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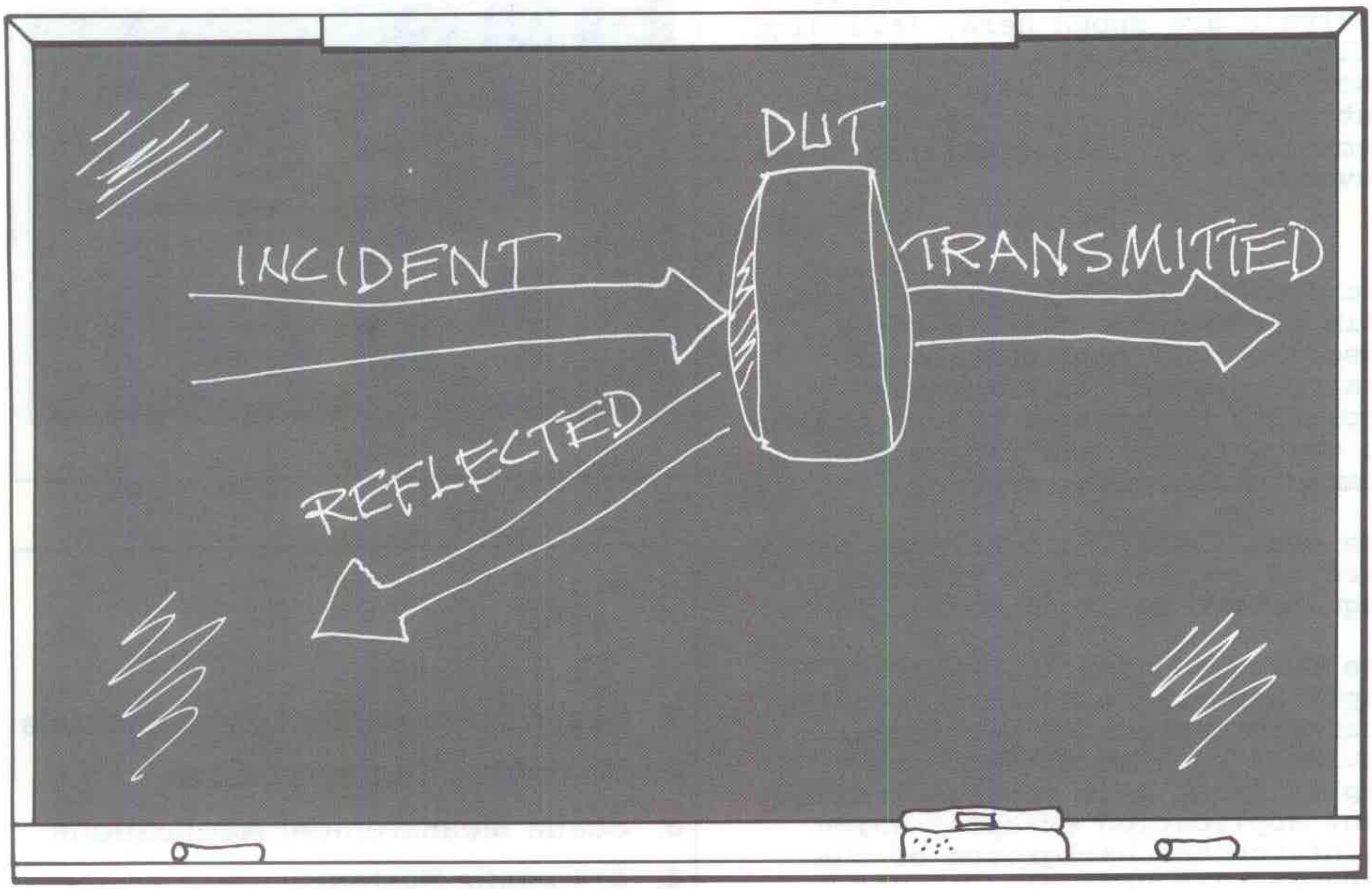
Scalar Measurement Fundamentals



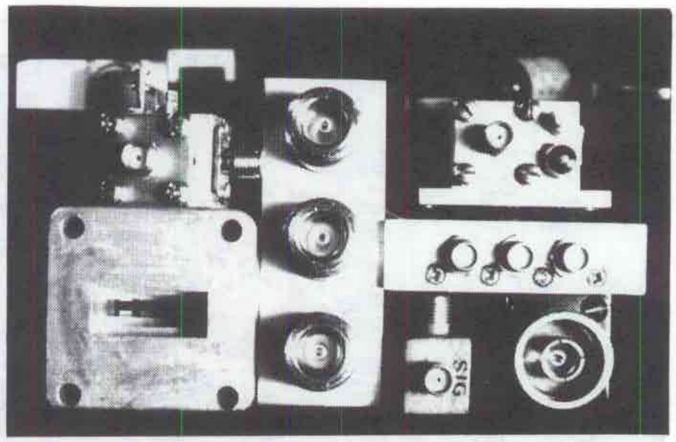
Welcome to the SCALAR MEASUREMENTS SEMINAR. This seminar will show you how to characterize RF and microwave components economically and effectively using scalar network analysis.

Welcome to

Hewlett-Packard's Scalar Measurements Seminar

3303

Some of the devices that can be characterized with scalar network analysis are shown here, including filters, amplifiers, mixers, and oscillators. This seminar will introduce you to the theory and techniques of characterizing these devices.



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The seminar is divided into four main parts. The first section describes the fundamentals of scalar network measurements, including background theory and how to characterize and reduce some common measurement errors.

The second section describes proper care of connectors, a critical requirement for good measurements.

The third section shows how to apply network measurements to the characterization of particular devices, such as filters and amplifiers. This section includes many application examples which reinforce the background of the fundamentals section.

The last section describes how to automate scalar network measurements to increase throughput and efficiency in network measurements.

1. **Scalar Measurement Fundamentals**
2. **Microwave Connector Care**
3. **Scalar Measurement Applications**
4. **Automatic Systems**

3333

SCALAR MEASUREMENT FUNDAMENTALS

- Basic Microwave Measurements
- Scalar Network Analysis System
- Scalar Reflection Measurements
- Transmission Measurements
- Power Measurements
- Product Summary

3457

In this section, we will discuss measurement fundamentals for network analysis, specifically scalar network analysis. We will look at what comprises a scalar network analysis system and how to make accurate scalar measurements. We will also look at HP's product offerings available to make scalar measurements.

SCALAR MEASUREMENT FUNDAMENTALS

- Basic Microwave Measurements

3457

First, let's look at the basic microwave measurements that are commonly made.

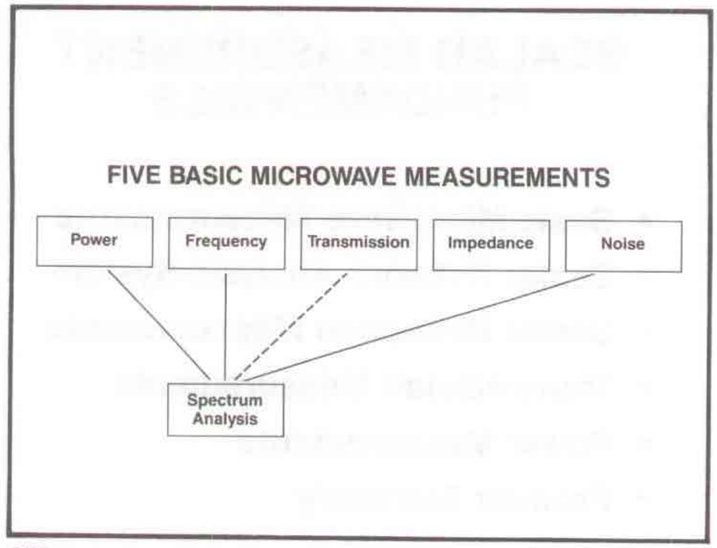
FIVE BASIC MICROWAVE MEASUREMENTS

Power	Frequency	Transmission	Impedance	Noise

3458

There are five basic microwave measurements.

Spectrum analysis primarily measures power, frequency, and noise.



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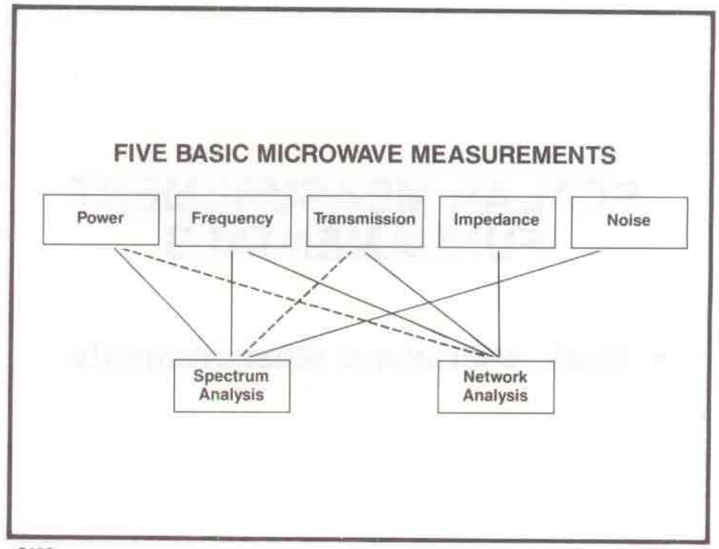
Network analysis is primarily concerned with impedance, transmission, and frequency. Power can also measured in network analysis.



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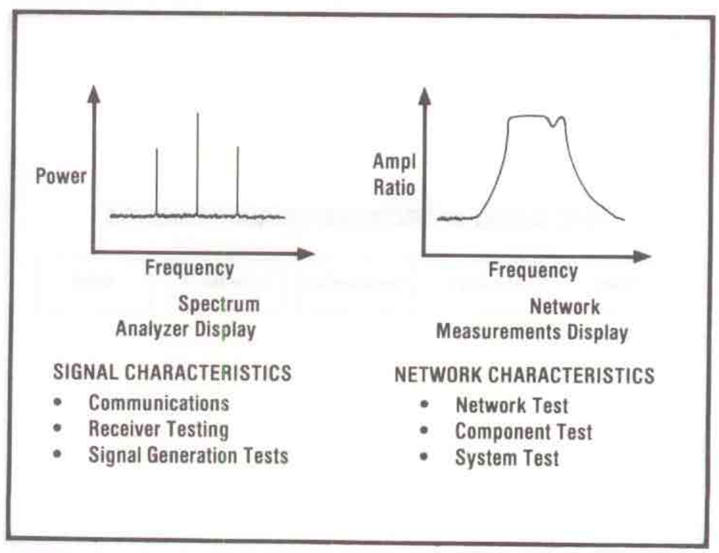
The major difference between spectrum and network analysis is illustrated here.

Spectrum analysis is primarily concerned with characterizing a signal; i.e., its spurious and harmonic components, modulation, noise, etc. It indicates discrete frequencies where microwave energy exists.

In network analysis, we want to characterize a microwave component; that is, determine how efficiently energy is transferred into the network (or out of the network), or measure its transmission characteristics to determine how effectively energy is transferred through the network. Frequency is important since parameters are usually measured and displayed as a function of frequency.



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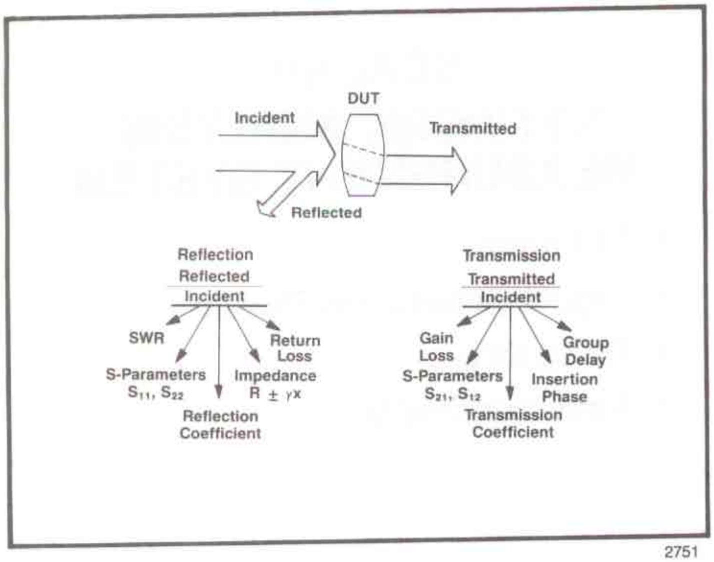

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Microwave energy can be likened to light energy. Throughout this seminar we will use this analogy. Three waves will be of interest to us: the incident, the reflected, and the transmitted waves. To characterize a network (or component) completely, both magnitude and phase information is necessary. For many applications, however, scalar (magnitude only) characterization is sufficient.

We will discuss phase only to the extent that it affects scalar measurement accuracies.

WHY MAKE SCALAR MEASUREMENTS INSTEAD OF VECTOR MEASUREMENTS???

$ **COST** $

3459

Why are we interested in making scalar (magnitude only) measurements instead of making vector (magnitude and phase) measurements?

The major reason is cost. A scalar network analyzer is about one-fourth the cost of a vector network analyzer.

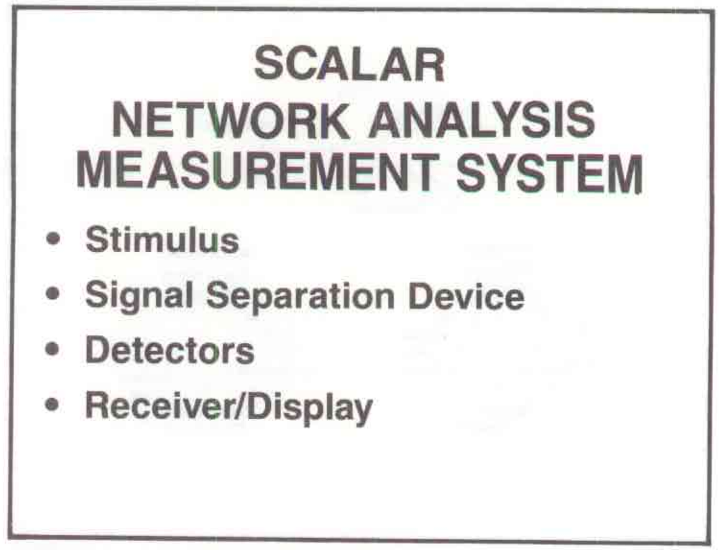
SCALAR MEASUREMENT FUNDAMENTALS

- **Basic Microwave Measurements**
- **Scalar Network Analysis System**

3457

Let's look at what makes up a scalar network analysis measurement system.

A scalar system consists of four parts; a microwave source, signal separation devices, detectors to convert the microwave energy to a DC or low frequency signal, and an analyzer which receives the detector output and displays the measurement results as a function of frequency.



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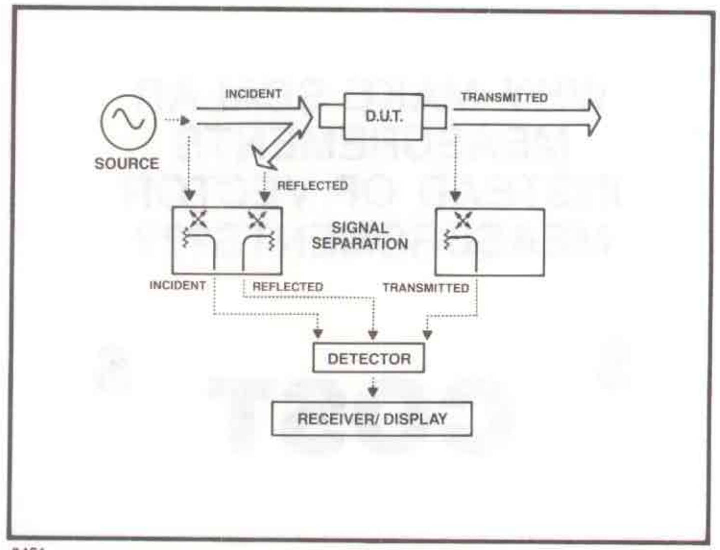
This setup shows the typical network measurement configuration. Note the device under test is analogous to the "lens" of our previous example with light, the component which we want to characterize.



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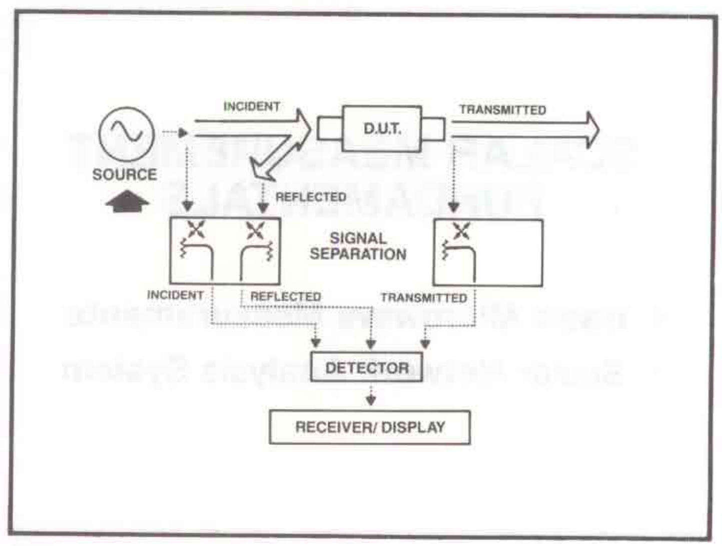
The microwave source provides the swept frequency stimulus for the measurement system.



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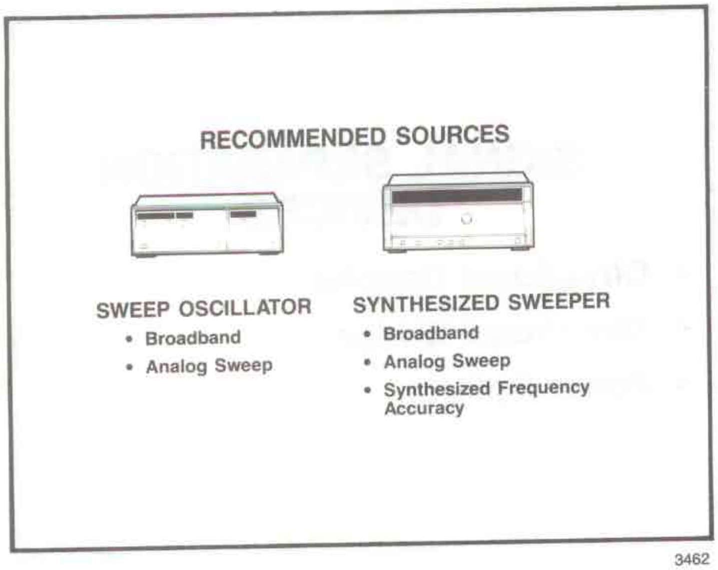
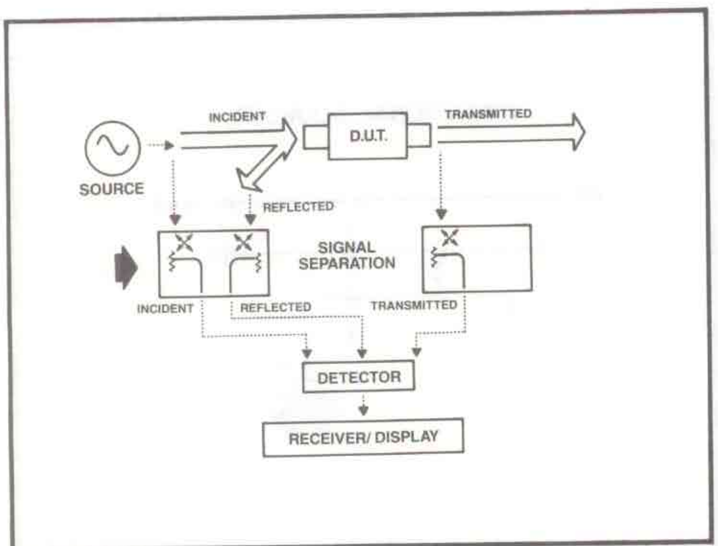


3462

The two major sources we will discuss are the sweep oscillator (more commonly called a "sweeper"), and the synthesized sweep oscillator.

The basic sweeper provides a signal (frequency) that is swept over a broad band of frequencies with settings to select the range over which the source is swept. Additional features such as internal and external power leveling, modulation (AM, FM, Pulse), and programmability are important for more accurate and cost effective systems as we'll see later.



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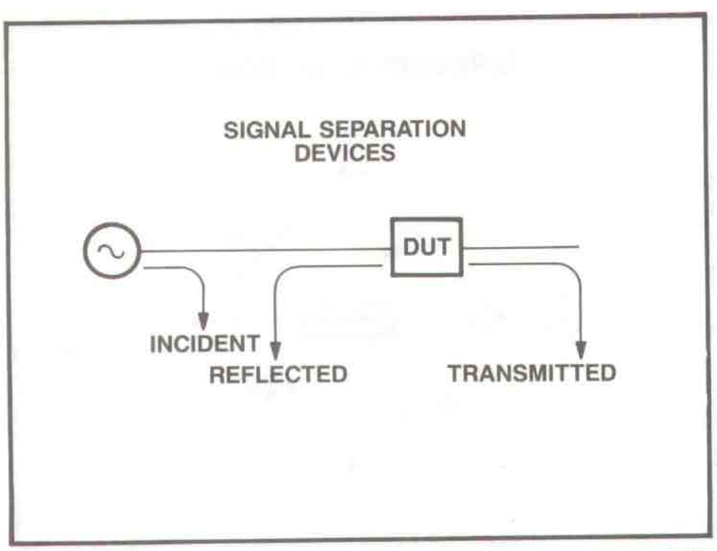
A synthesized sweeper has the additional capabilities of providing very accurate synthesized stepped CW sweeps as well as the standard broadband analog sweep. Narrowband, highly accurate, phase-locked sweeps are also possible with a synthesized sweeper.

Let's discuss signal separation devices and how they are used in network measurements.



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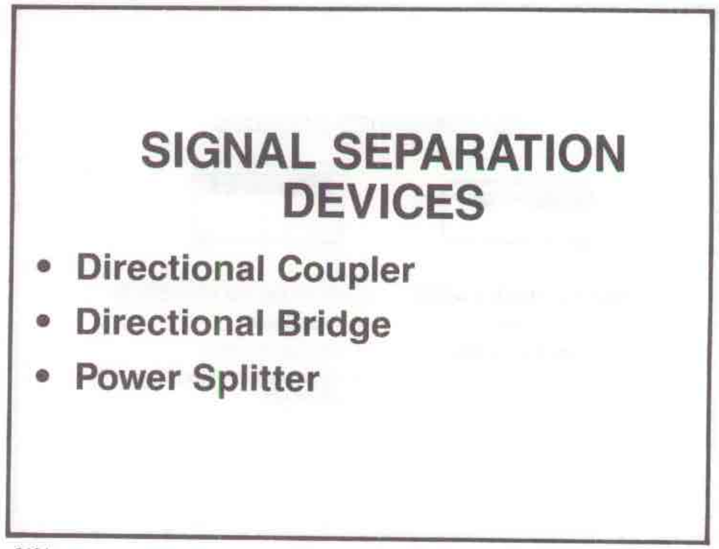
The signal separation device samples the test signal in one direction only. For example, a directional coupler used for reflection measurements only samples the test signal reflected from the input of the DUT but not the incident signal.

The three devices used for sampling the signal of interest are: (1) directional couplers, (2) directional bridges, and (3) the two resistor power splitter.



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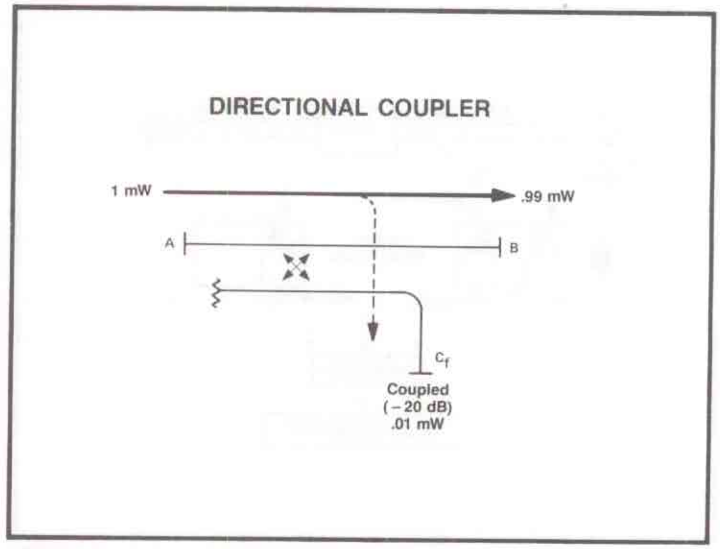
The coupled arm of a directional coupler samples a signal traveling in one direction only. The coupled signal is at a reduced level and the amount of reduced level is called the coupling factor. Notice that in this example of a 20 dB directional coupler that the coupled port is 20 dB below the input. A 20 dB reduction means that the coupled arm is 0.01xP(in) or 1% of the input power. The remainder of the signal (99%) travels through the main arm. There is also a frequency response or coupling variation associated with couplers, expressed in ±dB.



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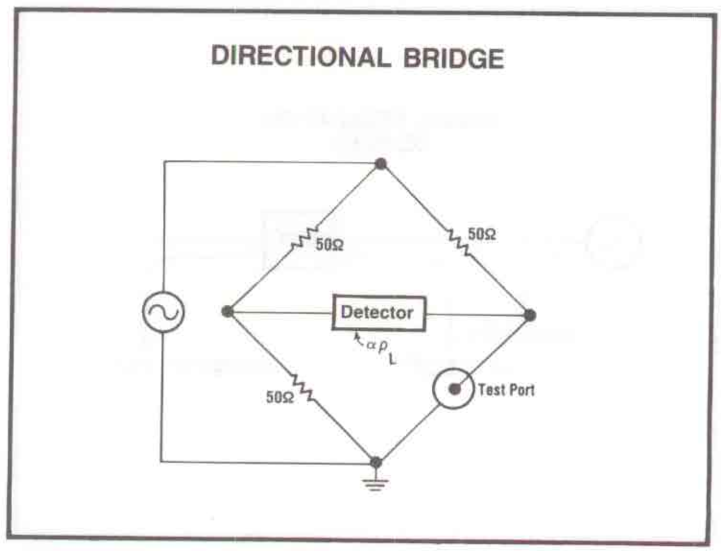
The coupler schematic represents the direction that signals will be coupled, depending on which way the arrows are pointing.

The next signal separation device used in measuring reflected signals is the directional bridge. Its operation is similar to the simple Wheatstone bridge. If all four arms are equal in resistance (i.e., test port = 50 ohms) a voltage null is measured. If the test port load is not 50 ohms, then the voltage across the bridge is proportional to the mismatch (deviation from 50 ohms) of the DUT.



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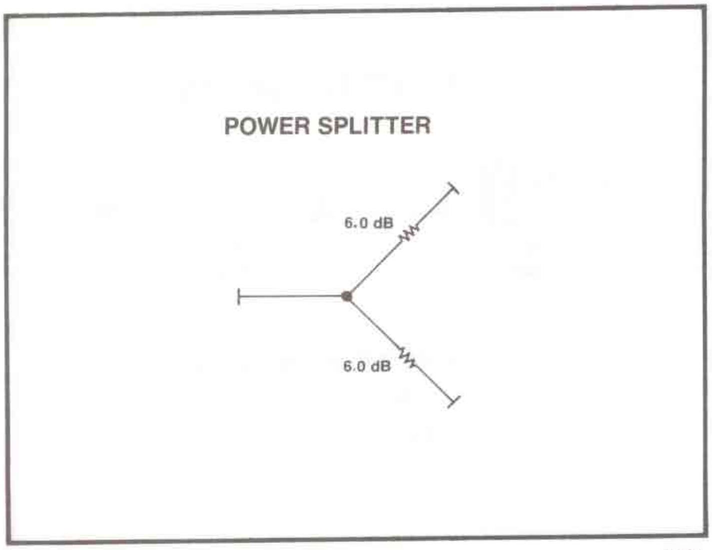

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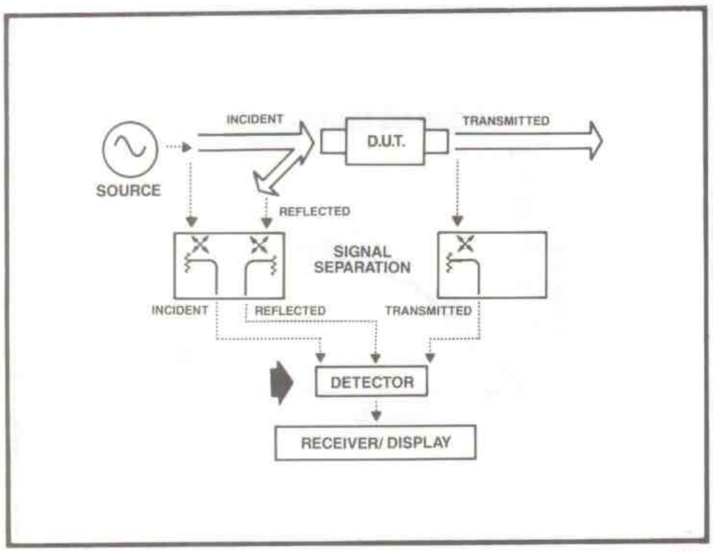
The two resistor power splitter is used to sample either the incident signal or the transmitted signal. The input signal is split equally between the two arms with the output signal (power) from each arm being 6 dB below the input. The typical microwave power splitter is broadband, operating over a frequency range from DC to 26.5 GHz.



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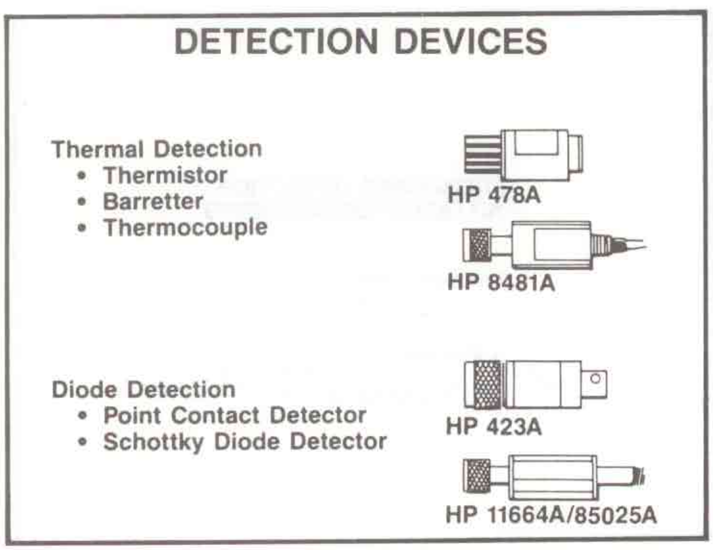
The next component in our scalar measurement system is the detector.



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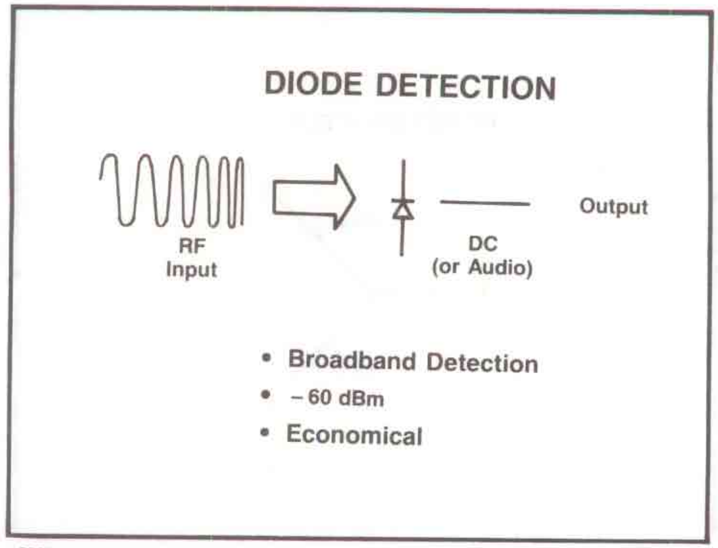
It is difficult to measure and display voltage and current at microwave frequencies with any degree of accuracy. A means for converting to DC or a lower frequency is necessary. There are several ways of accomplishing this conversion.

Thermal detectors are normally only used with power meters since they are very accurate. They are, however, slow responding devices. Diode detectors are used normally with scalar analyzers because they are fast and less expensive than other devices.

Diode detectors convert the RF signal to a proportional DC voltage. If the signal is amplitude modulated, the diode strips the modulation. Diode detectors can be very broadband (10 MHz to 26.5 GHz), have fast response times, and have a dynamic measurement range of up to 76 dB.



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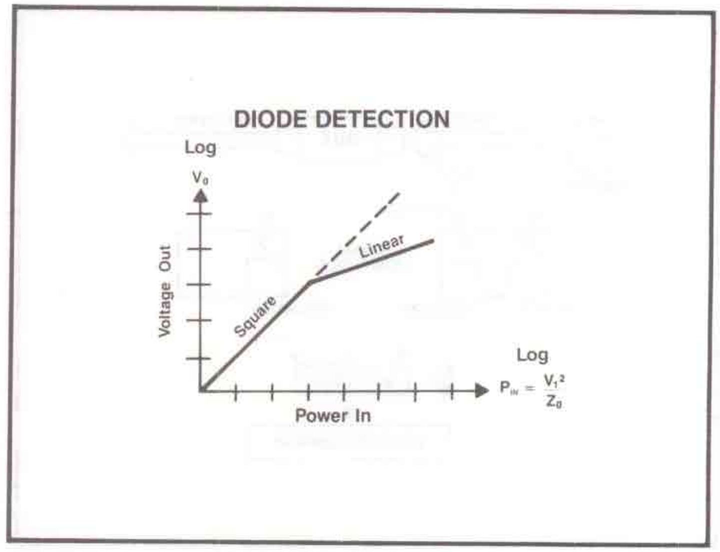
Diode detectors have a square law region over which the voltage out is proportional to the power in. This region is called the square law region since voltage out is proportional to the square of voltage in. Above a certain power level the response becomes linear. When a diode detector is used with an oscilloscope to display some detected response, its measurement dynamic range is limited to the square law range of the diode. Since the "knee" is predictable and repeatable with certain diodes (the type of diode used with scalar analyzers being one), scalar analyzers can compensate for this characteristic and hence have the ability to measure responses over a larger dynamic range.



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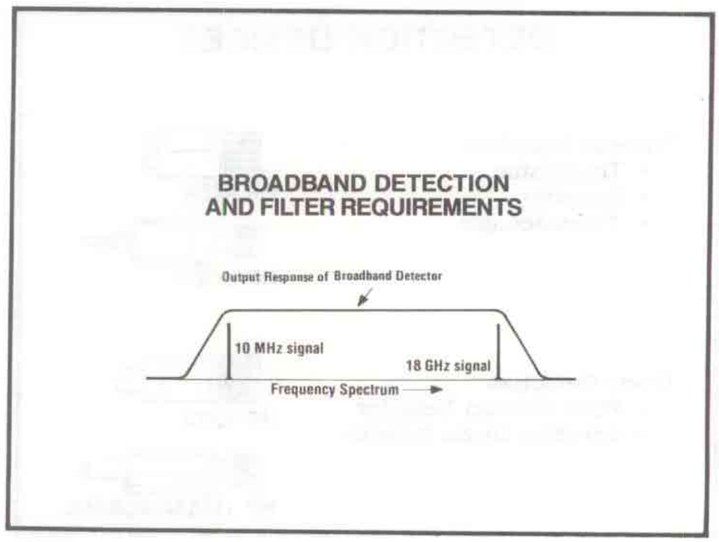
Broadband detectors will respond to any signal or signals present at the input port in the frequency range of the detector. For example, if we are interested in a network's response at 18 GHz, and in addition to 18 GHz there is also a 10 MHz signal present, the system will respond to the composite response. Therefore, in order to observe the response of the 18 GHz signal only, the unwanted signal must be removed in some way.



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DETECTORS

Spec.	Thermal	Diode
Bandwidth	10 MHz-26.5 GHz	10 MHz-40 GHz
Match	20 dB	16 dB
Response Time	Slow	Fast
Cost	Medium	Low
Dynamic Range	50 dB	76 dB

3470

This table summarizes and compares the important specs for thermal and diode detection schemes. The best reasons for using diode detection with scalar network analyzers are its wide bandwidth, its low cost, and its fast response time.

AC DETECTION
DC DETECTION

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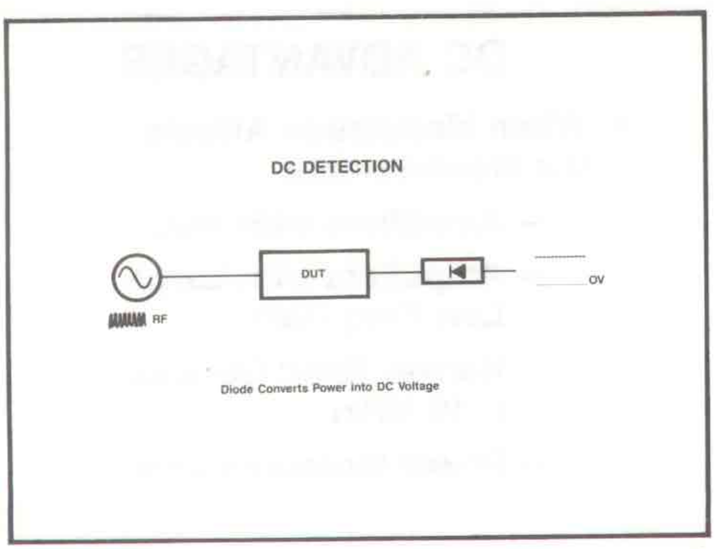
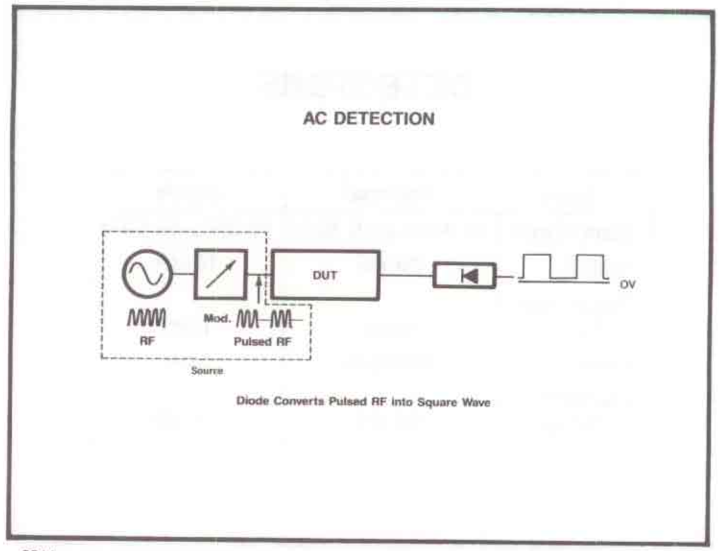
Diode detection schemes use either "DC detection" or "AC detection".



2910

DC detection produces a DC signal that is proportional to the power incident upon the diode. The diode's output is read directly by the analyzer making the analyzer a fancy voltmeter with a logarithmic response.

AC detection also produces a signal proportional to the power incident upon the diode. However, the RF power is modulated with a square wave signal. The pulsed RF travels through the DUT and stimulates the diode detector. The pulsed RF signal is turned into a square wave by the detector... the pulse being high when the RF is on and being low when the RF is off.



2911

AC detection can provide many benefits over DC detection because the detector is not affected by signals at the input that are not modulated.

AC ADVANTAGES

- No DC Drift
- Noise Immunity
- Reject Unwanted Signals
- Fast Response

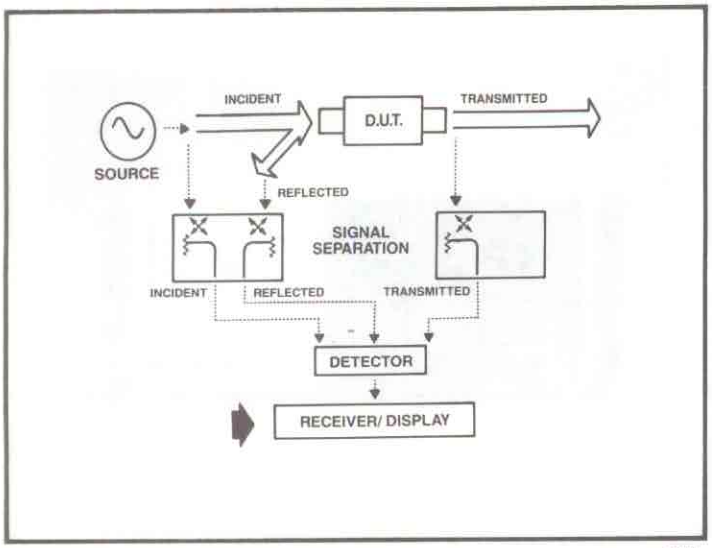
2912

Although AC detection is often preferred over DC detection, DC detection does provide some benefits. The major benefit is that there is no modulation of the RF signal to affect the DUT or the measurement results. Modulation can have adverse affects on the measurement of some devices.

DC ADVANTAGES

- When Modulation Affects the Measurement
  - — Amplifiers with AGC
  - — Amplifiers with Large Low Freq Gain
  - — Narrow Band Devices (<10 MHz)
  - — Power Measurements

3471



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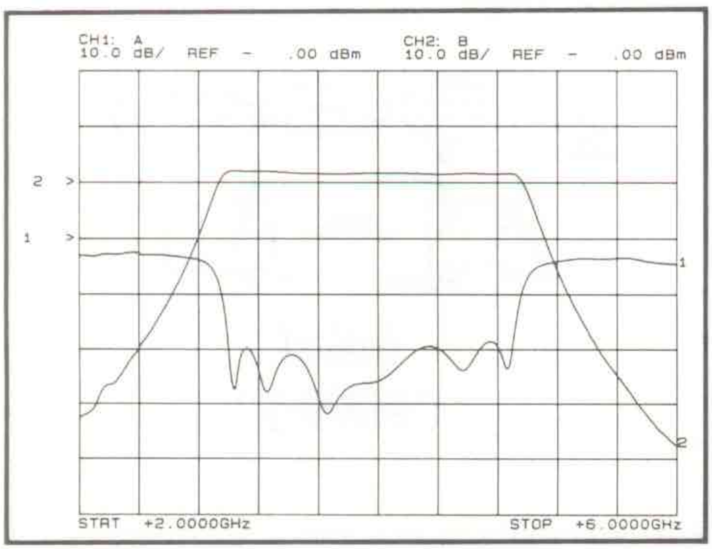
The last component of the scalar network analyzer system is the receiver/display. The main purpose of the receiver is to convert the voltage signal from the diode detector to a logarithmic or dB value for display.



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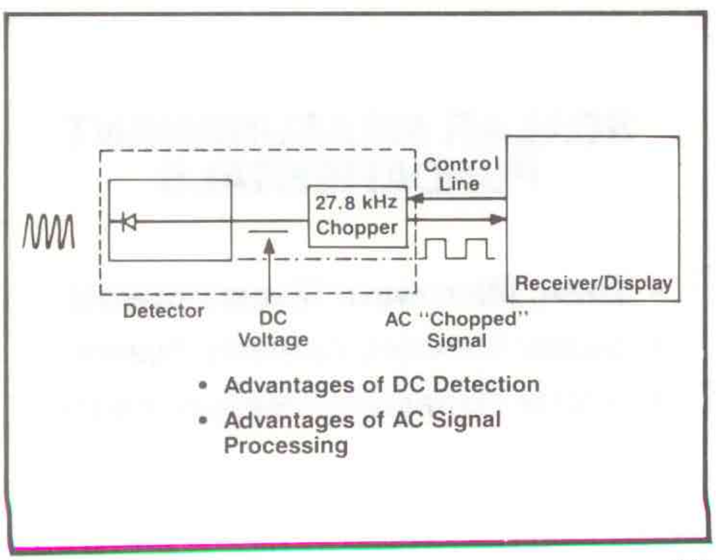


3515

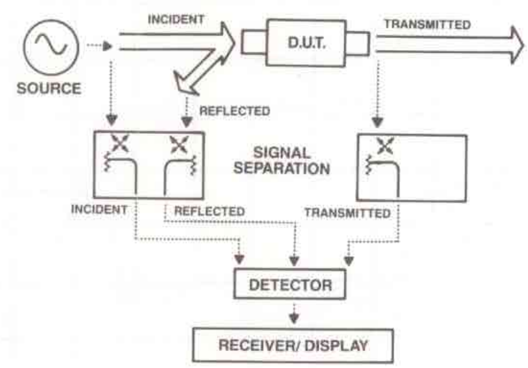
The time required to convert a DC voltage to a log value is largely dependent upon the power level incident on the detector - the lower the power level, the longer the processing time (thus the slower the sweep speed from the source). An AC voltage on the other hand is converted to a log value much faster and is not dependent upon the power level incident on the detector. HP scalar analyzers process an AC signal (27.8 kHz) to make processing time independent of incident power level.

With HP's DC detectors, the DC voltage is "chopped" to create the AC signal which HP's scalar analyzers then process. Thus, with the use of HP's DC detectors, the advantages of DC detection are combined with the advantages of AC signal processing.

So the "receiver/display" is nothing more than an AC voltmeter with a logarithmic response. With a built-in microprocessor, the CRT can also display measurement annotation, soft key labels, data traces and other information. Hard copies of the displayed information can be obtained by transferring the CRT information to a graphics plotter or printer directly.

3426

We have just described the four parts of a scalar network analyzer. Recall that scalar analyzers use broadband diode detection to measure the magnitude of the signal reflected from and transmitted through the device under test.



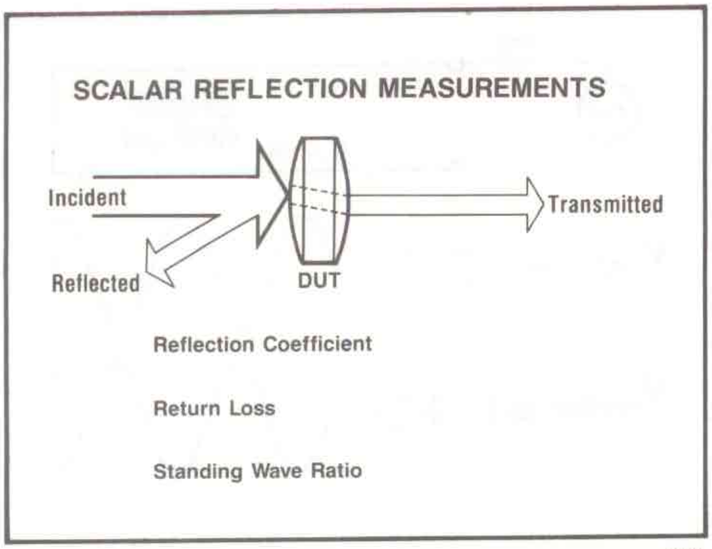
3461

Let's take a look at making some reflection measurements with our scalar analyzer system.

SCALAR MEASUREMENT FUNDAMENTALS

- Basic Microwave Measurements
- Scalar Network Analysis System
- Scalar Reflection Measurements

3457



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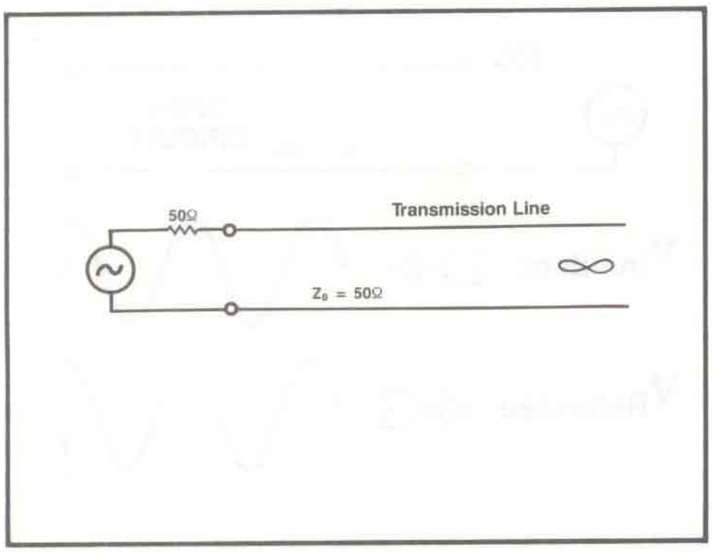
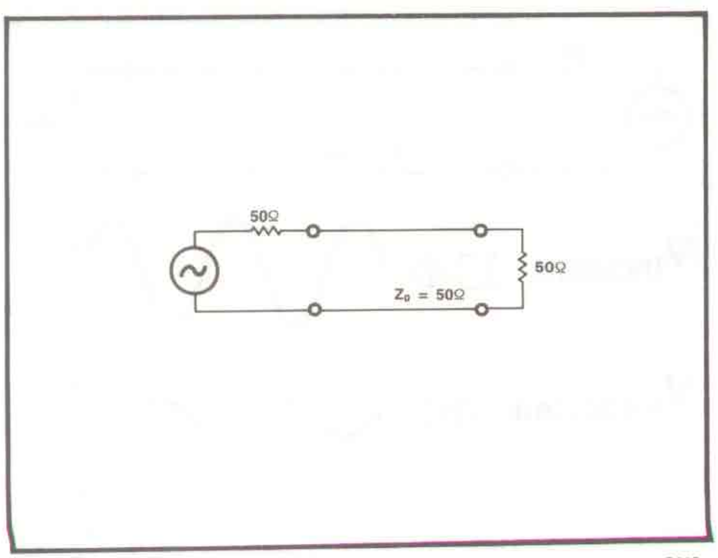
In reflection measurements the wave of interest is the reflected wave. By measuring the reflected wave we can determine the reflection coefficient (or Return Loss) of a DUT.



3415

Before we discuss measuring reflected waves, let's take a look at what causes them. If we have a source of microwave energy with a source impedance of 50 ohms then we can deliver maximum power to the load if the load impedance is equal to the source impedance.

In this case, we have an infinitely long transmission line of 50 ohms (characteristic impedance).



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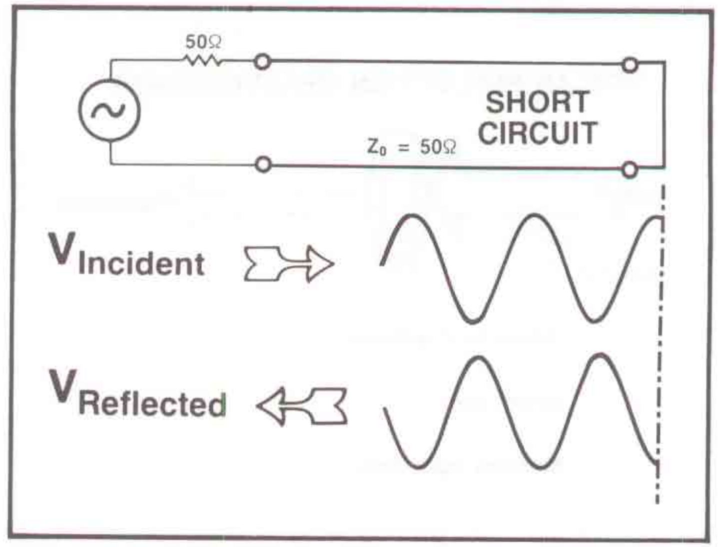
If we terminate the transmission line in 50 ohms, then the termination should absorb all of the power delivered from the source (i.e., the signal cannot tell the difference between a Zo load and a Zo transmission line of infinite length).

Let's terminate our line with a short circuit. Since a short circuit can dissipate no power, and since there is nowhere else for the energy to go, a "reflected" wave is launched back down the transmission line. Since the short can support no voltage, the reflected wave must be of equal magnitude to the incident wave and be 180 degrees out of phase with it (the sum of the incident voltage wave and the reflected voltage wave must equal zero at the short).



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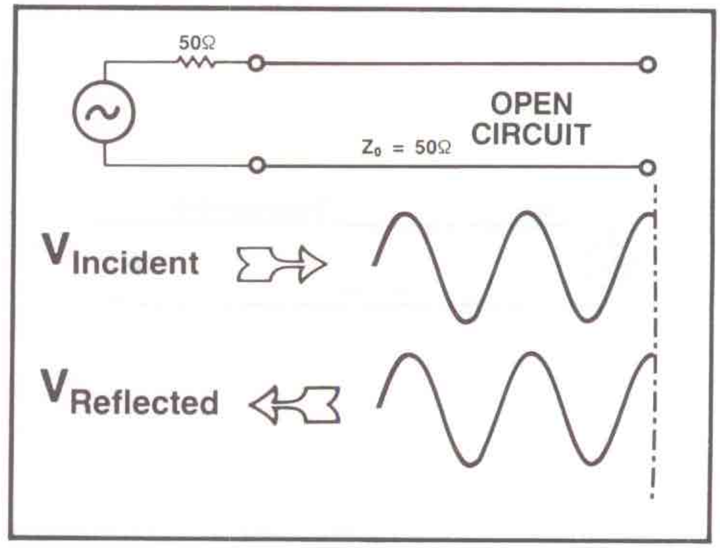
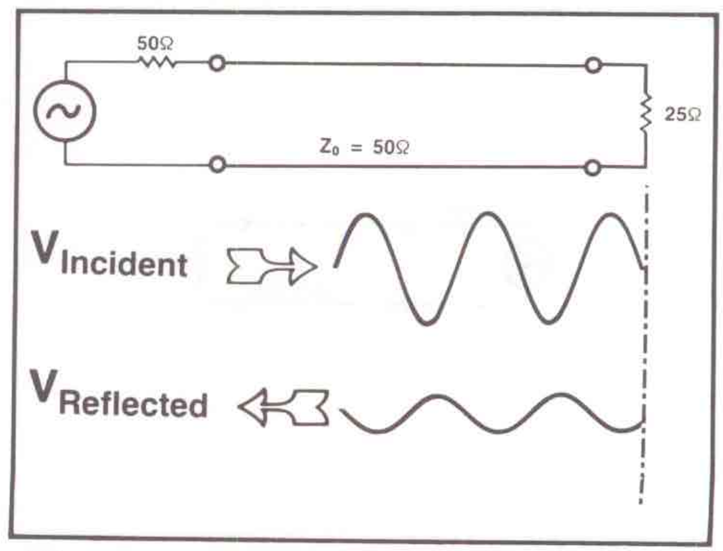
Similarly, when we terminate the transmission line with an open, there is nowhere for the energy to go (the load is an infinite impedance). A "reflected" wave is again launched back down the transmission line. Since an open can support voltage, the reflected voltage wave must be of equal magnitude and be in phase with the incident signal.



3518

If we terminate our transmission line with a 25 ohm resistor (an impedance somewhere between an open and a short), we will find that our reflected voltage wave will have an amplitude of 1/3 of that of the incident wave and that the two waves will be 180 degrees out of phase with each other.



3519

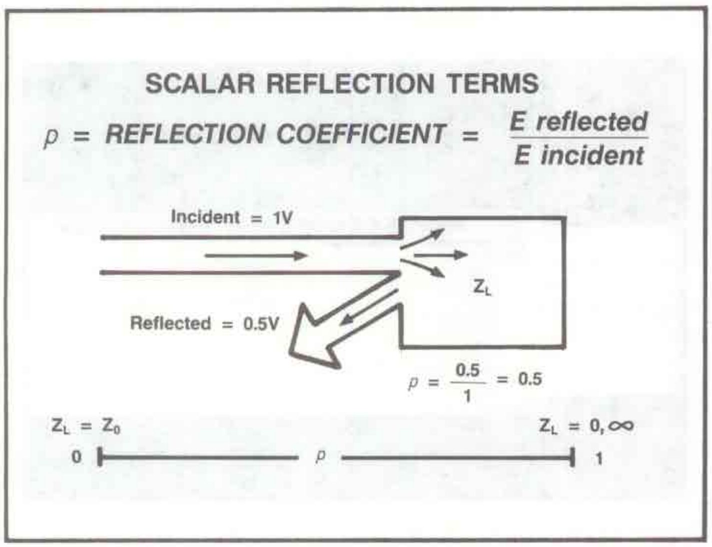
$$\Gamma = \frac{V_{REFL}}{V_{INC}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

$$\rho = |\Gamma|$$

3773

We can conclude from all of this that the reflected wave tells us something about the impedance of whatever we use to terminate the transmission line.

The exact mathematical relationship between the impedance of the termination and the reflected wave is shown on the slide. It's important because it shows clearly that since Zo is known, we can determine the load impedance by measuring Vi and Vr (the incident and reflected voltage waves).



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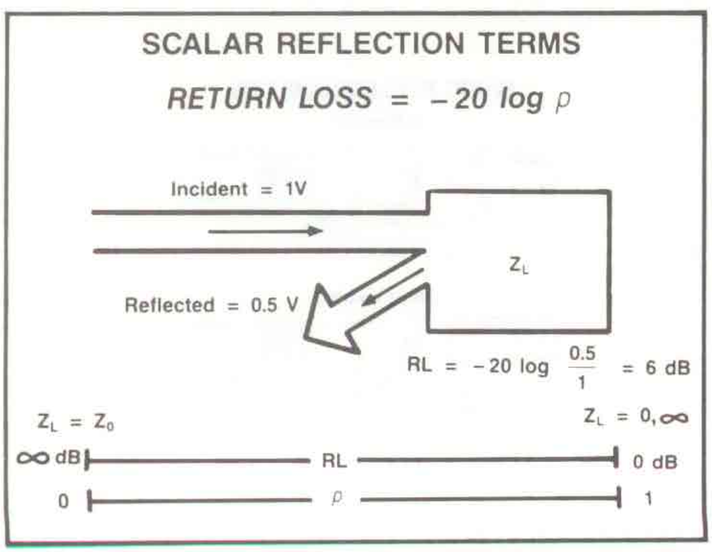
Reflection coefficient is equal to the ratio of the reflected voltage wave to the incident voltage wave. For a transmission line of characteristic impedance Zo terminated with a Zo load, all energy is transferred to the load and none is reflected: Er = 0 and p = 0. When the line is terminated with an open or short circuit, all of the energy is reflected and Er = Ei and p = 1. The range of possible values for p then is 0 to 1.

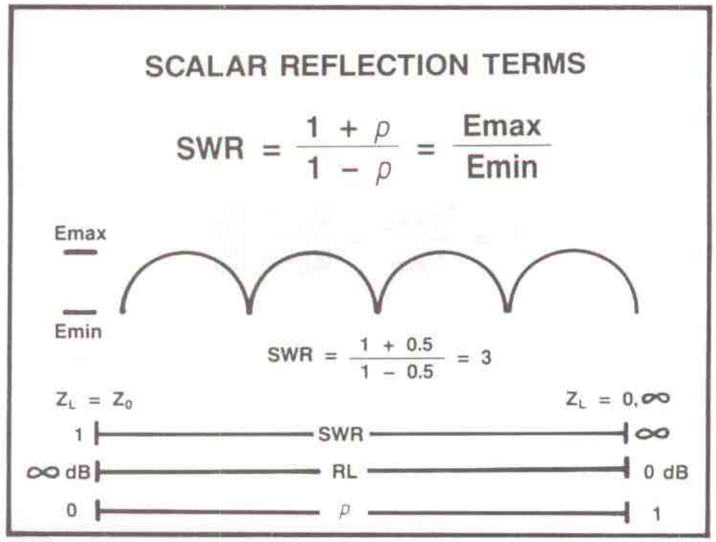


3520

Since many displays are logarithmic, we need a term to express reflection coefficient in dB. Return loss can be thought of as the number of dB that the reflected signal is below the incident signal. The range of values for return loss are infinity for a Zo impedance to 0 for an open or short circuit.

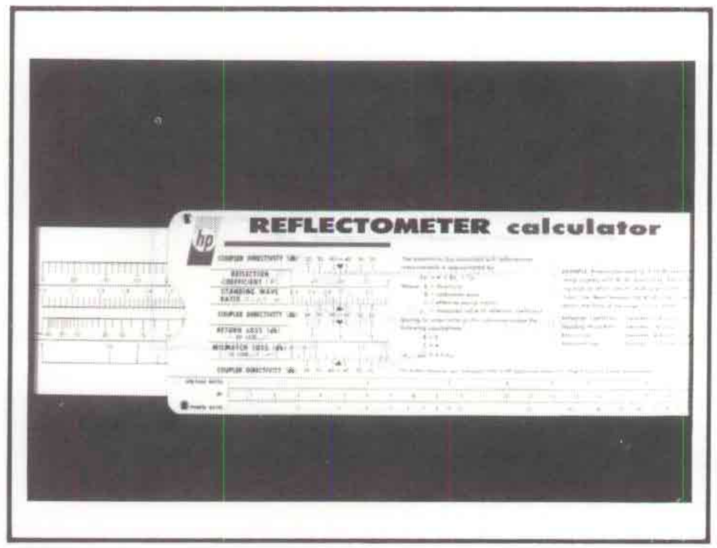
For an explanation of dB's, refer to Appendix A.

Any two waves traveling in opposite directions cause a "standing wave" to be formed on the transmission line. Standing wave ratio (SWR) is defined as the maximum voltage over the minimum voltage of the standing wave on our line. It can also be defined as (1 + p)/(1 - p). The values of SWR are 1 to infinity.



3062

We can use a reflectometer calculator to convert between reflection coefficient, return loss, and SWR. For example: let p = 0.5 and use the calculator to determine the equivalent return loss and SWR. Move the slide portion of the calculator until 0.5 on the reflection coefficient scale (the upper scale on the slide) is directly below the blue arrow. Read the return loss value on the return loss scale directly below the blue arrow and read the SWR value on the SWR scale directly above the blue arrow.

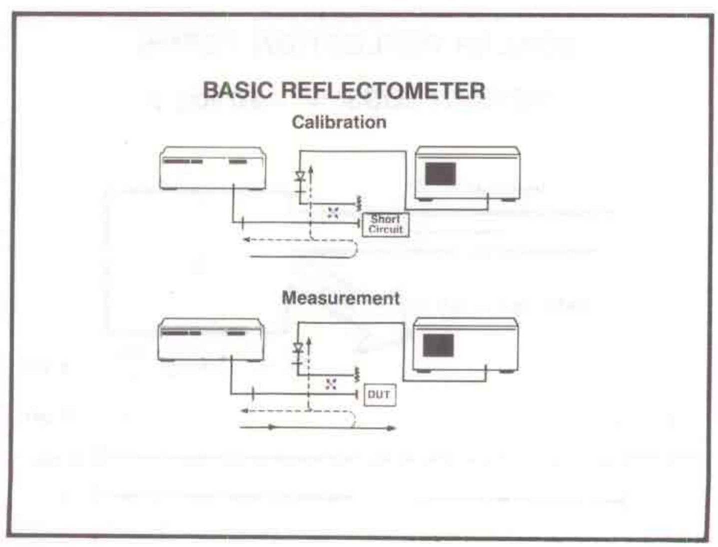


3473

There are two parts to a reflection measurement. First, a reference line is established on the CRT with a known standard (in this case a short circuit). This trace is stored for future subtraction (normalization). Measuring the short establishes a zero dB return loss reference line.

The dB change when the DUT is inserted is the return loss of the DUT.

We assume that the source has a perfect Zo output impedance and that the signal separation device can separate the reflected signal without any leakage of the incident signal.



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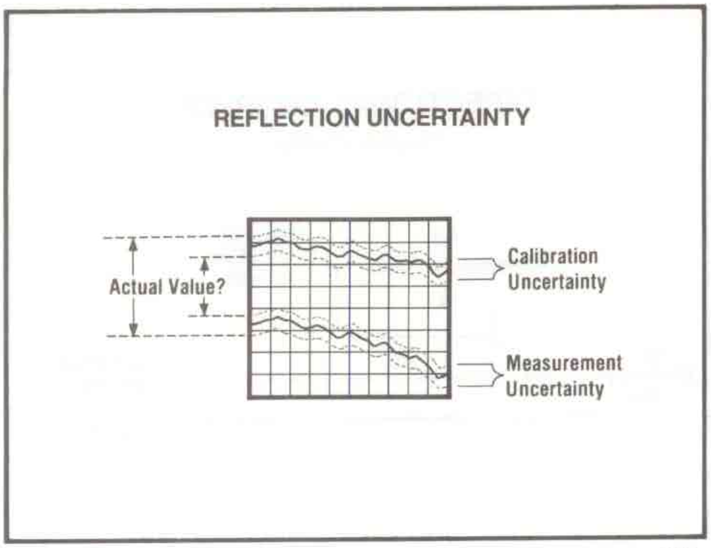

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The actual value of our DUT is the difference between the measured RL value and the calibration (Meas - Cal). But since we do not have "perfect" measurement system components, we have some uncertainty associated with our two measurements (Meas and Cal). This uncertainty will make it difficult for us to determine what the actual RL value of our DUT us. We need to qualify our system to determine if it is accurate enough for our requirements.

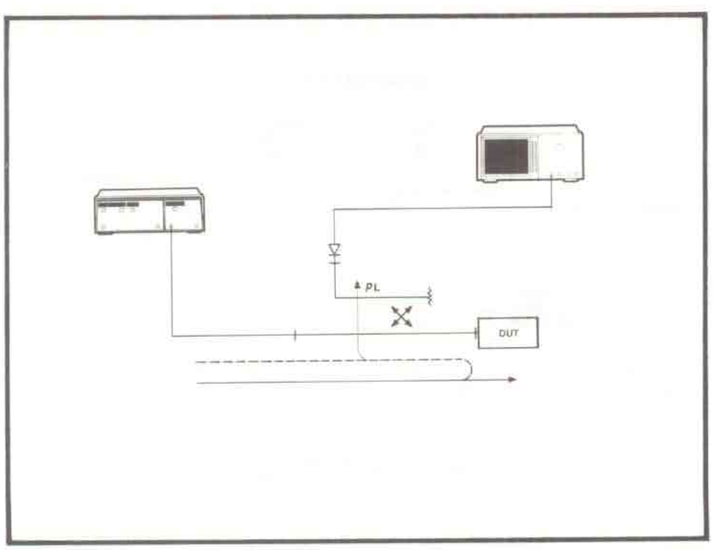
REFLECTION UNCERTAINTY EQUATION

$$\Delta\rho = A + B\rho_L + C\rho_L^2$$

- A = Directivity
- B = Calibration Error, Frequency Response, Display and Instrument Errors
- C = Effective Source Match
- ρ_L = Reflection Coefficient of DUT

3521

This equation is a simplification of a complex flowgraph analysis of reflectometer uncertainties. (Delta p) is the worst case uncertainty in the measurement where p_L is the measured reflection coefficient of the DUT. A, B, and C are all in linear terms. Each term in this equation will be analyzed separately.



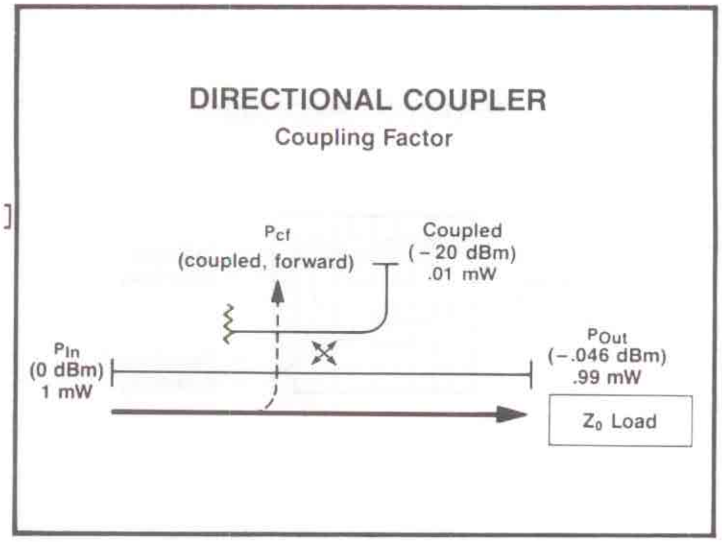
3522

Let's take a closer look at our basic measurement system to see what causes error signals to exist and how those signals add to the uncertainty of our measurement. The component we will start with is our signal seperation device - the directional coupler.

Recall that a directional coupler couples a portion of the signal flowing through the main arm to the auxiliary arm. We've defined the coupling factor (dB) to be:

Coup Fact (dB) = -10 log [P(cf)/P(in)]

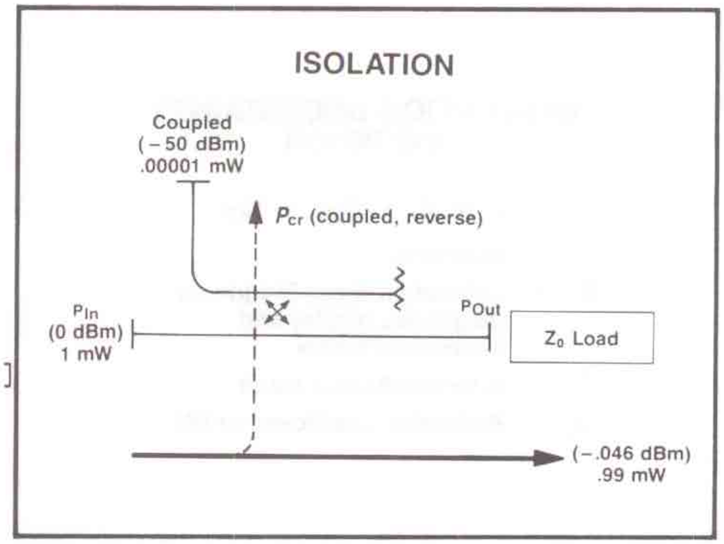
In defining coupling factor, we have assumed the coupler is terminated with a perfect load and thus no other signal is present in the auxiliary arm.



3476

If we turn the coupler around and flow power in the reverse direction through the coupler, we ideally would measure no power in the auxiliary arm. However, some energy does leak across the coupler (sneaks in the back door). A measure of this leakage signal is defined as the isolation of the coupler:

Isolation (dB) = -10 log [P(cr)/P(in)]



3477

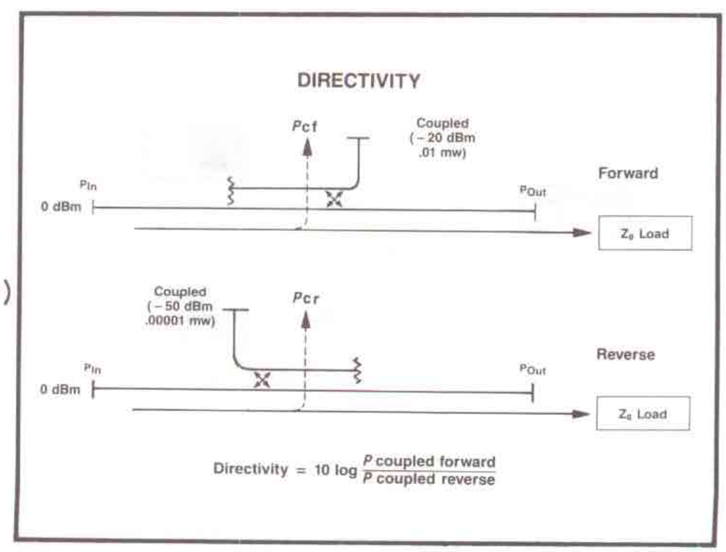
The ability to separate signals flowing in opposite directions within the coupler is directivity. We measure that ability by relating the power measured in the auxiliary arm from the coupler in the forward direction P(cf) to the power measured in the auxiliary arm with the coupler in the reverse direction P(cr). When measuring P(cf) and P(cr), notice that we have the coupler terminated in a Zo load and that we have the same input power level.

Directivity (dB) = 10 log [P(cf)/P(cr)]

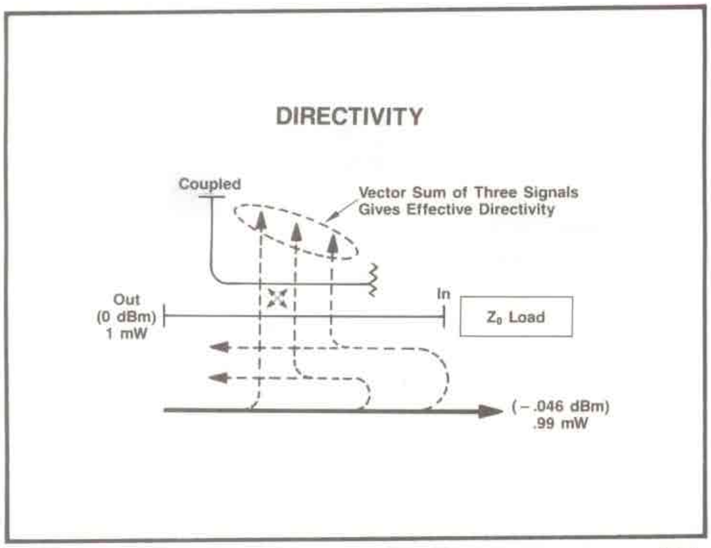
Equivalent expressions for directivity are in linear terms,

Dir = [Coup Fact/Iso]
and in dB,

Dir (dB)= Iso (dB)-Coup Fact (dB)

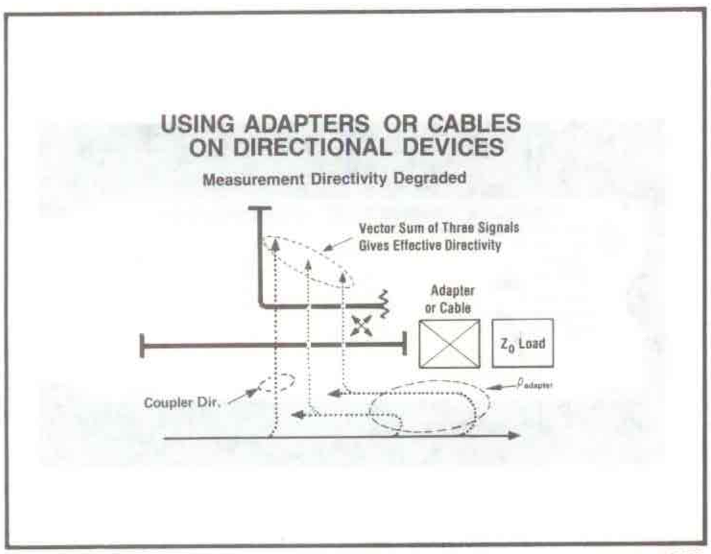


3523



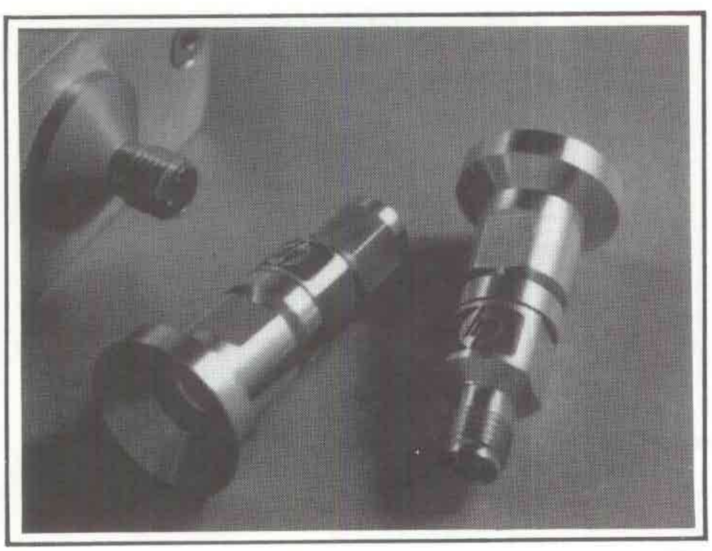
3524

The sources of imperfect directivity are 1) leakage, 2) internal coupler load reflections, and 3) connector reflections. Coupler directivity is the sum of all three signals.



2876

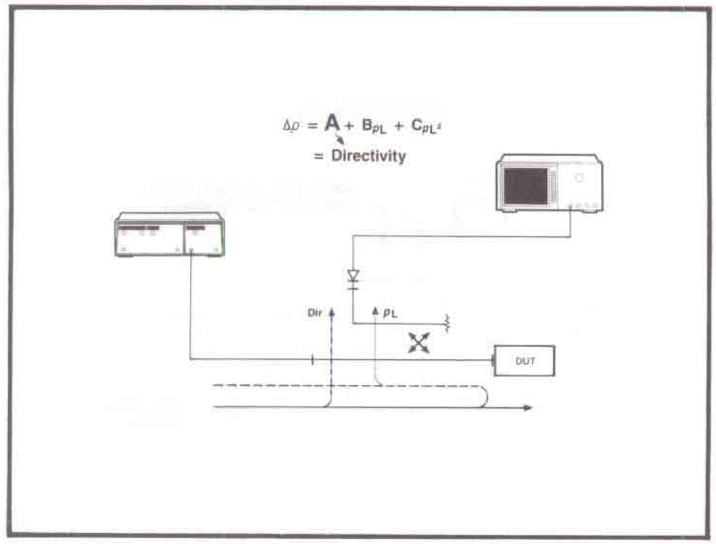
The effects of adapters on effective directivity are often misunderstood. As the flow-graph shows, the adapter has the same relationship to directivity as the output connector on the coupler. If the adapter has a poor SWR of say 1.5:1, the effective directivity of the coupler drops to no better than 14 dB, even if the coupler has infinite directivity. In other words, with a perfect Zo load on the output of the adapter, the reflected signal appearing at the coupled arm would be 14 dB less than the reflection from a short circuit.



3947

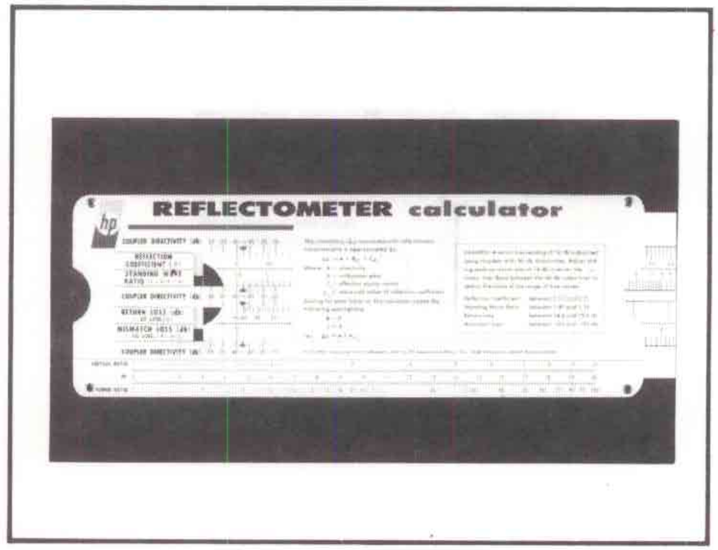
Using good low reflection adapters is very important to minimize the degradation in directivity. However, using adapters is often necessary, particularly when measuring devices with SMA connectors. Many SMA connections can go bad, and can damage a precision directional bridge or coupler. The adapter then becomes a "connector saver," saving the connector from costly repair.

The effect of directivity on our measurement is shown here. The **A** term in our uncertainty equation is directivity. It is independent of the reflection coefficient of the DUT and adds (worst case) directly to the total uncertainty. If the signal reflected from the DUT is large, for example for a short circuit, then the directivity will be small compared to the reflected signal and the effect of directivity will be insignificant. If the signal reflected from the DUT is small (high return loss), then the directivity signal will be significant compared to the reflected signal and the uncertainty due to directivity is significant.



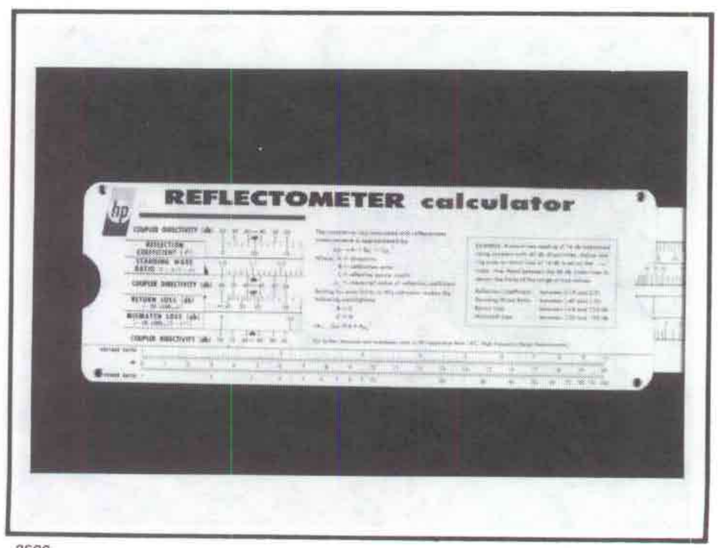
3525

We can use the reflectometer calculator to convert directivity in dB to a linear term for our uncertainty equation. For example, 40 dB directivity converts to A = 0.01.
On the reflectometer calculator, place the dB value for directivity under the blue arrow on the RL scale. Read the linear value below the blue arrow on the reflection coefficient scale.

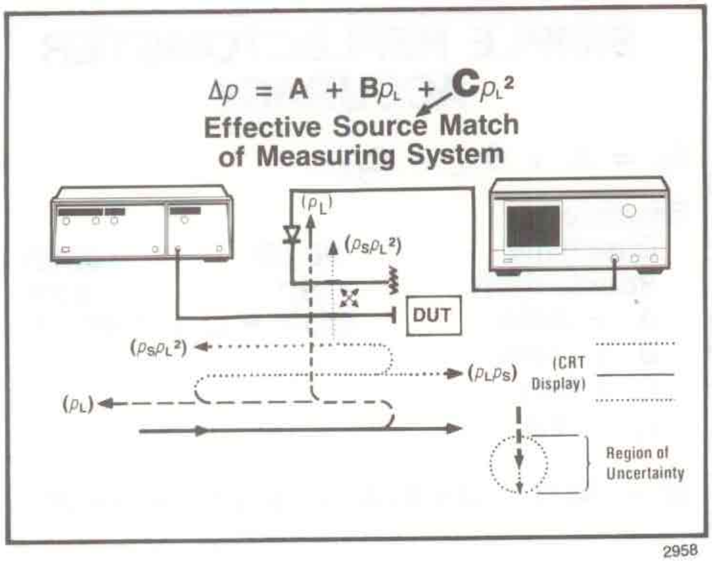


3553

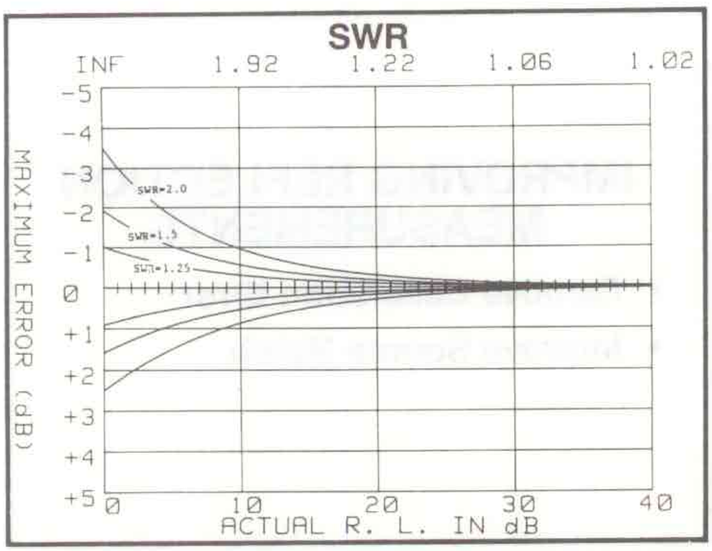
We can use the reflectometer calculator to see the effect of directivity on the uncertainty of a measurement. For example, set p to 0.05. Now read the error limits using the coupler directivity scale and the directivity of the coupler used in the measurement. A coupler with 40 dB directivity causes a ±0.01 error in the measurement of p = +0.05. On the return loss scale, this error is ±2.5 dB. This is significant measurement error. The coupler directivity error window in the reflectometer calculator uses the sum of two error terms, A & C (directivity and source match terms) and assumes that A = C. A discussion of the C term will follow directly. When p_L is small, p_L^2 is even smaller, and therefore, the effect of the C term is negligible, and directivity is the dominant error. If p_L^2 is large, i.e., near 1.0, then the C term has the significant error contribution.



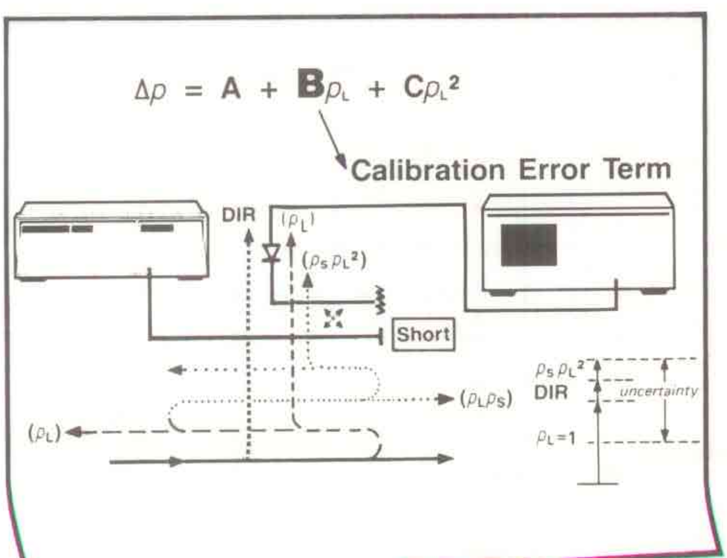
3526



2958



2959



3479

What happens to our measurement uncertainty when our source is not perfect (i.e., do not have perfect source impedance)?

From following the flowgraph, we can see that effective source match belongs in the **C** term. The first reflection from the DUT is p_L; this is what we want to measure. This signal continues back toward the source where it is re-reflected if the reflection coefficient of the source is not perfect, resulting in a signal normalized to $p_L * p_S$ flowing back toward the DUT where it is again reflected and sampled as $p_S * p_L^2$.

When the reflected signal is large (low return loss) source match causes a significant error. But if we measured a DUT with a low reflection (high return loss) then the effect of source match is very small. Recall that the effect of directivity is just the opposite, that is, significant for high return loss and less significant for low return loss.

The last contributor to our measurement uncertainty that we will discuss is calibration error. We calibrate with a short circuit because we know that the reflection coefficient of the short has a value of 1 (Return Loss = 0 dB).

But instead of measuring just the reflection coefficient of the short, we also measure some error terms. Directivity is always present and will be measured. Source match is also present and will be measured along with our standard. The sum of directivity and source match (A + C) will cause uncertainty in the measurement of our standard. If we assume no other errors are present then our best case calibration error (B term) is equal to the sum of directivity and source match.

$$B = A + C$$

Lets take a look at a simple example:

RL of DUT = 6 dB (.5)
Directivity = 30 dB (.0316)
Source Match = 1.9:1 (0.31)
B = A + C = (.3416)

$$\text{delta } p = A + B\,p_L + C\,p_L^2$$

$$= .0316 + .3416(.5) + .31(.5)^2$$
$$= \pm 0.28$$

SIMPLE REFLECTOMETER ACCURACY

$$\Delta\rho = A + B\rho_L + C\rho_L^2$$

Example:

Directivity	30 dB	(.0316)
Source SWR	1.9:1	(0.31)
	DUT R.L. = 6 dB (.5)	

$A = .0316$
$B = .3416$
$C = 0.31$
$\rho_L = 0.5$

$$\Delta\rho = .0316 + .3416\,(.5) + .31\,(.5)^2 = \pm 0.28$$

3480

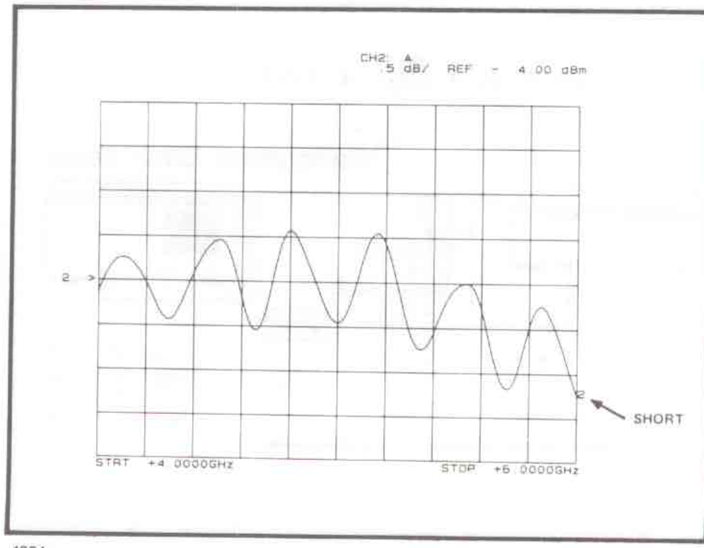
From our previous example, it should be obvious that we would want much less uncertainty in our measurement if we could get it. We can improve our reflection measurements (i.e., reduce uncertainty) by either removing our calibration error or by improving source match or both.

IMPROVING REFLECTION MEASUREMENTS

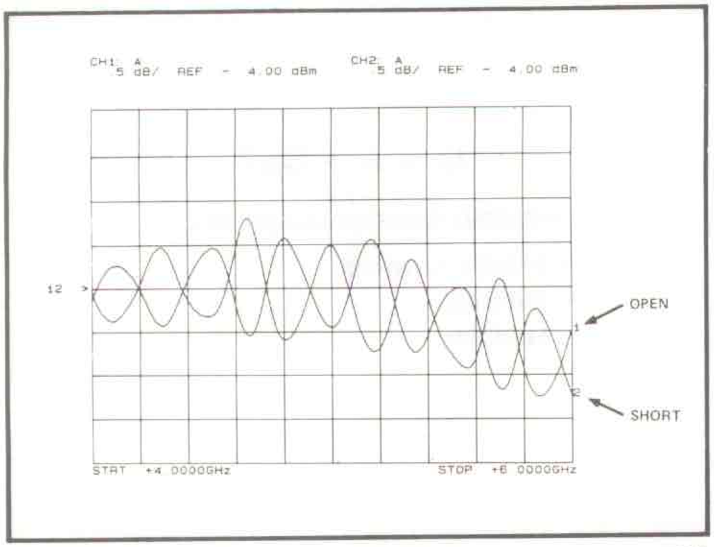
- Remove Calibration Error
- Improve Source Match

3481

For the reflection measurement, we used a short circuit as the calibration standard ($p = 1$). This plot shows the short circuit response. Notice the ripple caused by source match and directivity error vectors.

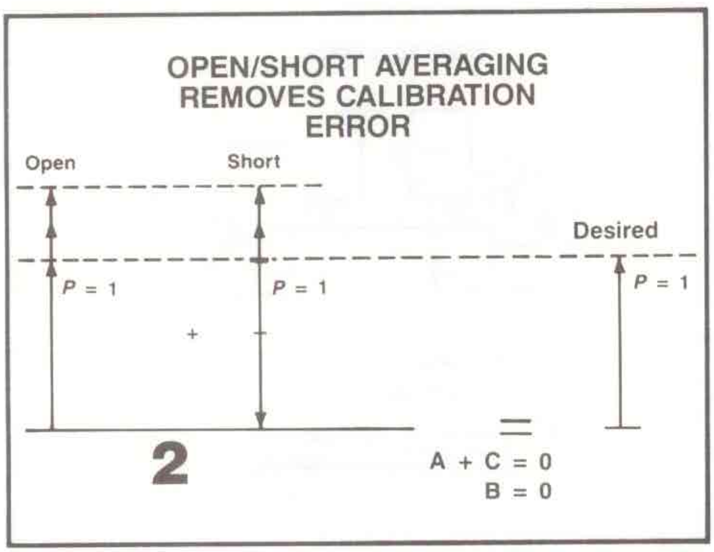


4004



4005

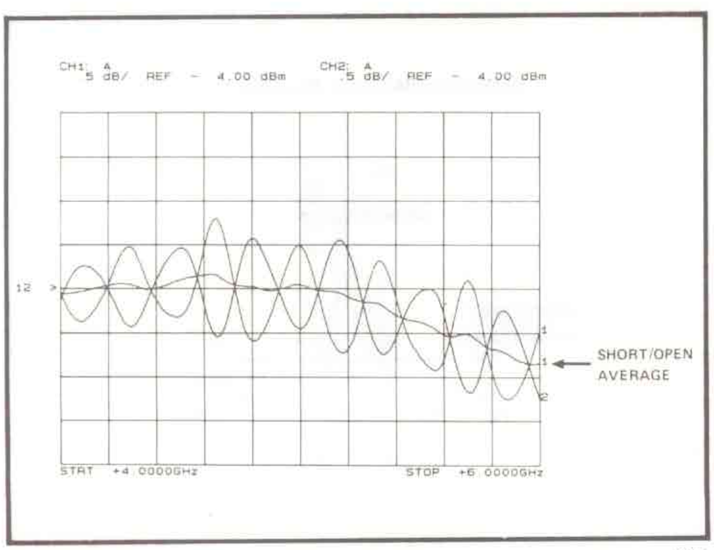
Another standard with p = 1, the open circuit, could also be used as the calibration standard. Notice that the ripple is still present, but the phasing is different. Ideally, for calibration purposes, we would like to see the p = 1 response without the error vectors.



3528

The calibration error due to the sum of the directivity and source match errors can be removed by averaging the short and open circuit responses. Though the reflection from an open circuit is 180 degrees out of phase with that from a short circuit, the errors due to the sum of directivity and source match do not change phase when the load is changed from an open to a short.

The open/short average then averages out calibration error thus making B=0.



4006

This slide shows the open/short average. Notice that the ripple is removed.

The other method of reducing uncertainty is by improving source match.

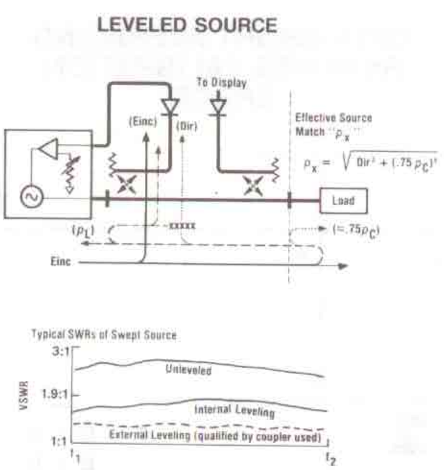
$$\Delta\rho = A + C_{\rho L}^2$$

IMPROVE SOURCE MATCH WITH:

- External Leveling
- Ratioing
- Isolation

3529

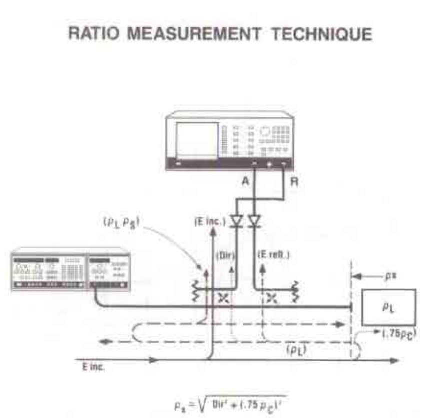
The perfect source would deliver a constant power to a load regardless of the reflections from the load. Leveling the sweeper output improves source match by varying the power out of the source to compensate for the power reflected by the source, thus the power delivered to the load is constant (it appears the source has absorbed the power flowing into it). Any signal re-reflected from the sweeper is sensed by the leveling loop which corrects the output from the sweeper accordingly.



2884

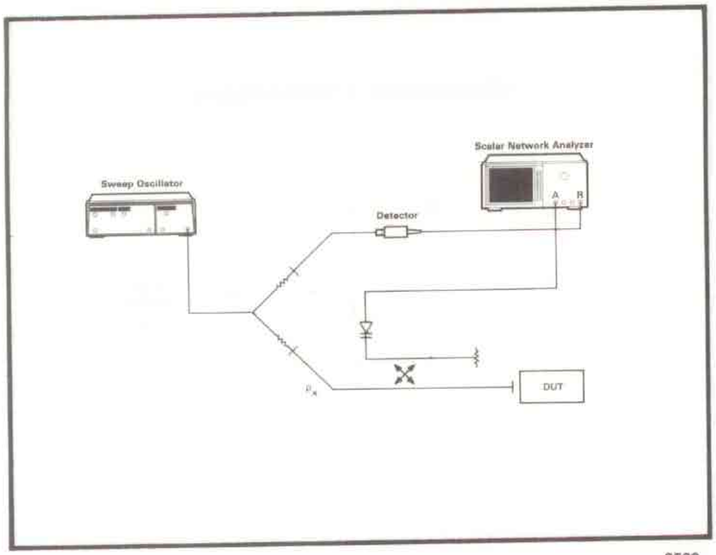
Although leveling improves source match, there are still inherent uncertainties. First, the output connector of the coupler has some reflection. In addition, directivity error also enters in. p_X is defined as effective source match. The equation for effective source match very closely approximates the flowgraph analysis of a leveled source using a directional coupler.

Effective source match can also be improved by ratioing the incident and reflected signals. With this technique, the absolute incident power is not controlled as in leveling but the variations are ratioed out. Any re-reflections are seen by both detectors and when you take the ratio A/R on the analyzer, the effect of p_S is cancelled.



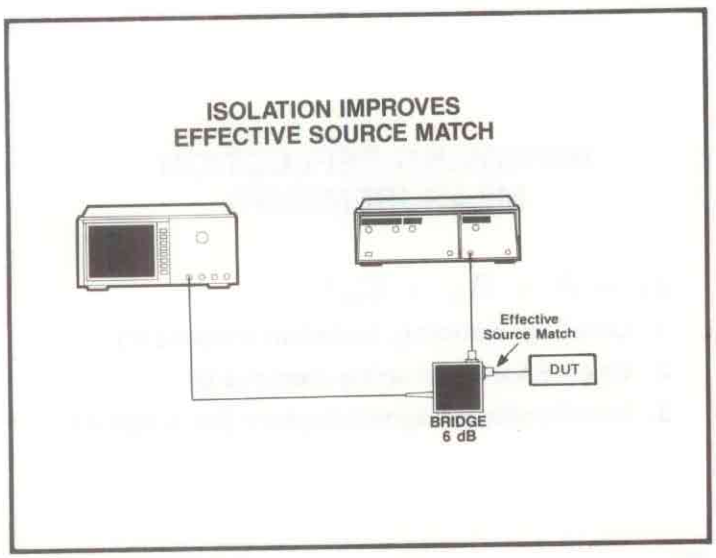
2885

Again since the coupler is not perfect, the "effective source match" must be calculated. Effective source match is determined by the same equation as for leveling.



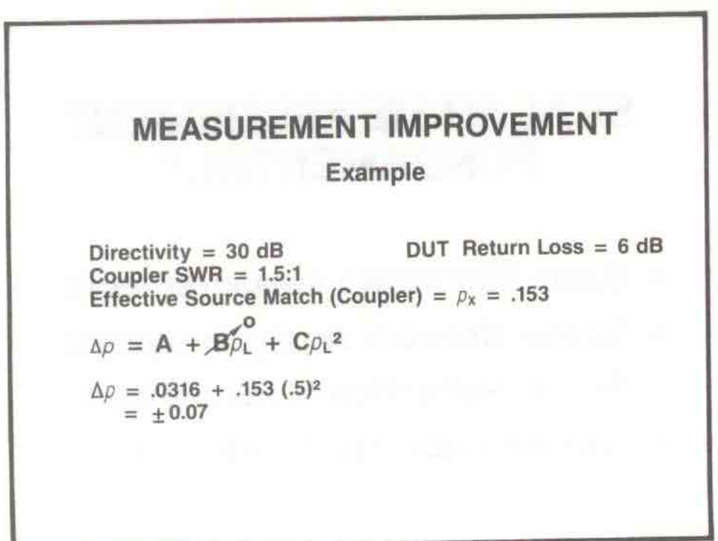
3560

Of course, a power splitter may be used for both of these examples rather than a directional coupler. A splitter may be a better choice due to its smaller size and broadband response but the equation for effective source match does not apply. Since we essentially "buy" source match, the effective source match is the specification on the data sheet of the splitter.



3531

The insertion loss of a directional bridge isolates the DUT from the source and improves the effective source match by attenuating the reflected and re-reflected signals each time they pass through the bridge. Assuming 12 dB isolation (6 dB each way) and bridge test port match of 1.25 SWR, the effective source match is improved from 1.9 to 1.46 SWR. An isolator or attenuator could also be used to achieve the same source match improvement.



3482

Let's see how much we reduce the uncertainty by removing the calibration error and improving the source match:

Effective source match = $p_X = 0.153$

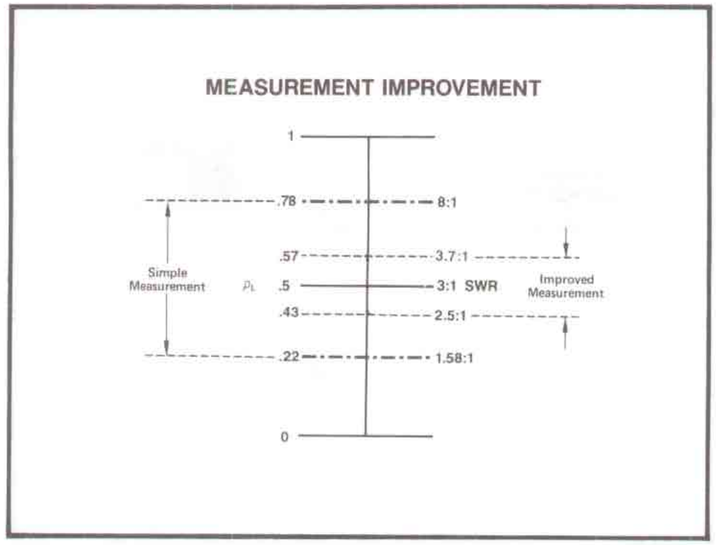
delta $p = A + B\,p_L + C\,p_L^2$

delta $p = .0316 + .153(.5)^2$ B=0

delta $p = \pm.07$

whereas before we had ± 0.28.

The improvement in reflection coefficient uncertainty translates to an improvement in SWR of between 2.5 and 3.7, much more reasonable than the 1.58 to 8.1 window with the simple reflectometer.



3483

We have discussed two ways of improving the accuracy of reflection measurements - both are simple and inexpensive. The source match improvement techniques reduce the C term of the uncertainty equation and open/short averaging (which is included in the HP 8756/8757 firmware) removes the B term from the same equation.

The high directivity (40 dB) bridges and low reflection adapters in HP's product line reduce the A term for accurate measurements of low reflection DUT's.

IMPROVING REFLECTION MEASUREMENTS

$$\Delta \rho = A + B\rho_L + C\rho_L^2$$

1. Leveling, Ratioing, Isolation (reduce C)
2. Open/Short Averaging (remove B)
3. Use Quality Bridges/Adapters (for small A)

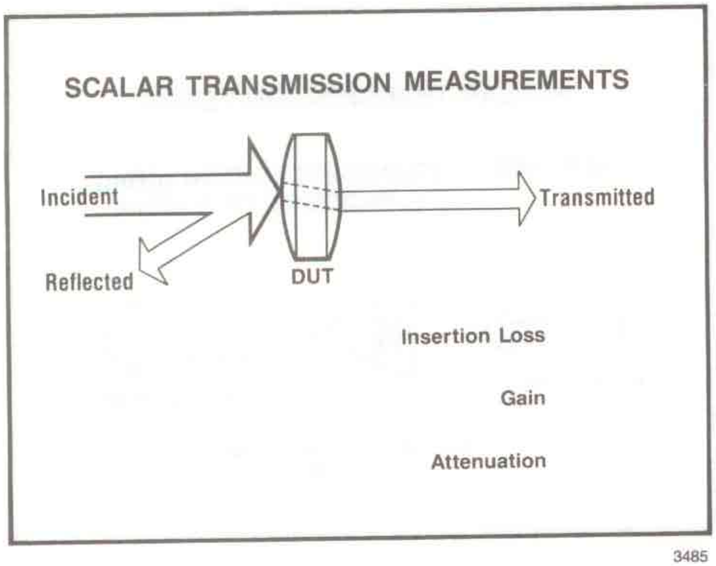
3532

The two basic measurements used to characterize linear networks are reflection and transmission. This next section will describe transmission measurements and investigate the associated errors.

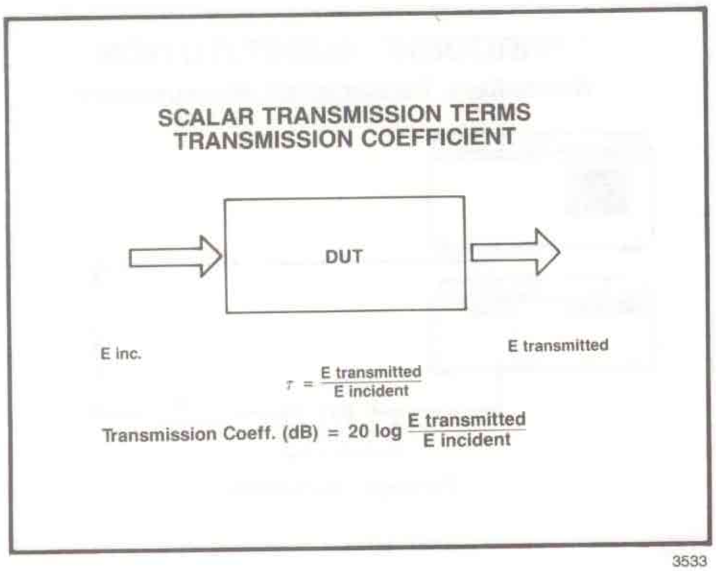
SCALAR MEASUREMENT FUNDAMENTALS

- Basic Microwave Measurements
- Scalar Network Analysis System
- Scalar Reflection Measurements
- Transmission Measurements

3457

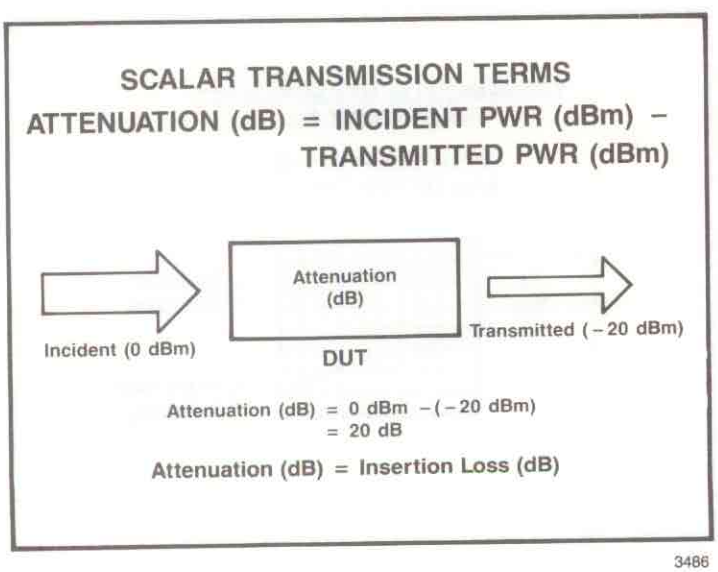


Scalar transmission is defined as the change in power (at a detector) resulting from the insertion of the device under test.



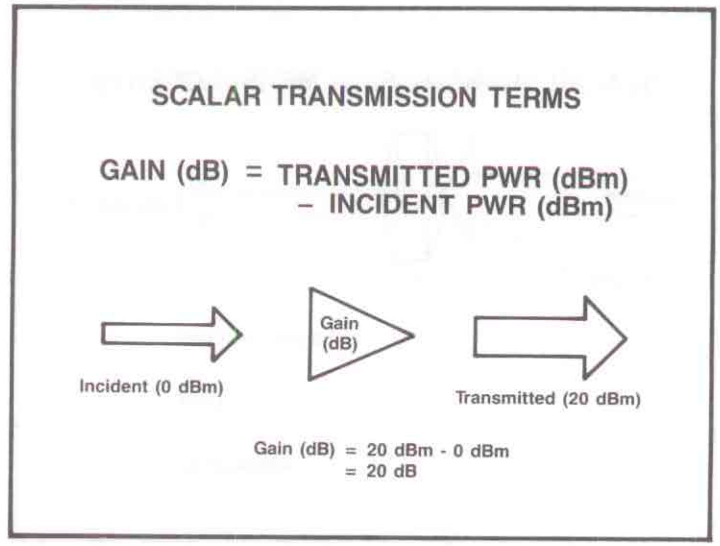
The scalar transmission coefficient is defined as the transmitted voltage divided by the incident voltage. The transmission coefficient (dB) is:

20 log [E transmitted/ E incident].



Attenuation (dB) or Insertion Loss (dB) is defined as the incident power (dBm) - transmitted power (dBm) when the transmitted power is less than the incident power.

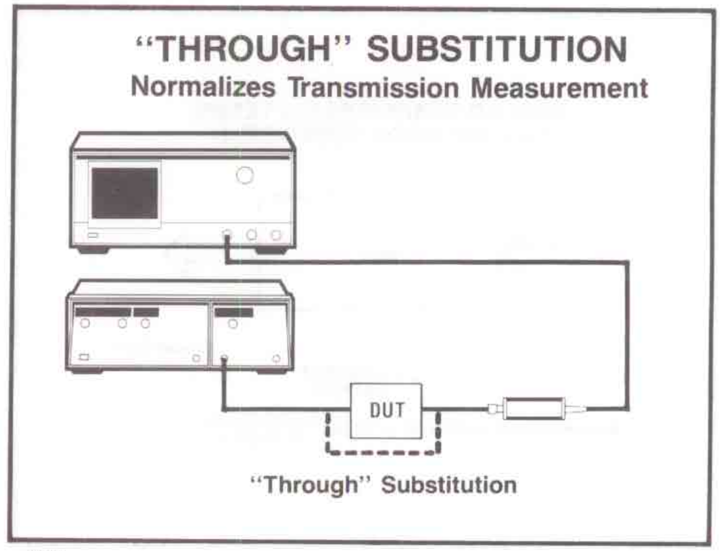
Gain (dB) is defined as the transmitted power (dBm) - incident power (dBm) when the transmitted power is greater than the incident power. In linear terms Gain = P(out)/P(in).



3064

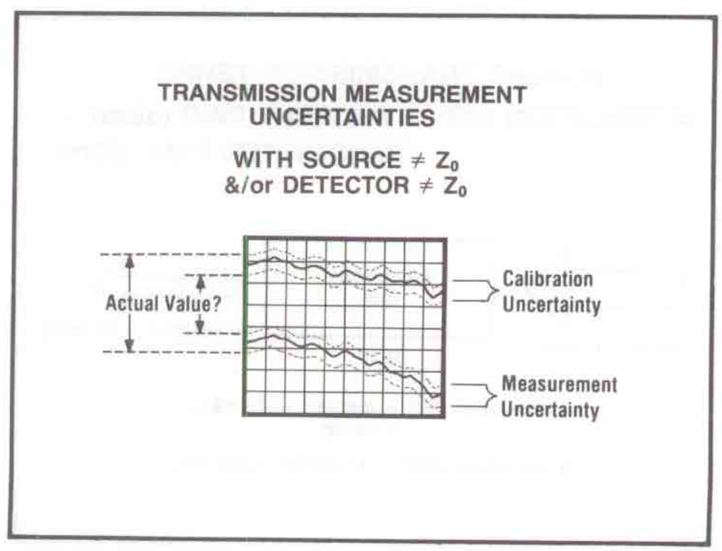
Before we can determine transmission loss or gain we must establish a reference (i.e. we need to know what the incident power is). By measuring a "through", we establish a 0 dB reference trace on the analyzer display.

By subtracting our "thru" reference from the measurement obtained with a DUT (**normalization**) we can determine what the insertion loss or gain of the DUT is. Normalization also removes the frequency response of the test setup.



2941

As with reflection measurements, uncertainties exist with transmission measurements. Total measurement uncertainty is affected by calibration uncertainty as well as the measurement uncertainty.



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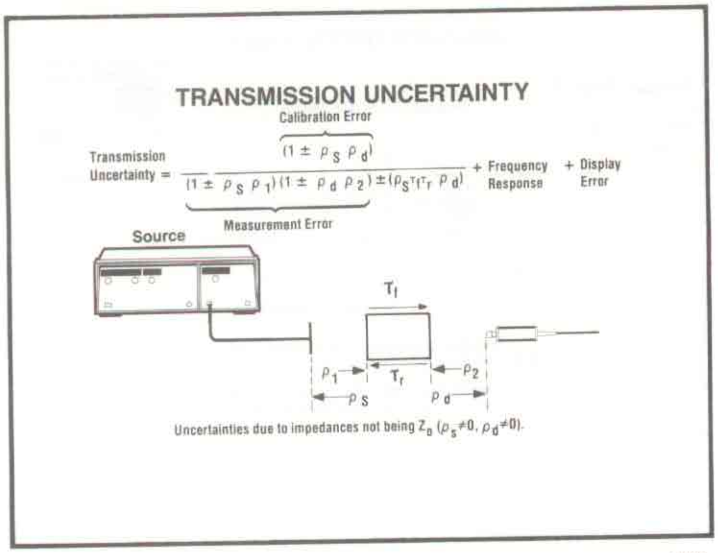
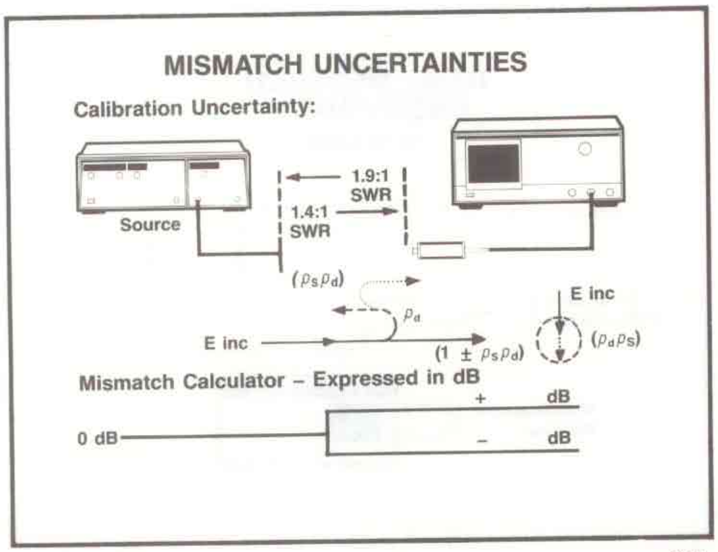


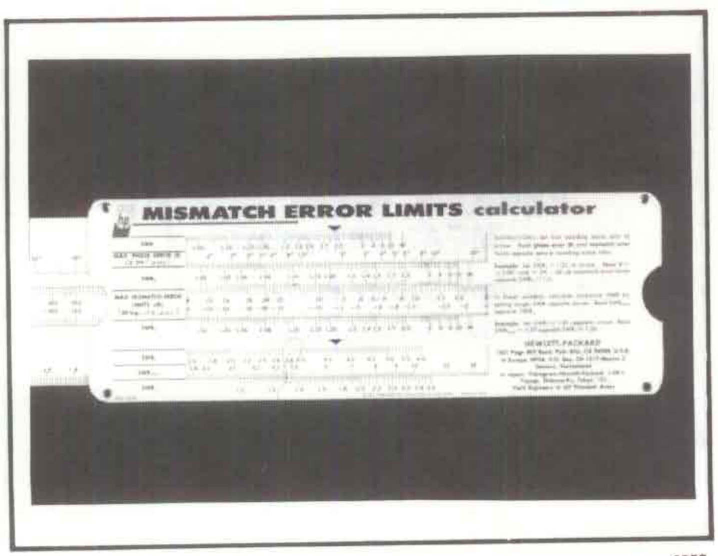
3488

The transmission uncertainty equation quantifies the worst case error window caused by the system. Source and detector mismatch cause an uncertainty around both the calibration and the measurement traces. Frequency response errors are elimated through normalization. Since it is a tedious task to evaluate this linear equation, let's explore an easier and more understandable quantification.



2944

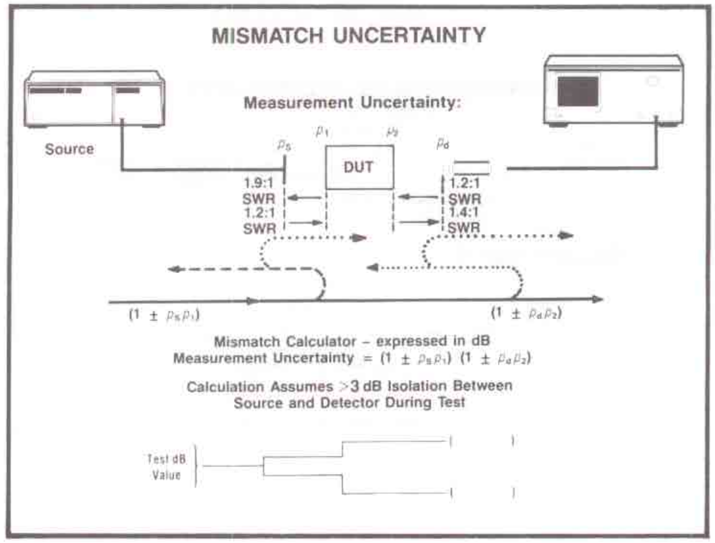
Let's first investigate the uncertainties associated with the calibration stage of the measurement. As shown, when the detector is connected to the source, the incident signal first encounters the detector impedance where part of the incident is reflected (normalized to p_D). This reflected signal is then re-reflected by the source mismatch resulting in an uncertainty vector of $p_S * p_D$ at some unknown phase relationship to the incident signal. Worst case, the extremes of the signal seen by the detector would be $1 \pm p_S * p_D$.



3552

The Mismatch Error Limits side of the reflectometer calculator converts the two SWR's into the uncertainty limits in dB. Place the black arrow over the SWR of either the source (1.9 in this example) or the detector (1.4). Under the SWR of the other device read the (+) value of Max Mismatch Error (+.44 dB). Directly below this read the (-) value (-.46 dB).

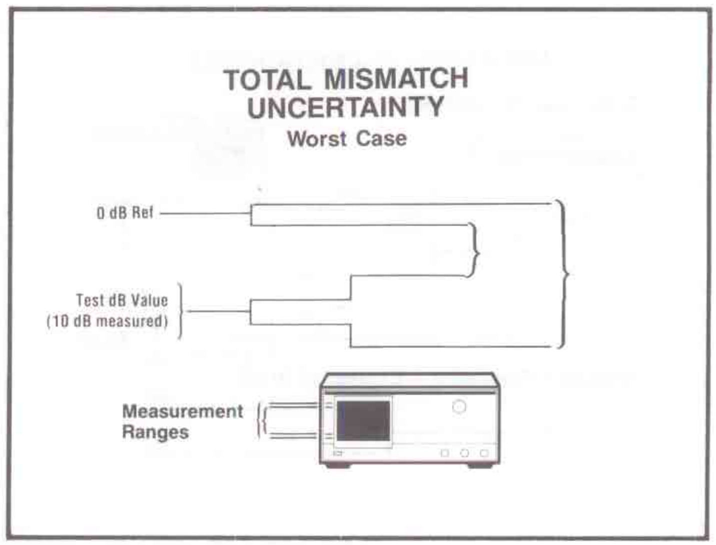
Similarly, there are uncertainties in the measurement stage due to the source/DUT input mismatch ($1 \pm p_S * p_1$) and the DUT output/detector mismatch ($1 \pm p_2 * p_D$). Each of these uncertainties can be found with the Mismatch Error Limits Calculator just as before. They are then added to get the uncertainty window in the measurement stage. Assume that the DUT SWR is 1.2:1.



2944

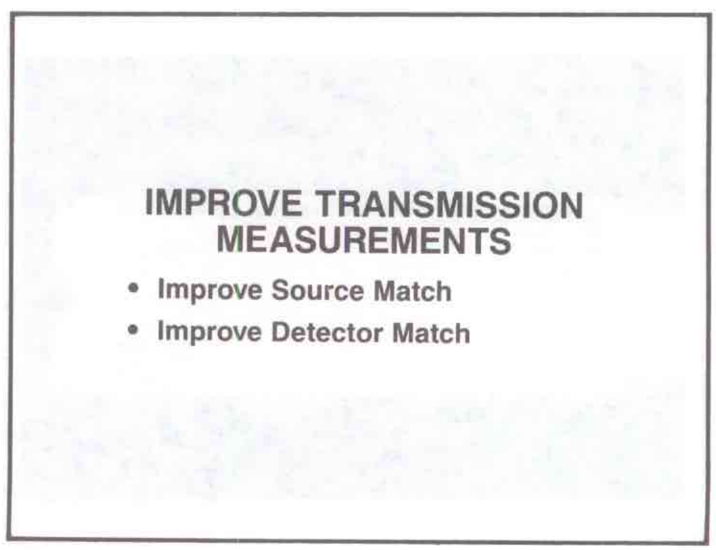
In this example we assume that the DUT has an input to output isolation of >3 dB so that multiple reflections have a negligible effect on the measurement uncertainty.

As the diagram shows, when the calibration window and the measurement window are combined, the total worst case uncertainty for a particular measuring system and DUT can be determined. In this example we see that the worst case uncertainty in measuring a 10 dB attenuator is almost ±1 dB.

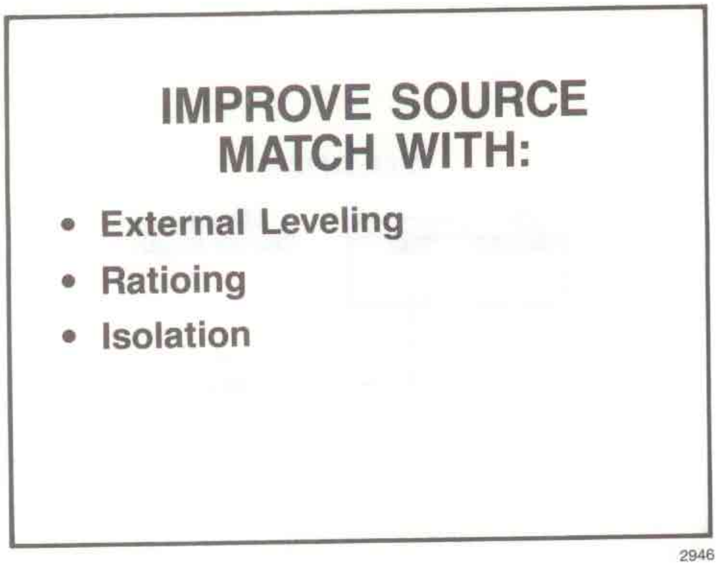


2945

Obviously, as seen from the previous example, we need to improve our transmission measurement accuracy.

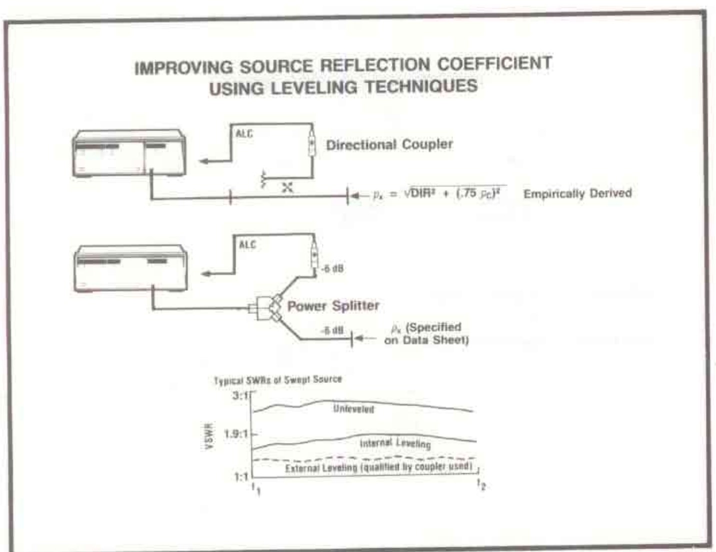


3489



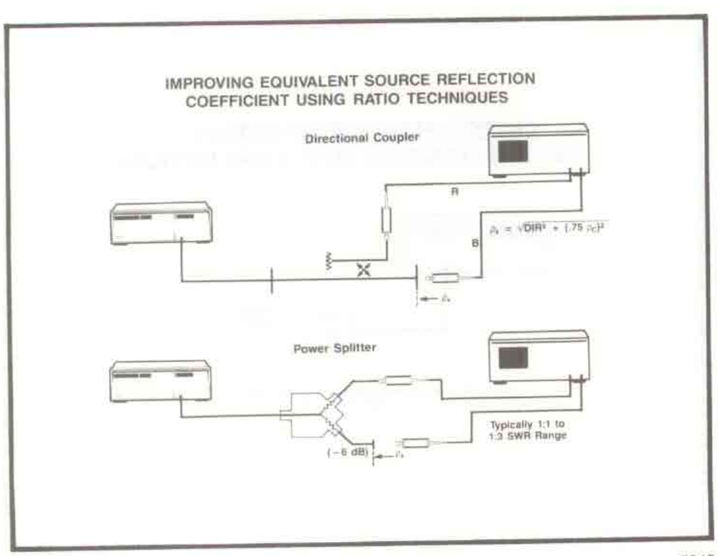
2946

As with reflection measurements, we can reduce transmission uncertainty by improving source match.



2947

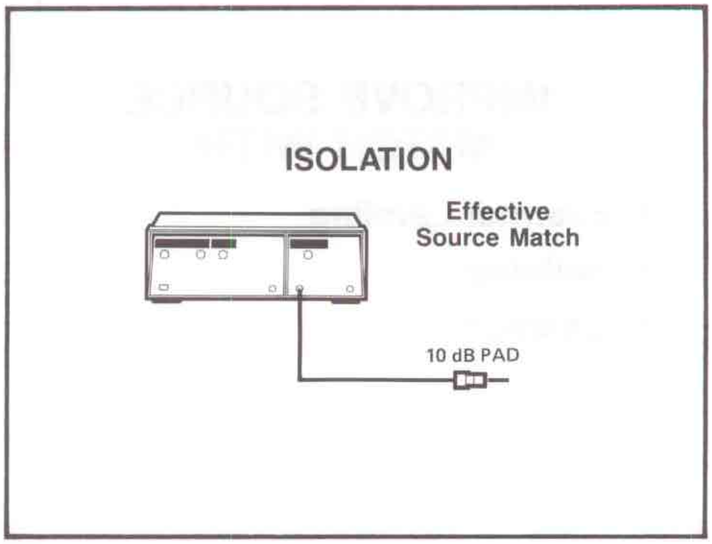
Leveling the source improves source match for transmission measurements. Source match improvement (when using a directional coupler) is similar to that gained in reflection measurements.



2948

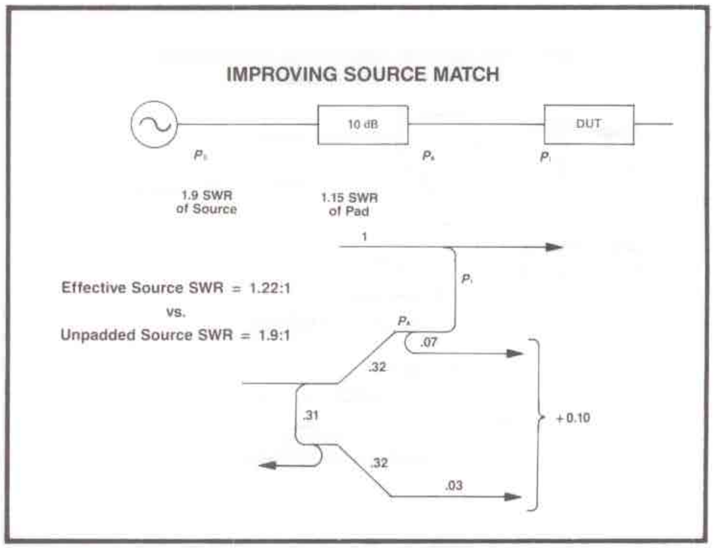
The effects of power variations are removed with ratioing. Source match improvement similar to that gained previously in reflection measurements is obtained.

Isolation improves source match by attenuating the reflected signal each time the reflected signal flows through the attenuator. An isolator achieves this same improvement without the loss of the attenuator. However, isolators typically operate over a limited bandwidth.



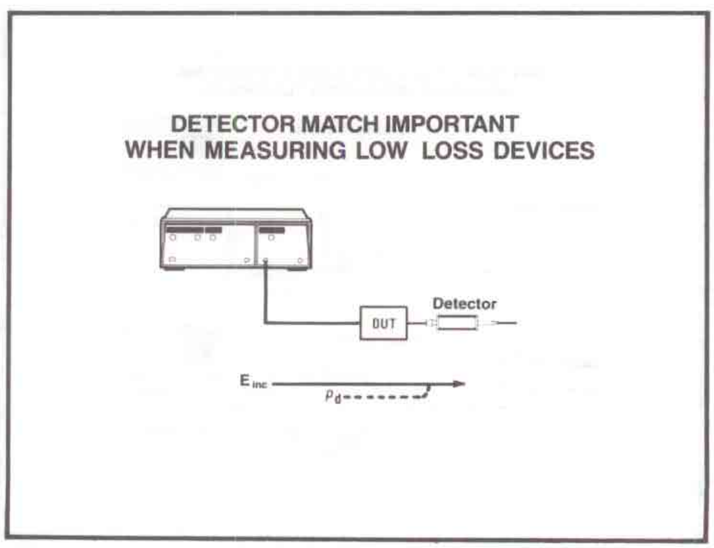
3490

We can see by this flow diagram that the 10 dB attenuator improves effective source match considerably. The major drawback to this method is the loss of measurement dynamic range.

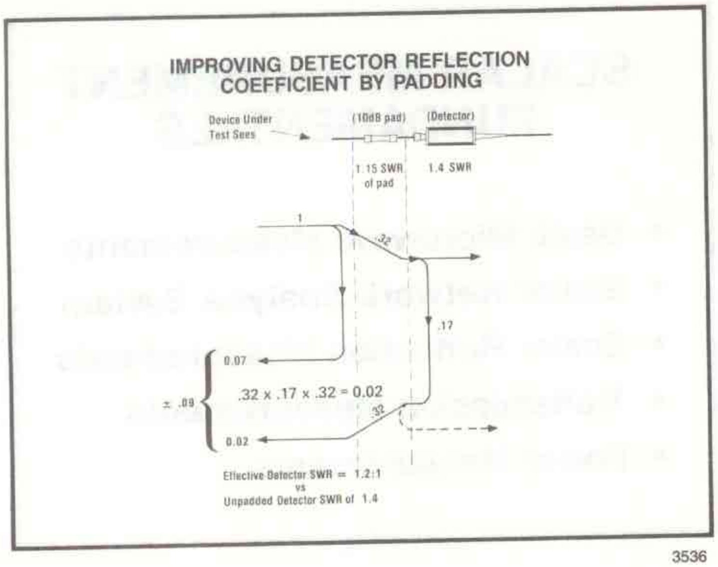


3534

Detector mismatch also contributes to transmission measurement error. If the DUT has low insertion loss (for example a transmission line), then the signal reflected from the detector and re-reflected from the source will cause a significant error.

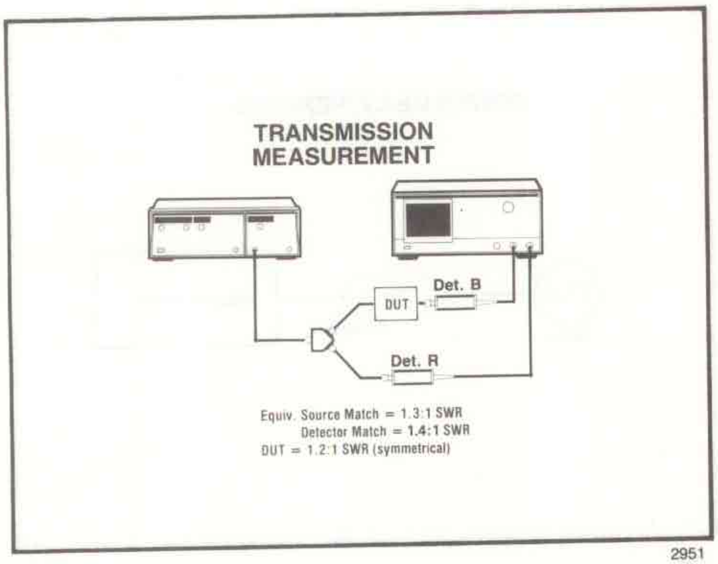


2953



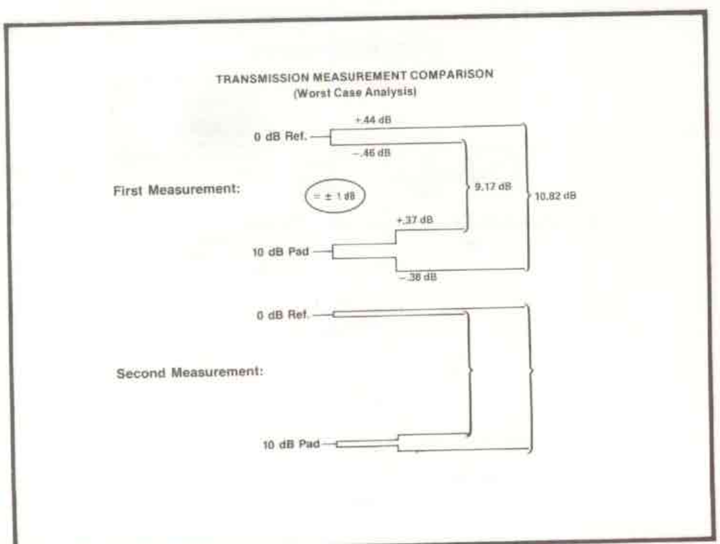
3536

A way of reducing detector mismatch is to use an attenuator for isolation. In this example, a 10 dB pad is used at the input of the detector to improve the match to that of the pad. The major drawback of this technique is that dynamic range is decreased.



2951

Here is an example on an improved transmission measurement system. Ratioing is used to improve the source match to 1.3:1 SWR.



2952

How much improvement do we get with ratioing? The top brackets show the uncertainty we obtained with the original simple measurement: approximately ±1 dB.

Using the Mismatch Error Limits calculator to calculate the improved uncertainty, we see it is approximately ±.4 dB. Again this is worst case uncertainty.

Note that the uncertainty is independent of the measured value of transmission as long as it is >3 dB (for example, if we measured a 20 dB pad the uncertainty would be the same as for a 10 dB pad).

In order to make accurate impedance and transmission measurements, some knowledge of absolute power is required so that (1) we are aware of the dynamic range available to us with the measuring system used, (2) we are assured that the analyzer's maximum power is not exceeded, and (3) we know the power level into such level-sensitive DUT's as amplifiers and mixers.

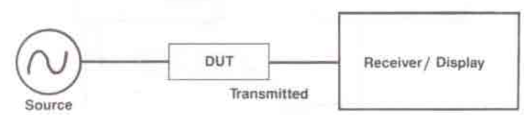
SCALAR MEASUREMENT FUNDAMENTALS

- Basic Microwave Measurements
- Scalar Network Analysis System
- Scalar Reflection Measurements
- Transmission Measurements
- Power Measurements

3457

A power measurement is similar to a transmission measurement.

POWER MEASUREMENTS



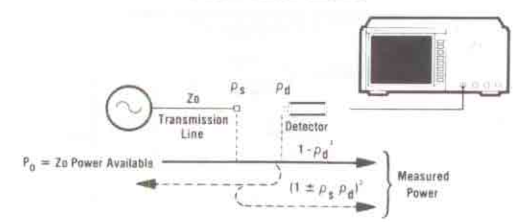
3492

However, since we are interested in the power that will be delivered to a load, we must account for simple mismatch loss. This is the power not seen by the detector because it is reflected by p_d, causing an error. This error can be accounted for using an offset, similar to the CAL factor on a power meter. The signals re-reflected result in further uncertainty. The actual Po available would then be between the limits defined by the equation.

The accuracy of the measurement also depends upon the frequency response of the detector.

Two parts of the uncertainty/error can be found using the Mismatch Loss scale and the Max Mismatch Error Limits scale on the reflectometer calculator.

POWER MEASUREMENTS



$$P_{meas} = P_0 \frac{1-\rho_d^2}{(1 \pm \rho_s \rho_d)^2}$$

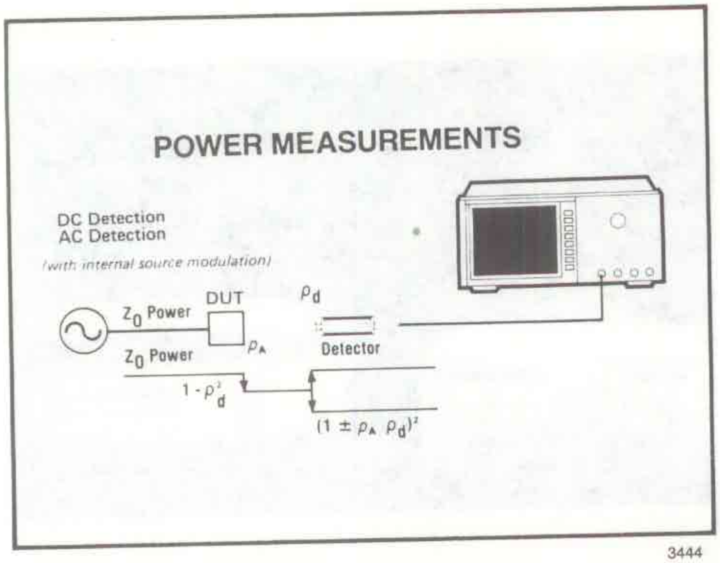
P_0 $(1-\rho_d^2)$ (-) (-) (+) $(1 \pm \rho_s \rho_d)^2$

$$P_0 \text{ (dBm)} = P_{meas} \text{ (dBm)} - [10 \log (1-\rho_d^2) - 20 \log (1 \pm \rho_s \rho_d)]$$

Add to meter reading → $[-10 \log (1-\rho_d^2) + 20 \log (1 \pm \rho_s \rho_d)]$

Reflectometer Calculator

3493



3444

Since the scalar analyzers have the capability to measure power, the same mismatch considerations apply. Using DC detection, the accuracy of the power level at the detector depends, as in the previous example, on the reflection coefficients p_d and p_A, where p_A is the reflection coefficient looking back towards the source.

However, if AC detection must be used to measure power of a DUT that cannot be modulated (i.e. an oscillator, an amplifier with an ALC loop, etc), then the mismatch and insertion loss of the additional external modulator must be accounted for. This increases the inherent inaccuracies.

SCALAR MEASUREMENT FUNDAMENTALS

- Basic Microwave Measurements
- Scalar Network Analysis System
- Scalar Reflection Measurements
- Transmission Measurements
- Power Measurements
- Product Summary

3457

We have concluded our discussions on scalar fundamentals. To wrap up this portion of the seminar, let's look at HP's scalar product line.

HEWLETT-PACKARD PRODUCT LINE OFFERING

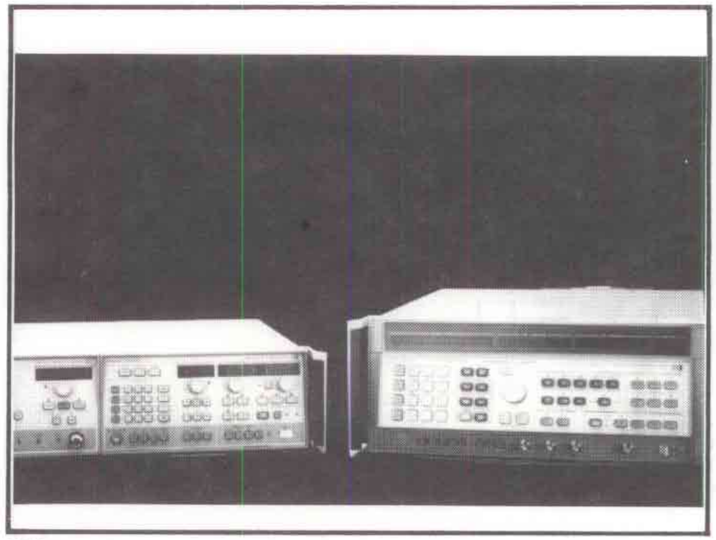
- Sources
- Signal Separation Devices
- Detectors
- Network Analyzers

3495

HP offers a complete product line for scalar network analysis from sources to network analyzers.

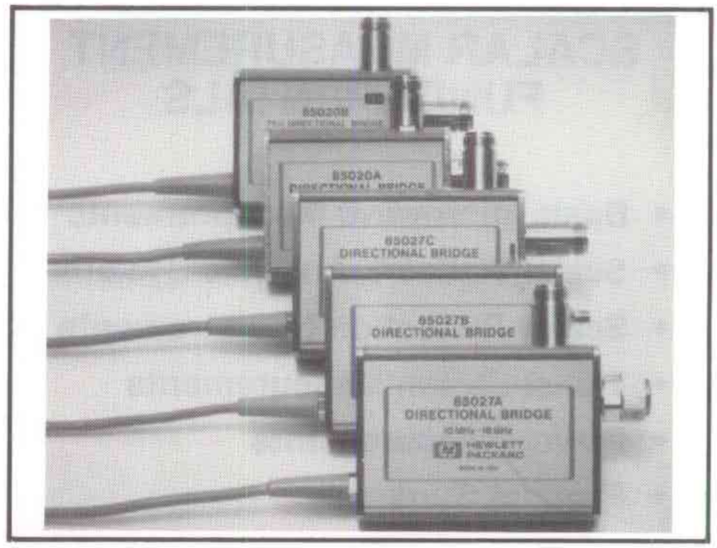
The HP 8350B and family of plug-ins offer a low cost, wide selection of swept sources.

The HP 8340/8341 synthesized sweepers offer both analog sweep and stepped CW sweep, with synthesizer accuracy at CW frequencies.



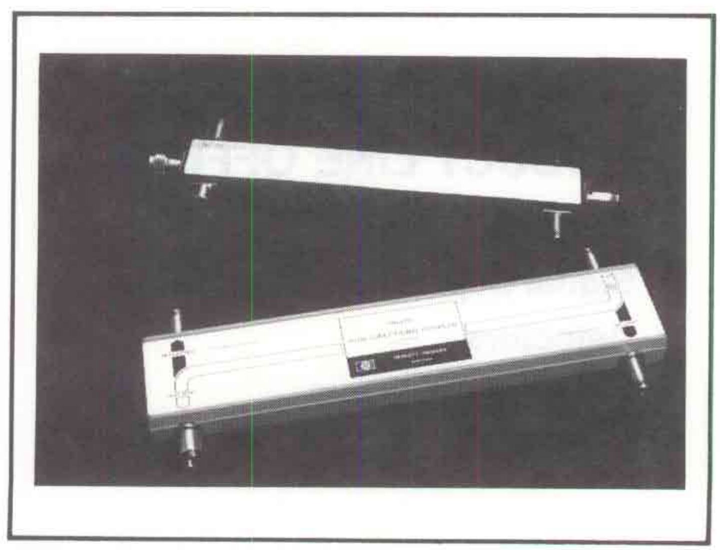
2917

A full line of 40 dB directivity reflectometer bridges from 10 MHz to 26.5 GHz are available to separate reflection signals.

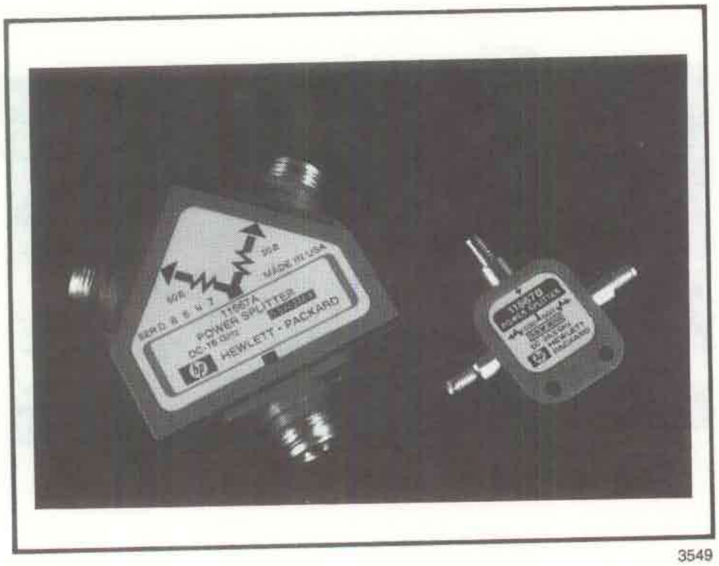


3497

Broadband as well as octave band couplers are available.

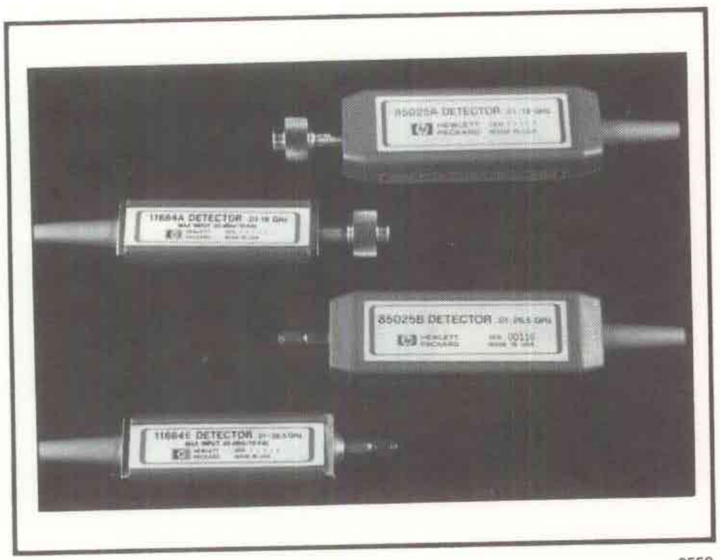


3535



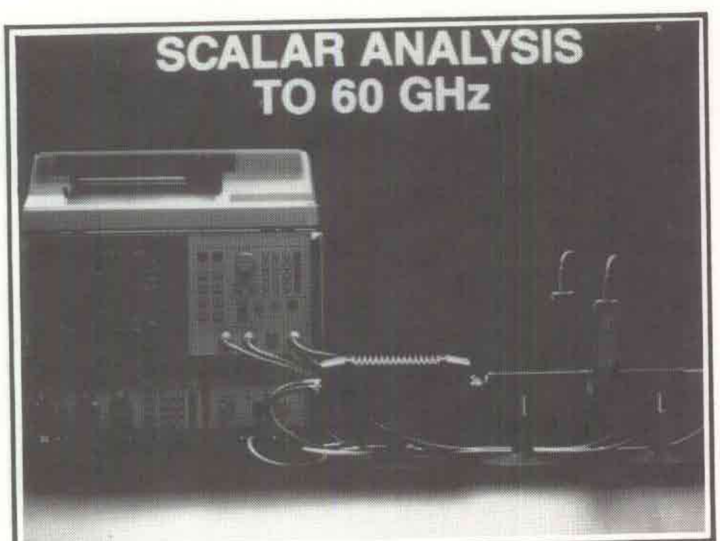
3549

Power splitters with various connector types are also available.



3550

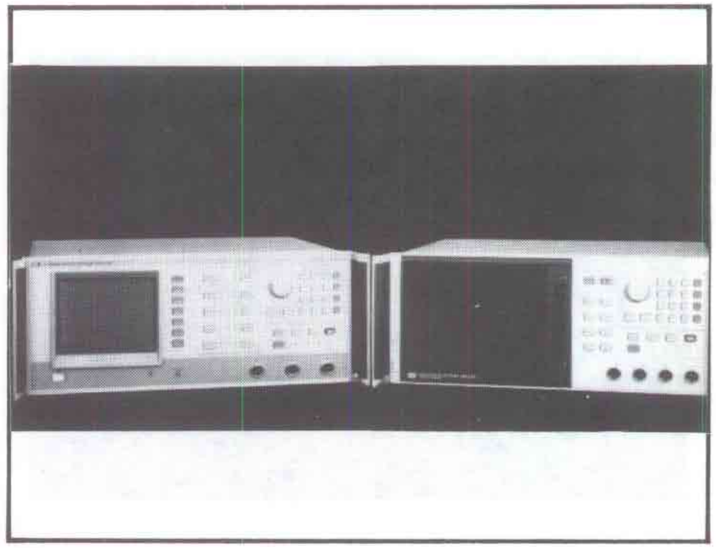
We have AC detectors from 10 MHz to 40 GHz and AC/DC detectors from 10 MHz to 60 GHz.



3855

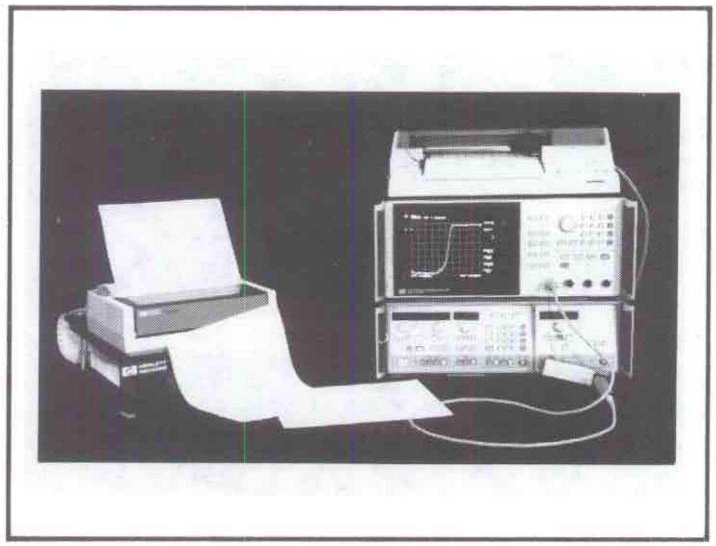
Waveguide measurement equipment is also available to extend the scalar measurement capability to millimeter-wave frequencies.

Two HP scalar network analyzers are available with very friendly operation and superb performance. In the next session of the seminar, we'll show how all these instruments are used in specific applications.



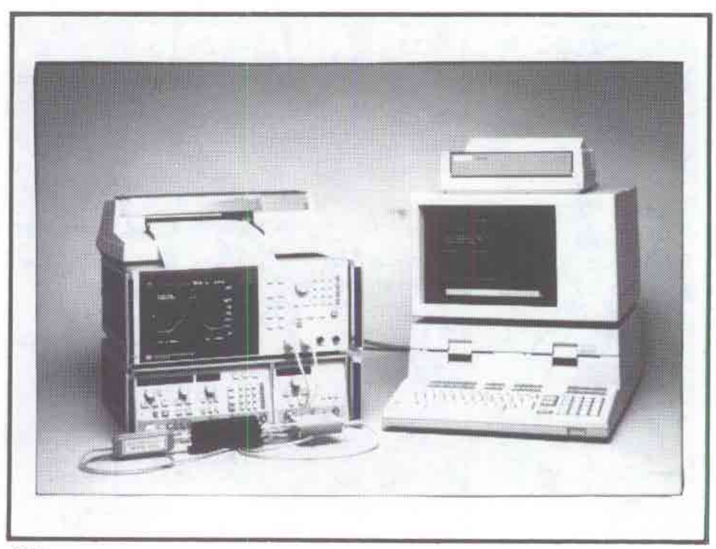
4003

A complete measurement system might look like this, with a plotter and a printer.



3397

By adding a computer, you can automate your system to improve productivity. The last section of this seminar will discuss automatic measurements.



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