Application Note

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Technique for Improving Low Insertion Loss VNA Measurements

Vector network analyzers (VNAs) are used to measure the performance of a wide variety of passive and active RF and microwave devices. Passive devices can be less demanding to test than active devices, thus requiring less performance from the VNA. However, one interesting exception to this is the measurement of very low insertion loss passive components such as precision adapters or airlines. These types of devices can present a difficult challenge to characterize because of the desire for very low uncertainties on these small insertion losses.

A technique called secondary match correction (SMC) is very helpful in improving measurement performance and reducing uncertainties for measurements of low insertion loss devices. SMC augments existing calibration techniques and essentially tries to correct a not completely valid mismatch assumption present in the error models. SMC does not offer much benefit in a number of cases (e.g., high loss DUTs) yet, when it does, the improvements can be substantial.

Take for example the insertion loss measurement of a precision adapter shown in Figure 1. It shows at worse about 0.05 dB peak ripple which is quite small. This is well below the measurement uncertainty of ~0.1 to 0.12 dB (peak) for the VNA used to make this measurement. Even though the data shows a very small amount of ripple and that it is within the measurement uncertainty of the VNA, it may still not be an acceptable result.

Note that residual error terms are on the order of 30-35 dB and the DUT match may be on the order of 25 dB, so the ripples could be rationalized as multiple reflections between those (effective) interfaces.

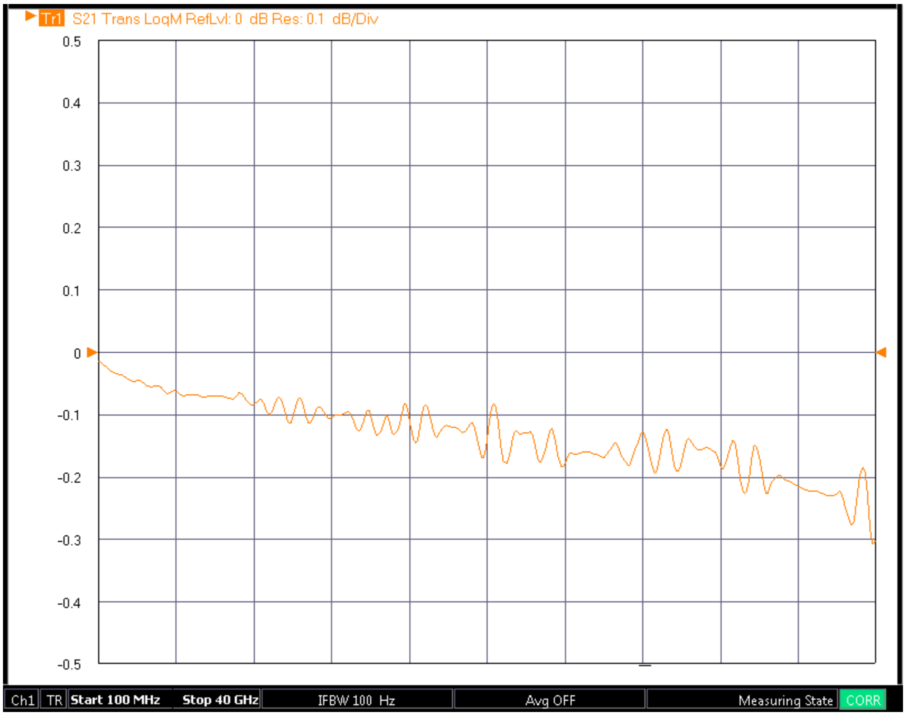

Figure 1. An example of a low insertion loss measurement.

Some of the measurement ripple can be due to several reasons including: high DUT reflections, reference plane problems from pin depth and connector mating issues, or other DUT or cal kit related explanations. However, one source of ripple that is not related to the physical test setup is how the VNA calibration model corrects for the measurement match.

Figure 2 shows the classic 2-port VNA error model with 12 term error correction that includes calibration factors for source and load match.

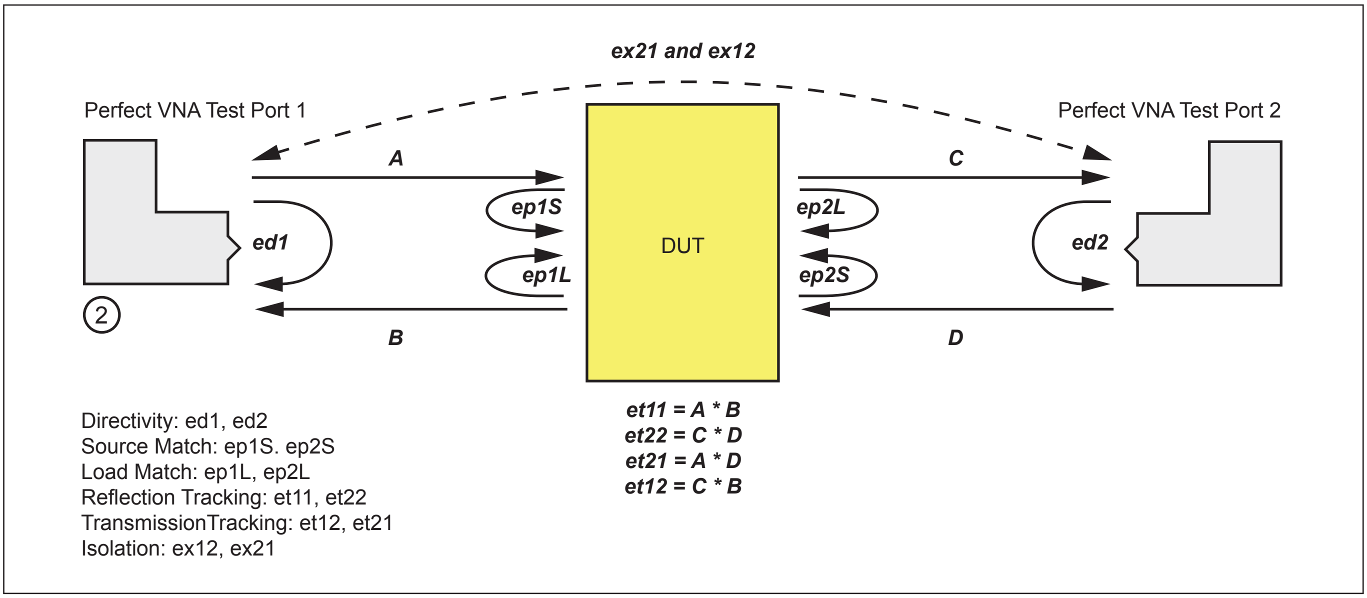

Figure 2. Classic 2-port VNA error model

The calibration error model tries to account for actual defects in a physical reflectometer used in the VNA, like the finite directivity and match of the coupling structure and non-flat frequency response of the signal chain. Part of the error model includes a simplified reflectometer structure shown in Figure 3.

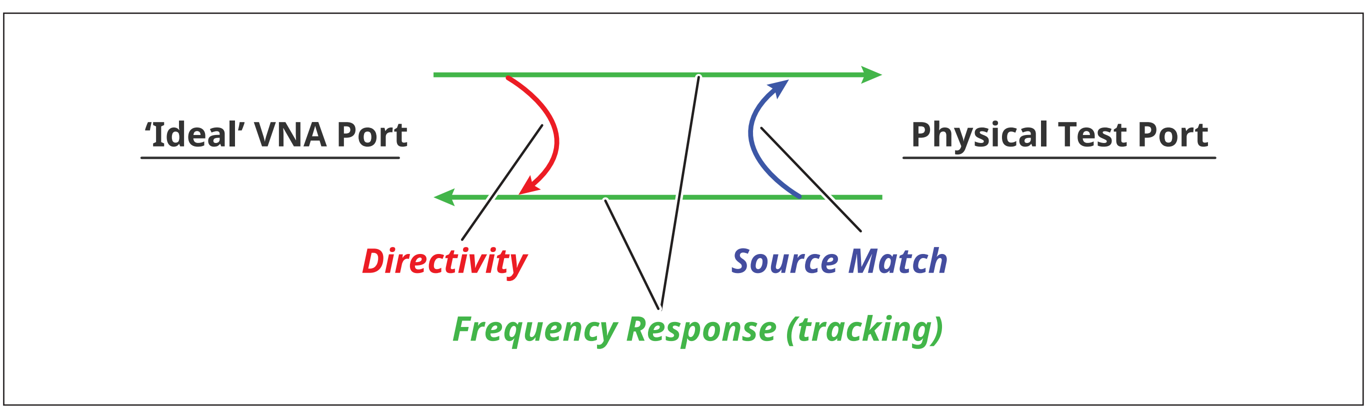

Figure 3. Simple reflectometer model

An expanded version of the reflectometer diagram is in Figure 4. If the dominant source of the actual mismatch is at position Y in Figure 4, then the signal propagates from the source and some of the energy is reflected back to the source and some gets transmitted. Some of the energy that gets transmitted gets reflected off of the DUT and re-reflected off of Y. The product of all of those reflections (approximated by eps*S11) is important since the product repeats on multiple re-reflections forming a geometric series.

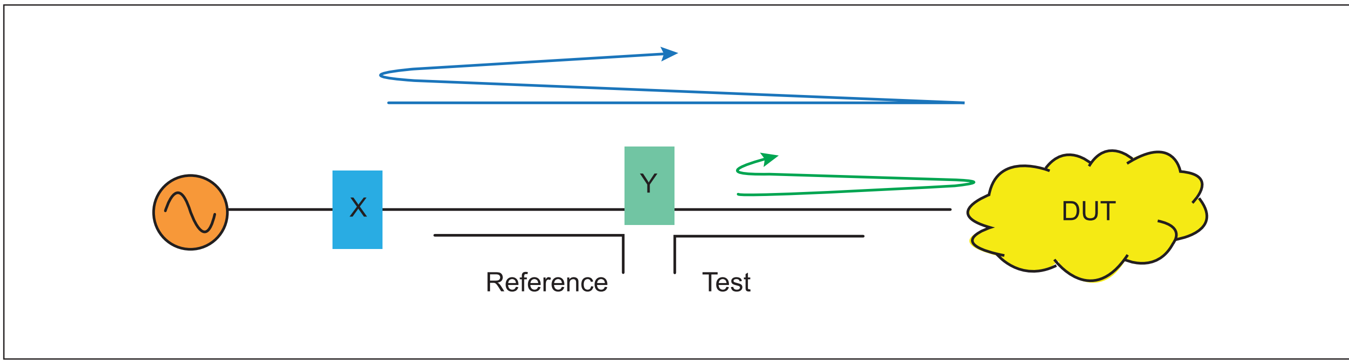

Figure 4. Expanded reflectometer model diagram

Looking at the basic reflectometer equation, Equation 1, the denominator reflects the result of this infinite geometric series. This example uses port 1 but any port may be used.

$$S_{11}^{m} = ed + \frac{et \cdot S_{11}^{act}}{1 - eps \cdot S_{11}^{act}}$$

Source match: eps
Actual reflection coefficient of the DUT: S_{11}^{act}
Transmission Tracking: et
Directivity: ed
Measured S11: S_{11}^{m}

Equation 1. Basic reflectometer equation using port 1

For the measurement case where Y is the dominant mismatch, the result from the error model is very close to the actual measurement because the test coupler sees all of the multiple reflections.

On the other hand, if a significant reflection happens at X in Figure 4, then both the reference and test couplers see the mismatch. The ratio that forms S11, test / reference, now sees a distorted picture of the reflection product and the reflectometer equation is really not as simple as the basic Equation 1.

The test coupler still sees the effective series of reflections, but the reference coupler also sees some of the reflections as well. The ratioing of the two results produces partial cancellation or amplification depending on the phasing.

The effect of the X location mismatch usually represents only a small perturbation on the effective port match. If the DUT is extremely lossy, the likelihood of these uncorrected mismatches interacting with the DUT decrease and the benefit of SMC may be small. Similarly, if the DUT is highly mismatched or has a number of moderate mismatch reflection centers within it, those structural effects in the data may swamp any possible correction by this method. However, for low insertion loss devices, the importance of the X and Y reflection locations can vary greatly depending on the measurement setup, and there are cases where the X location will have a noticeable effect on the measurement.

Additional calibration standards could be added to solve for a more elaborate match model to account for the mismatch but this would lengthen the calibration process. SMC uses the phase information in the calibration residuals to localize where the mismatch elements are to process a 2nd tier correction that primarily impacts the match terms.

Applying SMC to our previous example, one can see a significant reduction in the ripple that was not part of the DUT behavior after all (lighter trace is with SMC applied) in Figure 5.

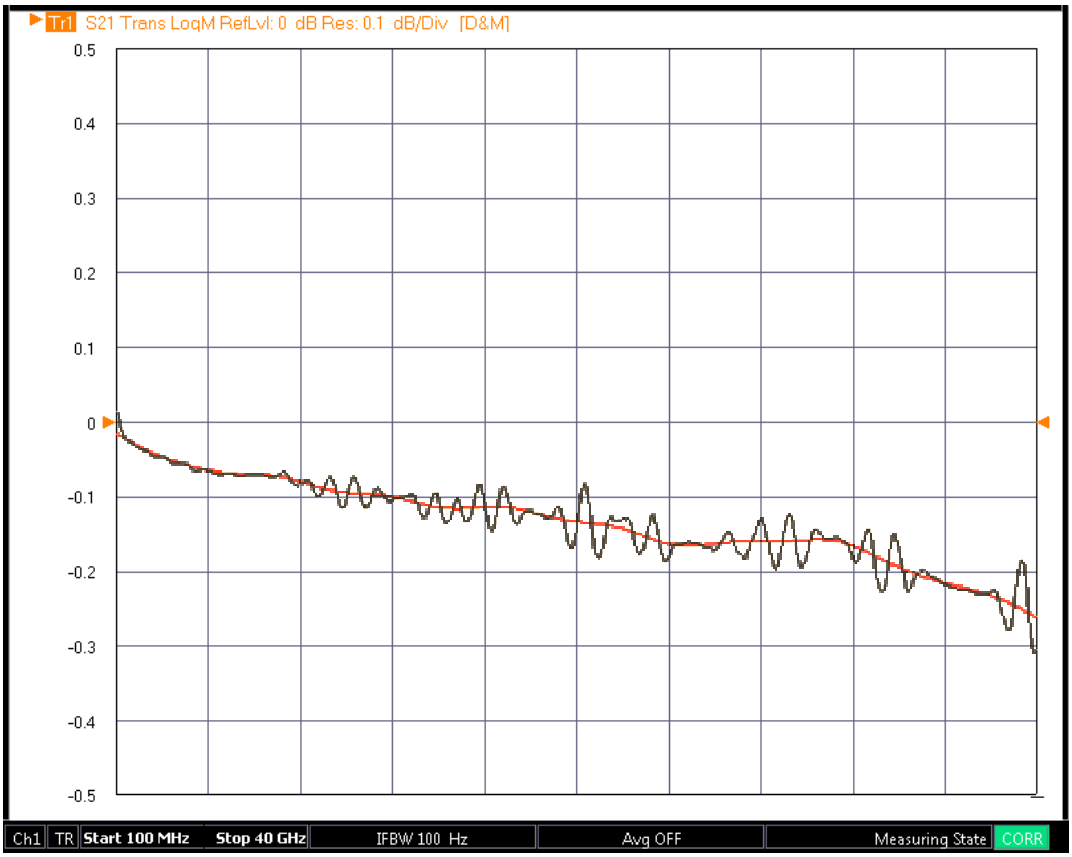

Figure 5. An adapter insertion loss measurement without SMC (darker trace) and with SMC (lighter trace) is shown here.

As previously discussed, SMC is mainly useful for very low loss device measurement, however, there is one exception where SMC will be useful with moderately lossy devices. If the device has a reasonable amount of loss but its main mismatch centers are near the measurement reference planes (e.g., the DUT is a relatively well-behaved transmission line but with some connector launch mismatch), SMC can again provide benefit since those DUT mismatches can interact with the uncorrected/partially corrected mismatches in the instrument (location X in Figure 4). As an example of such a measurement, a clean PC board-based microstrip line was measured without SMC and the results are shown in the top of Figure 6. There is a structural resonance in the DUT response but also some high-spatial frequency ripple. In this case that ripple arose from the PCB board-based connector launch mismatch interacting with the remaining instrument mismatch. The same measurement was performed with SMC applied and that result is shown in the bottom of Figure 6.

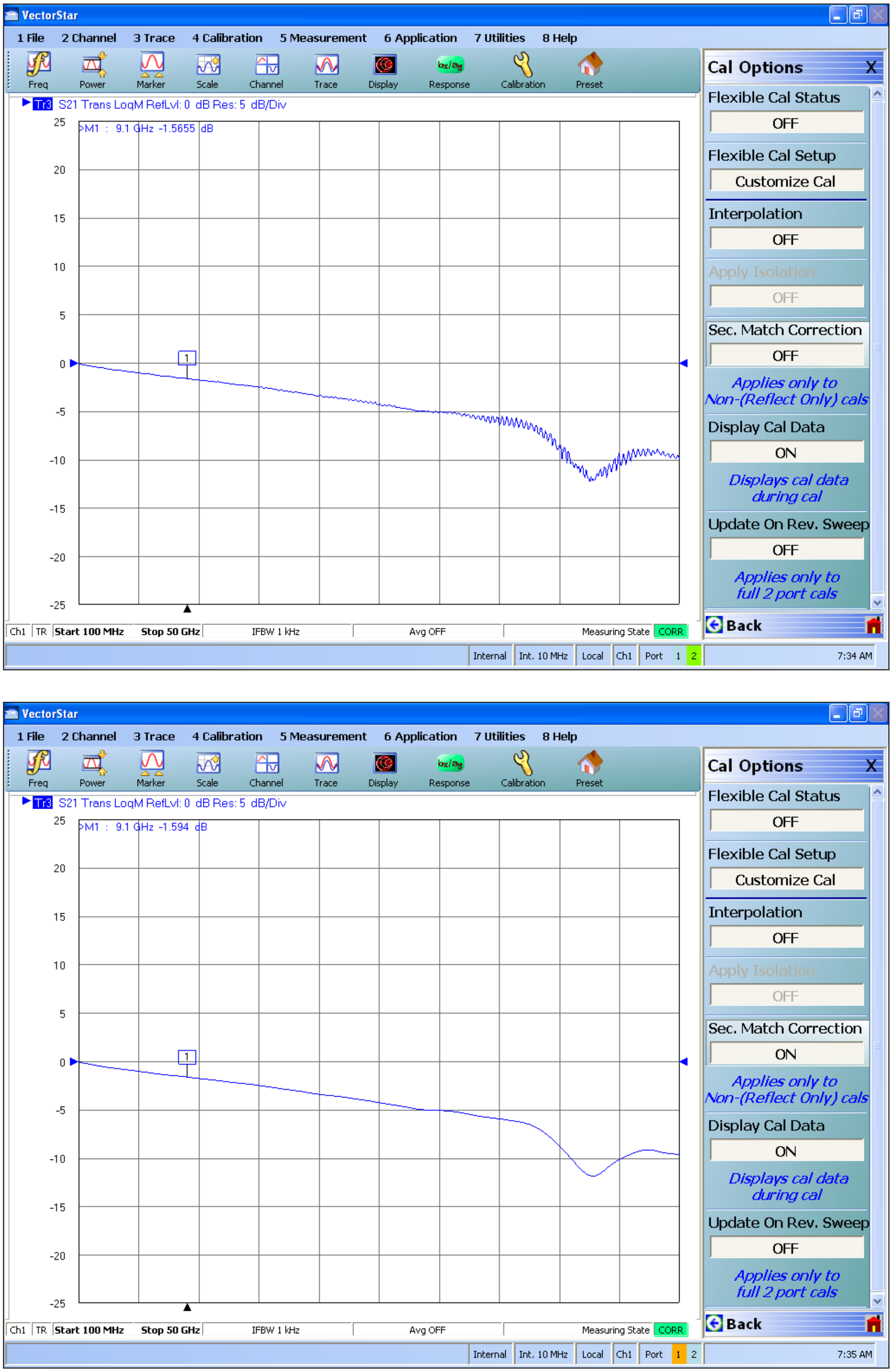

Figure 6. The measurement of a lossier device (a PC board microstrip line) with mismatch near the reference planes is shown here without (top) and with (bottom) SMC applied.

The before and after results with SMC look like they could have been achieved through other methods like smoothing. However, the difference is substantial and relates to what components of the measurement data are being altered. Bulk processing techniques, such as smoothing (and related ones with dithered frequency lists), treat all high-spatial frequency distortions the same and will remove all on a sliding scale. If all of those distortions were due to interior, uncorrected mismatch, that would not be a problem. However, in many cases, high-spatial frequency distortions may be due to the DUT itself and should not be removed. A clear example is a transmission line with launch reflections as well as an interior defect (suggested in Figure 7). A calibrated |S21| measurement with no additional trace processing is shown in Figure 8.

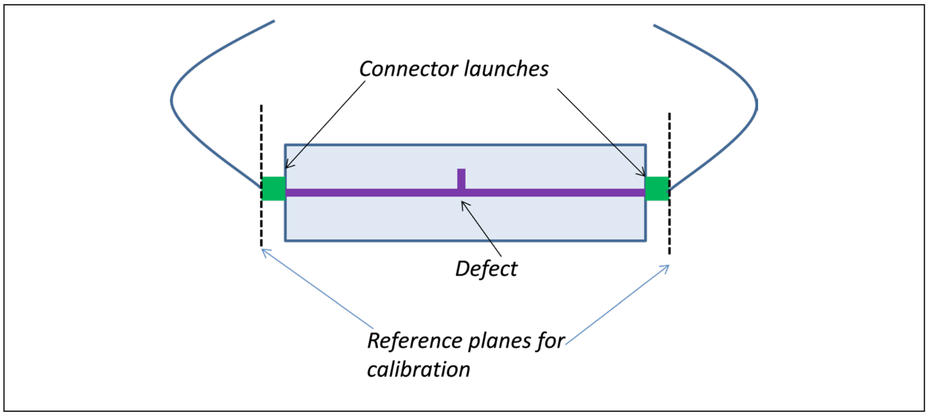

Figure 7. A sketch of the defective transmission line example DUT is shown here.

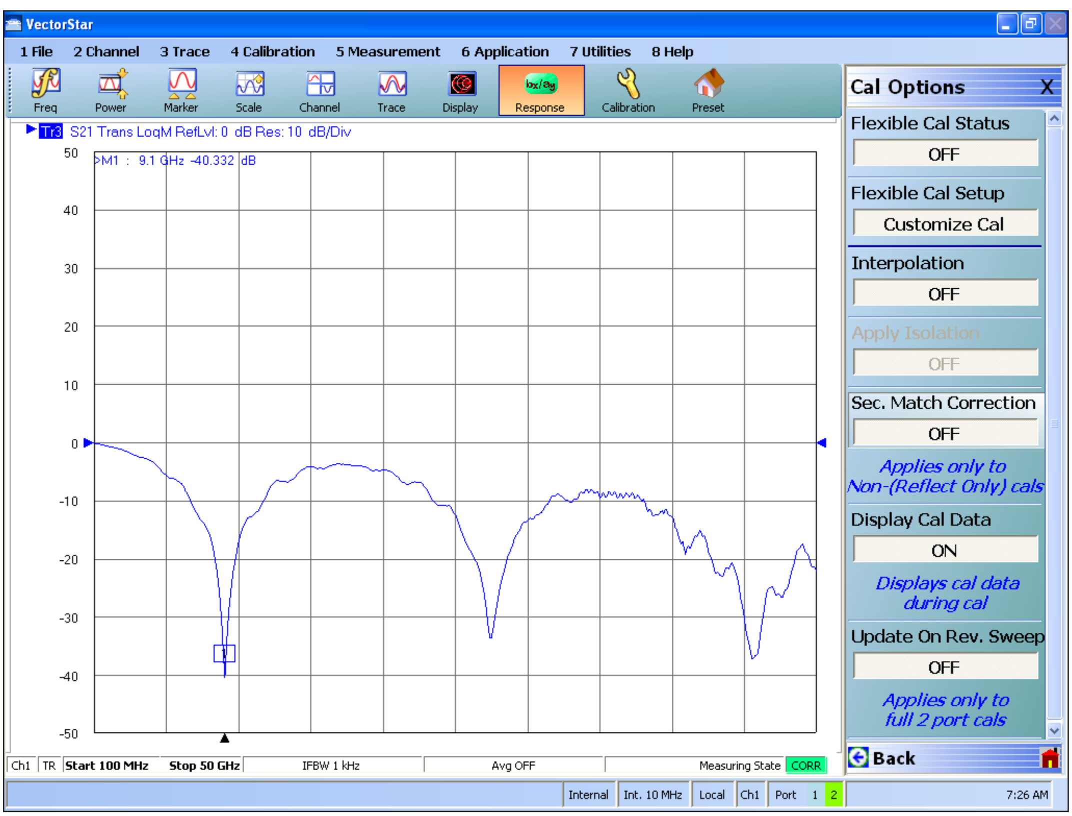

Figure 8. Insertion loss for the defective DUT with just the calibration applied is shown here.

In Figure 8, one can see the expected resonant nulls along with ripple, most of which is due to multiple reflections between the transmission line launches and the defect (and between the launches themselves). If one applies 2% and 5% smoothing (see Figure 9), the ripples do diminish in amplitude (whether or not they were part of the DUT) but the resonant null values also change (by ~6.5 and ~15.5 dB, respectively, for the first resonance). This then raises a question about whether or not applying smoothing distorts the measure data describing the DUT behavior.

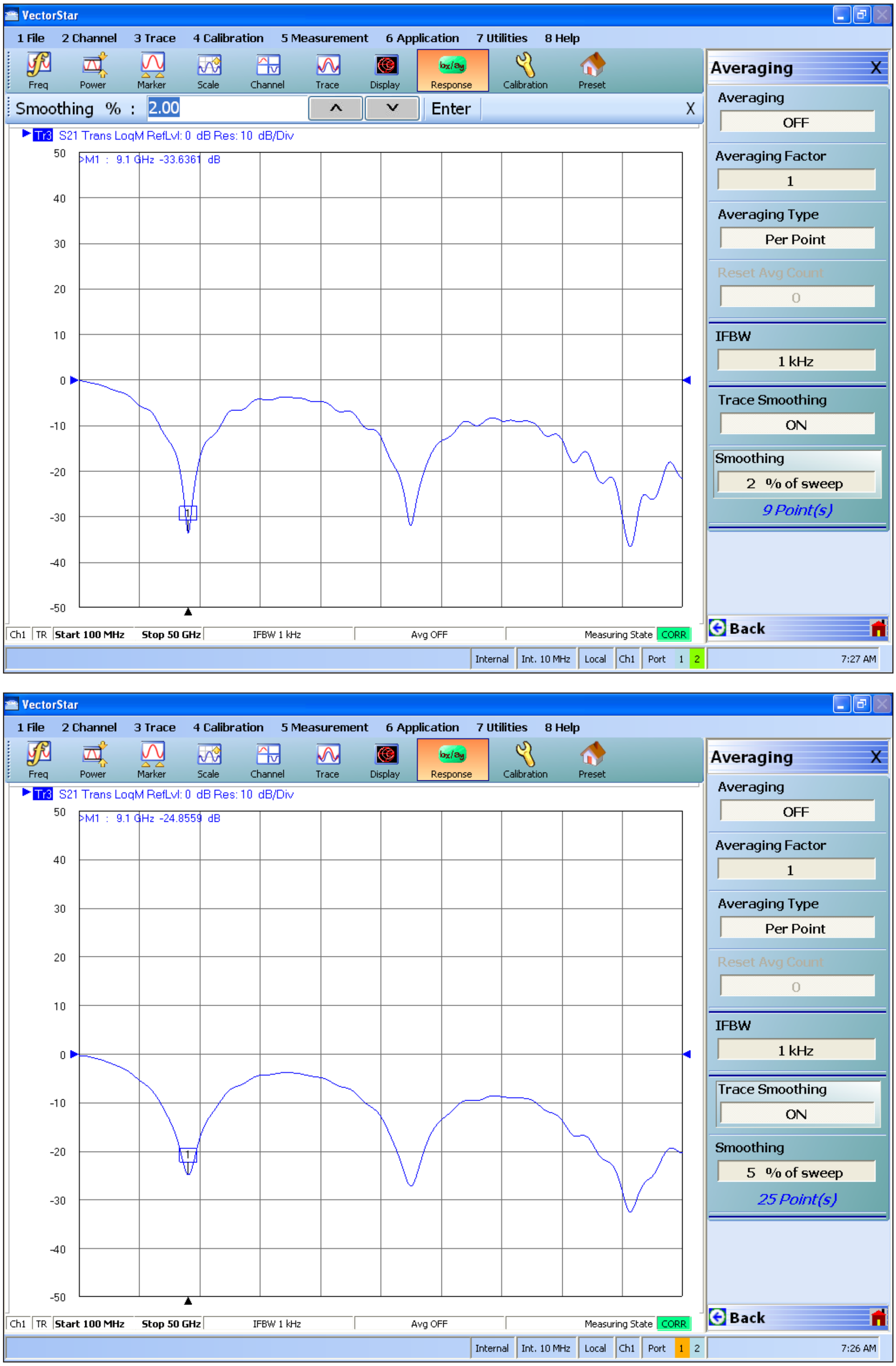

Figure 9. The measurement of the same DUT as Figure 8 is shown here but with 2% and 5% smoothing applied.

Contrast this to the application of SMC as shown in Figure 10. The depth of the resonant nulls have not changed (within the trace noise limits for this IF bandwidth) and the DUT structural ripples are still present. In this particular example, the actual secondary match defects missed by the calibration were insignificant compared to the structure in the DUT's actual data. This helps emphasize the point that SMC is intended to remove measurement errors that are not physically part of the DUT response.

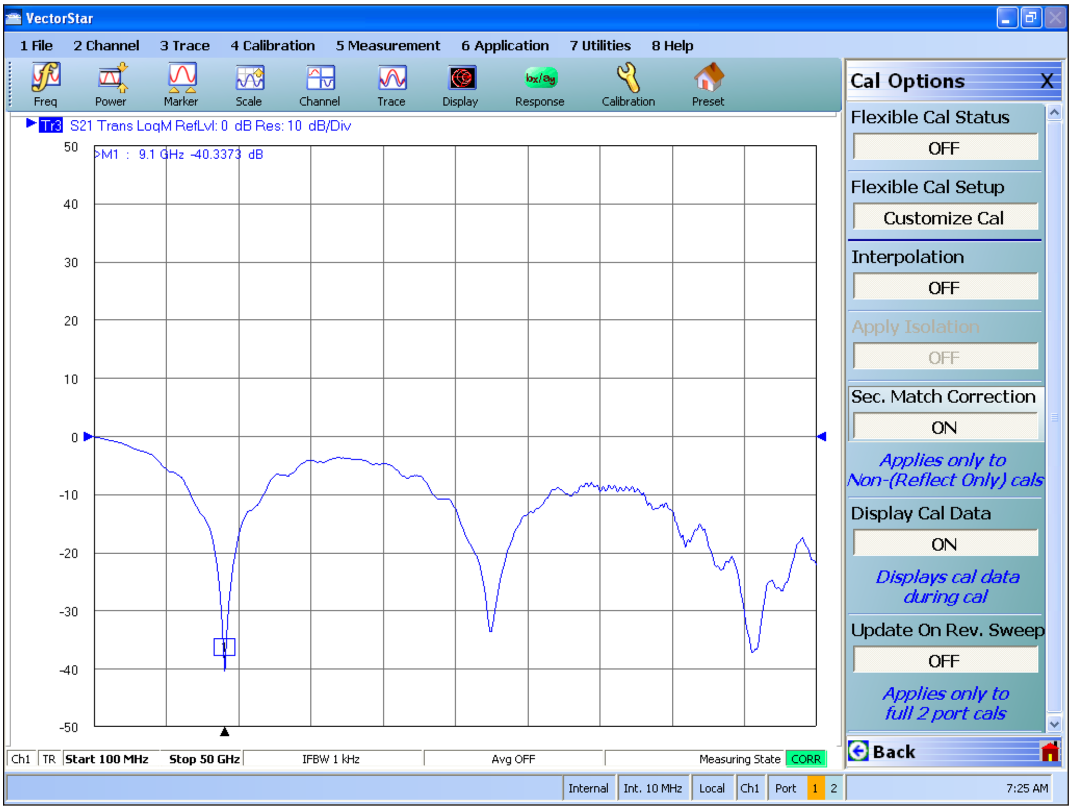

Figure 10. The measurement of the DUT of Fig. 7 is shown here but with SMC applied.

Conclusion

Secondary match correction process optimizes measurements of low insertion loss devices by correcting for a simplification made in the standard error model. The improvements are often on the scale of hundredths of a dB in insertion loss and picoseconds in group delay, but for low-loss adapter and fixture characterization those enhancements can be very valuable. SMC also does not come at the cost of distorting true DUT performance as do some other techniques for lowering ripple like smoothing.

Anritsu's VectorStar™ and ShockLine™ VNA solutions both have SMC capabilities built into the standard software, giving both platforms this valuable enhancement for characterizing low insertion loss devices.

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