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Verification of Automatic Network Analysers

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INTRODUCTION

Network Analysers are complex instruments which combine many different instruments within one measurement system. With this in mind it is easy to make apparently similar measurements with a variety of different instrument settings. Each setting may enhance one particular aspect of the measurement, but this is often traded off in another area. For example, to improve repeatability we might increase the averaging or decrease the bandwidth or use a combination of both. The resulting improvement in repeatability will usually be at the expense of the considerably increased measurement time.

This paper discusses different types of verification which may be applied to network analyser measurements to enable the user to assess or confirm the most appropriate choice of settings on the network analyser for their particular measurement scenario.

DEFINITION OF VERIFICATION

As with calibration it is important to understand the interpretation of the word "verification". The Oxford Reference Dictionary (1989) definition of the word "verify" is "to establish the truth or correctness of by examination or demonstration; (of an event etc.) to bear out, to fulfil (a prediction or promise)". This dictionary definition exactly describes the process of verification as applied to Automatic Network Analysers; the quality of measurements which the Analyser is capable of making is verified by comparing them with values obtained from another source, whereas calibration characterises the network analyser prior to "corrected" measurements being performed..

TYPES OF VERIFICATION

There are several different methods of verification so the method chosen needs to address the particular requirements of the user. In all cases the method chosen or designed should provide the user with at least acceptable confidence that the measurements being made with the network analyser meet the users minimum quality requirements. Verification limits are set using a combination of the measurement uncertainties and the acceptable product quality. Uncertainties should be assessed using an accepted method such as that described in EA-10/12, "Guidelines on the Evaluation of Vector Network Analysers", available free from: http://www.european-accreditation.org/.

Verification of Error Terms

As described in the previous paper, the corrected network analysers display is made up of the following elements:

a. Parameters of the device under test
b. Errors contributed by the measurement system
c. Corrections applied to the measurements
d. Residual errors present after correction

Verification of the network analysers residual errors after correction involves measuring and quantifying the residual errors present after the error correction has been applied. This method is perhaps one of the most difficult to perform, is the most time consuming, and requires the highest skill levels, but will enable the user to determine exactly which components may require attention without any additional measurements having to be performed. Typically, this type of verification provides the greatest insight into the characteristics of the network analyser and calibration kit used.

Verification of Measurements

This verification scheme involves calibrating the network analyser (usually as part of the normal measurement process) and then measuring a known artefact(s). Appropriate acceptance limits must be set when using this method as it is often possible for one parameter showing poor performance to be masked by other parameters where performance exceeds minimum expectations. Whilst this method provides the best assessment of all the contributors combining in the uncertainty budget combining, the danger is that one component in the calibration kit or network analyser which is beginning to deteriorate is masked by other parameters which are still exceeding expectations. This method, however is one of the easiest to implement, easiest to understand and quickest to perform so warrants consideration on these points alone.

On a production line this method might be implemented by periodically taking a "sample" Device Under Test (DUT) and re-testing it on a different network analyser or measurement system. If the measurements from both systems are compared and the results found to fall within the users acceptable quality limits it can be assumes that both systems are making acceptable measurements.

This method is often used by network analyser manufacturers and their service agents when maintaining customers equipment at the customer's site.

CALIBRATION SCHEME

It should be possible to perform verification of the network analyser irrespective of the calibration scheme used. The correction coefficients employed as a result of the calibration may affect the acceptance limits used for the verification but should have little or no influence on the method of verification. Ideally the calibration scheme employed will be identical to that used for measurements, and might even be exactly the same calibration. As the verification verifies the satisfactory operation of the network analyser, test port leads, adapters, and calibration kit it is essential to ensure that all of these items are used in the calibration and verification process.

ERROR TERM VERIFICATION

For a full two port measurement there are seven dominant error terms which could be checked. These are:

1. Effective Directivity
2. Effective Source Match
3. Effective Load Match
4. Effective Isolation
5. Effective Tracking
6. Effective Linearity
7. Repeatability

The term "effective" as used in the list above refers to the parameter after error correction has been applied. These terms are often referred to as the residual errors which are also contributors to the uncertainty of measurement. Methods for checking most of these terms are shown in EA-10/12.

1 Effective Directivity.

Directivity refers to the ability of a directional device, such as a coupler or directional bridge, to separate the forward and reverse signals. Where the bridge or coupler is embedded in a network analyser the most convenient way to measure this parameter is to first reflect all of the signal using a short or open circuit (the mean between the short and open circuit is considered the most accurate in this simplistic case) and set a reference. The short or open circuit is then replaced with a fixed termination of the correct characteristic impedance. Where the fixed termination has a good match (negligible voltage reflection coefficient) the network analysers display will be predominately comprised of the effective directivity. Since the perfect termination rarely exists, we need some method of separating the network analysers own errors from those generated by the fixed termination. These errors tend to increase as the measurement frequency increases. Two methods of "signal separation" are discussed below.

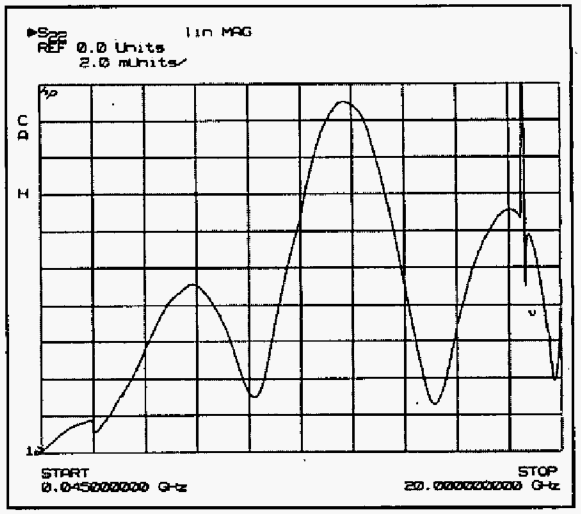


Figure 1: Typical network analyser display of the voltage reflection coefficient of a fixed broadband load.

Sliding Load Method. A Sliding Load can be used to separate the directivity from the terminating load. Where possible the network analyser should be set to display the measurements in "linear mode". After the reference has been recorded the sliding load is connected in place of the open or short circuits. If the load element is positioned furthest away from the input connector the network analyser will display a curve representing the match of the sliding loads load element with ripple superimposed upon the measurement. The majority of ripple is produced by the directivity either adding "in phase" or "anti-phase" with the load element measurement. There will also be a small error produced in this measurement contributed by the effects of imperfect source match and an imperfect sliding load element, however this error is often so small that it is neglected. The directivity may be assessed by measuring the height of the ripples, directivity will be one half the ripple amplitude. Sometimes the transitions in match of the sliding load make the measurement of the superimposed ripple difficult or impossible. In these cases it will be necessary to make a C.W. measurement. The network analysers marker is placed at the frequency of interest. The sliding load is adjusted so that a maximum value is observed using the marker and the value noted. The sliding load is now adjusted so that a minimum value is observed using the marker and the value noted. The directivity is one half of the difference between the two marker values.

The major problem with using a sliding load is that measurements on sliding loads are difficult to perform and traceability for these measurements may not be easy to obtain.

Offset Load or Airline Method. This method works in a very similar way to the sliding load method. After the reference has been recorded the airline and fixed termination are connected in place of the open or short circuits. The network analyser will display a curve representing the match of the fixed termination with ripple (from the directivity) superimposed upon the measurement. Half of the amplitude of the ripple is the directivity. This method has the same problems as the sliding load method regarding the effects of source match. Providing the fixed termination has a small reflection coefficient this problem will be kept to a minimum.

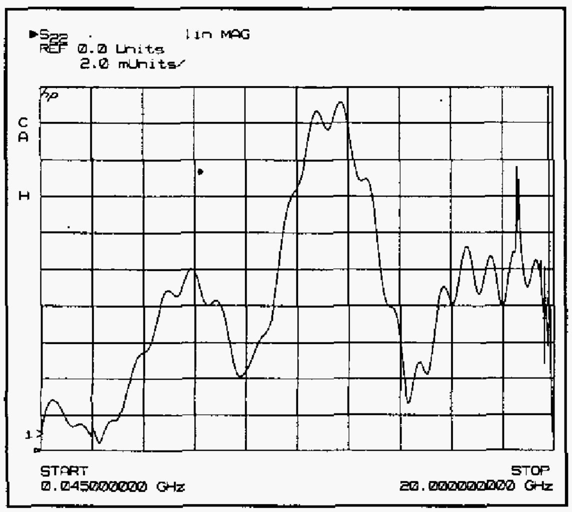


Figure 2: Ripple superimposed on the fixed load response caused by the interaction of directivity and the broad band load.

Where the fixed termination shows a rapid transition between two values of reflection coefficient it may not be possible to make an accurate measurement of directivity. Since this method should be independent of the fixed termination used it will be perfectly valid to select another fixed termination with a different reflection coefficient profile to provide more reliable directivity measurements at these more difficult frequencies.
The calibration devices used to characterise the effective directivity term are the lowband load (at lower frequencies), and the sliding load or short airline(s) at high frequencies except in broadband load calibrations where the broadband load is used exclusively to define the directivity term. The types of measurements most affected by directivity errors are low reflection measurements; high reflection measurements will often appear as normal.

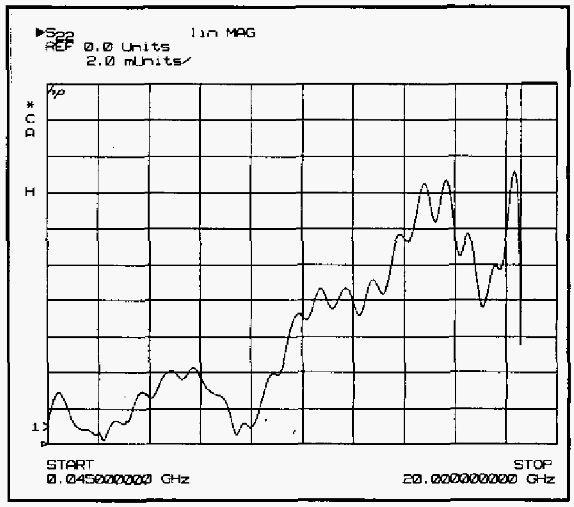


Figure 3: Using another broadband load with a different profile can make the ripples easier to determine.

2 Effective Source Match.

This term refers to the impedance of the directional bridge or coupler and associated cables and adapters as they are presented to the device under test. Methods of measurement are very similar to those used to measure effective directivity. However, since we are needing to measure source match we must feed a reasonable amplitude signal back into the directional bridge or coupler. This task is performed best using either a short or open circuit. The short or open circuit is usually connected to the directional bridge or coupler via an airline which provides some phase shift enabling the source match to be shown as ripple superimposed on the reflection characteristics of the short or open circuit. One problem in trying to present this data is that the loss of the airline used is often a major part of the displayed measurement. This can make it difficult to determine the ripple amplitude when the source match is fairly small. Shorter Airlines will reduce the loss and will also reduce the quantity of ripples observed so a suitable compromise must be achieved. Note in the following plots that there are some ripples of very short period which can be ignored as they are probably generated by other effects within the measurement system.

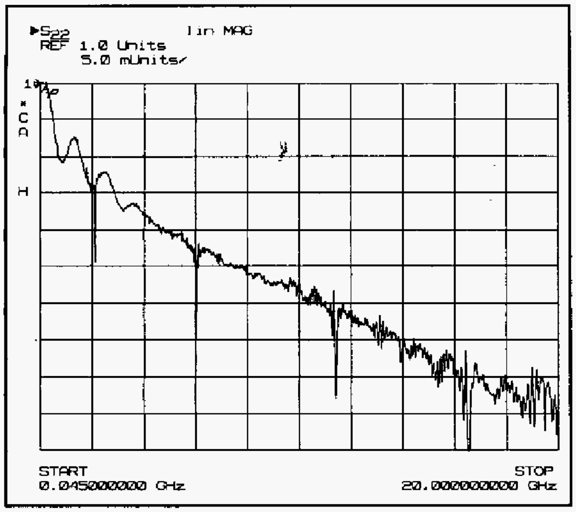


Figure 4: Ripple caused by the interaction of the source match and an open circuit.

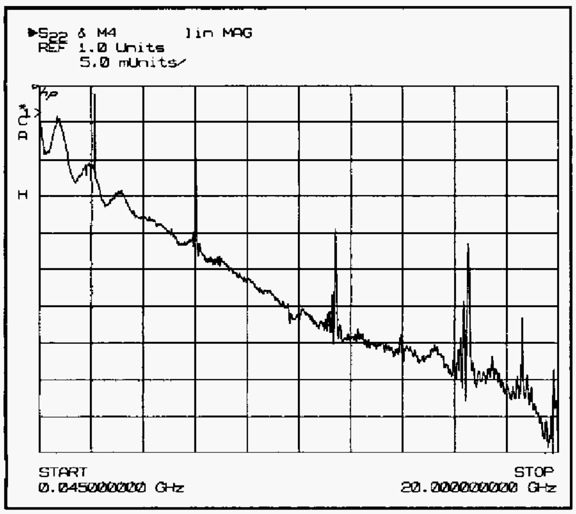


Figure 5: Ripple caused by the interaction of the source match and a short circuit.

As with directivity, the peak to peak height of the ripple is twice the source match. Note also that this measured source match also contains the directivity, which at any given frequency may either add to or subtract from the source match. Since we have no easy way of separating the source match and directivity we usually consider directivity as one of the sources of uncertainty when making source match measurements. Directivity is usually much smaller than source match so this assumption causes few problems.

Time Domain Gating (explained later) can be used to effectively separate these interacting terms. Unfortunately, it has not been possible to provide traceability for any measurements in the time domain so this function is best left to the development laboratories where it provides useful improvements in test development times.

One neat trick that can be employed to provide reliable and easy to read source match measurements is to either store or plot the display with a short circuit connected, then connect the open circuit. Assuming the short and open circuits are approximately 180° apart in reflection phase, the resultant display will be one of two traces where the "peaks & troughs" occur at approximately the same frequencies (looking similar to the envelope on an Amplitude Modulated signal).

The peaks and troughs can now be read at the same frequency, producing a more accurate value of source match at a particular frequency.

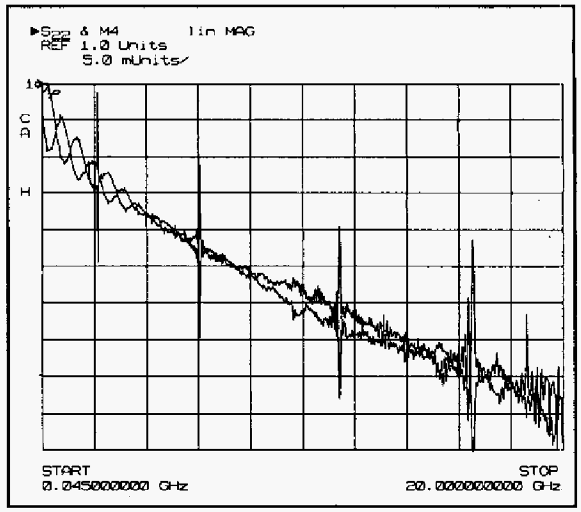


Figure 6: Ripple caused by the interaction of the source match and short and open circuits.

It is also possible to use a sliding short circuit to determine source match at any particular frequency, using a similar technique as described for the sliding load in the measurement of directivity. Unfortunately, sliding short circuits fitted with co-axial connectors are now getting harder to obtain. This technique is still useful where rectangular waveguide is employed as the transmission medium because sliding short circuits in rectangular waveguide are still supplied by several manufacturers.

The calibration items used to characterise the effective source match term are the short and open circuits. A poor connection of either of these devices will affect the effective source match. Further, open circuits usually have a centre pin supported with a delicate piece of dielectric, if this dielectric fractures and the centre pin is misplaced the effect on the source match will be massive. The measurements most affected by source match errors are high reflection measurements and transmission measurements of highly reflective devices. Poor cables can cause both the directivity and source match terms to vary as the cable is flexed. The effect of this variation will be errors in the measured values.

3 Effective Load Match.

Effective Load Match is the effective impedance of the load presented to the DUT. For a full two port measurement the load would be represented by the "receiving signal port". As there appear to no "classical" methods for measuring load match it is usually assumed that it has a similar value to the source match. Refer to "Network Analyser Uncertainty Computations for Small Signal Model Extractions" by Jens Vidkjær for more detailed information on this subject. The measurements most affected by effective load match are all transmission and reflection magnitude measurements of low insertion loss two-port devices.

4 Effective Isolation

Isolation is a measure of how much signal passes from one channel to the other when both channels are terminated in their characteristic impedance. Although the error correction routines are designed to compensate for some degree of poor isolation it is good practise to maintain as ideal a value as possible. The simplest way to measure Isolation is to connect the two test port cables together and set a transmission reference in each direction on the screen. Then connect reasonably well matched terminations to the DUT ends of the test port cables and repeat the transmission measurement. The screen display will be very noisy and should consist of a combination of the network analyser noise floor and the network analysers isolation. Poor isolation may be caused by loose connectors within the test set or poor or worn screening throughout the measurement system. In particular look at the test port extension cables as these are often subjected to plenty of flexing and plenty of wear and tear at the connector. Whilst connectors in poor condition will be obvious to the experienced eye, there will be few visible signs of any deteriorating screening making regular testing desirable. Where isolation is found to be a constant value at any particular frequency corrections are applied. With modern network analysers having very good isolation, often in the same area as the instruments noise floor, there is often a danger that the values due to the noise floor become entered into the isolation corrections causing further errors rather than correcting for them. Poor isolation would affect both reflection and transmission measurements where the test channel signal is at a very low level, i.e. reflection measurements and also transmission measurements where the insertion loss of the DUT is large (i.e. greater than a 50 dB attenuator).

5 Transmission and Reflection Tracking

This correctable error includes the effects of the insertion loss of the signal separation devices, detectors (or samplers), cables, signal paths and any other items in the signal paths. Residual errors after correction may be analysed by connecting the Test port cables together and examining the transmission trace. Any deviation from 0 dB may be due to tracking. Also, there may be an amplitude dependant tracking error, this would be checked in the same way, but in addition the source power would be varied and the trace deviation from the 0 dB level noted.
The calibration devices used to characterise transmission tracking are the transmission measurements of the "thru" connection. Large variations in the tracking terms might indicate a problem in the reference or test signal path in the test set or poor connections during the calibration process. All transmission measurements are affected by transmission tracking errors.
The calibration devices used to characterise reflection tracking are the short and open circuits. As with transmission tracking large variations in the tracking term might indicate a problem in the reference or test signal path in the test set or poor connections during the calibration process. All reflection measurements are affected by transmission tracking errors.

6 Effective Linearity

Deviation from Linearity may be checked by measuring a previously calibrated step-attenuator. Providing the step-attenuator has been calibrated with a sufficiently low measurement uncertainty, and the step attenuator has a good match in each direction, it can be assumed that any deviations noted are due to the network analysers deviation from ideal linearity. Effective linearity is a significant contributor in the uncertainty budget and needs to be assessed with the signal travelling in either direction.
Linearity is not a term characterised using the calibration kit. Some network analysers have corrections for linearity which may be updated when a routine maintenance check is performed. All measurements are affected by linearity.

Time Domain & De-embedding. Many of the higher frequency network analysers are capable of performing Fast Fourier Transforms (FFT). Where implemented this process allows measurements of components within complex networks to be displayed using a process known as "Time Domain Gating". The component under test or evaluation is mathematically de-embedded from it's surrounding network and it's response displayed on the screen of the Network

Analyser. This function can be employed to provide values of directivity and source match providing a suitable reference (usually an airline in same characteristic impedance as the coupler or directional bridge) is available. Unfortunately, traceability of measurement has not been developed for this type of time domain function so these measurement methods are best left for routine maintenance and diagnostic tasks rather than the task of ensuring traceability of measurement. The concept of time domain gating refers to mathematically removing a portion of the time domain response, and then viewing the result in the frequency domain. The intent is to remove the effects of unwanted reflections, say from connectors and transitions leaving just the response of the device being measured. An experienced operator will be able to perform measurements of directivity, source match and load match much faster using time domain gating rather than using any of the alternative methods described above.

VERIFICATION OF MEASUREMENTS

This method of verification is perhaps easier to understand and provides a much easier visualisation of the general health of the network analyser, calibration kit and test port cables. The method involves calibrating the network analyser then measuring an artefact or artefacts. The measurements are then compared either with measurements performed earlier, or if it is desired to obtain traceability this way they would be compared with measurements performed on the same artefacts at a laboratory operating at a higher echelon in the traceability chain. For this method to be effective the artefacts used for the verification need to be stable with both time and temperature. For these reasons "simple" devices such as fixed attenuators, fixed terminations and certain types of couplers are often chosen. Sometimes an artefact similar to that which it is desired to measure is chosen so that if an error occurs within the measuring system it's effect can be seen and assessed immediately.

Customised Verification Example

To improve throughput on one of the production lines it was decided to use an electronic calibration module with the network analyser testing input impedance. It was also desired to calibrate or check the e-cal module on site as the only alternative was to have it sent overseas to it's manufacturer which would cause unacceptable down-time. The specification of the e-cal module is excellent so straight forward testing of it could not be performed to the desired level. It was decided that an artefact which was representative of the manufactured product could be used to access the "general health" of the complete measuring system. The artefact chosen was a programmable attenuator with a short circuit connected to one port. This provides a range of mismatch which can be adjusted using software so maintaining the level of automation.

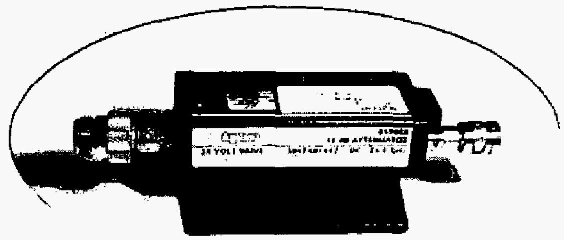


Figure 7: Artefact chosen for the comparison, an Agilent 84904K Programmable Step Attenuator with a type-N adapter and Short Circuit fitted.

It was not considered necessary to have all steps of the attenuator measured as this would provide too much information, much of which may never be looked at. The following were chosen,

1. Highest mismatch
2. Approx upper specification of DUT
3. Approx centre of specification of DUT
4. Approx lower specification of DUT
5. Lowest mismatch

This list provides plenty of measurements in the range where it is essential for the network analyser to provide the most accurate measurements possible, and some supplementary measurements (highest and lowest mismatch) which could be used to provide some rudimentary diagnosis should the need arise. The attenuator was calibrated using the best and most accurate and traceable equipment possible. The attenuator was then transferred to the production line where it was measured using the network analyser & e-cal system. A graphical representation of the two sets of results obtained is shown below. The process is fully automated so it can be used each time the network analyser is re-calibrated. Since accurate measurements can take a long time to obtain there were only 51 points measured by the "accurate" network analyser. This is adequate in this case because the attenuator is a linear resistive device so there is a high probability that linear interpolation can be used between measurement points, if necessary. The production line network analyser however, is normally measuring active devices so measurements are made at considerably more frequencies, albeit with slightly greater uncertainties in places. In order to make this quantity of measurements within the very short times demanded by production processes they must be made faster, with the trade-off being slightly increased measurement uncertainties.

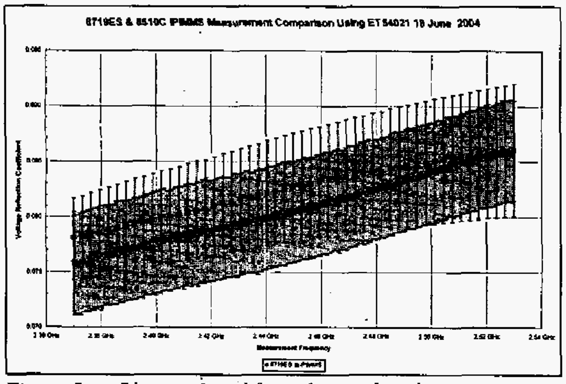
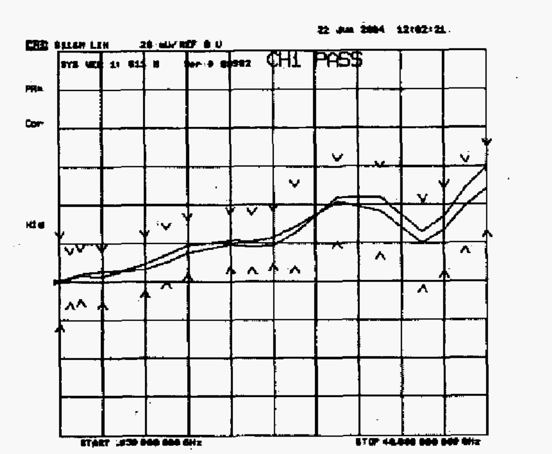


Figure 8: Plot produced from the results of a customised verification example showing all of the uncertainty bars overlapping.

Note in the example above that the reference measurements are performed at considerably fewer frequencies. This is quite normal as "quality measurements" can be expensive to perform. Sufficient measurements have been performed showing that linear interpolation between measured values is valid.

Manufacturer Supplied Verification Example

Many manufacturers supply verification procedures with their network analysers. The user will normally need to buy a verification kit which is often supplied with a disk containing measurements made on the component parts of the kit. Verification kits and associated procedures are usually designed to provide a quick "health check" on the network analyser. Testing that the network analyser (and calibration kit) meet their specification will often involve adjusting the settings on the network analyser resulting in the measurements taking far longer. The process begins with the operator performing an appropriate calibration (error correction). Test devices from the verification kit are then measured and the results compared with measurements that were made using a reference measurement system. If the comparison reveals that the results fall within prescribed limits the network analyser (and appropriate calibration kit) are said to be verified. This type of verification is intended as a routine "health check" and is used by some manufacturers as a routine check for equipment installed at a customers location. To this end the software required to automate this process and therefore improve consistency is often included within the operating firmware of the network analyser.



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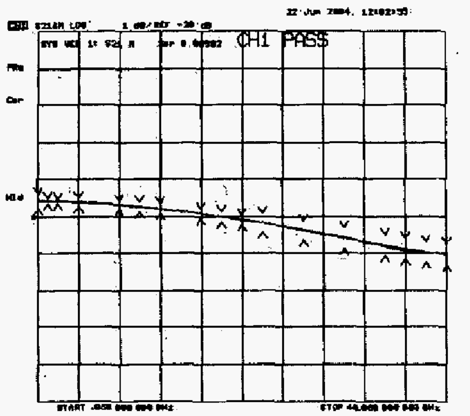
STIMULUS GHz	CH1 S11	Margin	Upper Lim	Lower Lim
.050 000 000	697.26 uU	21.935 mU	22.632 mU	-22.218 mU
1.000 000 000	2.1110 mU	11.948 mU	14.059 mU	-10.869 mU
2.000 000 000	3.6819 mU	11.770 mU	15.451 mU	-9.4835 mU
4.000 000 000	5.4853 mU	10.021 mU	15.506 mU	-10.527 mU
8.000 000 000	6.3417 mU	10.818 mU	22.972 mU	-4.4758 mU
10.000 000 000	10.127 mU	10.124 mU	27.511 mU	3.2993 uU
12.000 000 000	14.728 mU	10.237 mU	32.041 mU	4.4907 mU
16.000 000 000	19.140 mU	11.437 mU	35.282 mU	7.7032 mU
18.000 000 000	18.040 mU	10.861 mU	34.746 mU	7.1782 mU
20.000 000 000	18.255 mU	9.0996 mU	36.742 mU	9.1557 mU
22.000 000 000	25.071 mU	17.513 mU	49.247 mU	7.5582 mU
26.000 000 000	43.751 mU	18.717 mU	62.467 mU	20.554 mU
30.000 000 000	43.762 mU	14.968 mU	58.730 mU	14.917 mU
34.000 000 000	25.799 mU	15.700 mU	41.499 mU	-1.9594 mU
36.000 000 000	33.804 mU	14.946 mU	48.750 mU	5.1562 mU
38.000 000 000	48.391 mU	13.258 mU	61.649 mU	17.698 mU
40.000 000 000	59.458 mU	10.983 mU	70.441 mU	26.287 mU

Figure 9: Printed output from a typical verification program. A sheet similar to this is produced for both phase and magnitude for each s-parameter of each device tested.

The major problem with these types of verification (manufacturer supplied and customised) is that all of the "errors" and measurements are lumped together, the measured values contain both and there is no easy way to separate them. Degraded items can be offset by items still in their prime. This makes it very difficult to identify any one device in the calibration kit or network analyser which may be starting to drift into a problem state, but at least has the advantage of allowing the user to quickly estimate if their system is in a suitable state for measurements.

Presentation of the results can be difficult in certain circumstances, particularly transmission phase where the phase vector often rotates through it's full 360° and the test limit can be less than 1°.



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STIMULUS GHz	CH1 S21	Margin	Upper Lim	Lower Lim
.050 000 000	-19.540 dB	.15300 dB	-19.387 dB	-19.763 dB
1.000 000 000	-19.576 dB	.05700 dB	-19.518 dB	-19.644 dB
2.000 000 000	-19.588 dB	.06000 dB	-19.528 dB	-19.657 dB
4.000 000 000	-19.614 dB	.09800 dB	-19.516 dB	-19.716 dB
8.000 000 000	-19.681 dB	.10300 dB	-19.578 dB	-19.795 dB
10.000 000 000	-19.726 dB	.12100 dB	-19.604 dB	-19.865 dB
12.000 000 000	-19.790 dB	.13000 dB	-19.660 dB	-19.924 dB
16.000 000 000	-19.922 dB	.13100 dB	-19.787 dB	-20.053 dB
18.000 000 000	-20.007 dB	.13000 dB	-19.872 dB	-20.138 dB
20.000 000 000	-20.089 dB	.12600 dB	-19.949 dB	-20.216 dB
22.000 000 000	-20.181 dB	.23600 dB	-19.923 dB	-20.418 dB
26.000 000 000	-20.366 dB	.24400 dB	-20.122 dB	-20.634 dB
30.000 000 000	-20.582 dB	.28000 dB	-20.301 dB	-20.868 dB
34.000 000 000	-20.803 dB	.24800 dB	-20.493 dB	-21.052 dB
36.000 000 000	-20.934 dB	.22100 dB	-20.590 dB	-21.155 dB
38.000 000 000	-20.964 dB	.28700 dB	-20.677 dB	-21.253 dB
40.000 000 000	-21.035 dB	.29200 dB	-20.736 dB	-21.327 dB

Figure 10: Another example from the same verification routine, this time displaying a transmission parameter.