TECHNICAL ARTICLE

Techniques for VNA Measurements of Non-insertable Devices

While the simplest coaxial two port device to measure on a vector network analyzer (VNA) would be insertable (i.e., one male and one female connector), these are often in a minority of the devices to be tested. As a result, adapters or some other techniques are required during the calibration. In non-coaxial and mixed connector scenarios, the problems get even worse. Adapters, fixtures, and other structures are often needed and their mathematical characterization and removal is usually required. The intent of this document is to explore some of the options available to deal with these situations and their relative performance attributes. With the exception of a few items (noted in the text), all of the techniques apply to the 37XXX Lightning series and MS462XX Scorpion series of VNAs as well as the ME7808X Panorama broadband system.

Introduction

In some sense, the simplest 2-port VNA calibration scenario consists of two good cables ending in M and F connectors (ignoring the possibility of sexless connectors which, of course, is even easier). The thru step in such a calibration merely requires connecting the two cable-ends together.

Unfortunately, this rarely happens in practice. Many connectorized DUTs have the same sex connector thus requiring a similar symmetry at the calibration planes. In non-coaxial scenarios, things get even more complex. The DUT may need to be interfaced through an unusual fixture or probe assembly and calibration standards in the native DUT environment are not readily available. The DUT may also have one connectorized port and one that is not (waveguide for example), in which case it is a challenge to define a thru or line. While in some of these cases calibration standards may be available at the DUT plane (e.g., wafer probing), this is often not the case.

There are a number of approaches to solving this problem, each with varying levels of complexity and varying levels of uncertainty impact. We will explore a number of these options explaining the various trade-offs and illustrating with some example measurements. The key in all cases is in how the thru or line connecting the ports is defined and its impact on transmission tracking and load match behavior. While all measurements can potentially be affected, those of low loss passive devices are the most susceptible to problems in this area. Those classes of devices will receive special attention.

While not as general as some of the other techniques to be presented, time domain approaches can be useful in measurement extraction. Some aspects of the time domain approach are discussed in an appendix.

The VNA calibration algorithms selected have some bearing on the performance of these non-insertable techniques and it is assumed the reader has some familiarity with common calibrations. The main ones to be discussed include defined-standards methods such as Short-Open-Load-Thru (SOLT, e.g. [1]) and the Thru-Reflect-Line family of partially-defined-standards methods (TRL, LRM, etc.; e.g., [2]-[3]). While the discussion here is focused on two port measurements, all of the concepts extend to multiport VNA measurements as well.

Adapters Before or After Calibration

The coarsest technique of all would be to calibrate with one set of reference planes (M-F) and then add an adapter after calibration (or remove one) to get to the desired DUT interfaces without correcting further. If the frequencies are low enough and phase information is of no interest, this may be acceptable. One could also use reference plane extension to correct for the phase distortion due to the adapter. Depending on the adapter, the magnitude uncertainty penalty may be on the order of a few tenths of a dB at 3 GHz (and potentially up to 1 dB at 40 GHz) and there may be a potentially large penalty on reflection uncertainty.

Alternatively, we could have an adapter present during the calibration (and partially corrected within the calibration) and then remove it for the DUT measurement. This is the so-called non-zero-length thru approach. In the case of a defined-standards calibration like SOLT, the length (and possibly other information) of the adapter is entered to define it. In the case of the TRL family, the initial reference planes will be defined to be in the center of this adapter and then rotated to the ends for the measurement. This rotation requires propagation information about the adapter but this can be obtained other ways (e.g., [4]).

If the adapter has significant mismatch or loss, the system assessment of load match will be hampered. It will be a recurring theme that these attributes of an adapter will cause problems. The differences will be in how sensitive the measurement approach is to a pathological adapter. In this case, the sensitivity is fairly high for defined-standards approaches since the line will be assumed to be nearly perfect but certainly will not be.

To begin with measurement examples, consider the scenario pictured in Figure 1. The DUT is F-F (a delay line). M-M cable ends are used along with a F-F adapter for the ‘thru’ using a simple SOLT calibration.

Measurements using this setup are shown in Figures 2 (assumes adapter has zero length) and 3 (assumes adapter has an electrical length of 53 ps) using an SOLT calibration. The DUT in this case has an approximate electrical length of 106.7 ps or about 46.3 degrees at 19.95 GHz. As one can see here, the zero-thru assumption has an obvious phase error and some significant amplitude ripple due to a miscalculation of the load match (since the calibration had the length wrong). The non-zero-thru measurement has a better transmission measurement (both in terms of phase accuracy and ripple) but still gets the amplitude wrong since the line loss was not corrected here. The DUT should have a loss of about 0.13 dB at 30 GHz. Return loss results will be discussed later in the context of some of the other measurement techniques. A TRL calibration would have fewer problems here but the accuracy of positioning the reference planes may be suspect due to mismatch of the adapter.

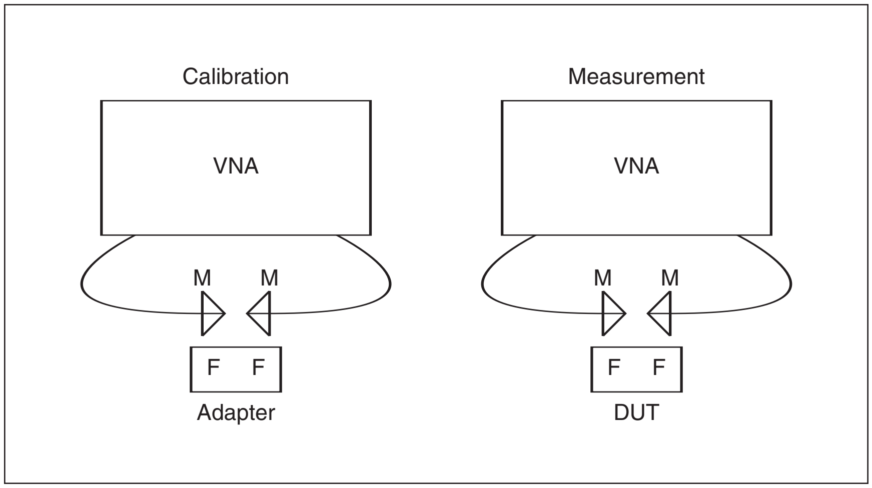

Figure 1. The setup for the first example group is shown here. An adapter is used for the thru; in one case its effects will be ignored and in the other its effects will be partially corrected.

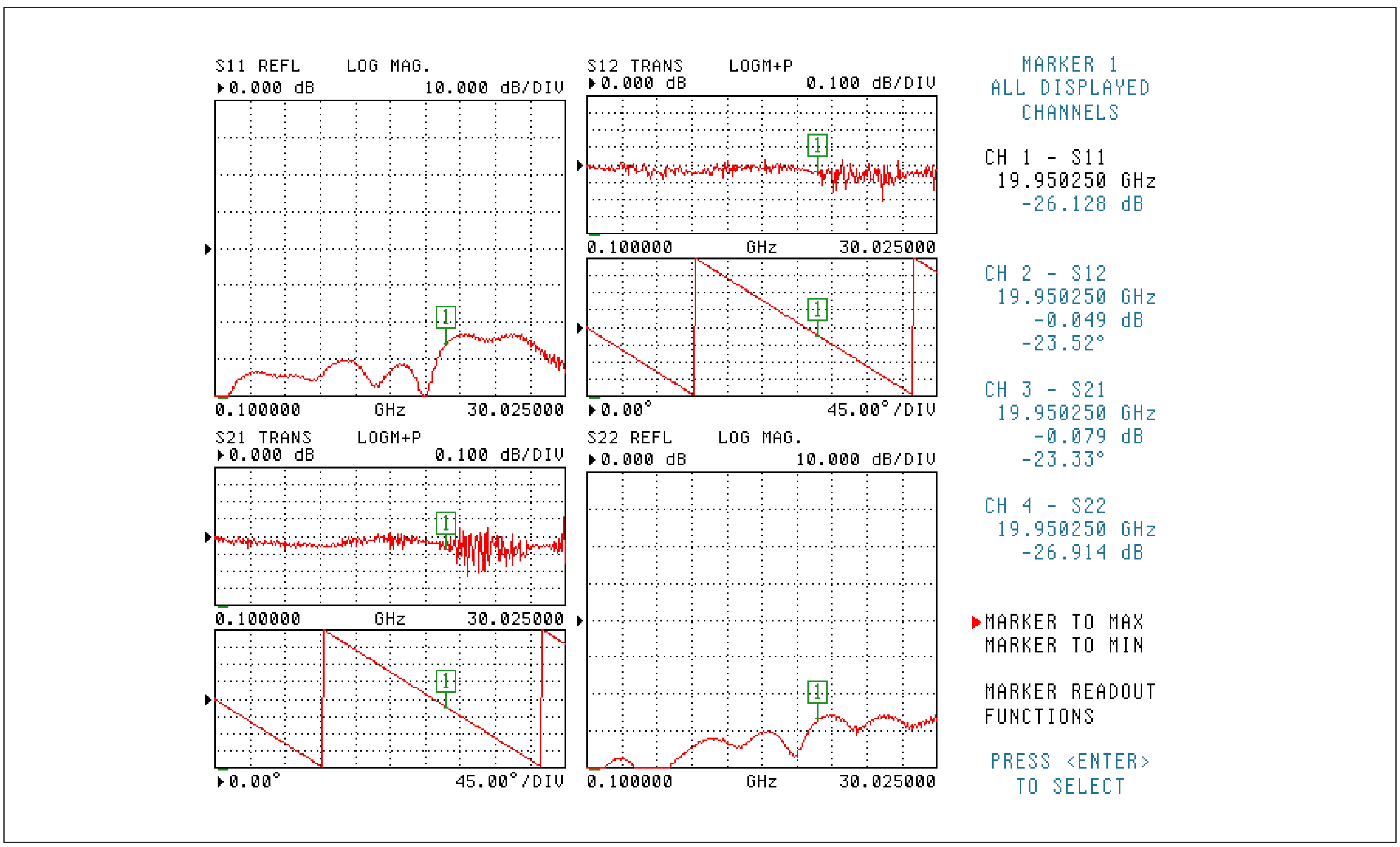

Figure 2. The measurement of a F-F delay line is shown here using the adapter scheme of Figure 1 but assuming it has zero length and loss. The transmission phase is completely incorrect as may be expected. The insertion loss is corrupted by an incorrect load match term and an uncorrected loss of the adapter.

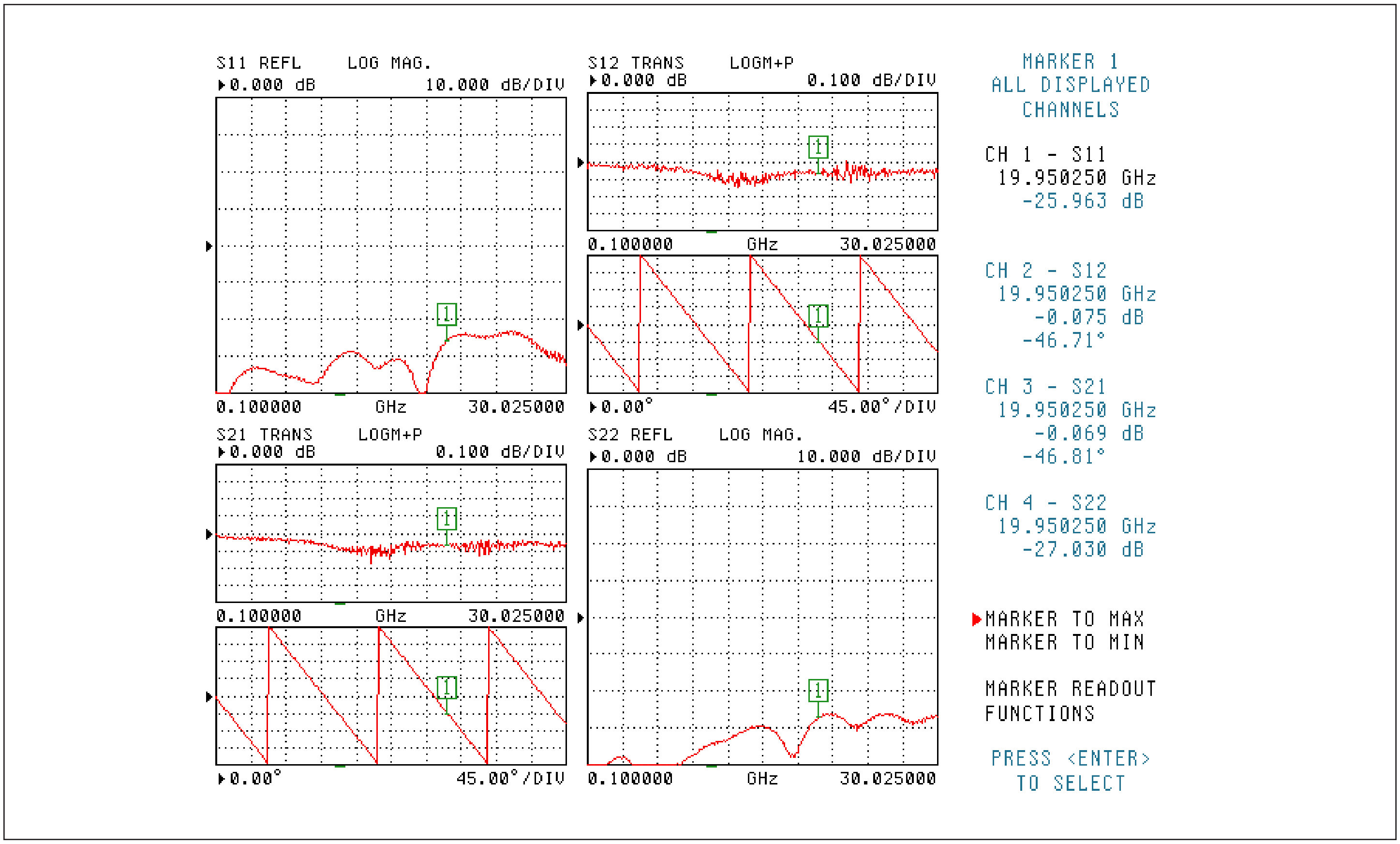

Figure 3. The measurement of Figure 2 is shown here but with the adapter length corrected for. The transmission phase is now essentially correct but the insertion loss is still affected by the uncorrected adapter insertion loss.

Phase Equal Insertables

An alternative to including an adapter as part of the calibration is to use equivalent adapters during different parts of the process. Included in Anritsu calibration kits (and perhaps from other vendors) are a set of adapters (M-M, M-F, and F-F) designed and verified to be of equal phase length. These devices are called Phase Equal Insertables (PEIs). Thus one could use a F-F adapter during the calibration to enable a zero-length thru and then switch the M-F version for the measurement. Accurate characterization of the adapter is no longer necessary and phase accuracy can be reasonably well preserved.

While the phase matching can be maintained to quite high standards, it may not be adequate at frequencies greater than 40 GHz or so where a 100 µm variance can cause a 5 degree phase error or greater. Also, while the transmission characteristics are well-matched, the return loss characteristics are not. Some errors pertaining to load match are possible and will be worse at higher frequencies.

The calibration and measurement schemes for example are shown in Figure 4. As discussed above, a simple substitution is used under the assumption of equivalence.

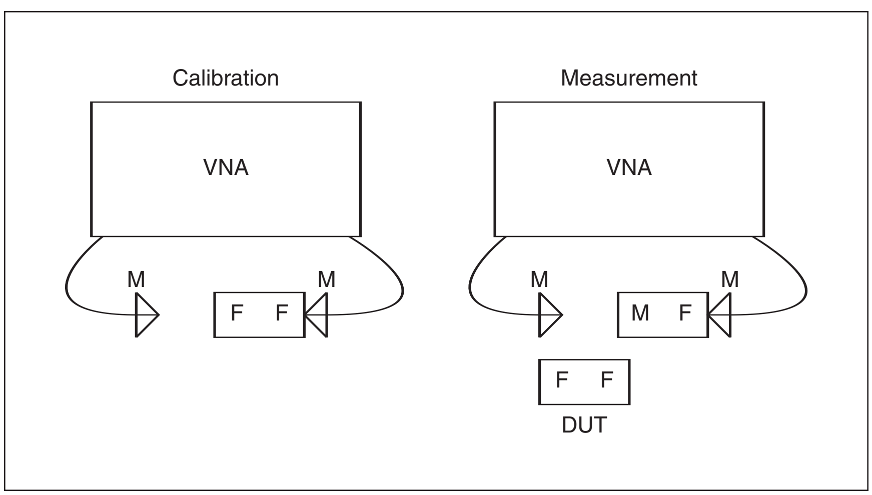

Figure 4. The PEI approach is shown here. A precision FF adapter is in place during calibration to enable a simple thru. During measurement, the adapter is replaced by its matched MF equivalent.

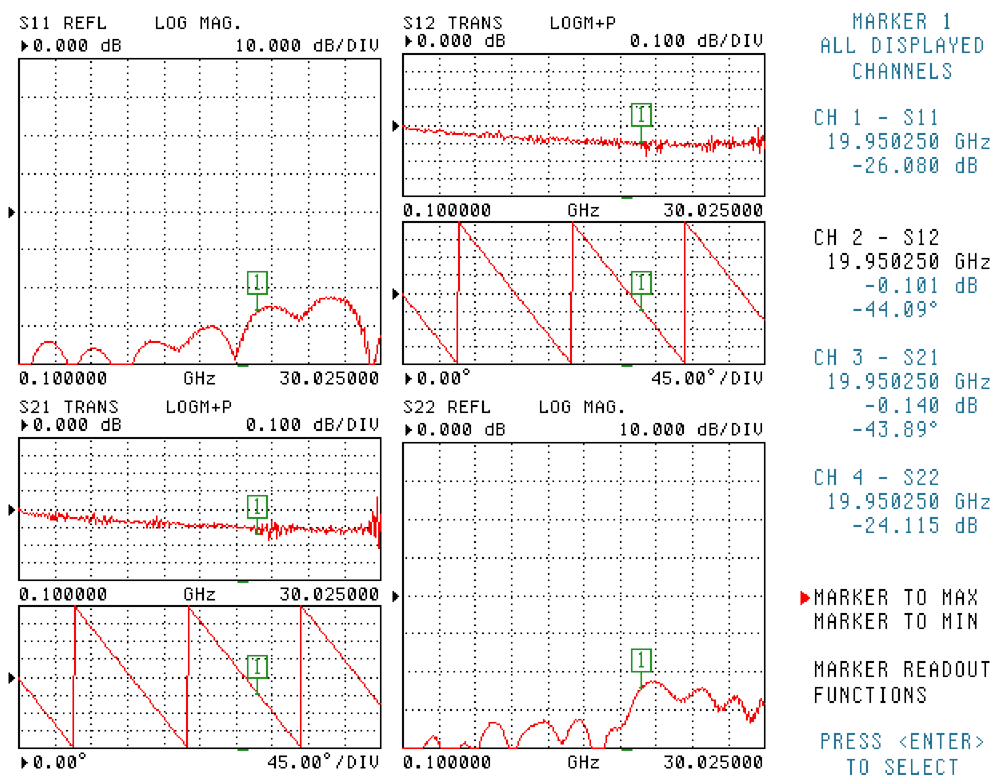

Figure 5. The delay line measurement example using the PEI approach is shown here. The insertion phase is correct but the insertion loss is overstated slightly; this may be due to a slight inequality in insertion loss between the PEIs (~.04 dB at 20 GHz).

The same measurement example as before is repeated for this technique and the results are shown in Figure 5. The phase accuracy is similar to before and the amplitude measurement is better although overstates the loss slightly. This may be because the losses of the PEIs are not strictly identical. The match differences between the PEIs may lead to the slightly corrupted return loss measurements at higher frequencies, particularly in low insertion loss DUTs.

The reader may notice the peak return loss is slightly lower than in Figures 2 and 3. Several factors influence this including (a) load match inaccuracies in the adapter approach (more so in Figure 2) and (b) unmatched return loss of the PEIs. Below a –20 dB match level, it is difficult to extract the differences.

Below 40 GHz and in low loss scenarios, transmission uncertainties with this method are expected to be in the range of 0.1 dB and 1 degree. In low return loss scenarios, which admittedly are not of paramount interest with these techniques, reflection uncertainties are expected to be on the scale of a few tenths of a dB below 40 GHz.

De-embedding

A more intensive version of the adapter approach is to perform a full de-embedding (e.g., [5]-[12]) of an offending adapter. If the full S-parameters of one or more adapters are known, they can be extracted directly. In principle, this is perfect but, of course, there are some limitations.

– The S-parameters of the adapter must be known. In some cases, an alternative cal can be performed to measure them separately or a 1-port unterminating procedure can be used [5]. In some cases, the adapter could also be modeled and those S-parameters used for the de-embedding. This, of course, requires high confidence in the modeled structure.

– De-embedding has issues with very high loss (>10 dB or so) or very poor match structures. This is due to signal-to-noise reasons usually but applies to many other methods as well.

The measurement structure for our example is shown in Figure 6. Here a M-F construct is used for the calibration and then a M-M adapter is added for the measurement and de-embedded. The adapter was characterized with an adapter removal technique (to be discussed in the next section) so any errors incurred there will propagate. If one adapter is reused many times, the de-embedding approach may make sense in reducing labor (since the same file can be used multiple times without multiple calibrations every time) as long as one tracks potential degradation of that adapter.

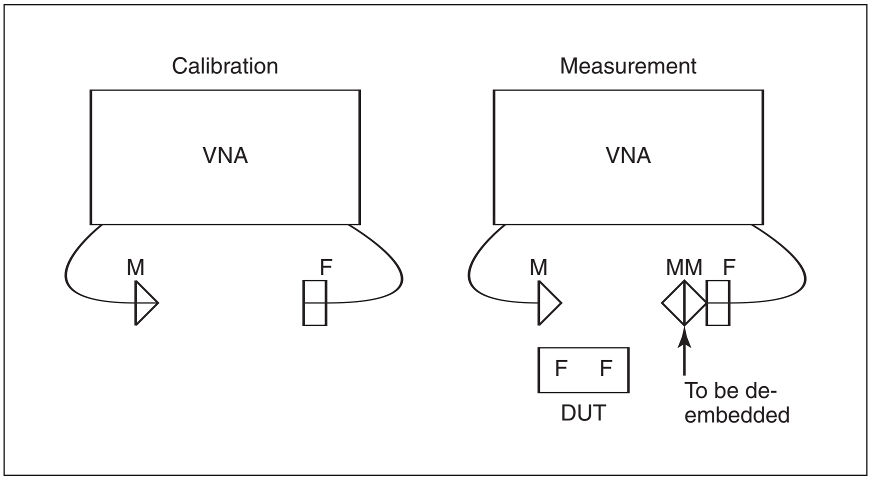

Figure 6. A de-embedding approach is shown here. An adapter is added after calibration and its effects removed by de-embedding.

The results are shown in Figure 7 for the delay line example. The phase accuracy is reasonable as is amplitude smoothnes. But there is some bulk amplitude inaccuracy midband which may be due to connector repeatability, since multiple measurement stages were involved. Some added ripple in insertion loss occurs near 30 GHz, presumably due to the multiple cable flexures needed for this measurement.

When de-embedding low-loss and well-matched structures, transmission uncertainties (low loss DUTs) are expected to be on the order of 0.1-0.2 dB and 1-2 degrees below 40 GHz. Low return loss reflection uncertainties would be expected to be on the order of a few tenths of a dB below 40 GHz.

Unlike the earlier techniques, de-embedding can be applied to mixed media problems (e.g., one port coax, one port waveguide) but acquiring the S-parameters of the adapter may be difficult or require simulation. The following methods are more suited to mixed media scenarios.

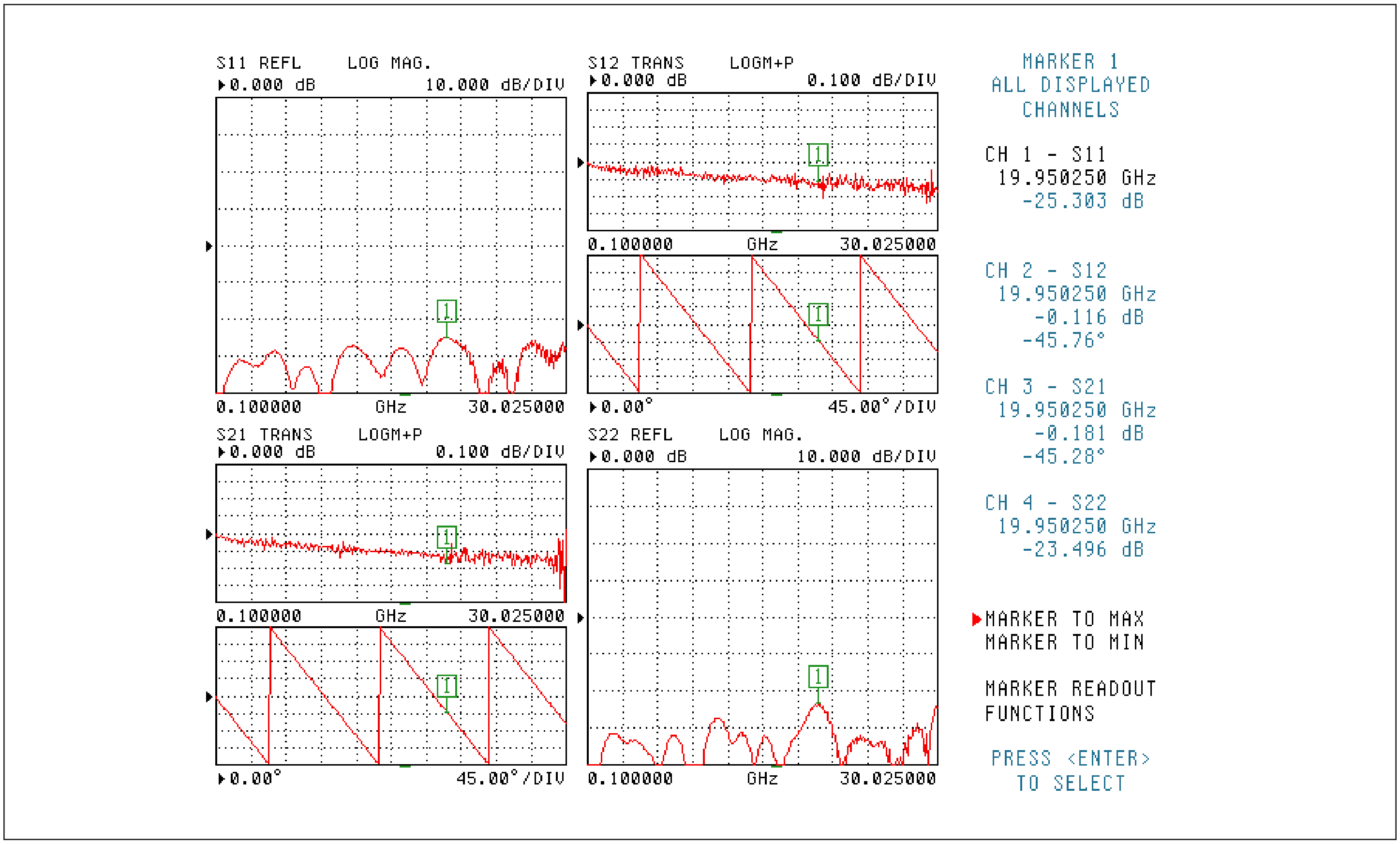

Figure 7. The de-embedding approach as applied to a delay line measurement is shown here. The return loss measurements and insertion phase are in decent shape. The insertion loss measurement shows a small deviation (~.05 dB) around 20 GHz that may be due to connector repeatability and/or cable flex since several steps were needed to characterize the adapter, make the cal, and perform the measurement.

Adapter Removal

Somewhat akin to real time de-embedding is the process known as adapter removal (e.g., [11]-[13]) in which a pair of calibrations is used to determine the S-parameters of the adapter and remove them from the error coefficients of one of the calibrations.

The concept of adapter removal relies on the existence of two related sets of reference planes: one set on either side of the adapter (see Figure 8; the drawing morphology is slightly different from before to emphasize the mixed media possibilities). Assuming one can perform a full calibration at each set of reference planes, there is enough information to extract the behavior of the adapter itself. When the calibration is being performed at the reference planes on the left (between planes X and X'), the adapter behavior is embedded in the characteristics of port X'. Similarly when the calibration is being performed between ports Y' and Y, the adapter behavior is embedded in that of port Y'. Since each of these two calibrations involve mating connector types, these are far easier to perform than the direct X-Y calibration. It will not be shown here, but the use of the two calibrations provides enough information to extract the parameters of the adapter itself (with some restrictions).

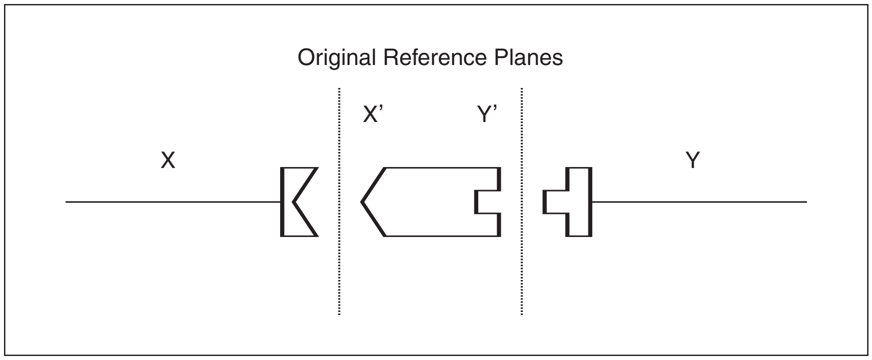

Figure 8. The structure of the adapter removal calibrations is shown here. Two calibrations are performed at the two sets of reference planes shown (between ports X and X' and between Y' and Y) which allows a determination of the adapter behavior. The resulting calibration (after adapter removal) will be between ports X and Y.

There are two caveats to this procedure. First, only the product $S_{21}S_{12}$ of the adapter can be determined from this procedure, not the two transmission terms individually. Since only the product is needed to de-embed the adapter effects, however, this is not much of a problem. Most adapters are passive and reciprocal anyway so the individual terms could probably be determined if necessary. Second, there is a complex square root operation involved so a root determination is necessary. To help this, the user must enter some guess as to the electrical length of the adapter (in ps of delay). The guess need not be very accurate, just within the correct half plane. At 2 GHz, this means the error in delay entry should be less than 125 ps to ensure the correct root is selected. In general, the time error must be less than $1/(4f)$ where f is the highest frequency being used.

The execution of adapter removal is quite simple. Two full 2-port calibrations must be performed and those calibrations (plus front panel setups) must be stored to the current directory on floppy or hard disk (usually the hard disk is used for speed). The setups for the two calibrations should be the same in terms of frequency range and number of points. Upon entering the adapter removal utility, the estimate for the electrical length of the adapter must be entered as well as the location of the two calibrations. Once this is done, the utility will generate a new calibration removing the adapter effects and will apply it. The menu and help screen are shown in Figure 9.

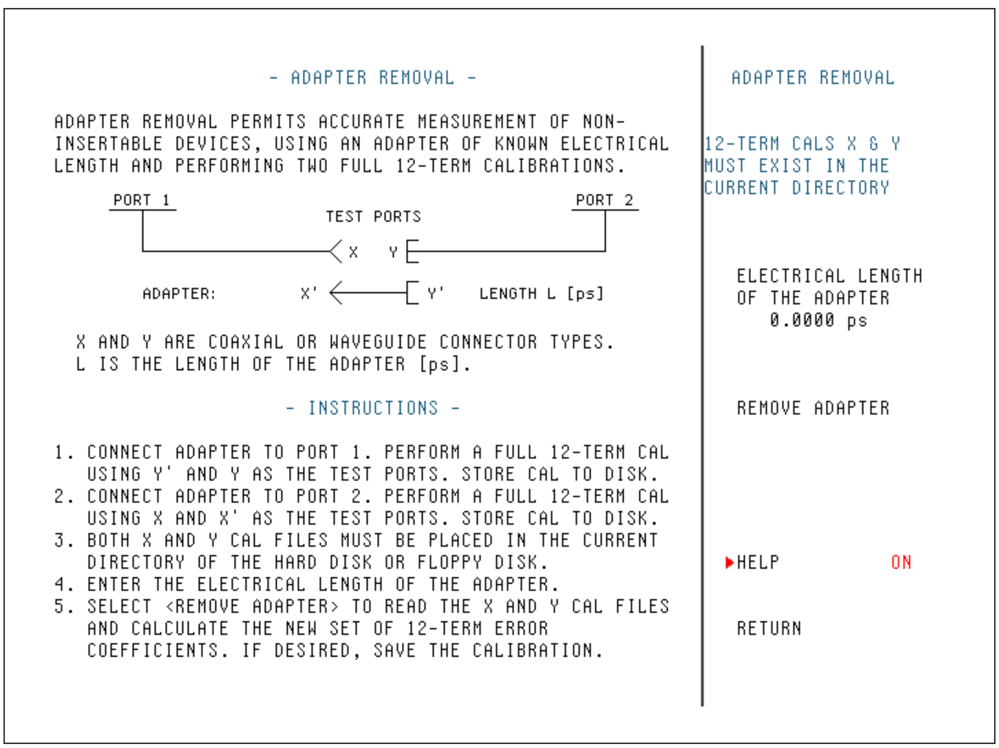

Figure 9. The menu and help screen for adapter removal are shown here. Slightly different help screens and menus will be seen on different instruments but the functionality is the same.

While not particularly practical, the following example should help illustrate the use of this utility. An adapter was constructed with about 3 dB of loss and 180 degrees of phase shift at 3 GHz. This leads to an estimate of the delay length of:

$$\phi = \omega\tau$$

$$\tau = \frac{\phi}{\omega} = \frac{\pi}{2\pi(3 \cdot 10^9)} \approx 167\ ps$$

Since the loss of this adapter is substantial, one could not simply use reference plane extension to remove the phase shift and hope for an accurate result. The two calibrations described earlier were performed and stored to hard disk and adapter removal executed.

A thru was then connected without the adapter in place. Normally this would not be possible (since the whole reason for using adapter removal was for situations when a thru would be difficult) but this example adapter was constructed just to show that algorithm's functionality. The results are shown in Figure 10. As expected, the thru without adapter shows nearly zero insertion loss and phase shift, and very good match. Any residuals are largely due to cable flex. Had this connection been made with one of the initial two calibrations applied, S21 would have shown about 3 dB of gain since the adapter had been built into each cal.

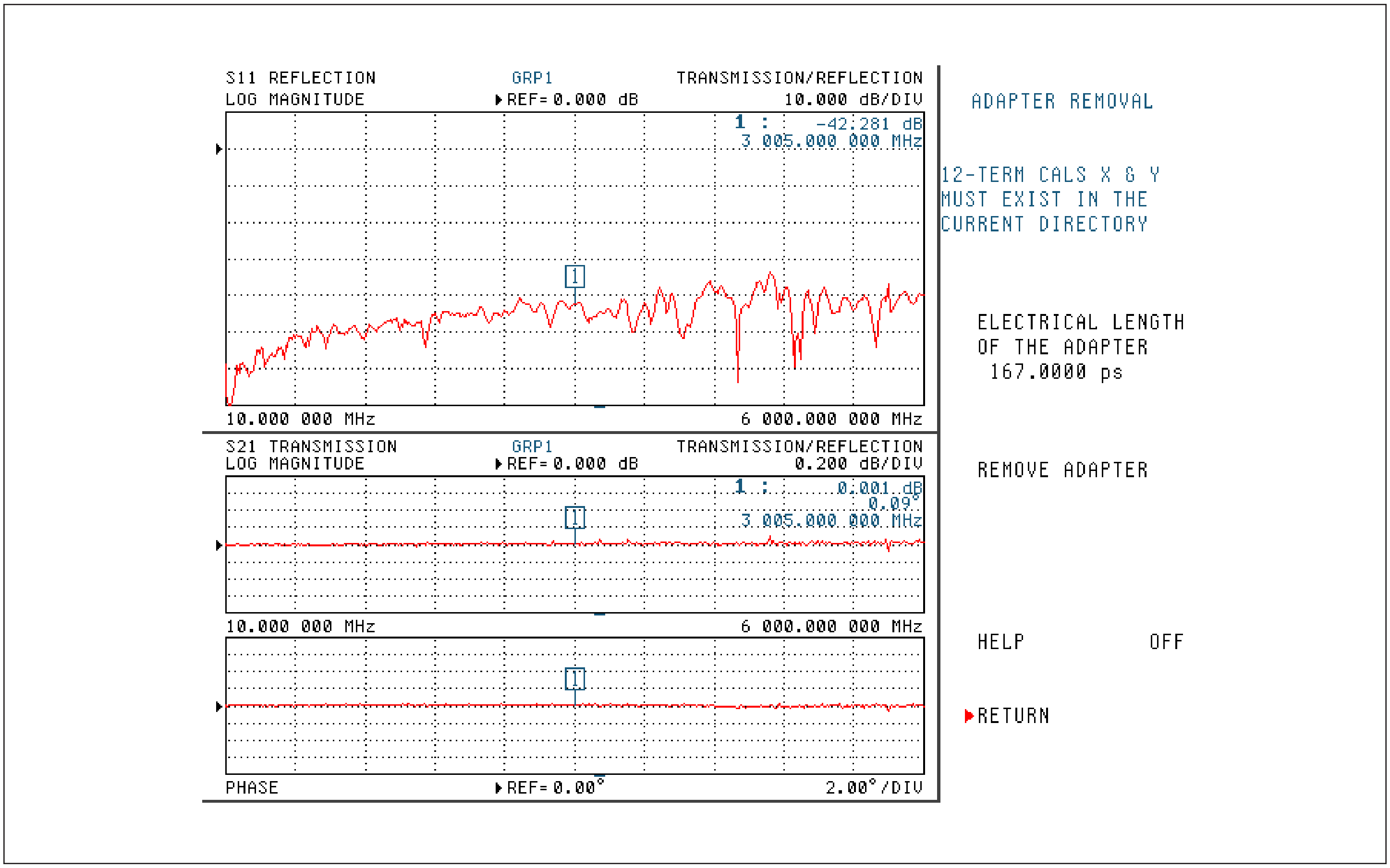

Figure 10. The result of adapter removal is shown here. The thru without adapter was connected after executing the utility and the near-perfect thru values for S21 show that the algorithm successfully removed the adapter from the calibrations.

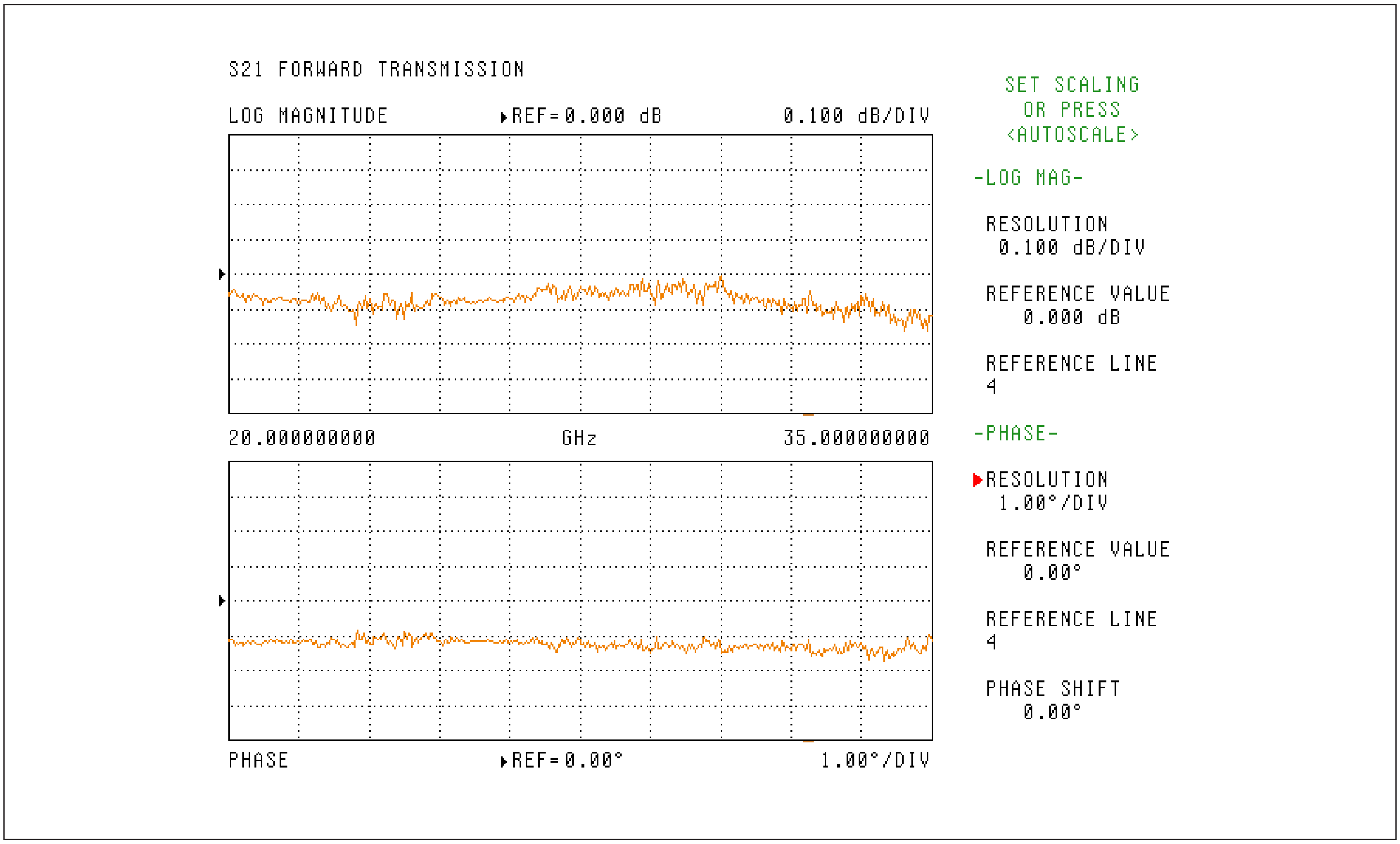

Figure 11. Another example adapter removal measurement is shown here, that of a waveguide-to-coax adapter.

Another example measurement is shown in Figure 11, this one of a waveguide-to-coax adapter. In this case, the X calibration was done all in coax (SOLT) while the Y calibration was done all in waveguide (offset short). The resulting adapter measurement after adapter removal shows an insertion loss on the order of 0.05-0.15 dB. The phase plot in this case has been reference plane normalized.

As usual, some limitations exist. Calibrations must be possible at the two ends of the adapter. If the adapter is extremely lossy or poorly matched, then there are eventually some limitations from low signal-to-noise ratios. Since there are usually fewer reconnects involved, the susceptibility is usually a little lower for adapter removal than for a classic de-embedding operation.

The process for our delay line example is illustrated in Figure 12. The two calibrations are done with the F-F adapter on opposite sides.

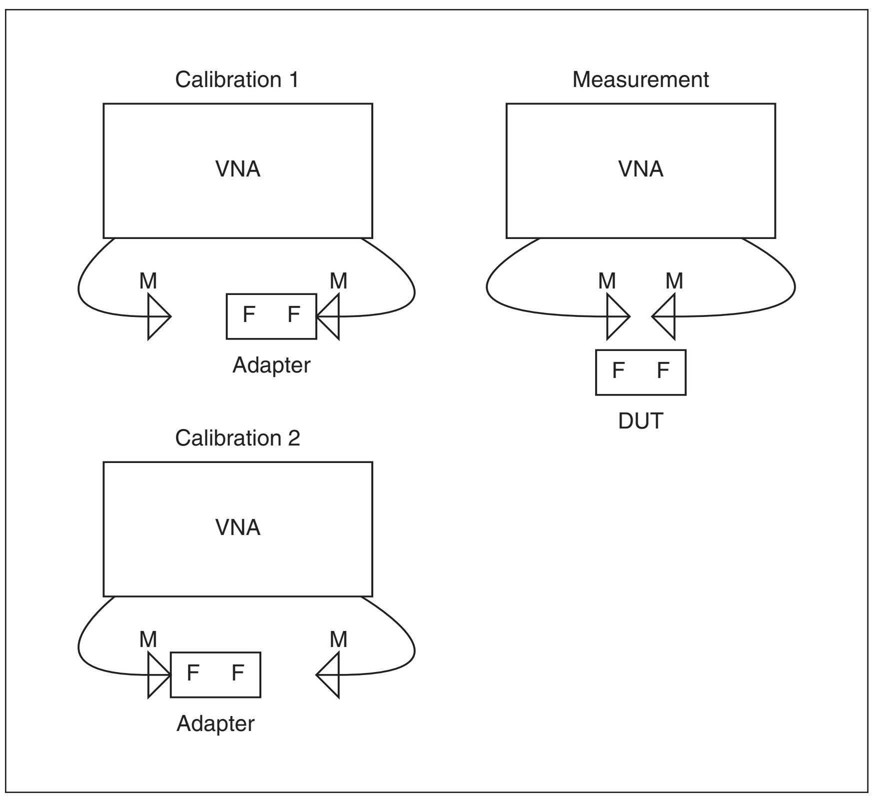

Figure 12. The adapter removal setup for our delay line example is shown here. Two calibrations are used to extract and delete the adapter's effects.

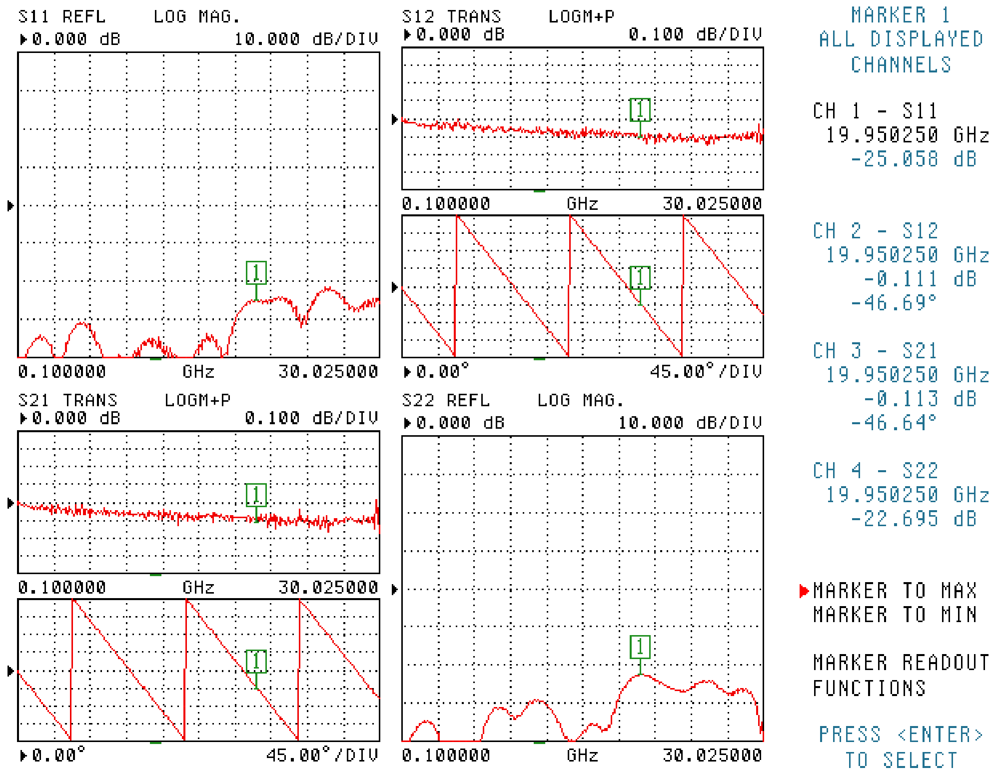

Figure 13. The delay line results using the adapter removal technique are shown here.

The results are shown in Figure 13 and show the smoothest responses of all methods so far and come closest to the correct answer for this DUT (error from expected result <0.03 dB on insertion loss and <0.4 degrees on insertion phase). Of course, the most effort of the techniques so far was expended in this measurement.

For low-loss transmission measurements with reasonable adapters (IL<20 dB, RL>10 dB), uncertainties will typically be better than 0.07 dB under 40 GHz with some constraints on measurement bandwidth and cable behavior. For low return loss measurements, uncertainties will typically be in the few tenths of a dB range.

SOLR…the Unknown Thru Calibration

Applies to Scorpion, v. 2.00 and higher; and certain versions of Navigator software used with either Scorpion or Lightning.

Another closely related approach is a different kind of calibration altogether. SOLR (e.g., [14]-[17]) is a hybrid between defined standards algorithms like SOLT and those requiring little standards information like TRL. The only requirement on the 'thru' is that it be reciprocal. Since there is less redundant information than adapter removal, it is a little more susceptible to problems with lossy or mismatched adapters. With well-behaved adapters, it can outperform adapter removal since fewer interconnections are required. Related algorithms like TAN (e.g., [2]) within the TRL family behave similarly but there is even less redundancy and hence they are even a bit more susceptible to problems with the adapter.

This approach is particularly powerful with on-wafer applications where the problem is not with variably defined ports but with the difficulty of implementing good thrus or lines (going around corners, for example, or with uncertain RF grounds). Like adapter removal, this approach is also quite useful in mixed media scenarios.

The setup for executing the example measurement is shown in Figure 14. The F-F element will act as the 'reciprocal' calibration device.

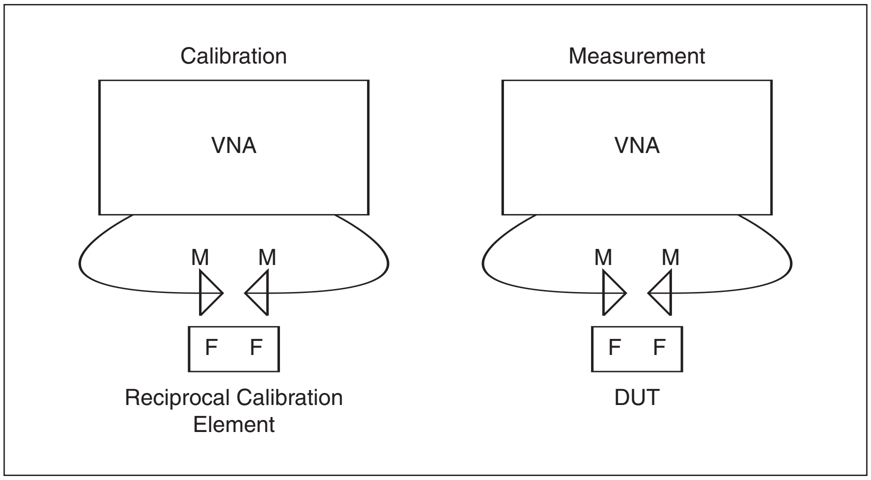

Figure 14. The SOLR calibration and measurement approach is shown here. Prior to use of the 'reciprocal' connecting element, one port calibrations are performed at the M interfaces shown.

The standard delay line example was performed using the DUT itself as the 'reciprocal' element. These results are shown in Figure 15. The insertion loss matches closely to that seen with adapter removal while return loss appears to be slightly higher. As discussed earlier, this is in the realm of connector repeatability and uncertainty limits so an assessment is difficult. Due to the lower reconnect count, this result is believed to be more accurate.

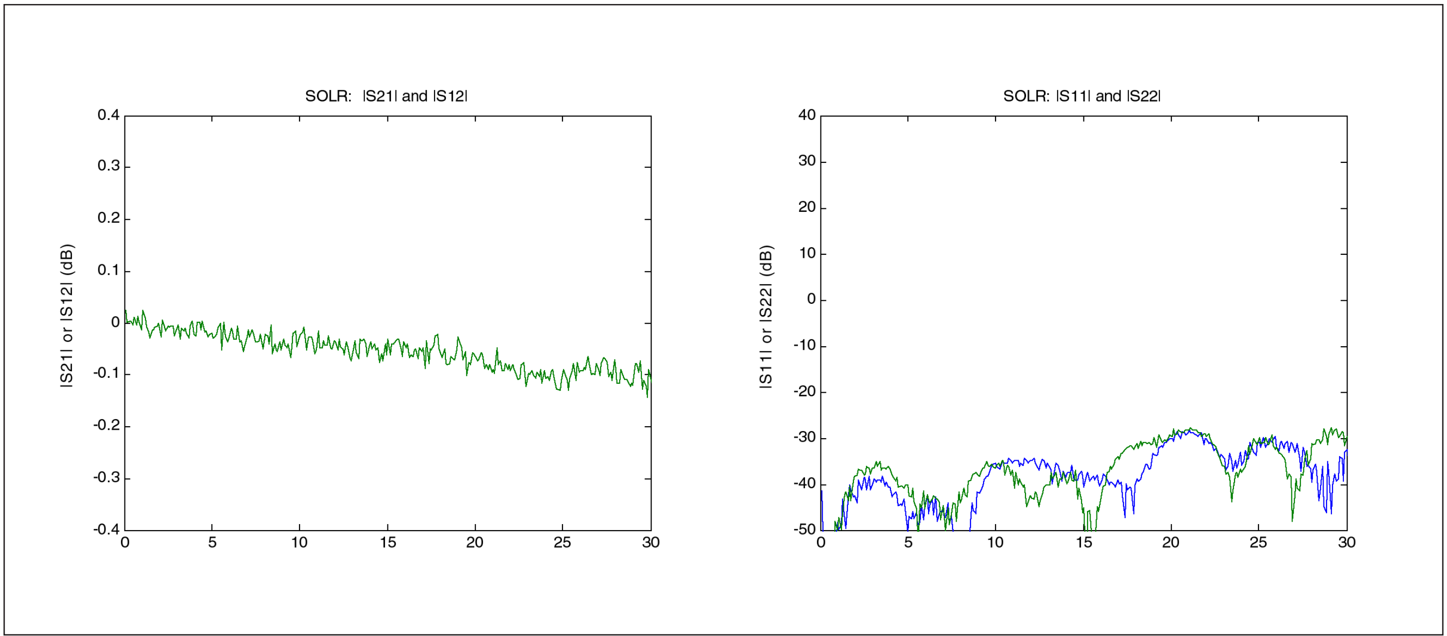

Figure 15. The delay line results using SOLR are shown here. The insertion loss is as expected and closely matches the adapter removal result. |S21| and |S12| overlay in the top graph. |S11| is the solid curve while |S22| is the dotted curve in the bottom graph.

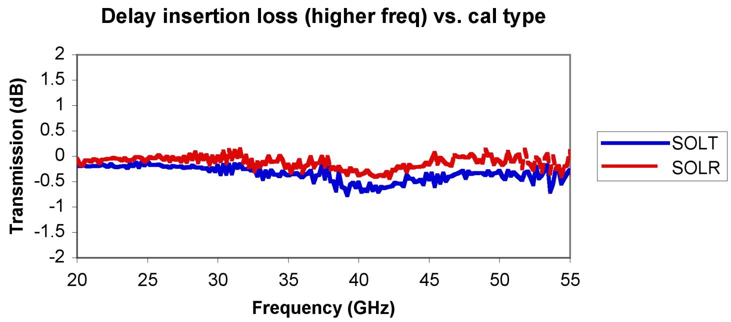

Figure 16. A 60 GHz delay line measurement comparison using SOLT (and the PEI method) and SOLR is shown here.[17]

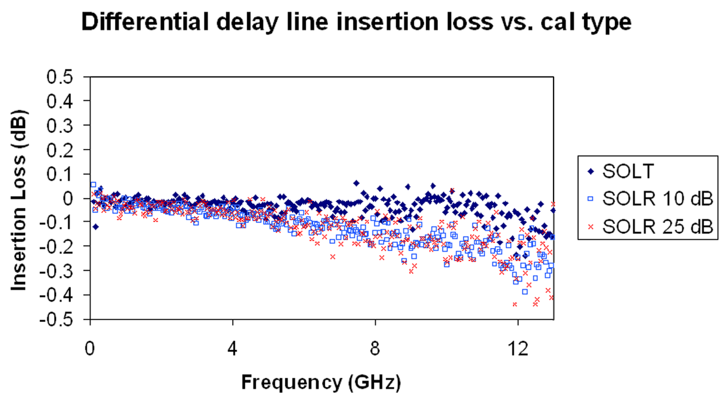

Figure 17. The dependence of SOLR behavior on 'reciprocal' loss is shown here (no issues at 10 dB, excess scatter at 25 dB). An SOLT measurement ignoring adapter loss is shown for comparison. [17]

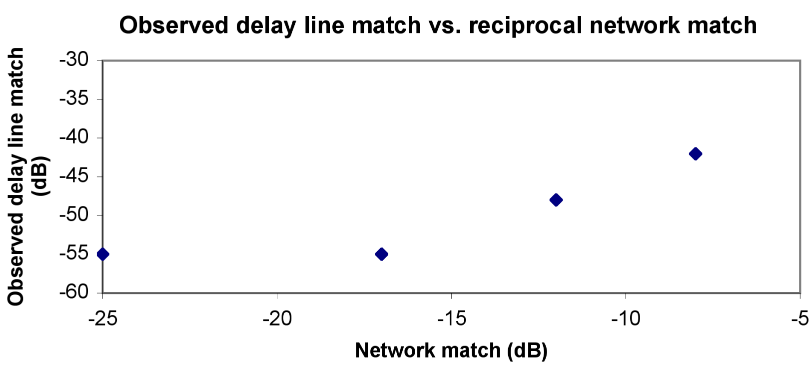

Figure 18. The dependence of SOLR behavior on reciprocal match is shown here. For return losses better than ~15 dB, no dependence was observed. [17]

Fairly extensive analysis has been performed by a number of workers on the sensitivities of SOLR. Only to give a flavor of these behaviors, we will illustrate with a few examples. SOLR has been shown to outperform classical calibrations at higher frequencies as well as in the 30 GHz range discussed to date. An example of a 65 GHz problem is shown in Figure 16 where an adapter was treated using SOLT and the PEI method and via SOLR.

As stated numerous times, most of these techniques may have problems with very lossy thru connects or very poorly matched ones. Some results with SOLR are shown in Figures 17-18 and indicate the losses of 10 dB or so are acceptable, while problems may occur above 20 dB. Return losses of better than 15 dB are acceptable while those worse than 10 dB may cause problems. Adapter removal will be slightly less sensitive than this (particularly on match), while de-embedding is much more sensitive.

For low loss transmission measurements with tighter constraints on adapter behavior, the uncertainties using this technique will typically be similar to those of adapter removal.

In Situ Calibration

Of course, the optimal scenario would be to perform the calibration in the native DUT environment. The difficulty here lies in creating high quality calibration standards or those that are well-known. A well-known scenario for this approach is in on-wafer measurements. The approach becomes more complex in the fixtured environment where structures are less standard, materials may be variable and geometries may be constrained.

Summary

	Advantages	Disadvantages
Adapter during cal	Simplest	Potentially largest uncertainty penalty. Must characterize adapter to some degree. Extremely sensitive to lossy or mismatched adapters. Usually not applicable to mixed media.
Phase equal insertables	Simple, no characterization required.	Limited matching at high frequency. Return losses not guaranteed equivalent. Not applicable to mixed media.
De-embedding	Solid foundation theoretically complete adapter characterization.	Characterization can be difficult. Quite sensitive to lossy adapters.
Adapter removal	Least sensitive to lossy or mismatched adapters. Sound foundation…real-time characterization and removal. Useful for mixed media.	Two calibrations required (on either side of adapter). Length estimate of adapter required.
SOLR…unknown thru	Modest sensitivity to lossy or mismatched adapters. Solid foundation…another cal technique. Useful for mixed media.	Length estimate of adapter required. A defined-standards cal (although TRL-like versions exist).
In situ calibration	Possibly best uncertainties. Possible for mixed media but complex.	Most complex. Good cal standards may not be practical.

Six different techniques have been presented for handling inconvenient DUT interfaces in VNA measurements. All involve some way of addressing the connection between ports that is required to complete the calibration and all vary in the complexity of the measurement, the uncertainty impact, and the sensitivity to the connection characteristics. While the best choice will vary with the exact DUT topology, it is hoped this discussion will lead to reasonable measurement protocol selection in a variety of situations.

Appendix

An entirely different approach is to use time domain and the spatial isolation of adapter defects to remove their behavior from the measurement. This topic has been saved for the appendix due to its slightly more limited applicability to this class of problem.

While discussed in detail elsewhere (e.g., [18]), the concept is to transform the measurement to the time domain and then delete the portion of the time data near the offending adapter (not included in the calibration) before transforming back to the frequency domain. In principle, this could be a nearly perfect exclusion of undesirable effects but the nature of the gating process reduces the efficacy. If a perfectly rectangular gate was used to remove the adapter, the sidelobes of that gate transformed back to the frequency domain would be substantial, thus introducing substantial error, particularly at the frequency extremes. This can be ameliorated by using larger frequency spans than needed (assuming DUT bandwidth permits it) and larger time spans. A gentler gate can also be used to limit frequency domain error but this only works if the adapter is physically quite separate from the DUT of interest.

As discussed so far, one may conclude this is primarily for reflection measurements and, in this case, that is largely correct. Time domain transmission is a powerful tool for identifying structure in a transmissive device but it is not terribly helpful in gating out adapter effects. When a pulse is transmitted through a network with adapters, generally one large impulse will appear at the output (corrupted by the adapter somewhat) followed by, perhaps, several smaller pulses due to internal reflections within the DUT or between the DUT and adapter, etc. While we can gate out those later reflections, we cannot remove the corruption of the original pulse. It is thus difficult to apply time domain gating to the insertion loss problem directly.

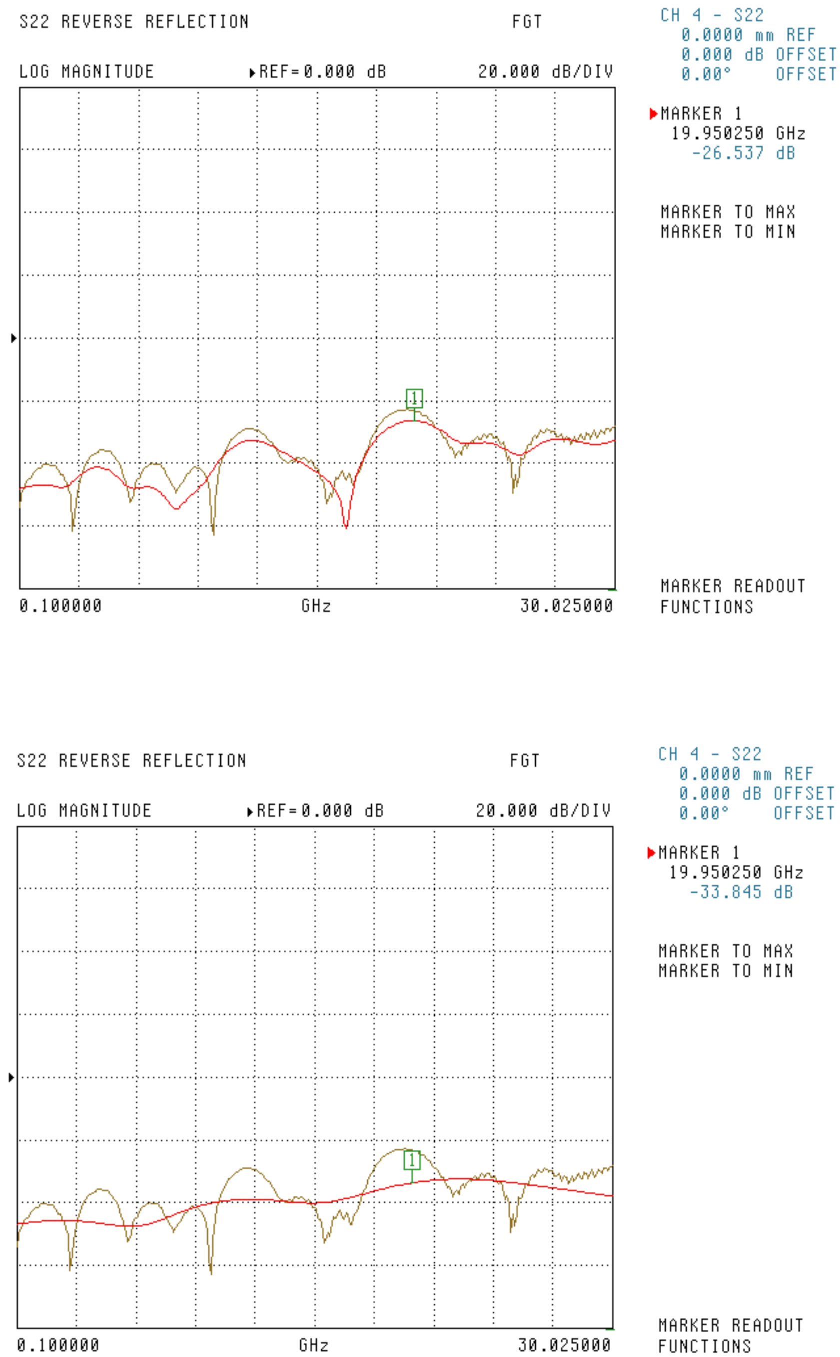

Figure 19. The reflection coefficient of our standard delay line is shown here without gating (light trace) and with gating (dark trace). In the top graph, a rectangular gate width matched to the adapter length was used and the results are reasonable (aside from some low frequency and high frequency inflections). In the bottom graph, a less well-defined window is used. While edge inflections are removed, much valid information is as well since there is physically little distance between adapter and DUT.

We can, however, look at the return loss of our standard delay line with and without gating and this is shown in Figure 19. In this case, the same setup of Figure 6 was used and the object is to gate out the M-M adapter. The adapter's electrical length is about 53 ps so we will set the gate width at 45 ps to account for some gate spill-over. The results with two different gate shapes are shown in Figure 19. With a rectangular gate, there is minimal distortion outside the area of interest and results are obtained similar to those seen earlier. When a nominal gate shape (-13 dB sidelobes [18]) is used with this very tight spacing between adapter and DUT, there is significant corruption. One should take into account the physical spacing when deciding on gate shape and gate width.

References

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Microwave Measurement Division
490 Jarvis Drive, Morgan Hill, CA 95037-2809
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