Application Notes

Electronic Vector-Network-Analyzer Verification

■ **Dylan Williams, Arkadiusz Lewandowski, Denis LeGolvan, and Ron Ginley**

The National Institute of Standards and Technology (NIST) recently introduced a new electronic approach for verifying microwave vector-network-analyzer (VNA) calibrations with a single computer-controlled electronic verification artifact. The verification results are captured in easy-to-understand performance metrics that, unlike those derived from measurements of mechanical verification artifacts, are independent of the actual artifacts employed. The approach also verifies VNA calibrations more completely than was previously possible. Finally, NIST's VeridiCal [ve·rid·i·cal, adj. 1. truthful. 2. corresponding to facts. (*Random House Dictionary*)] software automates the entire process and allows you to log results directly to NIST servers over the Internet or generate verification reports on site, greatly simplifying record keeping.

The Traditional Approach

VNA calibrations are usually verified through the measurement of a few mechanical verification artifacts that have been characterized with calibrations traceable to fundamental units [1]. The user calibrates his or her VNA, measures the scattering parameters of the mechanical verification artifacts, and then compares his or her measurements to traceable measurements of the same artifacts. The user may also form the difference of his or her measurements, and these traceable measurements and compare this difference to the uncertainties in the measurements. To instill confidence, the traceable measurements are usually performed by an instrument manufacturer, calibration laboratory, or national measurement institute.

While this traditional approach has served the community well, it is not without its difficulties. The most troublesome is extrapolating the confidence with which measurements of other devices can be made based on measurements of the verification artifacts. To address this, manufacturers typically try to select verification artifacts that cover as great a portion of the measurement space as possible. This is the motivation behind the Beatty line, a short section of impedance-mismatched transmission line often used as a verification standard. However, even when multiple verification artifacts are used, most of us would be hard pressed to extrapolate the accuracy of the measurement of a filter or an amplifier from measurements of the mechanical verification artifacts.

In fact, it has never been clear how to choose an optimal set of verification artifacts or even how to define the region of the Smith chart that has or has not been characterized. For example, most verification kits employ something like a Beatty line, one or two attenuators, and perhaps a short adapter. Are these adequate for fully verifying a VNA calibration? While it is clear that, with enough verification artifacts, one should be able to fully verify the performance of the analyzer, the criteria for the choice of these verification artifacts remain qualitative.

The new approach from NIST described here offers an elegant solution to this problem, taking a completely

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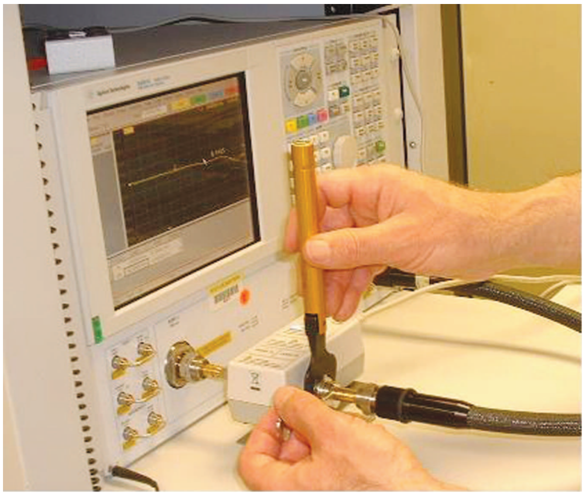


Figure 1. *A single connection of the electronic verification unit to the vector network analyzer is all that is required to accomplish the verification process. Once the electronic calibration unit is connected, all of the measurements and analysis are performed automatically.*

different approach to selecting verification artifacts, which marries the calibration comparison method [2] to a traceable electronic verification artifact. The approach not only resolves questions about how many and what type of verification artifacts are needed to fully verify the VNA's calibration but introduces a novel way of expressing the results that is both clear and succinct.

NIST's New Approach

The new approach from NIST allows VNA calibrations to be more completely verified than was possible in the past with a single connect of a single verification artifact (see Figure 1). This is accomplished by replacing a traditional mechanical verification kit with a commercially developed and computer-controlled electronic calibration unit capable of automatically switching to a number of predefined impedance and transmission states. However, instead of using the electronic calibration unit to calibrate the VNA, the unit is used to verify the VNA's calibration. The impedance and transmission states of the electronic calibration unit are characterized at NIST with traceable calibrations. These states are carefully chosen to allow a more complete verification of the VNA than is possible with any single verification artifact.

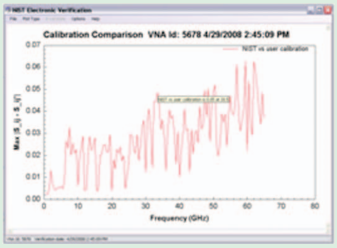
Using NIST's new approach is easy (see "Using NIST's Electronic Verification Approach"). First, calibrate the analyzer with your favorite calibration. This could even be done with a different electronic calibration unit. Then, connect the NIST-traceable electronic calibration unit to the VNA and run NIST's VeridiCal software. The software will automate the rest of the process, taking measurements and comparing your calibration to a calibration based on the NIST electronic calibration unit. This gives you a complete characterization of every aspect of the VNA calibration and even allows predictions of the accuracy of other two-port device measurements you might perform with this VNA calibration.

NIST's VeridiCal software fully automates the data analysis, provides greater information regarding your VNA's calibration, and presents that information with intuitive performance metrics derived from the

Using NIST's Electronic Verification Approach

Calibrate Your VNA with
Your Favorite Calibration

Connect the
Traceable Electronic
Calibration Unit



Run NIST's VeridiCal Software.
The Software Will Automate the
Measurements and Analysis.
View Results, Print Certificates,
and Archive Results on NIST Servers.

calibration comparison method. After the verification is complete, the NIST software also allows the generation and printing of verification certificates immediately. If required, the data can be uploaded to a NIST server over the Internet, where it is permanently archived. As you can see, NIST has striven to develop a convenient and integrated traceable verification approach to streamline and improve the VNA verification process.

The new approach from NIST resolves questions about how many and what type of verification artifacts are needed to fully verify calibration and introduces a novel way of expressing the results.

The Calibration Comparison Method

The calibration comparison method of [2] is at the heart of the new approach. The calibration comparison method was developed for on-wafer measurements; it is most commonly used to compare differences between conventional VNA calibrations and measure test-set drift [3]–[5] but has also been used to determine characteristic impedance [6]–[8] and measure the permittivity of thin films [9]. Rather than trying to compare measurements performed by a VNA directly, as is done in the traditional verification approach, we use the calibration comparison method to compare the VNA calibration directly to a traceable calibration of the VNA.

To do this, NIST's VeridiCal software works through the states of the electronic calibration unit one at a time and collects measurements of those states as corrected by your VNA calibration. The software then calls StatistiCAL, a powerful and flexible calibration engine that performs an optimized second-tier calibration of the VNA based on NIST measurements of the states of the electronic calibration unit. StatistiCAL uses the traceable measurements of the states of the electronic verification unit performed at NIST as standard definitions in this calibration and generates two error boxes that map measurements corrected by the calibration into measurements corrected by a NIST-traceable calibration of the VNA based on the measurements of the states of the electronic calibration unit.

The error boxes generated by StatistiCAL can be described by two two-port transmission-parameter matrices, T_1 and T_2. The transmission matrix T_{NIST} of a device corrected by the StatistiCAL calibration is calculated from the transmission matrix T_{user} corrected by your VNA calibration as $T_{\mathrm{NIST}} = T_1^{-1} T_{\mathrm{user}} T_2^{-1}$ [10]. If the two calibrations were identical, T_1 and T_2 would be identity matrices. The deviations of T_1 and T_2 from the identity matrix quantify the differences between your calibration and the traceable NIST calibration of the VNA [2].

This calibration comparison approach makes it clear exactly how many and what type of verification artifacts are required to fully verify a VNA's calibration. The verification artifacts need not cover the entire Smith chart. Instead, they must be capable of calibrating the VNA. Nothing more and nothing less!

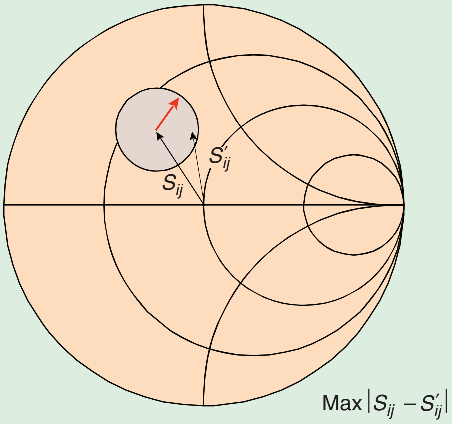
Quantifying Verification Results

Figure 2 shows a plot of one of the most common metrics that results from the calibration comparison method: the worst-case difference of any of the four scattering parameters of any passive two-port measured by two different VNA calibrations. The

NIST Metric for Calibration Accuracy

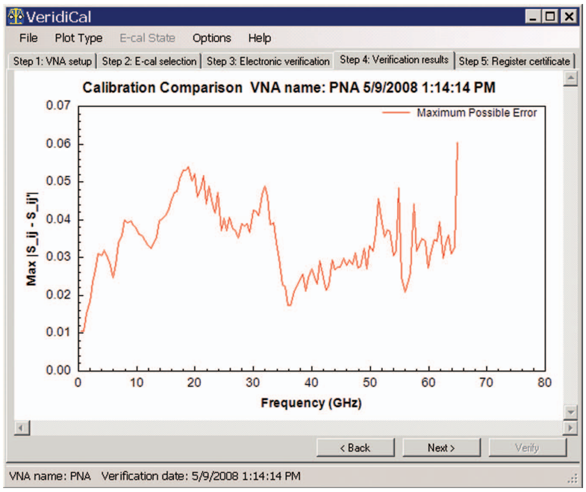
This figure illustrates the meaning of the most common metric derived from the calibration comparison method of [2], the maximum difference of the scattering parameters S_{ij} and S'_{ij} measured by two different calibrations at a given frequency. The metric is the radius of a circle around the tip of S_{ij} that will contain all of the S'_{ij} measured by the other calibration. The only assumption required is that the measured device is passive.

This metric can also be extended to bound differences in measurements of other specific classes of devices with bounded gain [2]. It is also possible to use the error boxes developed by the calibration comparison method to map any two-port measurement corrected by one calibration into a measurement corrected by the other calibration.



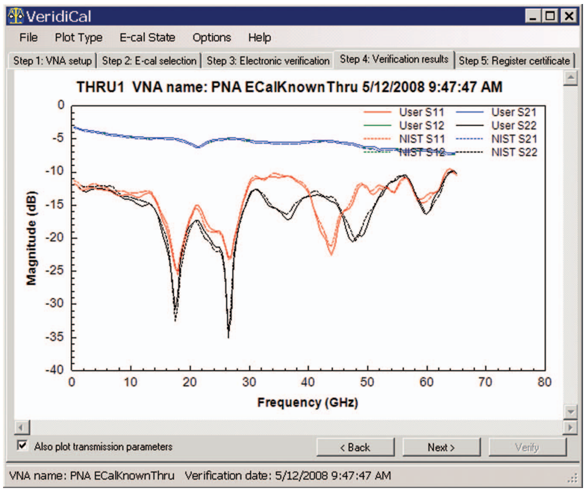
NIST's VeridiCal software fully automates the data analysis, provides greater information regarding the VNA's calibration, and presents that information with intuitive performance metrics.

calibration comparison method can compare the reference impedances and reference planes of VNA calibrations, as well as compare the effect of using different calibrations to correct raw measurements of specific devices or different general classes of devices. This is discussed in greater detail in [2]. See "NIST Metric for Calibration Accuracy" for a more detailed discussion of this metric. This is also the first result displayed by NIST's VeridiCal software. This single graph compresses a great deal of information about the VNA calibration into a single easy-to-understand metric that quantifies the differences between the VNA calibration and the traceable calibration based on NIST's electronic verification unit.



VNA name: PNA Verification date: 5/9/2008 1:14:14 PM

Figure 2. *This calibration comparison metric is the first thing shown after running NIST's VeridiCal software. It provides a bound on the differences of measurements corrected by your VNA calibration and measurements corrected by a traceable NIST calibration. See "NIST Metric for Calibration Accuracy" for more on the meaning of this metric.*



☑ Also plot transmission parameters

VNA name: PNA ECalKnownThru Verification date: 5/12/2008 9:47:47 AM

Figure 3. *NIST's VeridiCal software allows comparisons of your corrected measurements of the states of the electronic calibration unit to traceable NIST measurements.*

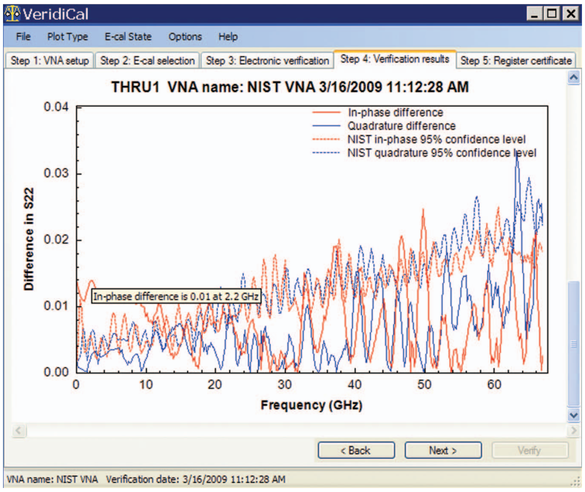
Not only is it easier to quantify the results of the calibration comparison method generated in this verification approach but the traceable NIST calibration is, to first order at least, independent of the details of the verification artifact itself. That is, while the various states of two different electronic calibration units may have quite different impedance and transmission levels and may not even be manufactured by the same company, the impedances and transmission properties of each state are characterized at NIST, and calibrations based on different units are nearly identical. This resolves another issue with conventional mechanical verification kits. When using NIST's new electronic approach to verify the VNA calibrations, there is no magic potion or mysterious advantage to using one set of verification artifacts over another. As long as the verification artifacts are complete enough to allow a calibration of the VNA, the results are the same.

Implementing the Traditional Approach

For those who don't yet feel comfortable comparing calibrations, NIST's VeridiCal software also allows comparison of the measurements of the states of the electronic calibration unit to the traceable NIST measurements of those same states. Figure 3 shows how the software displays your calibrated measurements and the NIST measurements of a given state of the electronic calibration unit. This feature of the software allows mimicking of the traditional approach to analyzing verification results.

NIST's VeridiCal software can also superimpose NIST measurement uncertainties on the differences between your calibrated measurements made of the states of the electronic calibration unit and the traceable NIST measurement. This can ease interpretation of the differences. Figure 4 shows an example of this comparison for a failed calibration. In this case, the measured difference clearly exceeds the uncertainty with which NIST measured the impedance and transmission properties of these states of the electronic calibration unit at the low frequencies, indicating a problem in the calibration.

Incidentally, the NIST measurement uncertainties are determined from a covariance approach that quantifies both uncertainties in the measurements and correlations between them.



THRU1 VNA name: NIST VNA 3/16/2009 11:12:28 AM

VNA name: NIST VNA Verification date: 3/16/2009 11:12:28 AM

Figure 4. *NIST's VeridiCal software compares the differences between your calibrated measurements and traceable NIST measurements of the states of the electronic calibration unit to the NIST uncertainties.*

The in-phase difference refers to the component of difference of the two measurements in the direction of the vector being measured and is a measure of the difference in the magnitude of the two vectors. The quadrature difference, on the other hand, refers to the component of difference of the two measurements perpendicular to the direction of the vector being measured and is a measure of the difference in the phases of the two vectors. See [11] and [12] for more on in-phase and quadrature differences and uncertainties.

Examine the Impact of Errors on Device Measurements

Detailed comparisons to your measurement needs also can be tailored with the VeridiCal software supplied by NIST. A pull-down menu allows selection of the scattering parameters of any device measured with the calibration and comparison of those calibrated results to data corrected with the second-tier NIST calibration. This software feature allows investigation of how specific parameters such as the gain of an amplifier, the ripple in a filter passband, or the attenuation in a filter stopband might be affected by errors in your calibration. This is another unique feature that cannot be accomplished with traditional verification kits.

Of course, each time verification of a calibration is done with NIST's new electronic approach, there are a lot of measurements to compare and much information to look at—enough to satisfy anyone's curiosity!

You Can Try It Out

NIST's new approach is currently being offered as a Special Test in the 1.85 mm connector size. This allows verification of a wide variety of VNAs to 65 GHz, including most VNAs marketed by Agilent, Anritsu, and Rohde and Schwarz. You can also take advantage of one-time loans of the traceable NIST electronic calibration units. Contact Ron Ginley at [+1] (303) 497-3634 or send an e-mail to Ron at ronald.ginley@nist.gov for more information.

VeridiCal works through the states of the electronic calibration unit one at a time and collects measurements of those states as corrected by the VNA calibration.

Disclaimer

We use trade names in this article only to illustrate the capabilities of NIST's VeridiCal software. This does not imply an endorsement by NIST of the named products. Other products may work as well or better.

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