MM-Wave S-Parameter Measurements with a Vector Field Analyzer in Antenna Measurement Systems

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Abstract — **Accurate antenna characterization is important in any wireless communication system. Traditionally, electrically large antenna ranges are not equipped to perform return loss measurements and thus a separate benchtop vector network analyzer (VNA) setup is required for measuring reflection coefficient or VSWR of an antenna under test (AUT).**

In this paper, we demonstrate the two-port S-parameter measurement capability of the NSI-MI Vector Field Analyzer™ (VFA) and how it can be used to integrate return loss measurements in an antenna range. We selected three known millimeter-wave components as devices-under-test (DUT) and measured the S-parameter matrix for each. These WR-10 band measurements were made using the VFA with Virginia Diodes VNAX frequency extension modules. Results are compared with Keysight's N5225A PNA network analyzer using the same set of extension modules for verification.

S-parameter measurements taken on VFA and PNA setups are compared based on three factors: Repeatability, reproducibility, and measurement comparison. The variations between successive measurements are presented in graphical form to compare repeatability of both instrument setups. Error distribution comparison is presented for reproducibility test data to show the difference between independent repeat measurements taken on both instrument setups. Measurement comparison result shows the total difference between independent VFA and PNA measurements taken for each DUT.

Index Terms — **Millimeter wave measurements, Scattering parameters, Calibration, Network Analyzers, Antenna measurements.**

I. INTRODUCTION

Antennas are used in virtually all wireless, communications and radar systems. As key elements in these applications, antennas play a crucial role in determining the system's overall performance. This makes accurate antenna characterization essential for any wireless application. The reflection coefficient or VSWR of an antenna under test (AUT) is an important antenna parameter which directly affects the power transmitted by the antenna [1]. Precise characterization of this parameter is vital as impedance mismatch between the device electronics and antenna can lead to component damage in the system. Benchtop vector network analyzers (VNA) are commonly used to measure an antenna's performance in terms of scattering parameters [2], often referred to as S-parameters.

The NSI-MI Vector Field Analyzer™ (VFA) is commonly used in antenna measurement systems for its unique ability to make accurate electromagnetic (EM) field measurements [3]. In this paper, we demonstrate the VFA's extended ability to perform full two-port calibrated S-parameter measurements on millimeter-wave microwave devices. The VFA's ability to perform multi-channel vector (amplitude and phase) electrical measurements and its long cable support using remote mixer interface (RMI) modules makes it well suited for antenna characterization, especially in electrically large measurement systems.

For this experiment, we used three known two-port millimeter-wave components as devices-under-test (DUT). For each DUT, we measured the full two-port S-parameter matrix from 75 GHz to 110 GHz using the VFA. We measured the same microwave devices with Keysight's N5225A PNA network analyzer and compared the results. The same Virginia Diodes (VDI) WR10-VNAX modules were used for frequency extension in both the VFA and PNA setups.

The remainder of this paper is organized as follows. Section II describes the test setup, procedure and parameters used for this experiment. Section III includes the test results and discussion. Conclusions and future work are discussed in Section IV and Section V, respectively.

II. TEST METHOD

For this experiment, three known microwave components with precision WR-10 waveguide flanges were selected as DUTs. DUT1 is a 30-dB attenuator, DUT2 is an 86 to 94 GHz bandpass filter, and DUT3 is a 20-dB directional coupler. Successive and independent S-parameter measurements were performed for each DUT on the VFA- and PNA-based systems from 75 to 110 GHz. For this test, we define these terms:

1) Successive measurements: Measurements are taken on the <u>same</u> instrument setup within a short time interval using the <u>same</u> calibration set and <u>without</u> disconnecting the DUT. Example: two measurements taken on VFA setup within 10 minutes using same calibration set. There is no disconnect or reconnect required between measurements.

2) Independent measurements: Measurements are taken on the <u>same or different</u> instrument setup using a <u>different</u> calibration set by <u>disconnecting and reconnecting</u> the DUT.

The SSLT (Short-Short-Load-Thru) method was used to calibrate the VFA and PNA setups for all measurements. A Python software tool was used for performing full two-port calibration on the VFA setup using the calibration techniques described in [4] and [5]. SmartCal (Guided Calibration) was performed on the PNA setup using the Calibration Wizard interface. Test parameters used for the VFA and PNA measurements are listed in Table I.

TABLE I. LIST OF TEST PARAMETERS

Parameter	VFA Setup	PNA Setup
Start Frequency	75 GHz	
Stop Frequency	110 GHz	
IF Bandwidth	250 Hz	300 Hz
Average	1	
IF Frequency	45 MHz	279 MHz
Sweep Points	401	

For the VFA measurement system shown in Figure 1. , NSI-MI Remote Mixer Interface modules were used to provide an LO and IF signal interface to the WR10-VNAX frequency extension modules. The RMI modules are designed to support up to 32 dB of cable loss in the LO path to allow for long cables between the VFA receiver and frequency extension modules. NSI-MI's ELE-SRC-FS Signal Source [6] is used as the RF source. An RF switch controlled by the VFA receiver routes the RF signal, switching between the two VNAX modules for measurements in both directions. The Python software tool was used to control the VFA receiver and ELE-SRC-FS Signal Source, perform the calibration, and plot the corrected S-parameters.

Keysight's N5225A PNA was set up to work with the WR10-VNAX extension modules as described in the reference guide [7]. PNA output power settings were adjusted to provide the required RF and LO power levels to the VNAX modules.

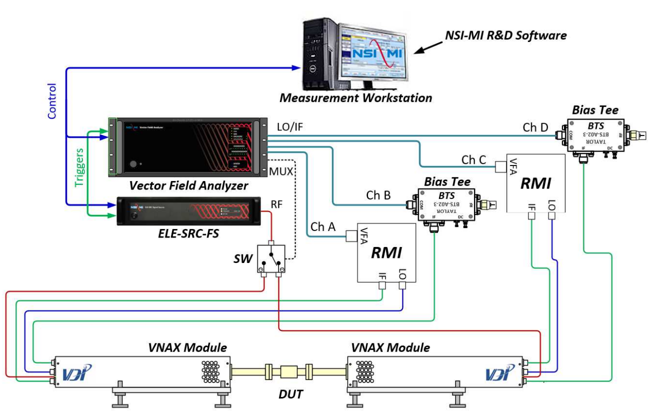

Figure 1. NSI-MI VFA setup with VDI VNAX modules

III. RESULTS

This section compares the successive and independent S-parameter measurements taken on VFA and PNA setups for each DUT based on three factors: Repeatability, reproducibility, and measurement comparison. We define these parameters as follows.

1) Repeatability: Comparison between <u>successive</u> measurements taken on the <u>same</u> instrument setup with the <u>same</u> calibration set. Example: Calibrate the VFA setup. Take two DUT measurements without changing any DUT connections. Compare the two measurements.

2) Reproducibility: Comparison between <u>independent</u> measurements taken on the <u>same</u> instrument setup with <u>different</u> calibration sets. Example: Calibrate the VFA setup and take a DUT measurement. Disconnect the DUT and calibrate the VFA setup again. Take another DUT measurement, then compare the two measurements.

3) Measurement Comparison: Comparison between <u>independent</u> measurements taken on <u>different</u> instrument setups with <u>different</u> calibration sets. Example: Calibrate the VFA setup and measure the DUT. Now calibrate the PNA setup and measure the DUT. Compare the VFA and PNA measurements.

A. *Repeatability*

Repeatability test results for all DUTs are shown in Figures 2-7. Successive transmission measurements are compared in Figures 2, 4 & 6. Similarly, successive return loss measurements are plotted in Figures 3, 5 & 7. Maximum errors (dB) measured between successive measurements for each DUT across the 75-110 GHz frequency band are summarized in Table II. The measured data indicate that there are no significant variations among successive measurements taken on the VFA and PNA setups for any of the three devices.

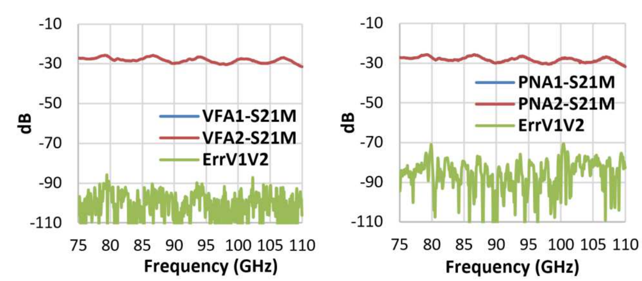

Figure 2. Transmission repeatability for DUT1: VFA and PNA

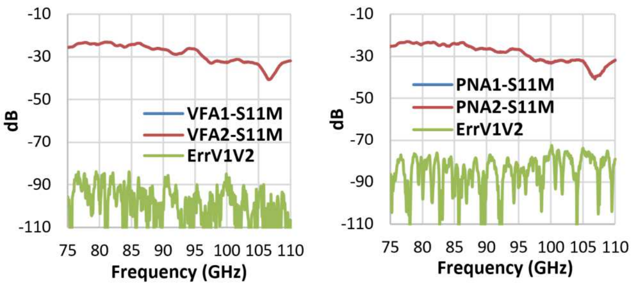

Figure 3. Reflection repeatability for DUT1: VFA and PNA

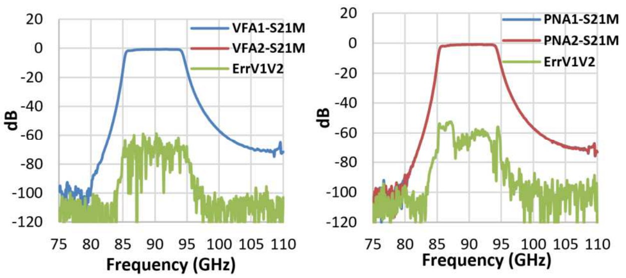

Figure 4. Transmission repeatability for DUT2: VFA and PNA

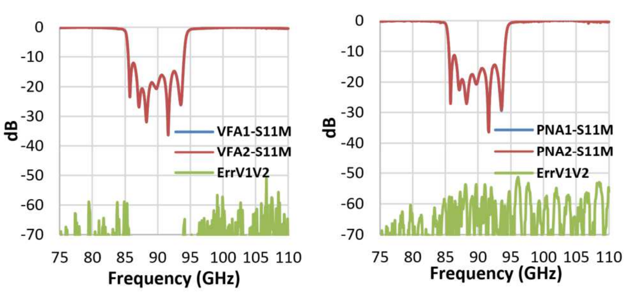

Figure 5. Reflection repeatability for DUT2: VFA and PNA

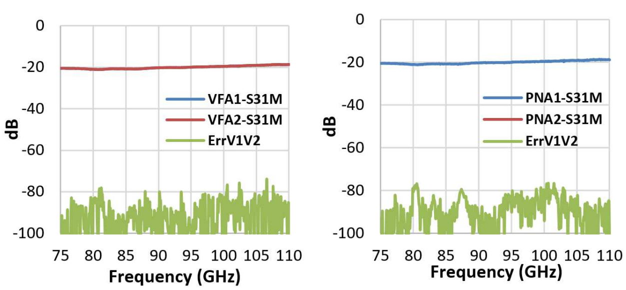

Figure 6. Transmission repeatability for DUT3: VFA and PNA

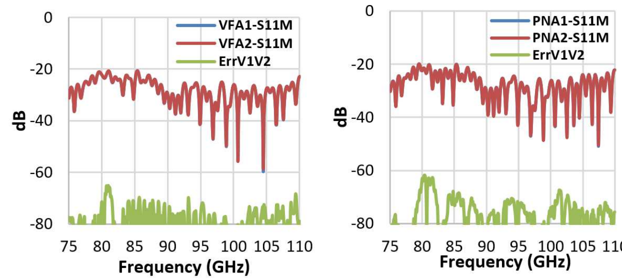

Figure 7. Reflection repeatability for DUT3: VFA and PNA

TABLE II. REPEATABILITY SUMMARY

Parameter	VFA Max. Error (dB)	PNA Max. Error (dB)
DUT1 S11	-84	-73
DUT1 S21	-86	-71
DUT2 S11	-51	-51
DUT2 S21	-59	-53
DUT3 S11	-65	-62
DUT3 S31	-74	-77

B. *Reproducibility*

For the reproducibility test, we compared five sets of independent measurements (2,005 data points) taken for each DUT on the VFA setup to measure the system's overall variability. We repeated the same on the PNA setup. DUT2 data plotted in Figure 8. shows that there are occasional differences in measurement values at certain frequencies in both VFA and PNA measurements. These random variations are not uncommon for WR-10 waveguide measurements and are mainly caused by waveguide connector repeatability, cable stability, system repeatability, noise, and ambient conditions [8]. These factors can introduce random variations in both reflection and transmission measurements. The independent measurements compared in Figure 8. are taken using different calibration sets, which requires making multiple disconnects and reconnects at the test ports for the calibration process and DUT measurements.

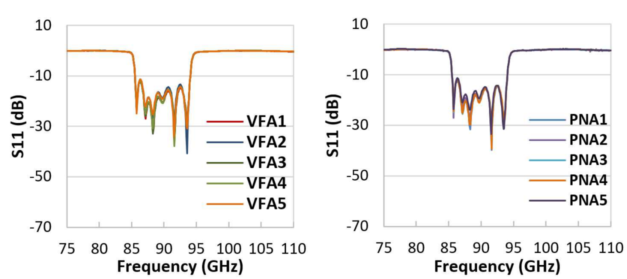

Figure 8. Reproducibility for DUT2: VFA and PNA

To compare these random variations in the two measurement setups, we calculated measurement errors for each data point for all DUTs and plotted the results for both instruments. Absolute delta values were calculated for each data point with respect to the average of five independent measurement sets taken on the same instrument. The delta values were then plotted in a normal distribution based on the mean and standard deviation. The results are shown in Figures 9-11. Figure 9. shows the error distribution comparison for S11 and S21 measurements of DUT1. Figure 10. and Figure 11. show the same for DUT2 and DUT3, respectively. The goal of this error analysis is to compare the measurement variations contributed by random sources for both instrument setups. Error plots for both devices show a normal distribution of random errors that vary within the same range as expected.

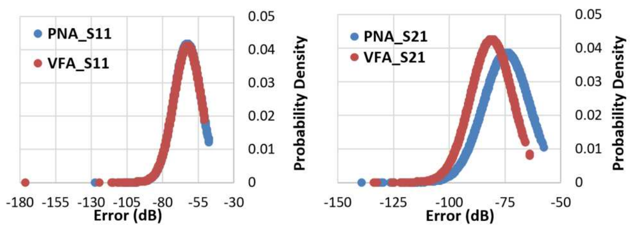

Figure 9. Error distribution for DUT1: S11 and S21

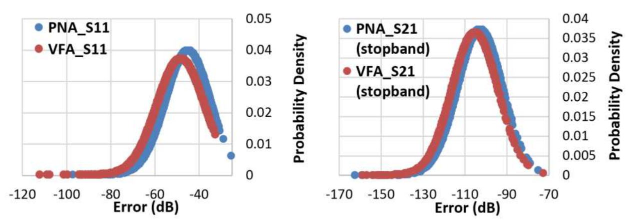

Figure 10. Error distribution for DUT2: S11 and S21

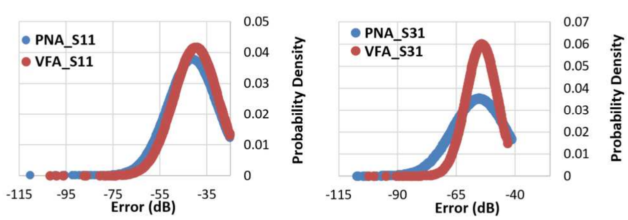

Figure 11. Error distribution for DUT3: S11 and S31

C. *Measurement Comparison*

In this section, we compare independent measurements taken on the VFA and PNA setups for each DUT. Figures 12-14 show the measurement comparison between the VFA and PNA setups for all DUTs. The maximum difference (dB) measured between VFA and PNA for each DUT across 75-110 GHz frequency band is summarized in Table III. The measured data show no significant discrepancies between the VFA and PNA results across the WR-10 band for all three DUTs. It is worth noting that because these independent measurements were performed on different instruments using different calibration sets, they are also susceptible to the random errors observed in the reproducibility test results.

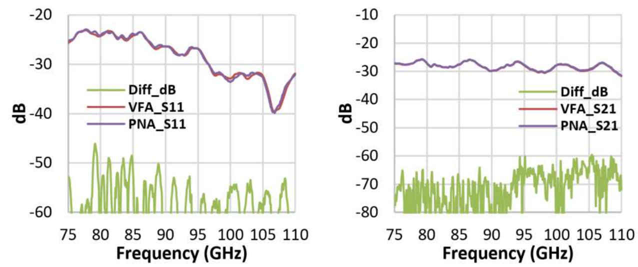

Figure 12. Measurement comparison for DUT1: S11 and S21

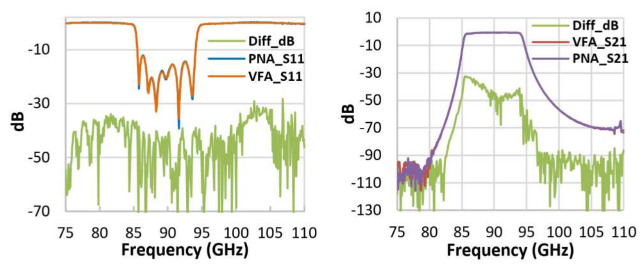

Figure 13. Measurement comparison for DUT2: S11 and S21

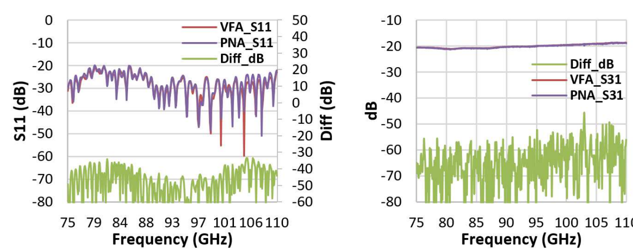

Figure 14. Measurement comparison for DUT3: S11 and S31

TABLE III. MEASUREMENT COMPARISON SUMMARY

Parameter	VFA vs. PNA Max. Difference (dB)
DUT1 S11	-46
DUT1 S21	-59
DUT2 S11	-28
DUT2 S21	-33
DUT3 S11	-34
DUT3 S31	-46

IV. CONCLUSION

In this paper, we have successfully demonstrated the NSI-MI Vector Field Analyzer's™ extended capability to perform S-parameter measurements for two-port microwave devices using the SSLT calibration technique. We measured the S-parameter matrix for three millimeter-wave devices across the 75-110 GHz frequency band using the VFA and compared the results with Keysight's N5225A PNA for validation. Virginia Diodes' WR10-VNAX modules were used for frequency extension in both VFA and PNA setups.

V. FUTURE WORK

S-parameter measurements presented in this paper were performed using a benchtop VFA setup. Future work will involve implementing this VFA solution in an electrically large antenna range and measuring calibrated return loss of an AUT. Figure 15. shows an example of a VFA based antenna measurement system equipped to perform calibrated return loss measurements. Virginia Diodes' VNAX TxRx modules are used for frequency extension. The Remote Mixer Interface modules are used for LO-IF interface to support up to 150 FT of cable length between the receiver and the extension modules.

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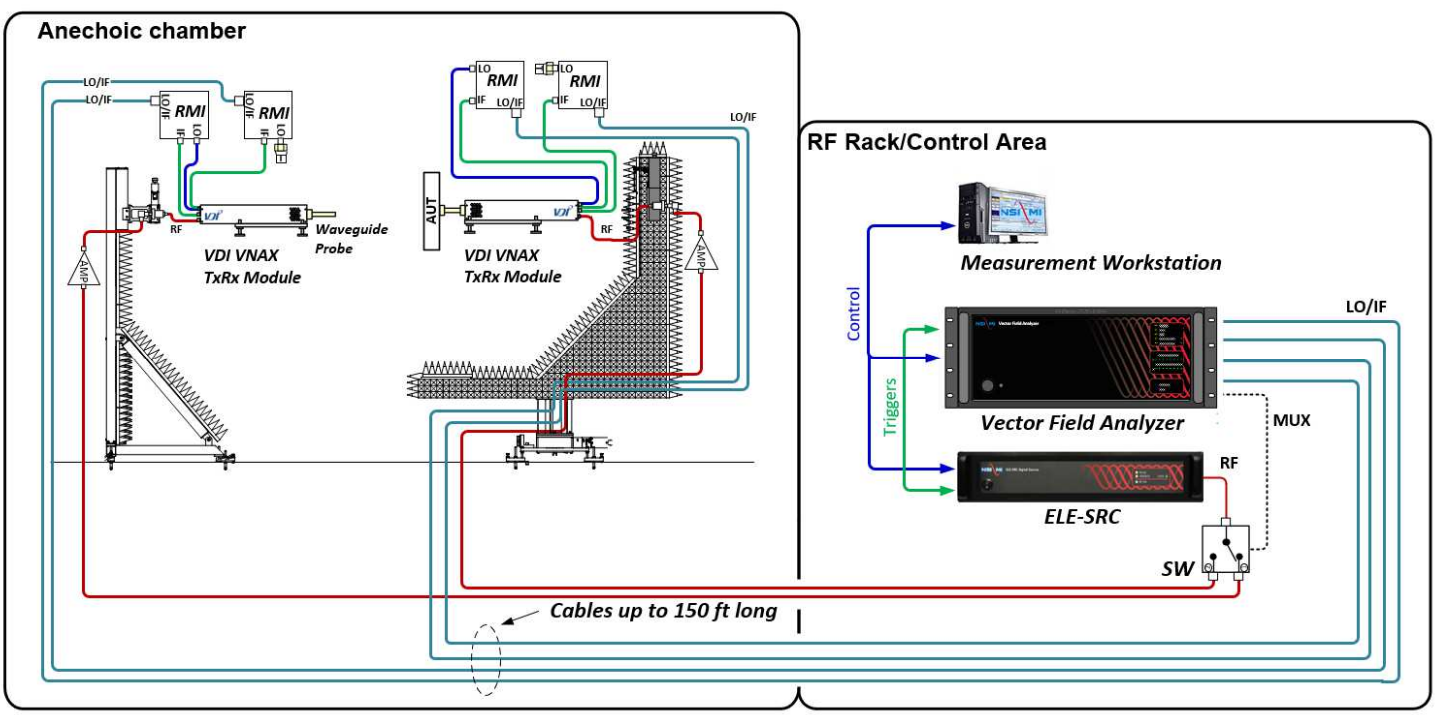

Figure 15. Example of a VFA based antenna measurement system