

# ANAMET REPORT

ANAMET Report 002

September 1996

Draft EAL Procedure for the Assessment  
of Vector Network Analysers (VNA)

R N Clarke, J P Ide, G R Orford & N M Ridler

ANAMET reports are produced by, and for, the members of ANAMET. They are intended for fast dissemination of technical information for discussion purposes and do not necessarily represent an official viewpoint. No responsibility is accepted by the author(s) or ANAMET for any use made of the information contained in this report.

Comments on this report should be sent to:

ANAMET  
PO Box 92  
Malvern  
United Kingdom  
WR14 3YS

Extracts from this report may be reproduced  
provided that the source is acknowledged.

*This report has been approved by the ANAMET Steering Committee.*

DRAFT EAL PROCEDURE FOR THE ASSESSMENT OF  
VECTOR NETWORK ANALYSERS (VNA)

**Foreword**

This report contains a draft version of a procedure for the assessment of an ANA (including evaluating the uncertainties). The draft has been under development for a substantial period of time with contributions coming from several working groups resulting in the current version of the document. In particular, the UK's ANA Traceability Working Party and, more recently, the EAL HF Experts Group. (EAL stands for European cooperation for Accreditation of Laboratories.)

The eventual aim is to publish the document as part of the EAL series of publications. The current draft is being circulated for public comment within Europe. We felt that the members of ANAMET would want to know about such an important document so we are issuing it as this ANAMET Report.

It should be emphasised that this document must be considered as a draft version. We thank all persons, past and present, who have contributed to the evolution of the document into its present state and welcome any comments, opinions and suggestions that will advance the development of this procedure.

*Bob Clarke* NPL, Teddington  
*Jezz Ide* NPL, Malvern  
*Geoff Orford* UKAS, Teddington  
*Nick Ridler* NPL, Malvern

September 1996



**DRAFT PROCEDURE FOR THE ASSESSMENT OF  
VECTOR NETWORK ANALYSERS (VNA)**

**Contents:**

1. Introduction
2. Documentation
3. Reference Standards
4. Uncertainty assessment for Reflection Measurements
5. Uncertainty assessment for Transmission Measurements
6. Calculation of Uncertainties
7. Examples of Uncertainty Budgets

**1. Introduction:**

This document describes the measurement procedures which are normally to be carried out for an assessment of VNAs to meet the requirements of accreditation against EN54001. The principles given in this document apply to any frequency range for which VNAs can be used and to any transmission medium, however, some of the techniques given for the assessment of uncertainties are only applicable to coaxial lines at frequencies above 500 MHz. The procedures specifically apply to measurements in coaxial line fitted with the following connectors having mating surfaces conforming to the relevant IEC 457 Recommendation or to the IEEE Draft Standard P287, The procedure may have to be modified for other types of connector:

Line Diameter	Connector
14 mm	GR 900 (or equivalent)
7 mm	Type-N (precision N)
7 mm	APC 7 (or equivalent)
3.5 mm	APC 3.5

Whilst the calibration of a VNA must, by definition, cover phase as well as magnitude capabilities, the uncertainties produced using this document are only applicable to magnitude quantities.

**2. Documentation**

The laboratory should conform to the normal requirements of accreditation with respect to procedure documents that describe the calibration and use of the VNA, this should include at least the following:

- General description of equipment
- List of reference standards and ancillary equipment
- Operating instructions (reference to manufacturer's documents)
- Method of calibration (reference to this document)
- Uncertainty analysis and uncertainty budgets
- Precautions for connector use
- Requirements for environmental conditions
- Other precautions to be taken

### 3. Reference Standards

A number of standards will be required as follows:

#### 3.1 Calibration Kit

At least one calibration kit will be required for each connector type. The calibration kit supplied by the manufacturer will normally suffice. The calibration kit or kits used must be specified and uniquely identified in the procedure document. Each kit should contain a good short-circuit standard capable of supporting the inner-conductor of a beadless reference air line.

#### 3.2 A set of Beadless Airlines:

At least one beadless reference airline will be required for each type of connector, with appropriately dimensioned contacts at each end. The nominal length of the airline should be between 100mm and 300mm. Its physical dimensions should be recorded, together with their estimated uncertainties, after measurement by a method which is traceable to national standards. The relevant dimensions are;

- a) the length between the mating faces of the outer conductor
- b) the length of the inner conductor, [for sexless connectors this should be measured from end to end. The reference surface for measurement of a female contact should be its end. That for a male contact should be the shoulder formed at the nominal inner-conductor diameter]
- c) the average outer diameter of the inner-conductor
- d) the average bore diameter of the outer-conductor.

A beadless airline supplied as part of a VNA manufacturer's verification kit may be used if its dimensions are suitably certified.

#### 3.3 A calibrated step attenuator or a set of fixed attenuators

These are used to verify the linearity of the VNA with respect to the national standard for RF attenuation. A series of fixed attenuators can be used for this purpose, eg 3, 6, 10, 20, 30, 30 dB attenuators can be used to generate steps up to 90 dB or higher. However, a step attenuator will generally provide a more repeatable measurement, particularly if a programable attenuator is used. The attenuator need not normally be calibrated at more than one frequency, although traceability to national standards will be required at this frequency. Its purpose is to check the linearity of both channels of the VNA by carrying out full-two-port calibrated  $s_{21}$  and  $s_{12}$  measurements. The measurements are normally carried out

at one frequency in the range of approval. The frequency should be toward the bottom end of the frequency range where the attenuator has better repeatability, normally below 100 MHz for a VNA with 45 MHz to 18 GHz frequency range. The attenuator, or attenuators should be capable of covering the full dynamic range for which accreditation is sought.

### 3.4 A traceability kit

The purpose of this kit is to demonstrate traceability to national standards on a continuing basis. The contents of this kit will have to be agreed with the accreditation body. For one connector type for which accreditation is sought, a kit similar to a manufacturer's verification kit will be needed, augmented by additional components. These additional components will comprise at least one fixed attenuator and at least one broadband mismatch, both to be measured at a number of frequencies covering the accredited frequency range. For subsequent connector types a kit similar to a VNA manufacturer's verification kit will suffice.

## 4. Uncertainty assessment for Reflection Measurements, $U_{VRC}$

For measurements of  $s_{11}$  and  $s_{22}$  the error model for a VNA can be represented using only the major error terms as follows:

$$U_{VRC} = D + T\Gamma + M\Gamma^2 + R_{VRC}$$

where:

$\Gamma$	is the Measured Voltage Reflection Coefficient
$D$	is the Measured Effective directivity
$T$	is the Estimated Tracking and Linearity
$M$	is the Measured Effective Test Port Match
$R_{VRC}$	represents all the Random effects

The above expression is not intended as a definitive model of all the error terms. The values for the terms are not used as corrections, ie they all have an assumed value of zero, but for each one there will be an associated uncertainty. These uncertainties should be based on measured data where this is possible and other sources, such as the manufacturer's specification, where measurements cannot provide a good estimate of the uncertainty. The random contributions will include at least the following:

- System repeatability (Resolution)
- System repeatability (Noise)
- Connector repeatability
- Effects of cable flexure
- Effects of ambient conditions

*The term effective, as in effective directivity, is used to denote the residual directivity after a full calibration of the relevant ports using the specified calibration kit has been carried out.*

The following procedures can be used to obtain data on the above uncertainty contributions;

### 4.1 Measurement of Effective directivity

First dimensionally check and clean all connectors to be used.

Calibrate the VNA in accordance with the procedure document for  $s_{11}$  measurements across the full frequency range of accreditation. Use 200 or more frequency points. Check that the calibration is valid by measuring a previously known standard. Connect the traceable beadless airline to the measurement port and terminate it with a suitable "matched" load (a load with Voltage Reflection Coefficient (VRC) in the range 0.1 to 0.2 is most suitable). Make a measurement of  $s_{11}$  and display 'linear' magnitude against frequency on the VNA screen. Use 'autoscale' or some other means to provide suitable axis scaling.

The display should show a discernable sinusoidal 'ripple' superimposed on the VRC plot of the load itself, see fig 1. Compute the effective directivity the effective directivity,  $D$ , as a function of frequency from the magnitude of the ripple:

$$D = \frac{\text{Maximum Ripple Amplitude}}{2}$$

The maximum ripple amplitude should be obtained from adjacent peaks and troughs with adjustment made for any slope caused by the variation with frequency of the VRC of the terminating load. A technique can be used to remove the effect of the load so that the ripple, caused by the interaction of the phases between the directivity component and the load, can be displayed or plotted by itself. This will produce a plot that makes the measurement of the ripple amplitude much easier, however, if such a technique is used plots with and without the load VRC should be retained. The plot gives some indication of the variation of effective directivity with frequency and will normally show a worse directivity at the higher frequencies. More discrimination, ie more ripples, will be obtained in proportion to the length of the airline, a 300mm airline will give ripples with a period of 500 MHz and a 100 mm line 1500 MHz. The line length will clearly limit the lowest frequency at which a meaningful result can be obtained, it should be possible to make a reasonable estimate of the effective directivity at frequencies down to 1 GHz using a 300 mm airline. For purposes of assigning a value for  $D$  it is recommended that the frequency range is not subdivided into more than three ranges, eg 1GHz - 8 GHz.; 8 GHz - 12 GHz; 12 GHz - 18 GHz.

Repeat the procedure for  $s_{22}$  and for other connector types where appropriate.

The procedure may be repeated with other airlines to check for consistency and should in any case be repeated several times using the same airline both with and without performing the VNA calibration procedure so that a good estimate can be made of the random variations in the value for effective directivity.

The effective directivity should normally be in the range 0.002 to 0.02 (-54 dB to -34 dB)

#### 4.2 Measurement of Effective Test Port Match

This procedure is identical to 4.1 except that the short circuit (section 3.1) is used in place of the matched load to terminate the airline.

In this case the VNA display (again in linear magnitude mode, after suitable scaling) should show that the loss of the line increases regularly with frequency, but superimposed upon this there will be a ripple which typically increases in amplitude with frequency (though not necessarily monotonically) with frequency, see fig 2.

Compute the 'effective test port match' ,  $M$ , as a function of frequency from the magnitude of the ripple:

$$M = \frac{\text{Maximum Ripple Amplitude}}{2} - D$$

It is necessary to subtract the effective directivity,  $D$  since the ripple obtained for this measurement will include both effects. It is only possible to obtain an approximate value for  $M$  applicable to the complete frequency range. However, since the uncertainty due to test port match is obtained by multiplying by  $\Gamma^2$  its effect will only be apparent when measuring relatively large values of  $\Gamma$ .

Repeat the procedure for  $s_{22}$  and for each connector type covered by the accreditation.

#### 4.3 Measurement of linearity

The uncertainty due to linearity is obtained from the procedures given in 5.1

#### 4.4 Tracking

It is considered that the effect on the overall uncertainty for reflection measurements caused by imperfect tracking between the incident and reflected signals will be relatively small and it is generally satisfactory to use the manufacturer's value for this contribution.

#### 4.5 System repeatability

The system repeatability can be divided between repeatability using the same calibration and repeatability after recalibration. Test should be conducted to determine the standard deviation of a series of readings using the same calibration without reconnecting the device being calibrated. This test gives a measure of the basic repeatability due to resolution and noise of the system and should be performed for several values of reflection coefficient at a number of frequencies, the internal averaging figure used must be recorded. Tests should also be made of the typical repeatability after recalibration, again this should be performed at a several values of reflection coefficient and several frequencies.

#### 4.6 Connector Repeatability

The test described in 4.5, when a recalibration is performed, will include contributions from connectors on the test ports and the calibration standards and it is difficult to separate out these effects. Normally the item being calibrated will be the dominant contribution to connector repeatability, however, it will not always be practical to make repeat measurement on this device, although this is recommended. One approach is to make a series of measurements of "typical" devices by simply reconnecting the device without a recalibration and to use the standard deviation of these results as a basis for estimating a global figure for connector repeatability. Separate assessments will be required for different connector types and over a range of frequencies. The more devices that are used for this assessment the more reliable will be the estimate of the uncertainty and it is recommended that this data is added to on a continuing basis.

#### 4.7 Cable Flexure

Where cables are used to connect to the device being calibrated there is a possibility of errors if the cable is moved after the calibration has been performed. A series of repeat measurements should be undertaken to determine the change in readings when only the cable position is changed in a defined way, eg bend through an angle of 90°. It is important to describe and record the way the cable position is changed so that the measurements can be repeated at a later date. Several typical cable positions should be assessed so that a global figure for the uncertainty can be assigned, the measurement should be performed over the accredited frequency range.

#### 4.8 Ambient Conditions

Ideally VNAs should be operated in typical laboratory conditions, eg 18°C to 25°C and RH 20% to 60% and if this is the case the manufacturer's specification can be used as a basis for estimating this uncertainty. Other than the contribution of the device being calibrated, which will have to be assessed at the time of measurement, the most sensitive devices are probably the airlines used in the calibration process but provided they are used within the above conditions their contribution will be negligible. It is often rapid changes in ambient temperature that can effect results, especially if there is significant changes between when the calibration is performed and when the device is calibrated, and this should be taken into account when assessing the uncertainty due to ambient conditions.

### 5 Uncertainty assessment for Transmission Measurements $U_{TM}$

For measurements of  $s_{12}$  and  $s_{21}$  the error model for a VNA can be represented using only the major error terms as follows:

$$U_{TM} = L + M_{TM} + I + R_{dB}$$

where:

$L$	is the measured System Linearity
$M_{TM}$	is the calculated Mismatch
$I$	is the estimated or measured Isolation
$R_{dB}$	represents all the Random effects

As with reflection measurements, the above expression is not the definitive error model but indicates how the major terms contribute to the uncertainty. Contributions should be based on measured results wherever possible. The random contributions will be from similar sources as reflection measurements:

- System repeatability (Resolution and Noise)
- Connector repeatability
- Effects of cable flexure
- Effects of ambient conditions

#### 5.1 Measurement of Linearity

The VNA should be calibrated according to the accredited procedure for  $S_{21}$  measurements. The procedure then consists of measuring the step attenuator, separate attenuators (para 3.3), at the frequency for which traceability to national

standards has been established, with reference to the zero setting of the attenuator. No other attenuators should be included in the circuit and the source level should be set to the level specified in the measurement procedure, this is to ensure that the level at the detectors approximately as it would be for normal measurements. It is recommended that results are obtained at not greater than 5 dB increments over the range for which accreditation is required and, if possible, at 10 dB greater than this range, eg if the accredited range is 0-70 dB results for the range 0-80 dB should be obtained. It is important that random effects are minimised therefore the results should be obtained from a sufficient number of repeat measurements, particularly at the high levels of attenuation. The internal averaging figure should be at least 1024

It is not normal practice to correct for the linearity errors in VNAs and the results obtained from the above measurements provide an estimate of the uncertainty that should be assigned to this contribution, in the form  $\Delta\text{dB}/\text{dB}$ . A plot of the difference between the VNA result and the calibration value against the reference attenuator value is the recommended method for estimating a reliable figure for the linearity uncertainty. The linearity should be assessed from the results between 0 dB and 50dB since beyond this setting the effects of imperfect isolation will contribute to the errors. The results above 50 dB can be used to assess the effects of imperfect isolation.

## 5.2 Mismatch

There will be an uncertainty due to mismatch arising from the residual source and load reflection coefficients and the input and output reflection coefficients of the item being measured, this is obtained from:

$$M_{TM} = 20 \log_{10} \frac{1 \pm [ |M s_{11}| + |\Gamma_L s_{22}| + |M \Gamma_L s_{11} s_{22}| + |M \Gamma_L s_{12} s_{21}| ]}{1 \pm |M| |\Gamma_L|}$$

where: M is the Effective Test Port Match  
 $\Gamma_L$  is the Effective Load Reflection Coefficient  
 $s_{11}, s_{22}, s_{12}, s_{21}$  are the Scattering coefficient of the device being measured.

The Effective Load Reflection Coefficient can be assumed to be equal to the Effective Directivity obtained using the procedure in section 4.1.

## 5.3 Isolation (Crosstalk)

The effects of imperfect isolation between the two ports can be based on the manufacturer's specification figure but this should be checked using the step attenuator linearity test results at readings above 50 dB. The isolation uncertainty will not be a linear function of the measured attenuation and can be calculated for each measured value of attenuation. However, it is usually more convenient to express the uncertainty as a linear function of the measured attenuation, broken down into ranges of say 5dB eg, an isolation of 90 dB will give the following approximate uncertainties:

60dB to 65dB	±0.48dB
65dB to 70dB	±0.83dB
70dB to 75dB	±1.42dB
75dB to 80dB	±2.39dB

The effects of isolation will vary with frequency therefore measurements should be made at different frequencies over the accredited range, using attenuators with adequate isolation, in order to check the validity of the manufacturer's specification figures.

#### 5.4 System repeatability (resolution)

As 4.5

#### 5.5 System repeatability (noise)

The contribution from noise will have a relatively greater impact on transmission measurements and should therefore be assessed for this parameter. The contribution from system noise can be assessed using the step attenuator by making a series of measurements at various levels of attenuation, without recalibration. The uncertainty is obtained from the standard deviation of these repeat measurements and should be assessed at different internal averaging settings. The noise contribution will be dependent on the level of signal reaching the detector and will therefore be dependent on source level and attenuator setting, it is therefore important that these values are recorded. The noise contribution will change significantly with frequency due mainly to the reduction in available signal level at the detectors as the frequency increases. The effects of noise must therefore be evaluated at various frequencies over the range of operation.

### 6 Calculation of Uncertainty

The uncertainty contributions should be combined in accordance with EAL recommendations to provide an expanded uncertainty based on a coverage factor of  $k = 2$  (a level of confidence of approximately 95%). The following points should be considered:

- While most of the contributions can be considered as being uncorrelated there is a possibility that the effective directivity and effective test port match will be correlated to some extent, due to common factors in the calibration process for a VNA. It is beyond the scope of this document to provide guidance for the evaluation of the likely correlation coefficients of these contributions and it has not been possible to find any references for such work. It is therefore recommended that, in the absence of reliable information, a correlation coefficient of +1 is assumed, which means that the uncertainty contributions for directivity and test port match should be added together before being combined with the other contributions in the usual manner, ie root-sum-of-squares.
- The contributions that are dependent on the relative phase of two vectors, such as directivity and test port match will have a probability distribution that is U-shaped in form. The standard uncertainty for these contribution is obtained by dividing the limit value by  $\sqrt{2}$ . However, when making transmission measurements, the uncertainty contribution calculated using the expression given in 5.2 above will be the combination of three U-shaped

contributions and it is recommended that a rectangular probability distribution is assumed for this contribution. A normal distribution can be assumed for the uncertainties derived from measured data (type A evaluations). It is recommended that a rectangular distribution is assumed for the effects of ambient conditions and manufacturer's data, unless there is evidence that the distribution is normal. The choice of the form of the probability distribution for the smaller contributions will, in general, have little effect on the expanded uncertainty and it is therefore not necessary to make a detailed study of the likely probability distribution for these contributions.

## 7 Example Uncertainty Budgets

The uncertainty budgets given in this document are not intended to imply any mandatory requirement. They provide guidance on what would be expected for the general approach to documenting the uncertainties derived from using the methods given in this document. These examples do not cover the complete capability of typical VNAs.

### 7.1 Reflection Measurements (magnitude of voltage reflection coefficient )

Frequency range = 1 GHz to 18 GHz  
 VRC range = 0 to 0.2  
 Effective directivity = 0.01  
 Effective test port match = 0.01

Contribution	Estimate	Uncertainty for VRC =0.2	Distribution	Divisor	Standard Uncertainty
Effective Directivity	0.01	0.01	U-shaped	$\sqrt{2}$	0.0071
Effective Test Port Match	0.01	0.0004	U-shaped	$\sqrt{2}$	0.0002
Sum of correlated quantities		0.0104	U-shaped	$\sqrt{2}$	0.0073
Tracking and Linearity	0.02	0.004	Rectangular	$\sqrt{3}$	0.0023
System Repeatability	0.005	0.005	gaussian	1	0.005
Cable Flexure	0.002	0.002	gaussian	1	0.002
Ambient Conditions	0.002	0.002	rectangular	$\sqrt{3}$	0.001
Connector Repeatability	0.005	0.005	gaussian	1	0.005
Combined Standard Uncertainty					0.011
Expanded Uncertainty ( $k = 2$ )					0.021

## 7.2 Reflection Measurements (magnitude of voltage reflection coefficient)

Frequency range	= 18 GHz to 26.5 GHz
VRC range	= 0.6 to 0.8
Effective directivity	= 0.015
Effective test port match	= 0.02

Contribution	Estimate	Uncertainty for VRC =0.8	Distribution	Divisor	Standard Uncertainty
Effective Directivity	0.015	0.015	U-shaped	$\sqrt{2}$	0.0106
Effective Test Port Match	0.02	0.0128	U-shaped	$\sqrt{2}$	0.009
Sum of correlated quantities		0.0278	U-shaped	$\sqrt{2}$	0.0196
Tracking and Linearity	0.02	0.016	Rectangular	$\sqrt{3}$	0.0023
System Repeatability	0.005	0.005	gaussian	1	0.005
Cable Flexure	0.004	0.004	gaussian	1	0.004
Ambient Conditions	0.002	0.002	rectangular	$\sqrt{3}$	0.001
Connector Repeatability	0.01	0.01	gaussian	1	0.01
Combined Standard Uncertainty					0.025
Expanded Uncertainty ( $k = 2$ )					0.050

## 7.3 Transmission Measurements (Attenuation magnitude)

Frequency range	= 100 MHz to 8 GHz
Attenuation range	= 0 dB to 20 dB
Linearity	= 0.002 dB / dB
Effective isolation	= 90 dB
Effective source match	= 0.01 VRC
Effective load match	= 0.01 VRC
s11 and s22	= 0.05 (maximum)

Contribution	Estimate dB	Uncertainty for 20dB	Distribution	Divisor	Standard Uncertainty dB
Linearity	0.002 dB/dB	0.04	gaussian	2	0.02
Mismatch	0.01	0.01	rectangular	$\sqrt{3}$	0.0058
Isolation	0.0	0.0	rectangular	$\sqrt{3}$	0.0
System Repeatability	0.001	0.001	gaussian	1	0.001
Noise	0.002	0.002	gaussian	1	0.002
Cable flexure	0.005	0.005	gaussian	1	0.005
Ambient Conditions	0.002	0.002	rectangular	$\sqrt{3}$	0.0011
Connector Repeatability	0.01	0.01	gaussian	1	0.01
Combined Standard Uncertainty					0.024
Expanded Uncertainty ( $k = 2$ )					0.048

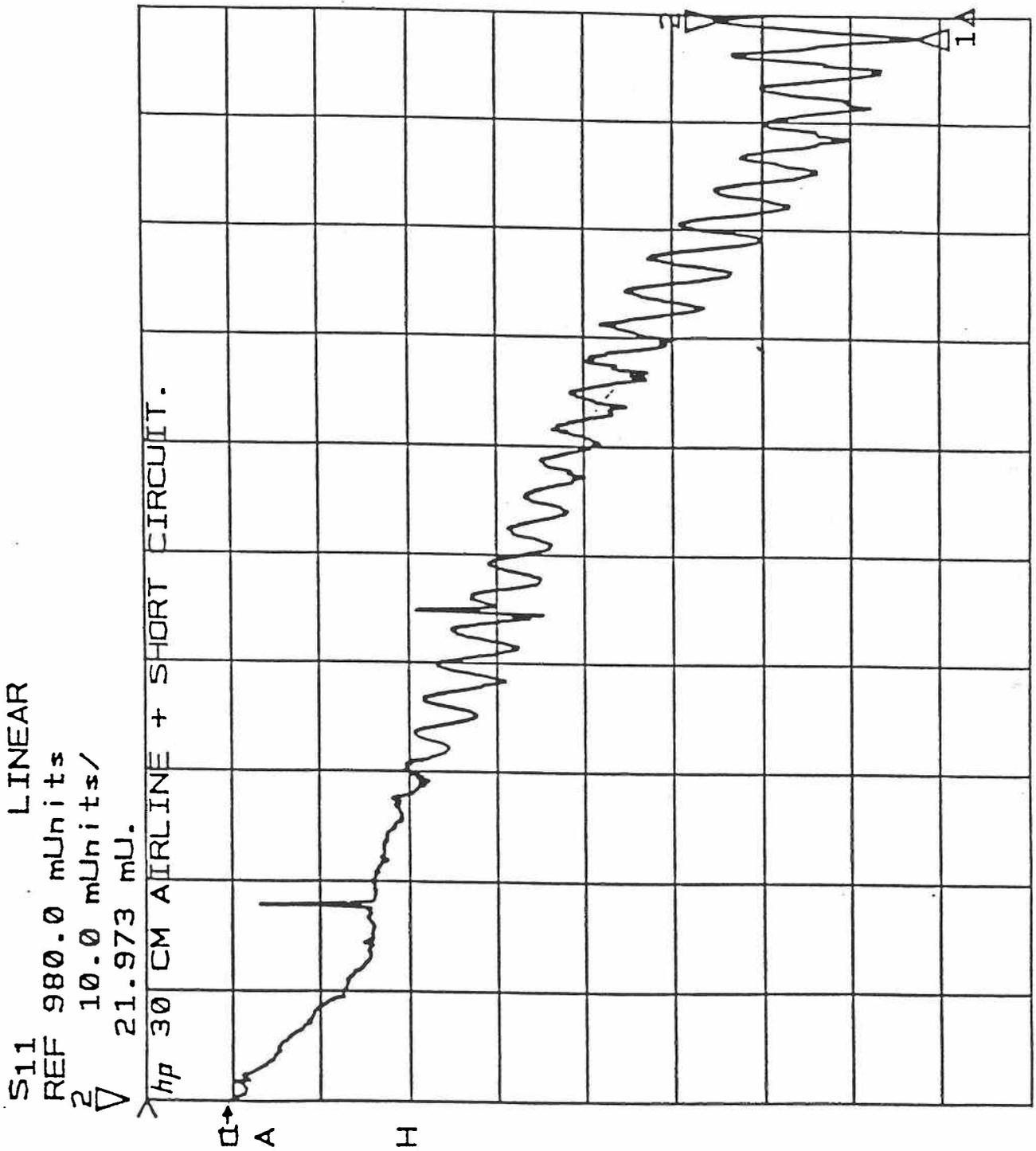
## 7.4 Transmission Measurements (Attenuation magnitude)

Frequency range	= 8 GHz to 18 GHz
Attenuation range	= 60 dB to 70 dB
Linearity	= 0.002 dB / dB
Effective isolation	= 90 dB
Effective source match	= 0.01 VRC
Effective load match	= 0.01 VRC
s11 and s22	= 0.05 (maximum)

Contribution	Estimate dB	Uncertainty for 70dB	Distribution	Divisor	Standard Uncertainty dB
Linearity	0.002 dB/dB	0.14	gaussian	2	0.07
Mismatch	0.01	0.01	rectangular	$\sqrt{3}$	0.0058
Effective Isolation	0.83	0.83	rectangular	$\sqrt{3}$	0.479
System Repeatability	0.001	0.001	gaussian	1	0.001
Noise	0.05	0.05	gaussian	1	0.02
Cable flexure	0.005	0.005	gaussian	1	0.005
Ambient Conditions	0.01	0.01	rectangular	$\sqrt{3}$	0.0058
Connector Repeatability	0.01	0.01	gaussian	1	0.01
Combined Standard Uncertainty					0.487
Expanded Uncertainty ( $k = 2$ )					0.97



hp APC-7 CONNECTORS.



START 2.00000000 GHz  
STOP 18.00000000 GHz

