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## Residual directivity and Test Port Match: What are actually measuring?

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# RESIDUAL DIRECTIVITY AND TEST PORT MATCH: WHAT ARE WE ACTUALLY MEASURING?

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## 1. INTRODUCTION

In this report the traceability of Vector Network Analysers, as regards the characterisation of residual parameters, is examined. So far, the evaluation of residual Directivity and Test Port Match has been made with calibrated air lines, using the popular "ripple technique" [1]. Some modelisations are presented here which put in relationship the results obtained using this method with the cal kit standards used. Our intention is to show that the reflection coefficients of the cal kit are included into the ripple results. In this way, the possibility of moving from the ripple technique onto the knowledge (characterisation or calibration) of the cal kit standards is explored.

## 2. THE "STATE-OF-THE-ART"

Let us briefly summarise where we are with respect to the traceability of measurements made with a Vector Network Analyser. A Calibration Kit is used on a daily basis in order to put the measurement system in a known reference state. This can be regarded as providing the VNA with a reference for subsequent measurements. Normally the cal kit supplied by the manufacturer will be adequate.

In order to assess traceability, a full characterisation of the VNA has to be performed in terms of a number of contributions that are described in detail in [1]. These terms are then put together with the measurement results and combined into an uncertainty budget. Traceability comes from:

1) A set of calibrated air lines (for measurement of residual Directivity and Test Port Match using the ripple technique).
2) A calibrated step attenuator or set of calibrated fixed attenuators (for measurement of Linearity and Noise).

Also the use of a traceable Verification Kit or set of verification items is recommended. It is used as a means to verify the daily calibrations performed. Although verifying our calibrations provides us with greater confidence in our measurements, the fact of passing a verification <u>does not assess by itself traceability</u> to the national standards.

## 3. PROBLEMS WITH THE RIPPLE TECHNIQUE

Some problems arise when dealing with the ripple technique for measurement of residual parameters. First of all, there are cases where the ripple technique is not applicable. For example, for assessment of VNAs below 500 MHz, the lack of a complete interval – or period – of the ripple signal makes it impossible to determine its mean and peak-to-peak values. Generally speaking, the technique is not applicable to low-frequency Network Analysers.

One solution could be the use of longer air lines, even moving onto long semi-rigid cables fitted with precision connectors. However, the uncertainty in the determination of input and output reflection coefficient would be higher than in the case of beadless air lines.

For low-frequency Analysers, this is what some manufacturers suggest for assessment of uncertainty terms:

1) Measurement of Directivity: to measure a good-quality Load, after calibration. Directivity is assumed to be the measured value of the Load.
2) Measurement of Test Port Match: to perform a calibration and to extract the Source Match term from the calibration constants. This is independent of any subsequent measurement. However, in the author's opinion, these constants are by definition removed after calibration, and therefore do not remain present when performing a measurement.

Let us finally consider the ripple technique from the point of view of the measurement system (the VNA). The air lines do not form part of our daily measurements. They are only used for the purposes of assessing uncertainty terms. However, they are taken as impedance standards (e.g., their reflection coefficient must be taken into account in the effective Directivity). To express it in plain English: is it necessary to introduce an external element to assess our system?

## 4. LOAD EFFECTS OF RIPPLE PLOTS

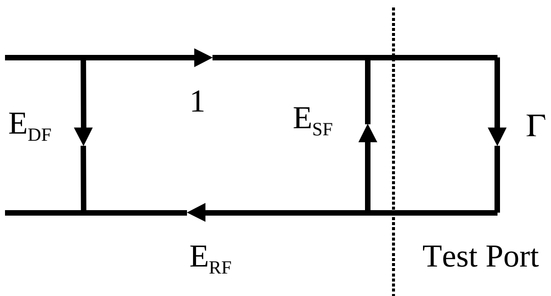
In [2] and subsequently in [3] some investigations are made about the influence of the terminations and air lines used for measurement of residual Directivity and Test Port Match. It is shown that the termination does have an effect on the results obtained, especially in the case of the Load used for evaluation of Directivity. The following Loads were used for the experimental results:

- Two Mismatches with different VSWRs
- Two Low Band Loads
- A Broadband Load previously used during calibration
- A Broadband Load not used during calibration

In their conclusions, the authors suggest the use of a Load with a "flat" frequency response, discarding those Loads with a significant VRC (e.g. mismatches).

## 5. THREE-TERM ERROR MODEL

As a reminder of the well-known error model for One-Port calibrations [4], let us include here the flow graph of the signals present.




Any device connected to the Test Port is measured by the VNA as:

$$\Gamma_m = E_{DF} + \frac{\Gamma \cdot E_{RF}}{1 - E_{SF} \cdot \Gamma}$$

Open-Short-Load Calibration: calling A, B and C the individual measurements of the Load, the Open and the Short, respectively:

$$\Gamma_{m(Load)} = E_{DF} + \frac{\Gamma_L \cdot E_{RF}}{1 - E_{SF} \cdot \Gamma_L} \equiv A \qquad \Rightarrow \qquad E_{DF} + A \cdot \Gamma_L \cdot E_{SF} + \Gamma_L \cdot E = A$$

$$\Gamma_{m(Open)} = E_{DF} + \frac{\Gamma_{OC} \cdot E_{RF}}{1 - E_{SF} \cdot \Gamma_{OC}} \equiv B \qquad \Rightarrow \qquad E_{DF} + B \cdot \Gamma_{OC} \cdot E_{SF} + \Gamma_{OC} \cdot E = B$$

$$\Gamma_{m(Short)} = E_{DF} + \frac{\Gamma_{SC} \cdot E_{RF}}{1 - E_{SF} \cdot \Gamma_{SC}} \equiv C \qquad \Rightarrow \qquad E_{DF} + C \cdot \Gamma_{SC} \cdot E_{SF} + \Gamma_{SC} \cdot E = C$$

Where $E = E_{RF} - E_{DF} \cdot E_{SF}$. Solving the resulting three-equation linear system with three unknowns, we can finally extract the matrix containing the three error terms as:

$$\begin{bmatrix} 1 & A \cdot \Gamma_L & \Gamma_L \\ 1 & B \cdot \Gamma_{OC} & \Gamma_{OC} \\ 1 & C \cdot \Gamma_{SC} & \Gamma_{SC} \end{bmatrix} \cdot \begin{bmatrix} E_{DF} \\ E_{SF} \\ E \end{bmatrix} = \begin{bmatrix} A \\ B \\ C \end{bmatrix}$$

$$[\Gamma] \cdot [E] = [M] \qquad \Rightarrow \qquad [E] = [\Gamma]^{-1} \cdot [M]$$

Measurement uncertainty: Once the error terms have been determined, it is possible to correct any *measured* reflection coefficient as:

$$\Gamma_{corr} = \frac{\Gamma_m - E_{DF}}{E_{RF} + E_{SF} \cdot (\Gamma_m - E_{DF})}$$

And the uncertainty in the measurement of Γ can be related to the uncertainty of the calibration standards [5]:

$$u_\Gamma = \left| \frac{(\Gamma - \Gamma_{OC}) \cdot (\Gamma - \Gamma_{SC})}{(\Gamma_L - \Gamma_{OC}) \cdot (\Gamma_L - \Gamma_{SC})} \right| \cdot u_L + \left| \frac{(\Gamma - \Gamma_{SC}) \cdot (\Gamma - \Gamma_L)}{(\Gamma_{OC} - \Gamma_{SC}) \cdot (\Gamma_{OC} - \Gamma_L)} \right| \cdot u_{OC} + \left| \frac{(\Gamma - \Gamma_L) \cdot (\Gamma - \Gamma_{OC})}{(\Gamma_{SC} - \Gamma_L) \cdot (\Gamma_{SC} - \Gamma_{OC})} \right| \cdot u_{SC}$$

Where $u_L$, $u_{OC}$ and $u_{SC}$ are the uncertainties with which the calibration items are known. Let us hence state things as follows:

NON-PERFECT KNOWLEDGE OF CALIBRATION ITEMS → INCORRECT DETERMINATION OF ERROR TERMS ($E_{DF}$, $E_{SF}$ AND $E_{RF}$) → MEASUREMENT OF Γ IS IN ERROR

In what follows we will try to apply this to the measurement of residual Directivity and Test Port Match. To do so, first the measurement system and the calibration items will be defined. Subsequently, the measurement of residual parameters will be simulated in order to see the effect of the calibration items on the aspect of the ripple signals obtained.

## 6. MEASUREMENT OF RESIDUAL DIRECTIVITY

### 6.1. Defining the system

- Calibration Kit (OSL): The nominal values considered for the Load, Open and Short are:

$$\Gamma_L = 0 \qquad \Gamma_{OC} = 1 \qquad \Gamma_{SC} = -1$$

- Error terms: defined in magnitude and phase. The phase of the tracking term has been modelled as the delay introduced by a transmission line of length 20 cm:

$$E_{DF} = 0.003\big|_{90^\circ} \qquad E_{SF} = 0.005\big|_{0^\circ}$$

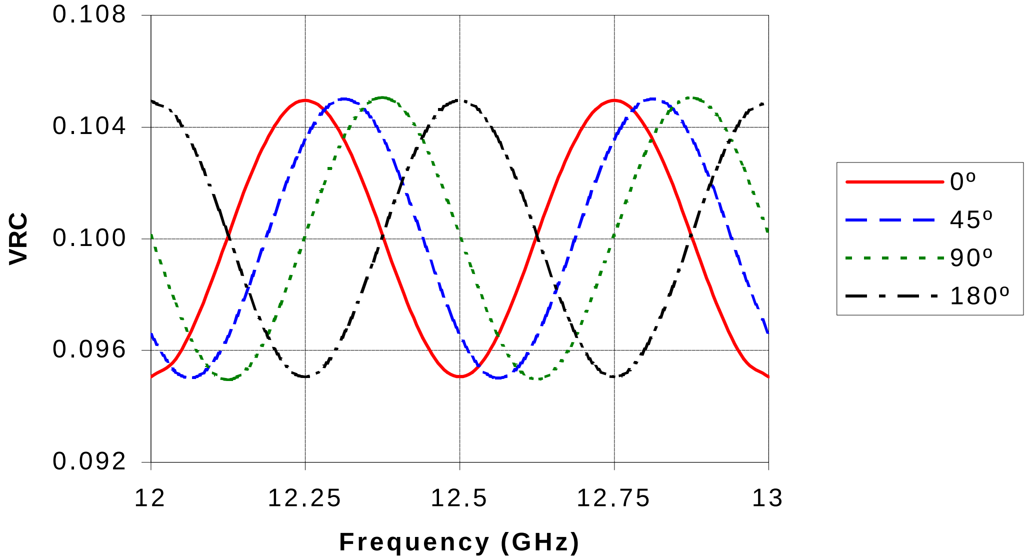
$$E_{RF} = 0.99 \cdot \left[\cos\left(\frac{2 \cdot 360^\circ \cdot L}{l}\right) + j \cdot sin\left(\frac{2 \cdot 360^\circ \cdot L}{l}\right)\right]$$

### 6.2.- How we measure residual Directivity

- Mismatch termination: a termination of reflection coefficient $\Gamma_T$=0.1.
- Air line: the length of the air line is 30 cm, so the reflection coefficient presented to the Test Port is modelled as:

$$\Gamma = \Gamma_T \cdot \left[\cos\left(\frac{2 \cdot 360^\circ \cdot L_{air\ line}}{l}\right) + j \cdot sin\left(\frac{2 \cdot 360^\circ \cdot L_{air\ line}}{l}\right)\right]$$

### 6.3.- Example I

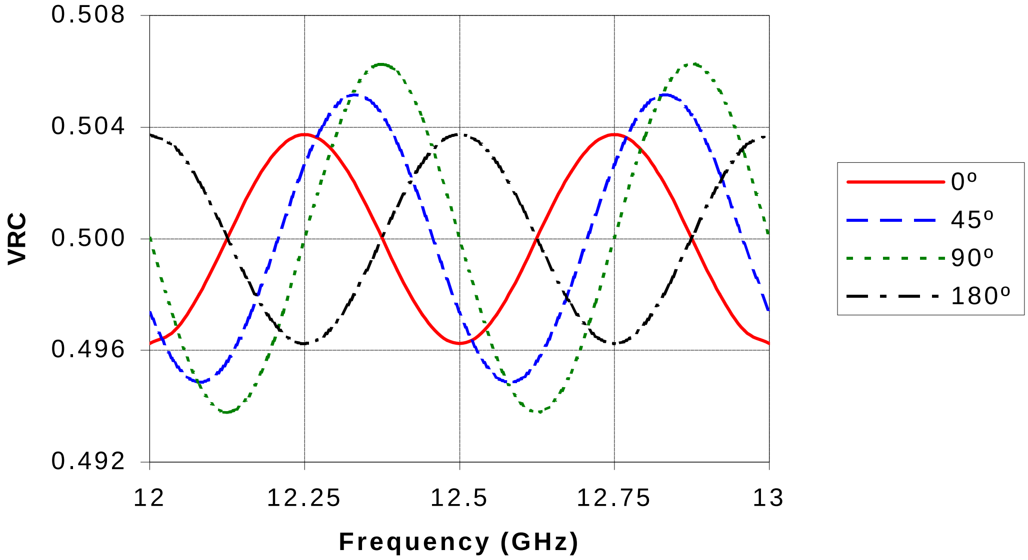



In this example the Load used in the calibration is a good one, with reflection coefficient $\Gamma_L$=0.005$|_{\Phi L}$. The curves shown are for several values of $\Phi_L$. Let us recall the formula that gives us the error in the determination of $\Gamma$ as a function of the errors in the knowledge of $\Gamma_L$:

$$e_\Gamma = \left(\Gamma^2 - 1\right) \cdot e_L$$

The measured residual Directivity is 0.005 in all four cases, which coincides with the VRC of the calibration Load.

6.4.- Example II

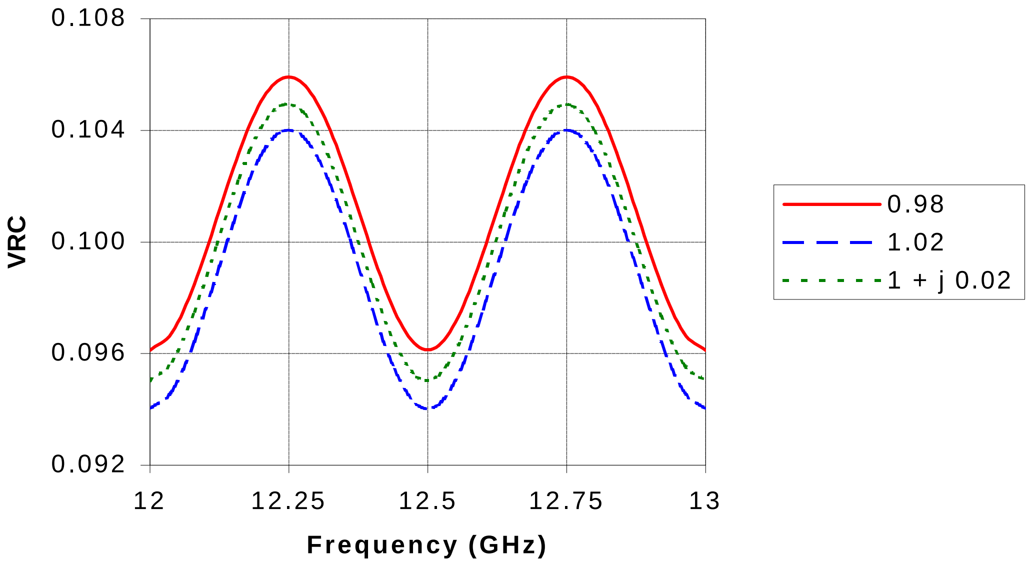



In this example the value of the mismatch termination has been changed. Let us assume a theoretical reflection coefficient of $\Gamma_T$=0.5. The rest of parameters remain the same. Looking at the above formula:

$$e_\Gamma = \left(\Gamma^2 - 1\right) \cdot e_L$$

We realise that the measured residual Directivity ranges from 0.00375 (for $\Phi_L$=0º and 180º) to 0.00625 (for $\Phi_L$=90º). These are the approximate limits of the above expression complex quantities! – when Γ is substituted for $\Gamma_T$ and $\varepsilon_L$ for $\Gamma_L$: $0.00375=(1-0.5^2)\cdot$ 0.005 and $0.00625=(1+0.5^2)\cdot$ 0.005. All vectorial combinations between $\Gamma_T$ and $\Gamma_L$ are possible due to the effect of the air line.

6.5.- Example III




So far, we have seen that the peak-to-peak ripple seems to be a function of both the calibration Load and the termination used. In this example the Load used in the calibration is $\Gamma_L$=0.005$|_{0^\circ}$ and the termination is again $\Gamma_T$=0.1. The three curves are for different Open Circuits, whose complex reflection coefficients are shown in the legend (all lying within a circle of radius 0.02). The error in the determination of $\Gamma$ as a function of the errors in the knowledge of $\Gamma_L$ and $\Gamma_{OC}$ is:

$$e_\Gamma = \left(\Gamma^2 - 1\right)\cdot e_L - \frac{\Gamma\cdot(1+\Gamma)}{2}\cdot e_{OC}$$

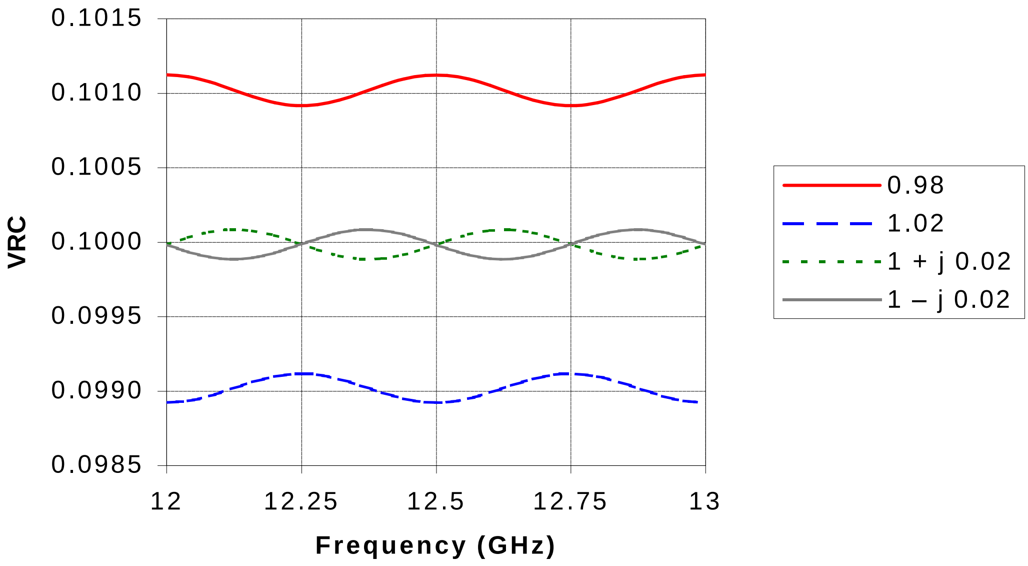
The measured residual Directivity is approximately given by the reflection coefficient of the Load, 0.005. However, the mean value of the ripple signal changes slightly depending on the complex value of the Open Circuit. If we take the first curve, we see that the maximum and minimum values are approximately given by the following expressions, in which we have substituted $\Gamma$ for $\Gamma_T$, $\varepsilon_L$ for $\Gamma_L$ and $\varepsilon_{OC}$ for $\Gamma_{OC}$:

$$0.1 + \left(1 - 0.1^2\right)\cdot 0.005 + \frac{0.1\cdot(1-0.1)}{2}\cdot 0.02 = 0.10585$$

$$0.1 - \left(1 - 0.1^2\right)\cdot 0.005 + \frac{0.1\cdot(1+0.1)}{2}\cdot 0.02 = 0.09615$$

We notice that the effect of the Open Circuit, especially when using good terminations to obtain the ripple signal, is smaller than the influence of the calibration Load.

6.6.- Example IV




Let us now try to isolate the effect of the calibration Open. The reflection coefficient of the Load has been assumed to be $\Gamma_L$=0. Four Open Circuits have been considered, again within a circle of radius 0.02, and their values are shown in the legend. The error in the determination of $\Gamma$ as a function exclusively of the error in the knowledge of $\Gamma_{OC}$ is:

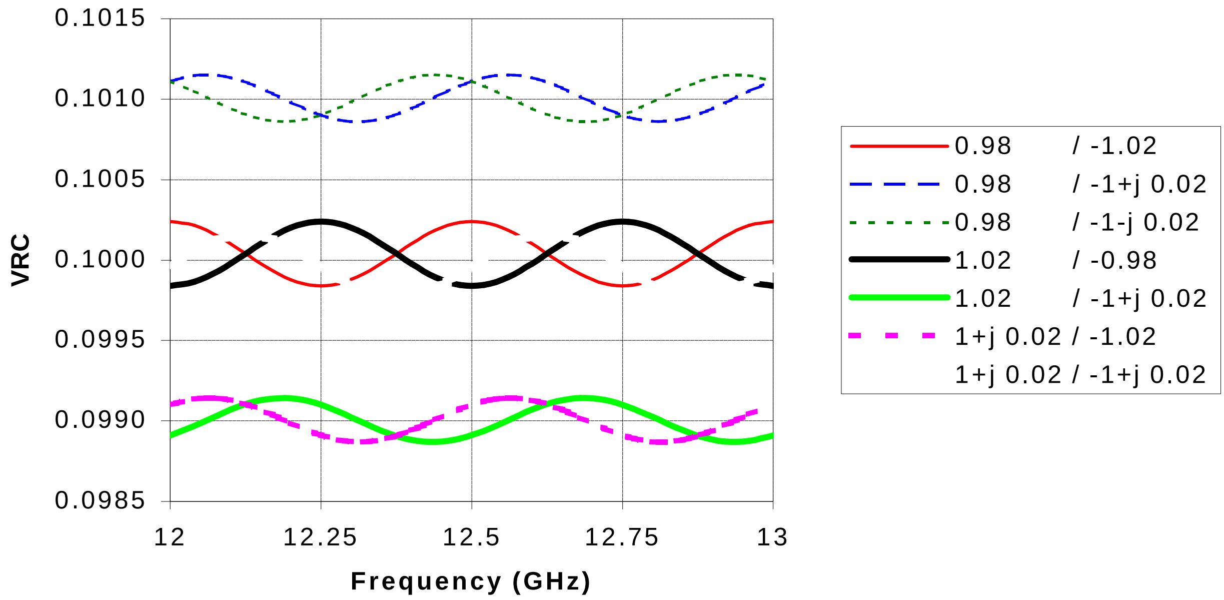
$$e_\Gamma = -\frac{\Gamma \cdot (1+\Gamma)}{2} \cdot e_{OC}$$

The measured residual Directivity is 0.0001 in all cases. If we substitute $\Gamma$ for $\Gamma_T$ and $\varepsilon_{OC}$ for $\Gamma_{OC}$, allow for the combination in-phase and counter-phase and compute the peak-to-peak value:

$$\left[\frac{0.1 \cdot (1+0.1)}{2} \cdot 0.02 - \frac{0.1 \cdot (1-0.1)}{2} \cdot 0.02\right] / 2 = 0.0001$$

All vectorial combinations between $\Gamma_T$ and $\Gamma_{OC}$ are possible due to the effect of the air line.

6.7.- Example V




Here the combined effect of the Open and the Short circuit can be seen. The Load has been assumed to be ideal. The legend shows the complex values considered for the Open and the Short, respectively. The error in the determination of Γ is given by:

$$e_{\Gamma} = -\frac{\Gamma \cdot (1+\Gamma)}{2} \cdot e_{OC} + \frac{\Gamma \cdot (1-\Gamma)}{2} \cdot e_{SC}$$

The measured residual Directivity ranges from 0.00014 to 0.00020. Looking at the first curve, for example, the maximum and minimum values can be approximately obtained substituting Γ for $\Gamma_T$, $\varepsilon_{OC}$ for $\Gamma_{OC}$ and $\varepsilon_{SC}$ for $\Gamma_{SC}$ in the above formula:

$$0.1 + \frac{0.1 \cdot (1+0.1)}{2} \cdot 0.02 - \frac{0.1 \cdot (1-0.1)}{2} \cdot 0.02 = 0.1002$$
$$0.1 + \frac{0.1 \cdot (1-0.1)}{2} \cdot 0.02 - \frac{0.1 \cdot (1+0.1)}{2} \cdot 0.02 = 0.0998$$

Which results in a residual Directivity of 0.00020.

## 7. MEASUREMENT OF RESIDUAL TEST PORT MATCH

7.1. Defining the system

- Calibration Kit (OSL): The nominal values considered for the Load, Open and Short are again:

$$\Gamma_L = 0 \qquad \Gamma_{OC} = 1 \qquad \Gamma_{SC} = -1$$

- Error terms: defined in magnitude and phase. The phase of the tracking term has been modelled as the delay introduced by a transmission line of length 20 cm. Note that the source match term $E_{SF}$ has been changed in order to show that it does not affect the results of the simulation:

$$E_{DF} = 0.003|_{90^\circ} \qquad E_{SF} = 0.2|_{0^\circ}$$

$$E_{RF} = 0.99 \cdot \left[ \cos\left( \frac{2 \cdot 360^\circ \cdot L}{l} \right) + j \cdot sin\left( \frac{2 \cdot 360^\circ \cdot L}{l} \right) \right]$$

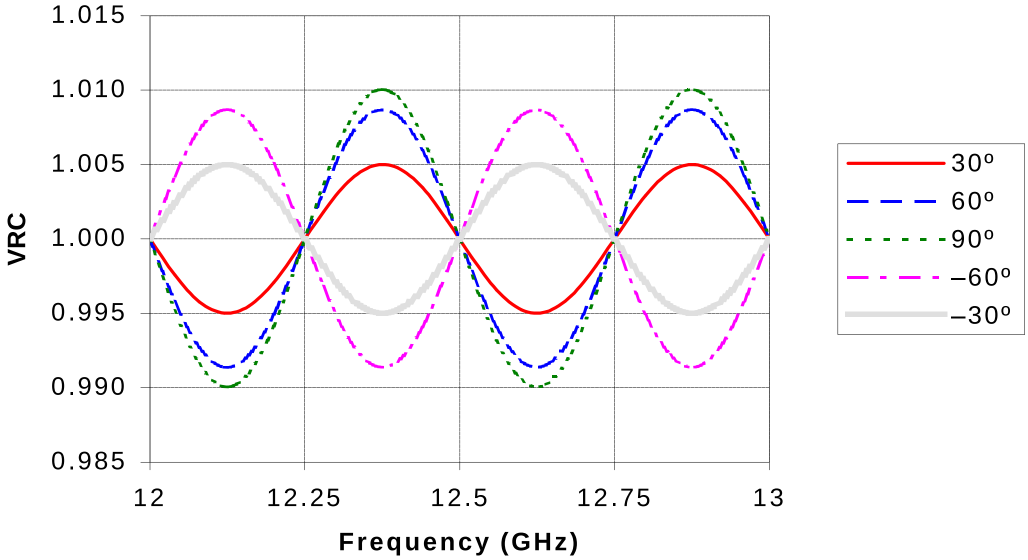
7.2.- How we measure residual Test Port Match

- Mismatch termination: an ideal Short termination with reflection coefficient $\Gamma_T$=1.

- Air line length: 30 cm. The reflection coefficient presented to the Test Port is modelled as:

$$\Gamma = \Gamma_T \cdot \left[ \cos\left( \frac{2 \cdot 360^\circ \cdot L_{air\ line}}{l} \right) + j \cdot sin\left( \frac{2 \cdot 360^\circ \cdot L_{air\ line}}{l} \right) \right]$$

7.3.- Example VI




The Load used in the calibration is $\Gamma_L$=0.005$|_{\Phi L}$ (the curves shown are for several values of $\Phi_L$). The error in the determination of Γ as a function of the errors in the knowledge of $\Gamma_L$ is again:

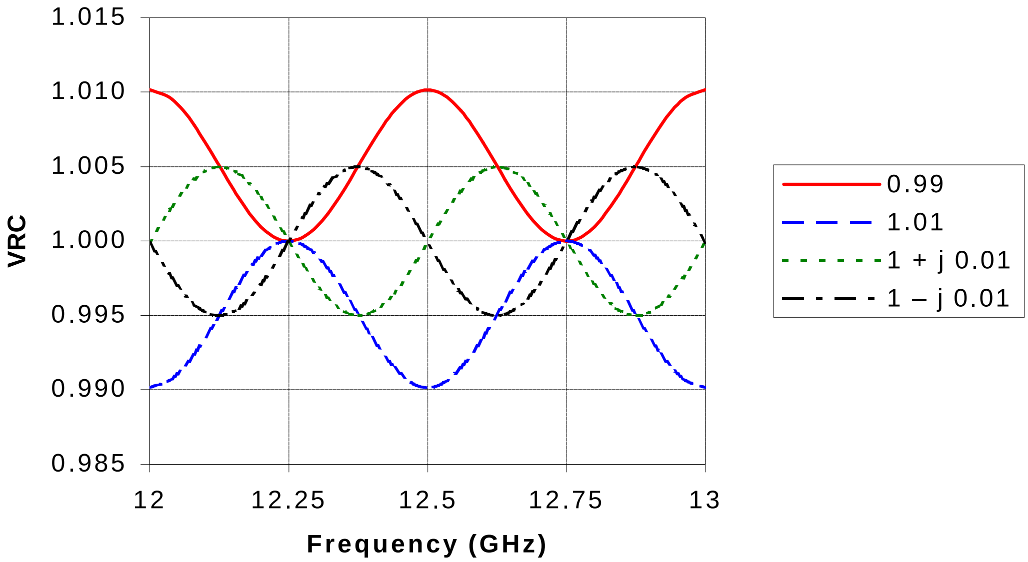
$$e_\Gamma = \left(\Gamma^2 - 1\right) \cdot e_L$$

The measured residual Test Port Match ranges from 0.005 (for $\Phi_L$=30º and –30º) to 0.010 (for $\Phi_L$=90º). A value of $\Phi_L$=0º or 180º cancels out the ripple signal. The peak-to-peak value can be predicted from the amplitude of the following complex expressions, in which we substitute $\Gamma$ for $\Gamma_T$ and $\varepsilon_L$ for $\Gamma_L$:

For $\Phi_L$=30º: $\left(1|_{30^\circ}\right)^2 - 1 = -0.5 + j\cdot\frac{\sqrt{3}}{2}$ $\quad \left|-0.5 + j\cdot\frac{\sqrt{3}}{2}\right|\cdot 0.005 = 0.005$

For $\Phi_L$=60º: $\left(1|_{60^\circ}\right)^2 - 1 = -1.5 + j\cdot\frac{\sqrt{3}}{2}$ $\quad \left|-1.5 + j\cdot\frac{\sqrt{3}}{2}\right|\cdot 0.005 = 0.00866$

7.4.- Example VII



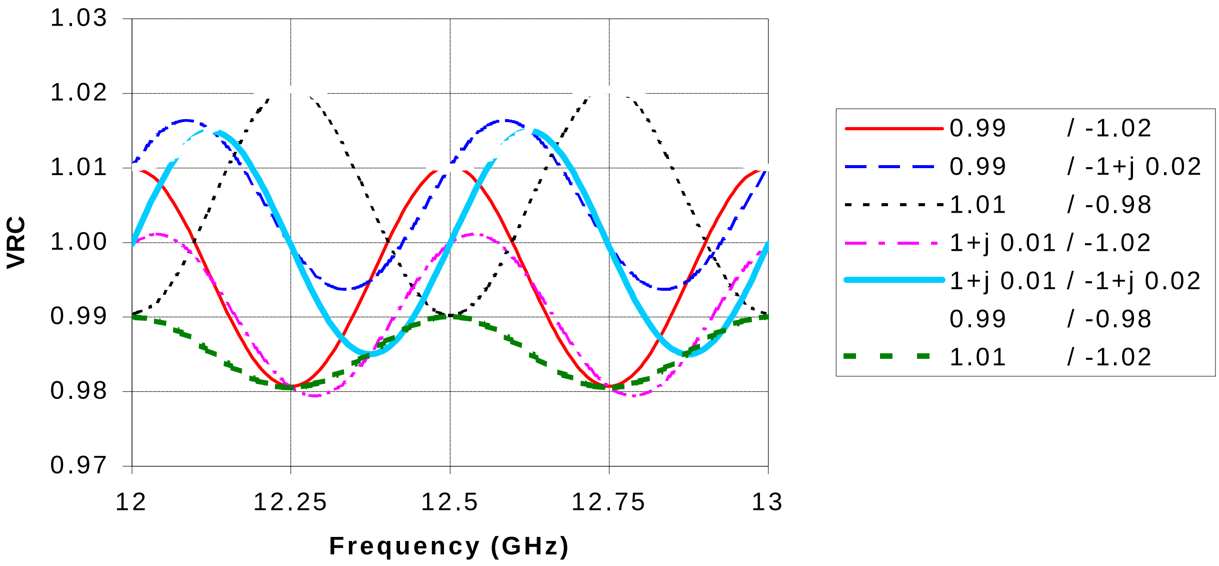

Let us now isolate the effect of the Open circuit used in the calibration. Four complex values have been represented. They all lie within a circle of radius 0.01 around the nominal value. Both the Load and the Short are assumed to be ideal. The error in the determination of $\Gamma$ as a function of the error in the knowledge of $\Gamma_{OC}$ is:

$$e_\Gamma = -\frac{\Gamma\cdot(1+\Gamma)}{2}\cdot e_{OC}$$

The measured residual Test Port Match is approximately 0.005 in all four cases. If we substitute $\Gamma$ for $\Gamma_T$ and $\varepsilon_{OC}$ for $\Gamma_{OC}$, allow for the combination in-phase and counter-phase and compute the peak-to-peak value:

$$\left[\frac{1\cdot(1+1)}{2}\cdot 0.01 - \frac{1\cdot(1-1)}{2}\cdot 0.01\right]/2 = 0.005$$

7.5.- Example VIII




Here the combined effect of the Open and the Short circuit can be seen. The Load has been assumed to be ideal. The legend shows the complex values considered for the Open and the Short, respectively ($\Gamma_{OC}$ is within a circle of radius 0.01 around the nominal value, and $\Gamma_{SC}$ within 0.02). The error in the determination of $\Gamma$ is given by:

$$e_\Gamma = -\frac{\Gamma \cdot (1+\Gamma)}{2} \cdot e_{OC} + \frac{\Gamma \cdot (1-\Gamma)}{2} \cdot e_{SC}$$

The measured residual Test Port Match ranges from 0.005 to 0.015. If we take for example the first curve, the maximum and minimum values are approximately given by:

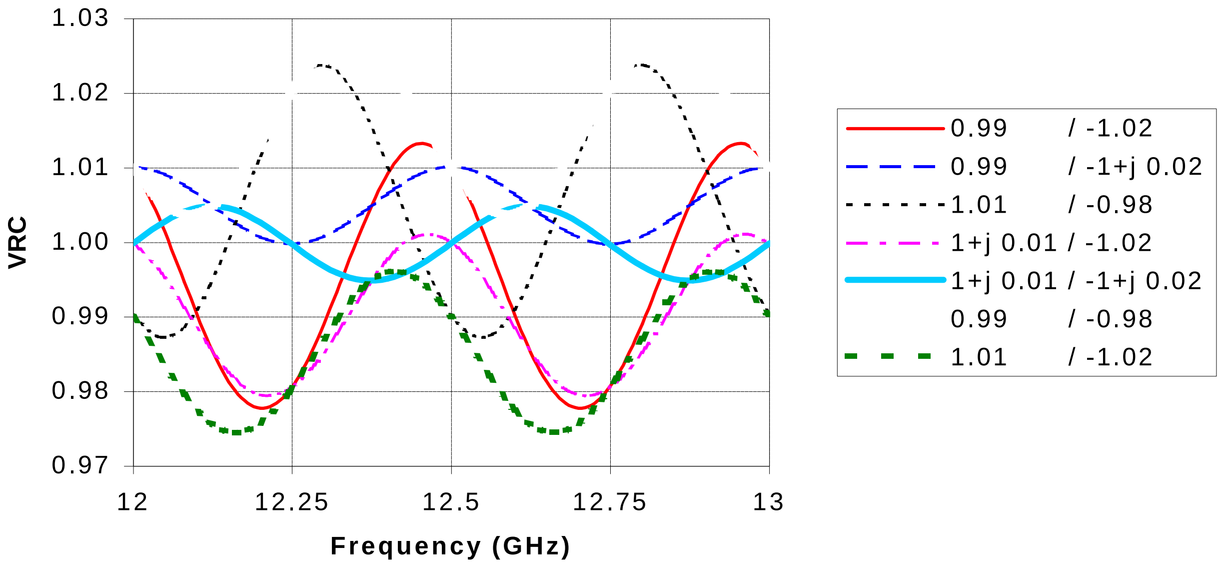
$$1 + \frac{1 \cdot (1+1)}{2} \cdot 0.01 - \frac{1 \cdot (1-1)}{2} \cdot 0.02 = 1.01$$
$$1 + \frac{1 \cdot (1-1)}{2} \cdot 0.01 - \frac{1 \cdot (1+1)}{2} \cdot 0.02 = 0.98$$

Which results in a residual Test Port Match of 0.015. Similarly, for the third curve shown in the legend:

$$1 - \frac{1 \cdot (1-1)}{2} \cdot 0.01 + \frac{1 \cdot (1+1)}{2} \cdot 0.02 = 1.02$$
$$1 - \frac{1 \cdot (1+1)}{2} \cdot 0.01 + \frac{1 \cdot (1-1)}{2} \cdot 0.02 = 0.99$$

Which gives the same Test Port Match.

7.6.- Example IX



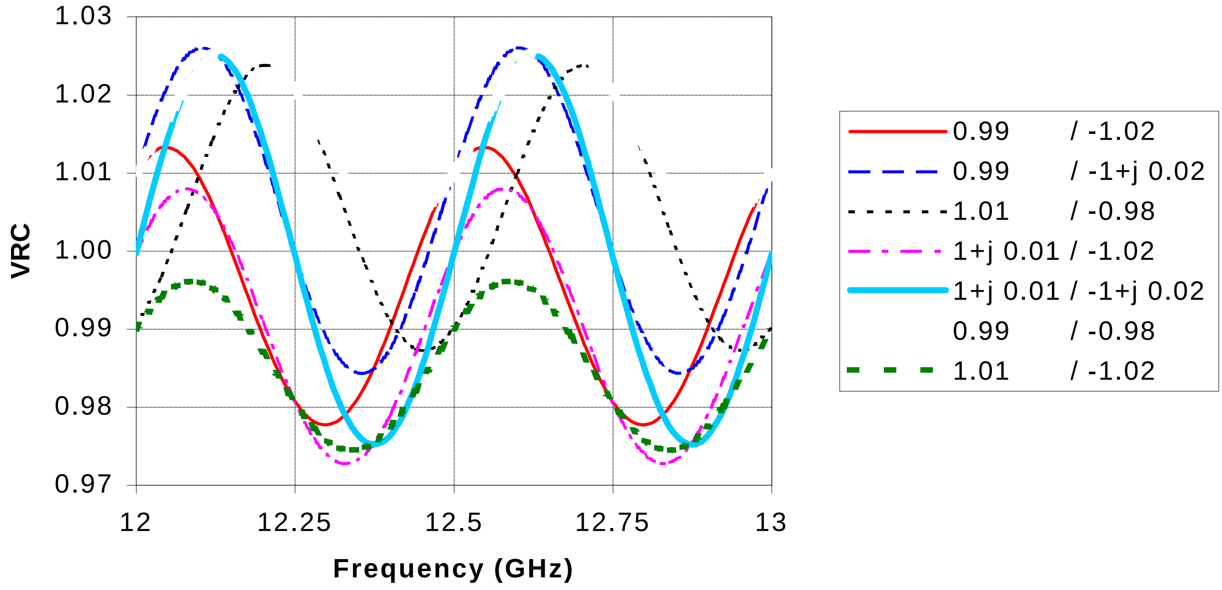

The same combinations as in the previous example are repeated here. The Load has been assigned the non-ideal value $\Gamma_L = 0.005\,|_{90^\circ}$ in order to show the influence of the calibration Load in the measurement of Test Port Match. The error in the determination of Γ is given by:

$$e_\Gamma = \left(\Gamma^2 - 1\right)\cdot e_L - \frac{\Gamma\cdot(1+\Gamma)}{2}\cdot e_{OC} + \frac{\Gamma\cdot(1-\Gamma)}{2}\cdot e_{SC}$$

The measured residual Test Port Match ranges from 0.005 to 0.018.

It is difficult to predict the theoretical values of the ripple, since interactions between three complex signals are involved. However, it can be observed that each curve in example IX is the superposition of the corresponding curve in example VIII with the third curve of example VI. Note that both examples contain separately the effect of the calibration Load and that of the Open and the Short. The superposition principle can be thus applied.

7.7.- Example X




This time the Load has been assigned the reversed phase, $\Gamma_L=0.005|_{-90^{\circ}}$ in order to show how the superposition of specific curves of example VI with those in example VIII can increase the overall peak-to-peak ripple.

The observed residual Test Port Match ranges from 0.011 to 0.025.

## 8. CONCLUSIONS

We have shown that the measurement of residual Directivity and Test Port Match is dependent on the calibration items, as well as on the termination used during the ripple assessment. For measurement of Directivity the calibration Load becomes critical, whereas the effect of the Open and the Short circuits becomes attenuated if use is made of a good termination, in agreement with [2] and [3]. This can be predicted by means of formulas that relate the error in the determination of Γ as a function of the knowledge of the calibration items. For determination of Test Port Match the effect of the three calibration items can add up in-phase under certain conditions.

In the author's opinion, residual parameters do not actually exist. Directivity and Test Port Match, as well as Tracking, are error terms which are compensated for once the calibration has been performed and is active. It is a convention to denote as "residual" any errors which still remain present. But these are due to the non-perfect knowledge of the calibration items. If the items were perfectly known – not if they were perfect! – no residual error would remain.

In other words, measurement of residual parameters can be regarded as "extracting the effect of the cal kit, which remains present after calibration". At the cost of:

- Introducing an external element which is not taking part of subsequent measurements, such as the air line.
- Having this external element characterised (insertion losses and reflection coefficients in both ends).
- Accounting for additional, unwanted reflections which will be present on the ripple signal.
- Introducing a second external element which also affects the ripple signal, such as the termination.

- Dealing with a low-precision scalar method, the ripple technique, which provides us with only a rough estimate of residual parameters over a frequency range.
- Being limited to the higher frequencies, since the ripple technique is not applicable below say 500 MHz.

Since formulas are available that relate the uncertainty of every measurement performed with the VNA to the cal kit standards, why not change from using the ripple technique to a technique based on our knowledge of the cal kit? This knowledge can be gained from a calibration certificate or, alternatively, through manufacturer's characterisation. A calibrated Calibration Kit would assure traceability to national standards, with no *a priori* frequency limitations.

The whole complex approach can be implemented with the aid of any general-purpose programming language. In a first approach, only the uncertainty calculations would be performed "externally" to the VNA, based on the uncertainty data gathered from the calibration certificates of the cal kit. But if we wish to take full advantage of the knowledge of the calibration items, one step forward would be to perform our daily calibrations externally, in order to include the reflection coefficients of the cal kit items in with the calibration constants. This means making use of a computer, instead of the VNA firmware, to perform, activate and store calibrations.

One final question: should some of these topics be incorporated into forthcoming versions of the EA Guidance Document [1]? Some suggestions might be:

- The importance of the Calibration Kit and the recommendation to have it calibrated, just as the Verification Kit, in order to claim traceability to national standards.
- To explore the alternatives to the ripple technique when this method is not applicable (e.g. low-frequency Analysers).
- To relate the residual Directivity and Test Port Match to the cal kit uncertainties.
- How to trace the measurements performed with the VNA to the calibration standards. Modifications of the mathematical treatment of residual contributions for One-Port calibrations.

## 9. ACKNOWLEDGEMENTS

The author wishes to thank Jan de Vreede and all the people who made possible the issue of reference [1]. Some of the viewpoints included in the present Report are mere suggestions, made with the aim of drawing the attention of the ANAMET community to some of the topics most frequently encountered when dealing with calibrated VNAs.

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