LA19-13-02 3 GHz VNA
CALIBRATION AND MEASUREMENT UNCERTAINTY

Nils Nazoa
LA Techniques Ltd

Nick Ridler
National Physical Laboratory
Teddington, UK

Contents

1 INTRODUCTION

This application note covers the calibration procedure and measured uncertainty of the LA19-13-02 VNA using the optional economy calibration kits (part numbers DW96634 iss. 2 and DW96635 iss. 2) that enable the VNA to be calibrated in the 2.92 mm line size. Each kit is made up of a set of standards and adaptors. Table 1 shows the details.

Table 1 Economy calibration kits

Male Cal Kit DW96634 used to calibrate female 2.92 mm test ports	Female Cal Kit DW96635 used to calibrate male 2.92 mm test ports
1 x Load standard (male) 1 x Short-circuit standard (male) 1 x Open-circuit standard (male) 1 x Through adaptor 1 x Load and Through calibration data 1 x N(male) to 2.92 mm (male) adaptor 1 x N(male) to 2.92 mm (female) adaptor	1 x Load standard (female) 1 x Short-circuit standard (female) 1 x Open-circuit standard (female) 1 x Through adaptor 1 x Load and Through calibration data 1 x N(male) to 2.92 mm (female) adaptor 1 x N(male) to 2.92 mm (male) adaptor

2 PRINCIPLE OF OPERATION

Reflection and transmission measurements using a non-perfect VNA system can be represented as shown in Fig. 2.1. In this, the system is represented by an ideal measurement system to which the device under test (DUT) is connected through 'error' networks. The latter represent the imperfections associated with the system.

There are two sets of errors. One for forward measurements and another for reverse measurements. There are a total of 12 error terms and they may be represented as follows:

Forward Measurements

E_D: Directivity error
E_S: Source match error
E_{RT}: Reflection tracking error
E_{TT} : Transmission tracking
E_L: Port 2 match
E_X: Leakage

Reverse Measurements

E_D': Reverse directivity error
E_S': Reverse source match error
E_{RT}': Reverse reflection tracking error
E_{TT}': Reverse transmission tracking
E_L': Port 1 match
E_X': Reverse leakage

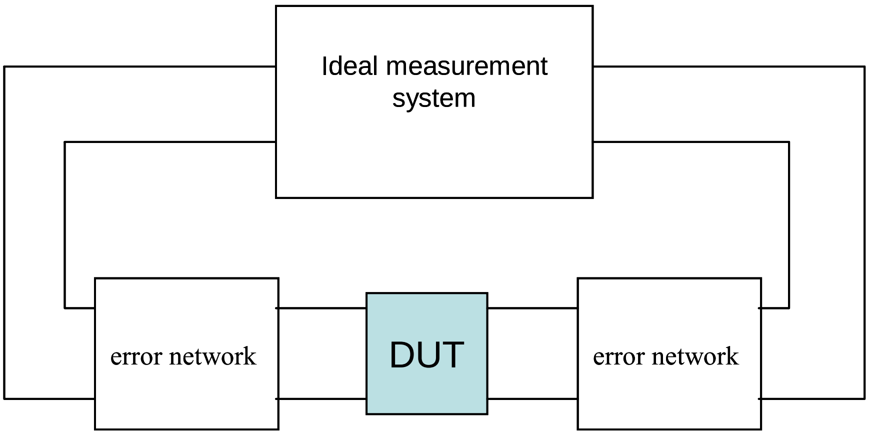

Figure 2.1 Representation of the VNA measurement set up

The error terms can be calculated by, first connecting three components (i.e. standards) with known reflection coefficients, Γ, on ports 1 and 2. This step allows the reflection terms to be calculated. Typically, an open-circuit, short-circuit and matched load are used as the known devices. This approach is the conventional open-short-load (OSL) calibration technique and is supported by the LA19-13-02 VNA. The final step in the calibration is to connect ports 1 and 2 together. This allows the remaining error terms to be calculated.

Typically, with an OSL calibration the matched load is assumed perfect, i.e. $\Gamma = 0$. Consequently any load imperfection directly impacts on the accuracy of the calibration. Therefore, a very low reflection coefficient load must be used. This requirement usually means the use of an expensive load.

In order to circumvent the expense of a very low reflection coefficient load, the approach adopted here is to accurately measure the reflection coefficient of each calibration kit matched load at the factory. This measured reflection coefficient data is then used by the calibration software instead of the usual assumption of $\Gamma = 0$.

In addition to using the load's measured reflection coefficient data, the open-circuit capacitance is modelled using the following polynomial:

$$C_{open} = C_o + C_1 Freq + C_2 Freq^2 + C_3 Freq^3$$

The polynomial describes the open-circuit capacitance as a function of frequency.

3 USING THE CALIBRATION KIT

3.1 Selecting which cal kit(s) to use

Measuring Insertable Devices

Figure 3.1 shows a typical arrangement for measuring insertable devices. In order to complete the calibration one female and one male calibration kit are needed.

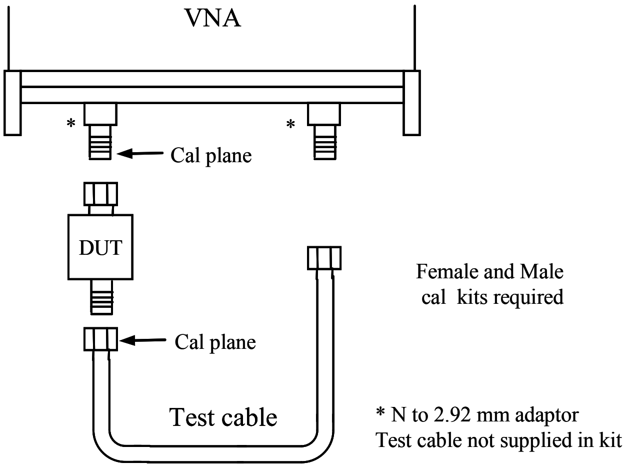

Figure 3.1: Possible arrangement for measuring an insertable device. For best performance use a test cable with 2.92 mm connectors.

Measuring Non-Insertable Devices

In this case, a single calibration kit is needed. Figure 3.2 show some possible arrangements. If the device under test has female connectors, then a female kit is required. On the other hand, a male kit is needed if the device has male connectors.

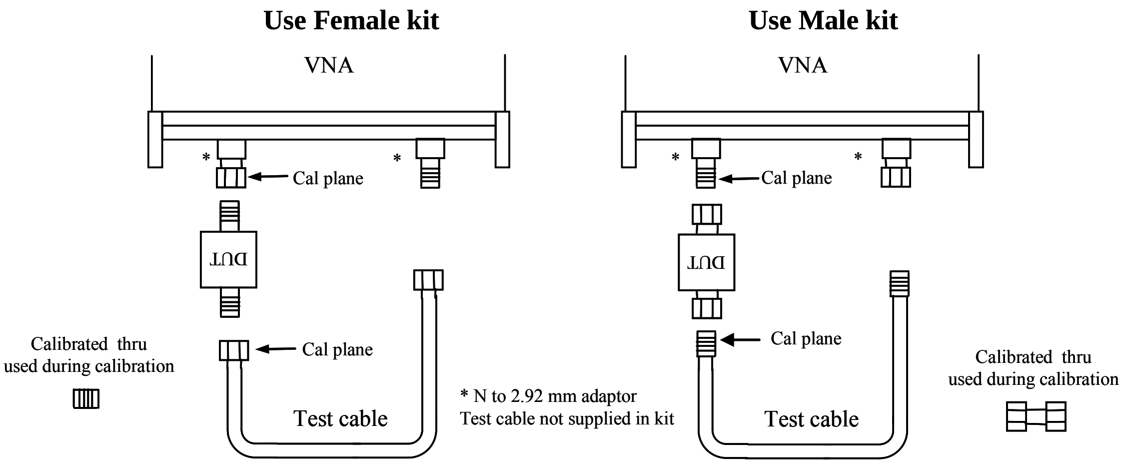

Figure 3.2: Possible DUT arrangements when measuring non-insertable devices. For best performance use a test cable with 2.92 mm connectors.

The calibration kits are provided with a calibrated through adaptor. This should only be used during the calibration procedure for the 'connect through' step. Using any other adaptor during this step is likely to lead to calibration errors.

3.2 The cal kit parameters window

The calibration kits are supplied with measured data as described in the previous section. The calibration kit parameters window (Fig. 3.3) displays the various values associated with the kit including an indication that reflection coefficient data for the matched load is available. Note that the load reflection coefficient and through adaptor data are supplied in the format shown in Figs. 3.4 and 3.5. Bear this in mind if the need arises to create a new kit.

In the following sections, loading the kit and calibrating the instrument are described.

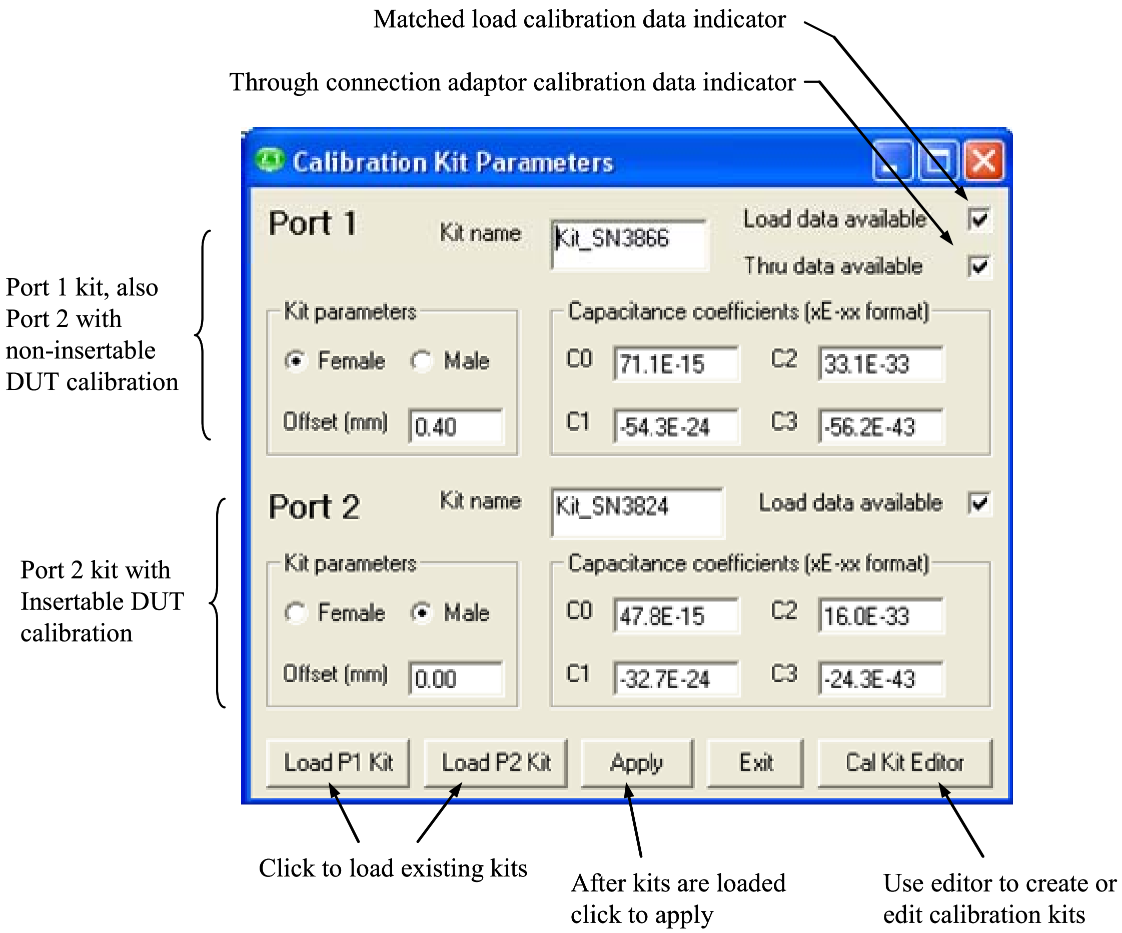

Figure 3.3: The calibration kit window shows the kit parameters

Frequency (MHz)	S11 (real)	S11 (imaginary)
3	-1.7265E-03	7.7777E-05
32.97	-1.6588E-03	3.3093E-04
62.94	-1.4761E-03	5.9003E-04
92.91	-1.4653E-03	1.0253E-03
122.88	-1.3841E-03	1.2608E-03
152.85	-1.1924E-03	1.5800E-03
182.82	-1.0884E-03	1.9085E-03
212.79	-8.7216E-04	2.1355E-03
242.76	-7.0326E-04	2.4109E-03
272.73	-5.7006E-04	2.6790E-03

There must be 101 data lines. Typically these should cover the band 3 MHz – 3 GHz. **No empty or comment lines are allowed at any point.**

Figure 3.4: The reflection coefficient matched load data format

Freq (MHz)	S11r	S11i	S21r	S21i	S12r	S12i	S22r	S22i
3	1.1450E-04	-1.0852E-04	9.9965E-01	-1.0394E-03	9.9947E-01	-7.4717E-04	1.0723E-04	4.9711E-05
32.97	2.9307E-04	1.9923E-04	9.9973E-01	-1.0241E-02	9.9934E-01	-1.0505E-02	2.0715E-04	2.0814E-04
62.94	4.1774E-04	4.3168E-04	9.9922E-01	-1.9672E-02	9.9927E-01	-1.9668E-02	2.8195E-04	2.8897E-04
92.91	5.3415E-04	5.7609E-04	9.9898E-01	-2.9165E-02	9.9855E-01	-2.8852E-02	4.0525E-04	2.8043E-04
122.88	7.1924E-04	6.4942E-04	9.9883E-01	-3.8214E-02	9.9846E-01	-3.8128E-02	4.0646E-04	2.8133E-04
152.85	7.8941E-04	7.5903E-04	9.9834E-01	-4.7690E-02	9.9807E-01	-4.7805E-02	5.4323E-04	2.2344E-04
182.82	9.9069E-04	7.8126E-04	9.9792E-01	-5.7033E-02	9.9758E-01	-5.7198E-02	5.7273E-04	2.9411E-04
212.79	1.0791E-03	8.0397E-04	9.9715E-01	-6.6419E-02	9.9699E-01	-6.5967E-02	5.7191E-04	2.6551E-04
242.76	1.2779E-03	8.5429E-04	9.9648E-01	-7.5557E-02	9.9625E-01	-7.5449E-02	6.3081E-04	2.9580E-04

101 frequency points

Figure 3.5: The through adaptor data format

3.3 Loading a cal kit

Loading the cal kit is very easy. First ensure that the calibration kit has been copied from the mini CD ROM to the hard disk. Typically, this should be in the LA19-13-02 directory. Then follow the steps below.

- Select Cal Kit from the Tools drop down menu
- The calibration kit parameters window should now be displayed (Fig. 3.3)
- Click on the Load P1 Kit button (loads a kit and assigns it to port 1)
- Select the kit using the file explorer dialogue box displayed
- If doing a calibration for an insertable device, click on the Port 2 Load Kit button

- If loading a kit for Port 2, then select the kit using the file explorer dialogue box displayed
- Click the Apply button
- Click the Exit button to close the window

The chosen calibration kit(s) is now loaded and ready for use.

3.4 Calibrating

The Calibration window (Fig. 3.6) is used to set up and carry out the calibration of the VNA. This is displayed by clicking on the Calibration button on the main window. The steps in performing a calibration are as follows:

Setting the frequency sweep

- Set the frequency sweep characteristics (start and stop frequency and number of points)
- Select the desired test port power level (the instrument is specified with its default setting of 0 dBm)
- Click the Apply button above the progress bar to program the synthesisers

Performing the calibration

- Select the measurement required
- Click on each standard button and follow the instructions
- When all standards have been done click on the Apply Cal button
- Click on the Close Window button

Note that when measuring a non-insertable device, the calibration kit associated with port 1 will be used to calibrate both ports of the instrument. The port 2 display will be greyed out as shown in Fig. 3.6.

If the kit loaded for port 1 does not have through adaptor data, then the user will be prevented from selecting the 'non-insertable DUT' option. Note that only issue 2 of the LA Techniques economy calibration kits support this feature.

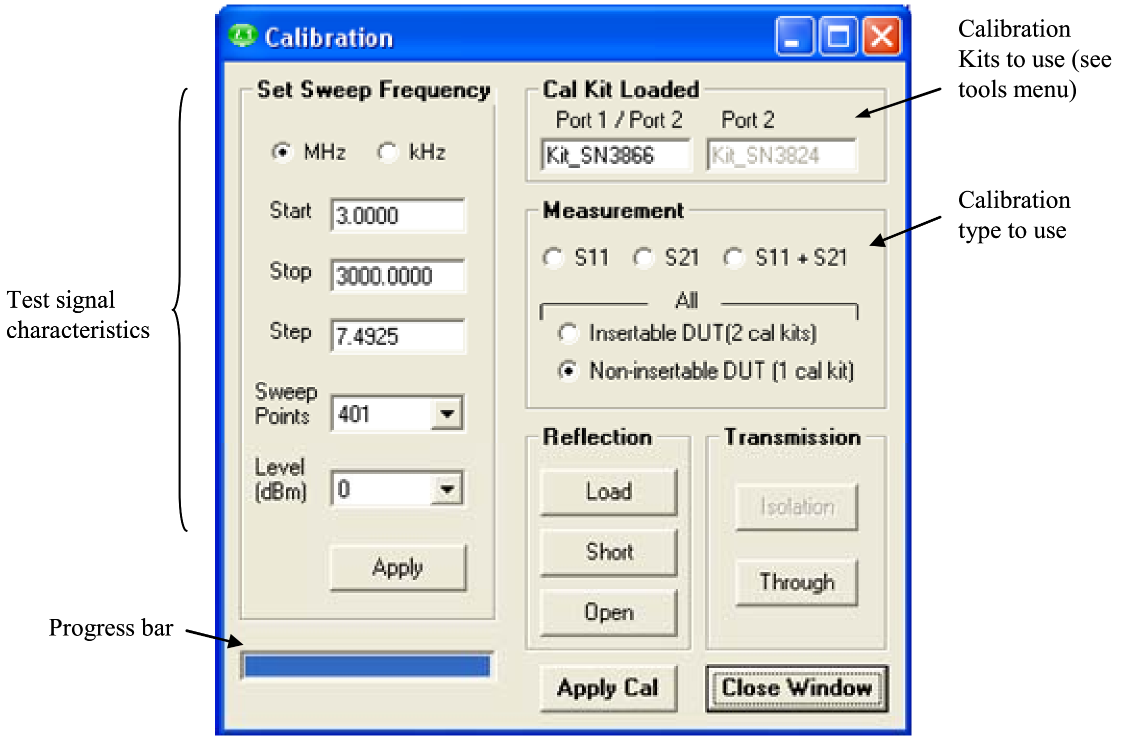

Figure 3.6: Setting up the calibration (click on the Calibration button)

3.5 Creating, editing, or re-creating the cal kit

Editing or creating a calibration kit can be done using the calibration kit editor as shown in Fig. 3.7. This is called from the Cal Kit Parameters window (Fig. 3.3) by clicking on the Cal Kit Editor button.

In order to **create a new kit from scratch**, follow this procedure.

- Click on the New Kit button to initialise all parameters
- Enter coefficient values, select the sex of the kit, enter the short circuit offset
- Enter a kit name
- If the kit is to have calibrated load data, check the 'Load data available' box
- If the kit is to have calibrated through adaptor data, check the 'Thru data available' box
- Click 'Save Kit'
- If the 'Load data available' box has been ticked, then the software will prompt the user to select a file holding the appropriate data
- If the 'Thru data available' box has been ticked, then the software will prompt the user to select a file holding the appropriate data
- Click the Exit button to close the editor

In order to **create a new kit using an existing kit as a template**, follow this procedure.

- Click on the 'Load Exiting Kit' button to initialise all parameters
- Modify parameter values as required
- Modify the kit name
- If the kit is to have calibrated load data, **uncheck** the 'Load data available' box and then **re-check** it
- If the kit is to have calibrated through adaptor data, **uncheck** the 'Thru data available' box and then **re-check** it
- Click 'Save Kit'
- If the 'Load data available' box has been ticked, then the software will prompt the user to select a file holding the appropriate data
- If the 'Thru data available' box has been ticked, then the software will prompt the user to select a file holding the appropriate data
- Click the Exit button to close the editor

In the case where the new kit is to have the same load and through adaptor data as that of the existing kit used as template, then miss out the step of un-checking and re-checking the load or through data boxes.

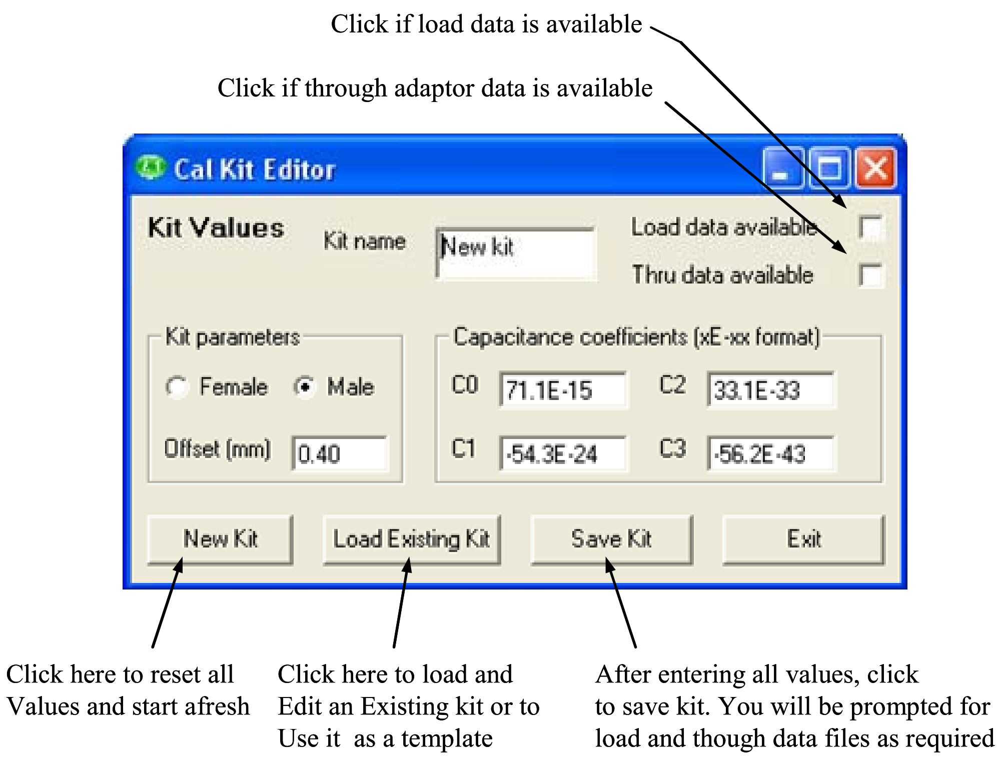

Figure 3.7: The Cal Kit Editor is used to create or edit calibration kits

3.6 The cal kit file

The cal kit file is a text file holding the relevant information about the kit. If a characterised matched load (characterised from measurements) is associated with the kit, then its reflection coefficient data will be included in the file. This will take the form of 101 lines with three entries per line. The first item is the frequency (MHz) followed by the real and imaginary parts of the reflection coefficient. Similarly, if the kit contains a calibrated through adaptor, the data will be included in the form of a set of s-parameters for 101 frequency points. Figure 3.8 shows how the file may appear when displayed using a text editor.

Name of kit

Offset (distance and time) Open circuit coefficients

```
Kit_SN3866
#FALSE#
0.0004      1.33E-12     7.11E-14    -5.43E-23    3.31E-32    -5.62E-42
#TRUE#
3           -0.0013838   -1.07E-04
32.97       -0.0010358   -2.01E-04
62.94       -6.23E-04    -3.58E-04
92.91       -0.0003012   -5.52E-04
            :
2940.06     -0.0027963   0.033432
2970.03     -0.0018974   0.034251
3000        -9.49E-04    0.035161

#TRUE#

3           -0.00016 -5.41E-05  0.99956 -0.001093  0.99955    -0.0010564 -1.45E-04  3.22E-05
32.97       1.29E-04  2.38E-04  0.99948 -0.010399  0.99945    -0.010363  0.000141  0.0001288
62.94       3.14E-04  4.02E-04  0.99932 -0.019703  0.99926    -0.019667  3.24E-04  1.59E-04
            :
2880.12     -6.29E-05 -0.003221  0.62462 -0.77819  0.6251     -0.77827  0.012011  0.0037811
2910.08     1.56E-04  -0.0031355 0.61735 -0.78396  0.61785    -0.78406  0.012404  0.003254
3000        2.79E-04  -0.0020004 0.59522 -0.80086  0.59579    -0.80103  0.01292   0.0011669
EOF
```

Load reflection coefficient data (101 points)

Through adaptor data (101 points)

Figure 3.8: The kit file is a text file that can be viewed with any text editor

4 MEASURED PERFORMANCE

The following sections provide uncertainty estimates for reflection and transmission measurements made using the LA19-13-02 VNA in conjunction with LA Techniques' 2.92 mm calibration kits that use loads characterised using the method described in [1]. This characterisation process provides increased measurement accuracy for a VNA calibrated using kits containing such loads. The information presented here complements an earlier application note [2] that described uncertainties for the LA19-13-01 model of VNA.

The methods used to evaluate the uncertainty in the VNA follow recognised practices [3]; these being based on internationally agreed guidelines [4]. The uncertainty estimates do not include contributions due to random errors (e.g. connector repeatability, system repeatability, cable flexure, noise and ambient conditions).[1] These estimates therefore provide a Best Measurement Capability [5] suitable for defining a Scope of Accreditation [6] for measurements made using this type of VNA and calibration kit. [2]

In section 4.1, the size of each of the six uncertainty contributions considered in this application note is evaluated. For convenience, the resulting values established for these uncertainty contributions are summarised in Tables 2 and 3, below. Section 4.2 presents the methods used to express uncertainty, including the use of logarithmic quantities (specifically, return loss) and phase. Sections 4.3 and 4.4 present overall uncertainty estimates for reflection and transmission measurements, respectively, and Section 4.5 presents some example results and comparisons with measurements made by NPL.

Table 2: Uncertainty contributions for reflection measurements (linear units)

Directivity	Test Port Match	Load Match
0.004	0.010	0.006

[1] Except for noise, these random errors come from 'outside' the VNA and so are not representative of the VNA's performance. They are caused by the other components involved in the overall measurement process – i.e. the cables and adaptors used to form the test port reference planes, the devices connected to the reference planes (both calibration standards and devices under test) – and the environment in which the VNA is operated.

[2] However, since worst-case estimates are used in this document to represent each of the uncertainty components that are considered, the resulting overall uncertainty estimates may well be comparable with user uncertainty estimates that may need also to take into account the random error effects – i.e., assuming that these random errors are not the dominant errors in the measurements.

Table 3: Uncertainty contributions for transmission (attenuation) measurements

Non-linearity	Isolation/cross/talk	Mismatch
0.002 dB/dB	-83 dB	0.015 dB

4.1 Uncertainty contributions

4.1.1 Residual Directivity

The residual directivity of the calibrated VNA is assessed by attaching a beadless air line terminated with a well-matched load to each of the VNA's test port reference planes. The traces obtained, presented in terms of linear voltage reflection coefficient (VRC), are shown in Figure 4.1. The residual directivity is given by half the difference between adjacent maxima and minima of the observed ripple trace [3].

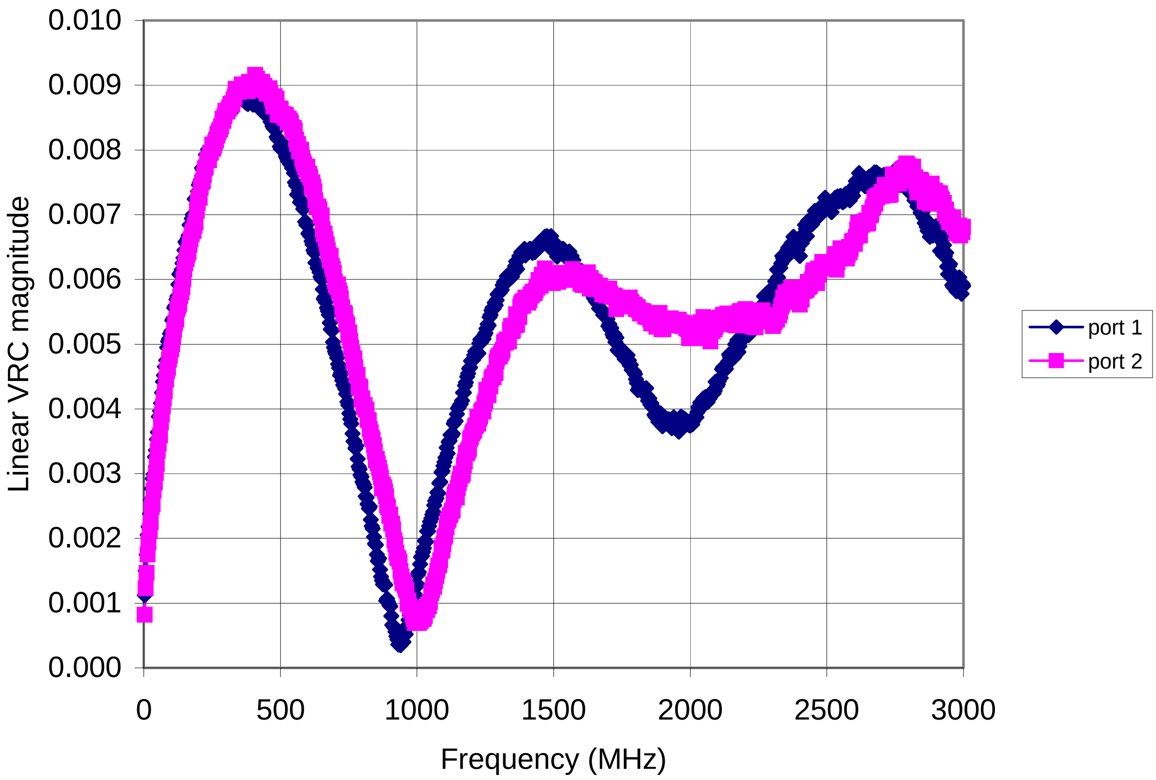

Figure 4.1: Ripple trace due to residual directivity in the calibrated VNA

The worst-case observed value for the residual directivity, *D*, is therefore:

$$D = \frac{(0.009 - 0.0005)}{2} \approx 0.004 \equiv -48 \text{ dB}$$

4.1.2 Residual test port match

The residual test port match of the calibrated VNA is assessed by attaching a beadless air line terminated with a high reflect (e.g. a short-circuit) to each of the VNA's test port reference planes. The traces obtained (in terms of VRC) are shown in Figure 4.2. The residual test port match is given by half the difference between the adjacent maxima and minima of the observed ripple trace [3].

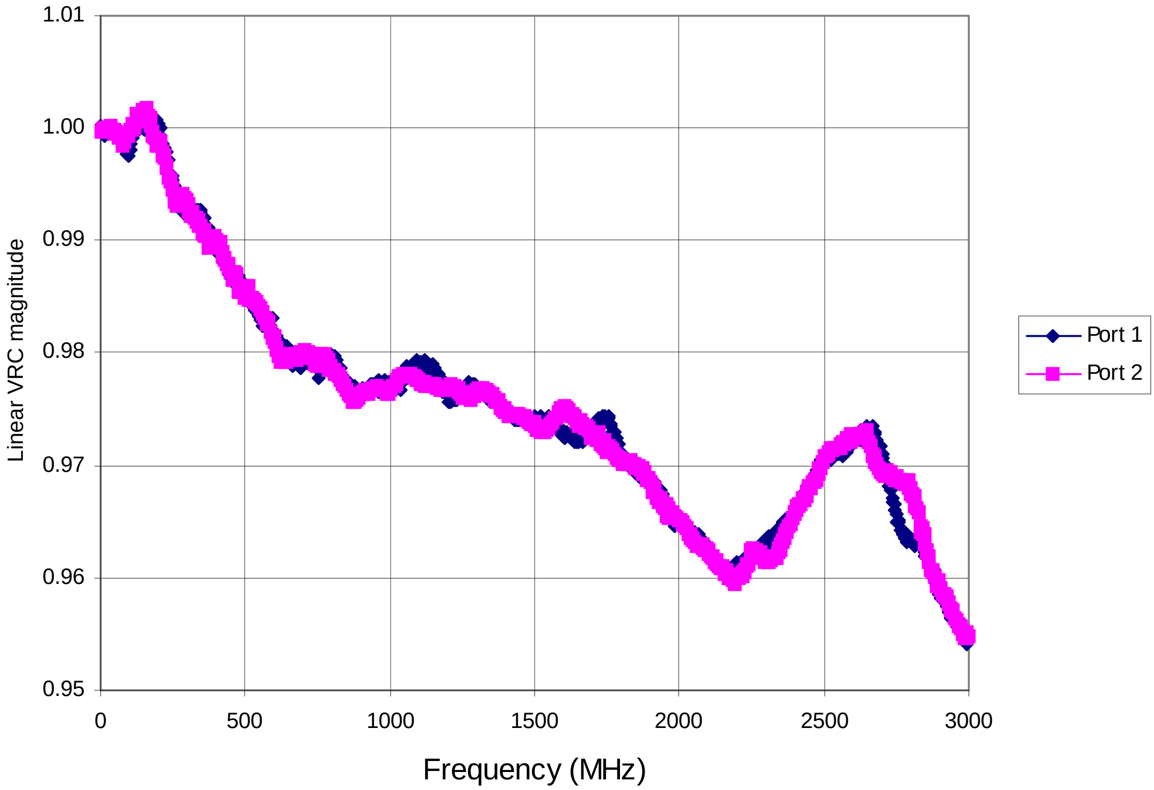

Figure 4.2: Ripple trace due to residual test port match in the calibrated VNA

The worst-case observed value for the residual test port match, M, is therefore:

$$M = \frac{(0.975 - 0.955)}{2} \approx 0.01 \equiv -40 \text{ dB}$$

4.1.3 Residual load match

The residual load match, Γ_L, is related to the uncertainty in measuring the reflection coefficient of the actual (uncorrected) load match, Γ, of the VNA's receiver port. (The receiver port will be port 2 when measuring in the forward direction and port 1 when measuring in the reverse direction.) Therefore, the residual load match can be estimated using [3]:

$$\Gamma_L = 2\left(\frac{D}{\sqrt{2}} + \frac{M\Gamma^2}{\sqrt{2}}\right) \qquad (1)$$

A measurement of the uncorrected load match, Γ, is shown in Figure 4.3. This shows that Γ for both ports is less than 0.07 (-23 dB) and so the worst-case observed value for Γ_L is given as:

$$\Gamma_L = 2\left(\frac{0.004}{\sqrt{2}} + \frac{0.01 \times 0.07^2}{\sqrt{2}}\right) \approx 0.006 \equiv -44 \text{ dB}$$

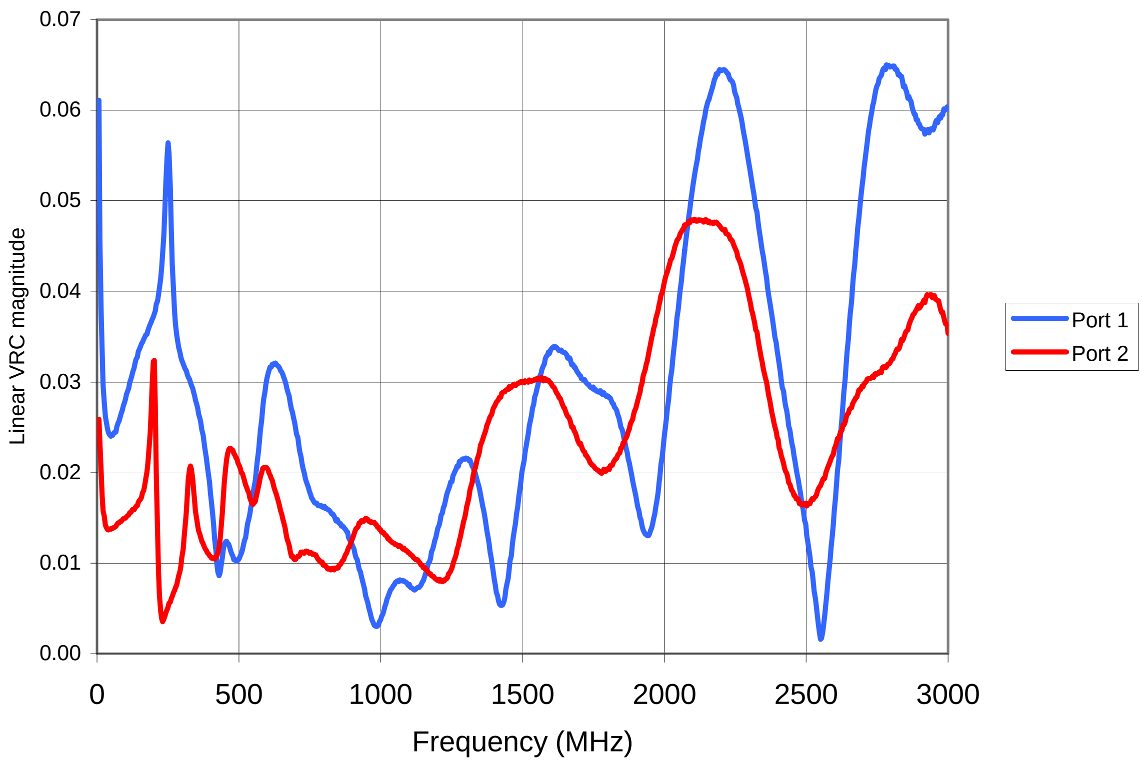

Figure 4.3: Measured uncorrected load match at ports 1 and 2

4.1.4 Non-linearity

The non-linearity, *L*, in the VNA's transmission measurements is assessed by measuring a calibrated step attenuator at one or more frequencies across the VNA's bandwidth. On this occasion, an assessment of non-linearity was made at a relatively low frequency (5 MHz) and a relatively high frequency (500 MHz) within the VNA's bandwidth.

The procedure [3] for determining non-linearity uses results obtained over a 10 dB to 50 dB range, in steps of 5 dB. At each value of attenuation, the attenuation measured by the VNA is compared with the calibrated value. The difference between these values divided by the nominal attenuation value is referred to as the VNA's non-linearity. Figures 4.4 and 4.5 show the results obtained at 5 MHz and 500 MHz, respectively.

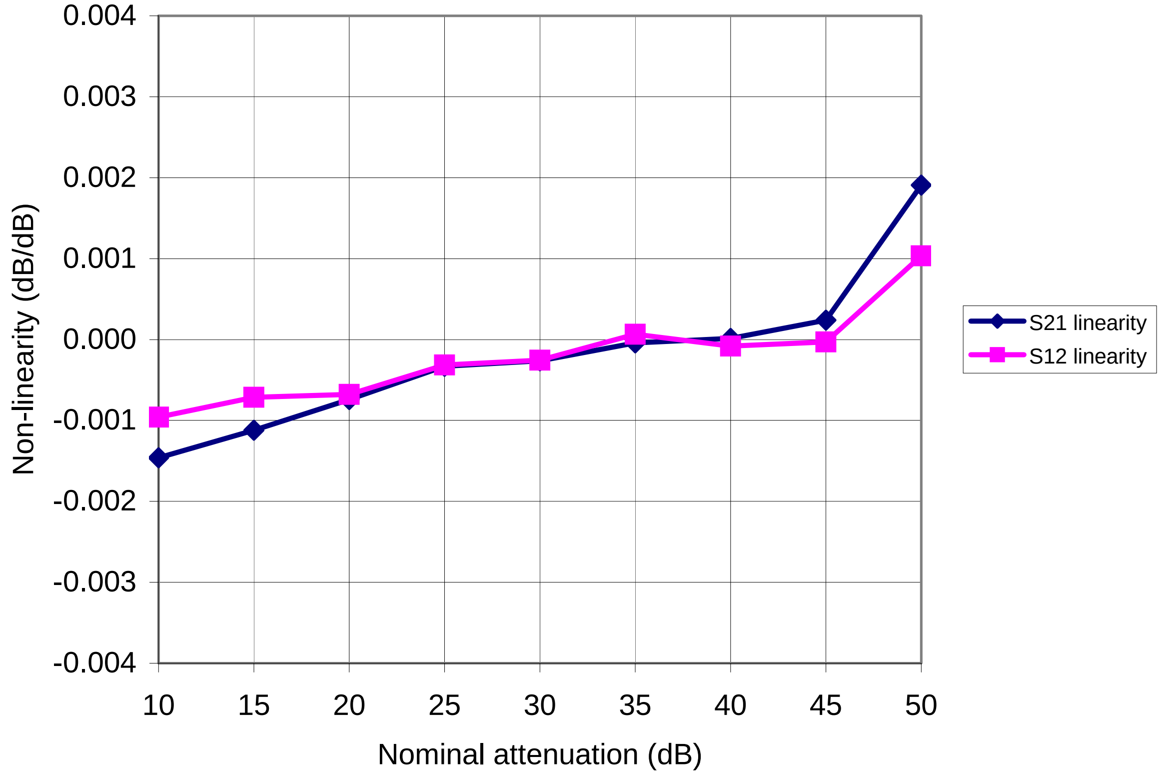

Figure 4.4: Measured non-linearity at 5 MHz

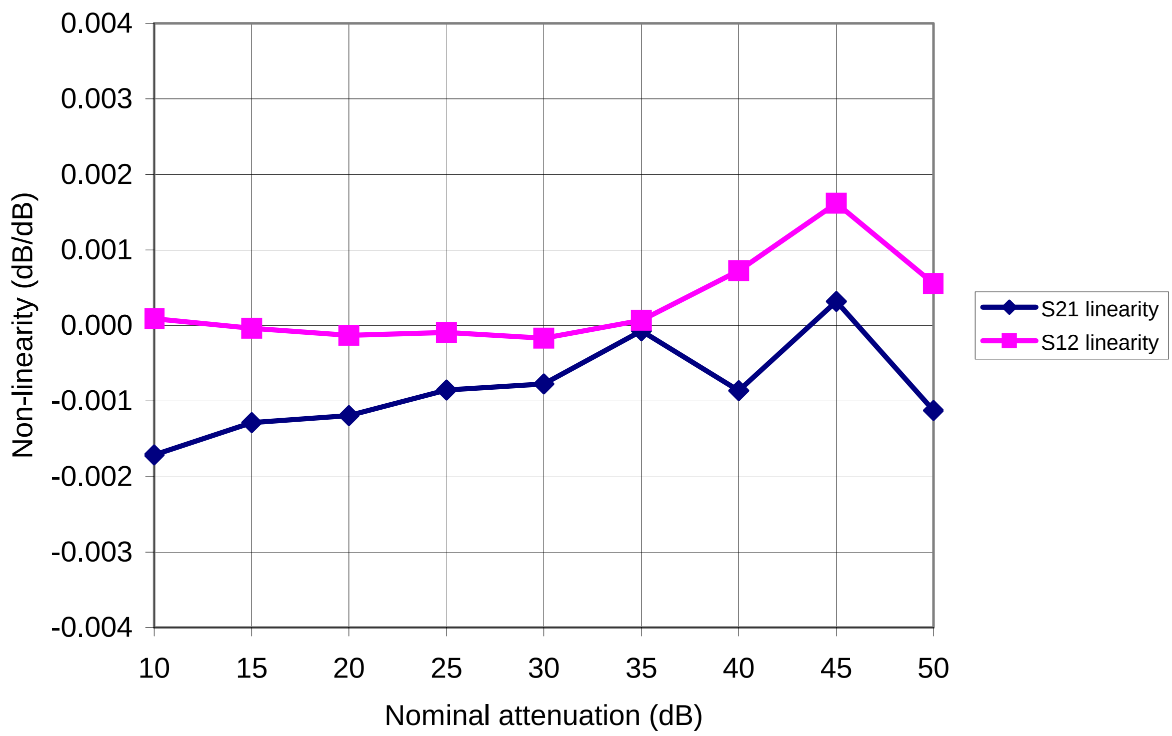

Figure 4.5: Measured non-linearity at 500 MHz

These plots are further summarized in Table 4, in terms of the maximum observed non-linearity at all measured levels of attenuation. Based on these values, a worst-case value of 0.002 dB/dB is used to represent the uncertainty contribution due to VNA non-linearity at all measurement frequencies.

Table 4: Summary of measured non-linearity at 5 MHz and 500 MHz

Frequency	**Maximum observed non-linearity (dB/dB)**	
	S_{21}	S_{12}
5 MHz	0.001 9	0.001 0
500 MHz	0.001 7	0.001 6

4.1.5 Isolation/cross-talk

The isolation/cross-talk in the VNA is determined by measuring (as S_{21} and S_{12}) the amount of signal that is transmitted and detected when both ports of the VNA are terminated with one-port devices. On this occasion, the one-port devices were chosen to be well-matched loads. The observed transmission responses are shown in Figure 4.6, along with two straight lines that have been fitted to each plot.

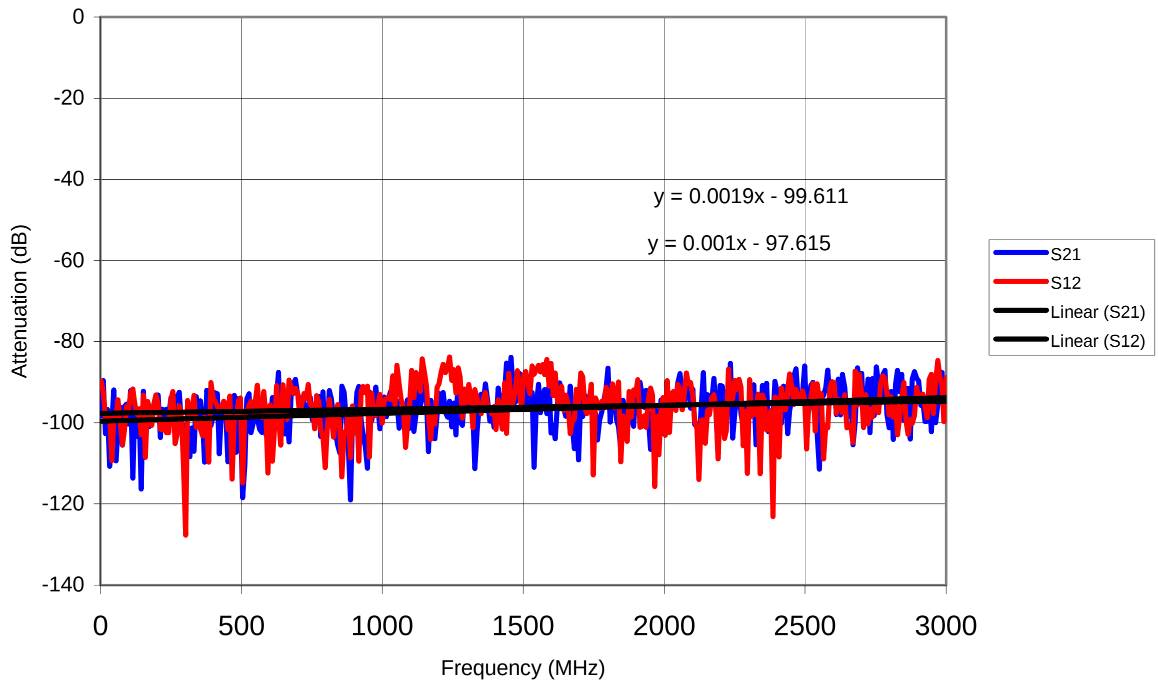

Figure 4.6: Measured isolation after terminating both ports with well-matched loads

The equations to these straight lines are used to show the average variation in isolation/cross-talk as a function of frequency. This information is further summarised in Table 5, along with the worst-case value (-83 dB) that is used to represent the isolation/cross-talk uncertainty contribution, *I*, for the VNA.

Table 5: Summary of measured isolation

S-parameter	Isolation/cross-talk at 3 MHz	Isolation/cross-talk at 3 GHz	Worst case isolation/cross-talk
S_{21}	-99.6 dB	-93.9 dB	-83 dB
S_{12}	-97.6 dB	-94.6 dB	-83 dB

During measurement of a particular device under test, the size of the uncertainty contribution due to isolation/cross-talk, *dA*, will vary depending on the measured attenuation, *A*, according to [3]:[3]

[3] This equation has been modified to take account of the negative sign used here for the isolation term, i.e. *I* = -83 dB rather than *I* = +83 dB, as would be used in [3]. This also assumes that the measured attenuation, *A*, is expressed as a positive number, e.g. *A* = +20 dB.

$$dA = 20\log_{10}\left[1 + 10^{\frac{(I+A)}{20}}\right] \qquad (2)$$

This is shown in Figure 4.7, for measured attenuation ranging from 0 dB to 80 dB.

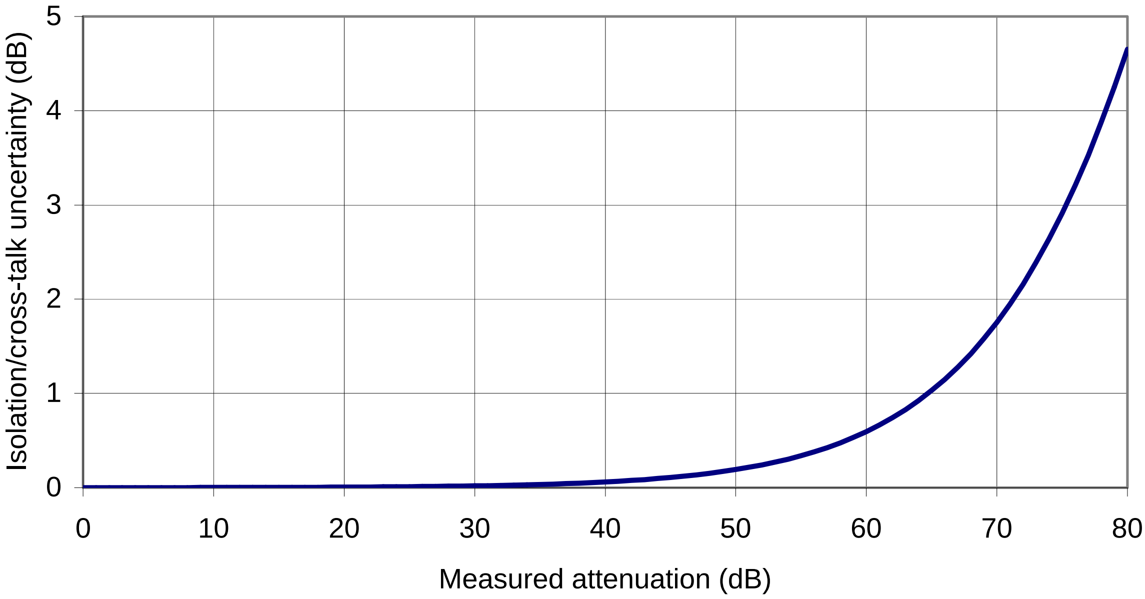

Figure 4.7: Isolation/cross-talk uncertainty contribution

4.1.6 Mismatch

The expression used to evaluate the mismatch uncertainty contribution is [3]:

$$M_{\mathrm{TM}} = 20\log_{10}\frac{1+(|MS_{11}|+|\Gamma_L S_{22}|+|M\Gamma_L S_{11}S_{22}|+|M\Gamma_L S_{21}S_{12}|)}{1-|M||\Gamma_L|} \tag{3}$$

Only relatively well-matched devices (where $|S_{11}|$ and $|S_{22}|$ will not be greater than 0.1) are considered here. Therefore, for uncertainty budgeting purposes, it is assumed that $|S_{11}| = |S_{22}| = 0.1$.[4] Under these conditions, the worst-case value of M_{TM} is 0.015 dB (regardless of the values of S_{21} and S_{12}).

4.2 Expressing uncertainty

4.2.1 Expanded uncertainty

In the sections that follow, the overall uncertainties quoted for both reflection and transmission measurements are expanded uncertainties [4] that define an interval estimated to have a level of confidence of 95 percent. This is common practice for expressing uncertainties for measurements at RF and microwave frequencies.

4.2.2 Uncertainty expressed in dB

For reflection measurements, uncertainty is evaluated in terms of VRC (i.e. S_{11} and S_{22}) then converted to the equivalent return loss uncertainty, U(RL), using [7]:

$$U(RL) \approx 8.686 \times \frac{U(|S_{ii}|)}{|S_{ii}|} \tag{4}$$

where S_{ii} (i = 1, 2) is the measured reflection coefficient and $U(|S_{ii}|)$ is the expanded uncertainty in $|S_{ii}|$.

4.2.3 Uncertainty in phase

For a given S-parameter, S_{ij} (i = 1, 2; j = 1, 2), the expanded uncertainty in phase, $U(\varphi)$, can be estimated using [8]:

$$U(\varphi) = \sin^{-1}\left(\frac{U(|S_{ij}|)}{|S_{ij}|}\right) \tag{5}$$

[4] For devices where $|S_{11}|$ and $|S_{22}|$ are greater than 0.1, these calculations need to be repeated using the measured values of S_{11} and S_{22} in the above equation.

where S_{ij} is the measured *S*-parameter and $U(|S_{ij}|)$ is the expanded uncertainty in $|S_{ij}|$.

When calculating the uncertainty in transmission phase, it is first necessary to determine the uncertainty in the magnitude of the linear transmission coefficient (i.e. $U(|S_{21}|)$ or $U(|S_{12}|)$). This can be derived from the measured attenuation, *A*, and the uncertainty in the measured attenuation, $U(A)$ using [7]:

$$U(|S_{ij}|) \approx \frac{1}{8.686} \times 10^{-\frac{A}{20}} \times U(A) \qquad (6)$$

4.3 Uncertainty in reflection measurements

4.3.1 One-port devices

The uncertainty, $U(\Gamma)$, of a VRC measurement of a one-port device can be estimated using [3]:

$$U(\Gamma) = 2\left(\frac{D}{\sqrt{2}} + \frac{M\Gamma^2}{\sqrt{2}}\right) \qquad (7)$$

where Γ is the measured VRC of the device under test. Using the values of *D* and *M* determined in section 4.1, a plot of the return loss uncertainty as a function of measured return loss is shown in Figure 4.8. The associated uncertainty in reflection phase is shown in Figure 4.9.

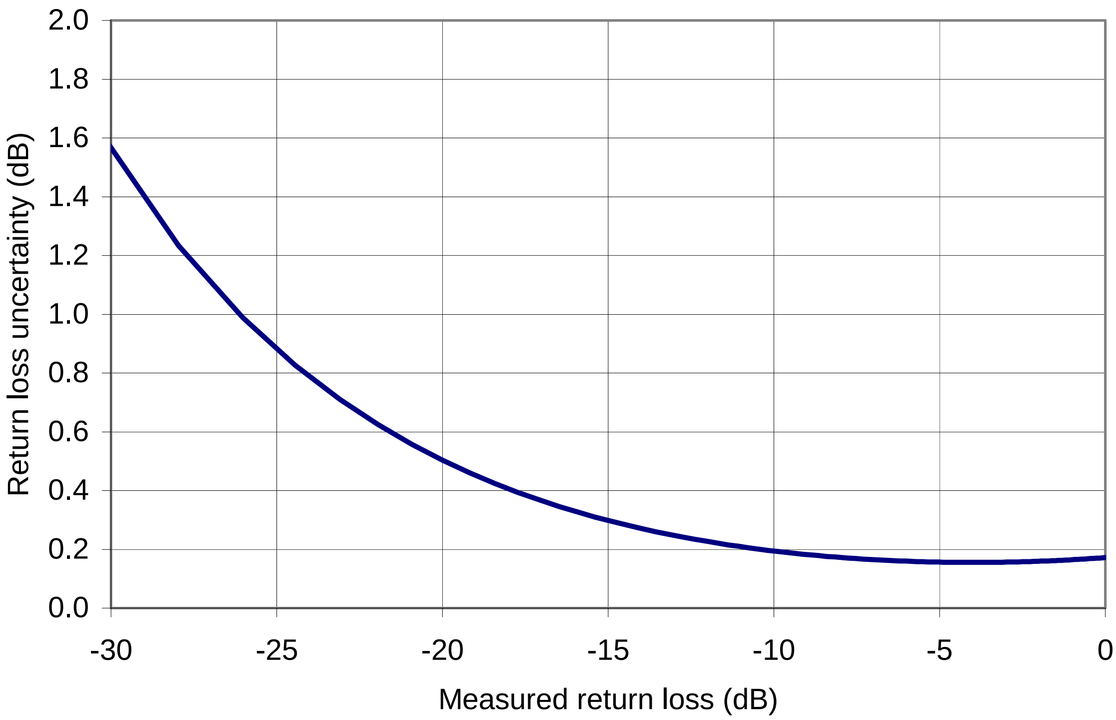

Figure 4.8: Return loss uncertainty for one-port devices

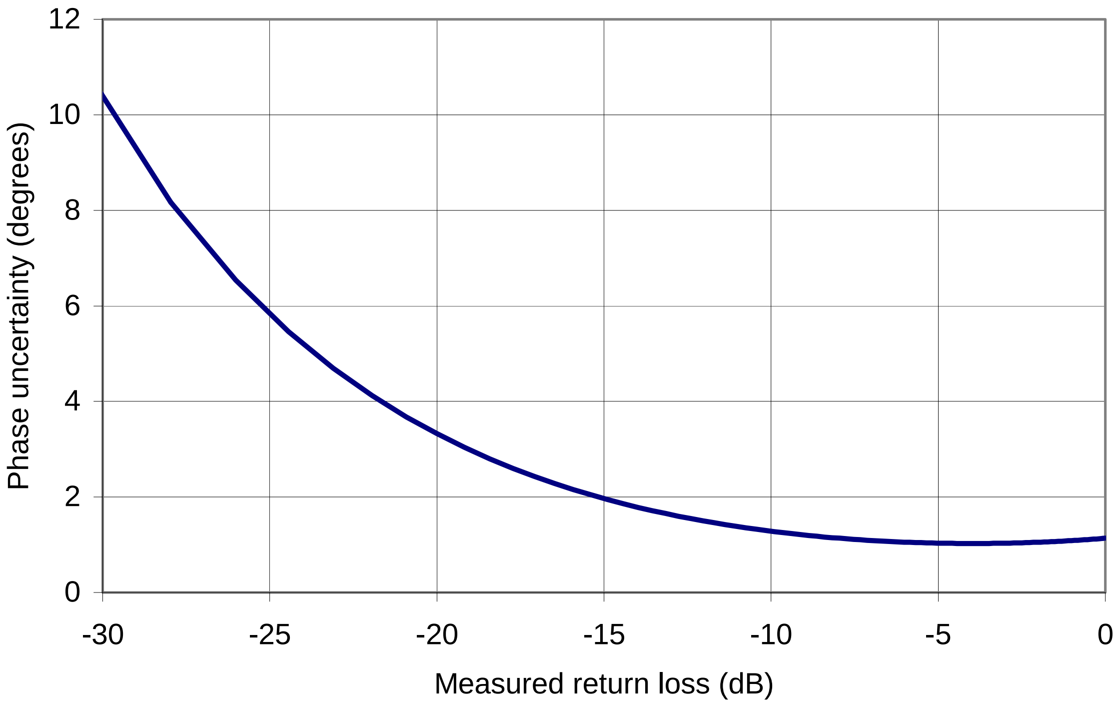

Figure 4.9: Reflection phase uncertainty for one-port devices

4.3.2 Two-port devices

The uncertainty, $U(\Gamma)$ of a VRC measurement of a two-port device can be estimated using [3]:

$$U(\Gamma) = 2\sqrt{\left(\frac{D}{\sqrt{2}} + \frac{M\,\Gamma^2}{\sqrt{2}}\right)^2 + \left(\frac{\Gamma_L {S_{21}}^2}{2}\right)^2} \qquad (8)$$

where Γ and S_{21} are the measured VRC and linear transmission coefficient, respectively, of the device under test. This is assumed to apply to both forward and reverse directions (i.e. for reciprocal devices having $S_{21} = S_{12}$). This expression is similar to the one used for one-port VRC measurements (equation (7)), and only becomes significantly different when measuring low values of attenuation (i.e. when $|S_{21}| > 0.5$ or, equivalently, when the measured attenuation is less than 6 dB). Therefore, as a rule of thumb, when the measured attenuation is greater than 6 dB, the return loss and reflection phase uncertainty is that shown in Figures 4.8 and 4.9, respectively. When the measured attenuation is less than 6 dB, the return loss and reflection phase uncertainty is shown in Figures 4.10 and 4.11, respectively.

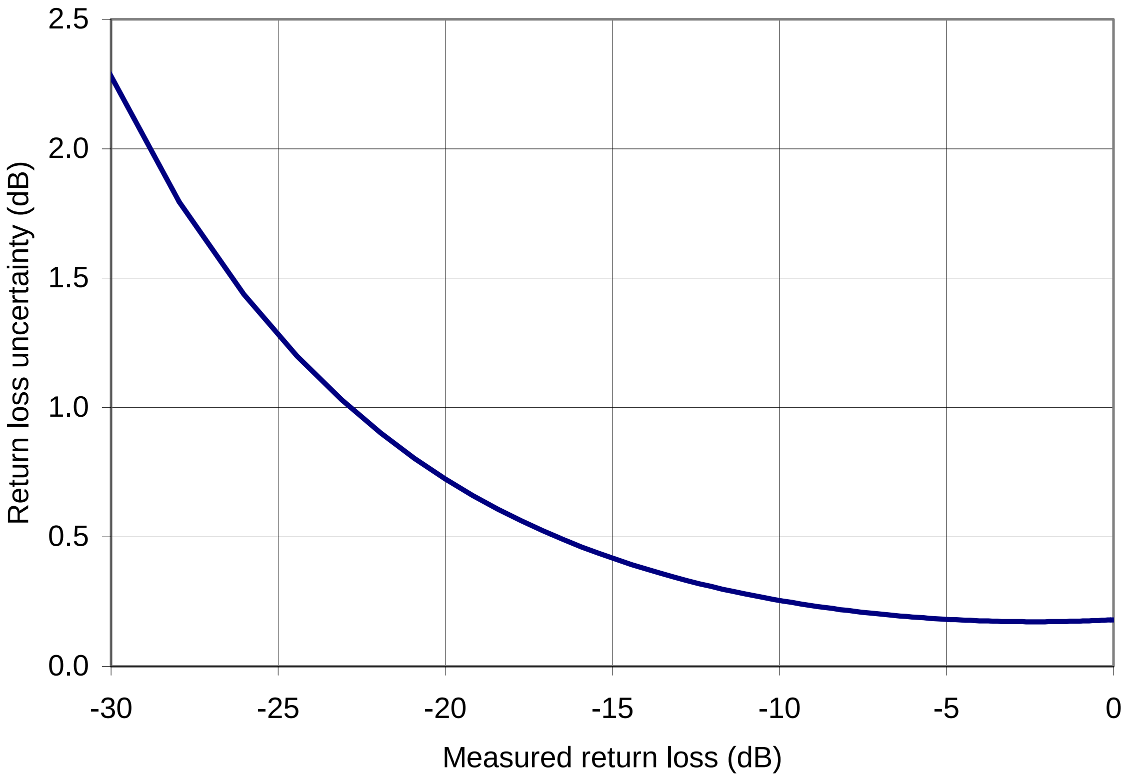

Figure 4.10: Return loss uncertainty for two-port devices with low attenuation (i.e. < 6 dB)

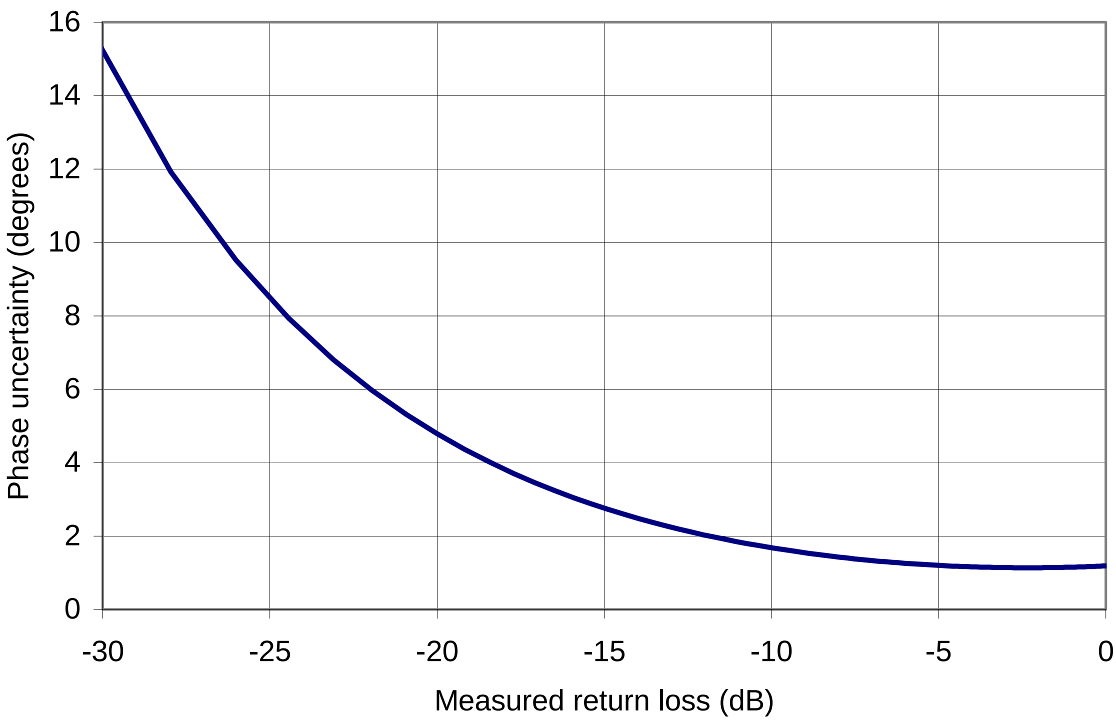

Figure 4.11: Reflection phase uncertainty for 2 port devices with low attenuation

4.4 Uncertainty in attenuation/transmission coefficient measurements

The uncertainty, U, of an attenuation measurement of a two-port device can be estimated using [3]:

$$U = 2\sqrt{\left(\frac{L}{2}\right)^2 + \left(\frac{M_{TM}}{\sqrt{2}}\right)^2 + \left(\frac{dA}{\sqrt{3}}\right)^2} \tag{9}$$

Using the values of L, M_{TM} and dA determined in section 2, plots of the attenuation uncertainty are shown in Figure 4.12 (for measured attenuation from 0 dB to 40 dB) and Figure 4.13 (for measured attenuation from 40 dB to 80 dB). The respective uncertainty in transmission phase associated with these two ranges of attenuation is shown in Figures 4.14 and 4.15.

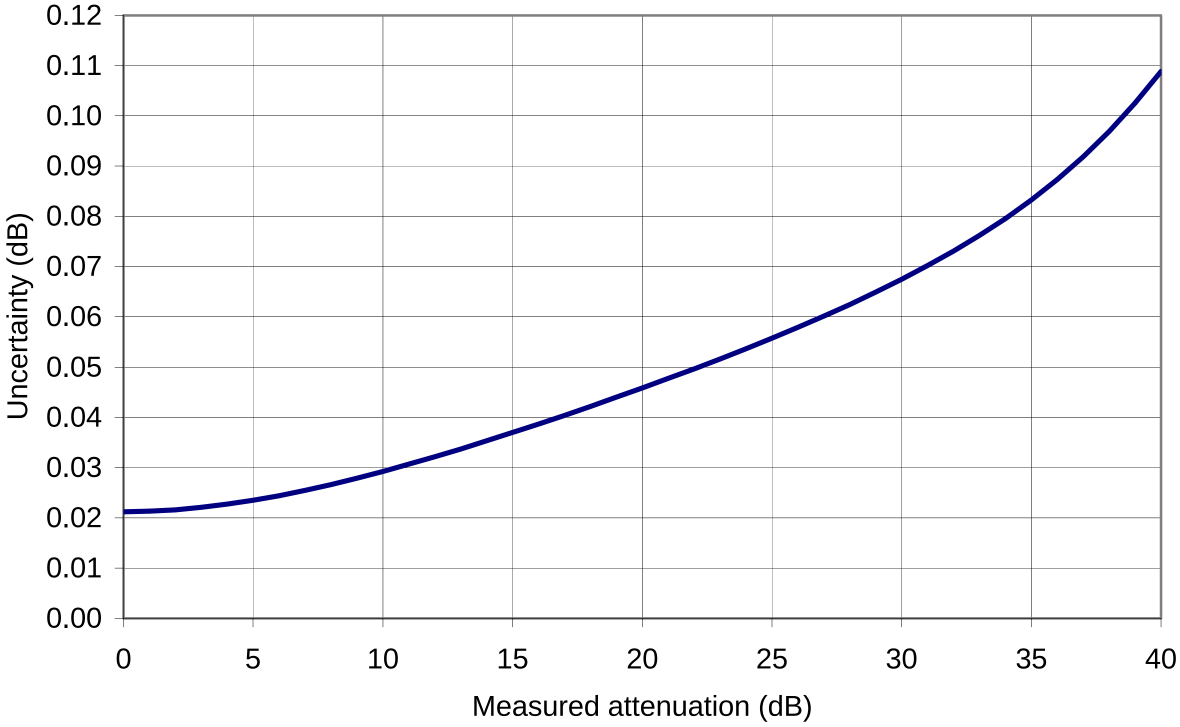

Figure 4.12: Attenuation uncertainty for measurements to 40 dB

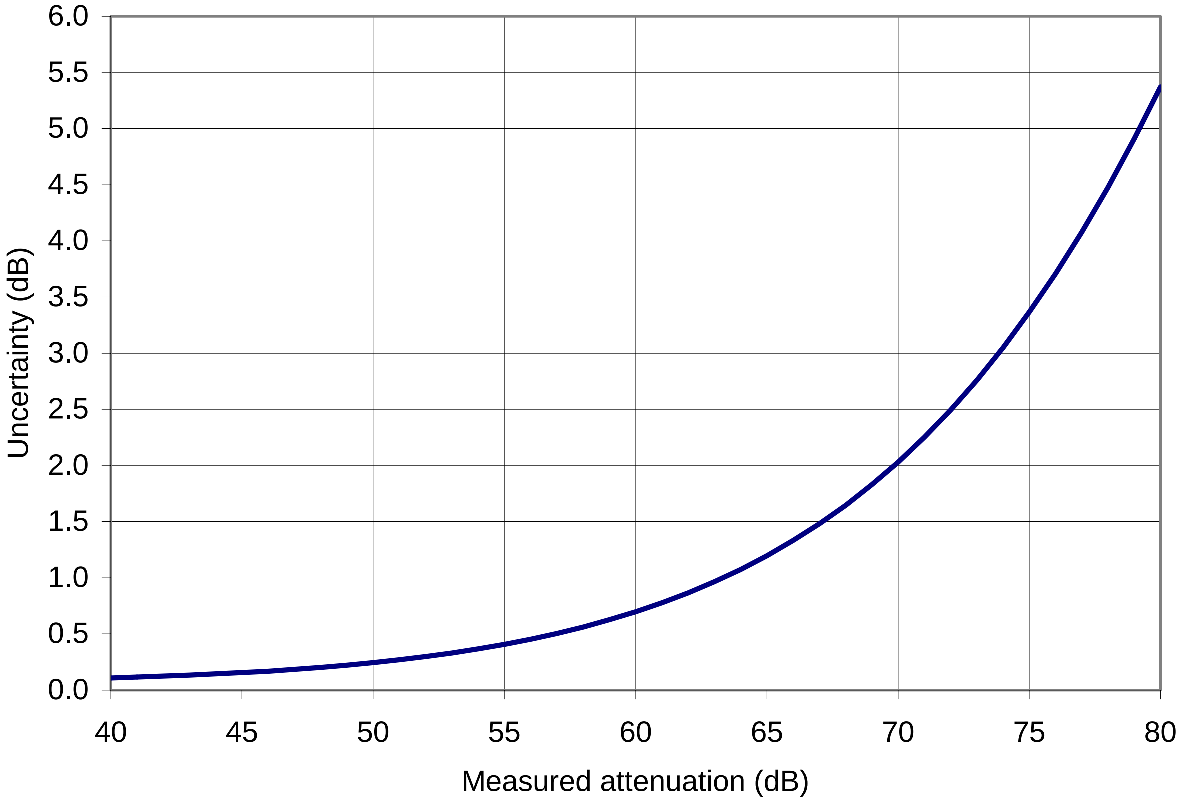

Figure 4.13: Attenuation uncertainty for measurements above 40 dB

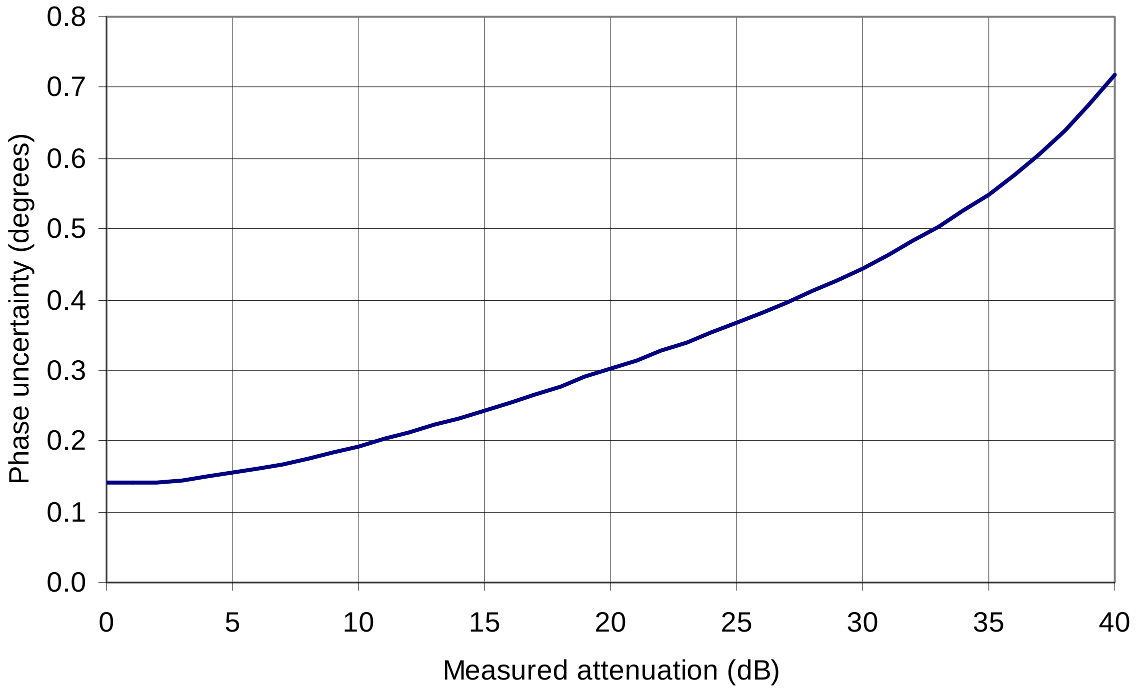

Figure 4.14: Transmission phase uncertainty for attenuation measurements to 40 dB

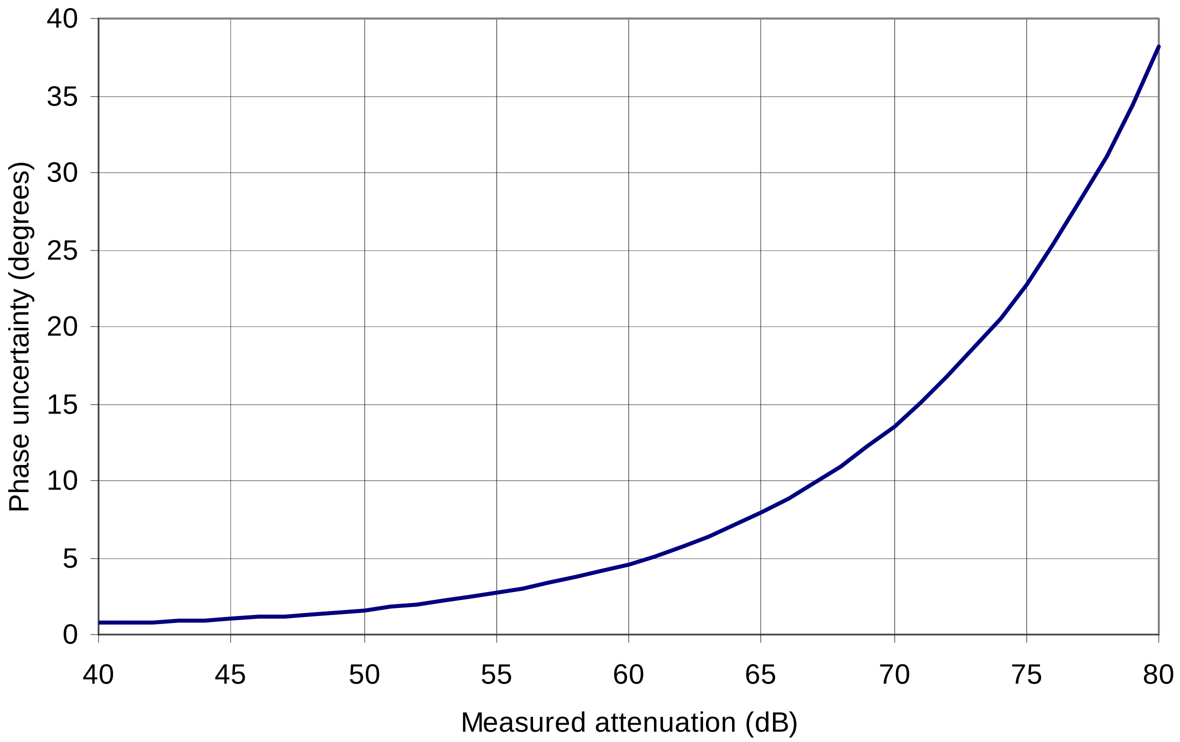

Figure 4.15: Transmission phase uncertainty for attenuation measurements above 40 dB

4.5 Examples and comparisons

This section presents comparisons of measurements made using the LA19-13-02 VNA with measurements made by NPL[5]. Each set of results also shows the uncertainties for the LA19-13-02 VNA measurements evaluated using the methods presented in this application note. Measurements of two devices are shown: a one-port mismatch (with nominal VSWR of 2.0); and, a (two-port) 20 dB attenuator.

The measured phases (both reflection and transmission) for these devices vary rapidly as a function of frequency. Therefore, when presenting comparisons of the phase measurements, a plot of the difference at each frequency between the LA19-13-02 value and the NPL value is given. This effectively normalises the results to the values given by NPL.

4.5.1 One-port mismatch (VSWR = 2.0)

A nominal VSWR of 2.0 is equivalent to a linear VRC magnitude of 0.3333 and a return loss of -9.54 dB. Using equation (7), the uncertainty in VRC magnitude is ±0.007 3, which is equivalent to a return loss uncertainty of ±0.19 dB. This value of uncertainty is shown as error bars applied to the results in Figure 4.16, which also shows the results obtained by NPL.

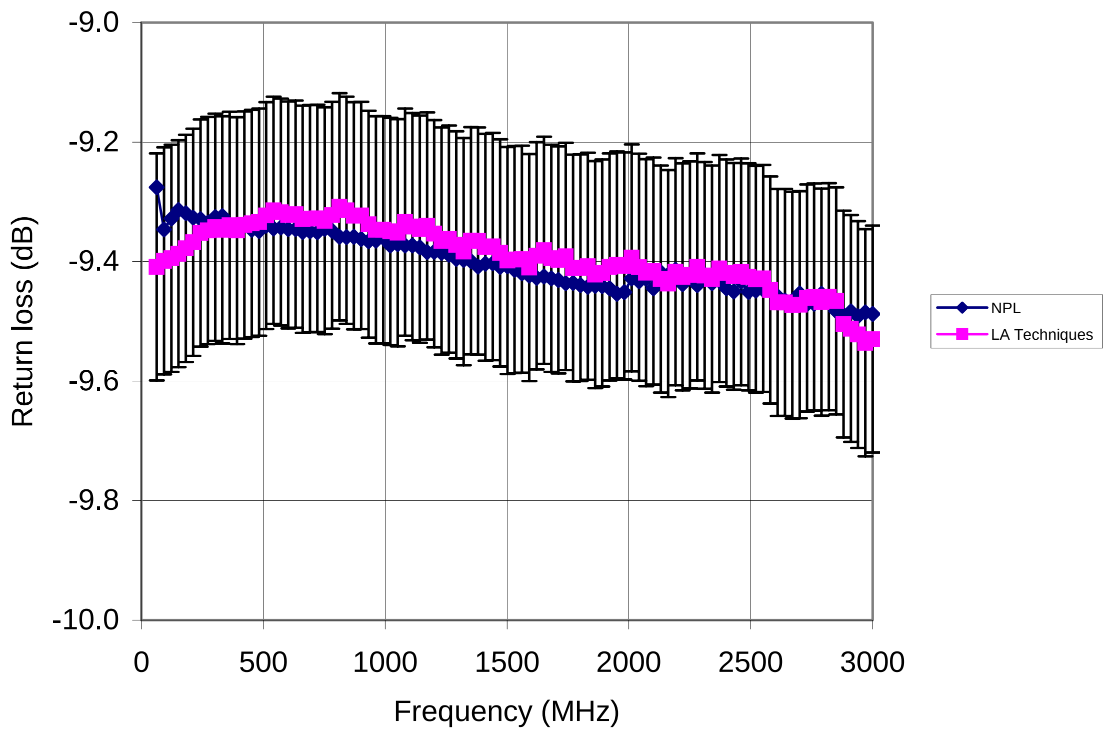

Figure 4.16: Measurement comparison (between LA Techniques and NPL) for the return loss of a one-port mismatch (VSWR = 2.0)

[5] For clarity of presentation, no uncertainties are shown for the measurements made by NPL. This also implies that these values are considered here as reference values (or assigned values [9]) for the purpose of these comparisons.

Using equation (5), the uncertainty in reflection phase is ±1.3°. This value of uncertainty is shown as error bars in Figure 4.17, which shows the differences between the LA19-13-02 and NPL measured values.

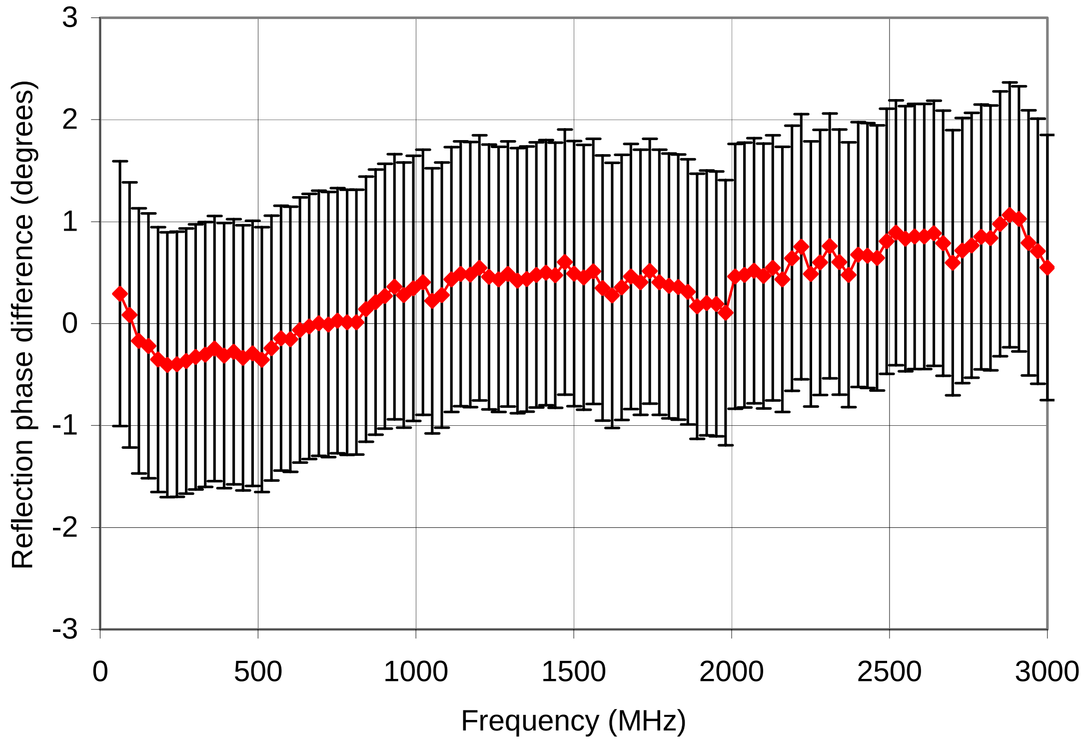

Figure 4.17: Measured difference (between LA Techniques and NPL) for the reflection phase of a one-port mismatch (VSWR = 2.0)

4.5.2 Two-port attenuator (20 dB)

<u>Reflection (return loss) measurement</u>

A nominal attenuation of 20 dB is equivalent to $|S_{21}|$ value of 0.1. This means that equation (7) is used to determine the uncertainty in VRC. Since the measured magnitude of the VRC is very small, only the first term in this equation (involving the residual directivity, *D*) is needed. This produces an uncertainty in VRC of ±0.005 7. The uncertainty in return loss is calculated using equation (4) using the measured value of VRC magnitude at each frequency. These values of uncertainty are shown in Figure 4.18.

The reflection phase of such low values of VRC magnitude (i.e. return loss < -40 dB) is difficult to measure reliably. This is because phase becomes indeterminate as the VRC magnitude reduces to zero[6]. Therefore, there is little value in comparing the

[6] This can be seen in equation (5): when the VRC magnitude is less than the uncertainty in the measured VRC magnitude, the associated uncertainty in phase effectively becomes ±180° implying that the phase is indeterminate.

measured reflection phase for such low values of VRC magnitude and so these results are not presented here.

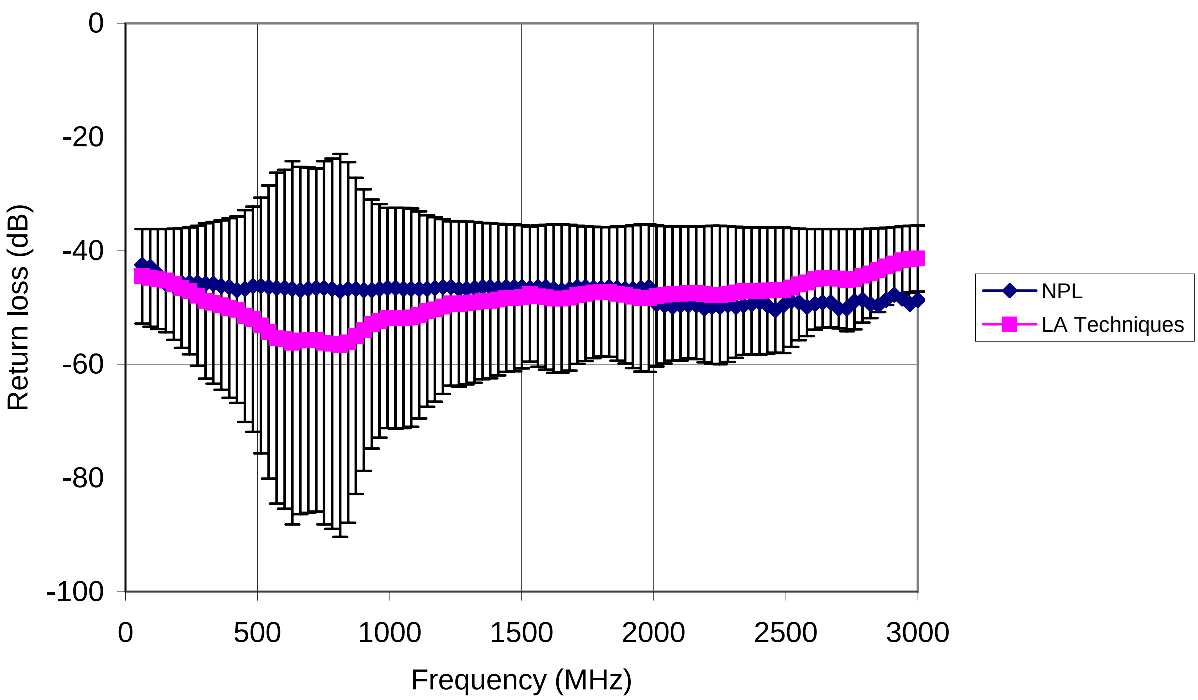

Figure 4.18: Measurement comparison (between LA Techniques and NPL) for the return loss of a 20 dB attenuator

4.5.3 Transmission (attenuation) measurement

From equation (9), the uncertainty in the attenuation measurement of the 20 dB attenuator is ±0.046 dB. This value of uncertainty is used in Figure 4.19.

Using equations (5) and (6), the uncertainty in transmission phase is ±0.31°. This value of uncertainty is used in Figure 4.20, which shows the differences between the LA19-13-02 and NPL measured values.

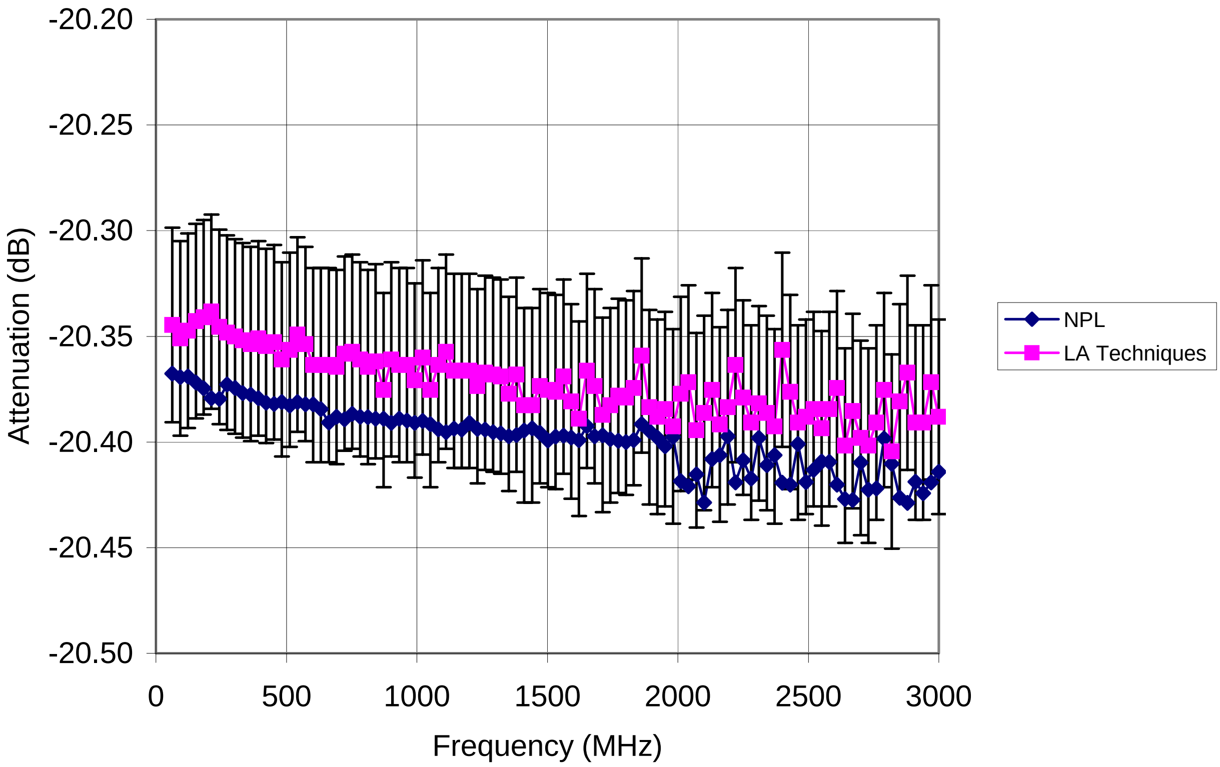

Figure 4.19: Measurement comparison (between LA Techniques and NPL) for the attenuation of a 20 dB attenuator

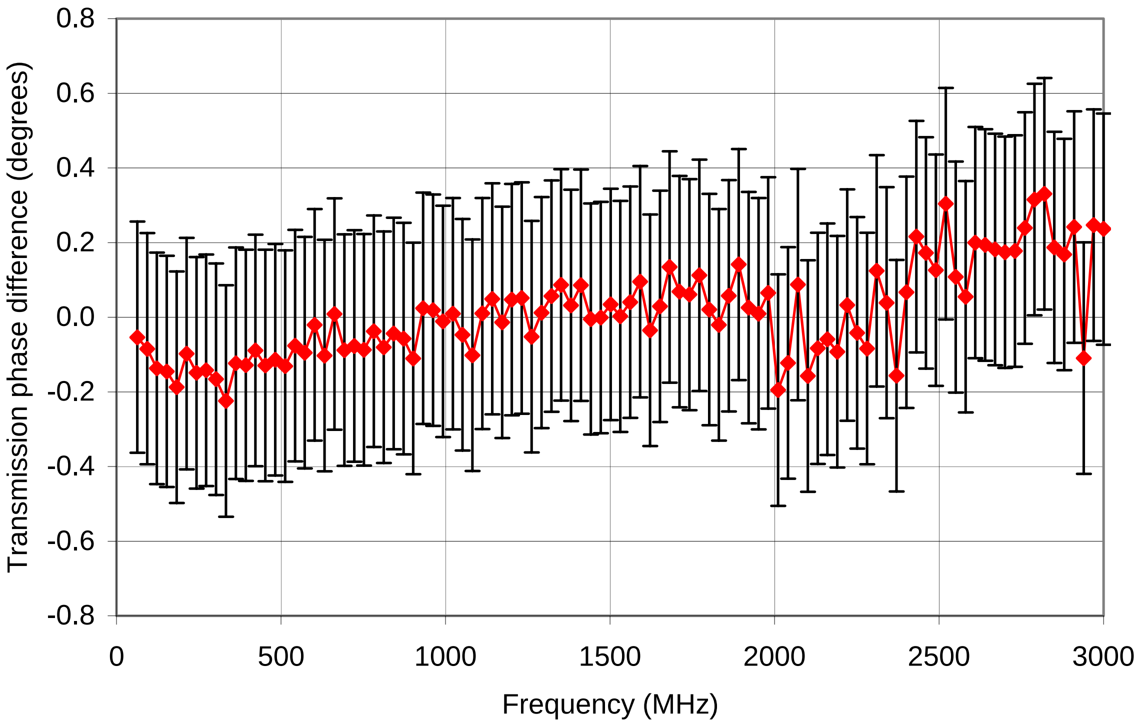

Figure 4.20: Measured difference (between LA Techniques and NPL) for the transmission phase of a 20 dB attenuator

4.6 Observations and summary

The comparisons in section 4.5 show good agreement between the LA19-13-02 VNA measurements and the NPL reference values (i.e. the uncertainty intervals for nearly all the LA19-13-02 measurements encompass the reference values provided by NPL). This shows that the sizes of the uncertainty intervals are realistic – being neither optimistic (i.e. too small) nor pessimistic (i.e. too large). This suggests that values for the uncertainty contributions (given in Tables 2 and 3) could be used as part of the specification of this type of VNA when used in conjunction with the LA Techniques' characterised load calibration kits [1].

The uncertainties in reflection measurements vary as a function of measured reflection. This is summarised in Table 6, below, which gives values at the extremes of the measurement range – i.e. complete absorption (i.e. |VRC| = 0) and complete reflection (i.e. |VRC| = 1).

Table 6: Summary uncertainties[7] for reflection measurements

Measured |VRC| (linear units)	Uncertainty in |VRC| (linear units)
0	±0.005 7
1	±0.020

The uncertainties in transmission measurements (i.e. attenuation) also vary as a function of measured attenuation. This is summarised in Table 6, below, in terms of values at selected levels of attenuation to 60 dB - beyond this level, the error due to isolation/cross-talk in the VNA dominates the overall uncertainty of measurement.

Table 7: Summary uncertainties[7] for transmission (attenuation) measurements

Measured attenuation (dB)	Uncertainty in attenuation (dB)
0	±0.021
20	±0.046
40	±0.054
60	±0.70

The values given in these two tables can therefore be used to express a Best Measurement Capability [5] for laboratories using this type of VNA for accredited measurements [6].

[7] These uncertainties define an interval estimated to have a level of confidence of 95 percent.

5 CARE OF THE CALIBRATION KITS

In order to maintain the performance of the VNA, it is important that the calibration kits are treated with care. Use the following guidelines when using the kits. Further information can be found in [11].

- Check the **pin depth** of the connectors: If possible, check that the pin depth is within the range 0" to -0.005" (i.e. –5 thou). A suitable gauge to check 2.92 mm connectors is required for this.
- Do not **over torque** the connectors: Always use a suitable torque spanner (set to provide a torque of between 5 lb.in and 9 lb.in). Never use pliers or an adjustable wrench.
- Do not subject the kit components to **mechanical shock**: Handle the kit components with care. Do not drop them.
- Regularly **clean the connectors**: Routinely inspect and carefully clean the connectors. It is recommended that a cotton swab damped in isopropyl alcohol is used to gently clean the connectors. Do not put lateral pressure on the centre conductor. Ensure that no material has been left behind in the connector after cleaning.

6 CONCLUSIONS

The economy calibration kits for use with the LA19-13-02 VNA can provide excellent measurement results for most applications. Measured results demonstrate a residual directivity of better than -48 dB, a residual test port match of at least -40 dB, a linearity of generally better than 0.002 dB/dB, a worst-case load match of -29 dB and worst-case crosstalk of -83 dB.

7 REFERENCES

[1] Nick Ridler and Nils Nazoa, "Using simple calibration load models to improve accuracy of vector network analyser measurements", *67th Automatic RF Techniques Group (ARFTG)* conference digest, pp 104-110, San Francisco, California, USA, June 2006.

[2] Nils Nazoa and Nick Ridler, "LA19-13-01 3 GHz VNA calibration and measurement uncertainty", LA Techniques Ltd, *Technical Note Ref LAP02*, January 2006. (Available from www.latechniques.com.)

[3] "EA guidelines on the evaluation of Vector Network Analysers (VNA)", *European co-operation for Accreditation*, publication reference EA-10/12, May 2000.

[4] "Guide to the expression of uncertainty in measurement", *International Organization for Standardization*, 1995.

[5] "Expression of the uncertainty of measurement in calibration", *European co-operation for Accreditation*, publication reference EA-4/02, December 1999.

[6] ISO/IEC 17025: 2005, "General requirements for the competence of testing and calibration laboratories".

[7] N M Ridler, "Converting between logarithmic and linear formats for reflection and transmission coefficients", *ANAMET ANA_tips Technical Note No 4*, October 2000. (Available from www.npl.co.uk/anamet.)

[8] N M Ridler and J C Medley, "An uncertainty budget for VHF and UHF reflectometers", *NPL Report DES 120*, May 1992. (Available from www.npl.co.uk.)

[9] "International vocabulary of basic and general terms in metrology", *International Organization for Standardization*, 2nd edition, 1993.

[10] Applying Error Correction to Network Analyser Measurements, *Agilent application note AN 1287-3.*

[11] "ANAMET connector guide – using coaxial connectors in measurement", downloadable free from www.npl.co.uk/anamet/connector_guide.html

