NEW TECHNIQUE CHECKS ACCURACY OF IMPEDANCE MEASUREMENTS

This method evaluates measurement uncertainties for vector network-analyzer and calibration standards.

VECTOR network analyzers can provide high measurement resolution with amazing accuracy, but that accuracy should never be taken for granted. By properly tracking measurement uncertainties, it is possible to safeguard that accuracy with a wide range of calibration standards.

For years, the United Kingdom's National Physical Laboratory (NPL) has been developing automatic network analyzers (ANAs) and reflectometers based on the six-port technique.¹ A difficulty in the performance of these instruments has been the need to assess the accuracy of each instrument following design and development stages. However, a new evaluation method, which can be applied to all instruments of this type, solves this problem.

The technique assesses the accuracy of the United Kingdom's primary coaxial standards at RF and microwave frequencies. It has also been applied to commercial vector network analyzers such as the HP 8510 and HP 8753 analyzers from Hewlett-Packard Co. (Palo Alto, CA).²,³ In principle, the technique can be applied to any ANA since minimal assumptions are made about the instrument itself.

As described in this article, the technique will concentrate on vector network analyzers used for one-port (reflection) measurements. (A more-detailed exposition of the technique is available elsewhere.⁴)

Numerous processes affect the accuracy of an ANA. These processes are known as contributions to the measurement uncertainty, which represents the doubt about the accuracy of the measurement. In accordance with international recommendations,⁵ contributions evaluated statistically are termed type A contributions, while those evaluated by other means are termed type B contributions. For this evaluation method, measurement and calibra-
tion repeatability (including connector repeatability), instrument stability, and noise are treated as type A contributions. Incomplete knowledge of the calibration item's properties and detector nonlinearities are treated as type B contributions.

The evaluation technique uses the facility available on most modern network analyzers to send uncorrected vector readings to an external storage medium. Such data is collected for both calibration artifacts and devices under test (DUTs). The data are then processed using in-house calibration and measurement algorithms. This allows uncertainty contributions to be evaluated off-line in a controlled manner.

Type A contributions are evaluated by performing a series of n calibrations (cal) and measurements (meas) sequentially, i.e., cal 1, meas 1, cal 2, meas 2, ... cal n, meas n.

The term calibration denotes the process in which an ANA's vector readings are collected for the items (such as impedance standards) which will be used to calculate the instrument's calibration constants at each frequency. The term measurement denotes the process in which the ANA's vector readings are collected for a DUT for which the electrical characteristics (such as reflection coefficient) are required. The number n is chosen to enable statistical techniques to be applied meaningfully, and is usually between 6 and 10.

Results are produced for the DUT in two stages: (1) the vector readings for the calibration items are used to determine the calibration constants at each frequency, and (2) the vector readings for the DUT are corrected using the calibration constants. For n sets of calibration and measurement data, these readings are combined in the two-stage results process to produce n x n permutations.

Care must be taken in the subsequent statistical manipulations to allow for the interdependence of these permutations. The interdependence affects the choice of the number of degrees of freedom in the statistical evaluation (for example, variance calculations and the choice of Student's t-statistic used to obtain confidence intervals).

Gross errors (statistical anomalies due to experimental blunders) can occur during both calibration and measurement processes. For example, a gross calibration error can occur by a poor connection of an air-line standard, since these items are notoriously difficult to connect properly. Such errors in calibration and measurement are detected prior to calculation using a data-validation process which examines the dispersion of all vectors collected for an item, rejecting vectors which fall outside of a predetermined range. The rejected vectors play no part in the calculation of results.

Different calibration items of the same class (such as open circuits or short circuits) are used, when available, in the multiple calibrations to allow for item-to-item differences such as surface finish and asymmetry. For the same reasons, the orientation of air-line standards is also varied for each of the calibrations.

An error in the characterization of the measurement system contributes to the final uncertainty of a measurement. Parameters used in modeling calibration items (such as the dimensions and conductivity of conductors, permittivity of dielectric and source frequency) have associated contributions to the overall uncertainty, and these are treated as type A contributions.

Each such parameter is modeled, either theoretically or from experimental data, to give an expected value and estimated error. Two results are then calculated; the first using the expected value of the parameter and the second using an upper limit derived from the parameter model. The difference between these results is treated as the uncertainty contribution due to this parameter. The contributions are calculated again for each DUT.

The overall uncertainty is obtained by combining type A and type B contributions using accepted sta-
stistical procedures and obtaining an interval about the mean. A fundamental problem with uncertainty concepts applied to ANAs is that all the data are complex numbers. Conventional statistical procedures are adapted to allow for complex data, resulting in uncertainties which form circles in the complex plane. An uncertainty expressed as a single value for a complex parameter (such as the reflection coefficient) represents the radius of a circle centered on the mean, with the circle representing the region of uncertainty.

Typical results were obtained using the evaluation technique applied to an HP 8753B ANA for a nominal 50-Ω resistor and a 1-pF capacitor (see table). Both items were fitted with precision coaxial connectors. The measured voltage reflection coefficients, with respect to 50 Ω, are given at VHF (100, 200, and 300 MHz) and UHF (1, 2, and 3 GHz). The sizes of the type A and type B uncertainty contributions are also shown. The overall uncertainty figures also contain a contribution due to rounding errors in the presentation of the results. All uncertainties are quoted at a confidence level of 95 percent or higher.

Several interesting observations can be made about the size of the overall estimated uncertainties for the reflection-coefficient magnitude results. The results are a function of frequency and nominal value of the DUT; they are smaller for both items at VHF compared to UHF, and they are lower for the capacitor than for the resistor at VHF, although this is reversed at UHF. This can be explained by examining the uncertainties in the reflection-coefficient magnitude produced by DUTs over the entire complex plane at both frequency bands. This gives rise to a surface (for each band) in three dimensions representing the size of the expected uncertainties as a function of position in the complex plane.

The height of the surface above the complex plane at any point is proportional to the measurement uncertainty in the reflection-coefficient magnitude. Figure 1 shows that the best resolution (0.0005) is achieved at ±1+j and −1+j. The uncertainty at the VHF origin is typically 0.0008. The surface in Figure 1 transforms gradually into the surface of Figure 2 as frequency is increased. Figure 2 shows that, at UHF, the best resolution (0.0015) is achieved at the origin, while the worst resolution (0.0030) occurs around the circumference of the unit circle.

The shape of the uncertainty profiles are dependent upon the method used to calibrate the ANA. These profiles were produced using short-circuit and open-circuit standards as calibration items.

It is also interesting to note that measurement uncertainties in the reflection-coefficient phase results are ±180 deg. at two VHF points for the 50-Ω resistor. This indicates that the region of uncertainty in the complex plane encompasses the origin, implying that phase information can not be discerned, which is consistent with a near-ideally-matched termination.

A further observation is that the majority of the reflection-coefficient magnitude measurements for the 1-pF capacitor are greater than 1, implying gain. This obvious error in the measurement is allowed for, however, since the uncertainty accompanying the measured value produces a range of suitable values (including values of less than 1).

The expected performance of the new technique as applied to an HP 8753A ANA reveals equivalent return loss of 66 dB at VHF and 56 dB at UHF. Expected return-loss performance for a nominally-matched 50-Ω load is 62 dB at VHF and 56 dB at UHF.

Note
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