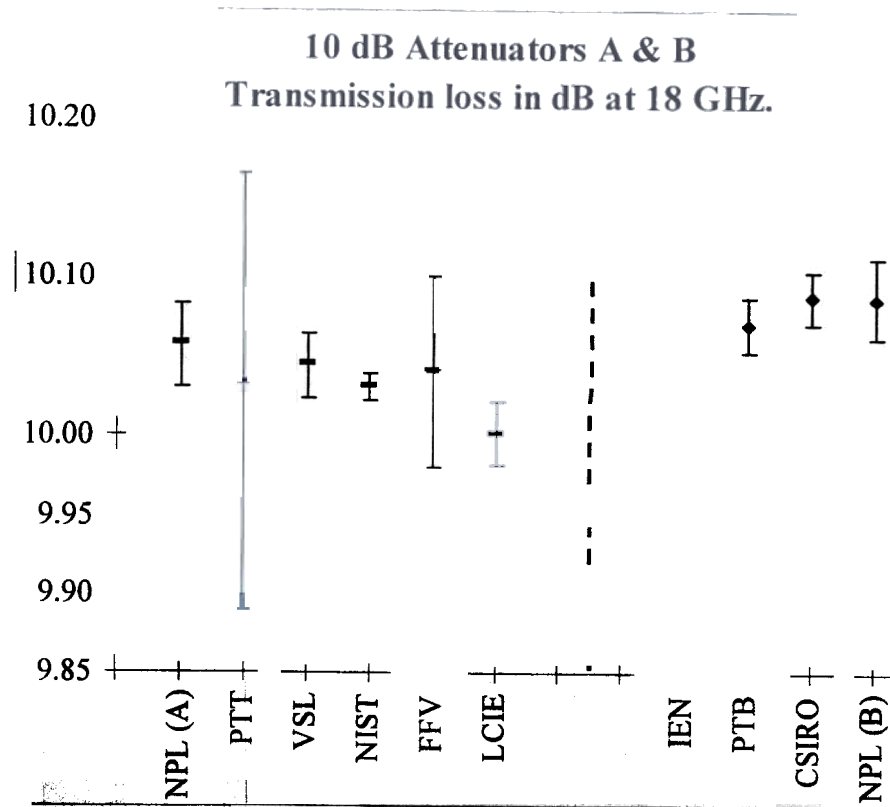
Figures 15A & 15B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 1 at 2 GHz



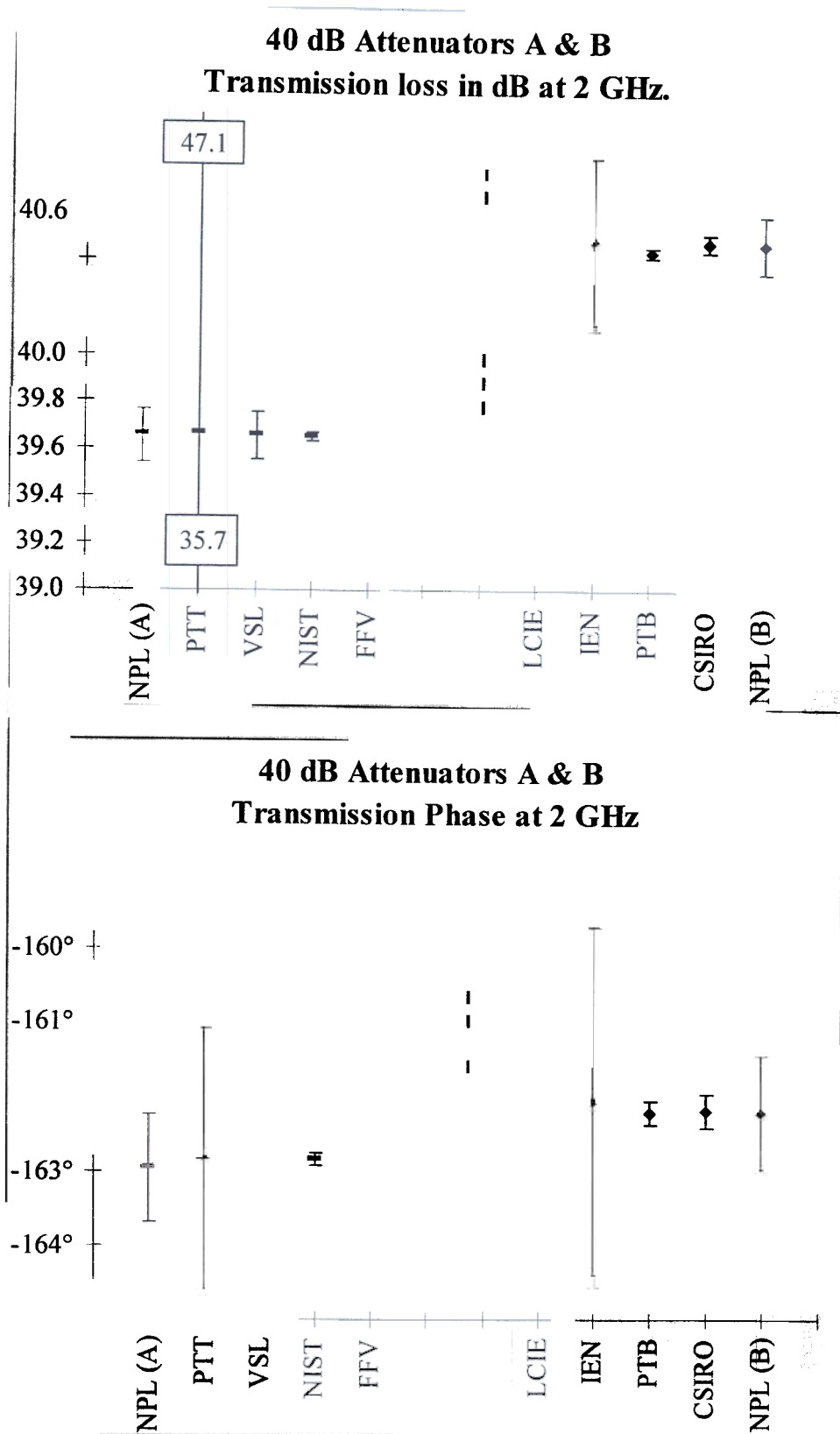
Figures 16A & 16B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 1 at 10 GHz



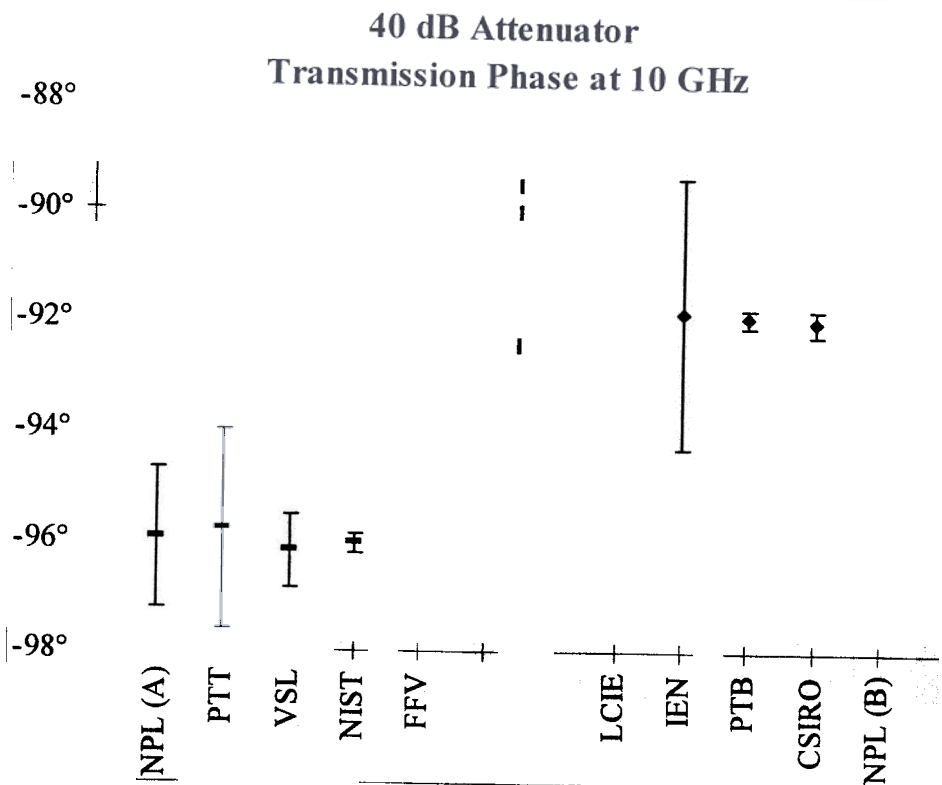
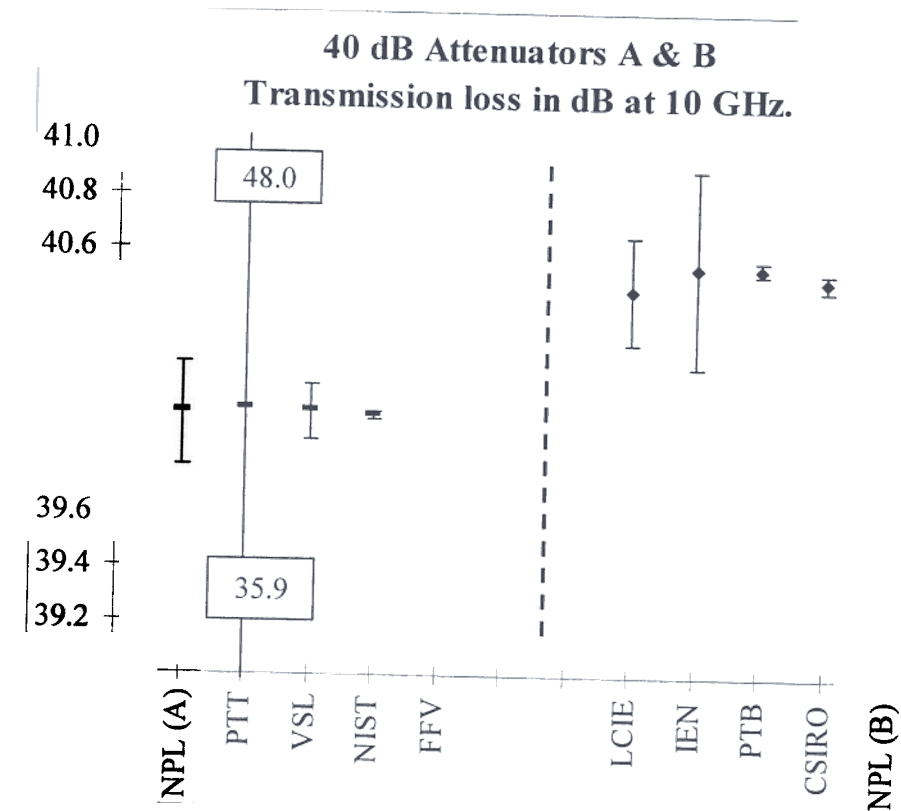
Figures 17A & 17B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 1 at 18 GHz



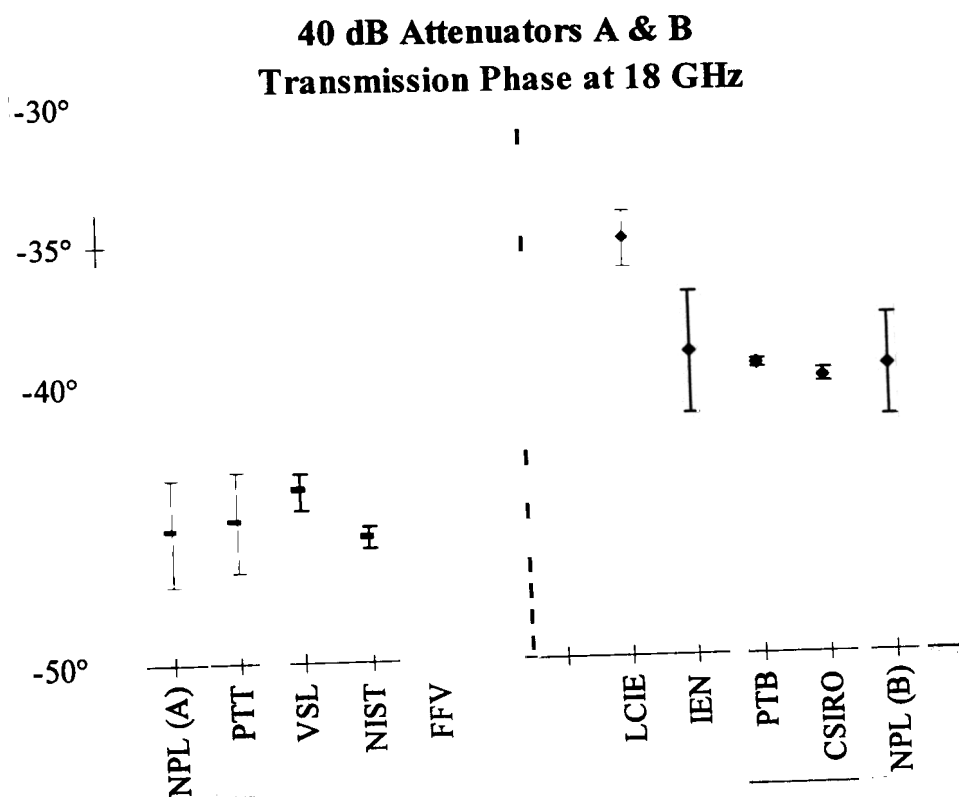
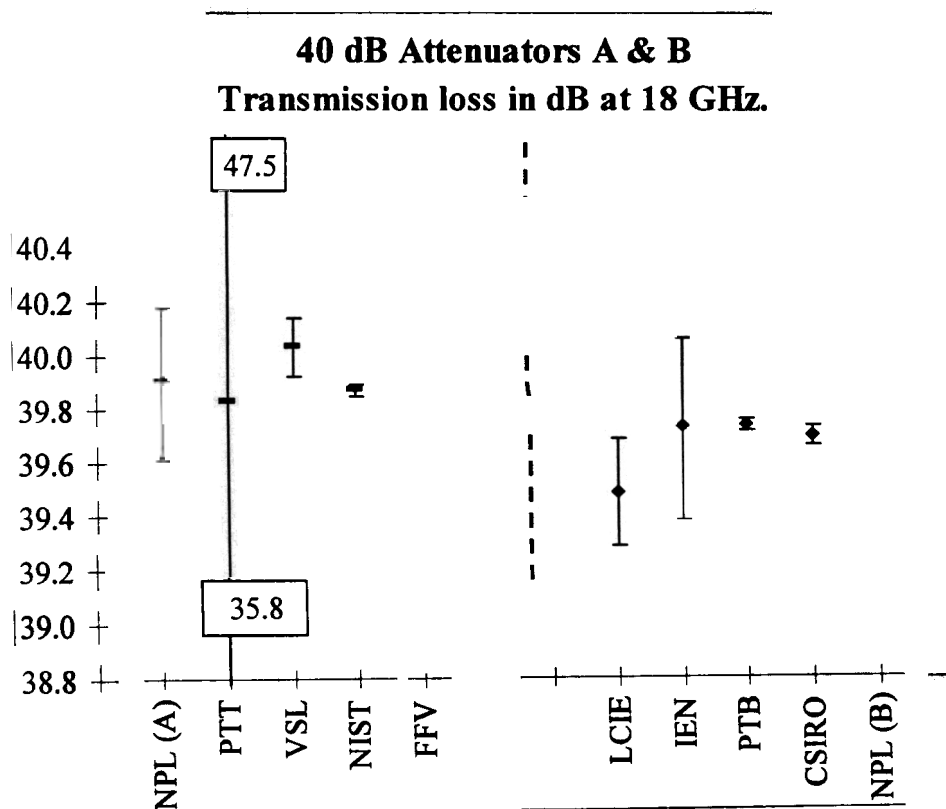
Figures 18A & 18B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 2 at 2 GHz



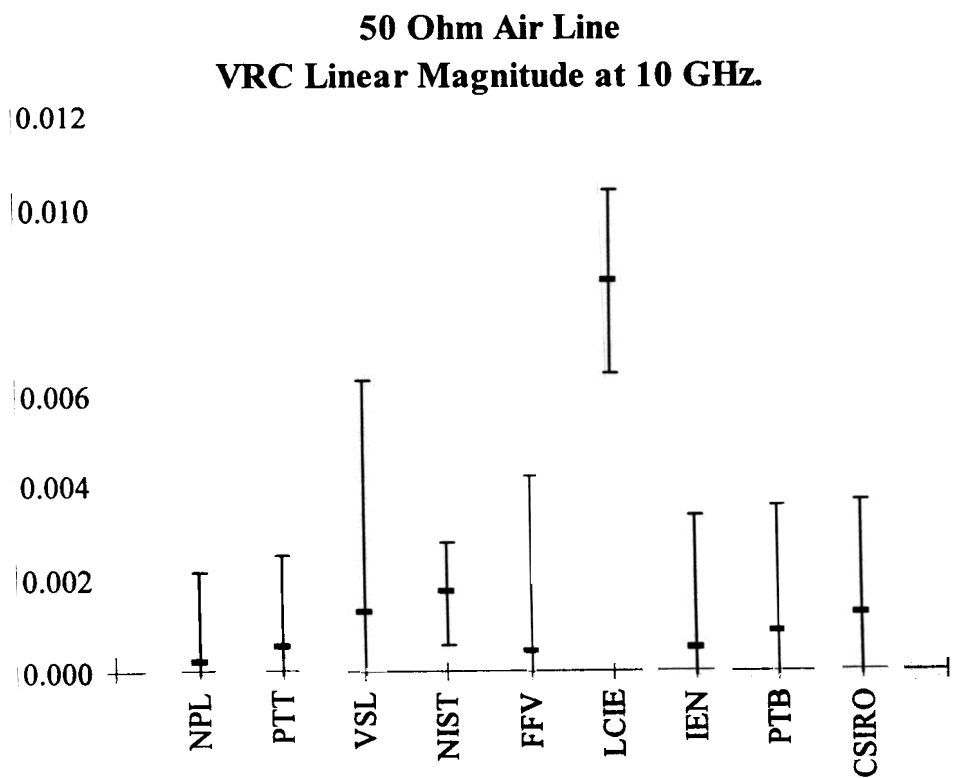
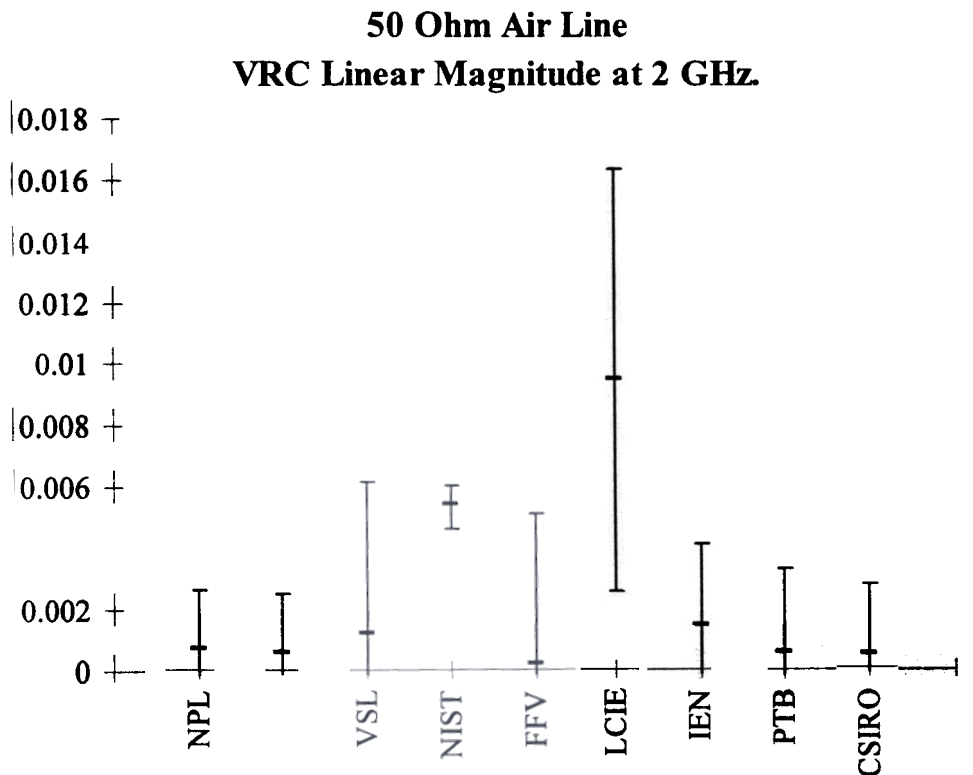
Figures 19A & 19B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 2 at 10 GHz



Figures 20A & 20B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 2 at 18 GHz



Figures 21A & 21B

Comparison of Magnitude (in linear units) with uncertainties
Reflection Coefficient of Item 3 at 2 and 10 GHz

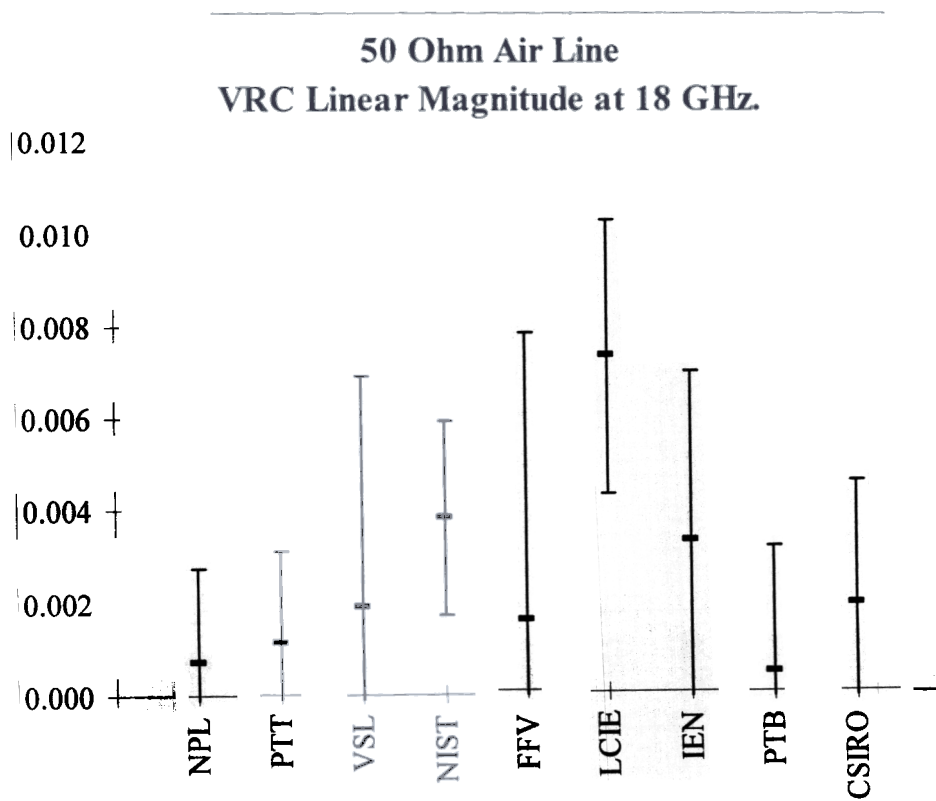
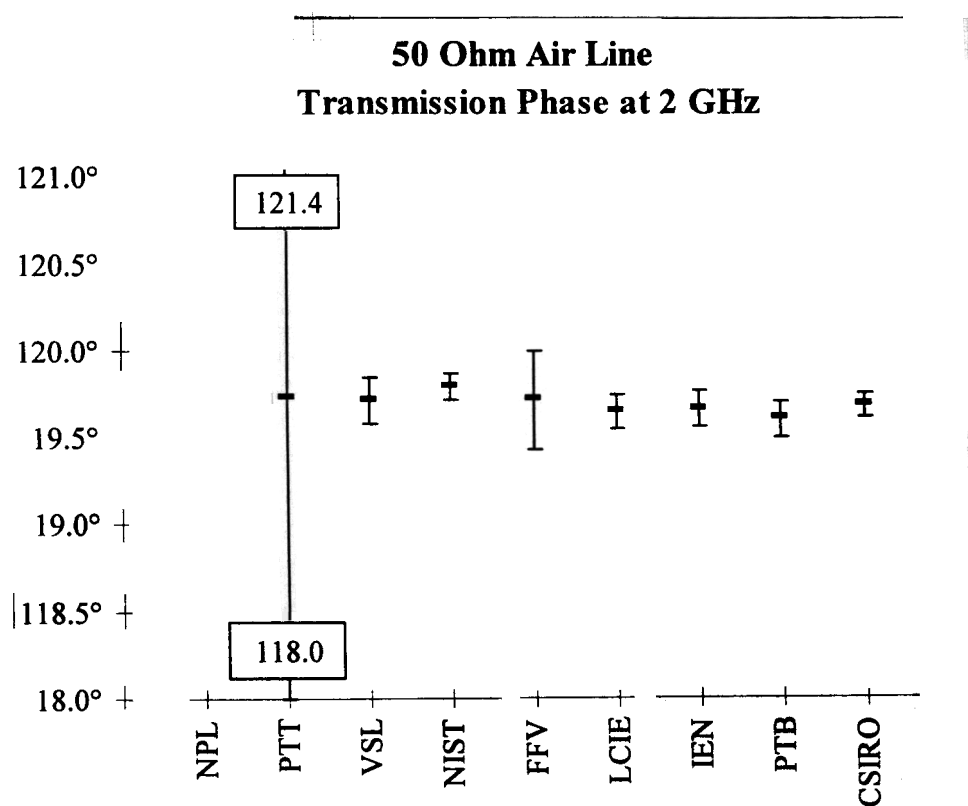
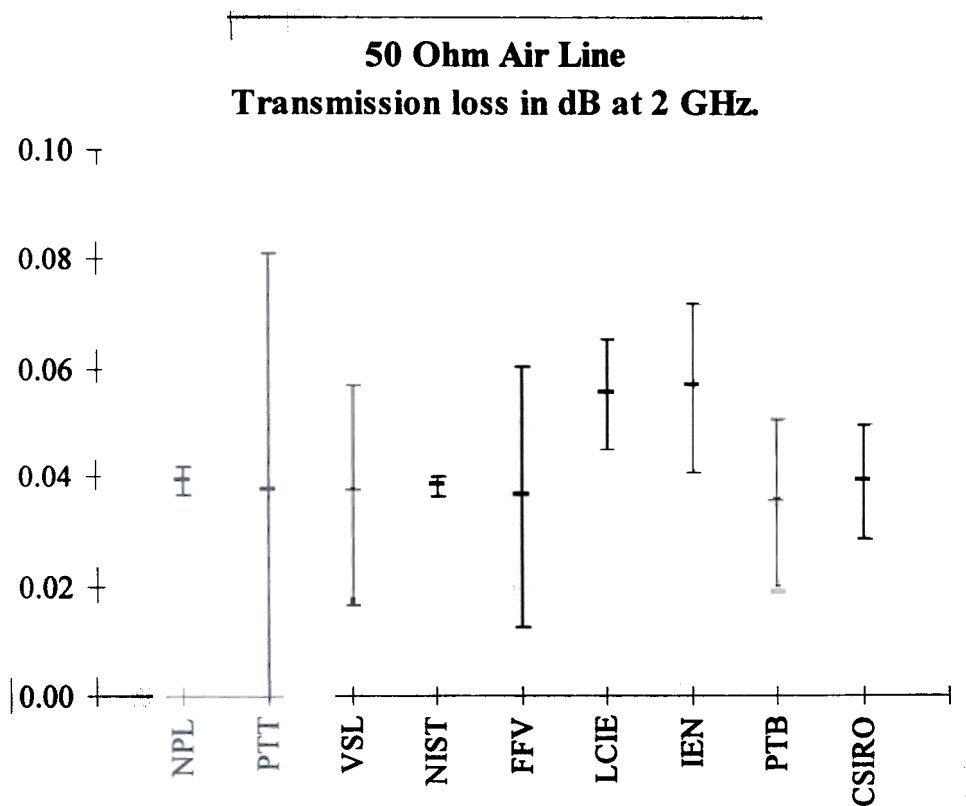


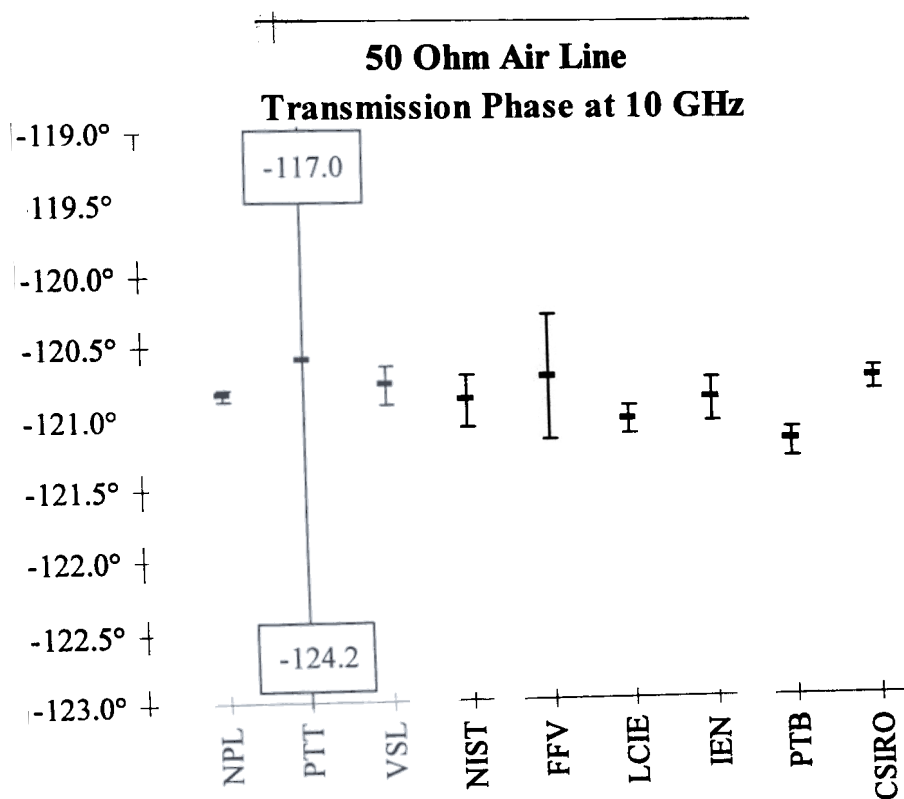
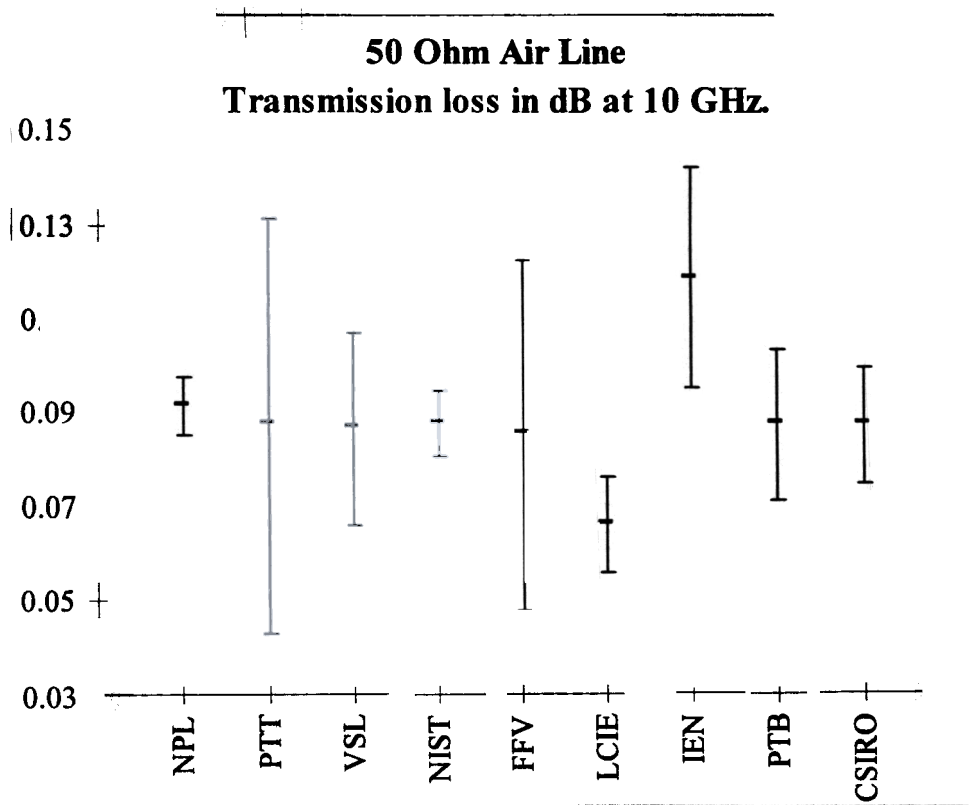
Figure 21C

Comparison of Magnitude (in linear units) with uncertainties
Reflection Coefficient of Item 3 at 18 GHz



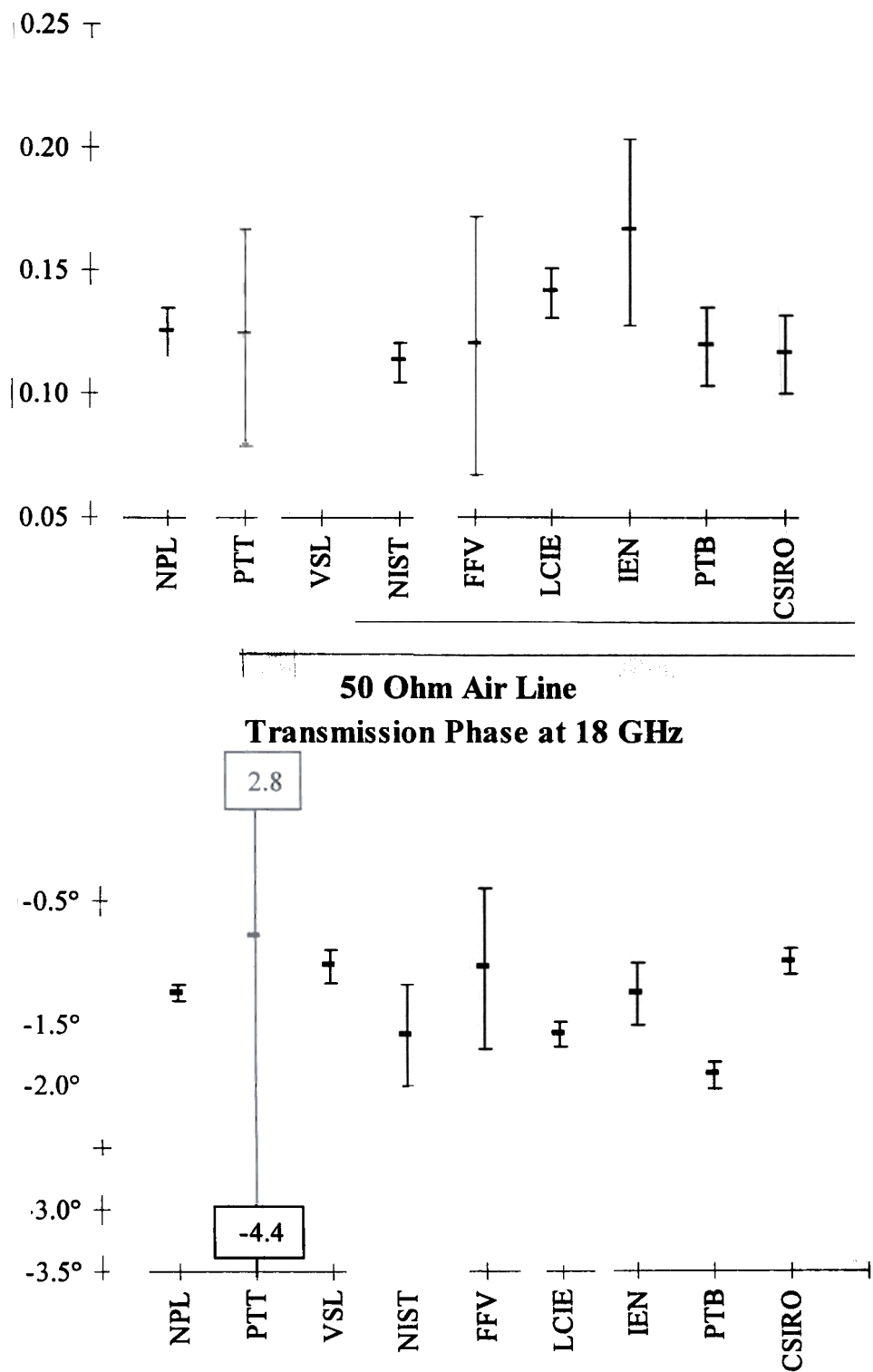
Figures 22A & 22B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 3 at 2 GHz



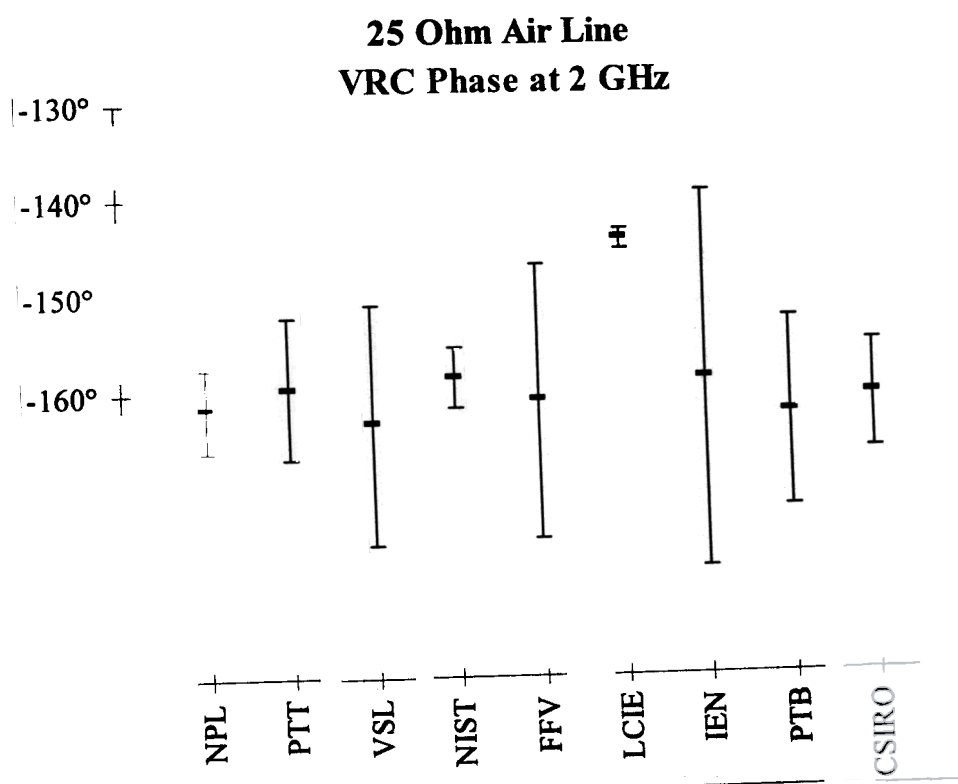
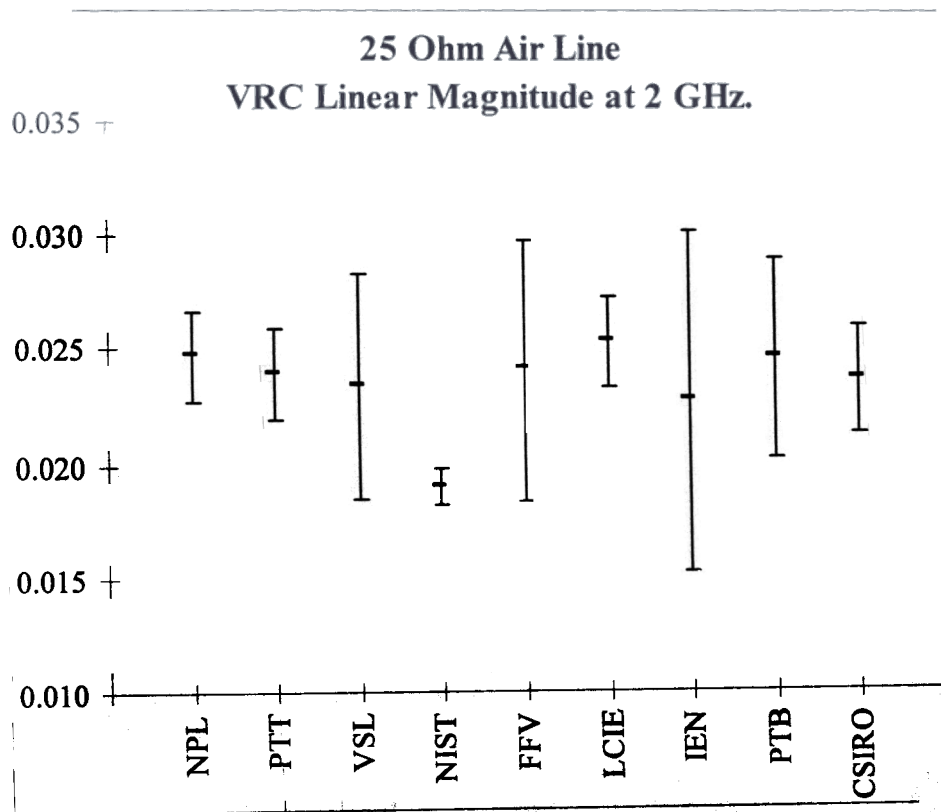
Figures 23A & 23B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 3 at 10 GHz



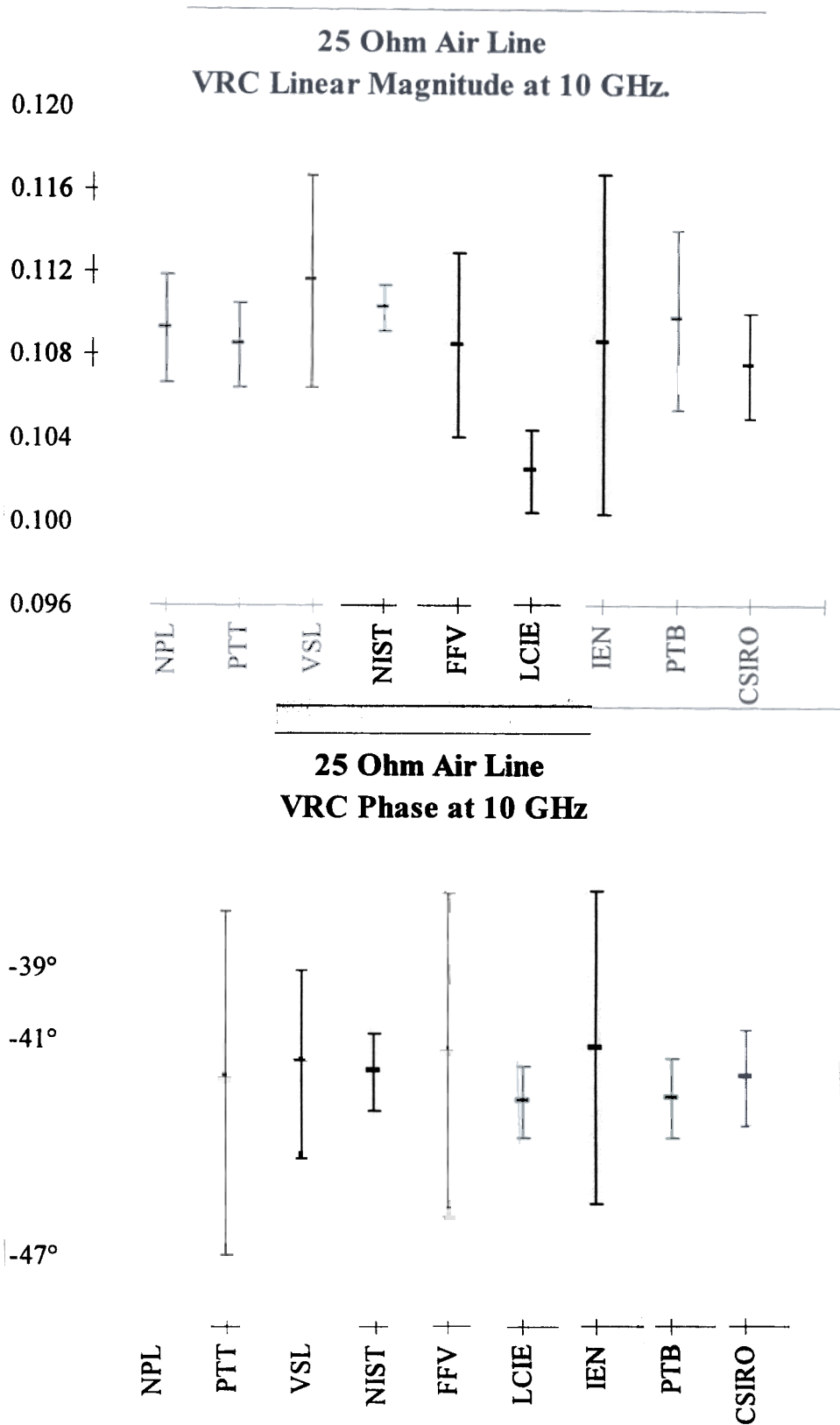
Figures 24A & 24B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 3 at 18 GHz



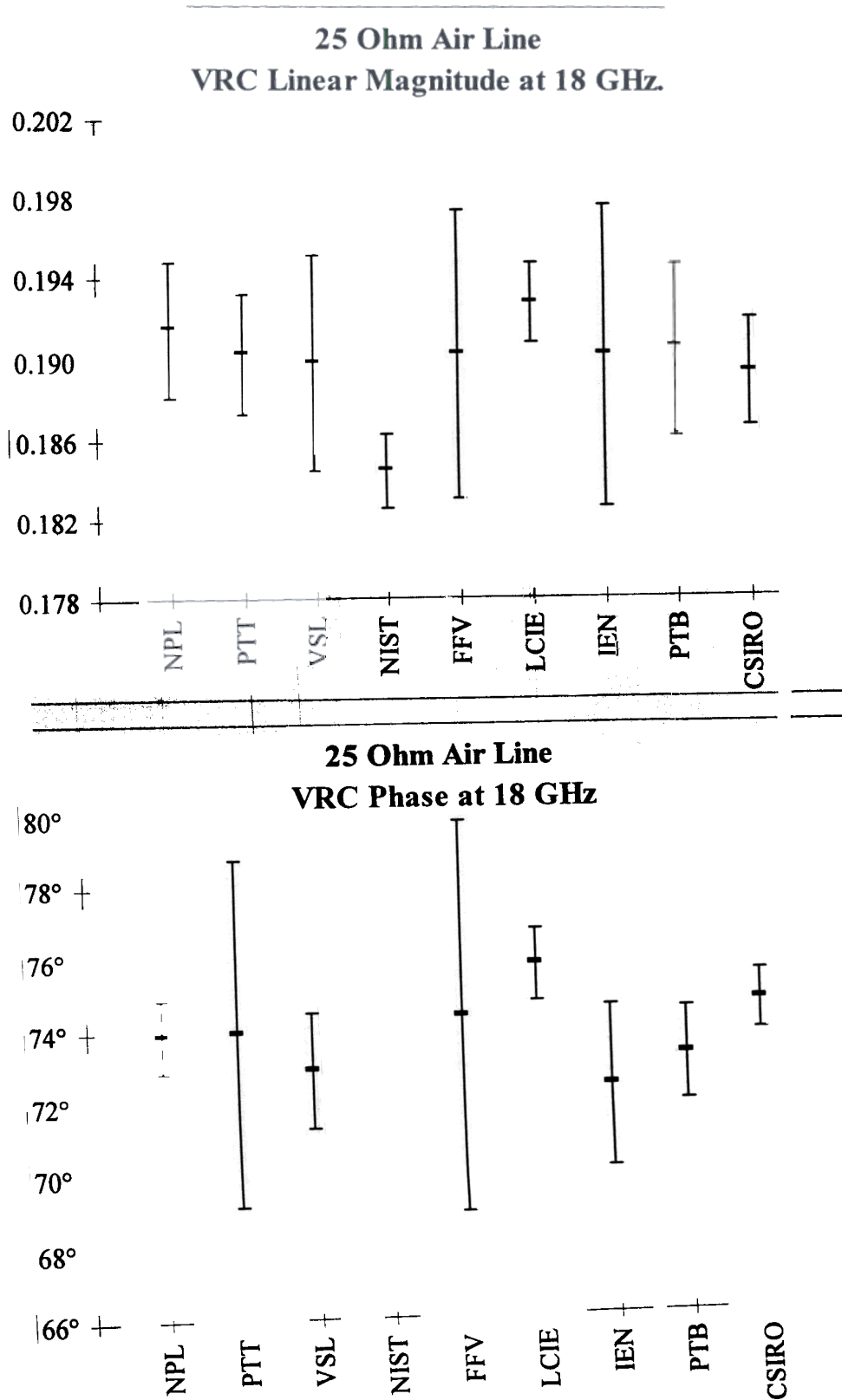
Figures 25A & 25B

Comparison of Magnitude (in linear units) and Phase (°) with uncertainties
Reflection Coefficient of Item 5 at 2 GHz



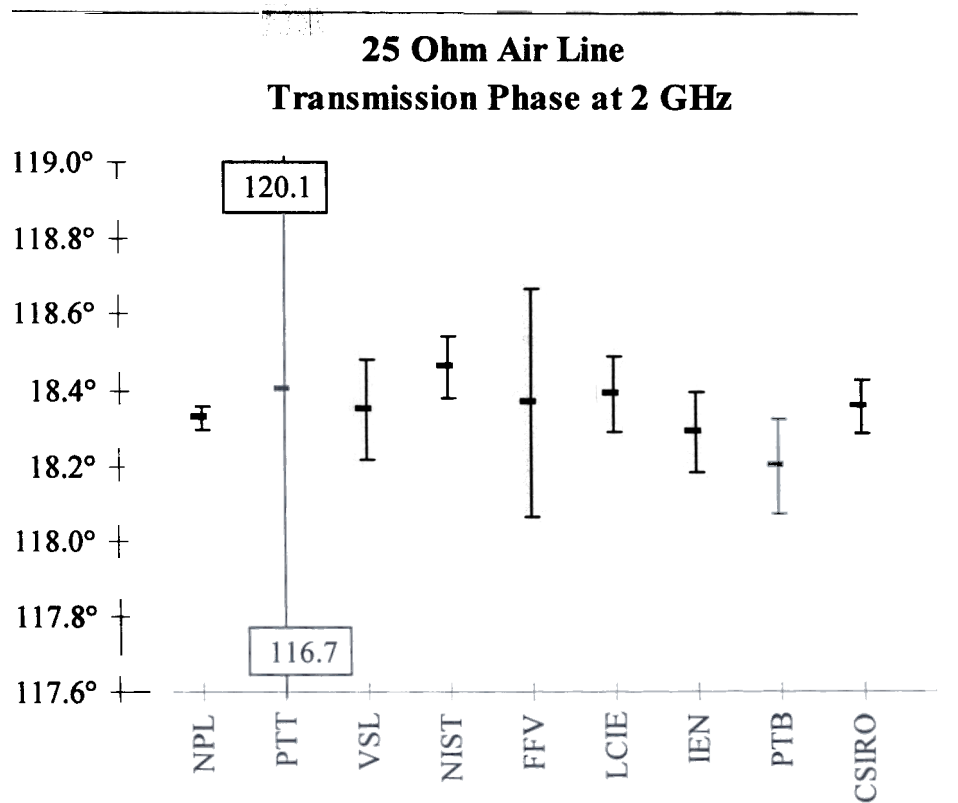
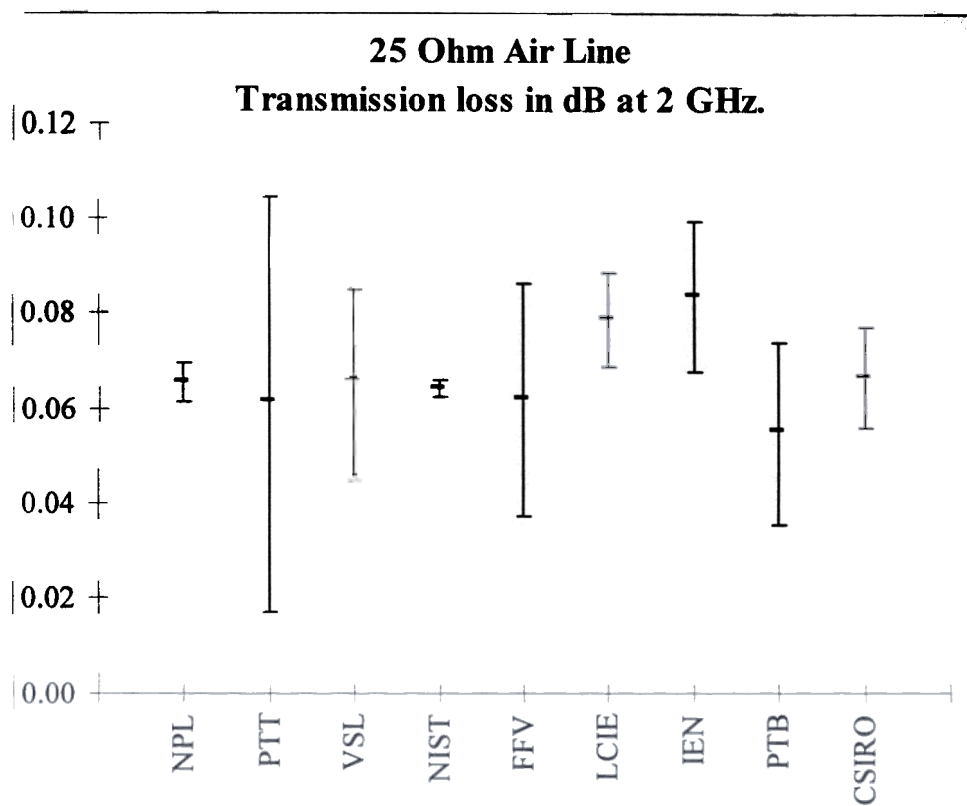
Figures 26A & 26B

Comparison of Magnitude (in linear units) and Phase (°) with uncertainties
Reflection Coefficient of Item 5 at 10 GHz



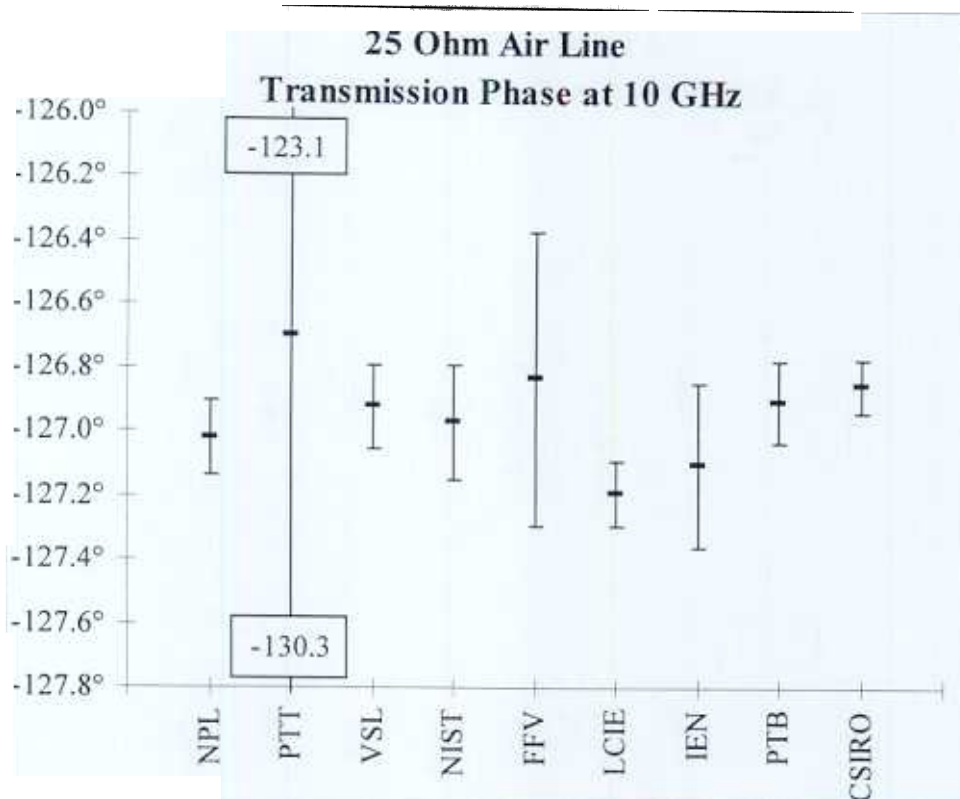
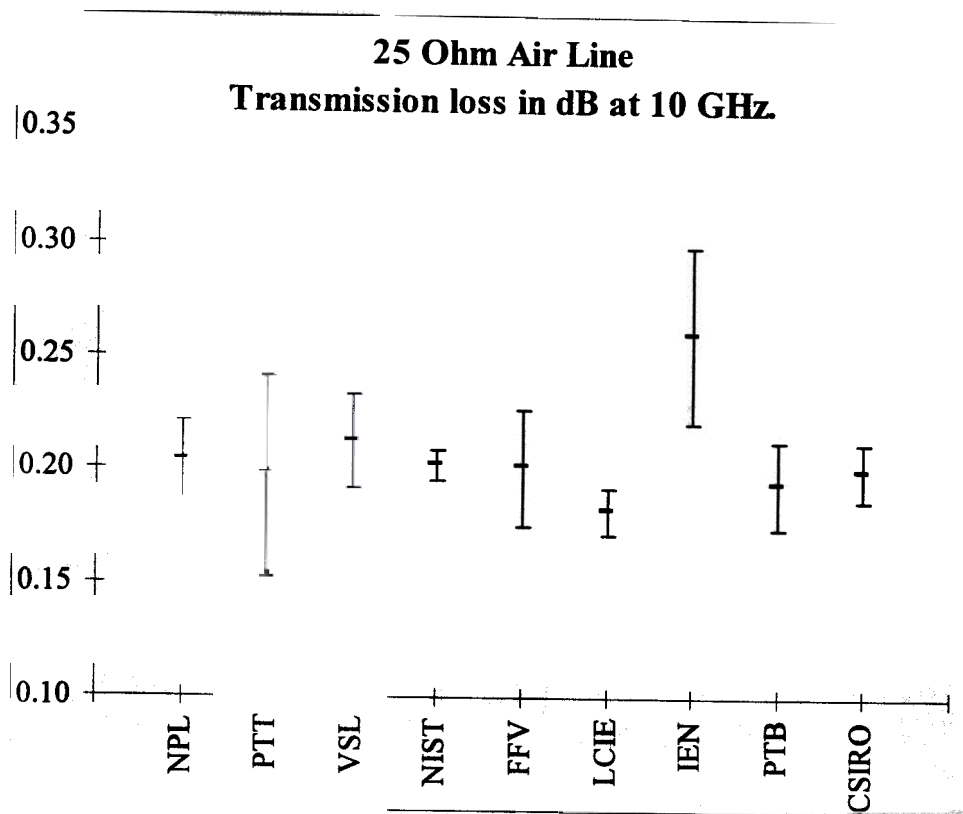
Figures 27A & 27B

Comparison of Magnitude (in linear units) and Phase (°) with uncertainties
Reflection Coefficient of Item 5 at 18 GHz



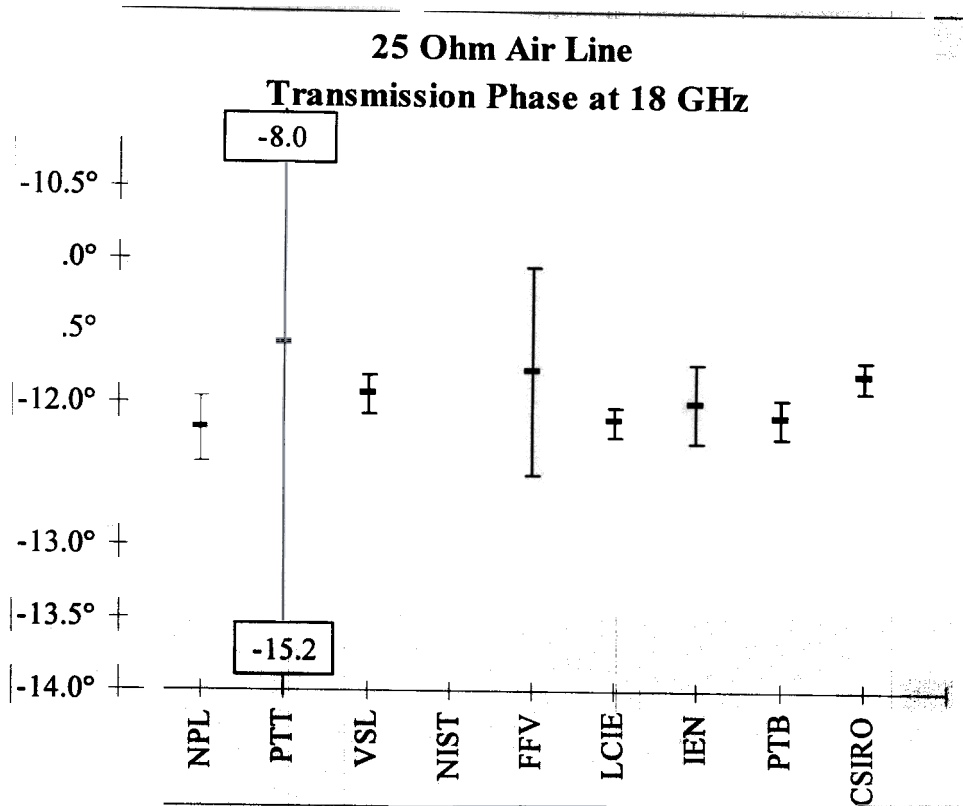
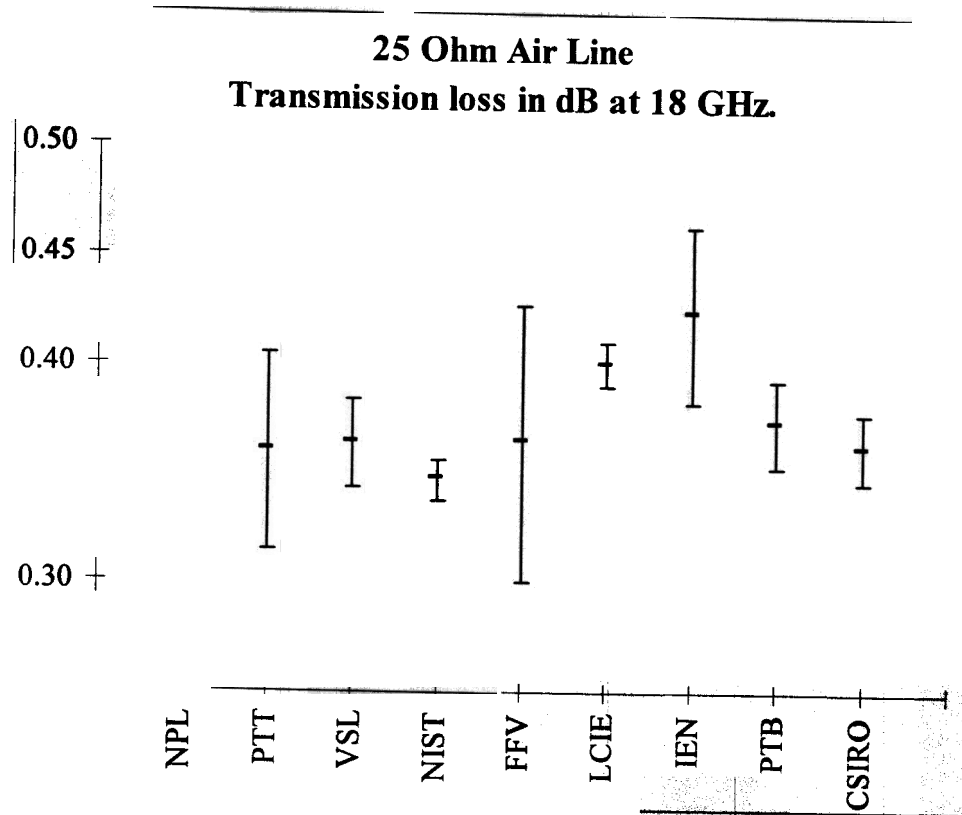
Figures 28A & 28B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 5 at 2 GHz



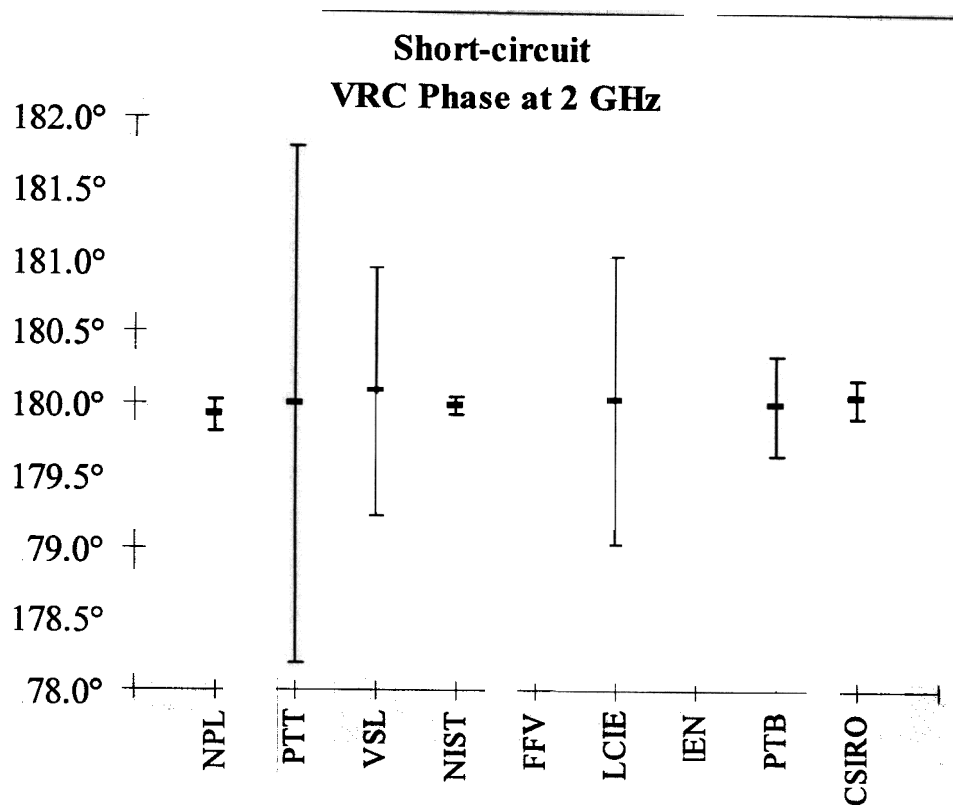
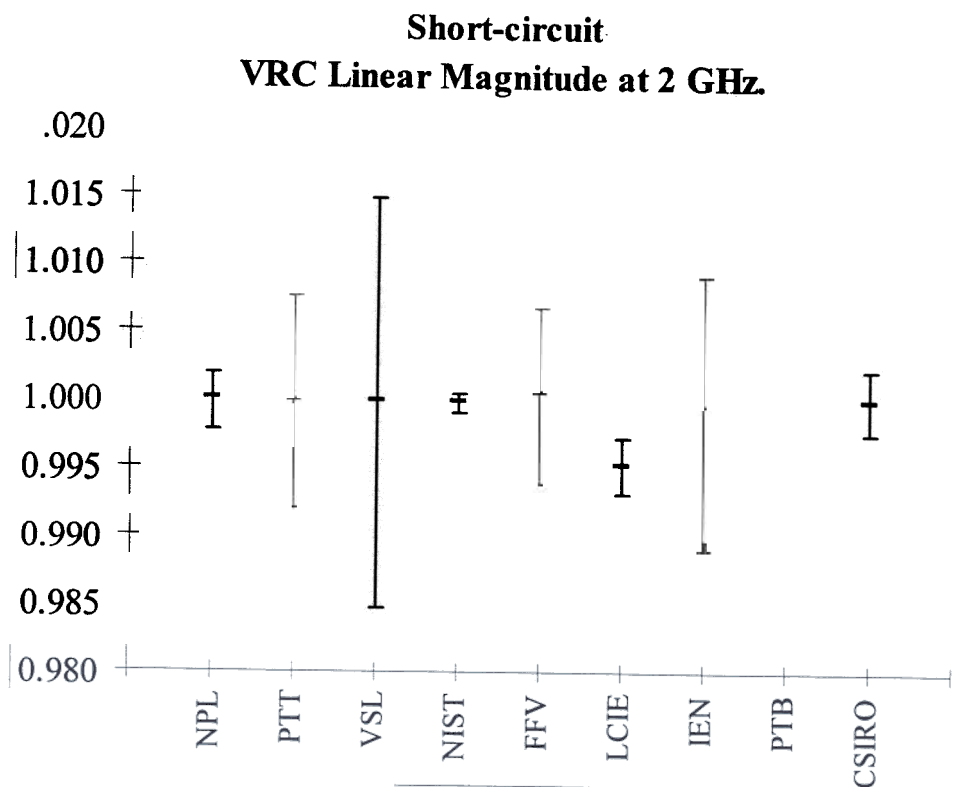
Figures 29A & 29B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 5 at 10 GHz



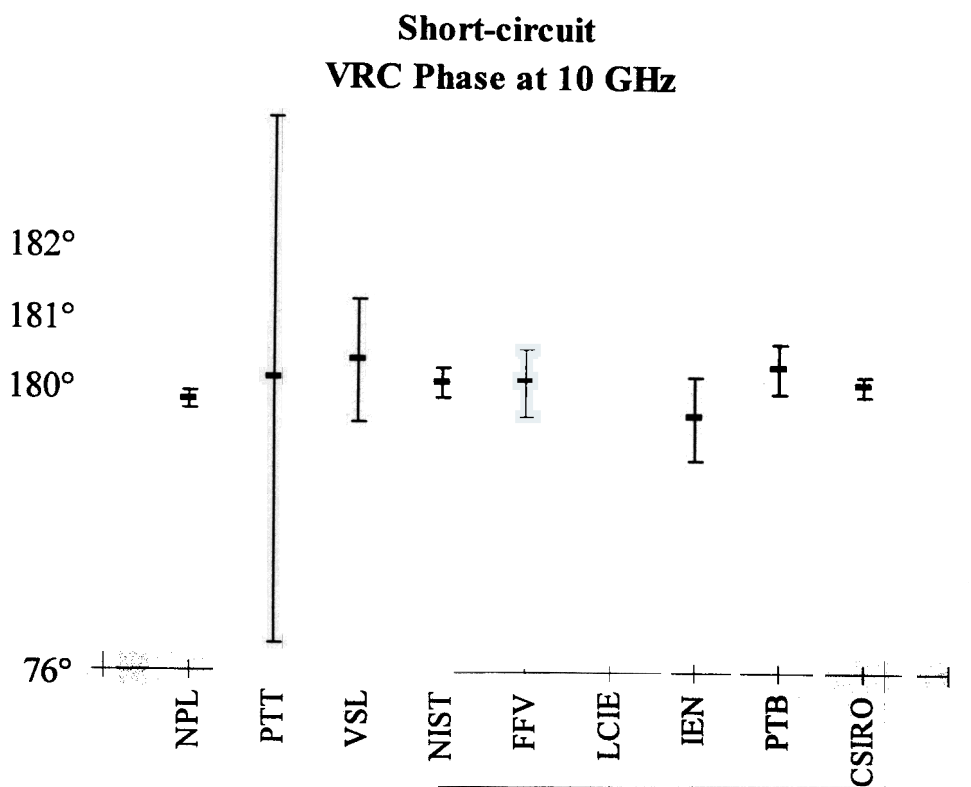
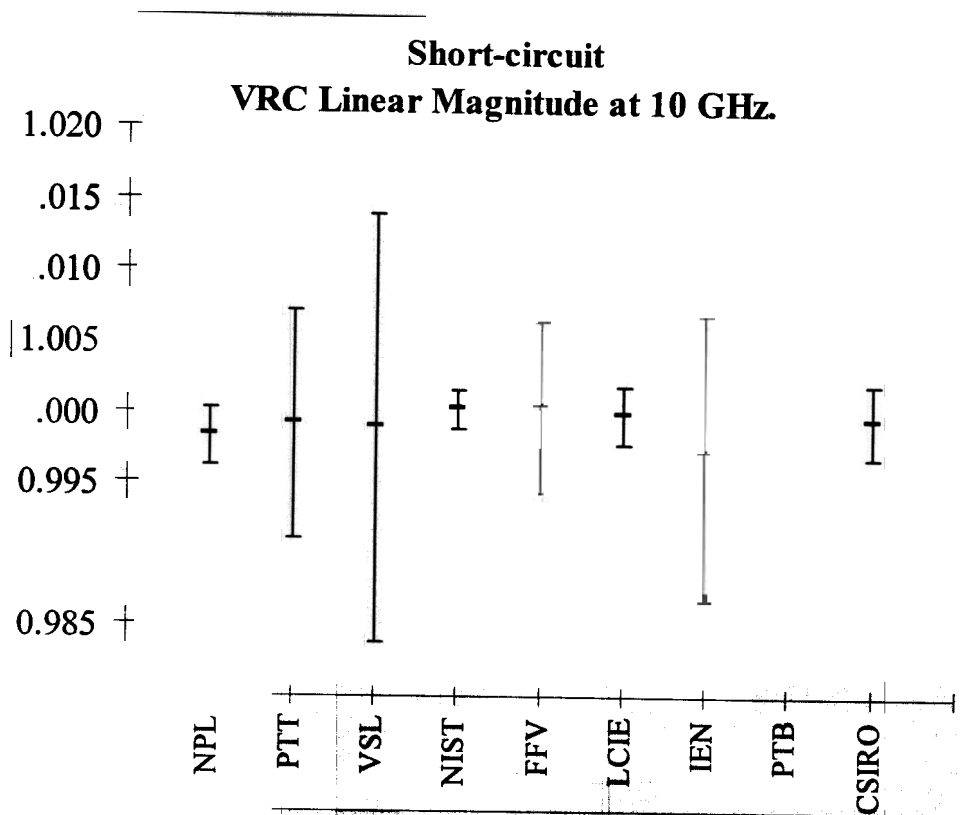
Figures 30A & 30B

Comparison of Magnitude (in dB) and Phase (°) with uncertainties
Transmission Coefficient of Item 5 at 18 GHz



Figures 31A & 31B

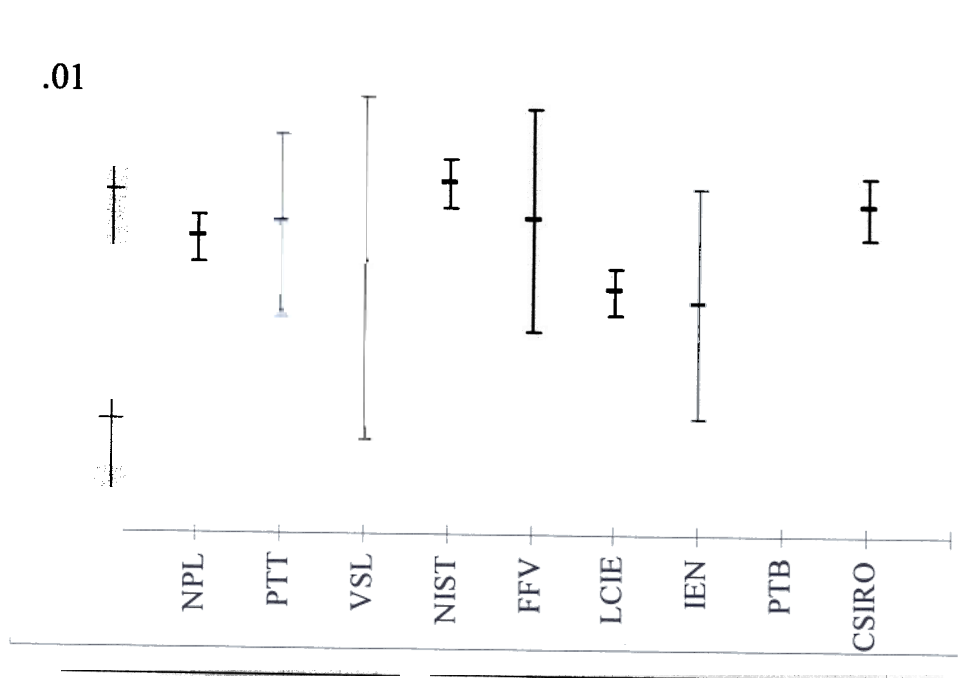
Comparison of Magnitude (in linear units) and Phase (°) with uncertainties
Reflection Coefficient of Item 7 at 2 GHz



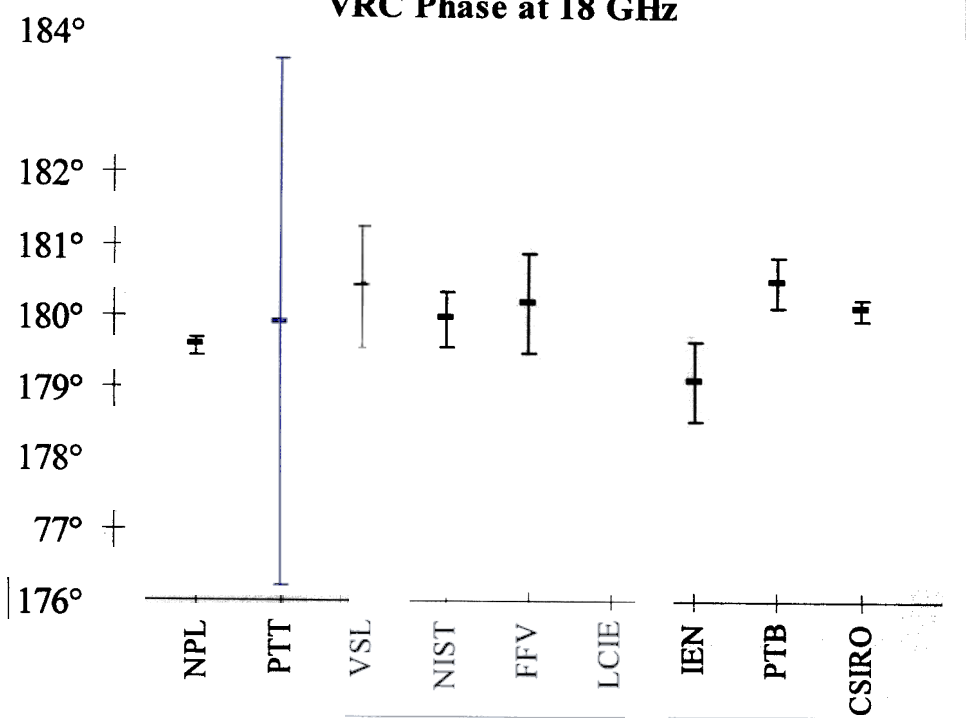
Figures 32A & 32B

Comparison of Magnitude (in linear units) and Phase (°) with uncertainties
Reflection Coefficient of Item 7 at 10 GHz

**Short-circuit
VRC Linear Magnitude at 18 GHz.**

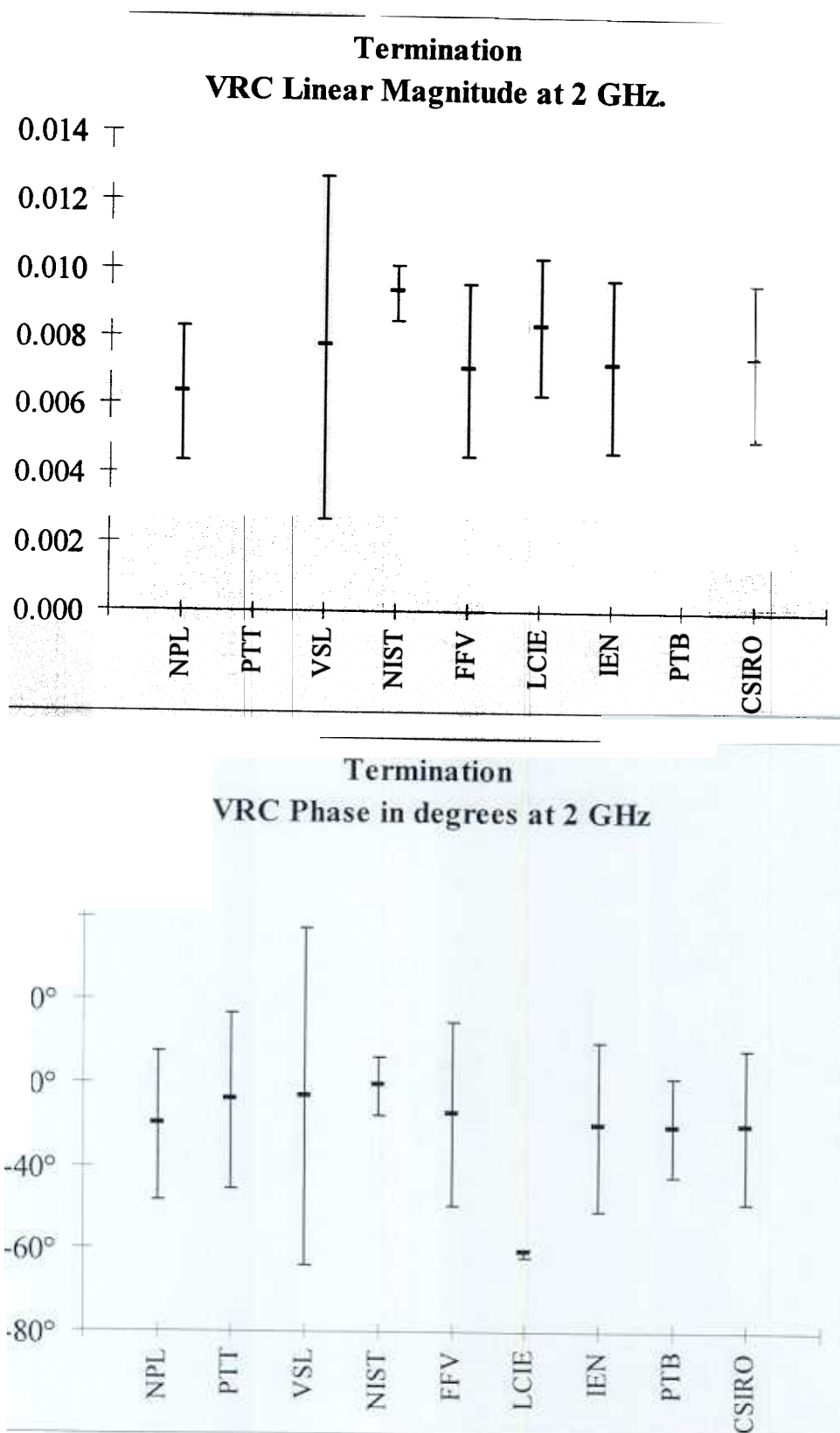


**Short-circuit
VRC Phase at 18 GHz**



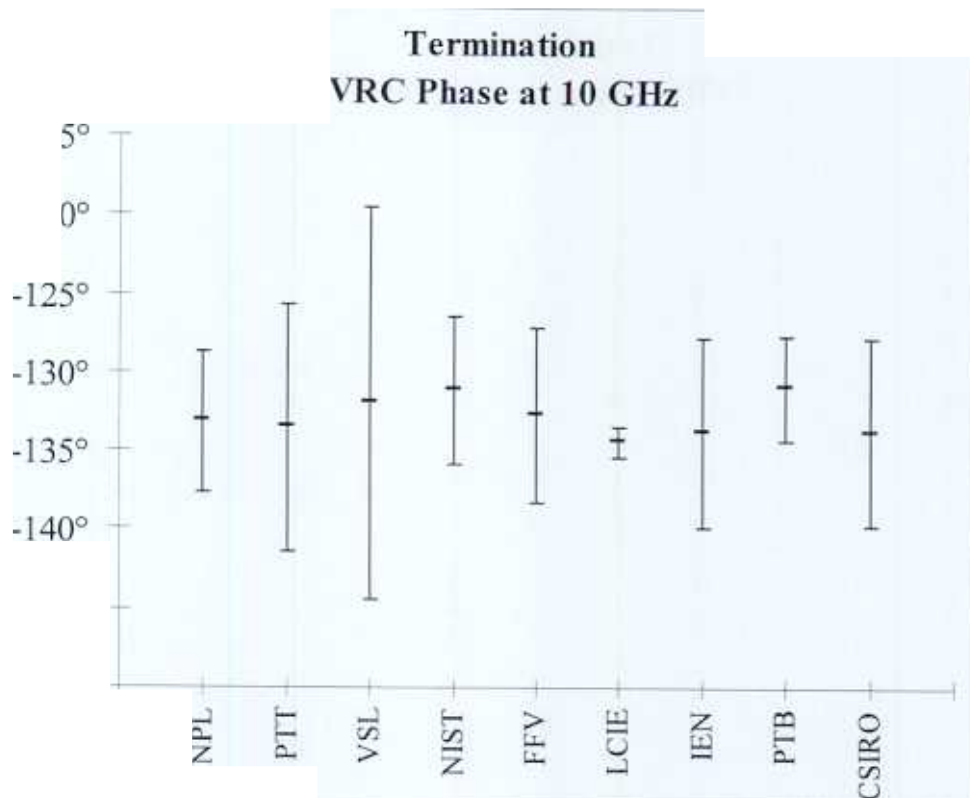
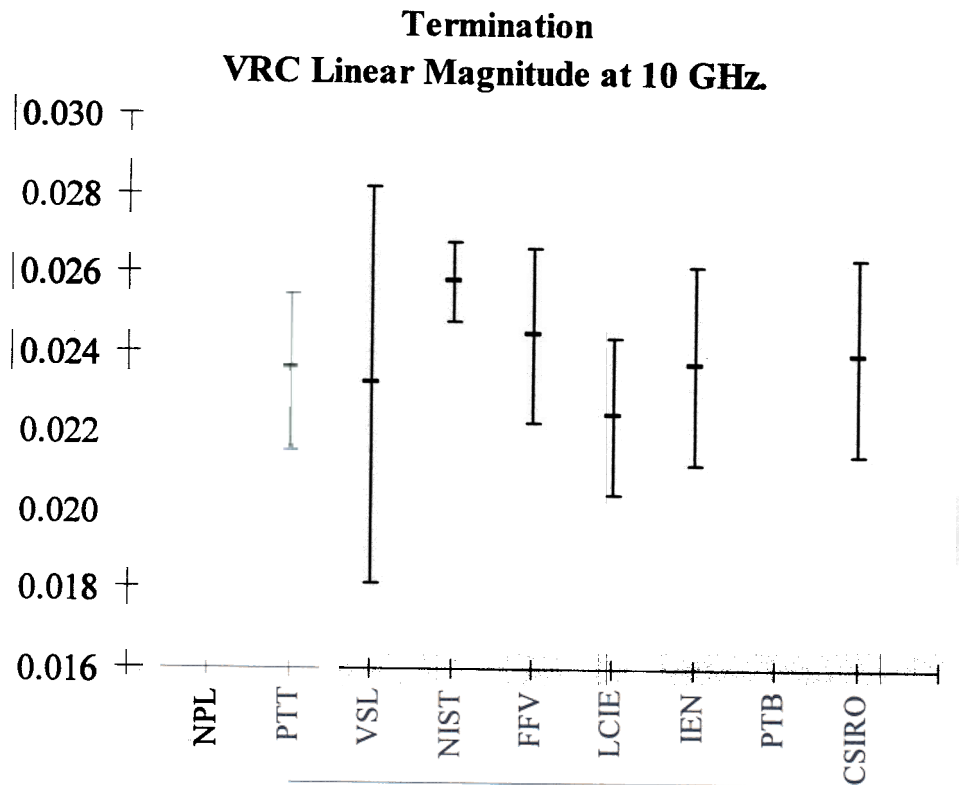
Figures 33A & 33B

Comparison of Magnitude (in linear units) and Phase (°) with uncertainties
Reflection Coefficient of Item 7 at 18 GHz



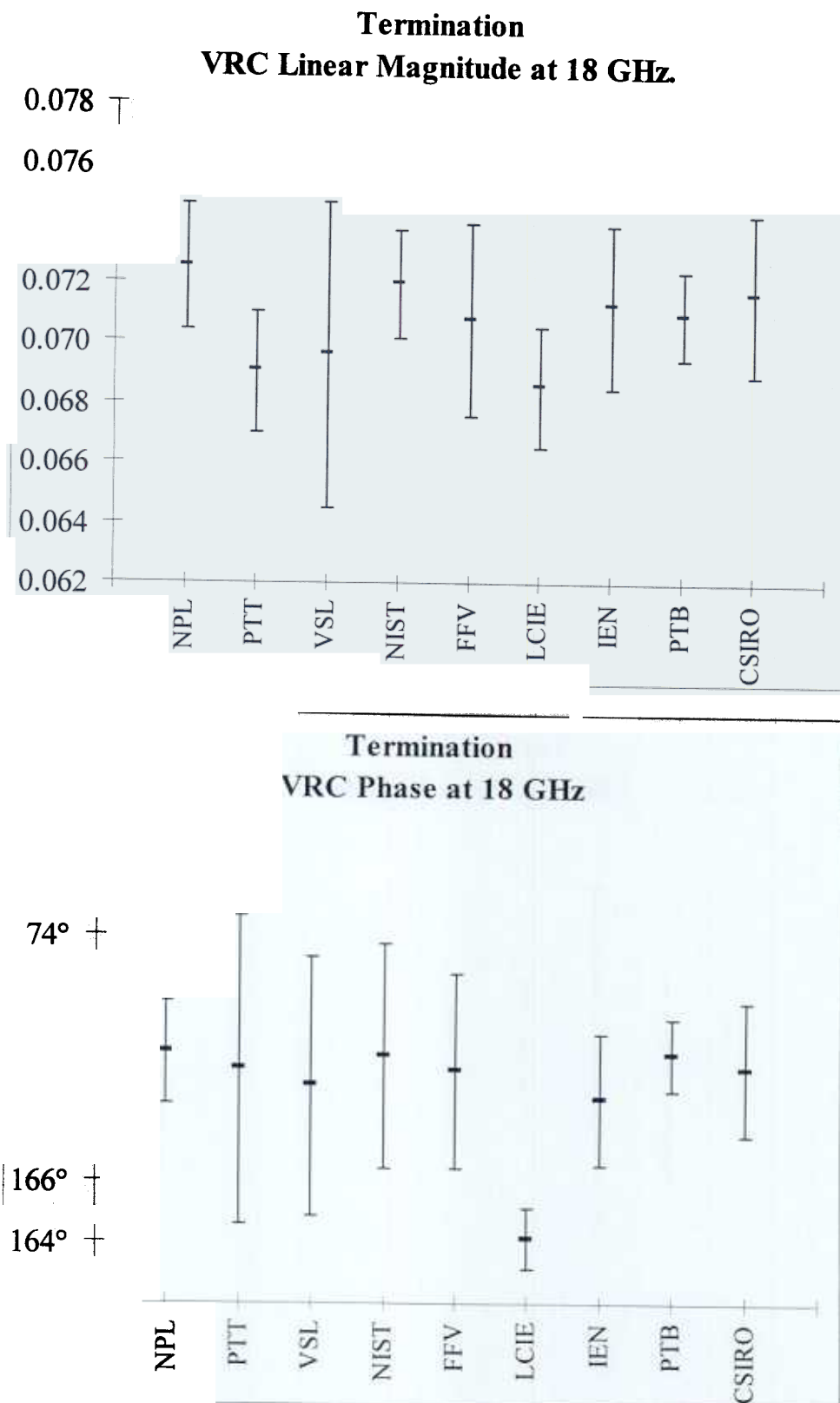
Figures 34A & 34B

Comparison of Magnitude (in linear units) and Phase (°) with uncertainties
Reflection Coefficient of Item 8 at 2 GHz



Figures 35A & 35B

Comparison of Magnitude (in linear units) and Phase (°) with uncertainties
Reflection Coefficient of Item 8 at 10 GHz



Figures 36A & 36B

Comparison of Magnitude (in linear units) and Phase (°) with uncertainties
Reflection Coefficient of Item 8 at 18 GHz

Appendix A: The GPC-7 Connector and the Air Line.

- 1 This purpose of this appendix is to give some background on the General Purpose Connector - 7 mm (GPC-7) connector and its collets and the use of a air-dielectric unsupported coaxial line - or air line.
- 1.1 The GPC-7 connector is a hermaphroditic connector designed for 7 mm 50 ohm cable. The hermaphroditic part implies that both halves of the connector pair are identical. To make the connector have a characteristic impedance of 50 ohms at microwave frequencies, the relevant diameters of the inner and outer conductors have been set as 3.040 mm and 7.000 mm respectively. The inner conductor is held rigidly with respect to the outer conductor by a dielectric bead set back from the reference plane.
- 2 The dimensions were chosen to ensure that the connector would not support modes other than TEM below its maximum operating frequency of 18 GHz.
- 1.3 Figure A1. shows the cross-section and end view of a typical GPC-7 connector. The centre and outer conductors are shown along with the dielectric support bead that holds the inner conductor in the correct relationship to the outer and the six-fingered collet that ensures good connection between the mating surfaces of the inner conductors. The older versions of the collets were constructed with four fingers. These were superseded by six-fingered collets to reduce the risk of resonances in the collet affecting the performance of the connector. The dielectric bead is shaped to minimise the discontinuity that it causes. Note that the inner conductor does not actually reach the reference plane, this allows for imperfections and tolerances in the manufacturing, assembly and measurement processes. The gap between the end of the inner conductor and the reference plane is often called the pin depth recession.

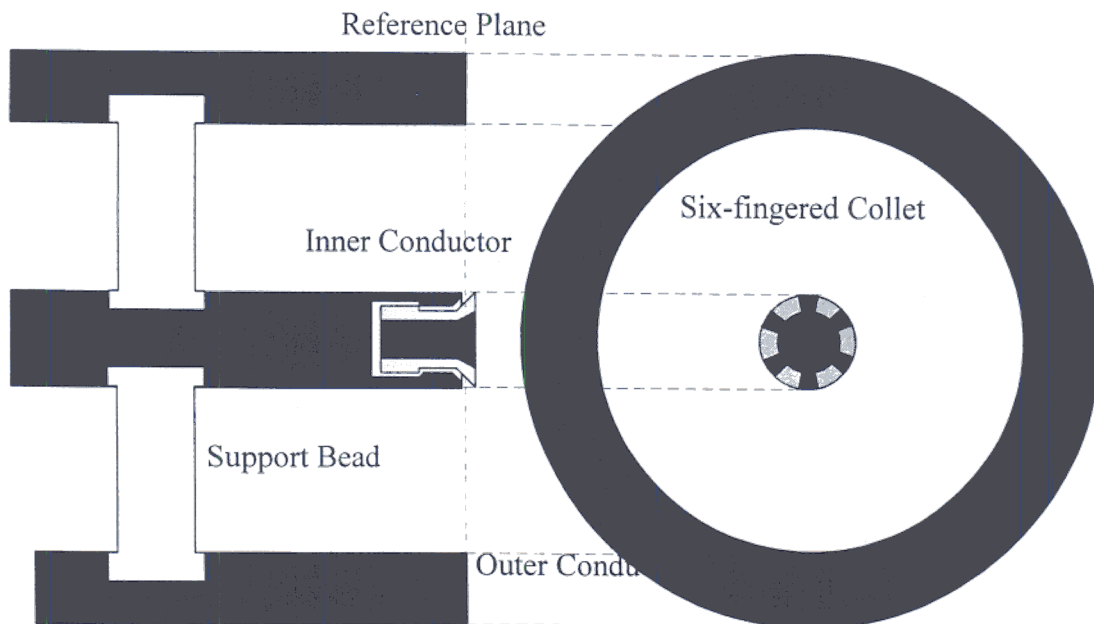


Figure A1 Cross-section (left) and end view (right) of GPC-7 connector with six-fingered collet.

- 1.4 In an ideal connector the inner and outer conductors terminate at the reference plane and so when the connector is tightened up, equal pressure is exerted on the inner and outer conductors. In practice there will almost always be a discrepancy between the lengths and if the inner protrudes beyond the outer there is a possibility that the inner conductors will meet before the outer conductors and then damage will occur as the connector is tightened to the correct torque. One way to avoid this is to ensure that the inner conductor is always recessed and then use collets to bridge the resulting gap, as shown in Fig A2. Note that the gaps between the fingers are randomly aligned and because the gaps are much smaller than the fingers, there will very rarely be gaps through the pair of collets. In the diagram the collets meet exactly at the reference plane, in practice the position of the join will depend on the relative strengths of the fingers. The other point of contact is at the back of the collets and the position and quality of the contact will depend on the amount of wear that the connector has suffered and any eccentricity between the hole that the collet is held in and the inner conductor.

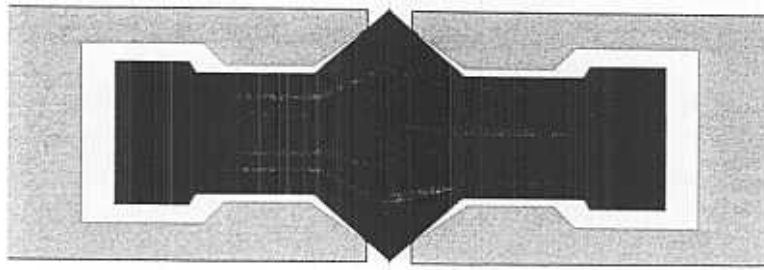


Figure A2 A pair of collets meeting at the reference plane in a good connection.

2. There are two problems relating to the use of unsupported air lines which arise from this scheme. The first concerns the use of the special TRL adaptor and the other concerns supporting the long air lines used as verification standards.
- 2.1 The TRL algorithm requires the use of a short line (≈ 7 mm in length to cover 2 to 18 GHz) as the LINE standard. The system implemented by Hewlett Packard utilises a line with a threaded protrusion at one end which screws into a special adaptor. Unfortunately the presence of a threaded hole in the centre of the inner conductor prevents the use of a conventional collet. Figure A3 shows the junctions of the inner conductor at the reference plane between a conventional connector and the special TRL adaptor, without and with the short line. The connections for the outer conductor are not shown for clarity but they are fairly simple and do not impose any restrictions on the use of the system. The position of the inner conductor in the special adaptor is carefully adjusted so that the pin recession depth is as small as possible and is generally zero within the resolution of typical laboratory pin depth gauging systems.
- 2.2 The amount of force used to screw the line into the special adaptor determines the repeatability of the connection and any undertightening might cause the inner conductor

to protrude beyond the outer conductor with the consequent risk of damage. On the other hand, over-tightening will damage the screwthreads and the use of any mechanical system to grip the line will almost certainly damage the surface. Good repeatability requires good training and skilled staff.

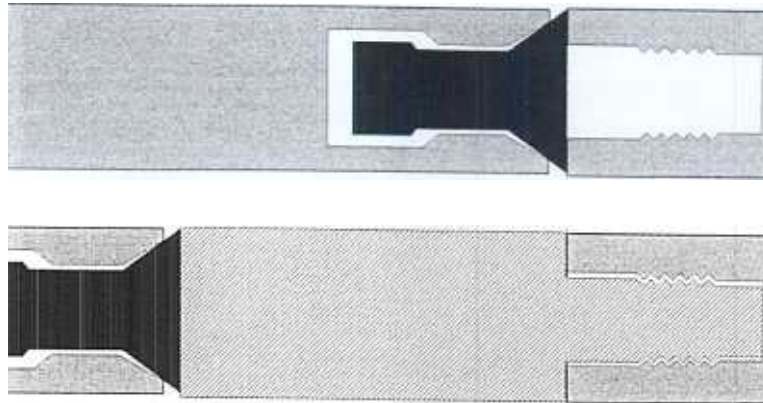


Figure A3. Collet and adaptor arrangement before, and after, inserting a short TRL line.

- 2.3 One of the requirements of the TRL technique is that the 'Reflect' must appear to be identical to the two test ports. If the connector making up port 1 contains a collet and that for port 2 does not then it is impossible for the same item to appear identical on both ports. A better solution is to ensure that the connection made to the 'Reflect' always contains a single collet and this is achieved by using two different short-circuits, one containing a collet and one without.
- 2.4 The problem with the unsupported air lines also concerns arrangements for the inner conductor. There are no supports within the air line and so it relies totally on the connections to the test ports for alignment and support. The ends of the air line contain sprung-loaded 'bullets' with a prong to enable initial support during connection and a tapered section to ensure good alignment. Figure A4. shows a cross-section of one end of an air line inner conductor unconnected and mated with a conventional collet.

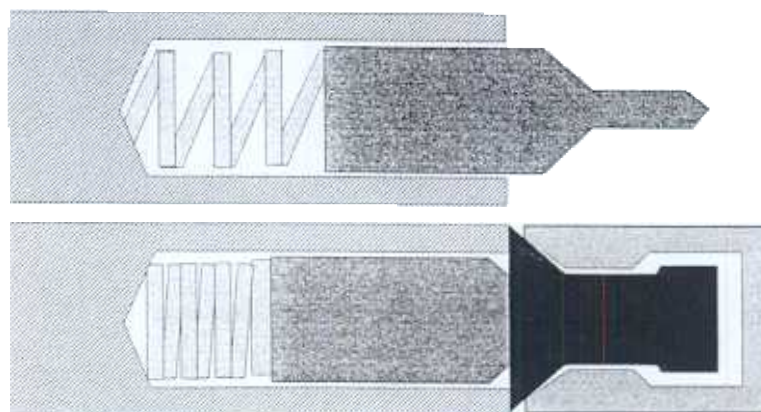


Figure A4. Connecting the unsupported air line to a conventional collet

- 2.5 For connections between an unsupported air line and the special TRL adaptor other arrangements must be made. A special pin/collet assembly has been developed which has a cone to support and align the inner conductor during connection and provides a collet to bridge any gap in the junction. The pin/collet assembly is shown before and after connection in Figure A5.

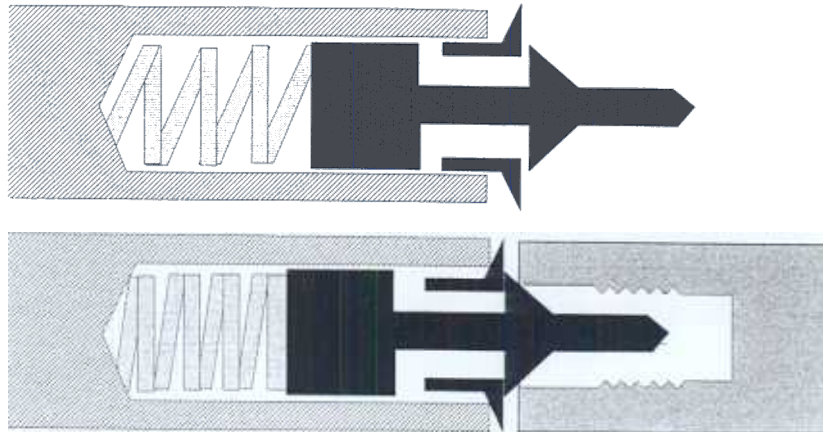


Figure A5. Pin/collet arrangement for the junction between an unsupported air line and the special TRL adaptor.

- 2.6 The final position assumed by the line, in terms of the distribution of the gaps, and the extent of the eccentricity, will depend on the relative strengths of the various collets and the alignment technique. For this reason the repeatability of connection of an unsupported air line is relatively poor.
3. The reason for using an unsupported air line is the simplicity of the traceability to known standards. If the connector effects are ignored then a very simple formula relates the dimensions of the line to the characteristic impedance that the line will present to a wave propagating in a TEM mode along the line. There are small additional effects due to the material of the lines but these effects decrease rapidly with frequency and are not significant for anything but the most accurate requirements. The dimensions are not subject to change in normal circumstances so unsupported air lines provide stable, calculable, and via dimensional metrology, traceable impedance standards which are readily accessible to any standards laboratory.

Appendix B: Copy of instructions for participants.

INTERNATIONAL COMPARISON (GT-RF/83-4) 2-18 GHz S-parameter Measurements

Instructions for Participants

1. INTRODUCTION

This document describes the artefacts to be circulated in International Comparison (GT-RF/83-4) and the connection and measurement procedures to be followed by the participants. Details of the presentation of the measured data to the pilot laboratory and the measurement information are also included.

The measurements required are: all four S-parameters of a number of two-port artefacts, and the reflection coefficients of two one-port items, in the frequency range 2-18 GHz. In the Appendix, a listing of measured results for the items is supplied as an aid to the participants.

2. COMPARISON ORGANISATION

The pilot laboratory for this comparison is the National Physical Laboratory (NPL) based in Malvern, UK. The artefacts have been obtained by this laboratory and have been measured. The comparison will follow a 'rosette' circulation process where the artefacts are returned to the pilot laboratory after each participating laboratory has measured them.

The items are to be collected from NPL, Malvern by a member of the participating laboratory and a date for their return will be agreed which will be no more than four weeks after their collection. The start of this four week period will be agreed between the two laboratories. A member from the pilot laboratory will then collect the items and return them to NPL, Malvern. It is the responsibility of the participating laboratory to obtain the necessary documentation for the return of the items to the UK. This procedure was agreed in a meeting at PTB on 1st/2nd October 1990. These arrangements apply to the laboratories in Europe. Separate arrangements will be made with laboratories outside Europe.

3. ITEMS TO BE MEASURED

Six items are to be measured in this comparison, all of which have 7mm coaxial connectors of either the GPC-7 design or the beadless airline design (which uses sprung contacts on the inner conductors). The items are listed below.

The items are contained in a box in which there is also a spanner for holding the items stationary while the connections are made. The use of a torque wrench (not supplied), set to a level of 12 lb-in or 1.36 N-m, is strongly recommended.

Item No.	Description	Serial Number
	10 dB two-port attenuator	
2	40 dB two-port attenuator	
3	50 Ω beadless airline	
4	25 Ω beadless airline	569
5	50 Ω matched termination	
6	Plain short circuit	

4. CARE AND INSPECTION OF CONNECTORS

Standard procedures concerning the inspection and cleaning of connectors are to be followed as described in the Hewlett Packard Application Note 326, "Coaxial Systems, Principles of Microwave Connector Care". When cleaning the GPC-7 connectors avoid removing the centre collets if at all possible. The items will be cleaned and gauged prior to being sent to each of the participating laboratories. It should not be necessary to dismantle the connectors on any of the items other than the beadless airlines; if a connector is dismantled, the pilot laboratory should be informed when the items are returned.

In some instances, when measuring the beadless airlines, it may be necessary to remove the sprung contact. If this is the case do not handle the centre conductor with bare hands. Wear thin cotton gloves, which provide both thermal insulation and reduce the possibility of dirt or finger grease being deposited on the conductor. Special care must be taken with the airline components. It is possible to remove the dot on each of the centre conductors with solvent cleaners. Please ensure that these marks are NOT removed. The centre conductors may be cleaned with either compressed air or a clean, dry, lint-free cotton swab.

The ports of the measurement system should be rigorously inspected and cleaned before connecting any of the items. The artefacts used to calibrate the measurement system should be treated in the same way.

If in any doubt about the connection of any item please do not hesitate to contact the pilot laboratory.

5. CONNECTION ORIENTATION OF THE ARTEFACTS

A connection orientation has been defined, related to the writing on the two-port items to be measured. When a two-port item is held in the hand with the writing displayed the correct way up (as when reading it), port 1 of the item is the port on the left. For the conventional connection, port 1 of the item should be connected to port 1 of the measurement system so that S11 relates to the reflection coefficient looking into port 1 of the item. For reverse connections, port 2 of the item is connected to port 1 of the measurement system. The test ports to which the one-port items should be connected are specified in Section 6.

When measuring the beadless airlines the centre and outer conductors need to be correctly

assembled. A small black dot on each centre conductor will be found close to the end which is port 1. This should be aligned with port 1 of the outer conductor (identified by the writing on it, as described above). Care must be taken in inserting the centre conductors into the outer conductors to ensure the surfaces are not scratched. Standard connection techniques should be used to connect the airlines to the measurement system.

If an HP 85050C 7mm TRL calibration kit is used to calibrate the system, then certain other actions are necessary. The use of the TRL adaptor, which produces a non-colleted test port, requires that a pin/collet assembly (found in the calibration kit) must be used when measuring the airlines. This replaces the sprung contact assembly at the end of the centre conductor which mates with the TRL adaptor. It has the effect of including a collet into the measurement port, allowing measurements made with identical test ports to be compared to those made with the TRL adaptor in place. It would be preferable, for the sake of compatibility, if the TRL adaptor was connected to port 2 of the measurement system, to maintain consistency across the participants. The use of the pin/collet assembly is described in the manual for the HP 85050C calibration kit.

6. MEASUREMENT CONDITIONS

The general measurement conditions are given in this section. The actual data supplied will be dependent upon the type of system used. The instructions here are orientated towards the use of an HP 8510B or 8510C network analyser.

The maximum frequency range to be covered is 2-18 GHz in integral steps of 250 MHz. This produces up to 65 frequencies. If an ANA is used then internal averaging of 1024 should be used (to reduce the system noise level and improve the repeatability of measurements). The instrument should be situated in an environment with control of temperature and relative humidity. The items should be allowed to stabilise in the laboratory where the measurements are to be made for a period of 1 or 2 days. The exact time necessary for this stabilisation is dependent upon the temperature variation of the items during transit from NPL, Malvern to the laboratory where the items are to be measured. It is important that the items, when transported by air, should be carried as hand baggage to avoid the extreme temperature changes which occur in the hold of an aircraft.

Functions such as electrical delay compensation and/or phase delay should not be used when making the measurements. Sufficient measurements should be taken to obtain consistency. The definition of this condition is dependent upon the uncertainties calculated by the laboratory.

The required connections are listed below. The items are assumed to be connected in the conventional orientation (defined in Section 5) unless otherwise stated.

Item Number	Item Description	Item Orientation
1	10 dB two port attenuator (s/n 19821)	Conventional
	40 dB two-port attenuator (s/n 1685)	Conventional
3	50 Ω beadless airline (s/n 609)	Conventional
4	50 Ω beadless airline (s/n 609)	Reverse
5	25 Ω beadless airline (s/n 569)	Conventional
6	25 Ω beadless airline (s/n 569)	Reverse
7	50 Ω matched termination (s/n 226)	Port 2
8	Plain short circuit	Port 1

7. INFORMATION REQUIRED BY THE PILOT LABORATORY

The pilot laboratory requires three sets of information from the participants: details of the measurement system used, the actual error-corrected results and the associated uncertainties. This section lists the information required and how it should be presented to the pilot laboratory.

(i) The measurement system

This describes the system used and also the environmental parameters which affect the measurements. The following information is required.

Type of measurement system, i.e. commercial network analyser (with the name of the manufacturer) or dual six-port system, etc.

The calibration method used (e.g. TRL, LRL) and the artefacts employed

The test port adaptors used, if any, e.g. waveguide to coaxial or the HP TRL adaptor

The settings of the analyser (if an ANA is used)

The number of measurements averaged to produce the mean measurement values

The temperature and relative humidity of the laboratory in which the measurements were made, with variation limits

(ii) The measurement results

The mean values of each of the four s-parameters (S_{11} , S_{21} , S_{12} , S_{22}) at each frequency for each specified connection are required. This data should be in either real and imaginary format or linear magnitude and phase format. Full uncertainty estimates for each of the mean values supplied, with an explanation of the mathematics involved in calculating the uncertainty limits, are also necessary. The uncertainties are to be quoted for one standard deviation (1σ).

The presentation of the data to the pilot laboratory is an important issue. The format was

discussed at a meeting at LCIE on 2/3rd October 1989. The following points were agreed between the participants.

- (i) All the data is to be sent in the form of ASCII code recorded on magnetic disc. The discs should be either 3.5 inch or 5.25 inch in size and compatible with either an IBM PC type computer or one of the Hewlett Packard 98XX series machines (9836 etc). As an absolute last resort magnetic tapes of the type used with the HP 8510B network analyser would be acceptable, but the data must be in ASCII format.
- (ii) Each disc must have a description of its contents suitable for listing to a printer from a computer.
- (iii) A full paper listing of all the data should also be supplied.

8. SUMMARY

This document has described the process to be followed for the international comparison of two-port s-parameter measurements. The type of information required by the pilot laboratory and the format of the presented data have been listed. The Appendix contains a listing of measured s-parameter data for the items described in this document.

If there are any questions they should be referred to the pilot laboratory, preferably using facsimile transmission facilities if available. The person to contact at the pilot laboratory is

Mr. J.P. Ide
National Physical Laboratory
c/o RSRE, St Andrews Road
Malvern, Worcestershire, UK.
WR14 3PS

Telephone +44-684-894386
Fax +44-684-894540

9. APPENDIX

This ¹Appendix contains listings of the measured s-parameters of the items to be distributed in the comparison. The linear magnitude and phase data is for a single set of measurements, to provide an indication of the responses of the items. An uncertainty assessment has not been included. The data was taken on an HP 8510B network analyser, using the HP 85050C TRL calibration kit (with the TRL adaptor from the calibration kit). The pin/collet assembly included in the TRL calibration kit was employed when measuring the two airlines. Internal averaging in the analyser was set to 1024. The laboratory temperature was 23 Celsius.

The two one-port items were measured as a two-port with zero transmission. The short circuit was connected to port 1 of the measurement system (a colleted test port) and the matched termination was connected to port 2 (the TRL adaptor).

¹ The original appendix contained nominal values for all the items. This NPL report only has the values for the first item as a sample of the layout.

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10 DB TWO-PORT ATTENUATOR (S/N 19821), CONVENTIONAL ORIENTATION

Freq (GHz)	S11		S21		S12		S22	
	Mag.	Phase	Mag.	Phase	Mag.	Phase	Mag.	Phase
2.00	0.0022	-16.65	0.3139	-174.64	0.3140	-174.57	0.0162	-18.50
2.25	0.0014	-48.45	0.3138	163.56	0.3138	163.59	0.0171	-39.40
2.50	0.0007	-109.72	0.3137	141.75	0.3137	141.82	0.0195	-59.63
2.75	0.0014	-147.68	0.3136	119.94	0.3136	119.99	0.0210	-75.11
3.00	0.0027	-172.52	0.3135	98.10	0.3136	98.18	0.0221	-93.98
3.25	0.0037	160.00	0.3134	76.28	0.3136	76.34	0.0237	-111.88
3.50	0.0049	142.39	0.3133	54.44	0.3134	54.51	0.0253	-130.71
3.75	0.0064	120.93	0.3133	32.60	0.3132	32.66	0.0274	-148.90
4.00	0.0075	100.49	0.3133	10.76	0.3133	10.81	0.0287	-165.57
4.25	0.0087	83.30	0.3132	-11.10	0.3133	-11.03	0.0297	176.99
4.50	0.0098	68.38	0.3133	-32.97	0.3133	-32.91	0.0305	159.58
4.75	0.0108	52.20	0.3133	-54.84	0.3133	-54.79	0.0315	142.50
5.00	0.0122	35.92	0.3133	-76.73	0.3133	-76.69	0.0348	125.92
5.25	0.0137	18.72	0.3133	-98.65	0.3134	-98.58	0.0318	109.78
5.50	0.0158	1.23	0.3134	-120.55	0.3134	-120.50	0.0315	93.45
5.75	0.0179	-17.23	0.3136	-142.50	0.3135	-142.42	0.0303	77.61
6.00	0.0202	-36.32	0.3136	-164.44	0.3137	-164.37	0.0288	61.09
6.25	0.0225	-56.10	0.3136	173.58	0.3138	173.65	0.0275	44.87
6.50	0.0252	-75.50	0.3138	151.61	0.3138	151.65	0.0249	29.12
6.75	0.0283	-95.25	0.3140	129.58	0.3138	129.66	0.0221	14.07
7.00	0.0316	-114.05	0.3141	107.58	0.3140	107.65	0.0190	-0.60
7.25	0.0352	-132.94	0.3141	85.50	0.3142	85.58	0.0157	
7.50	0.0388	-151.90	0.3142	63.42	0.3142	63.52	0.0123	
7.75	0.0426	-170.99	0.3143	41.34	0.3143	41.42	0.0093	
8.00	0.0462	170.08	0.3144	19.25	0.3144	19.32	0.0055	
8.25	0.0495	151.65	0.3145	-2.89	0.3145	-2.81	0.0025	-42.99
8.50	0.0521	133.39	0.3146	-25.04	0.3146	-24.95	0.0021	25.08
8.75	0.0541	115.29	0.3147	-47.22	0.3146	-47.12	0.0042	32.16
9.00	0.0558	97.09	0.3148	-69.40	0.3148	-69.33	0.0074	23.83
9.25	0.0570	78.94	0.3149	-91.63	0.3148	-91.56	0.0102	10.12
9.50	0.0573	60.52	0.3150	-113.89	0.3149	-113.81	0.0121	-3.28
9.75	0.0568	41.56	0.3151	-136.17	0.3150	-136.08	0.0154	-23.11
10.00	0.0558	22.57	0.3151	-158.49	0.3152	-158.39	0.0182	-43.31
10.25	0.0539	3.05	0.3152	179.18	0.3152	179.27	0.0218	
10.50	0.0521	-17.60	0.3152	156.81	0.3152	156.88	0.0259	
10.75	0.0499	-38.14	0.3152	134.42	0.3152	134.50	0.0298	
11.00	0.0477	-59.79	0.3153	111.99	0.3152	112.07	0.0354	-126.11
11.25	0.0454	-82.19	0.3153	89.51	0.3153	89.61	0.0409	-145.75
11.50	0.0433	-105.75	0.3154	67.00	0.3153	67.09	0.0467	-164.42
11.75	0.0419	-128.69	0.3153	44.46	0.3153	44.55	0.0537	
12.00	0.0410	-152.14	0.3153	21.89	0.3152	21.98	0.0603	
12.25	0.0404	-174.37	0.3151	-0.71	0.3152	-0.64	0.0672	
12.50	0.0400	164.58	0.3150	-23.37	0.3150	-23.28	0.0740	
12.75	0.0394	143.81	0.3149	-46.07	0.3149	-45.94	0.0809	
13.00	0.0395	123.96	0.3147	-68.81	0.3147	-68.69	0.0872	86.55
13.25	0.0392	104.90	0.3144	-91.57	0.3143	-91.49	0.0922	69.79
13.50	0.0379	85.37	0.3138	-114.41	0.3139	-114.31	0.0979	52.98
13.75	0.0354	64.47	0.3127	-137.24	0.3126	-137.14	0.1019	35.61
14.00	0.0301	45.95	0.3121	-159.88	0.3116	-159.79	0.1055	18.97
14.25	0.0250	31.40	0.3122	177.41	0.3119	177.53	0.1087	
14.50	0.0215	18.61	0.3125	154.55	0.3124	154.68	0.1106	
14.75	0.0173	5.16	0.3129	131.62	0.3129	131.73	0.1087	
15.00	0.0124	-6.76	0.3133	108.59	0.3132	108.72	0.1095	
15.25	0.0078	-12.03	0.3137	85.51	0.3136	85.66	0.1060	
15.50	0.0037	-2.30	0.3140	62.36	0.3138	62.51	0.1000	-87.24
15.75	0.0041	66.08	0.3143	39.17	0.3140	39.30	0.0953	-106.61
16.00	0.0084	67.21	0.3145	15.88	0.3145	16.03	0.0865	-124.61
16.25	0.0133	59.56	0.3146	-7.45	0.3145	-7.30	0.0809	
16.50	0.0177	42.47	0.3149	-30.84	0.3147	-30.67	0.0711	
16.75	0.0224	24.08	0.3150	-54.30	0.3147	-54.17	0.0604	
17.00	0.0263	1.32	0.3150	-77.83	0.3147	-77.66	0.0514	
17.25	0.0304	-22.59	0.3151	-101.42	0.3150	-101.26	0.0406	153.82
17.50	0.0347	-47.01	0.3151	-125.00	0.3148	-124.90	0.0292	142.38
17.75	0.0396	-73.15	0.3150	-148.71	0.3148	-148.58	0.0208	149.72
18.00	0.0456	-98.90	0.3148	-172.44	0.3146	-172.35	0.0184	174.14