# Use of Electronic Calibration Units for Vector-Network-Analyzer Verification*

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## Abstract

We present measurements demonstrating that electronic calibration units are stable enough to be used in place of mechanical vector-network-analyzer verification artifacts. This enables a new fully automated approach to verifying microwave vector-network-analyzer calibrations with a single computer-controlled electronic verification artifact. The new system presents verification results in easy-to-understand performance metrics that, unlike those derived from measurements of mechanical verification artifacts, are independent of the actual artifacts employed.

## Introduction

Vector-network-analyzer (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 between his or her measurements and these traceable measurements, and compare this difference to the uncertainties in those measurements. To provide 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 aspect of the traditional approach 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, it is difficult to extrapolate the measurement accuracy for a device from measurements of the mechanical verification artifacts.

NIST recently introduced a new approach [2] to VNA verification that marries the calibration comparison method [3] to a traceable electronic verification artifact. While the calibration comparison method is usually used to verify calibrations[3-15], it has also found use in the measurement of characteristic impedance [16;17] and to determine permittivity [18]. The approach introduced in [2] uses an electronic calibration unit in place of mechanical verification standards to more completely characterize the VNA calibration. The procedure is fully automated by NIST's VeridiCal[1] software, which not only presents results with intuitive easy-to-understand metrics, but can be used to log results directly to NIST servers over the Internet and to generate verification reports on site. In this paper, we will briefly review the approach, which is more fully described in [2], study the stability of the electronic verification units we use as verification artifacts, and present data showing that these units are stable enough to be used as verification artifacts.

## Summary of the approach

NIST's new approach to VNA verification replaces 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.

The verification procedure is quite straightforward, and is illustrated in Fig. 1 below. The

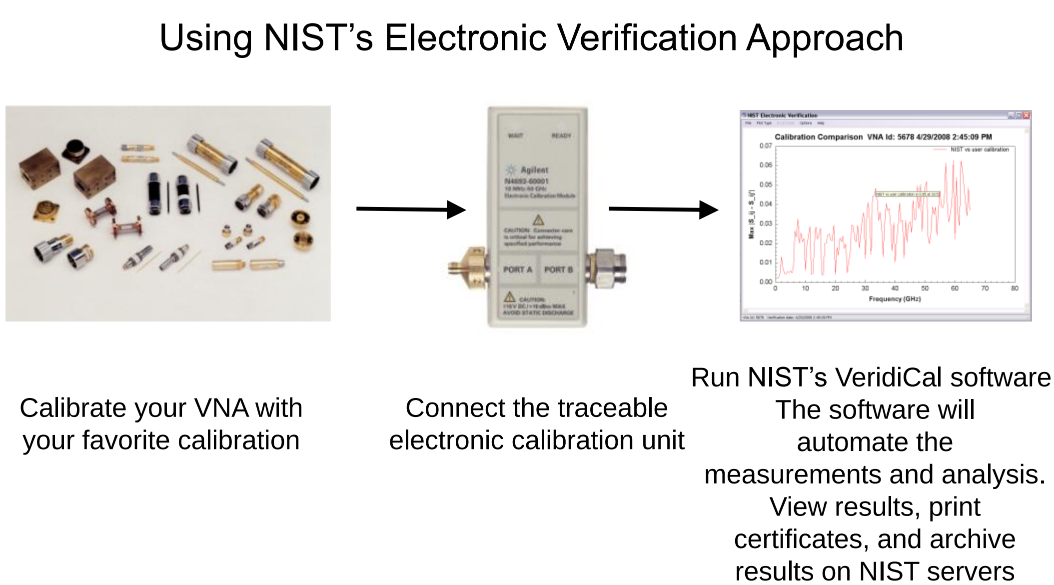


Fig. 1. Illustration of the use of NIST's electronic verification approach (from [2]).

[1] ve·rid·i·cal, *adj*. **1.** truthful; veracious. **2.** corresponding to facts; not illusory; real; actual; genuine. Random House Dictionary of the English Language: The Unabridged Edition, 1983.

user first calibrates his or her VNA and then connects the NIST-traceable electronic calibration unit to the VNA. NIST's VeridiCal software automates the rest of the process. The software works through the states of the electronic calibration unit one at a time and collects measurements of those states as corrected by the user's VNA calibration. The software then calls StatistiCAL™ to perform an optimized "second-tier" calibration of the VNA based on the 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 user's calibration into measurements of those states corrected by a traceable calibration at NIST.

The software then uses the calibration comparison method of [3] to compare the user's calibration to the second-tier calibration based on the NIST unit. This provides a complete characterization of every aspect of the initial VNA calibration, and even allows predictions of the accuracy of other two-port device measurements that might be performed with that calibration. The software also allows users to directly compare their measurements of the individual states of the electronic calibration unit to measurements performed at NIST, to compare those differences to NIST measurement uncertainties, and to investigate differences in specific device measurements calibrated with the user's calibration and the second-tier calibration based on the NIST electronic verification artifact.

## Stability of the electronic verification artifacts

In order to investigate the stability of the NIST electronic verification units we performed, over a 14 month period, the nine sets of repeated measurements listed in Table I. We designated one of our electronic control units as a “NIST control unit.” The NIST control unit remained at NIST during the entire 14 month period. However, during this same period, we also occasionally mailed our other electronic verification units to other laboratories. We called these “traveling units.” In some cases the units were simply returned to NIST, but in other cases they were tested at another laboratory before they were returned to NIST.

Each measurement set began with a complete traceable mechanical calibration. We then measured the scattering parameters of the electronic states of several electronic verification units, including the NIST control unit, the scattering parameters of a second mechanical calibration kit, and the scattering parameters of a commercial verification kit. Finally, we repeated the first mechanical calibration at the end of each measurement set. We corrected the measured data with a joint calibration consisting of both the “before” and “after” measurements of the calibration artifacts with StatistiCal$^{TM}$ [19;20]. We used differences between these two before and after calibrations to track drift during the measurements and identify connection errors.

The measurements performed on April 11 and April 14, 2008 were performed with one brand of VNA, while the other measurements were performed with a VNA from a different manufacturer. We inadvertently acquired data corrected by a previous calibration in the two measurement sets taken on September 3 and December 26, 2008. Measurements from these dates were corrected with a second-tier algorithm, and showed some discrepancies not present in the rest of our data.

Figure 2 compares typical reflection and transmission measurements of two different states of the NIST control unit over this 14 month period. The figure shows that the differences between the measurements are quite small. The largest systematic differences we observed seemed to be related to the inadvertent acquisition of corrected data taken on September 3 and December 26, 2008. This was typical of the other states of the NIST control unit as well.

Table I

List of measurements performed on electronic calibration units

| Number | Date | Calibration type | VNA type |
|---|---|---|---|
| 1 | April 11, 2008 | First tier | 1 |
| 2 | April 14, 2008 | First tier | 1 |
| 3 | April 30, 2008 | First tier | 2 |
| 4 | August 26, 2008 | First tier | 2 |
| 5 | September 3, 2008 | Second tier | 2 |
| 6 | December 26, 2008 | Second tier | 2 |
| 7 | January 6, 2009 | First tier | 2 |
| 8 | January 28, 2009 | First tier | 2 |

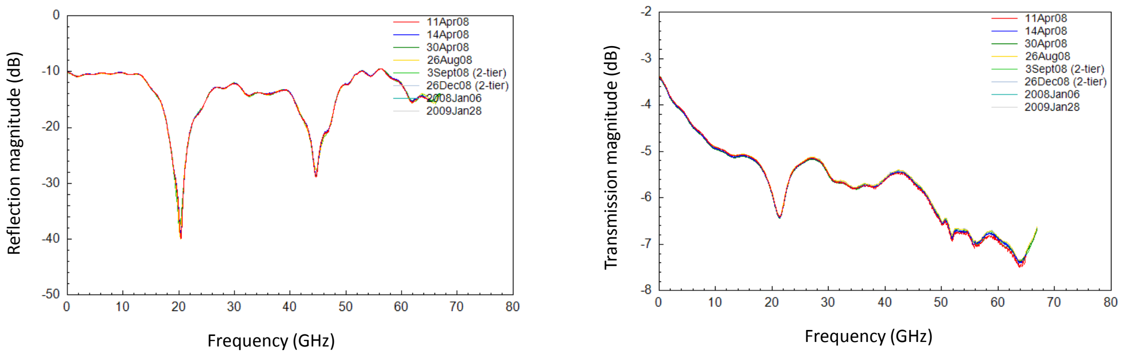


Fig. 2. The magnitudes of our measurements of the reflection and transmission coefficients of two states of our control unit over a 14 month period. The dates indicate the measurement set.

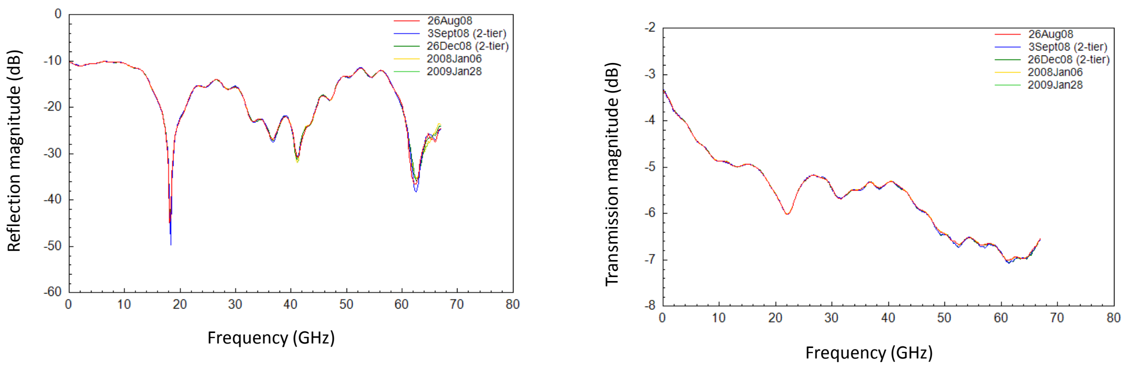


Fig. 3. The magnitudes of our measurements of the reflection and transmission coefficients of two states of one of our traveling units over a 14 month period. The dates indicate the measurement set.

Figure 3 compares the reflection and transmission coefficients of the same state of one of the traveling units that we sent to other laboratories for testing. As was true of all of the states of our traveling units, they exhibited drift and other differences similar to that of the NIST control unit.

To better evaluate the stability of our electronic verification units, we compared their stability to that of the second mechanical calibration kit and the mechanical verification artifacts we also measured over the same period. We first formed the differences of the scattering parameters of each state or artifact and its mean value measured over the 14 month period. We then used these differences to estimate the overall standard deviations of the reflection and transmission coefficient measurements we performed. Figure 4 compares these standard deviations. The figure shows that, to within our measurement precision, the stability of our two traveling electronic calibration units and our control

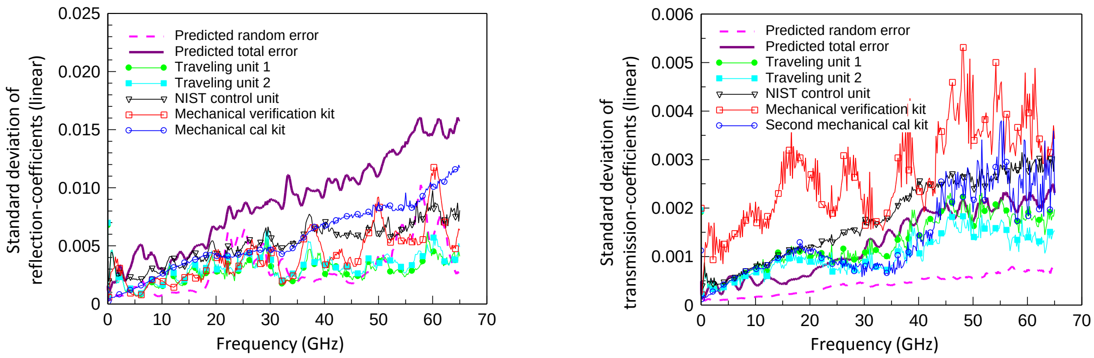


Fig. 4. The standard deviations of our measurements of the reflection and transmission coefficients of the states of our electronic calibration units and mechanical artifacts over a 14 month period. The dates indicate the measurement set.

unit were comparable to the stability of the artifacts in the second mechanical calibration kit and the mechanical verification kit we tested over the 14 month period.

Figure 4 also shows the total and random components of the standard uncertainty we predicted from a covariance-based error analysis. We observed that our prediction of the standard uncertainty (dashed lines in Fig. 4) is often significantly smaller than our measured standard deviations. We revised our uncertainty analysis to address this by replacing the random component in our total predicted standard uncertainties with the larger of our predicted standard uncertainty and our estimated standard deviation derived from the square root of the sample variance of the measurements of the NIST control unit and the two traveling units we tested in these experiments. We did this separately for each state in the in-phase and quadrature uncertainty representation of [19] we used.

We also had occasion to borrow several different units from the manufacturer's pool of demonstration units. These units were returned to the pool between measurements and we were able to include them only occasionally in our measurement sets. The connectors on these units showed obvious signs of heavy use when returned to NIST.

We did observe some additional drift in these demonstration units that we did not see in our control or traveling units. While we were not able to acquire enough data to investigate this fully, this may be a sign that improper care of the connectors can adversely impact the stability of these electronic calibration units.

## Conclusion

We investigated the stability of the electronic verification units used in NIST's new all-electronic approach to VNA verification. We found that when we used these units carefully in a standard laboratory environment, we saw no greater lack of stability in our electronic calibration units than we saw in our mechanical artifacts. However, there were some indications that improper care of the connectors may adversely affect the repeatability of the electronic calibration units.

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