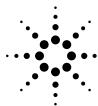
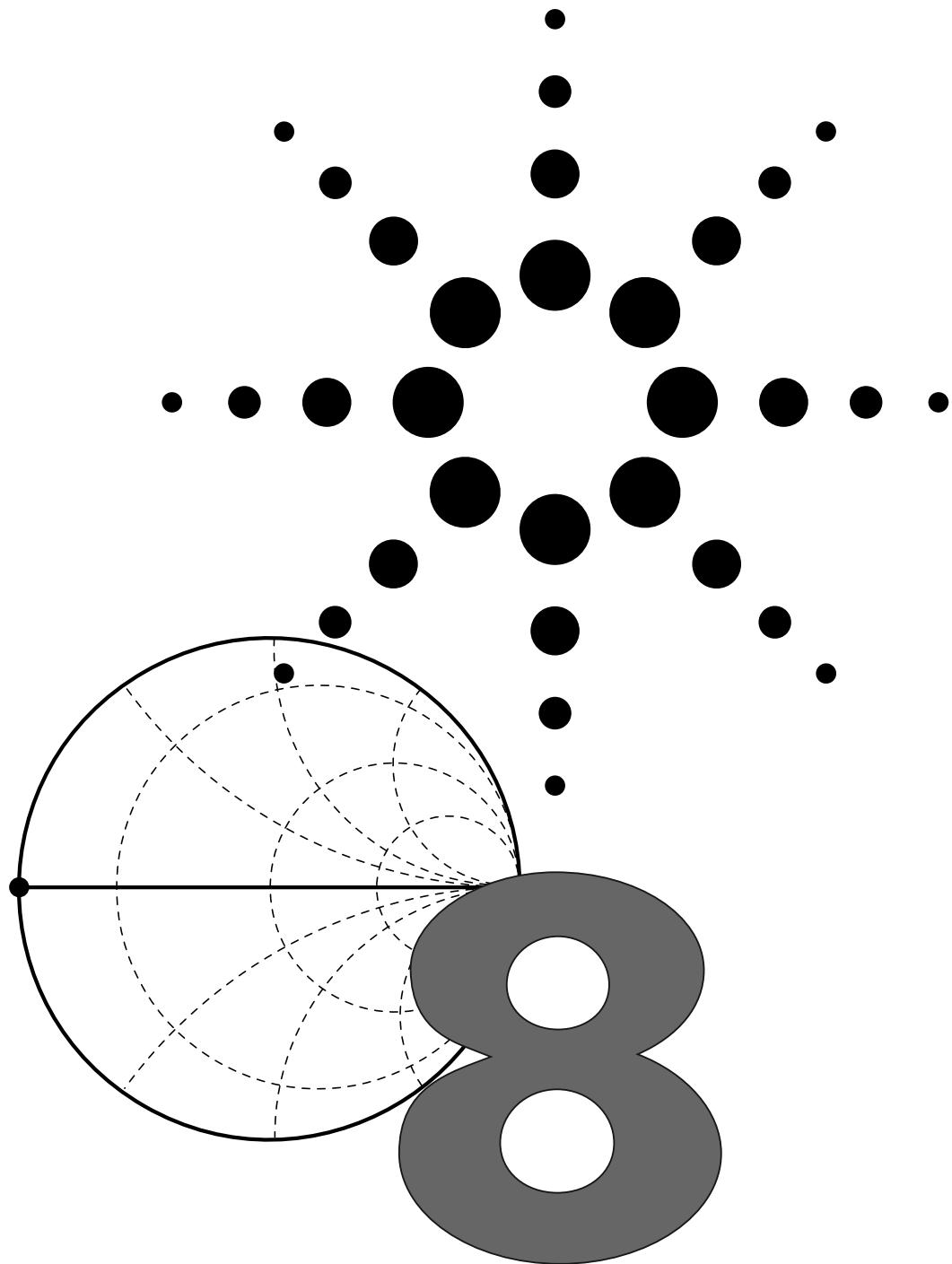


**Agilent Technologies**  
**Hints for making Better**  
**Network Analyzer Measurements**  
Application Note 1291-1



**Agilent Technologies**  
Innovating the HP Way

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## Introduction

This application note contains a variety of hints to help you understand and improve your use of network analyzers, along with a quick summary of network analyzers and their capabilities.

## Overview of network analyzers

Network analyzers characterize active and passive components, such as amplifiers, mixers, duplexers, filters, couplers, and attenuators. These components are used in systems as common and low-cost as pagers, or in systems as complex and expensive as communications or radar systems. Components can have one port (input or output) or many ports. The ability to measure the input characteristics of each port, as well as the transfer characteristics from one port to another, gives designers the knowledge to configure a component as part of a larger system.

## Types of network analyzers

**Vector network analyzers** (VNAs) are the most powerful kind of network analyzer and can measure frequencies from 5 Hz up to 110 GHz. Designers and final test in manufacturing use VNAs because they measure and display the complete amplitude and phase characteristics of an electrical network. These characteristics include S-parameters, magnitude and phase, standing wave ratios (SWR), insertion loss or gain, attenuation, group delay, return loss, reflection coefficient, and gain compression.

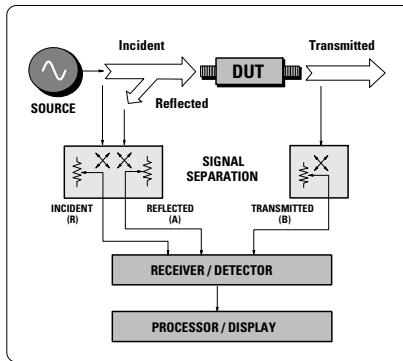
VNA hardware consists of a sweeping signal source (usually internal), a test set to separate forward and reverse test signals, and a multi-channel, phase-coherent, highly sensitive receiver. In the RF and microwave bands, typical measured parameters are referred to as S-parameters, and are also commonly used in computer-aided design models.

## Scalar network analyzers

A scalar network analyzer (SNA) measures only the amplitude portion of the S-parameters, resulting in measurements such as transmission gain and loss, return loss, and SWR. Once a passive or active component has been designed using the total measurement capability of a VNA, an SNA may be a more cost-effective measurement tool for the production line to reveal out-of-specification components. While SNAs require an external or internal sweeping signal source and signal separation hardware, they only need simple amplitude-only detectors, rather than complex (and more expensive) phase-coherent detectors.

## Network/spectrum analyzers

A network/spectrum analyzer eliminates the circuit duplication in a benchtest setup of a network and spectrum analyzer. Frequency coverage ranges from 10 Hz to 1.8 GHz. These combination instruments can be economical alternatives in design and test of active components like amplifiers and mixers, where analysis of signal performance is also needed.



Network Analyzer Block Diagram

## HINT 1.

### How to boost and attenuate signal levels when measuring high-power amplifiers

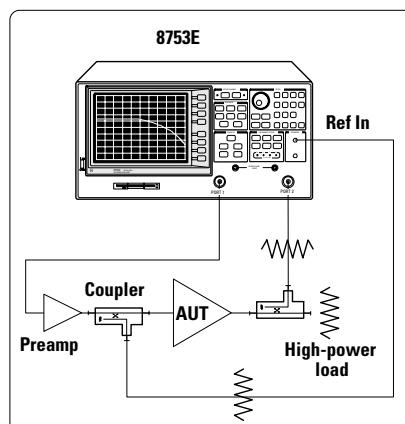
Testing high-power amplifiers can sometimes be challenging since the signal levels needed for test may be beyond the stimulus/response range of the network analyzer. High-power amplifiers often require high input levels to characterize them under conditions similar to actual operation. Often these realistic operating conditions also mean the output power of the amplifier exceeds the compression or burn-out level of the analyzer's receiver.

When you need an input level higher than the network analyzer's source can provide, a preamplifier can be used to boost the power level prior to the amplifier under test (AUT). By using a coupler on the output of the preamplifier, a portion of the boosted input signal can be used for the analyzer's reference channel. This configuration removes the preamplifier's frequency response and drift errors (by ratioing), which yields an accurate measurement of the AUT alone.

When the output power of the AUT exceeds the input compression level of the analyzer's receiver, some type of attenuation is needed to reduce the output level. This can be accomplished by using couplers, attenuators, or a combination of both. Care must be taken to choose components that can absorb the high power from the AUT without sustaining damage. Most loads designed for small-signal use can only handle up to about one watt of power. Beyond that, special loads that can dissipate more power must be used.

The frequency-response effects of the attenuators and couplers can be removed or minimized by using the appropriate type of error-correction. One concern when calibrating with extra attenuation is that the input levels to the receiver may be low during the calibration cycle. The power levels must be significantly above the noise floor of the receiver for accurate measurements. For this reason, network analyzers that have narrowband, tuned-receivers are typically used for high-power applications since their noise floor is typically  $\leq 90$  dBm, and they exhibit excellent receiver linearity over a wide range of power levels.

Some network analyzers with full two-port S-parameter capability enable measuring of the reverse characteristics of the AUT to allow full two-port error correction. If attenuation is added to the output port of the analyzer, it is best to use a higher power in the reverse direction to reduce noise effects in the measurement of S22 and S12. Many VNAs allow uncoupling of the test-port power to accommodate different levels in the forward and reverse directions.



## HINT 2.

### Compensate for time delay for better cable measurements

A network analyzer sweeps its source frequency and tuned receiver at the same time to make stimulus-response measurements. Since the frequency of a signal coming from a device under test (DUT) may not be exactly the same as the network analyzer frequency at a given instant of time, this can sometimes lead to confusing measurement results. If the DUT is a long cable with time delay  $T$  and the network analyzer sweep rate is  $df/dt$ , the signal frequency at the end of the cable (input to the vector network analyzer's receiver) will lag behind the network analyzer source frequency by the amount  $F = T * df/dt$ . If this frequency shift is appreciable compared to the network analyzer's IF detection bandwidth (typically a few kHz), then the measured result will be in error by the rolloff of the IF filter.

Figure 1 shows this effect when measuring the transmission response of a 12-foot cable on an 8714ET network analyzer. The upper trace shows the true response of the cable, using a 1-second sweep time. The lower trace uses the default sweep time of 129 msec, and the data is in error by about  $-0.5$  dB due to the frequency shift through the cable. This sweep time is too fast for this particular DUT.

The lower trace of figure 2 shows an even more confusing result when measuring the same cable on an 8753E with 100-msec sweep time. Not only is there an error in the data, but the size of the error makes some sharp jumps at certain frequencies. These frequencies are the band-edge frequencies in the 8753E, and the trace jumps because the network analyzer's sweep rate ( $df/dt$ ) changes in different bands. This leads to a different frequency shift through the cable, and hence, a different amount of error in the data. In this case, instead of increasing the sweep time, the situation can be corrected by removing the R-channel jumper on the front panel of the 8753E and connecting a second cable of about the same length as the DUT cable. This balances the delays in the reference and test paths, so that the network analyzer's ratioed transmission measurement does not have the frequency-shift error. The upper trace of figure 2 shows a measurement of the DUT using the same 100-msec sweep time, but with the matching cable in R channel.

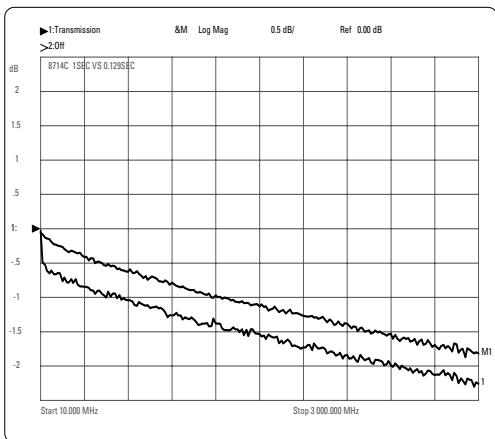


Figure 1

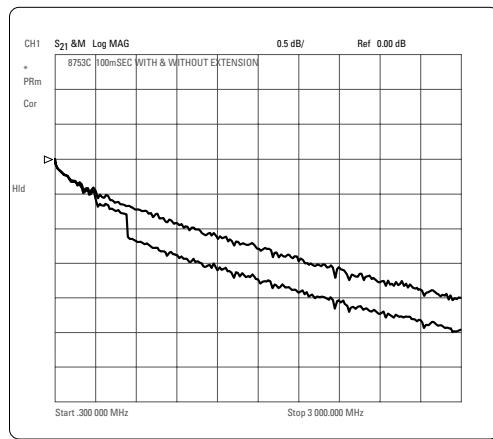


Figure 2

### HINT 3.

#### Proper termination— Key to improving reflection measurements

Making accurate reflection measurements on two-port devices with transmission/reflection (T/R)-based analyzers (such as the 8712ET and 8714ET RF analyzers) requires a good termination on the unmeasured port. This is especially true for low-loss, bidirectional devices such as filter passbands and cables. T/R-based analyzers only offer one-port calibration for reflection measurements, which corrects for errors caused by directivity, source match and frequency response, but not load match.

One-port calibration assumes a good termination at port 2 of the device under test (the port not being measured), since load match is not corrected. One way to achieve this is by connecting a high-quality load (a load from a calibration kit, for example) to port 2 of the device. This technique yields measurement accuracy on a par with more expensive S-parameter-based analyzers that use full two-port calibration.

However, if port 2 of the device is connected directly to the network analyzer's test port, the assumption of a good load termination is not valid. In this case, measurement accuracy can be improved considerably by placing an attenuator (6 to 10 dB, for example) between port 2 of the device and the test port of the analyzer. This improves the effective load match of the analyzer by twice the value of the attenuator.

Figure 1 shows an example of how this works. Let's say we are measuring a filter with 1 dB of insertion loss and 16 dB of return loss (figure 1A). Using an analyzer with an 18 dB load match and 40 dB directivity would yield a worst-case measurement uncertainty for return loss of  $-4.6$  dB,  $+10.4$  dB. This is a rather large variation that might cause a filter that didn't meet its specifications to pass, or a good filter to fail. Figure 1B shows how adding a high-quality (for example, VSWR = 1.05, or 32 dB match) 10-dB attenuator improves the load match of the analyzer to 29 dB [(2 x 10 + 18 dB) combined with 32 dB]. Now our worst-case measurement uncertainty is reduced to  $+2.5$  dB,  $-1.9$  dB, which is much more reasonable.

An example where one-port calibration can be used quite effectively without any series attenuation is when measuring the input match of amplifiers with high-reverse isolation. In this case, the amplifier's isolation essentially eliminates the effect of imperfect load match.

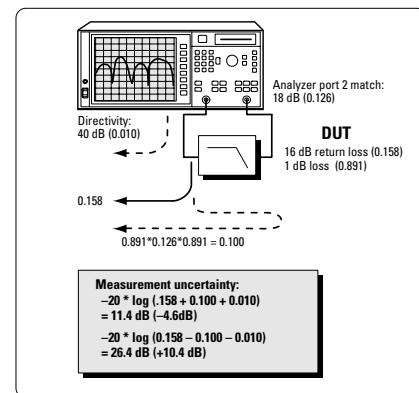


Figure 1A

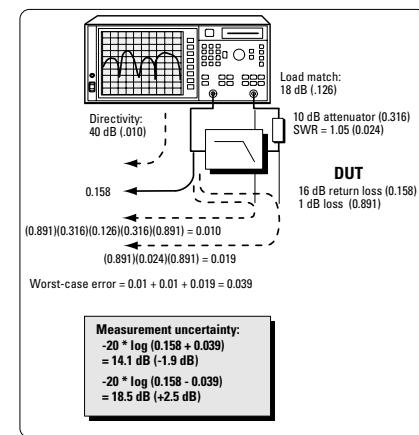


Figure 1B

**HINT 4.**  
**Use frequency-offset mode**  
**for accurate measurements of**  
**mixers, converters and tuners**

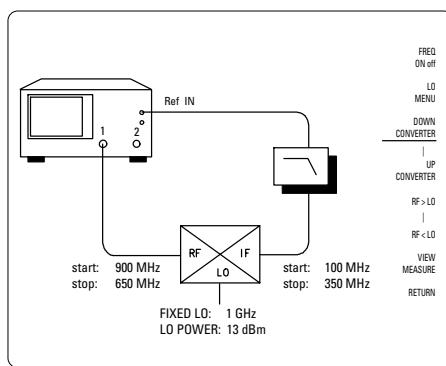
Frequency-translating devices such as mixers, tuners, and converters present unique measurement challenges since their input and output frequencies differ. The traditional way to measure these devices is with broadband diode detection. This technique allows scalar measurements only, with medium dynamic range and moderate measurement accuracy.

For higher accuracy, vector network analyzers such as the 8753E and 8720D offer a frequency-offset mode where the frequency of the internal RF source can be arbitrarily offset from the analyzer's receivers. Narrow-band detection can be used with this mode, providing high dynamic range and good measurement accuracy, as well as the ability to measure phase and group delay.

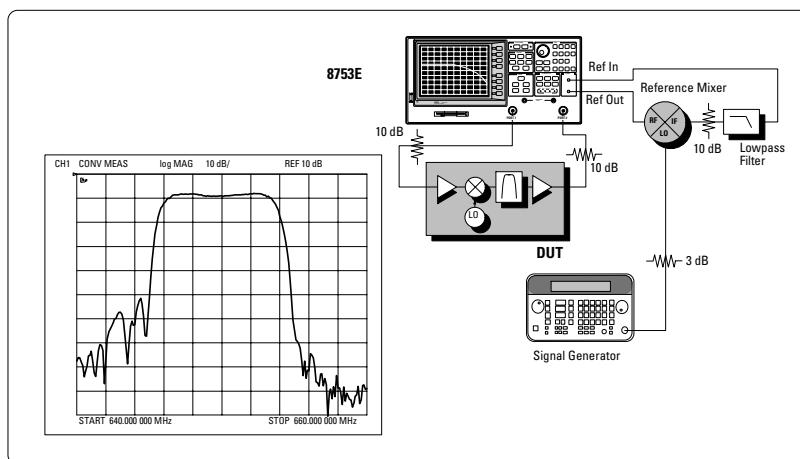
There are two basic ways that frequency-offset mode can be used. The simplest way is to take the output from the mixer or tuner directly into the reference input on the analyzer (see figure 1A). This technique offers scalar measurements only, with up to 35 dB of dynamic range; beyond that, the analyzer's source will not phase lock properly. For mixers, an external LO must be provided. After specifying the measurement setup from the front panel, the proper RF frequency span is calculated by the analyzer to produce the desired IF frequencies, which the receiver will tune to during the sweep. The network analyzer will even sweep the RF source backward if necessary to provide the specified IF span.

For high-dynamic-range amplitude measurements, a reference mixer must be used (see figure 1B). This mixer provides a signal to the R channel for proper phase lock, but does not affect measurements of the DUT since it is not in the measurement path. For phase or delay measurements, a reference mixer must also be used. The reference mixer and the DUT must share a common LO to guarantee phase coherency.

When testing mixers, either technique requires an IF filter to remove the mixer's undesired mixing products as well as the RF and LO leakage signals.



**Figure 1A**



**Figure 1B**

## HINT 5. Increasing the accuracy of noninsertible device measurements

Full two-port error correction provides the best accuracy when measuring RF and microwave components. But if you have a noninsertible device (for example, one with female connectors on both ports), then its test ports cannot be directly connected during calibration. Extra care is needed when making this through connection, especially while measuring a device that has poor output match, such as an amplifier or a low-loss device.

There are four basic ways to handle the potential errors with a through connection for a noninsertible device:

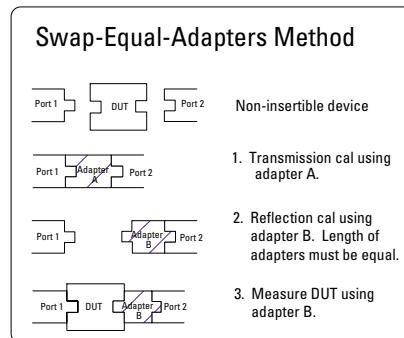
**1. Use a very short through.** This allows you to disregard the potential errors. When you connect port 1 to port 2 during a calibration, the analyzer calculates the return loss of the second port (the load match) as well as the transmission term. When the calibration kit definition does not contain the correct length of the through, an error occurs in the measurement of the load match. If a barrel is used to connect port 1 to port 2, the measurement of the port 2 match will not have the correct phase, and the error-correction algorithm will not remove the effects of an imperfect port 2 impedance.

This approach will work well enough if the through connection is quite short. However, for a typical network analyzer, “short” means less than one-hundredth of a wavelength. If the through connection is one-tenth of a wavelength (at the frequency of interest), the corrected load match is no better than the raw load match. As the through length approaches a one-quarter wavelength, the residual load match can actually get as high as 6 dB worse than the raw load match. For a 1-GHz measurement, one-hundredth of a wavelength means less than 3 mm (about 0.12 inches).

### 2. Use swap-equal-adapters.

In this method you use two matched adapters of the same electrical length, one with male/female connectors and one that matches the device under test.

Suppose your instrument test ports are both male, such as the ends of a pair of test-port cables, and your device has two female ports. Put a female-to-female through adapter, usually on port 2, and do the transmission portion of the calibration. After the four transmission measurements, swap in the male-to-female adapter (now you have two male test ports), and do the reflection portion of the calibration. Now you are ready to measure your device. All the adapters in the calibration kits are of equal electrical length (even if their physical lengths are different).



### 3. Modify the through-line-standard.

If your application is manufacturing test, the “swap-equal-adapters” method’s requirement for additional adapters may be a drawback. Instead, it is possible to modify the calibration kit definition to include the length of the through line. If the calibration kit has been modified to take into account the loss and delay of the through, then the correct value for load match will be measured. It’s easy to find these values for the male-to-male through and the female-to-female through. First, do a swap-equal-adapter calibration, ending up with both female or both male test ports. Then simply measure the “noninsertible” through and look at S21 delay (use the midband value) and loss at 1 GHz. Use this value to modify the calibration kit.

### 4. Use the adapter-removal

**technique.** Many Agilent vector network analyzer models offer an adapter-removal technique to eliminate all effects of through adapters. This technique yields the most accurate measurement results, but requires two full two-port calibrations.

## HINT 6.

### Check for aliasing in phase or delay format

When measuring a device under test (DUT) that has a long electrical length, use care to select appropriate measurement parameters. The VNA samples its data at discrete frequency points, then “connects the dots” on the display to make it more visually appealing. If the phase shift of the DUT changes by more than 180 degrees between adjacent frequency points, the display can look like the phase slope is reversed! The data is undersampled and aliasing occurs. This is analogous to filming a wagon wheel in motion, where typically too few frames are shot to accurately portray the motion and the wheel appears to spin backward.

In addition, the VNA calculates group delay data from phase data. If the slope of the phase is reversed, then the group delay will change sign. A surface acoustic wave (SAW) filter may appear to have negative group delay—clearly not a correct answer. If you suspect aliasing in your measurements, try this simple test. Just decrease the spacing between frequency points and see if the data on the VNA’s display changes. Either increase the number of points, or reduce the frequency span.

Figure 1 shows a measurement of a SAW bandpass filter on an 8714ET RF economy network analyzer, with 51 points in the display. The indicated group delay is negative—a physical impossibility. But if the number of points increases to 201 (figure 2), it becomes clear that the VNA settings created an aliasing problem.

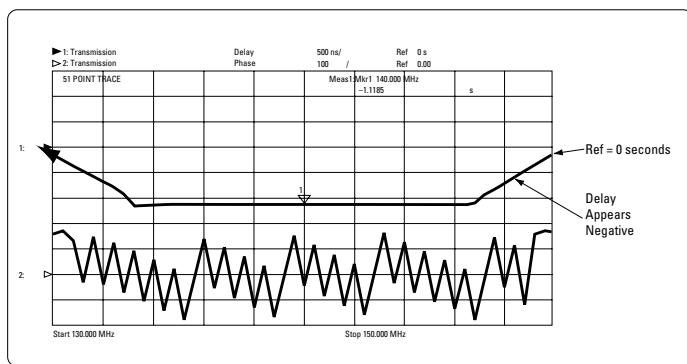


Figure 1

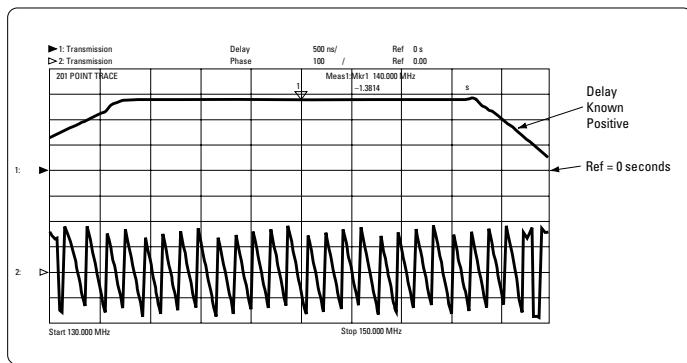


Figure 2

## HINT 7.

### Quick calibration verification

If you've ever measured a device and the measurements didn't look quite right, or you were unsure about a particular analyzer's accuracy or performance, here are a few "quick check" methods you can use to verify an instrument's calibration or performance. All you need are a few calibration standards.

#### Verifying reflection measurements

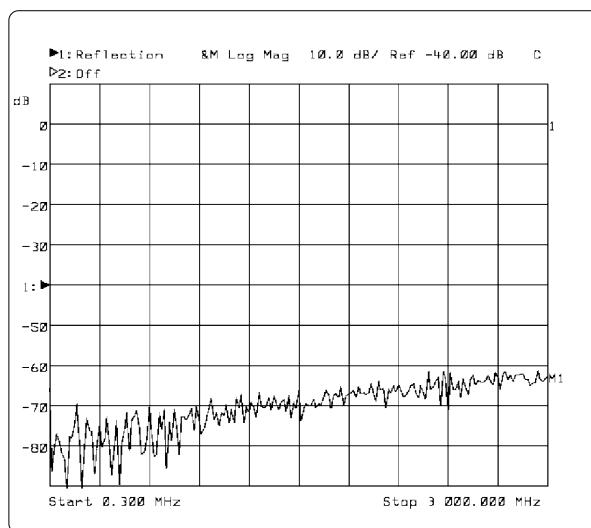
To verify reflection (S11) measurements on the source port (port 1), perform one or more of the following steps:

1. For a quick first check, leave port 1 open and verify that the magnitude of S11 is near 0 dB (within about  $\pm 1$  dB).
2. Connect a load calibration standard to port 1. The magnitude of S11 should be less than the specified calibrated directivity of the analyzer (typically less than -30 dB).
3. Connect either an open or short circuit calibration standard to port 1. The magnitude of S11 should be close to 0 dB (within a few tenths of a dB).

#### To verify transmission (S21) measurements:

1. Connect a through cable from port 1 to port 2. The magnitude of S21 should be close to 0 dB (within a few tenths of a dB).
2. To verify S21 isolation, connect two loads: one on port 1 and one on port 2. Measure the magnitude of S21 and verify that it is less than the specified isolation (typically less than -80 dB).

To get a more accurate range of expected values for these measurements, consult the analyzer's specifications. You might also consider doing these verifications immediately after a calibration to verify the quality of the calibration



## HINT 8.

### Making your measurements real-time, accurate and automated

Tuning and testing RF devices in a production environment often requires speed and accuracy from a network analyzer. However, at fast sweep speeds an analyzer's optimum accuracy may be unavailable. For those analyzers that do not provide "fast sweep-list mode," the use of save/recall registers can enable both fast and accurate measurements.

#### Using save/recall registers

For example, when adjusting the passband and stopband rejection of a bandpass filter, first set up the basic measurement on the analyzer (the start and stop frequencies, power level, etc.).

Then increase the IF bandwidth and reduce the number of data points (to speed up the trace) and save this as State 1.

Next, reduce the IF bandwidth and increase the number of data points (to get a more accurate measurement).

Add the final limit lines and save this as State 2. Now, by alternately recalling these two states you can adjust the filter in real time and then accurately verify its specifications.

#### Hands-free toggling between instrument states

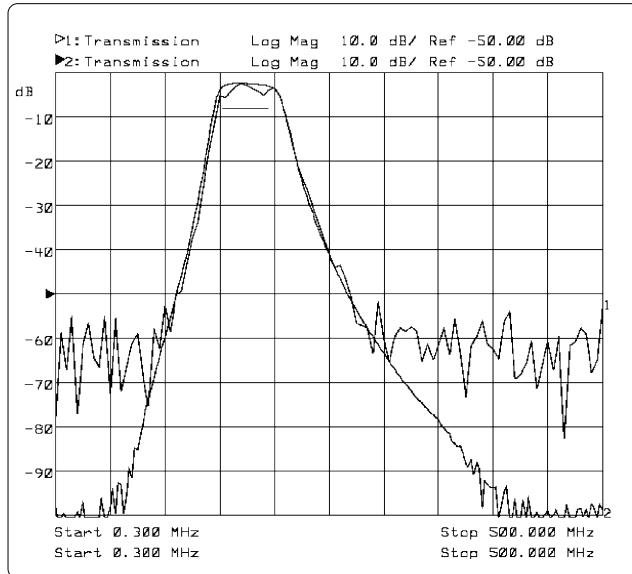
Some network analyzers like the 8712/8714 family include a BNC input that can be connected to a footswitch for toggling between two (or more) states.

#### Instrument automation

For more complex testing such as final test, an analyzer with IBASIC programming capability (8712/Agilent 8714 family, E5100, and 8751) provides complex computation and control so you can easily automate measurements.

Using the IBASIC program doesn't require programming experience.

You can easily customize each test or combination of tests and activate them by a softkey or footswitch to automatically set up system parameters for each device you test.



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2 OUTPUT 8#p8714;"SENS1:STAT ON; +HRI"
3 OUTPUT 8#p8714;"SENS1:FUNC 'XFR:PO4:RAT 1,0';DET NBR
4 OUTPUT 8#p8714;"SENS2:STAT ON; +HRI"
5 OUTPUT 8#p8714;"SENS2:FUNC 'XFR:PO4:RAT 2,0';DET NBR
6 OUTPUT 8#p8714;"CALC2:FORM MLIN"
7 OUTPUT 8#p8714;"CALC2:MARK1 ON"
8 OUTPUT 8#p8714;"CALC2:MARK2 FUNC BHID"
9 OUTPUT 8#p8714;"SENS2:RVER:CLE ; +HRI"
10 OUTPUT 8#p8714;"SENS2:RVER:COUN 0; +HRI"
11 OUTPUT 8#p8714;"SENS2:BHID 15 HZ; +HRI"
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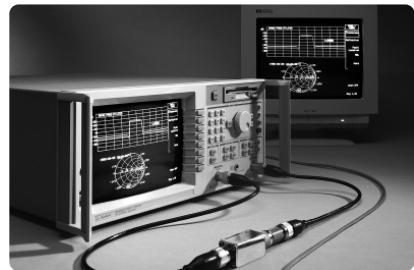
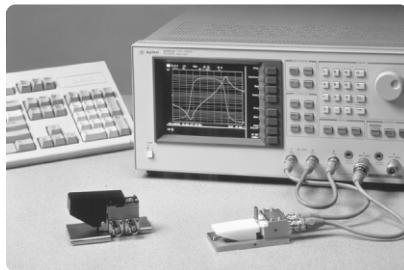
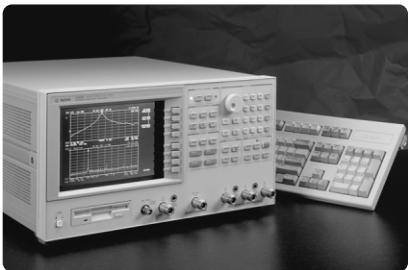
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## Guide to Agilent network analyzers



### 4396B Network/spectrum/impedance analyzer

The 4396B provides excellent RF vector network, spectrum, and optional impedance measurements for lab and production applications. Measure and evaluate, with one instrument, the gain, phase, group delay, distortion, spurious, carrier-to-noise ratio, and noise of your components and circuits. As a vector network analyzer, the 4396B operates from 100 kHz to 1.8 GHz with 1 MHz resolution for network analyzer measurements. When combined with a test set, the 4396B provides reflection measurements, such as return loss, and SWR and S-parameters.

### E5100A/B High-speed network analyzers

The E5100A/B network analyzers have been designed for resonator and filter manufacturers who need high throughput. Numerous options tailor these analyzers with a minimum investment. The frequency range is from 10 kHz to 300 MHz. With 0.04 ms/point measurement speed, waveform analysis capability, very low noise circuitry, and IBASIC automation capability, the E5100 will improve your manufacturing productivity.

### 8712 and 8714 RF Economy network analyzers

The 8712 and 8714 family of RF economy network analyzers is optimized for cost-conscious, high-volume manufacturing by delivering the best combination of speed, accuracy, productivity features and low cost. Depending on your application, choose between the optimum performance of an S-parameter analyzer, and the lower cost of a T/R analyzer. The frequency range of these analyzers is 300 kHz to 1.3 or 3 GHz, and they are available in both 50- and 75-ohm versions. All models are loaded with powerful features, including a synthesized source, narrowband and broadband detectors, a large display, an internal disk drive, IBASIC, and LAN capability.



### 8751A Precision network analyzer

For highly accurate measurements at lower frequencies (5 Hz to 500 MHz), the 8751A network analyzer provides 0.001 Hz, and 10 ps resolution using full two-port calibrations. The 8751A also offers unique features such as conjugate matching analysis. With IBASIC automation and built-in disk drive, the 8751A is also ready for manufacturing applications.

## Agilent network analyzers (cont'd)



### 8752C RF network analyzers

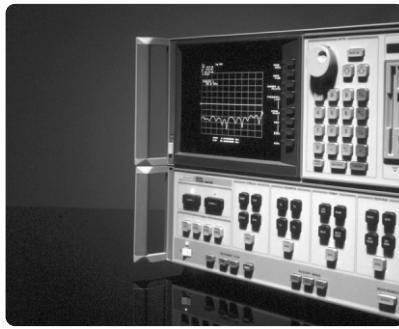
The 8752C is ideal for small spaces, but is a powerful, affordable performer offering productivity features to speed your measurements in the 300 kHz to 6 GHz range. Tailor it to your specific needs through a comprehensive set of options.

### 8753E RF network analyzers

The high-performance 8753E accurately measures the linear and nonlinear behavior of active and passive RF components up to seven times faster than its popular predecessor, the 8753D. Operating from 30 kHz to 6 GHz, the Agilent 8753E family will reduce your design time and increase your throughput. The analyzers simultaneously display all four S-parameters while tuning devices. The 8753E interfaces to Agilent's RF electronic calibration products.

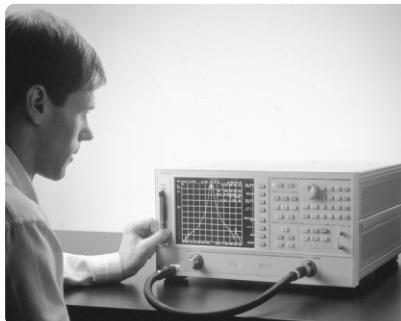
### 8720D Microwave network analyzers

The newly enhanced 8720D network analyzers (up to seven times faster than before) offer high performance at an affordable price. A faster CPU and wider bandwidth IF filters provide exceptional sweep speed, error correction, register recall and data-transfer rates. Compact and easy to use, this family has the same control and interface as the 8753E RF network analyzer, but provides frequency-response coverage from 50 MHz to 13.5, 20, or 40 GHz. Options include four-sampler architecture for full TRL/LRM calibrations for on-wafer and other noncoaxial measurements, a high-power test set, direct sampler access, and time domain.



### 8510C Microwave network analyzer

Since their introduction in 1985, the 8510 series of microwave network analyzers have set the standard for performance. These analyzers provide a complete solution for characterizing the linear behavior of active or passive networks from 45 MHz to 50 GHz. On-wafer, millimeter-wave measurements, pulsed-RF measurements, broadband bias, calibration and control—the 8510 does it all. With options for electronic calibration, frequency to 110 GHz, frequency converters for mixer measurements and multiple-test-set support, the 8510 family meets every need.



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#### Canada:

Agilent Technologies Canada Inc.  
5150 Spectrum Way  
Mississauga, Ontario, L4W 5G1  
(tel) 1 877 894 4414

#### Europe:

Agilent Technologies  
European Marketing Organization  
P.O. Box 999  
1180 AZ Amstelveen  
The Netherlands  
(tel) (31 20) 547 9999

#### Japan:

Agilent Technologies Japan Ltd.  
Measurement Assistance Center  
9-1, Takakura-Cho, Hachioji-Shi,  
Tokyo 192-8510, Japan  
(tel) (81) 426 56 7832  
(fax) (81) 426 56 7840

#### Latin America:

Agilent Technologies  
Latin American Region Headquarters  
5200 Blue Lagoon Drive, Suite #950  
Miami, Florida 33126, U.S.A.  
(tel) (305) 267 4245  
(fax) (305) 267 4286

#### Australia/New Zealand:

Agilent Technologies Australia Pty Ltd  
347 Burwood Highway  
Forest Hill, Victoria 3131  
(tel) 1-800 629 485 (Australia)  
(fax) (61 3) 9272 0749  
(tel) 0 800 738 378 (New Zealand)  
(fax) (64 4) 802 6881

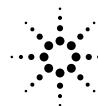
#### Asia Pacific:

Agilent Technologies  
24/F, Cityplaza One, 1111 King's Road,  
Taikoo Shing, Hong Kong  
(tel) (852) 3197 7777  
(fax) (852) 2506 9284

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Agilent Technologies  
Printed in U.S.A. 2/00  
5965-8166E



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