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Microwave Network Analyzers A Discussion of Verification Methods

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Verification of Vector Network Analyzers (VNAs) is very important to the measurement process as well as to establish confidence in the uncertainty of the system. This paper presents a basic discussion about VNA verification including what verification is, check standard selection, and different verification methods. Verification methods explored include: quick check, check standards, calibration at higher-level laboratories, interlaboratory comparisons, error separation, calibration comparison, VNA system comparison, and traveling verification kits.

When making a measurement on a VNA, you must consider exactly what you want from the measurement. Some measurements are "quick and dirty" just to take a quick look at something, while others may be for proof of measurement proficiency for accreditation. The different levels of measurements have associated sets of requirements that must be met before the measurements can be accepted. To ensure that the VNA measurements are as accurate as specified and the VNA is operating properly, the measurement system must be verified.

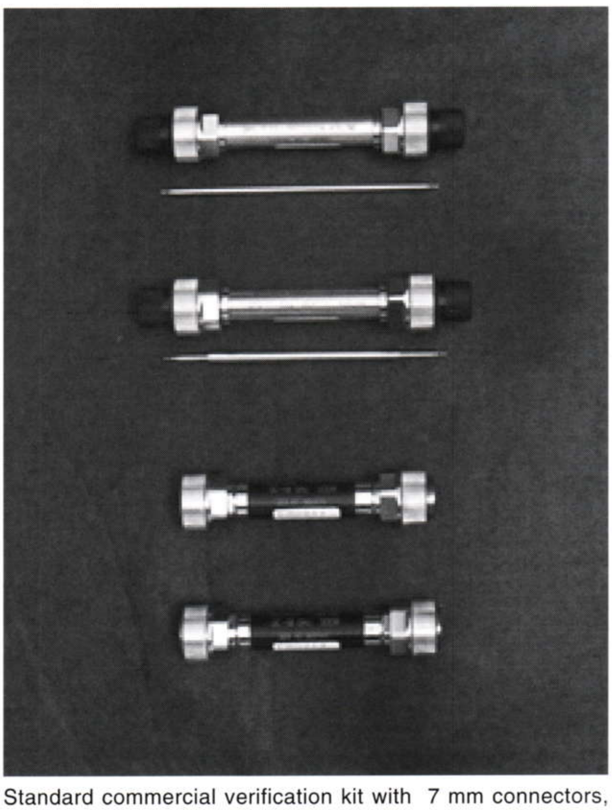
Verification sometimes is thought of as ascertaining the validity of a current calibration on a VNA. A more thorough view shows that verification is used to confirm the operation and performance of a VNA. Moreover, verification can be used to help establish uncertainty bounds, traceability and measurement process control.

It is possible to write books about the details of the verification process. It is not possible to go into that detail in this paper. This paper is meant to be a basic survey of verification for VNAs. First, the definition of verification is examined. Also, how verification and uncertainty of the system tie together is discussed. Different types of check standards and the selection of the best set of standards will then be addressed. Finally, several different verification techniques will be detailed.

Verification

To understand verification, let us first start with what a vector network analyzer is doing in a measurement. A VNA measures the relationship between waves incident on a device and the waves reflected and transmitted from the device. S- parameters, reflection coefficient and other microwave parameters can be determined by utilizing the relationship between incident, reflected and transmitted waves.

To make the uncertainty in the measurement from a network analyzer as small as possible, the VNA needs to be calibrated with a known set of standards. Once a system has been calibrated, it is necessary to make sure that the calibration is good and the VNA is operating correctly. This is verification.



Standard commercial verification kit with 7 mm connectors, includes a precision air line, Beatty standard (mismatch air line), 20 dB and 50 dB attenuators.

There are many different techniques for verifying a VNA. These include: comparing measured values of devices with known values; comparing multiple calibrations to determine error bounds; comparing one VNA to another reference system; error separation techniques; using the values of devices measured at a higher-level laboratory; and interlaboratory comparisons. There are also techniques that use the time domain capabilities of the VNAs; for simplicity, these will not be considered in this paper. In essence, verification involves taking data for a set of well characterized devices, comparing that data to a reference set of data, and determining if the VNA is functioning within measurement specifications based on the comparison.

The uncertainty of a measurement on a VNA is independent of how the VNA is verified; however, the confidence that the uncertainties are correct is directly linked to the verification. This can be demonstrated by looking at the difference between a visual type of verification and the use of check standards. Visual verification is where a device is measured and the results are compared to what is expected for the device. For example, if a flat short was measured, the expected results would be a reflection coefficient of 1 and a phase angle of 180 degrees. If the measurement approximates those values, then the calibration is behaving more or less how it should (for shorts, that is). Because real shorts are not ideal, the actual values are not very well known and can vary from the expected values. The measured values can vary from the expected values by a fairly large margin and still be acceptable, the confidence in the uncertainty of the measurement will be correspondingly low. Check standard verification compares current measurements of a set of devices against values for those devices which are known from statistically compiled results of past measurements. Through statistical analysis of the data for the devices, the values for the devices are established and, thus, the confidence in the measurement uncertainty will be much higher.

Check/Verification Standards

The proper choice of verification standards is important. Only the standards used for calibration are necessary for techniques that compare calibrations to determine error bounds; they will not be considered in this section.[1, 2] For techniques based on the classical use of check/verification standards, the standards need to cover an adequate range of reflection and transmission characteristics. Minimally, it is necessary to cover the part of the complex plane where the responses of the devices being measured are located. If, for example, only matched terminations are being measured, it would not be good to use only highly reflecting devices for verification.

The "standard" verification kits, which are available commercially, are comprised of an air line, a Beatty standard (mismatch air line), and two attenuators. This is a good set of devices, however, the air line and the Beatty standard in the kits are difficult to connect properly and are fragile. Also, the kits contain only two-port devices and these are less than ideal to appropriately support one-port measurements. The addition of an offset short and a matched termination to the standard verification kit allow for more complete coverage of the complex plane and better support for one-port measurements. Several other standards will allow other error sources such as residual directivity, test port match, system repeatability terms, mismatch, crosstalk, isolation, and response linearity to be determined.[3, 4]

The extra devices include another dimensionally calibrated air line, a flat short, and a variable attenuator or a set of fixed attenuators.For obtaining the highest confidence in the uncertainty statement of a system using the classical verification approach, the verification standards should not be the same as the standards used to calibrate the system. A calibrated measurement of one of the calibration standards is merely a measure of the VNA's repeatability and not its overall performance.[5]

Techniques

Many different methods can be used to verify a VNA. Some of the main techniques will be detailed in this section.

Quick Check Method [6]

This is a quick method that can be used to get a rough verification of an instrument's calibration or performance. All that is needed are a few of the calibration standards. For verifying reflection measurements:

1. Leave either test port open and see if the measured magnitude of the reflection coefficient is near 0 dB (within about ±1 dB),
2. Connect a calibration load to a test port, the magnitude of the reflection coefficient should be less than the specified calibrated directivity of the analyzer (typically less than -30 dB),
3. Connect either a calibration short or open to a test port and see if the magnitude of the reflection coefficient is close to 0 dB (within approximately ±0.3 dB).

For verifying transmission measurements:

1. Connect a through cable from port 1 to port 2; the magnitude of S^{12} should be close to 0 dB (within approximately ±0.3 dB),
2. To verify S^{12} isolation, connect two loads, one on each port, measure the magnitude of S^{12}, and verify that it is less than the specified isolation (typically less than -80 dB).

Because this method is meant to give a very crude check, it does not support very high confidence in the system accuracy.

Check Standards

Check standards are a set of devices whose responses adequately cover the complex measurement plane. These devices can help ascertain uncertainties for the measurement process, as well as help to maintain statistical process control. Check standards can be considered an internal part of a measurement control program. A history is created for the standards that are being used by compiling measurements from multiple calibrations. A current set of measurements can then be compared to the historical mean and measurement uncertainties to verify the calibration and functioning of the analyzer. This method can be used to verify everyday calibrations. There is a catch to this type of internal check: there can be a systematic type of offset in the measurements that would not be shown by this kind of test.

Device Calibration at a Higher-Level Laboratory

In this method, a set of devices is sent to a higher-level laboratory and measured. The devices are then measured on your own system and those values are compared to those of the higher-level laboratory. If your measurement and the measurement from the higher-level laboratory compare to within the overlap of the uncertainty bars of the respective measurements, then the system being verified should be capable of making good measurements, and systematic offsets are not present. For example, if you had a reflection measurement of 0.3 ± 0.15, and the higher-level laboratory measured the same device at 0.5 ± 0.1, the measured values do not fall within the uncertainty bounds of either laboratory separately, but they do compare to within the overlap of the uncertainty bounds, thus, the measurement would be acceptable.

There are more rigorous statistical methods for comparing the difference in values to the uncertainties if a higher level of confidence is needed. This method is known as a top-down verification method. It works best when the measurement uncertainties of the higher-level laboratory are much smaller than the measurement uncertainties of the network analyzer that is being verified. This is also a good method for verifying day-to-day calibrations.

For today's network analyzers, systems at the lower- and higher-level laboratories are capable of making measurements at the same accuracy. Therefore, it is not possible to verify the system's accuracy to a high level of confidence by measuring a set of verification devices using the top-down method. By using compiled data from many different measurements of the verification standards, the statistical system performance limits can be established (that is, use these standards as check/verification standards). Additional participation in industry, national, or international measurement comparisons will also give assurance that the network analyzer being verified is performing properly.

Interlaboratory Comparisons

Formal Interlaboratory Comparisons (ILCs) are a good technique for verification of a network analyzer. ILCs can verify the performance of the network analyzer and calibration as an overall system. They do not, however, allow each calibration to be verified. The ILCs give comparative data with the other participants of the comparison. For optimum effectiveness, the ILC should include a higher-level laboratory.

Error Separation [7]

Error separation uses a length of precision transmission line inserted between the measurement port and the device under test (DUT). When the frequency is swept, the phase path of the DUT is much longer than the path length of the measurement port, resulting in a sinusoidal ripple as the phasors interact. A measurement system can be viewed in the same way, with the measurement port producing one of the mismatches and the DUT the other mismatch. Source match and directivity can be determined by using a transmission line terminated with a short and then a matched termination. The technique can be used either to measure a DUT with greater accuracy or to establish the bounds of uncertainty of the test system.

Calibration Comparison [1, 2]

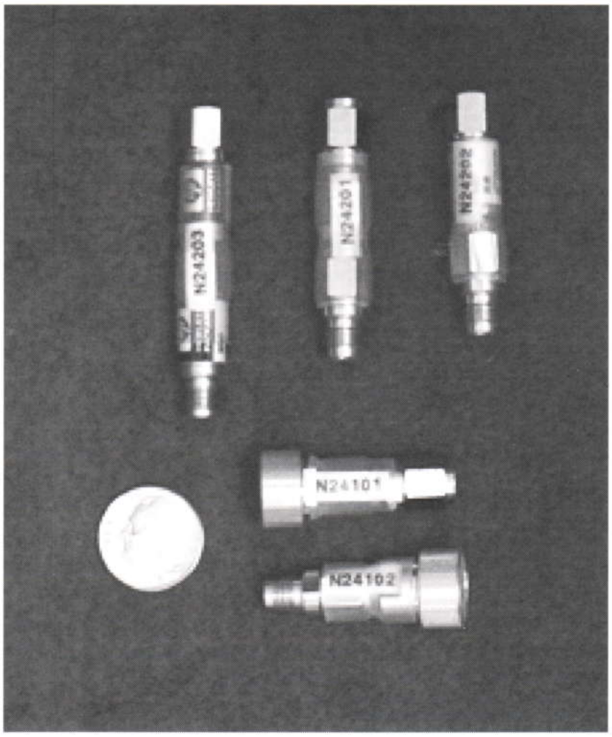
In this method, two calibrations from the same VNA are compared against each other. The technique determines the reference impedance, reference plane position, and worst-case deviations of measurements. It is particularly useful for on-wafer measurements, but it has not been used much for coaxial and waveguide measurements. Because the deviations are worst-case estimates, they are only representative of actual measurement deviations.

VNA System Comparison [8]

For this technique, two VNAs are compared by using measurements of a specific set of verification devices. The method produces a single scalar estimate of the worst-case differences between an ensemble of measurements made with two VNAs. This is particularly useful if there are many systems that can be checked against a reference system. Again, though, this method deals with a worst-case estimate.

Traveling Verification Kits

Another class of comparisons gives a good handle on



NIST traveling verification kit with 2.4 mm connectors, includes a 50 dB attenuator, low-loss 2-port, 20 dB attenuator, male offset short, and female offset short.

the verification of the operation of a network analyzer. In these comparisons a set of traveling standards is measured. The data of the measurements are then sent back to the principal laboratory (for example, NIST). This laboratory will then show your measurements in comparison with their measurements, and they will also identify their uncertainties. This type of comparison will allow the verification of the operation of the analyzer as well as providing means to establish uncertainty statements. This method can not be used for the verification of daily calibrations.

Conclusion

Verification is much more than making sure that the calibration just completed is good. It really deals with the total operation of the network analyzer and the confidence in the uncertainty of the measurements. The stricter the verification, the higher the confidence in the uncertainty.

The selection of check standards is important. When choosing the standards it is important to consider the type of measurement that will be made and verified. A good overall set of devices includes an airline, a Beatty standard, two fixed attenuators (one medium loss, the other high loss), an offset short, and a matched termination. Again, the information that is obtained from the measurement of check standards (reflection measurement verification, statistical process control, etc.) will define the best set of standards.

From internal verification tests such as "visual" checks and the measurement of check standards, it can be determined if a current calibration is good. Also from these tests, information can be maintained for statistical process control and the test results can contribute to a system's uncertainty analysis. These techniques may not show all the errors in a system, some systematic errors could be excluded. External verification tests such as using devices measured at a higher-level laboratory, interlaboratory comparisons, and traveling kits will allow verification of the overall measurement process.

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