Measuring Output VSWR For An Active Levelled Source

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Abstract - Mismatch error is one of the major contributions to measurement uncertainty in RF & Microwave calibration. When a signal source is used in calibration applications, knowledge of the output impedance (or source VSWR) is necessary to enable users to estimate the mismatch uncertainty contribution when performing their measurement uncertainty calculations. However, measuring the output match of an active levelled source can be difficult. The measurement techniques generally used for passive components cannot be used for active levelled sources. If those methods are used, they are likely to give erroneous misleading results. This paper discusses the output VSWR measurement method chosen for use in manufacturing test and calibrations systems for a new RF & Microwave source instrument. It also describes the steps taken to validate results by comparisons with other methods less well-suited for automation and production line usage.

Introduction

Most electrical measurement practitioners are aware of the maximum power transfer theorem – usually introduced to students as part of basic circuit theory for the case of a DC voltage source and resistive load. For maximum power transfer to the load, the source and load resistances must be equal. The concept of maximum power transfer appears again when considering transmission line theory, often accompanied by complicated (and confusing) mathematics. The practical implications are very familiar to RF & Microwave metrologists – the need to maintain matching between source and load impedance and any transmission lines (cables, adapters, etc) used to make interconnections in their measurement system. Knowledge of the degree of mismatch can be used to determine measurement uncertainties, and therefore drives the need to specify and measure the impedance of the devices concerned.

The majority of 'load' or 'interconnect' devices used in RF & Microwave measurements such as power sensors, attenuators, adapters, are well specified for their impedance (match) characteristics. However, the same is not usually true for signal sources. The majority of signal sources used in RF & Microwave calibration applications are general purpose signal generators. When a new signal source was developed specifically for RF & Microwave calibration applications it was considered essential to provide detailed output impedance (VSWR) specifications and include measurement data on calibration certificates issued at manufacture and routine recalibrations – not only to confirm specification compliance but also to provide the source impedance information required for users to perform mismatch uncertainty calculations.

A number of impedance/match characteristics measurement techniques are available and commonly used, such as reflection bridges and network analysers. The measurement results can be expressed in a variety of terms such as Reflection Coefficient, VSWR (Voltage Standing Wave Ratio) and Return Loss, S-parameters, etc, and a value expressed as one parameter can easily be converted to another. (The references at the end of this paper contain a few of the many sources of detailed explanations of the theory and relevance to RF & Microwave measurements[1, 2]). The key issue is that measurements are typically made by applying a signal to the impedance under test and measuring the signal reflected, from which the required parameter can be calculated. Unfortunately in the case of an active source, which is

itself producing a signal, the result obtained using these methods can be misleading or incorrect. Other techniques for generator output impedance measurement are available, based on reflecting some or all of the generator's own power back into itself but these tend to be cumbersome, time consuming, and difficult to automate.

In the case of the signal source discussed in this paper, the objective was to implement a technique that could easily be implemented in an automated system [3] deployed in the manufacturing plant and service centres, which would not require manual intervention during the measurement process. More onerous procedures could be tolerated for making cross-checks to validate the results, and validation measurements were also sought from independent external laboratories having relevant expertise and experience of generator source match measurement.

Signal Source Design Architecture

The signal source requiring measurement is the Fluke 9640A RF Reference Source, with a frequency range from 10Hz to 4GHz at amplitudes from +24dBm to -130dBm. It is designed to generate the signals necessary for the most common RF & Microwave calibration applications and provide inherent accuracy without the need to monitor or characterise the output with additional equipment during use. (For example, measuring of the output amplitude with a power splitter and power sensor, etc).

In order to facilitate delivery of the output signal direct to the load or Unit Under Test (UUT) input and minimize performance degradation due to cabling and interconnections, the instrument has an external levelling head (see Figure 1). Signals are generated in the mainframe and fed to the levelling head containing the level detector and attenuator circuits.

Figure 1. The Fluke 9640A showing the Levelling Head containing levelling and attenuator circuits.

The 9640A output impedance is level dependent. At high output levels, the output impedance is defined by the levelling circuits and at low levels by the attenuators. These attenuators are realised by a series of switched step attenuators allowing the attenuation value to by set in 10dB increments. The attenuators and levelling circuits are controlled from the output amplitude setting. Only two individual output impedance conditions are presented at the output throughout the amplitude range requiring use of the attenuators, and a third is presented for higher amplitudes when no attenuation is required.

When the output impedance is defined by the attenuators, the output signal is at sufficiently low level that the typical VSWR measurement methods used for passive devices can be employed without problems. However, at the high output levels when the levelling circuits define the output impedance a different technique must be used.

Measurement Methods For Active Outputs

A traditional measurement method for an 'active' or 'levelled' output is to use a short circuit or mismatch to reflect some or all of the generator under test's own output back into itself. With a perfect match, all of this returned signal would be absorbed by the generator output impedance. However, an imperfect source match will reflect some of the returned signal back out of the generator. The portion of the signal reflecting back from the generator output combines with the original output signal and either adds or subtracts by some amount dependent on its phase relationship. In order to distinguish between the

original output signal and the reflected signal the phase of the returned signal is varied by some form of extendable transmission line or sliding the short or mismatch inside a fixed line. As the phase of the reflected signal is varied the combined output signal will peak when the signals are in phase, original output and reflected signals adding; and show a minima when they are in anti-phase, the reflected signal subtracting from the original output signal. The maximum to minimum level of the combined output signal gives the peak to peak value of the reflected signal. Therefore by changing the phase relationship of the two signals the original and reflected can be separated. It is possible to automate this process but it is slow and still requires a number of lines to cover the required frequency range. This technique can be used for validation purposes, but is not ideally suited for manufacturing or service centre use.

With modern frequency synthesised sources such as the 9640A there is a simpler way to cause a phase variation in order to detect the maxima and minima and hence the reflected signal level. If another signal generator is used to inject a signal which has a small fixed frequency offset, say 10 Hz from the UUT output frequency, the original and reflected signals will add and subtract at a rate of 10 Hz. The second generator (another 9640A) is connected to the UUT with a return loss bridge, which also allows connection of a detector, as shown in Figures 2 and 4. If the resultant signal is detected with a spectrum analyser the 'zero span' mode can be used to observe the variation in amplitude with time, using the cursors to measure the maxima and minima. With the UUT replaced by an open and a short, a reference level can also be measured. Configuring the spectrum analyser to report in units of voltage, the Voltage Reflection Coefficient can be calculated as shown in Figure 3. An example zero span display is shown in Figure 5.
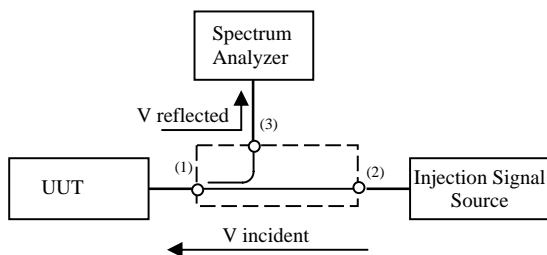

Figure 2. Diagram showing equipment setup.

$Z_{Max} =$ mean signal with Open & Short connected

$Z_{UUT} =$ half (max – min) signal with UUT connected

$$\rho_\ell = \frac{Z_{UUT}}{Z_{Max}} \qquad VSWR = \frac{1+\rho_\ell}{1-\rho_\ell}$$

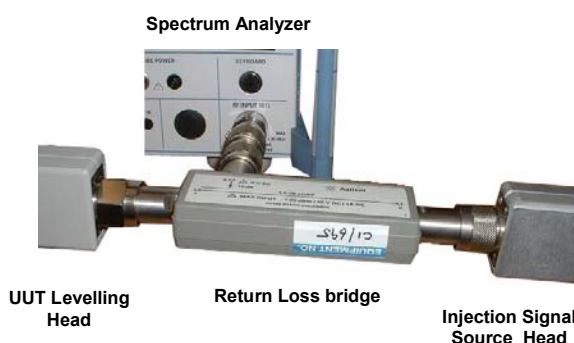**Figure 3. Results calculation formulae.**

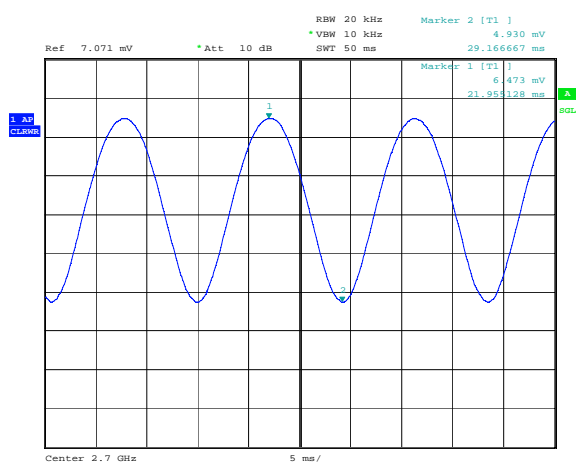**Figure 4. Actual equipment setup.**

Figure 5. Spectrum Analyzer zero span display.

Results And Measurement Uncertainty Estimates

Results for measurement of a 9640A output at +13 dBm at frequencies up to 4 GHz are shown in Figure 6 (as the dark line), with uncertainty bars superimposed. The estimates of the applicable measurement uncertainty are also shown in Figure 7.
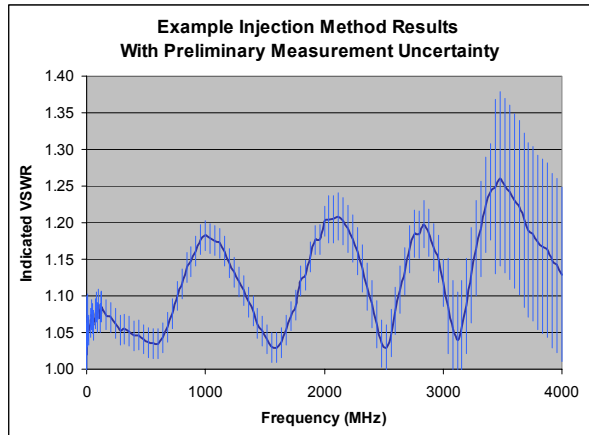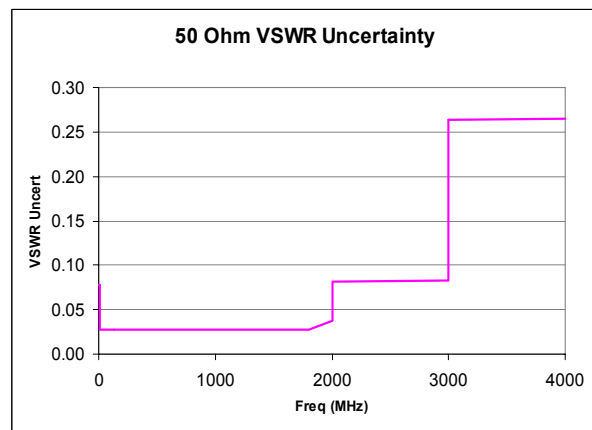

Figure 6. VSWR results, with uncertainty bars.

Figure 7. VSWR uncertainty estimates.

The most significant contributions to measurement uncertainty arise from the return loss bridge directivity and test port match and the uncertainty with which their values are known. Use of an alternative bridge with improved high frequency directivity would significantly reduce uncertainties above 3 GHz. For example, directivity above 3 GHz could be improved from 25 dB, the figure for the device used in these measurements, to 40 dB by using a high frequency bridge. Unfortunately, many bridges with better high frequency directivity are not capable of the low frequency operation required in this particular case.

Other less significant contributions are the linearity of the spectrum analyser and repeatability of the VSWR measurement. This latter contribution is a Type A, the others Type B. Other potential contributions found to be insignificant are variations in the reference level, the injection source output changing under different measurement conditions and the effect of the injection source output match. Results of a test to explore the effect of injection source output match are shown in Figure 8, where deliberately increasing injection source output VSWR is demonstrated to have insignificant effect on UUT measurement results.
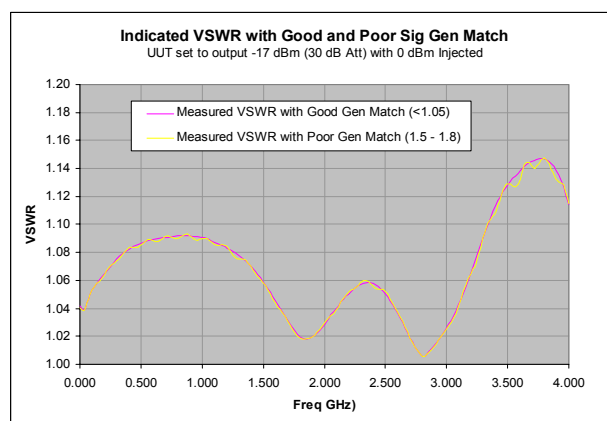

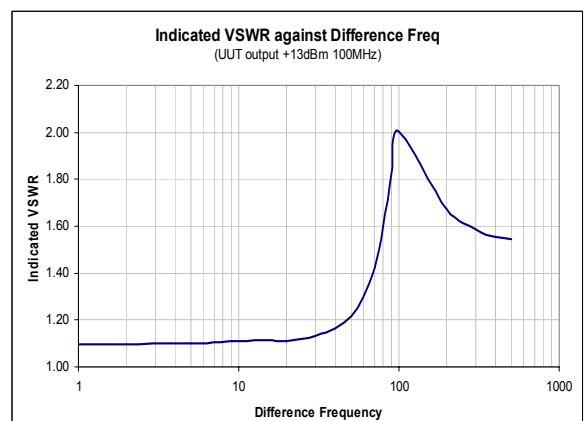Figure 8. Measured UUT output VSWR for different values of injection source match.

Figure 9. Effect of injection frequency difference on measured UUT output VSWR at 100MHz.

An important factor in the success of this method, and therefore measurement uncertainty and results validity is the UUT amplitude control loop bandwidth. The injected signal must be as close as possible to

the UUT signal frequency in order that its effect closely replicates the reflection at the actual signal frequency i.e. is within the amplitude control loop bandwidth. The difference between UUT output and injected signal frequencies must be large enough to ensure accurate detection and measurement of the resulting ripple. Figure 9 shows how the result for 9640A output VSWR measurement at 100 MHz changes with injection frequency difference. For the 9640A, the amplitude control loop bandwidth is essentially independent of output frequency, so a 10 Hz frequency difference, located comfortably within the flat portion of the characteristic, will be a suitable for all output frequencies.

Validation Techniques And Results

As discussed above, there are methods for measuring signal source output VSWR which reflect the source's own output signal back into itself and detect the resulting standing waves. One such technique has been used to provide measurements to compare with results from the injection method.

A test was performed using the setup shown in Figure 10. The UUT output is connected to a transmission line which is deliberately terminated in a mismatch in order to reflect some of the signal back towards the UUT output impedance. The transmission line is a 2 m length of precision 50 Ω coaxial cable. In this case the mismatch (100 Ω) is produced by a combination of a 50 Ω power sensor and two 50 Ω to 75 Ω converters, connected to preserve matching through the combination such that only one gross mismatch is present to generate a reflected signal. The power sensor also provides a means of detecting signal levels. In this case the line length remains fixed and the frequency is varied. The power sensor detects the maxima and minima caused by the interaction of the signals at the UUT output, from which the UUT output VSWR can be calculated. Figure 11 is a pictorial representation of the equipment setup, showing the mismatch consisting of the power sensor and impedance converters attached to the transmission line.
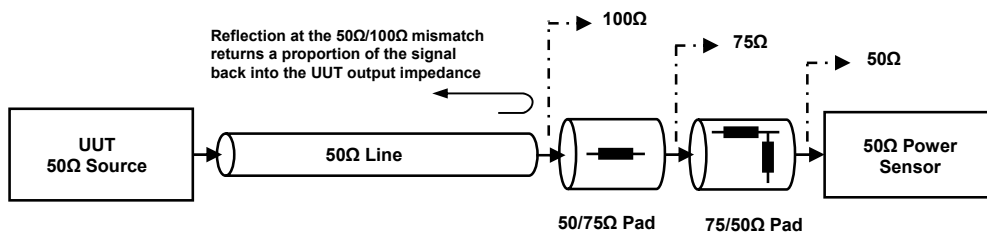

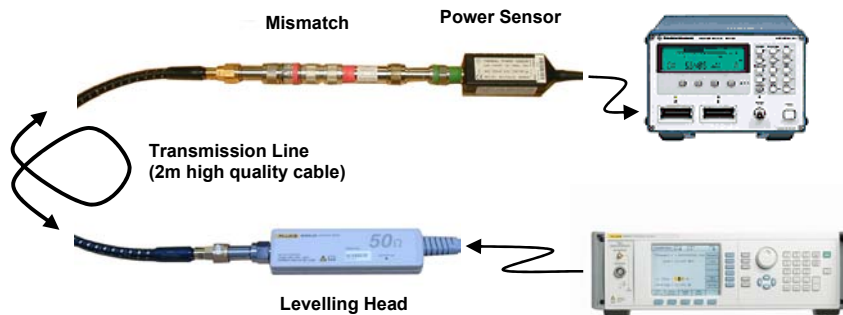**Figure 10. Diagram of mismatched line measurement method.**

Figure 11. Pictorial representation of mismatched line measurement method, showing configuration of the mismatch terminating the line.

Results of this test (the mismatch method) are shown in Figure 12 as a comparison with those obtained by the injection method. In practice, the mismatch method was implemented by stepping the UUT output

frequency from 10 MHz to 4 GHz in 10 MHz increments, and the 'mismatch method' line in Figure 12 consists of results for each of these frequency steps. The VSWR value for each frequency corresponds to the height of the vertical line for that frequency. The 'ripple' in the measured UUT VSWR can easily be seen, and closely matches the results obtained by the injection method. The estimated uncertainty for the injection method is also shown in Figure 12 as uncertainty bars at frequencies corresponding to the highest VSWR values. In all cases the mismatch method returns a lower VSWR than the injection method employed in the factory and service centre calibration systems, suggesting the VSWR values reported by these systems using the injection method are conservative. The results correlation also suggests that the uncertainty estimates are realistic.

Additional validation of the injection method was obtained by comparing results for lower level 9640A outputs where the output VSWR is determined by the attenuators. Under these conditions the traditional return loss bridge approach works well because the output impedance is essentially passive and the UUT output signal is sufficiently small not to disturb the measurement. Results for 9640A output VSWR measurements obtained at -7 dBm using the injection and return loss bridge methods are shown in Figure 13. These results correspond very closely and are particularly useful in confirming that the software and calculations implemented in the factory measurement systems employing the injection method are correct – the measurement data shown for the injection method was taken from those systems.
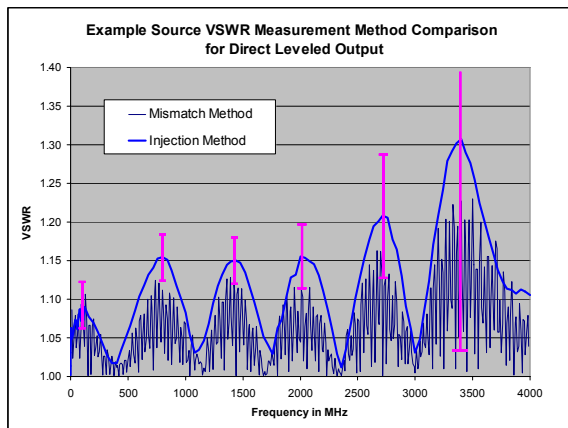

Figure 12. Results comparison between Injection and Mismatch methods for the UUT +13dBm output. Uncertainty bars are for the injection method.
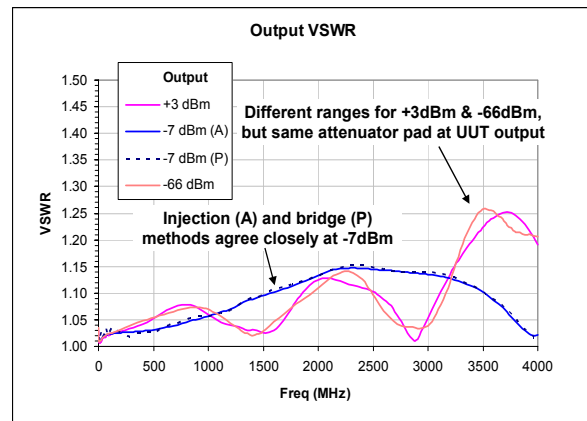
Figure 13. Additional results comparisons.

Figure 13 also shows VSWR results for 9640A output levels of +3 dBm and -66 dBm. At these two widely different output levels the same step attenuator pad is presented at the 9640A output, and the results confirm the expected output VSWR similarity.

Further validation measurements are currently in progress involving external independent laboratories with capability to measure active levelled source output VSWR. Figure 14 shows preliminary results obtained for measurement of a 9640A output at +13 dBm (left chart) and -7 dBm (right chart). The individual (yellow) dots are results from the external laboratory obtained using a sliding short method, but uncertainty estimates for their results are not available at the time of writing this paper. The solid line is results obtained from the factory calibration system employing the injection method, with uncertainty bars (light grey) for that method. Results are encouraging showing close agreement between the methods, although the sliding short result for +13 dBm at 800 MHz is somewhat higher at 1.2 compared with 1.15 from the injection method and 1.1 from the mismatched line method. (Note that the published VSWR specification for the 9640A at 800 MHz is 1.2).
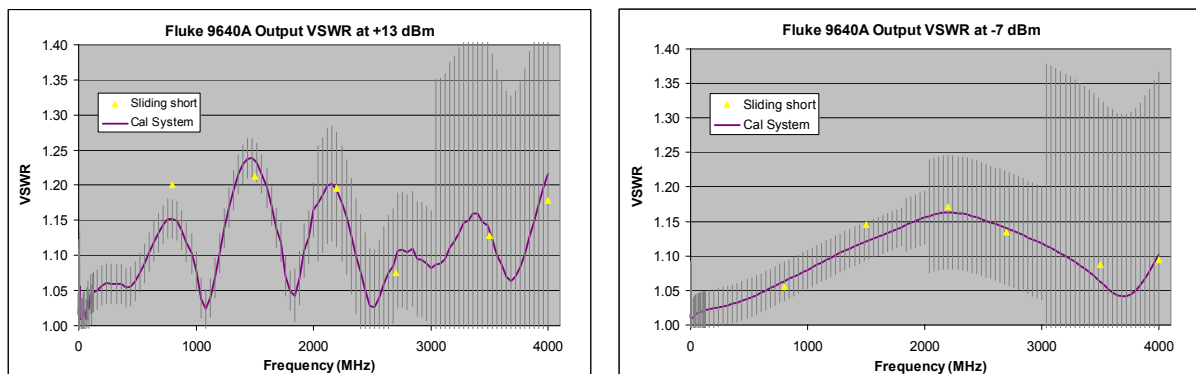
Figure 14. Comparison of factory calibration system Injection method with results from an external laboratory using a Sliding Short method.

Conclusions

Adoption of the injection method described to make output VSWR measurements has been shown to be effective in factory and service centre calibration systems. The simplicity of the connections and measurement procedure allows the automated measurements to be made rapidly and with minimal operator intervention. The method also lends itself to simple and effective non-automated implementation. It is also included as an optional test in the calibration and verification procedure published in the 9640A Users Manual, allowing self-maintainer users to duplicate measurements made at the factory and service centres, and have confidence in obtaining similar results. Many users are familiar with the method from its use and description by other test equipment manufacturers [4].

Results of the validation tests demonstrate that the injection method is an appropriate method for the 9640A design architecture, and that it produces results that compare favourably with other methods. In particular the results for the chosen injection method and two other methods for measuring the high amplitude levelling system outputs agree closely, with a test using one of those methods being performed entirely independently at an external laboratory. Also, the injection method is in close agreement with a traditional return loss bridge method for the 9640A output ranges where the output impedance is essentially passive and use of the return loss bridge is appropriate.

Uncertainty estimates for the injection method with the particular equipment used are somewhat higher at frequencies above 3 GHz compared to lower frequencies. This is due to the test port directivity specifications of the return loss bridge employed, which is the dominant uncertainty contribution as these frequencies. Validation results show very close agreement with other methods, suggesting that the bridge directivity is likely to be much better than may be expected from its specifications and that these uncertainty estimates may be too large. However, until further investigation confirms this supposition the VSWR measurement uncertainties stated on calibration certificates for the 9640A will be those shown in this paper.

Validation work is continuing, with measurements under way at another independent external laboratory using other different techniques based on reflecting the source output signal back into its output impedance.

References

[1] Agilent Technologies: Application Note AN1499, Fundamentals of RF & Microwave Power Measurements.

[2] Anritsu Corporation: Application Note Reflectometer Measurements - Revisited.

[3] P. C. A. Roberts "The Verification and Calibration of an RF and Microwave Calibration Source", NCSL Conference & Symposium, 2006.

[4] Rhode & Schwarz SML Signal Generator Operating Manual, Section 10, Performance Test.