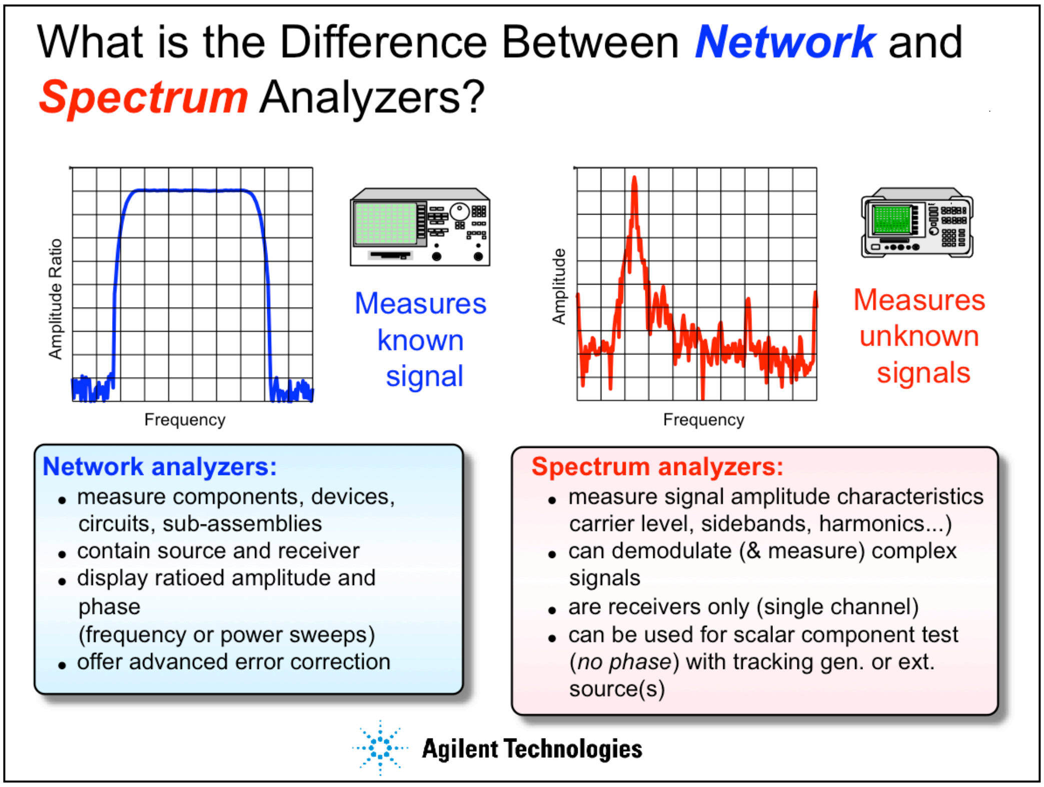

What is the Difference Between ***Network*** and ***Spectrum*** Analyzers?

Measures known signal

Measures unknown signals

Network analyzers:

- measure components, devices, circuits, sub-assemblies
- contain source and receiver
- display ratioed amplitude and phase
  (frequency or power sweeps)
- offer advanced error correction

Spectrum analyzers:

- measure signal amplitude characteristics carrier level, sidebands, harmonics...)
- can demodulate (& measure) complex signals
- are receivers only (single channel)
- can be used for scalar component test (*no phase*) with tracking gen. or ext. source(s)

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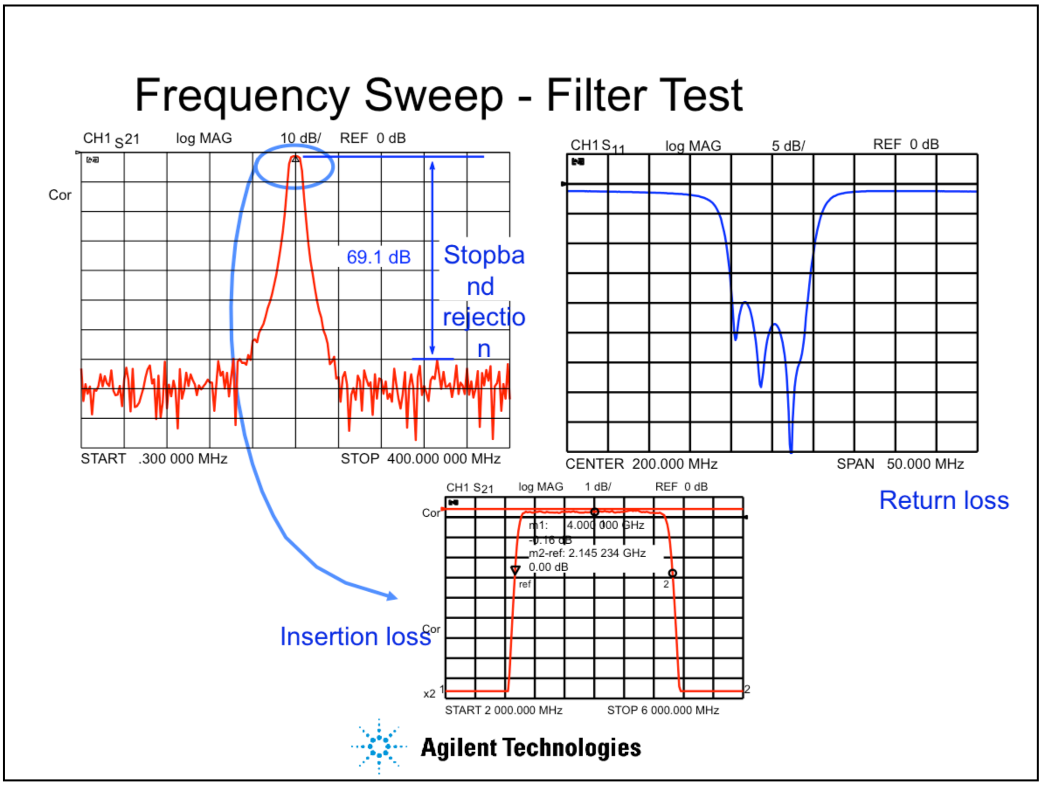
Slide 32

Now that we have seen some of the measurements that are commonly done with network and spectrum analyzers, it might be helpful to review the main differences between these instruments. Although they often both contain tuned receivers operating over similar frequency ranges, they are optimized for very different measurement applications.

Network analyzers are used to measure components, devices, circuits, and sub-assemblies. They contain both a source and multiple receivers, and generally display *ratioed* amplitude and phase information (frequency or power sweeps). A network analyzer is always looking at a *known* signal (in terms of frequency), since it is a stimulus-response system. With network analyzers, it is harder to get an (accurate) trace on the display, but very easy to interpret the results. With vector-error correction, network analyzers provide much higher measurement accuracy than spectrum analyzers.

Spectrum analyzers are most often used to measure signal characteristics such as carrier level, sidebands, harmonics, phase noise, etc., on *unknown* signals. They are most commonly configured as a single-channel receiver, without a source. Because of the flexibility needed to analyze signals, spectrum analyzers generally have a much wider range of IF bandwidths available than most network analyzers. Spectrum analyzers are often used with external sources for nonlinear stimulus/response testing. When combined with a tracking generator, spectrum analyzers can be used for scalar component testing (magnitude versus frequency, but no phase measurements). With spectrum analyzers, it is easy to get a trace on the display, but interpreting the results can be much more difficult than with a network analyzer.



Frequency Sweep - Filter Test

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Slide 79

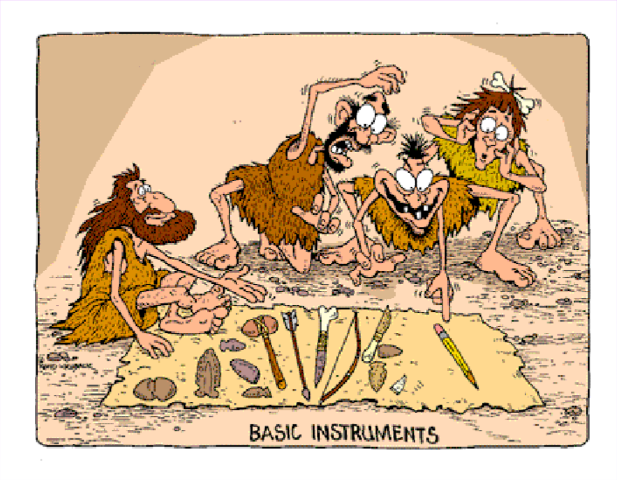
Shown above are the frequency responses of a filter. On the left and bottom we see the transmission response in log magnitude format, and on the right we see the reflection response (return loss).

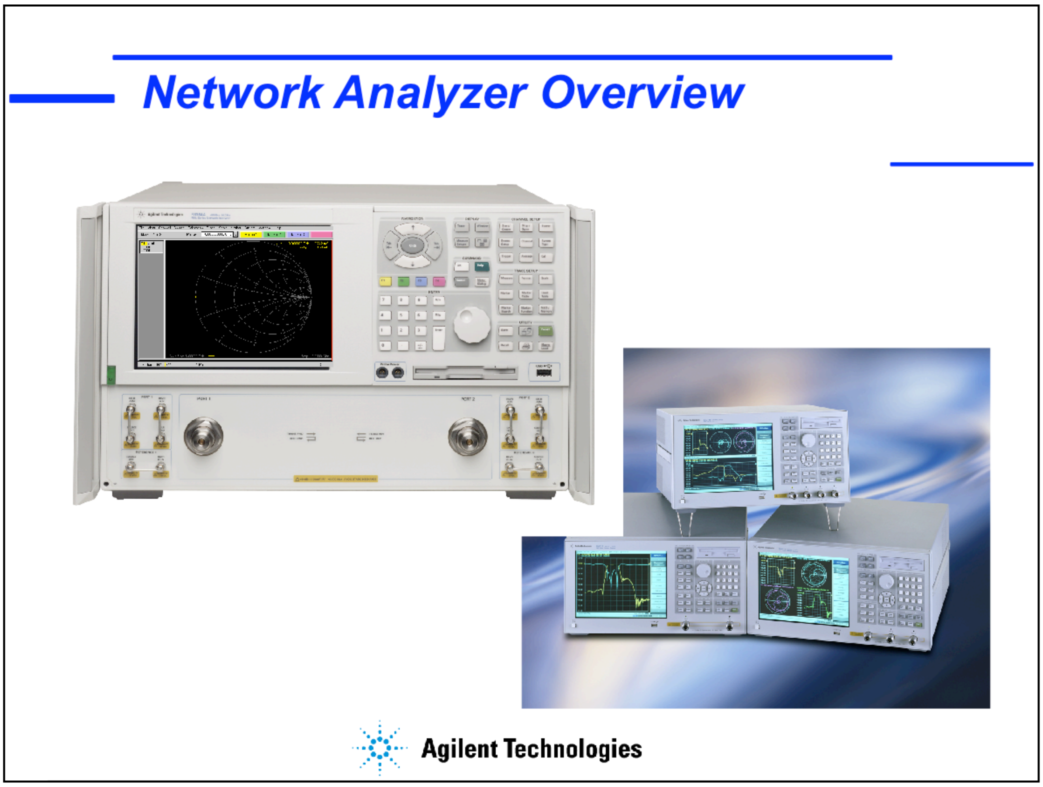
The most commonly measured filter characteristics are insertion loss and bandwidth, shown on the lower plot with an expanded vertical scale. Another common parameter we might measure is out-of-band rejection. This is a measure of how well a filter passes signals within its bandwidth while simultaneously rejecting all other signals outside of that same bandwidth. The ability of a test system to measure out-of-band rejection is directly dependent on its system dynamic-range specification.

The return loss plot is very typical, showing high reflection (near 0 dB) in the stopbands, and reasonable match in the passband. Most passive filters work in this manner. A special class of filters exist that are absorptive in both the passband and stopband. These filters exhibit a good match over a broad frequency range.

For very narrowband devices, such as crystal filters, the network analyzer must sweep slow enough to allow the filter to respond properly. If the default sweep speed is too fast for the device, significant measurement errors can occur. This can also happen with devices that are electrically very long. The large time delay of the device can result in the receiver being tuned to frequencies that are higher than those coming out of the device, which also can cause significant measurement errors.

Modern VNA





Network Analyzer Overview

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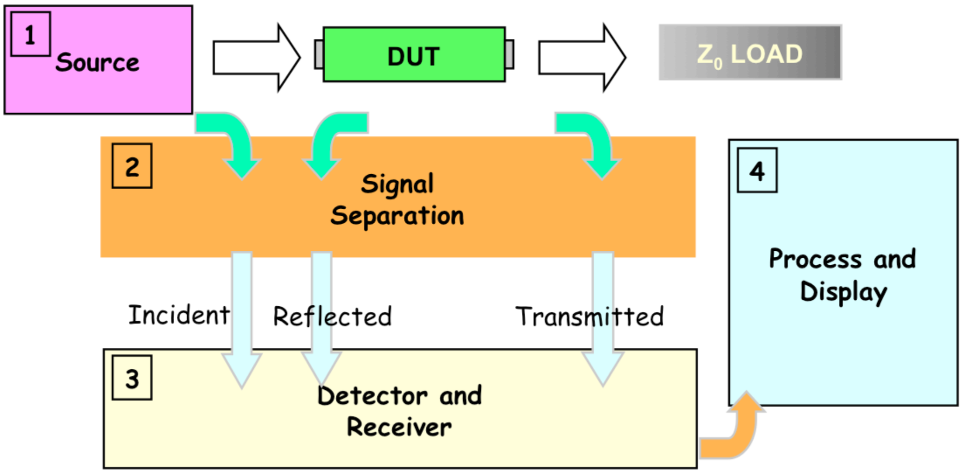
Abstract

This presentation covers the principles of measuring high-frequency electrical networks with network analyzers. You will learn what kind of measurements are made with network analyzers, and how they allow you to characterize both linear and nonlinear behavior of your devices. The session starts with RF fundamentals such as transmission lines and the Smith Chart, leading to the concepts of reflection, transmission and S-parameters. The next section covers all the major components in a network analyzer. Error modeling, accuracy enhancement, and various calibration techniques will then be presented. Finally, some typical impedance matching examples will be covered.

Network Analyzer

the four blocks



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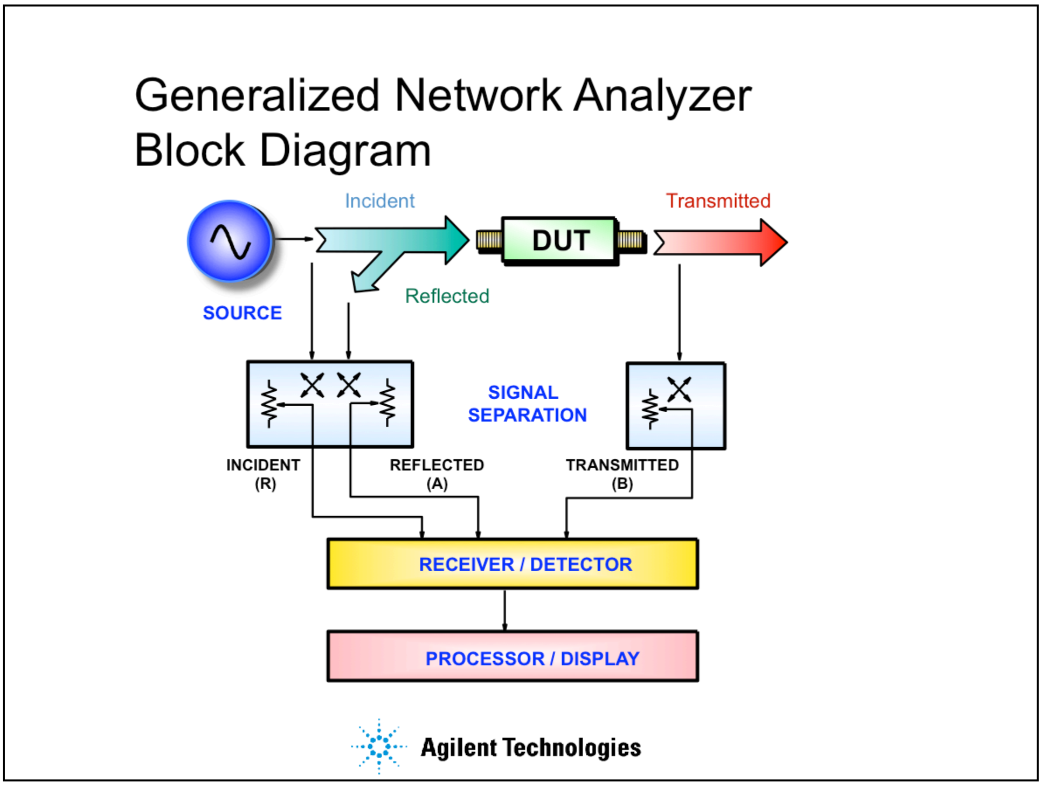

Generalized Network Analyzer Block Diagram

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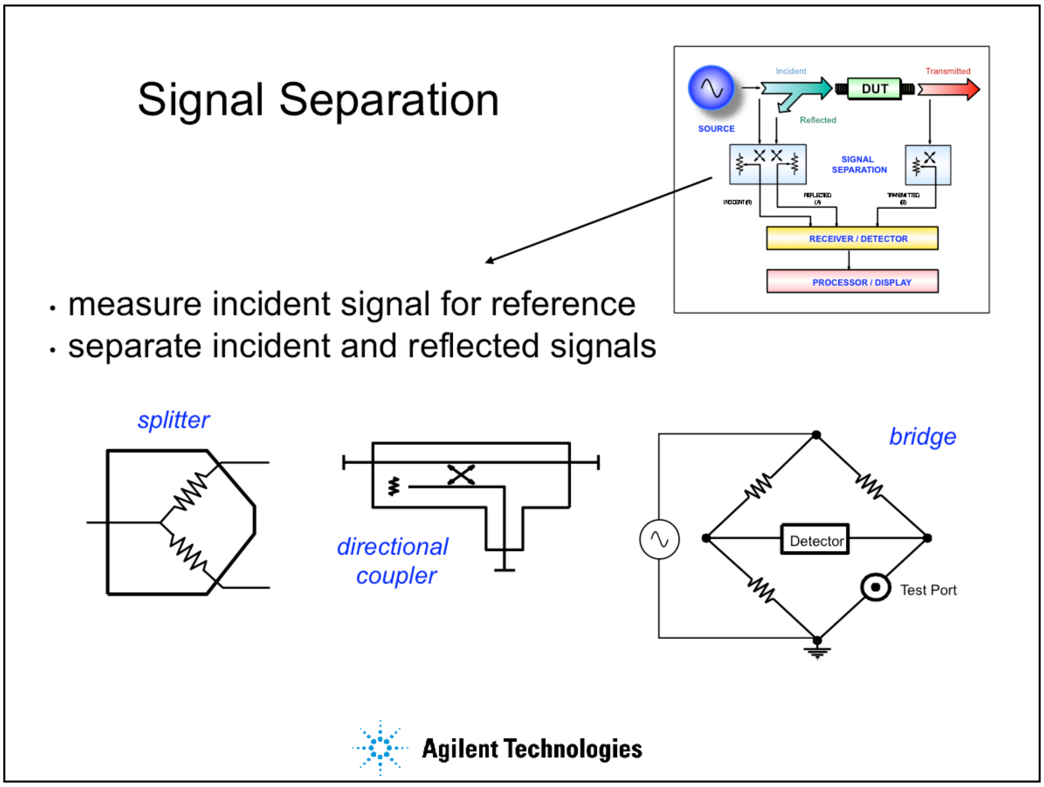
Slide 34

Here is a generalized block diagram of a network analyzer, showing the major signal-processing sections. In order to measure the incident, reflected and transmitted signal, four sections are required:

- Source for stimulus
- Signal-separation devices
- Receivers that downconvert and detect the signals
- Processor/display for calculating and reviewing the results

We will briefly examine each of these sections. More detailed information about the signal separation devices and receiver section are in the appendix.



Signal Separation

- measure incident signal for reference
- separate incident and reflected signals

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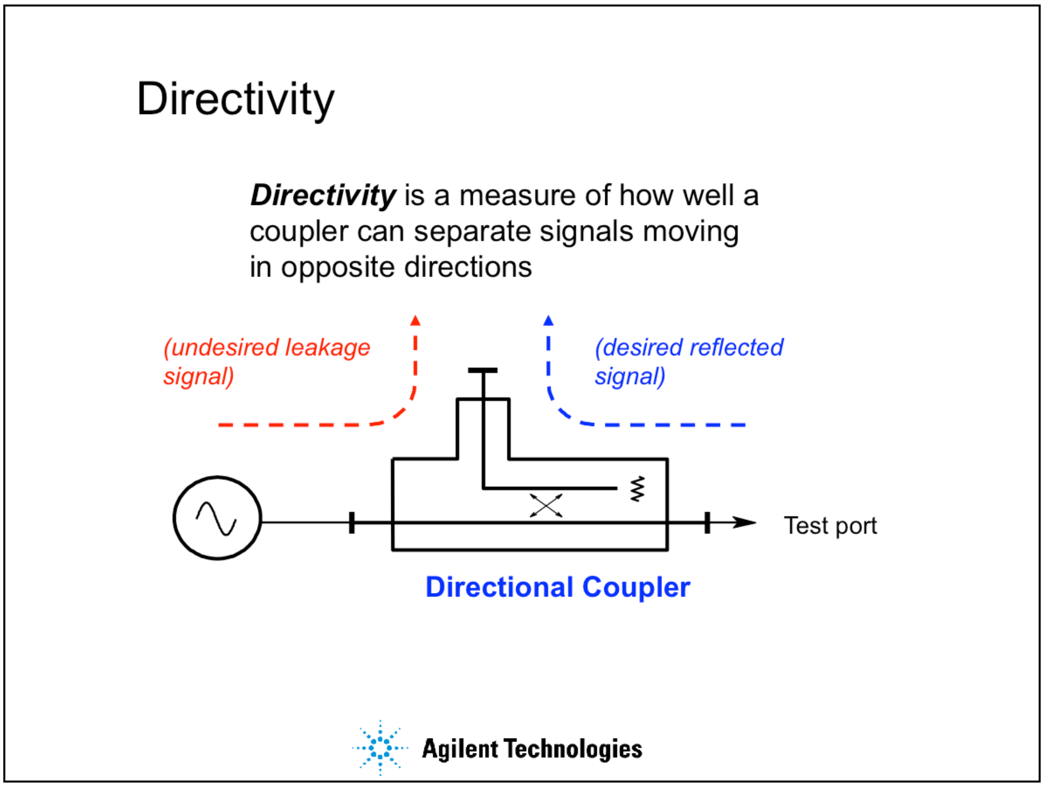
Slide 36

The next major area we will cover is the signal separation block. The hardware used for this function is generally called the "test set". The test set can be a separate box or integrated within the network analyzer. There are two functions that our signal-separation hardware must provide. The first is to measure a portion of the incident signal to provide a reference for ratioing. This can be done with splitters or directional couplers. Splitters are usually resistive. They are non-directional devices (more on directionality later) and can be very broadband. The trade-off is that they usually have 6 dB or more of loss in each arm. Directional couplers have very low insertion loss (through the main arm) and good isolation and directivity. They are generally used in microwave network analyzers, but their inherent high-pass response makes them unusable below 40 MHz or so.

The second function of the signal-splitting hardware is to separate the incident (forward) and reflected (reverse) traveling waves at the input of our DUT. Again, couplers are ideal in that they are directional, have low loss, and high reverse isolation. However, due to the difficulty of making truly broadband couplers, bridges are often used instead. Bridges work down to DC, but have more loss, resulting in less signal power delivered to the DUT. See the appendix for a more complete description of how a directional bridge works.



Directivity

Directivity is a measure of how well a coupler can separate signals moving in opposite directions

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Slide 37

Unfortunately, real signal-separation devices are never perfect. For example, let's take a closer look at the actual performance of a 3-port directional coupler.

Ideally, a signal traveling in the coupler's reverse direction will not appear at all at the coupled port. In reality, however, some energy does leak through to the coupled arm, as a result of finite isolation.

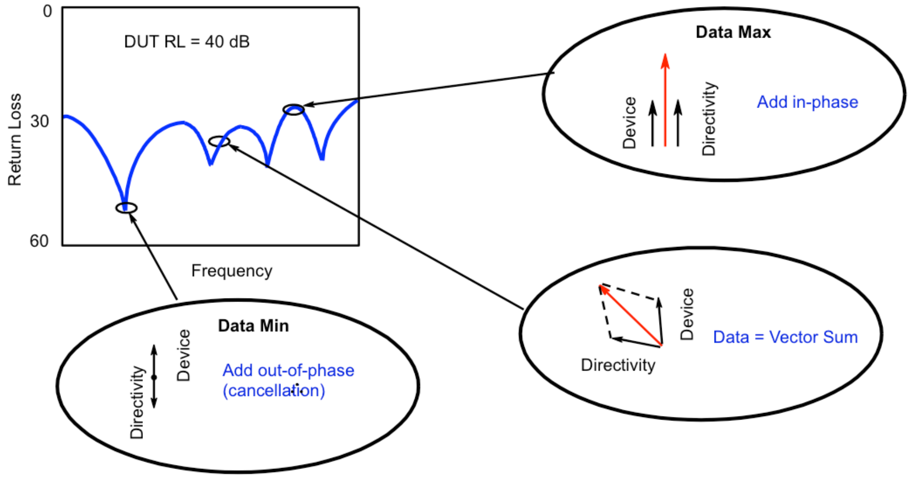
One of the most important parameter for couplers is their directivity. Directivity is a measure of a coupler's ability to separate signals flowing in opposite directions within the coupler. It can be thought of as the dynamic range available for reflection measurements. Directivity can be defined as:

Directivity (dB) = Isolation (dB) - Forward Coupling Factor (dB) - Loss (through-arm) (dB)

The appendix contains a slide showing how adding attenuation to the ports of a coupler can affect the effective directivity of a system (such as a network analyzer) that uses a directional coupler.

As we will see in the next slide, finite directivity adds error to our measured results.

Interaction of Directivity with the DUT (Without Error Correction)



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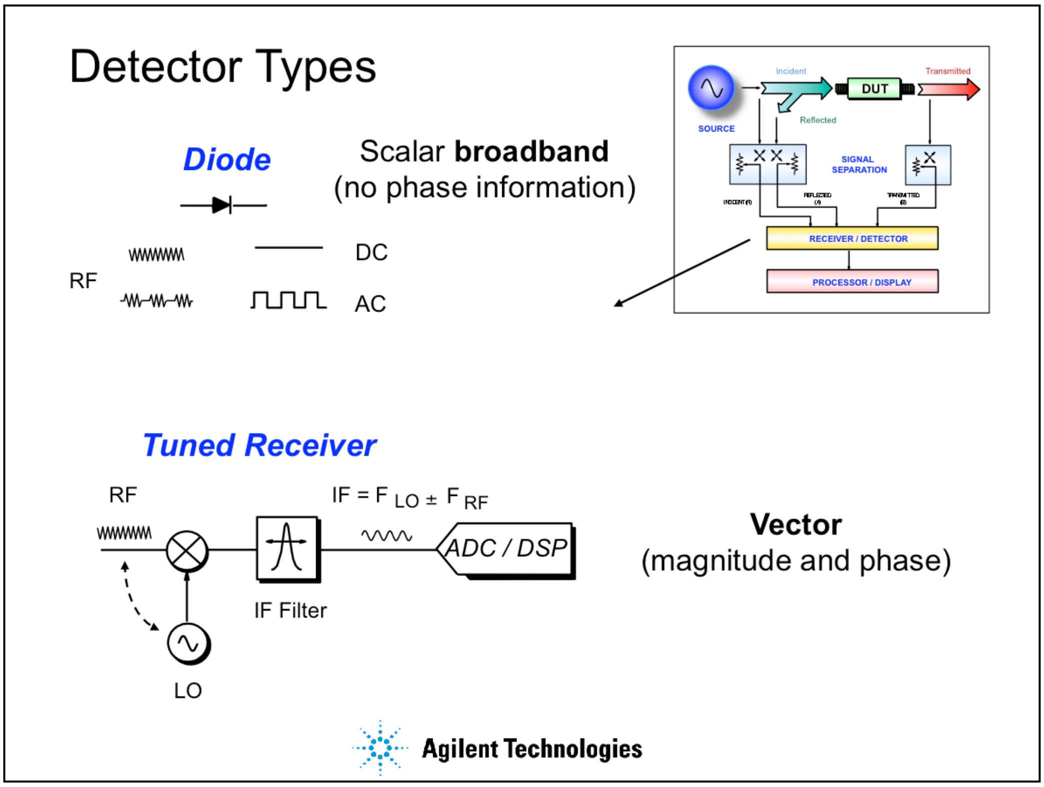
Directivity error is the main reason we see a large ripple pattern in many measurements of return loss. At the peaks of the ripple, directivity is adding in phase with the reflection from the DUT. In some cases, directivity will cancel the DUT's reflection, resulting in a sharp dip in the response.



Detector Types

Diagode

Scalar **broadband**
(no phase information)

Tuned Receiver

Vector
(magnitude and phase)

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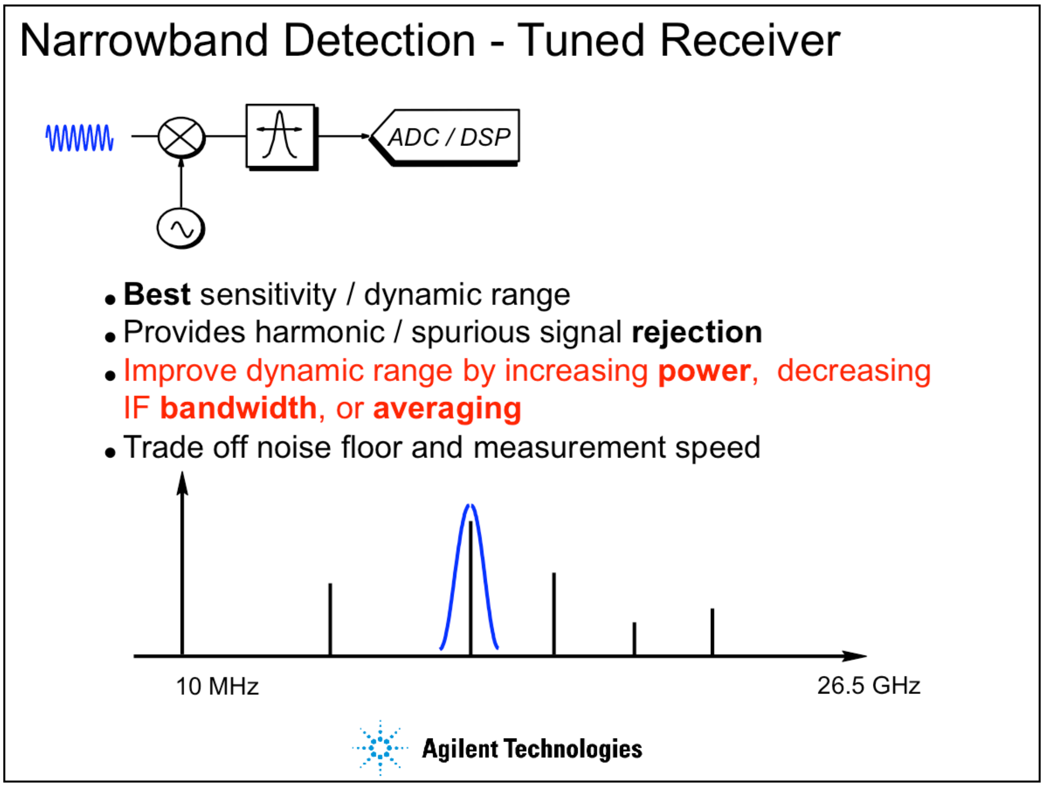
Slide 39

The next portion of the network analyzer we'll look at is the signal-detection block. There are two basic ways of providing signal detection in network analyzers. Diode detectors convert the RF signal level to a proportional DC level. If the stimulus signal is amplitude modulated, the diode strips the RF carrier from the modulation (this is called AC detection). Diode detection is inherently scalar, as phase information of the RF carrier is lost.

The tuned receiver uses a local oscillator (LO) to mix the RF down to a lower "intermediate" frequency (IF). The LO is either locked to the RF or the IF signal so that the receivers in the network analyzer are always tuned to the RF signal present at the input. The IF signal is bandpass filtered, which narrows the receiver bandwidth and greatly improves sensitivity and dynamic range. Modern analyzers use an analog-to-digital converter (ADC) and digital-signal processing (DSP) to extract magnitude and phase information from the IF signal. The tuned-receiver approach is used in vector network analyzers and spectrum analyzers.



Narrowband Detection - Tuned Receiver

- **Best** sensitivity / dynamic range
- Provides harmonic / spurious signal **rejection**
- Improve dynamic range by increasing **power**, decreasing IF **bandwidth**, or **averaging**
- Trade off noise floor and measurement speed

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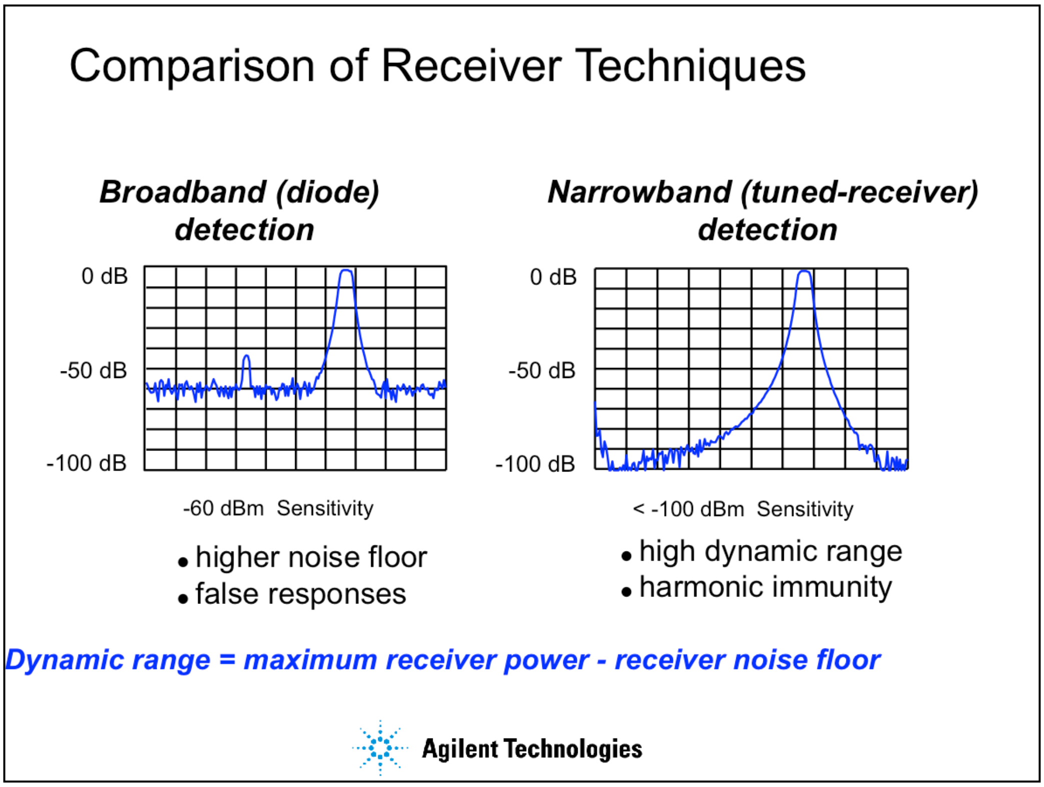
Slide 41

Tuned receivers provide the best sensitivity and dynamic range, and also provide harmonic and spurious-signal rejection. The narrow IF filter produces a considerably lower noise floor, resulting in a significant sensitivity improvement. For example, a microwave vector network analyzer (using a tuned receiver) might have a 3 kHz IF bandwidth, where a scalar analyzer's diode detector noise bandwidth might be 26.5 GHz. Measurement dynamic range is improved with tuned receivers by increasing input power, by decreasing IF bandwidth, or by averaging. The latter two techniques provide a trade off between noise floor and measurement speed. Averaging reduces the noise floor of the network analyzer (as opposed to just reducing the noise excursions as happens when averaging spectrum analyzer data) because we are averaging complex data. Without phase information, averaging does not improve analyzer sensitivity.

The same narrowband nature of tuned receivers that produces increased dynamic range also eliminates harmonic and spurious responses. As was mentioned earlier, the RF signal is downconverted and filtered before it is measured. The harmonics associated with the source are also downconverted, but they appear at frequencies outside the IF bandwidth and are therefore removed by filtering.



Comparison of Receiver Techniques

Broadband (diode) detection

-60 dBm Sensitivity

- higher noise floor
- false responses

Narrowband (tuned-receiver) detection

< -100 dBm Sensitivity

- high dynamic range
- harmonic immunity

Dynamic range = maximum receiver power - receiver noise floor

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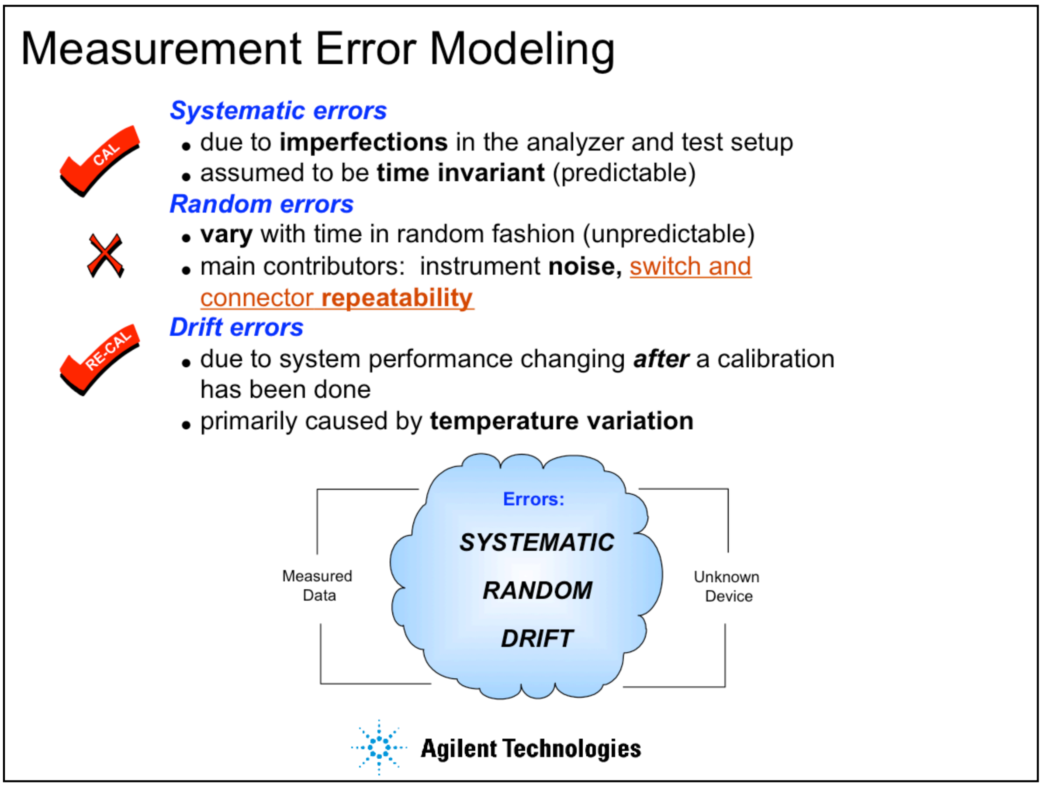
Slide 42

Dynamic range is generally defined as the maximum power the receiver can accurately measure minus the receiver noise floor. There are many applications requiring large dynamic range. One of the most common is measuring filter stopband performance. As you can see here, at least 80 dB dynamic range is needed to properly characterize the rejection characteristics of this filter. The plots show a typical narrowband filter measured on an 8757 scalar network analyzer and on an 8510 vector network analyzer. Notice that the filter exhibits 90 dB of rejection but the scalar analyzer is unable to measure it because of its higher noise floor.

In the case where the scalar network analyzer was used with broadband diode detection, a harmonic from the source created a "false" response. For example, at some point on a broadband sweep, the second harmonic of the source might fall within the passband of the filter. If this occurs, the detector will register a response, even though the stopband of the filter is severely attenuating the frequency of the fundamental. This response from the second harmonic would show on the display at the frequency of the fundamental. On the tuned receiver, a false signal such as this would be filtered away and would not appear on the display. Note that source subharmonics and spurious outputs can also cause false display responses.

Calibration and error correction



Measurement Error Modeling

Systematic errors

- due to **imperfections** in the analyzer and test setup
- assumed to be **time invariant** (predictable)

Random errors

- **vary** with time in random fashion (unpredictable)
- main contributors: instrument **noise,** switch and connector **repeatability**

Drift errors

- due to system performance changing ***after*** a calibration has been done
- primarily caused by **temperature variation**

Measured Data

Errors:

SYSTEMATIC

RANDOM

DRIFT

Unknown Device

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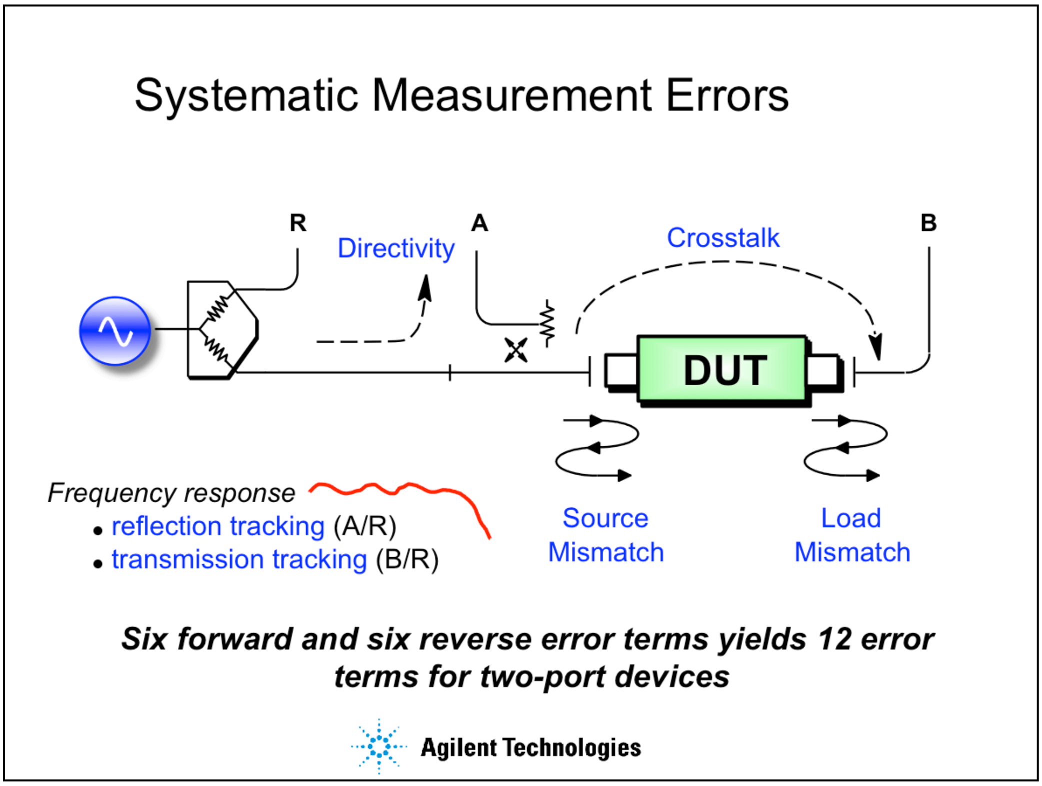
Slide 52

Let's look at the three basic sources of measurement error: systematic, random and drift.

Systematic errors are due to imperfections in the analyzer and test setup. They are repeatable (and therefore predictable), and are assumed to be time invariant. Systematic errors are characterized during the calibration process and mathematically removed during measurements.

Random errors are unpredictable since they vary with time in a random fashion. Therefore, they cannot be removed by calibration. The main contributors to random error are instrument noise (source phase noise, sampler noise, IF noise).

Drift errors are due to the instrument or test-system performance changing *after* a calibration has been done. Drift is primarily caused by temperature variation and it can be removed by further calibration(s). The timeframe over which a calibration remains accurate is dependent on the rate of drift that the test system undergoes in the user's test environment. Providing a stable ambient temperature usually goes a long way towards minimizing drift.



Systematic Measurement Errors

Frequency response
- reflection tracking (A/R)
- transmission tracking (B/R)

Six forward and six reverse error terms yields 12 error terms for two-port devices

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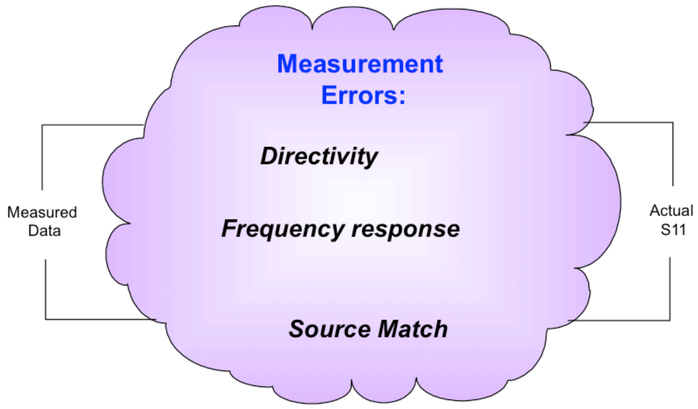
Slide 53

Shown here are the major systematic errors associated with network measurements. The errors relating to signal leakage are directivity and crosstalk. Errors related to signal reflections are source and load match. The final class of errors are related to frequency response of the receivers, and are called reflection and transmission tracking. The full two-port error model includes all six of these terms for the forward direction and the same six (with different data) in the reverse direction, for a total of twelve error terms. This is why we often refer to two-port calibration as twelve-term error correction

Major source of errors (I)

REFLECTION MEASUREMENTS



Measurement Errors:

Directivity

Frequency response

Source Match

Measured Data

Actual S11

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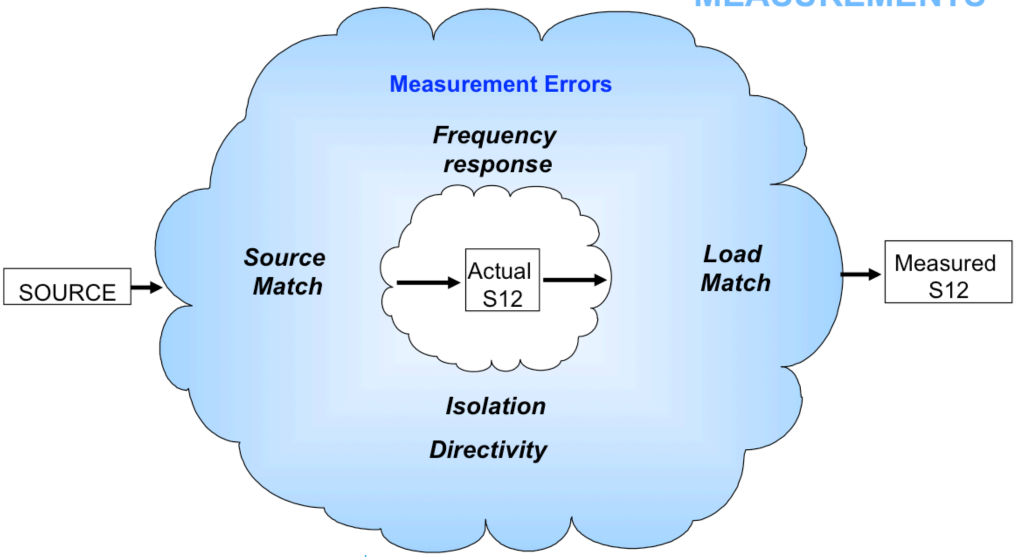
Major source of errors (II)

TRASMISSION MEASUREMENTS



Measurement Errors

Frequency response

Source Match

Load Match

Isolation

Directivity

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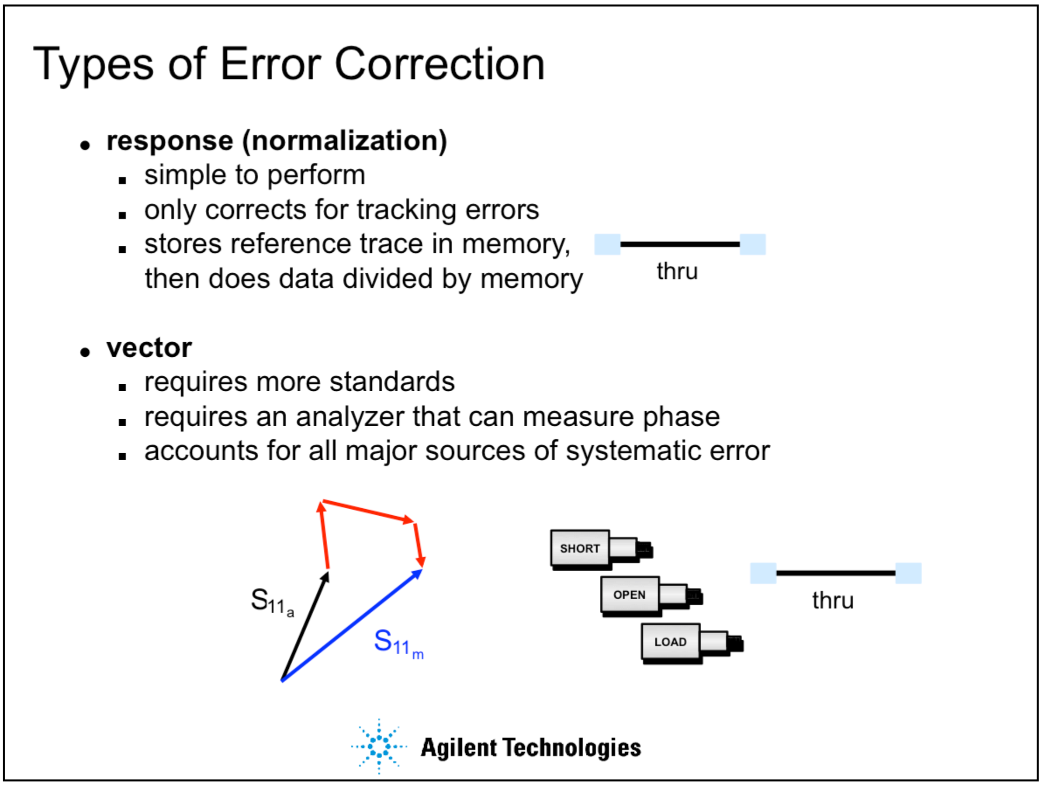

Types of Error Correction

- **response (normalization)**
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory
- **vector**
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error

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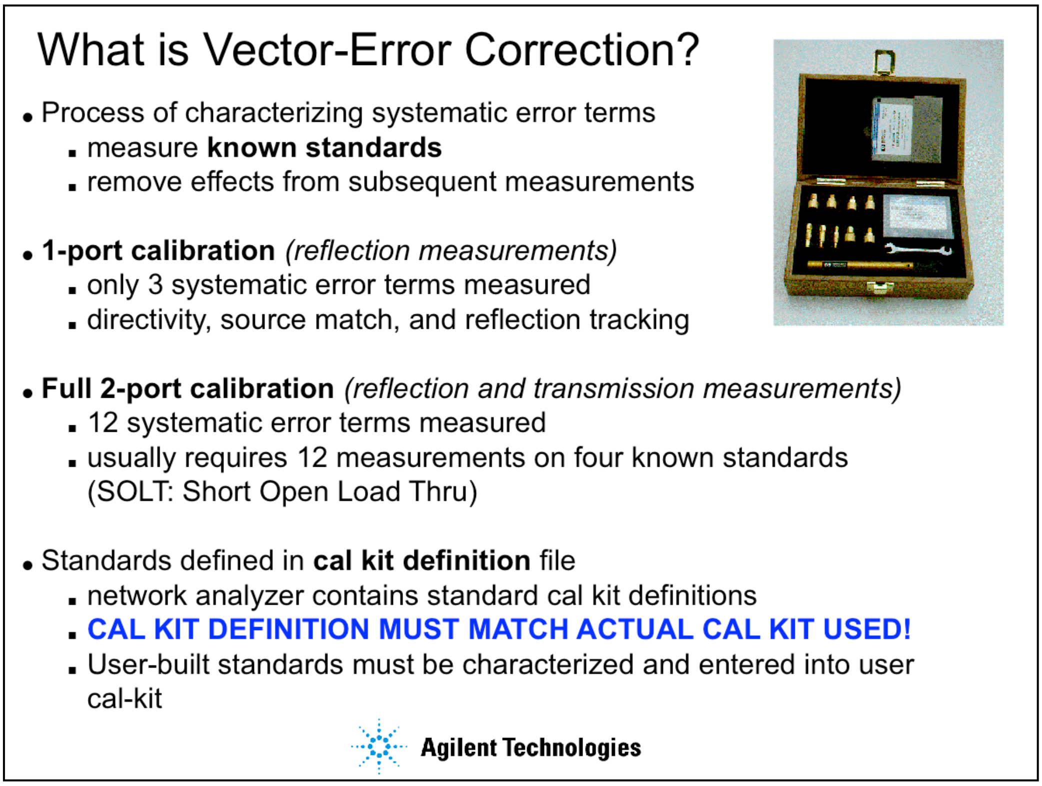
Slide 54

The two main types of error correction that can be done are response (normalization) corrections and vector corrections. Response calibration is simple to perform, but only corrects for a few of the twelve possible systematic error terms (the tracking terms). Response calibration is essentially a normalized measurement where a reference trace is stored in memory, and subsequent measurement data is divided by this memory trace. A more advanced form of response calibration is open/short averaging for reflection measurements using broadband diode detectors. In this case, two traces are averaged together to derive the reference trace.

Vector-error correction requires an analyzer that can measure both magnitude and phase. It also requires measurements of more calibration standards. Vector-error correction can account for all the major sources of systematic error and can give very accurate measurements.

Note that a response calibration can be performed on a vector network analyzer, in which case we store a complex (vector) reference trace in memory, so that we can display normalized magnitude or phase data. This is not the same as vector-error correction however (and not as accurate), because we are not measuring and removing the individual systematic errors, all of which are complex or vector quantities.



What is Vector-Error Correction?

- Process of characterizing systematic error terms
  - measure **known standards**
  - remove effects from subsequent measurements
- **1-port calibration** *(reflection measurements)*
  - only 3 systematic error terms measured
  - directivity, source match, and reflection tracking
- **Full 2-port calibration** *(reflection and transmission measurements)*
  - 12 systematic error terms measured
  - usually requires 12 measurements on four known standards (SOLT: Short Open Load Thru)
- Standards defined in **cal kit definition** file
  - network analyzer contains standard cal kit definitions
  - **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
  - User-built standards must be characterized and entered into user cal-kit

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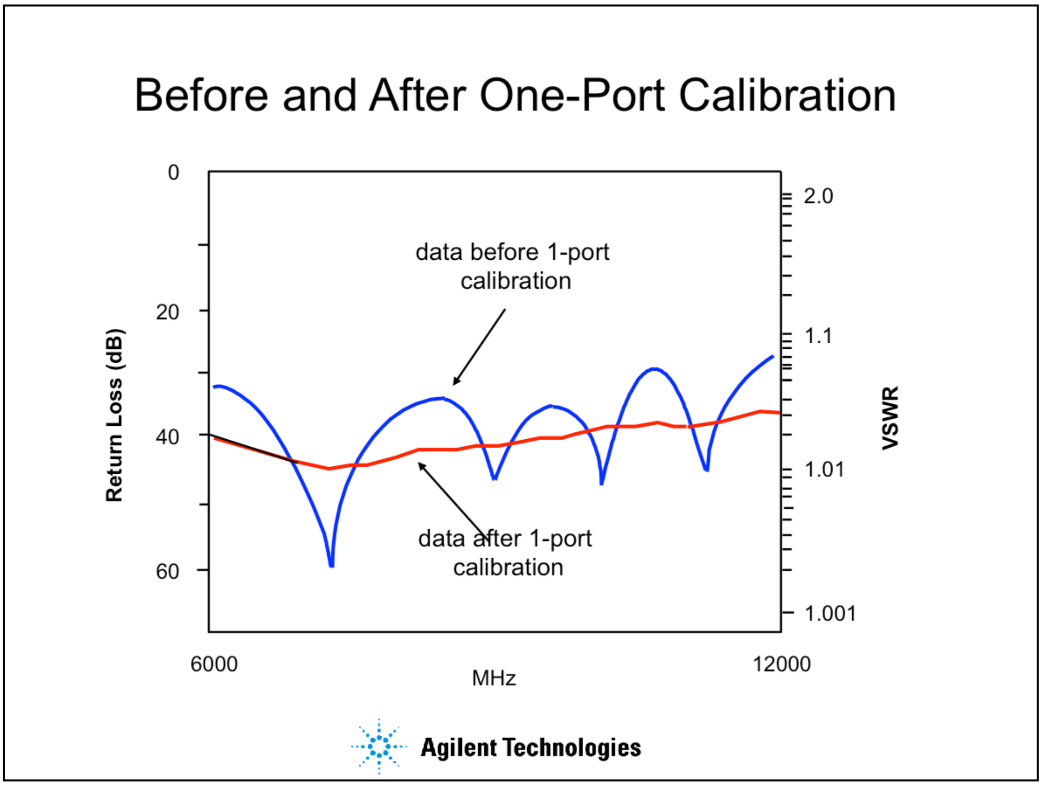
Vector-error correction is the process of characterizing systematic error terms by measuring known calibration standards, and then removing the effects of these errors from subsequent measurements.

One-port calibration is used for reflection measurements and can measure and remove three systematic error terms (directivity, source match, and reflection tracking). Full two-port calibration can be used for both reflection and transmission measurements, and all twelve systematic error terms are measured and removed. Two-port calibration usually requires twelve measurements on four known standards (short-open-load-through or SOLT). Some standards are measured multiple times (e.g., the through standard is usually measured four times). The standards themselves are defined in a cal-kit definition file, which is stored in the network analyzer. Agilent network analyzers contain all of the cal-kit definitions for our standard calibration kits. In order to make accurate measurements, the cal-kit definition MUST MATCH THE ACTUAL CALIBRATION KIT USED! If user-built calibration standards are used (during fixtured measurements for example), then the user must characterize the calibration standards and enter the information into a user cal-kit file. Sources of more information about this topic can be found in the appendix.



Before and After One-Port Calibration

data before 1-port calibration

data after 1-port calibration

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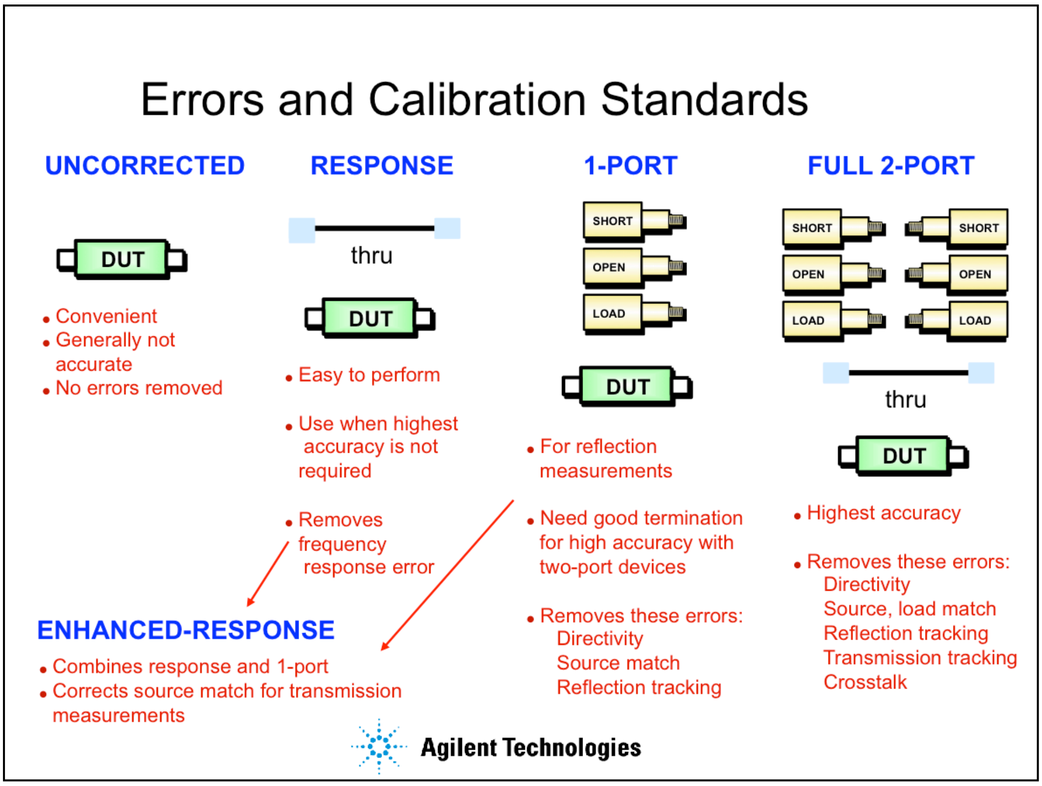
Slide 57

Shown here is a plot of reflection with and without one-port calibration. Without error correction, we see the classic ripple pattern caused by the systematic errors interfering with the measured signal. The error-corrected trace is much smoother and better represents the device's actual reflection performance.



Errors and Calibration Standards

UNCORRECTED

- Convenient
- Generally not accurate
- No errors removed

RESPONSE

- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT

- For reflection measurements
- Need good termination for high accuracy with two-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

FULL 2-PORT

- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

ENHANCED-RESPONSE

- Combines response and 1-port
- Corrects source match for transmission measurements

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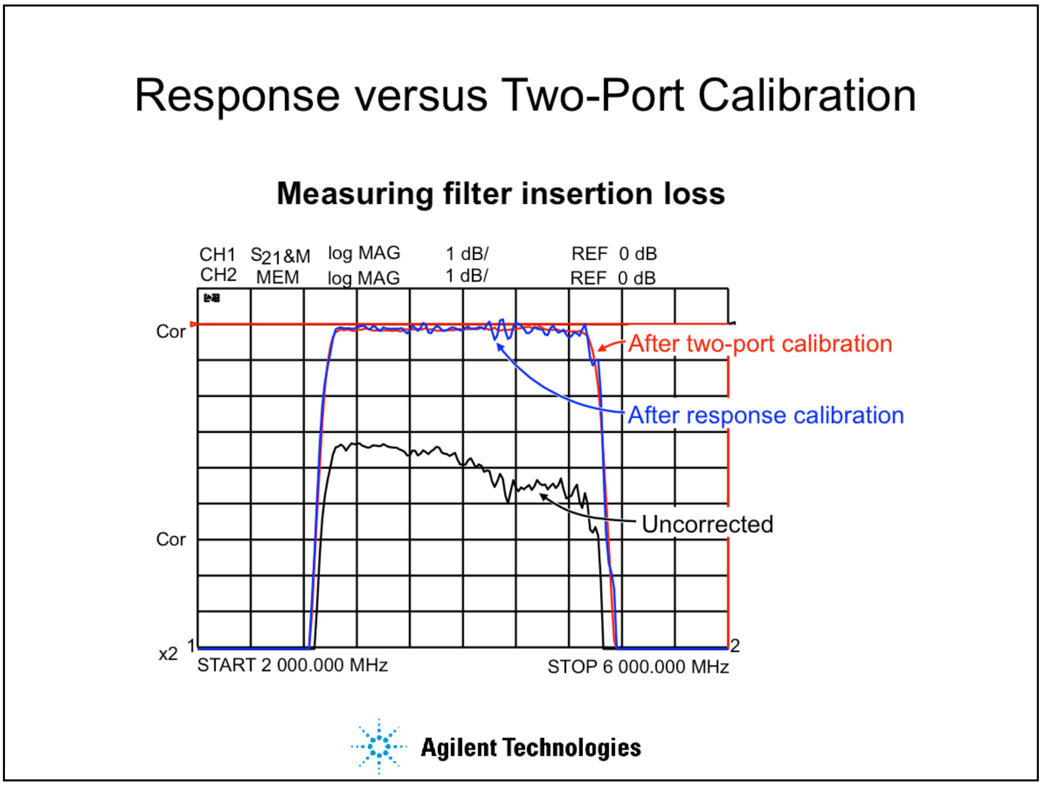
Slide 60

A network analyzer can be used for uncorrected measurements, or with any one of a number of calibration choices, including response calibrations and one- or two-port vector calibrations. A summary of these calibrations is shown above. We will explore the measurement uncertainties associated with the various calibration types in this section.



Response versus Two-Port Calibration

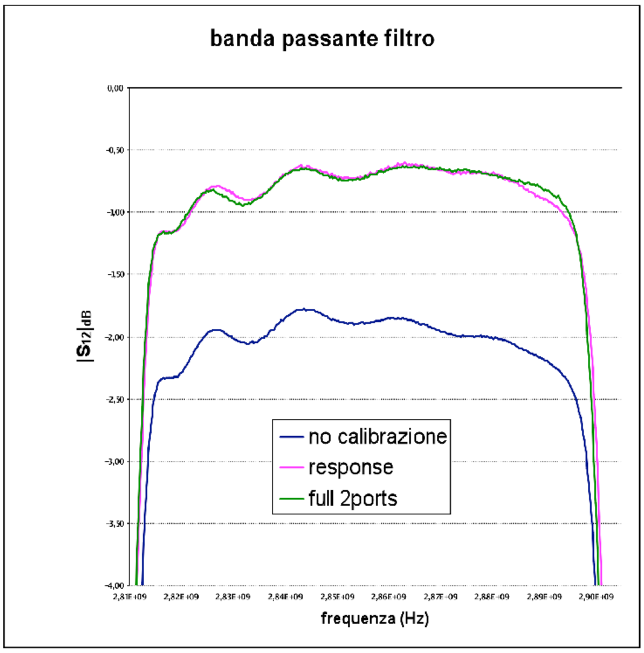
Measuring filter insertion loss

Slide 71

Let's look at some actual measurements done on a bandpass filter with different levels of error correction. The uncorrected trace shows considerable loss and ripple. In fact, the passband response varies about ± 1 dB around the filter's center frequency. Is the filter really this bad? No. What we are actually measuring is the sum of the filter's response and that of our test system.

Performing a normalization prior to the measurement of the filter removes the frequency response of the system (transmission tracking error) from the measurement. The loss that was removed was most likely caused by the test cables. After normalization, the frequency response of the filter still contains ripple caused by an interaction between the system's source and load match. This ripple even goes above the 0 dB reference line, indicating gain! However, we know that a passive device cannot amplify signals. This apparent anomaly is due to mismatch error.

The measurement shown after a two-port calibration is the most accurate of the three measurements shown. Using vector-error correction, the filter's passband response shows variation of about ± 0.1 dB around its center frequency. This increased level of measurement flatness will ensure minimum amplitude distortion, increase confidence in the filter's design, and ultimately increase manufacturing yields due to lower test-failure rates.


banda passante filtro
0,00
-0,50
-1,00
-1,50
-2,00
-2,50
-3,00
-3,50
-4,00
$|S_{12}|_{dB}$
2,81E+09
2,82E+09
2,83E+09
2,84E+09
2,85E+09
2,86E+09
2,87E+09
2,88E+09
2,89E+09
2,90E+09
frequenza (Hz)
no calibrazione
response
full 2ports

IF BW and averaging

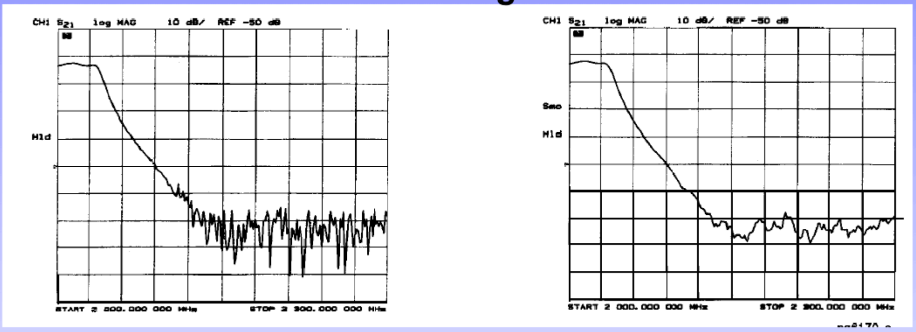
Heterodyne detection scheme

IF BW reduction

Averaging

Dynamic Range (definition)

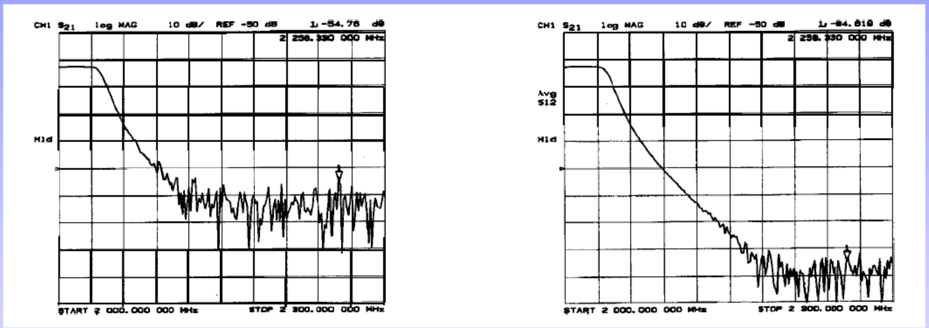
Smoothing trace



Smoothing (similar to video filtering) averages the formatted active channel data over a portion of the displayed trace. Smoothing computes each displayed data point based on one sweep only, using a moving average of several adjacent data points for the current sweep. The smoothing aperture is a percent of the swept stimulus span, up to a maximum of 20%.

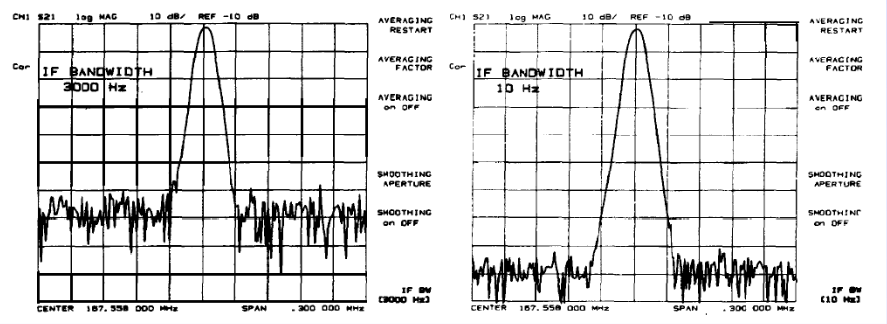
Rather than lowering the noise floor, smoothing finds the mid-value of the data. Use it to reduce relatively small peak-to-peak noise values on broadband measured data. Use a sufficiently high number of display points to avoid misleading results. Do not use smoothing for measurements of high resonance devices or other devices with wide trace variations, as it will introduce errors into the measurement.

Averaging trace



Averaging computes each data point based on an exponential average of consecutive sweeps weighted by a user-specified averaging factor. Each new sweep is averaged into the trace until the total number of sweeps is equal to the averaging factor, for a fully averaged trace. Each point on the trace is the vector sum of the current trace data and the data from the previous sweep. A high averaging factor gives the best signal-to-noise ratio, but slows the trace update time. Doubling the averaging factor reduces the noise by 3 dB.

IF BW reduction



IF bandwidth reduction lowers the noise floor by digitally reducing the receiver input bandwidth. It works in all ratio and non-ratio modes. It has an advantage over averaging as it reliably filters out unwanted responses such as spurs, odd harmonics, higher frequency spectral noise, and line-related noise. Sweep-to-sweep averaging, however, is better at filtering out very low frequency noise. A tenfold reduction in IF bandwidth lowers the measurement noise floor by about 10 dB. Bandwidths less than 300 Hz provide better harmonic rejection than higher bandwidths.