A New Calibration Method for Achieving High Insertion-Loss Measurements with a Vector Network Analyzer*

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***Abstract* — We present a new calibration method for achieving high insertion-loss measurements with a vector network analyzer (VNA). The method requires a characterized attenuator and other additional hardware, including an amplifier, an isolator, two directional couplers, and two attenuators. With this setup, we measure wave-parameters rather than scattering-parameters. This technique enables us to shift the dynamic range of our measurements while decreasing uncertainties due to the noise floor of the VNA. With hardware available in our laboratory, we can measure values of insertion-loss up to 150 dB.**

***Index Terms* — attenuator, calibration, directional coupler, insertion loss, isolator, measurement, uncertainty, vector network analyzer.**

I. INTRODUCTION

The need to accurately characterize high values of insertion loss is paramount to applications involving near- to mid-range antenna measurements. In free-field environments, insertion losses greater than 100 dB are often encountered, especially in non-line-of-sight applications or when separation distances between transmit and receive antennas are significant. Standard methods for measuring high values of insertion loss are inadequate, as the noise floor of the VNA limits the ability to accurately characterize such channels [1].

In a previous study [2], we presented a straightforward method for shifting the dynamic range of our VNA by measuring wave-parameters rather than scattering parameters (*S*-parameters), and utilizing only two additional pieces of hardware, namely an attenuator and an amplifier. This allowed us to increase the upper limit of insertion loss measurements from approximately 110 dB to 130 dB, while decreasing uncertainties due to the noise floor of the VNA.

In this paper, we further shift the upper limit of our VNA measurements to 150 dB by utilizing a new calibration method that requires a characterized attenuator and other additional hardware, and involves measuring wave-parameters. In the following sections, we describe our measurement setup, explain the new calibration method, and provide measured results with uncertainties.

II. MEASUREMENT SETUP

Figure 1 shows a simplified schematic diagram of a four-sampler VNA. The source is switched between Ports 1 and 2 so all four *S*-parameters can be calculated from the measured incident and reflected signals. This setup works well for moderate insertion losses, but as these values increase, the measurements become noisier due to the limited dynamic range of the VNA.

In our previous study [2], we developed a method that uses an amplifier between the source and the couplers on Port 1, and a compensating attenuator between the coupler and receiver on Port 1. This setup measures the incident power, while preventing damage to the receiver, as shown in Figure 2. Here, we were required to measure wave-parameters rather than *S*-parameters because the amplifier was placed in the system after the calibration, which changed the switch terms that correct for differences in the reflection coefficients of the terminating resistor switched between ports 1 and 2 [3]. Wave-parameters automatically compensate for this phenomena since incident and reflected signals are directly measured.

In this study, we further shift the upper limit of insertion-loss measurements by utilizing a new calibration method, along with additional hardware, shown in Figure 3. A 43 dB amplifier with a noise figure of 6.0 dB is placed external to the ports of the VNA so none of its internal components will be damaged. This requires two extra couplers for separating the incident and reflected signals, as well as two attenuators to protect the VNA's receivers on Port 1. Here, we had access to two 10 dB couplers, which required two 30 dB attenuators to protect the receivers. We also placed an isolator directly after the output of the amplifier to prevent any reflected signals from reaching it.

With this setup, both the calibration and device-under-test (DUT) measurements are performed with all the hardware in place. The new calibration is referred to as Short-Open-Load-Attenuator (SOLA). The attenuator is required to decrease the power incident on Port 2, and must be previously characterized with a separate calibration. In our case, we utilized a 40 dB attenuator calibrated with a Short-Open-Load-Thru (SOLT) technique. All measurements and calibrations in this study were performed with Type-N coaxial connectors on a frequency grid between 2.0-4.0 GHz (the bandwidth of our amplifier and isolator) with a spacing of 5 MHz (401 points), and an IF bandwidth of 20 Hz with no averaging. Furthermore, we measured wave-parameters rather than S-parameters since the switch terms could not be accurately measured at the lower powers originating from the source on Port 2, which are attenuated before reaching Port 1. In the following section, we describe the SOLA calibration in more detail.

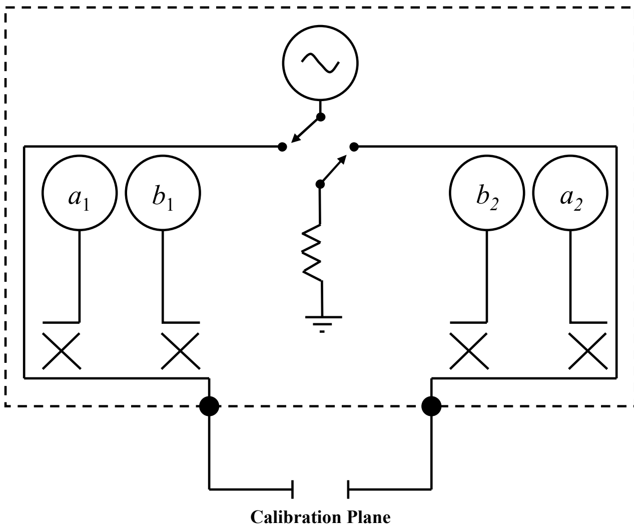

Fig. 1. Simplified schematic diagram of a four-sampler VNA.

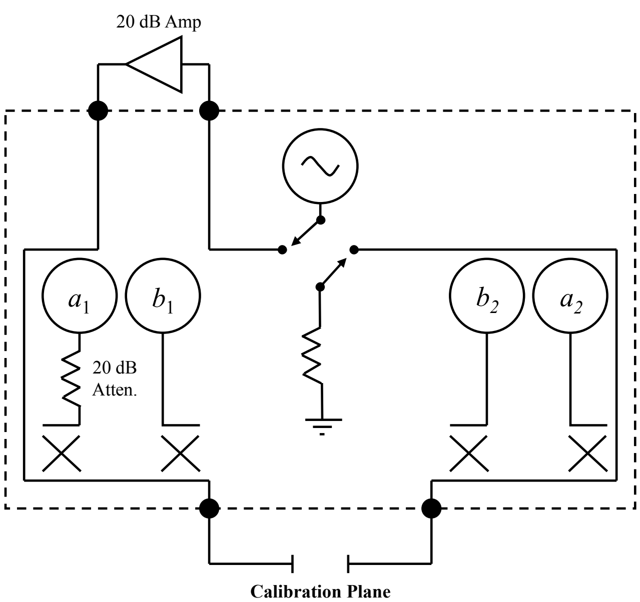

Fig. 2. Simplified schematic diagram of a four-sampler VNA with a 20 dB amplifier and 20 dB attenuator inserted for improving high-insertion-loss measurements.

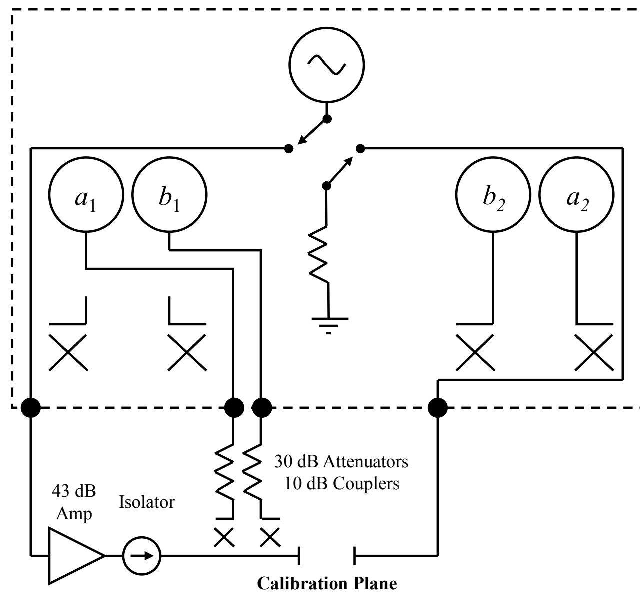

Fig. 3. Simplified schematic diagram of a four-sampler VNA with a 43 dB amplifier, isolator, two 10 dB couplers, and two 30 dB attenuators inserted for further improving high-insertion-loss measurements.

III. SOLA Calibration

SOLA and SOLT calibrations are similar. Both require three known standards to be connected to Ports 1 and 2, namely a short circuit, an open circuit, and a nominally-matched load. These standards need not be ideal assuming they are characterized and well-separated on the Smith Chart. Additionally, the SOLA calibration requires a characterized attenuator be placed between Ports 1 and 2 rather than a Thru.

Like SOLT, the SOLA calibration is realized with an eight-term error model in our software, the NIST Microwave Uncertainty Framework [4], [5]. The short, open, and load measurements, along with their respective definitions, allow us to determine the two reflection terms for each of the calibration error boxes. This leaves four transmission terms, of which only three are required since they can be arbitrarily normalized. Assuming the amplifier is placed on Port 1, as in Figure 3, the measured and defined values of the attenuator's forward transmission coefficients (S_{21}) allow us to solve for S_{21} of the two error boxes. In our normalization scheme, S_{12} of the Port 1 error box is set equal to S_{21} of the Port 1 error box, and S_{12} of the Port 2 error box is calculated to be consistent with the remainder of the Port 2 error box terms. Note that with any calibration utilizing an eight-term error model, either the measured *S*-parameters must be corrected for switch terms, or the *S*-parameters can be calculated directly from measured wave-parameters, in which case switch-term correction is not needed.

TABLE I

COMPARING INSERTION-LOSS MEASUREMENTS OF TWO DIFFERENT CALIBRATIONS

Attenuator Setting (dB)	$\lvert S_{21}\rvert$ Mean ± Std. Dev. (dB)	
	SOLT Calibration	SOLA Calibration
40	-40.51 ± 0.12	-40.60 ± 0.12
50	-50.54 ± 0.12	-50.62 ± 0.12
60	-60.47 ± 0.12	-60.55 ± 0.13
70	-70.49 ± 0.12	-70.58 ± 0.13
80	-80.42 ± 0.13	-80.57 ± 0.13
90	-90.40 ± 0.26	-90.53 ± 0.13
100	-100.40 ± 0.67	-100.42 ± 0.14
110	-110.32 ± 2.42	-110.45 ± 0.15
120	-118.83 ± 5.16	-120.37 ± 0.21
130	-121.12 ± 5.50	-130.30 ± 0.57
140	-	-140.08 ± 1.78
150	-	-149.22 ± 4.19
160	-	-153.65 ± 5.95

IV. MEASUREMENT RESULTS

For comparison purposes, we performed both SOLT and SOLA calibrations, and measured a DUT consisting of a 40 dB fixed attenuator connected to a 120 dB step attenuator, which allowed us to vary the settings from 40 to 160 dB. Physical models of the SOLT calibration standards were developed and validated using a multiline Thru-Reflect-Line (TRL) calibration within the NIST Microwave Uncertainty Framework [4], [5]. The Short, Open, and Load standards of the SOLA calibration were the same as those of the SOLT calibration. The definition of the 40 dB attenuator utilized in the SOLA calibration was measurement-based rather than a physical model, and was previously determined with an SOLT calibration.

The SOLT calibration and corresponding DUT measurements were made with the standard VNA setup, as illustrated in Figure 1. Here, the output power of the VNA was set to 0 dBm, and we measured *S*-parameters.

The SOLA calibration and corresponding DUT measurements were performed with the high-insertion-loss setup, illustrated in Figure 3. Here, the output power of the VNA was set to –6 dBm, and we measured wave-parameters.

Table 1 lists the mean values and standard deviations of the magnitudes of S_{21} calculated over the measured frequencies at attenuator settings of 40-160 dB using the two calibrations. Although both calibrations provided comparable mean values up to 110 dB, the standard deviations increased much more drastically with increased attenuator settings for the case where *S*-parameters were measured using the standard setup. For instance, at the attenuator's 110 dB setting, the SOLT measurements resulted in a standard deviation of ± 2.42 dB, while the SOLA measurements resulted in a much lower standard deviation of ± 0.15 dB.

At the 120 dB setting, the SOLT measurements were approaching the noise floor, while the SOLA measurements continued to deliver reasonable results up to 150 dB before reaching the noise floor.

Figures 4-6 illustrate the measurements of $\lvert S_{21}\rvert$ at the 90, 110, and 130 dB settings for the two calibrations. These graphs clearly show how much more noise is present in the SOLT measurements for the standard setup than the SOLA measurements for the modified setup.

Figure 7 plots the measurements and 95 % confidence intervals of $\lvert S_{21}\rvert$ for the variable attenuator at the 90 dB setting (a typical value we may encounter during non-line-of-sight, free-field measurements).

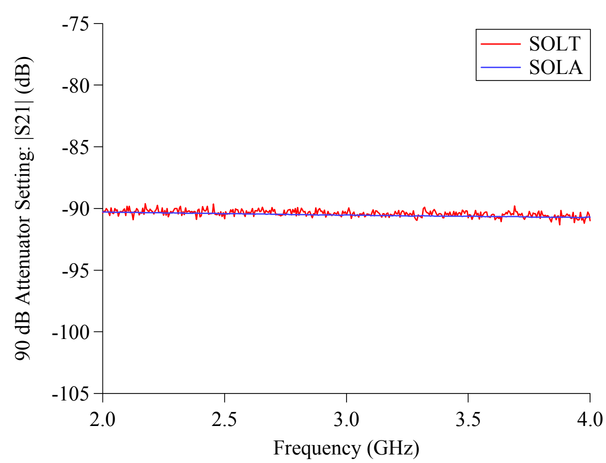

Fig. 4. Comparing measurements of $\lvert S_{21}\rvert$ at the 90 dB attenuator setting for two different calibrations.

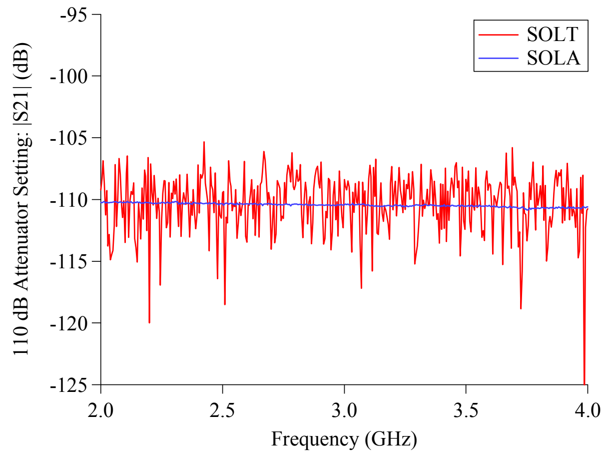

Fig. 5. Comparing measurements of $|S_{21}|$ at the 110 dB attenuator setting for two different calibrations.

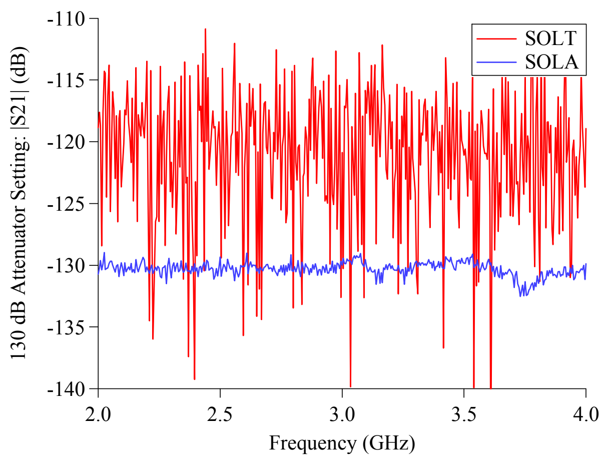

Fig. 6. Comparing measurements of $|S_{21}|$ at the 130 dB attenuator setting for two different calibrations.

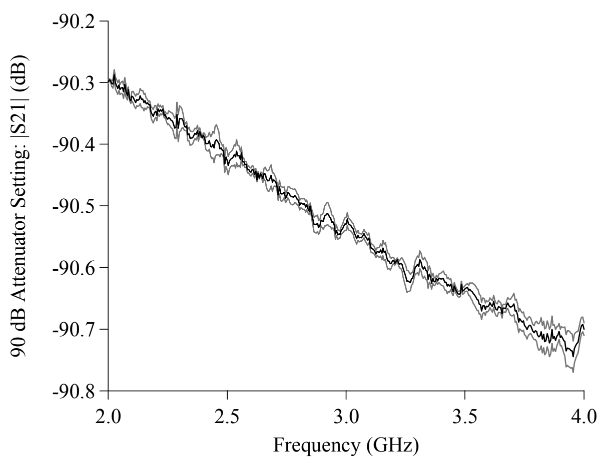

Fig 7. Nominal measurements (black curve) and 95 % confidence intervals (grey curves) of $|S_{21}|$ for the 90 dB setting as determined with the SOLA calibration.

V. Conclusions

By measuring wave-parameters and utilizing a new SOLA calibration method in conjunction with a characterized attenuator and other additional hardware, we shifted the dynamic range of our VNA while decreasing uncertainties due to the noise floor. This modified setup decreased the standard deviations of $|S_{21}|$ by an order of magnitude for attenuator settings at and above 110 dB. Although we were limited to a maximum measured insertion loss of 150 dB with the equipment we had readily available in our laboratory, we should be able to measure even higher values with more powerful amplifiers and other hardware with higher power ratings. However, at some point leakage signals could potentially become problematic. This may be a topic of a future study.

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