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Return Loss Measurements on Non-insertable Two-port Devices

by David Hall (AMP, Harlow, UK)

1. Introduction

In particular this Note refers to non-insertable, reciprocal, coaxial two-port devices, although no doubt some of its content can also be applied to non-coaxial devices. At some points the Note also makes specific reference to devices which are of low loss and low reflection.

There are several methods available for measuring non-insertable devices, but none of them is fully satisfactory. They can be compared for their convenience and ease of use, and for their accuracy, as quantified by the measurement uncertainty achieved by each method. Before considering non-insertable devices, this Note will briefly examine the measurement uncertainty for a 2-port insertable device, which will be denoted as U_o.

2. Two-port Insertable Devices

The measurement uncertainty, U_o, for reflection measurements on an insertable 2-port device will be established as a bench-mark. According to Ref. (1), ignoring the random contributions for the present,

$$U_o = D_S + T_S\Gamma_M + M_S\Gamma_M{}^2 + S_{21}{}^2\Gamma_L ,$$

where D_S is the effective source directivity, T_S is the source tracking and linearity, Γ_M is the measured reflection coefficient, M_S is the effective source match, S_{21} is the attenuation of the DUT, and Γ_L is the effective load reflection coefficient, which can be taken to be equal to the effective load directivity, D_L.

3. Non-insertable Devices: One-port Technique

In this method a simple one-port calibration is performed, the DUT is attached and a low reflection fixed load is attached to the second port of the DUT. The uncertainty expression for a one-port measurement is (1):

$$V_o = D_S + T_S\Gamma_M + M_S\Gamma_M{}^2 ,$$

but we also have to take into account the fact that the termination used is imperfect. This then adds in an extra term, $S_{21}{}^2\Gamma_L$, where S_{21} is as before, and Γ_L is the reflection coefficient for the physical load, rather than for the VNA, as before. Thus the uncertainty expression remains in exactly the same form as that for the insertable two-port. If Γ_L happened to be the same for both situations, the uncertainties would be identical.

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Thus far, if only the reflection coefficient of the 'input' port of the 2-port DUT is of interest, the two methods give **potentially** identical uncertainties. However the 2-port method measures the reflection coefficients of both ports of the insertable device, while the non-insertable device would have to be measured from each end separately to obtain the same information. If the DUT is of low loss, however, it may be noted that the reflection coefficients from the two ends must be very similar, and there is the possibility of measuring from one end only and deducing the return loss at the other end,

but with a slightly larger uncertainty. In the worst possible case the two return losses can differ only by twice the attenuation of the DUT, but in practice this is extremely unlikely. Typically, for example, if the attenuation is 1 dB, an acceptable estimate of the second port reflection coefficient may be obtained by a single one-port measurement, as the calculations and trials may very well show that a difference of only 0.5 dB is likely to occur. Furthermore, in most cases where the DUT is a cable with connectors at each end a further feature can be noted. Any cable assembly is one of two types: two identical connectors, with individual return losses that are almost always closely matched; or two different connectors, which in most cases will have individual return loss characteristics that are different from each other in a consistent way. In the former case the return loss is almost guaranteed to be virtually the same from either end; in the latter case it is almost guaranteed to be better at one end than the other, in a predictable way. In this case the measurement should be made from the worst end, and only the return loss at this end needs to be measured.

However, given the use of the word 'almost', there will be situations in which a detailed uncertainty analysis would have to be performed in order to guarantee that a certain specification has been exceeded to a particular level of confidence, and it would undoubtedly be considerably more complex than before.

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Consider now the situation in which the DUT has very low loss and low reflection. It is now clear that the uncertainty for either the insertable, full 2-port case or the non-insertable 1-port case is approximately,

$$U_o = V_o = D_S + \Gamma_L ,$$

where D_S is the effective source directivity, and Γ_L is the effective or actual load reflection coefficient, which in the full 2-port case can be taken to be equal to the effective load directivity, D_L. We note from Ref. (2, 3) that to a good approximation it is the reflection coefficients of the cal. kit loads that determine the (residual) directivities, D_S and D_L, of the VNA. D_S and D_L can therefore be taken to be equal to the reflection coefficients of the calibration loads, Γ_{MALE} and Γ_{FEMALE}. Now we have, approximately,

$$U_o' = \Gamma_{MALE} + \Gamma_{FEMALE} \qquad \text{for the 2-port insertable case, or}$$
$$V_o' = \Gamma_{MALE} + \Gamma_L \text{ or } \Gamma_{FEMALE} + \Gamma_L \quad \text{for the 1-port case.}$$

The calibration loads may be either fixed loads or sliding loads; the latter can be assumed to be better than fixed loads at the frequencies at which they are usable (say above 2-3 GHz). The load used for testing DUT's using the 1-port cal. (Γ_L) is necessarily a fixed load for all frequencies, and is now assumed to be equal in performance to the fixed loads in the calibration kit. Now we can draw some useful initial conclusions for (all) non-insertable devices:

- If the measurement is to be at low frequencies – less than 2-3 GHz – the reflection coefficients of the loads will be the same, and thus the measurement uncertainties will be the **same for both techniques**, apart from the considerations noted above regarding the return loss at the second port of the DUT.
- If the measurement is to be at higher frequencies, and sliding loads are available, the full 2-port cal. is better than the 1-port technique, **assuming** the method that is used to allow a 2-port measurement to take place on a non-insertable DUT does not degrade the measurement. **This assumption is never entirely true.**

4. Test Methods for 2-port Measurements of Non-insertable Devices

In this section we introduce the possibility of the non-insertable device also being transitional. Such devices are ones in which the connectors at each port are of different series, rather than merely being same-sex connectors within one series.

For reference, first of all, we may note that the 1-port Calibration-plus-Fixed-Load Technique, referred for short as the 1-port Technique, is attractive because it is fast, easy to perform and will accommodate a wide range of different connector types, making it excellent for transitional devices. Normally only the return loss is measured, though the insertion loss can also be measured if the far end of the DUT is terminated with an open circuit or short circuit instead, giving a return loss approximately equal to twice the insertion loss. It can also accommodate phase length measurements, again by deduction from the reflection phase measurement.

The first true 2-port method to consider for non-insertable devices is the Adaptor Removal technique. This leads to a two-port calibration with full 12-term error correction, and is therefore often cited as being the most accurate technique. Since two conventional 2-port calibrations are performed within this technique, however, its measurement uncertainty can reasonably be estimated to be approximately twice U_0. It is undoubtedly the most complicated and time-consuming method to perform, but may be the only acceptable technique in some cases, particularly transitional devices.

Secondly, one can use the Adaptor Substitution technique. This can be a useful method, particularly when quick, but fairly rough measurements are required. It would be hard to produce a general system to calculate the measurement uncertainty, since this can be expected to be dominated by the difference between the two adaptors that are substituted. The similarity of these adaptors is likely to vary considerably from one measurement situation to the next. The technique will handle transitional devices, though this only makes the task of designing equal adaptors that much harder.

A third method exists, which assumes the existence of a near-perfect adaptor, which has the same connectors as the DUT. It is most appropriate when these are simply two identical connectors, as in this case a short air-line can be used, and a high degree of perfection can be achieved. The air-line may either be used **within** the cal., with the network analyser's cal. kit definition being modified to include it (Finite Thru), or it may be used **during** the cal. **without** modifying the cal. kit definition (for instance two female testports could be created after the cal. by removing a near-perfect male to male air-line from an originally female testport). The present author has tried the former method, but obtained poor results; possibly the latter variant would be more successful. It is possible to view this technique as a close relative of the Adaptor Removal or Substitution methods. As noted above, this technique is not well suited to transitional devices.

There is also a fourth method, which has not been widely written about or, perhaps, used. It is the technique of using gating in the Time Domain and then transforming back into the Frequency Domain. If the calibration and DUT performance are sufficiently broadband, and if air-lines or other reliable lines are placed before and after the DUT to isolate it, it could be very accurate. It will also accommodate transitional devices well. Calculating the measurement uncertainty is beyond the scope of this document, but the method should be borne in mind, although the assumption of the existence of good air-lines implies that the third method, above, is also possible and is perhaps more flexible unless the DUT is transitional.

In conclusion, if it is absolutely necessary to perform a 2-port calibration in order to measure a DUT adequately, one must make a difficult choice from several methods. If the device is transitional this limits the choice a little, and if it is difficult to obtain or construct good adaptors or air-lines this limits the choice a great deal. However every situation is different, and no firm course of action can be advocated, except as follows:

> - If measurements are to be made at frequencies where sliding loads are available, the full 2-port cal. is better than the 1-port technique, assuming the method that is used to allow a 2-port measurement to take place does not degrade the measurement. This assumption is never entirely true, as noted in the above discussion, and the decision to be made is whether the increased complexity and uncertainty arising from the method adopted can be justified. If the difference between the fixed load and the sliding load is very small, **any** additional uncertainty contribution is quite likely to remove that potential advantage and turn to disadvantage.

5. References

1. J P M de Vreede, ANAMET Report 019, "Draft procedure for the assessment of vector network analysers (VNA)".
2. Manuel Rodriguez, ANAMET Report 020, "Three-term error correction in one-port calibrations".
3. Karel Drazil, ANAMET Report 021, "One-port calibration: non-ideal standards and residual error terms".