Investigating the Effects of IF Bandwidth and Averaging on Calibrated Scattering-Parameter Measurements

Jeffrey A. Jargon, Amanda A. Koepke, and Paul D. Hale

National Institute of Standards and Technology, 325 Broadway, M/S 672.03, Boulder, CO 80305 USA
Email: jeffrey.jargon@nist.gov, Tel: +1.303.497.4961

***Abstract* — We investigate the effects of IF (intermediate-frequency) bandwidth and averaging on calibrated scattering-parameter measurements made with a vector network analyzer. We begin by examining the sweep times and noise-floor levels for various combinations of the two settings. Then, we study how these settings influence calibrated measurements and compare the results to uncertainties due to systematic and random effects for devices with varying insertion-loss values.**

***Index Terms* — averaging, bandwidth, calibration, intermediate frequency, measurements, scattering parameters, vector network analyzer.**

I. Introduction

The dynamic range of a vector network analyzer (VNA) is an important specification. This is especially true when measuring devices with high insertion loss, such as high-valued attenuators and filters, which may have both low-insertion loss in the passband and high-insertion loss in the stopband [1]. There are two ways to extend the dynamic range of a VNA: (1) by increasing the averaging, and (2) by decreasing the bandwidth of the IF filter [2-3].

Most commercial VNAs perform averaging by taking exponentially-weighted moving averages of the complex data from each sweep. Increasing the averaging by a factor of ten lowers the noise floor by 10 dB, but also increases the sweep time by approximately a factor of ten. The IF bandwidth (BW) reduces the noise floor by filtering noise outside the bandwidth of the digital IF filter. Decreasing the IF bandwidth by a factor of ten lowers the noise floor by 10 dB, but also increases the sweep time by almost tenfold. According to reference [2], reducing IF bandwidth has a slightly smaller effect on sweep time than increasing averaging a corresponding amount.

In this paper, we begin by examining the sweep times and noise-floor levels of our commercial VNA for various combinations of averaging and IF bandwidth. Next, we study how these settings influence calibrated measurements for devices with varying insertion-loss values and compare these results to uncertainties due to systematic and random effects.

II. Sweep Times and Noise Floor

Prior to performing any calibrations, we investigated the sweep times and noise-floor levels of our VNA for various combinations of averages between 1 and 1,000, and IF bandwidths ranging from 1 Hz to 10,000 Hz. To achieve this, we measured a 150-dB attenuator with our VNA at frequencies between 50 MHz and 18 GHz (360 points). From experience, we know the noise-floor level is higher than -150 dBm, so we measured the transmission parameter S_{21} of the attenuator with a VNA output power of 0 dBm.

Table 1 lists the sweep times in seconds for various combinations of averaging and IF bandwidth settings. We did not measure the blank entries, which required sweep times of over an hour. From the tabulated results, we see for a given number of averages, decreasing the IF bandwidth by a factor of ten increases the sweep time by about ten times. Likewise, for a given IF bandwidth, increasing the averages by a factor of ten increases the sweep time approximately tenfold.

Table 2 lists the means of the magnitudes of S_{21} taken over all measured frequencies for various combinations of averaging and IF bandwidth. These means effectively provide us with the noise-floor level of our VNA. From the tabulated results, for a given number of averages, decreasing the IF bandwidth by a factor of ten decreases the noise floor by about 10 dB until a lower limit is reached. Likewise, for a given IF bandwidth, increasing the number of averages by a factor of ten decreases the noise floor by about 10 dB until the lower limit is reached. The lowest value we measured was -131 dB, corresponding to a noise-floor level of -131 dBm.

From Table 2, we find we can reach the lowest noise-floor level with the following combinations (IF BW = 1 Hz and Avg. = 1; IF BW = 10 Hz and Avg. = 10; IF BW = 100 Hz and Avg. = 100; or IF BW = 1,000 Hz and Avg. = 1,000). Each of these combinations requires a sweep time of over ten minutes. If the user does not need the entire dynamic range for their application, other combinations may be chosen that offer much faster sweep times (i.e., IF BW = 10 Hz and Avg. = 1 provides a noise-floor level of -125 dBm with a sweep time of 67 sec.)

Table 1. Sweep time of a vector network analyzer as a function of IF bandwidth and number of averages.

Sweep Time (sec.)				
IF BW (Hz)	Number of Averages			
	1	10	100	1,000
1	637	-	-	-
10	67	687	-	-
100	7	74	728	-
1,000	1	10	104	1036
10,000	<1	4	40	387

Table 2. Mean of a 150-dB attenuator's $|S_{21}|$ values as a function of IF bandwidth and number of averages.

mean{|S21|} (dB)				
IF BW	Number of Averages			
(Hz)	1	10	100	1,000
1	-130	-	-	-
10	-125	-130	-	-
100	-116	-125	-130	-
1,000	-106	-115	-124	-131
10,000	-96.3	-106	-116	-125

III. Calibrated Measurements

Next, we examined how IF bandwidth influences calibrated measurements for devices with varying insertion-loss values and compared these effects to systematic and random uncertainties.

We performed short-open-load-thru (SOLT) calibrations and measured four devices, an airline, a 20-dB attenuator, a 40-dB attenuator, and a 110-dB attenuator. Measurements were made on a frequency grid from 50 MHz to 18 GHz in steps of 50 MHz at a VNA output power of 0 dBm with 3.5 mm coaxial connectors. The offline calibrations and associated uncertainty analyses were performed using the NIST Microwave Uncertainty Framework (MUF) [4-6].

The calibration standards and devices were each measured using Avg. = 1 and IF bandwidths of 10 Hz, 100 Hz, 1,000 Hz, and 10,000 Hz. In this experiment, we kept the number of averages constant, while varying the IF bandwidth. We could have also kept the IF bandwidth constant, and varied the number of averages, but since the two methods have the same effect, we chose the former since reducing IF bandwidth is a more common practice. To avoid variations due to repeated connections, each calibration standard and device was measured at all the IF-bandwidth settings without disconnections. From a previous study, we know that variability due to repeated measurements without disconnections is very low [7]. For example, we connected our short standard to the VNA and measured it at each of the various IF-bandwidth settings prior to disconnecting it and connecting the open standard. After all the standards and devices were measured and the data saved, we performed four offline calibrations at the respective IF-bandwidth settings. Thus, we could isolate the effects of IF bandwidth from connector repeatability.

Figures 1 and 2 illustrate measurements of $|S_{21}|$ for the 40-dB and 110-dB attenuators, respectively, at the various IF-bandwidth settings. For the 40-dB attenuator, the measurements were noticeably noisier at the higher IF-bandwidth settings but followed the same curve as a function of frequency. In contrast, measurements of the 110-dB attenuator were not just noisier at the higher-bandwidth settings, but the noise-floor levels at the 1,000 Hz and 10,000 Hz settings were too high to accurately measure the device.

To quantify the effect of varying the IF bandwidth, including noise and amplitude offset, we considered one setting as a baseline (IF BW = 10 Hz and Avg. = 1), and compared measurements taken with the other settings to the baseline using the mean (over the frequencies) of the absolute values of the differences of the two S_{21} magnitudes. For example, to compare the baseline S_{21} magnitude (IF BW = 10 Hz and Avg. = 1) to the setting of IF BW = 100 Hz and Avg. = 1, we calculated

$$\text{mean}\{\text{abs}[|S_{21}|_{\text{IFBW=100Hz}} - |S_{21}|_{\text{IFBW=10Hz}}]\}.$$

These differences, reported in Table 3, increase as the IF BW increases for all the measured devices.

To put the differences between IF bandwidth settings in context, we quantified the uncertainties due to systematic and random effects using the baseline setting (IF BW = 10 Hz and Avg. = 1). To determine the uncertainties due to random effects, we repeated the calibration five times with disconnects between every device and standard measurement. Figures 3 and 4 illustrate repeated measurements of $|S_{21}|$ for the 40-dB and 110-dB attenuators, respectively.

From these repeated measurements, we used the half-width of a prediction interval to describe the spread of the measurement results at a given frequency and a reasonable range for a new observation [8]. The half-width for a two-sided 95% prediction interval (referred to as "95% HW Random") is

$$t_{.975,n-1} s \left(1 + \frac{1}{n}\right)^{1/2},$$

where $n = 5$, $t_{.975,4} = 2.776$, and s is the sample standard deviation of the five S_{21} magnitudes at that frequency. This half-width tells us how far we expect a new measurement taken with this baseline setting to be from the mean of these five measurements. We report the mean value (over the frequencies) of this half-width as "mean{95% HW Random}" for each measured device in Table 3.

In Table 3, we also report the mean values (over the frequencies) for the half-widths reported by the MUF for the uncertainties due to systematic effects for one of the calibrations as "mean{95% HW Systematic}." The random and systematic half-widths give us a sense of scale when comparing against the differences calculated from the various IF-bandwidth settings. This is not a statistical test for significant differences, but rather a general guideline for the range of differences we expect to see due to random and systematic effects. Here we assumed that the uncertainty about the baseline measurement used to calculate the differences was the same as the uncertainty for the distribution we observed for the five repeat calibrations under the baseline setting. This provides us with an idea of how unlikely these differences are, given the distribution of baseline measurements and the uncertainty due to systematic effects. Figures 5 and 6 illustrate 95% uncertainty bounds of $|S_{21}|$ for the 40-dB and 110-dB attenuators, respectively.

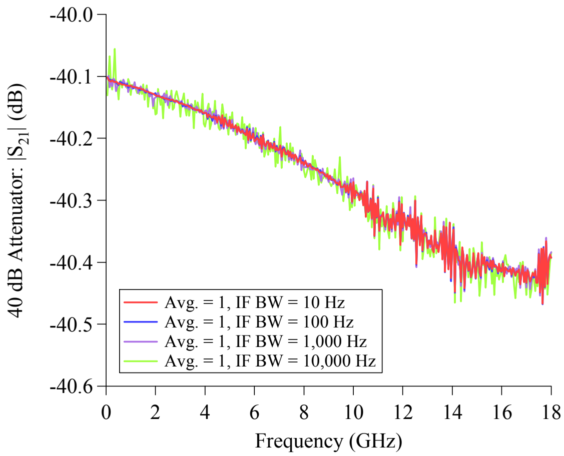

Fig. 1. Measurements of $|S_{21}|$ for the 40-dB attenuator at various IF bandwidth settings.

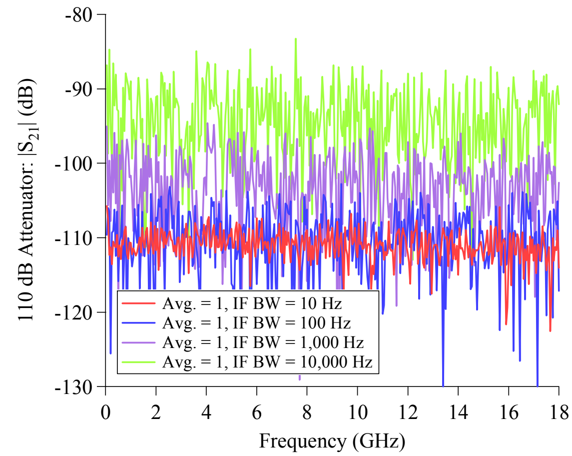

Fig. 2. Measurements of $|S_{21}|$ for the 110-dB attenuator at various IF bandwidth settings.

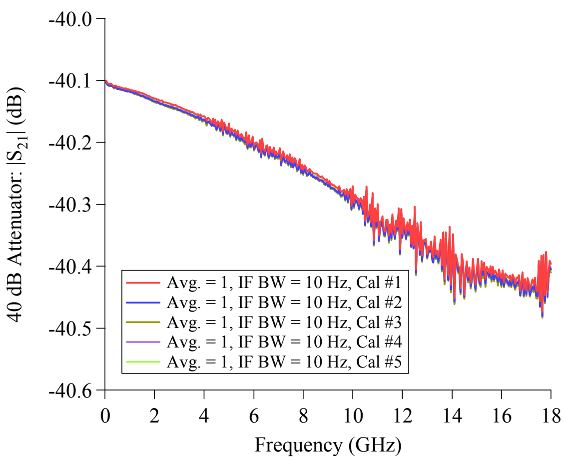

Fig 3. Five repeated measurements of $|S_{21}|$ for the 40-dB attenuator at an IF bandwidth of 10 Hz.

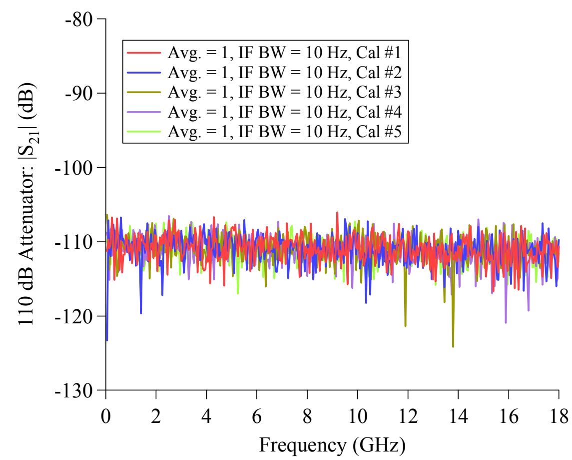

Fig 4. Five repeated measurements of $|S_{21}|$ for the 110-dB attenuator at an IF bandwidth of 10 Hz.

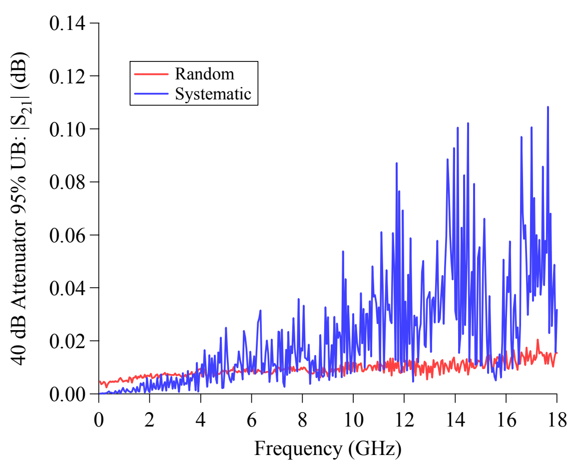

Fig. 5. The 95% interval half-widths for uncertainties of the 40-dB attenuator at an IF bandwidth of 10 Hz.

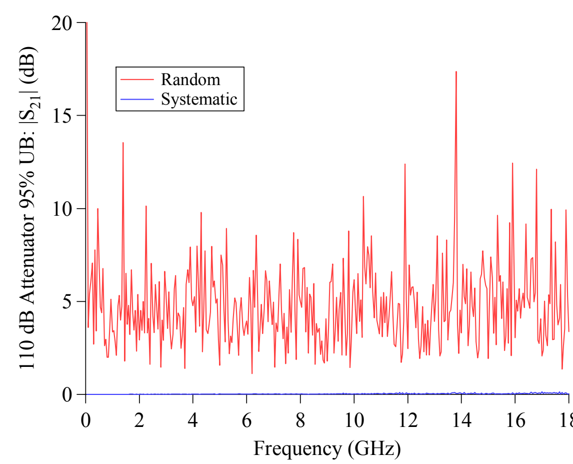

Fig. 6. The 95% interval half-widths for uncertainties of the 110-dB attenuator at an IF bandwidth of 10 Hz.

Table 3. Comparison of baseline setting (IF BW = 10 Hz) to other IF BW settings, and 95% interval half-widths for the airline and attenuators.

Airline	
mean{abs[$\|S_{21}\|_{IFBW=100Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	0.0006 dB
mean{abs[$\|S_{21}\|_{IFBW=1,000Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	0.0010 dB
mean{abs[$\|S_{21}\|_{IFBW=10,000Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	0.0024 dB
mean{95% HW Random}	0.0189 dB
mean{95% HW Systematic}	0.0218 dB
20 dB Attenuator	
mean{abs[$\|S_{21}\|_{IFBW=100Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	0.0003 dB
mean{abs[$\|S_{21}\|_{IFBW=1,000Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	0.0006 dB
mean{abs[$\|S_{21}\|_{IFBW=10,000Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	0.0039 dB
mean{95% HW Random}	0.0067 dB
mean{95% HW Systematic}	0.0210 dB
40 dB Attenuator	
mean{abs[$\|S_{21}\|_{IFBW=100Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	0.0013 dB
mean{abs[$\|S_{21}\|_{IFBW=1,000Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	0.0040 dB
mean{abs[$\|S_{21}\|_{IFBW=10,000Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	0.0116 dB
mean{95% HW Random}	0.0093 dB
mean{95% HW Systematic}	0.0218 dB
110 dB Attenuator	
mean{abs[$\|S_{21}\|_{IFBW=100Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	3.920 dB
mean{abs[$\|S_{21}\|_{IFBW=1,000Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	8.253 dB
mean{abs[$\|S_{21}\|_{IFBW=10,000Hz}$ - $\|S_{21}\|_{IFBW=10Hz}$]}	16.37 dB
mean{95% HW Random}	4.781 dB
mean{95% HW Systematic}	0.024 dB

Examining Table 3 in more detail, we made several observations: (1) the mean{95% HW Random} is higher for the airline than for the 20-dB and 40-dB attenuators, which may be attributed to the airline being more difficult to connect due to its "floating" center conductor; (2) the mean{95% HW Random} for the 110-dB attenuator is much higher than for the other devices since its measurement is approaching the noise-floor level of the VNA; (3) the mean{95% HW Systematic} for the four devices have similar values since they all share the same calibration standards and associated uncertainties; (4) all the means of the differences due to varying IF bandwidth settings are less than mean{95% HW Random} for the airline and 20-dB attenuator, and just slightly larger for the 40-dB attenuator at the highest IF bandwidth setting; (5) the means of the differences due to varying IF bandwidth settings are on the same order or greater than the mean{95% HW Random} for the 110-dB attenuator due to increased noise and amplitude offsets.

IV. Conclusions

We investigated the effects of averaging and IF bandwidth on calibrated scattering-parameter measurements made with a VNA. We began by examining the sweep times and noise-floor levels for various combinations of the two settings. We verified that decreasing the IF bandwidth by a factor of ten decreases the noise floor by about 10 dB until a lower limit is reached and increasing the averaging by a factor of ten decreases the noise floor by about 10 dB until the lower limit is reached. Next, we studied how these settings influence calibrated measurements and compared the results to uncertainties due to systematic and random effects for devices with varying insertion-loss values. We found that at lower attenuation levels, the mean difference (over frequency) we see between measurements made with different IF bandwidth settings and the baseline are similar in magnitude to the mean difference (over frequency) we expect to see between a new measurement under the baseline setting and the mean of the replicate baseline measurements (quantified by mean{95% HW Random}). Thus, the user may employ higher IF bandwidths or less averaging for faster sweep times without a significant penalty in terms of uncertainty. However, as the attenuation levels approach the VNA's noise-floor level, it becomes more important to choose a lower IF bandwidth setting or make use of more averaging.

Acknowledgement

The authors thank Jolene Splett, Jerome Cheron, Ari Feldman, and Dylan Williams for their helpful comments.

References

[1] Y. S. Lee, "Testing Dynamic Accuracy of Vector Network Analyzers Using the 40 GHz Step Attenuator," *65th ARFTG Microwave Measurement Conference*, Long Beach, CA, Jun. 2005.

[2] "Understanding and Improving Network Analyzer Dynamic Range," Keysight Application Note, 2018.

[3] M. Hiebel, "Fundamentals of Vector Network Analysis," Rohde & Schwarz, 2008.

[4] D. F. Williams, NIST Microwave Uncertainty Framework, Beta Version, www.nist.gov/services-resources/software/wafer-calibration-software, 2017.

[5] A. Lewandowski, D. F. Williams, P. D. Hale, C. M. Wang, and A. Dienstfrey, "Covariance-Matrix-Based Vector-Network-Analyzer Uncertainty Analysis for Time- and Frequency-Domain Measurements," IEEE Trans. Microwave Theory Tech., vol. 58, no. 7, pp. 1877-1886, July 2010.

[6] J. A. Jargon, C. H. Cho, D. F. Williams, and P. D. Hale, "Physical Models for 2.4 mm and 3.5 mm Coaxial VNA Calibration Kits Developed within the NIST Microwave Uncertainty Framework," *85th ARFTG Microwave Measurement Conference*, Phoenix, AZ, May 2015.

[7] A. Koepke and J. A. Jargon, "Quantifying Variance Components for Repeated Scattering-Parameter Measurements," *90th ARFTG Microwave Measurement Conference*, Boulder, CO, Nov. 2018.

[8] G. J. Hahn and W. Q. Meeker, "Statistical Intervals: A Guide for Practitioners," vol. 92, John Wiley & Sons, 201