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Characterization of RF and Microwave Measurement Cables Used with Vector Network Analyzers

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A vector network analyzer (VNA) is as useful as the accuracy of the measurements it makes, and this requires the instrument to be calibrated. Very often those measurements need a test setup that includes not only the VNA and a calibration kit but also one or more measurement cables and adapters. The calibration process employs a technique called vector error correction, in which error terms are characterized using known standards so that errors can be removed from actual measurements. The process of removing these errors requires the errors and measured quantities to be measured vectorially (thus the need for a VNA). Directly after this calibration process, the best measurement accuracy can be expected. Changing anything may decrease measurement accuracy. Typically influences are temperature changes, bending/movement of the measurement cables, vibration and drift. This article concentrates on the measurement cables. It clarifies why and how cable bending and movement influence the accuracy and how measurement cables can be characterized to estimate their influence on the accuracy.

With vector error correction of the entire measurement setup, the transmission and reflection behavior of the measurement cables in magnitude and phase are mathematically removed. Subsequent movement of a measurement cable causes small internal dimensional changes, compression of dielectric materials, changing of contact resistances and shielding. All these effects may result in slight changes of the transmission and reflection behavior so that the vector error correction is no longer fully valid and measurement accuracy is decreased.

VNA MEASUREMENT UNCERTAINTY

For different branded microwave VNAs there are specifications for the "accuracy of measurements," "typical accuracy" or "uncertainty" in tabular and/or graphical form. These values are valid for certain combinations of a VNA type and a calibration kit type and are limited to defined conditions such as source power level and temperature change. Measurement cables are typically not included.

Values of "transmission uncertainty" for a higher end VNA in conjunction with a defined calibration kit are shown in ***Figure 1***. ***Table 1*** lists such uncertainties for an insertion loss range from 0 to 20 dB taken from Figure 1.

MEASUREMENT CABLE SPECIFICATIONS

Measurement cables specially designed for use with high-end VNAs are commonly called test port cables. They are intended for frequent use with movement and bending for adapting to specific test setups and are often armored to prevent damage from mechanical stress. ***Table 2*** shows a selection of measurement cables that work up to 40 GHz. Besides hard specifications, (i.e."maximum"), often "typical" values are mentioned, sometimes graded in the frequency range. Note that these specifications change with cable length and are valid for different bending conditions. Commonly used synonyms for "insertion loss stability" are "attenuation stability" and "amplitude stability."

When comparing VNA transmission uncertainties in Table 1 with the measurement cable transmission specifications in Table 2, VNA S_{21} magnitude uncertainty corresponds to measurement cable insertion loss stability (typical or maximum), and VNA S_{21} phase uncertainty corresponds to measurement cable phase stability. If measurement cables are used on both VNA test ports, then cable specifications must be considered twice.

In this example, the measurement cable clearly dominates the phase influence at all frequencies and the magnitude at low frequencies. With two measurement cables, the magnitude at medium and higher frequencies is influenced similarly by the VNA and the measurement cables.

Reflection measurements are also influenced by measurement cables. Typically, the change in reflection magnitude is evaluated only and expressed as a return loss value. A detailed comparison between VNA uncertainties and measurement cable influence is not discussed here.

Depending on acceptable measurement uncertainties for a particular measurement task, it may be necessary to evaluate the influence of an individual measurement cable more specifically, for example in terms of frequency range and bending conditions, to reduce the total measurement uncertainty.

CABLE STABILITY MEASUREMENT DESCRIPTION

The most basic electrical properties of a measurement cable are insertion loss and return loss. Because the influence of cable stability is significant in VNA applications, the following describes how to characterize test port cable insertion loss, phase and return loss stability for VNA measurements.

Two Port Measurements

The most accurate way to do this is to use a two port VNA calibration with mechanically fixed test ports; however, this tolerates a very limited degree of freedom in bending and movement. This can be mitigated when the two test ports of the VNA are equipped with long, unfixed, measurement cables that are included in the VNA calibration. In this case, the measurement cables belonging to the VNA contribute their instability to the measurement.

One Port Measurements

One port measurements overcome these problems and provide freedom in bending and movement. Measurement cables belonging to the VNA are not neces-

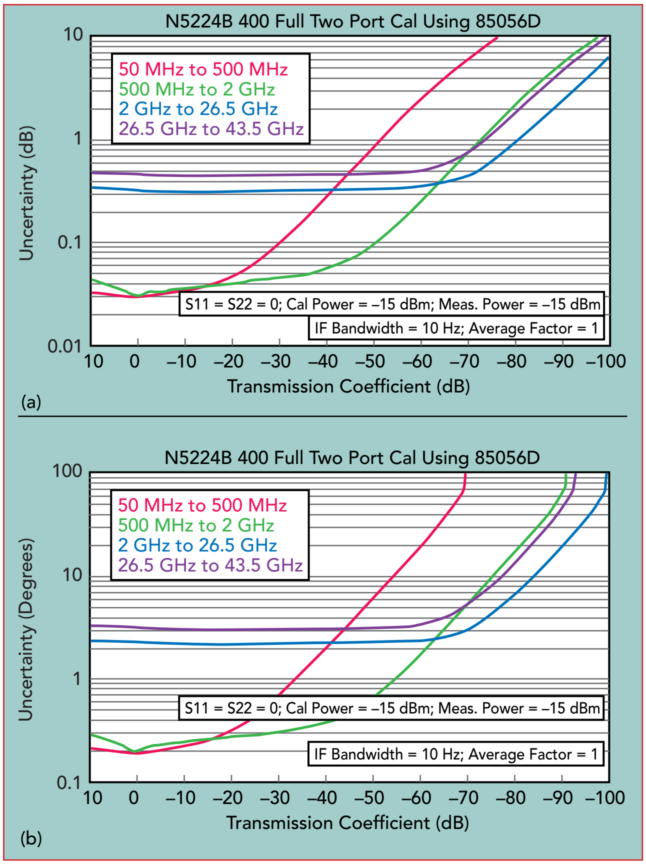

Fig. 1 VNA transmission uncertainty: magnitude (a) and phase (b).[1]

TABLE 1

VNA TRANSMISSION (S_{21}) UNCERTAINTIES

Frequency (GHz)	Magnitude Uncertainty (dB)	Phase Uncertainty (°)
1	0.03–0.04	0.20–0.27
3	0.10–0.12	0.70–0.80
20	0.10–0.12	0.70–0.80
40	0.18–0.19	1.2–1.3

TABLE 2

TEST PORT CABLE TRANSMISSION SPECIFICATIONS

	Typical Insertion Loss Stability (dB)	Worst Case Insertion Loss Stability (dB)	Typical Phase Stability (°)	Worst Case Phase Stability (°)
Maury[2]	0.05	0.10	4.5	8.5
Radiall[3]		0.05 at 40 GHz		5.0 at 40 GHz
Gore[4]	0.02	0.08	1.5	3.7
Huber+Suhner[5]	0.05		5.0	
Rohde & Schwarz[6]		< 0.08		< 3.7
Rosenberger[7]		0.03–0.08		1.3–6.0

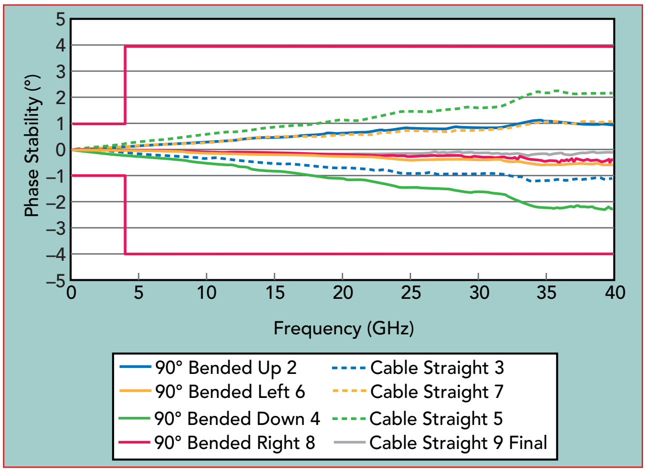

Fig. 2 **Phase stability vs. frequency.**

sary or can be fixed mechanically. Guideline VDI/VDE/DGQ/DKD 2622 Part 19[8] describes one port measurements with the measurement cable connected to a calibrated VNA test port.

Rosenberger uses a different method. The measurement cable is connected to the uncalibrated VNA test port and VNA calibration is performed at the free end. This setup is the same as for the intended use and provides some advantages in evaluating the results for transmission stability measurements, since the measurement uncertainty is significantly reduced. This is a benefit for longer cables and higher frequency bandwidths.

Transmission Stability

The basic setup terminates the free end of the measurement cable with a calibration standard short. This puts the measurement cable in the reference position and uses the VNA trace math to normalize the measured return loss and reflection phase on two different traces. The measurement cable is bent and moved to a different position as needed. The observed change in return loss and reflection phase must be divided by 2 to obtain insertion loss stability and phase stability. This is because the test signal emitted from the VNA travels through the measurement cable and is reflected back to the VNA by the calibration SHORT. It includes twice the cable transmission instabilities. The trace math function and all data processing can alternatively be done on an external PC.

Reflection Stability

The basic setup is to terminate the free end of the measurement cable with a calibration standard load. This puts the measurement cable in the reference position and uses the VNA trace math, or an external PC, to normalize the measured return loss. Again, the cable is bent and moved to a different position as needed.

Bending Conditions

Rosenberger measurement cables are specially designed for use with VNAs and are specified for 90 degrees of bending and relaxation (original position after 3x 90 degrees of bending). This is tested in four different directions. The 90-degree bending test represents a typical change in cable orientation between a two port VNA calibration and measurement. Bending procedures used at Rosenberger are the following:

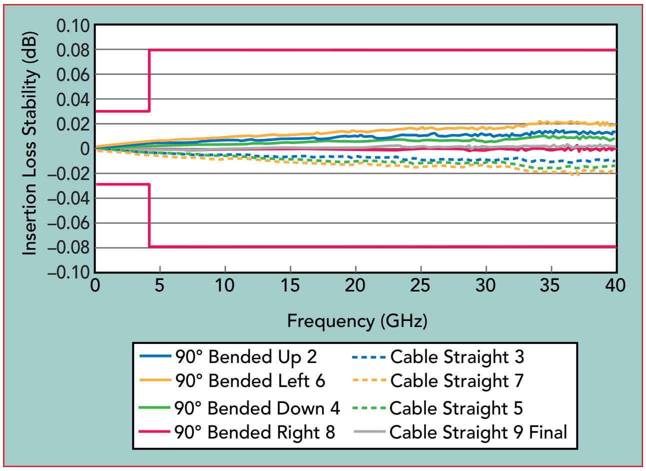

Fig. 3 **Insertion loss stability vs. frequency.**

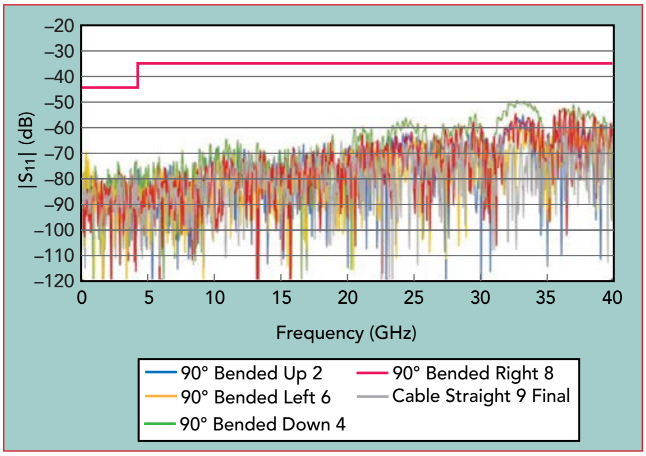

Fig. 4 **$|S_{11}|$ stability vs. frequency.**

1 × 90-degree bending test The measurement cable is bent into nine positions and measured: straight, up, straight, down, straight, left, straight, right and straight. The evaluation starts with the change from one position to the next, 1 to 2, 2 to 3 and so on. Example results are shown in ***Figures 2*** through ***4***.

3 × 90-degree relaxation test The measurement cable is bent into seven positions and measured: straight, up, straight, up, straight, up and straight. Measurements are taken and results are calculated for position 1 and 7. This is repeated for the directions down, left and right.

MEASUREMENT EXAMPLE

Transmission and reflection stability are evaluated for a measurement cable after more than three years of lab use. The solid green and green dashed traces in Figure 2 show bending from the straight position into the down position and back again to the straight position. The amount of phase change for both sequences is the same but in opposite directions, as expected. The blue curves show that the up-direction sequences behave similarly but at about half the magnitude.

Bending to the right position corresponds to the "natural bending" of the measurement cable and shows the smallest phase changes. After production, coaxial

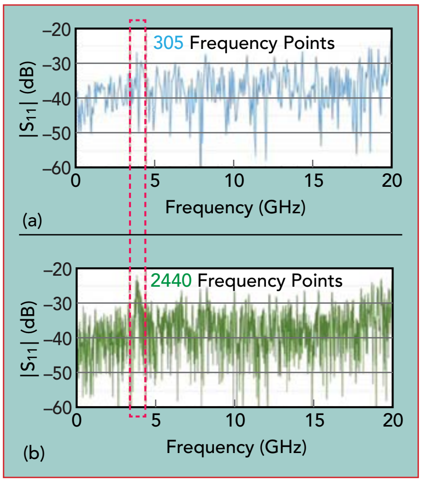

Fig. 5 **$|S_{11}|$ comparison between 305 (a) and 2440 (b) frequency samples.**

cables typically exhibit a "natural bending." The coaxial measurement cable has a non-straight form. Measurement cables often show best stability when bent in this direction. For the most accurate VNA measurement, bending in the direction with best stability should be considered.

Figure 3 can be interpreted similarly, although the bending direction with the worst stability is different.

Return loss stability (see Figure 4) is well within specification limits. The bending direction with the worst return loss stability corresponds to the one with the worst phase stability.

MEASUREMENT POINTS

The number of the measurement points is often not included in illustrations, test plots or other marketing material; although, without a proper minimum number of measurement points spikes cannot be detected. Spikes are a result of a repeated discontinuities along the cable. In VDI/VDE/DGQ/DKD 2622 Part 19[8] and IEC 60966-1 Chapter 8.1.2[9], there are formulas to calculate the minimum number of points to detect spikes (see ***Figures 5*** and ***6***). The measurement of spikes is described in these documents as follows: "cable assemblies might have narrow return loss spikes. For continuous network analyzer systems, the sweep rate shall be low enough and for digital network analyzer systems, the number of measurement points shall be high enough for resolving eventual return loss spikes." Figure 6 compares measurements with 305, 610, 1220, 2440 and 4880 measurement points. Spikes are visible between 3.7 and 4.2 GHz. Using the formula:

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}} \qquad (1)$$

$\varepsilon_r \cong 1.45$ results in a wavelength of 65.6 mm.

A half wavelength is 65.2 mm divided by 2 = 32.8 mm. The cable braid in this example is 12 sections with eight strands each. The distance between one full rotation of a section is 28 mm. The velocity factor of the cable results in an electrical length of about 33.7 mm. The reason for the spike is likely a too strongly wrapped cable section (see ***Figure 7***).

The minimum number of measurement points is:

$$n \geq 3 \cdot \left(f_{Stop} - f_{Start}\right) \cdot L_{Cable} \cdot \frac{1}{120} \qquad (2)$$

where:

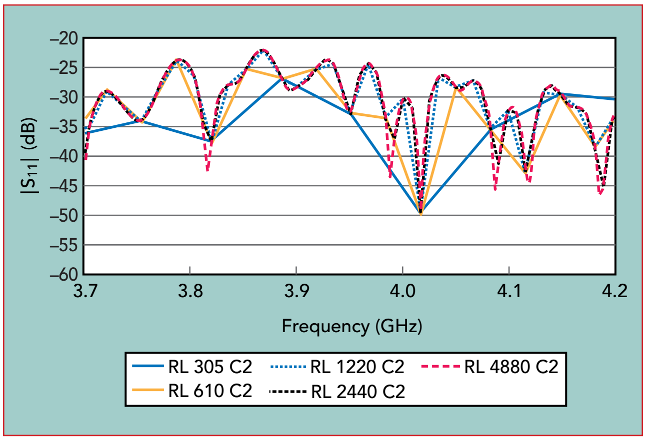

Fig. 6 **$|S_{11}|$ comparison among 305, 610, 1220, 2440 and 4880 samples from 3.7 to 4.2 GHz.**

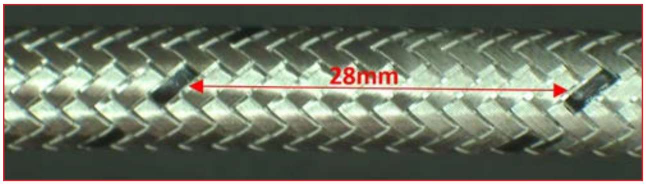

Fig. 7 **Tightly wrapped cable section is the possible cause of a return loss spike.**

n = number of measuring points in the frequency range f_{Start} to f_{Stop}

f_{Start} = lowest frequency in the measurement range, in MHz

f_{Stop} = highest frequency in the measurement range, in MHz

L_{Cable} = physical length of the RF measuring cable, in meters (ignores the relative permittivity ε_r)

The velocity factor is determined by:

$$\Delta f \leq 40 \cdot k_v \cdot \frac{1}{L_{Cable}} \qquad (3)$$

Where Δf is the maximum increment of frequency, in MHz, L_{Cable} is the physical length of the RF measuring cable in meters and k_v is the velocity factor.

CARE AND HANDLING OF CABLE ASSEMBLIES

Connector mating is a significant factor influencing performance. Damaged connectors can also permanently damage equipment. Use of a gauge is recommended to check the references of the connector before each measurement (see ***Figure 8***). Center pin protrusion is critical; if it is too large it can cause damage and if it is too short it can result in poor electrical performance. A

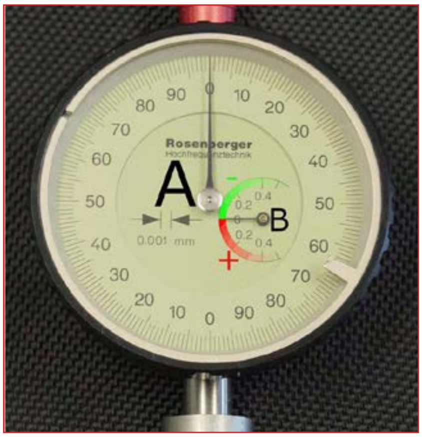

Fig. 8 **Connector gauge.**

proper torque wrench is necessary for repeatedly reliable contact without damage. For storage, protection from solar radiation, temperature changes and high humidity should be avoided. A proper storage environment and the use of protective caps will ensure longevity.

Some customers may be familiar with our measurement protocols. They provide instructions on care and handling, which include important factors to minimize mechanical stress like adhering to minimum bending radii and avoiding pinching, pulling twisting and free floating.

CONCLUSION

Cables used for VNA measurements contribute significantly to accuracy and repeatability. RF characteristics like reflection, attenuation and phase length are critical factors. Test cables should be measured on a regular basis and replaced when they fail to meet specifications. Proper care and handling will be rewarded with higher accuracy and repeatability. ■

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