TROUBLESHOOTING MICROWAVE TRANSMISSION LINES

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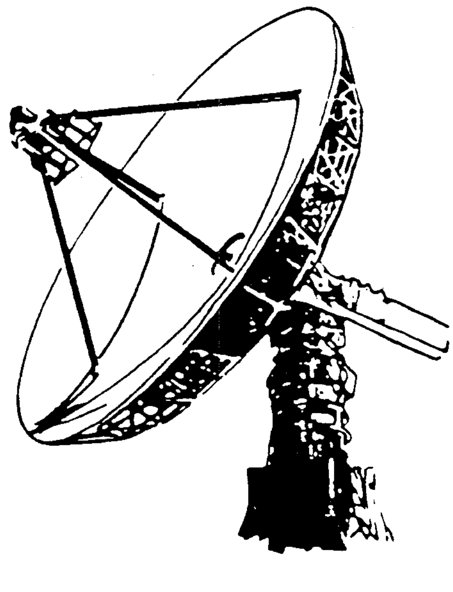
RF & Microwave Measurement Symposium and Exhibition



HEWLETT PACKARD

TROUBLESHOOTING MICROWAVE TRANSMISSION LINES

ABSTRACT:

Traditional and new techniques for locating and identifying faults in coax cables and waveguide runs are described. Particular emphasis is placed on Frequency Domain Reflectometry (FDR) using a software-enhanced scalar network analyzer. Measurement and accuracy considerations are discussed as are sources of error. This scalar technique is also compared with Time Domain analysis performed with the vector network analyzer.

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Troubleshooting coax and waveguide interconnect cables and difficult to access lines poses a difficult measurement problem. This paper discusses some present day solutions.

TROUBLESHOOTING TRANSMISSION LINES

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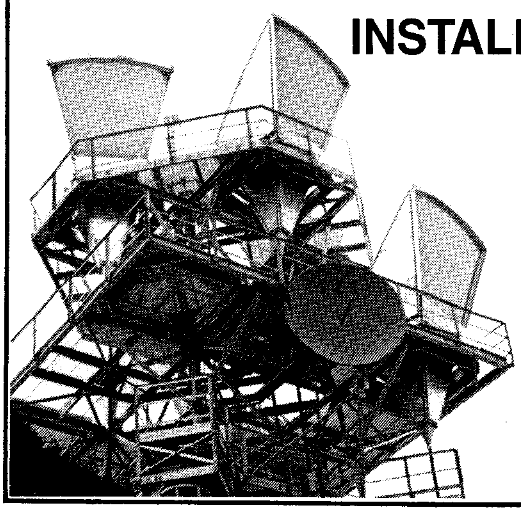
Solutions do exist to this measurement problem. This paper will discuss what they are, how they're used, and why. With recent advances in computational and measurement equipment, an old technique is now much more cost-effective and helpful.

- WHO NEEDS IT?
- TECHNIQUES USED
- TWO FDR SOLUTIONS
- MEASUREMENT SEQUENCE
- MEASUREMENT EXAMPLES
- MEASUREMENT CONCERNS
- SUMMARY

Transmission lines are used in every microwave installation. As sophisticated setups become commonplace, how do we know when the cables we use are good or bad?

INSTALLATION



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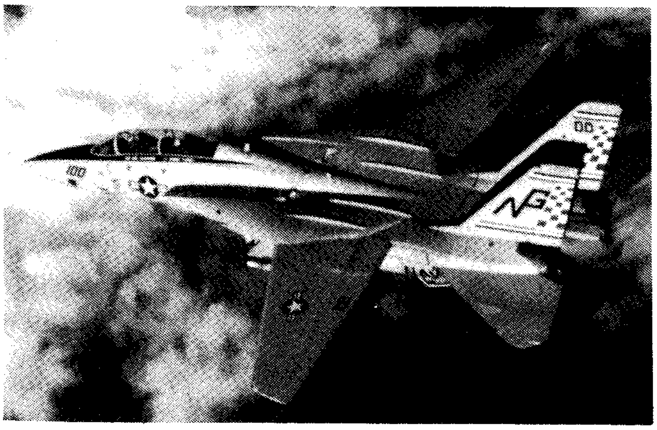
MAINTENANCE



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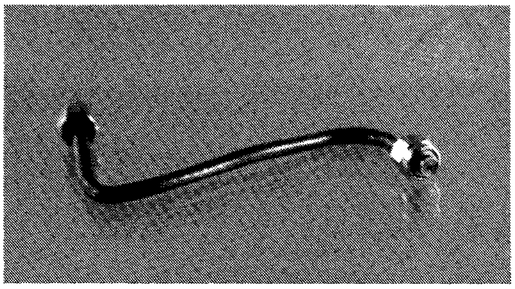
Numerous electronic systems are included in aircraft and ships, each at different frequencies and various types of lines. How do you know if a problem exists and where before dismantling the entire system piece-by-piece?

PRODUCTION & INCOMING INSPECTION



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With a spool of waveguide or a custom semi-rigid interconnect cable used in a subassembly, how do you know if they were properly manufactured?

- **TECHNIQUES USED**

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Several techniques and test systems have been built to diagnose faults in transmission lines. Each incorporates 3 main functional tests. Let's look at each one.

The simplest line tests are the network analysis characteristics -- insertion loss and return loss. These however require access to both ends of the line, sometimes a difficult task due to the lengths involved or accessibility. The ideal test involves only one connection, not two, and produces reflection information vs. distance as opposed to frequency.

TWO END TESTS:

- **Insertion Loss vs. Frequency**
- **Return Loss vs. Frequency**

ONE END TEST:

- **Fault Return Loss vs. Distance**

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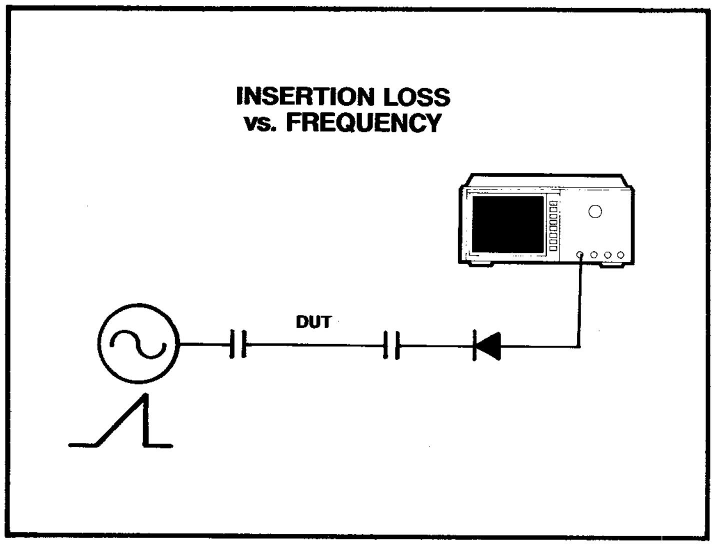
The standard swept test of insertion loss vs. frequency provides information on flatness and amplitude dropouts. If a dropout does occur, do we know what caused it?



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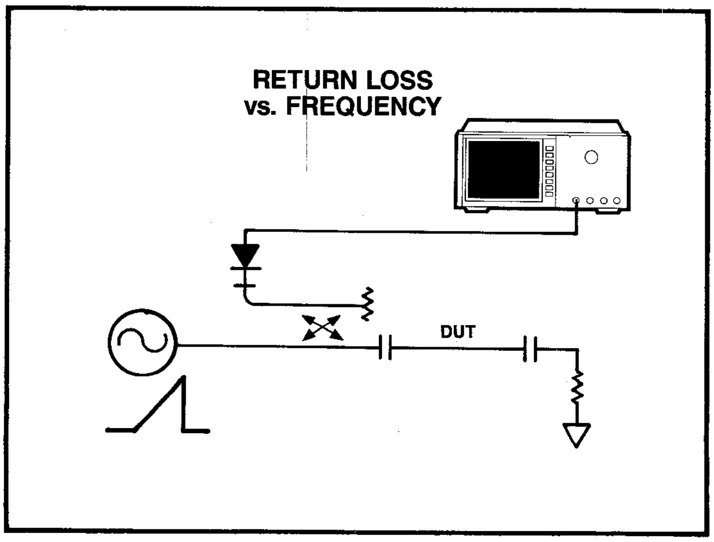
The swept test of return loss vs. frequency provides the much needed reflection characteristics. Since lines have low loss, any fault creates a reflection and hence a complex return loss trace. Are we ever able to discern if a fault exists or that a cables' response is ok?



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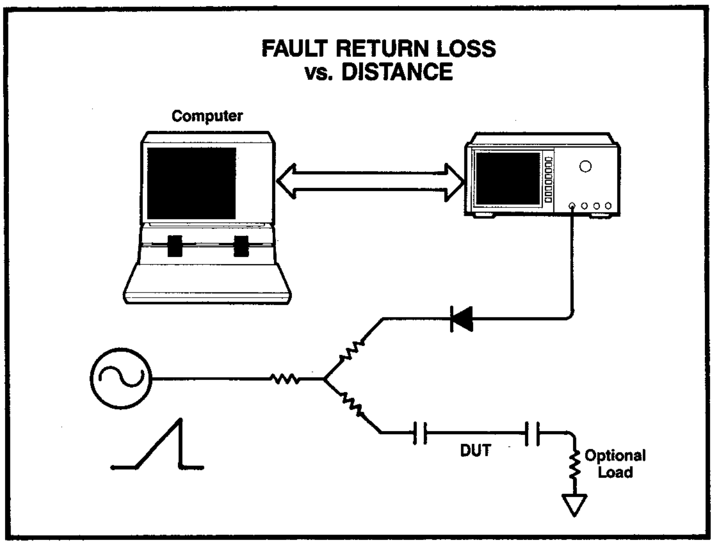

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The third test provides information in a more desirable format -- reflection characteristics vs. distance. There are two main techniques used, each requires a connection to only one end of the line and gives an indication of the cables performance vs. length.

HOW TO MEASURE RETURN LOSS vs. DISTANCE?

- TDR
- FDR

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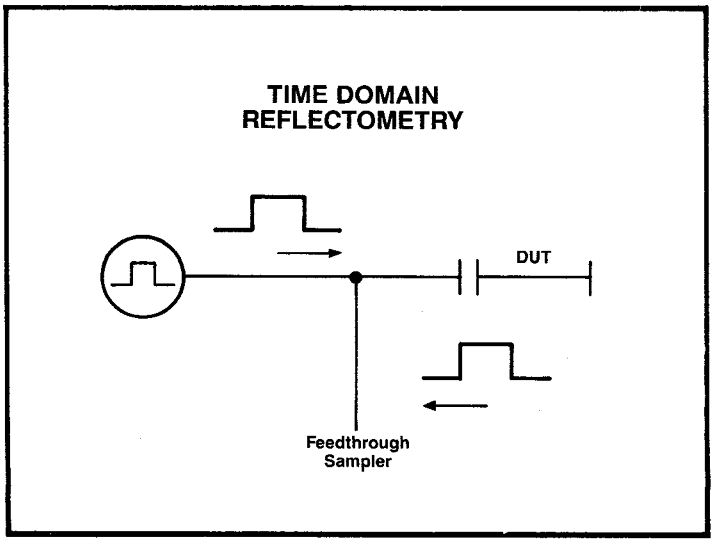
Two distance techniques are used: Time Domain Reflectometry (TDR), and Frequency Domain Reflectometry (FDR). They differ in how the device is tested, how the response is analyzed, and what is displayed.



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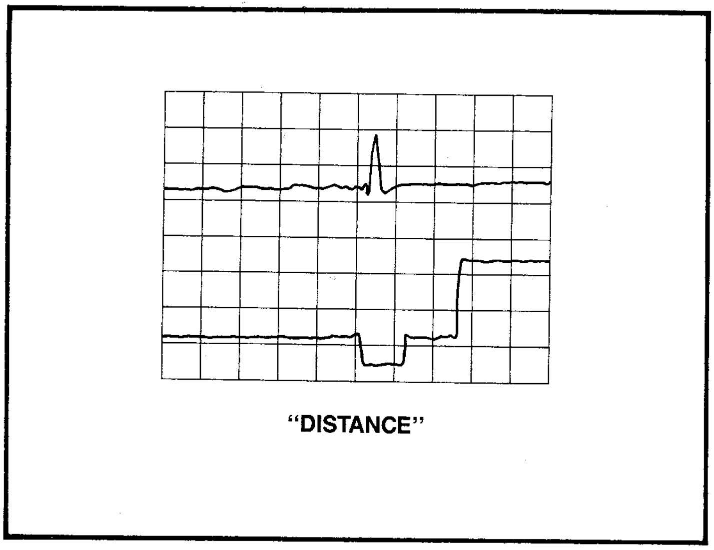
TDR relies on distance being determined by a calibrated time interval between the transmission of a pulse and its return (reflected) pulse. A sampler detects both pulses, the receiver provides the calibrated time/distance information.

Here are two typical TDR displays. Using an oscilloscope display calibrated in distance, we can determine when signal changes occur and their relative level. The upper trace shows a bad connection, the lower trace shows a section of line with a different impedance, then an open circuit. Hence, we can find cable splices and bad connections.



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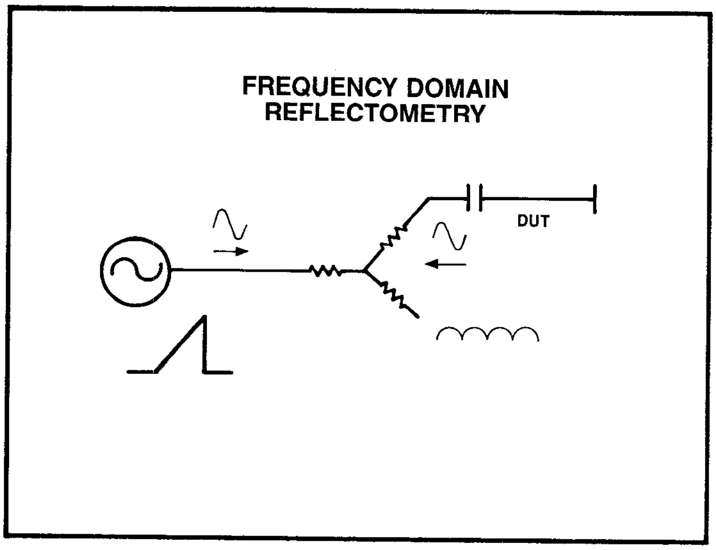
FDR relies on performing a swept return loss measurement, then using Fourier Analysis to separate the individual reflections into specific distances. Here a swept source and a power divider essentially create a swept slotted line system. The power divider measures the incident sinewave and combines it with the reflected sinewave. The result is a standing wave -- one for each reflection.



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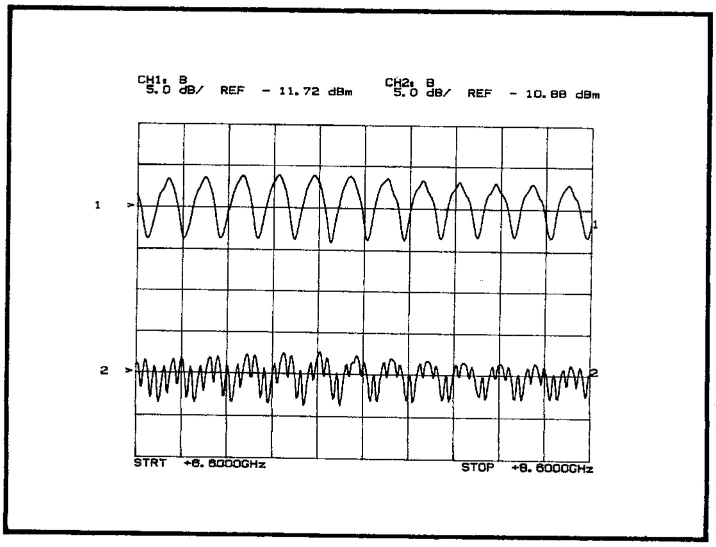
The top swept return loss trace shows a single reflection. The lower trace shows several reflections, the result being a superposition of standing waves and hence a complex, rippled trace.



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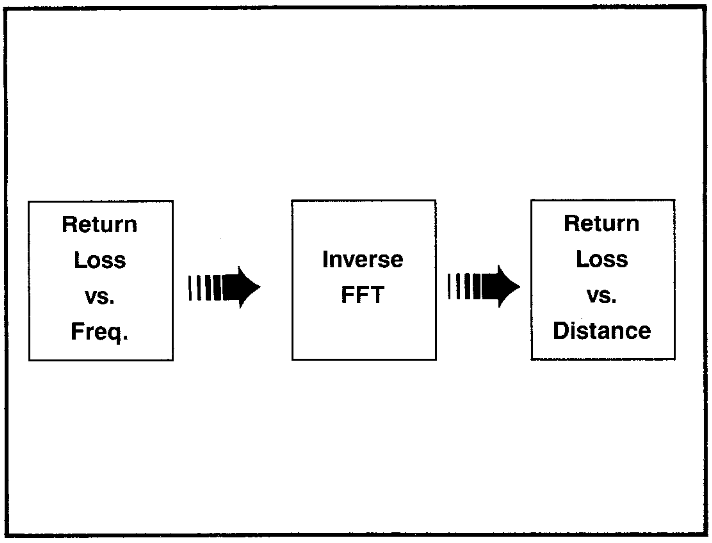

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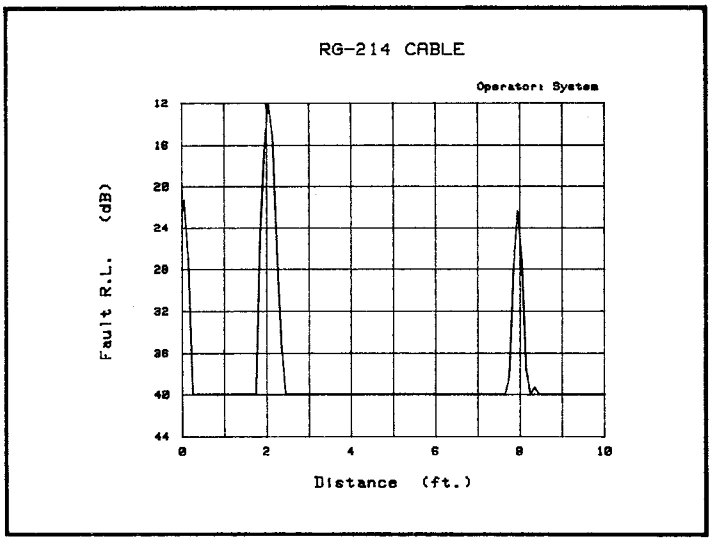
This swept return loss data is converted from the frequency domain into the distance domain by the Inverse Fourier Transform. Since each reflection causes a standing wave at a different ripple amplitude and frequency, the Inverse FFT can separate these out.



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The result is a return loss value at a specific distance. The distance is the physical distance, derived from the known propagation velocity of the line.

ADVANTAGES OF TDR

- **Simple Test Setup**
- **Portable**
- **Variable Impedances**

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Why do 2 techniques exist? TDR was the easiest to implement, being a simple equipment setup -- essentially an RF sampler plug-in for an oscilloscope mainframe. It is small, lightweight and portable. TDR can be easily configured to measure several different impedances with the same hardware.

Unfortunately, TDR doesn't allow the user to test bandlimited devices like waveguide -- it requires a broad frequency coverage to transmit the pulse. Likewise, the accuracy of amplitude responses is poor. If multiple faults exist, the TDR waveform is complex and difficult to diagnose. FDR overcomes all of these limitations since the frequency span is controllable, plus the system is a broadband network analyzer.

ADVANTAGES OF FDR

- **Insertion Loss, Return Loss vs. Frequency, plus Return Loss vs. Distance**
- **Can Test Band Limited Devices**
- **Multiple Fault Detection**

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HP provides two different FDR measurement systems. They differ in speed, performance, capability, and cost.

- **TWO FDR SOLUTIONS**

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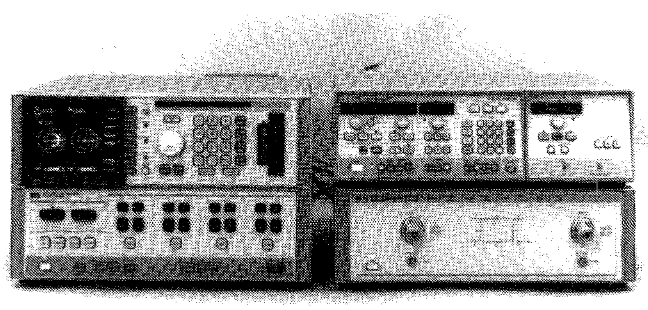
The HP 8510A Microwave Vector Network Analyzer with Option 010 provides Time Domain Analysis capability. In addition to 45 MHz to 26.5 GHz vector network analysis, an extremely versatile distance domain analyzer exists. The user has complete control over the FFT windowing, gating over specific distances, and enhanced frequency response measurements by removing distance specific responses.

For RF only measurements, the HP 8753A Option 010 RF Vector Network Analyzer provides similar capability from 300 kHz to 3 GHz.

HP 8510A NETWORK ANALYZER



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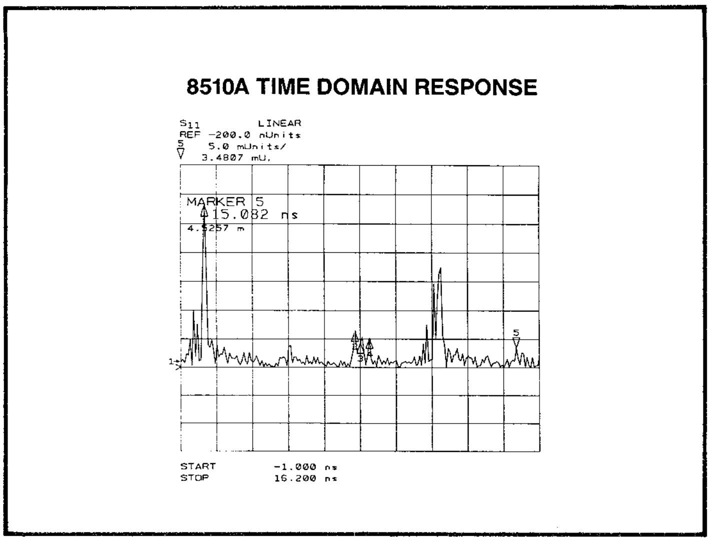

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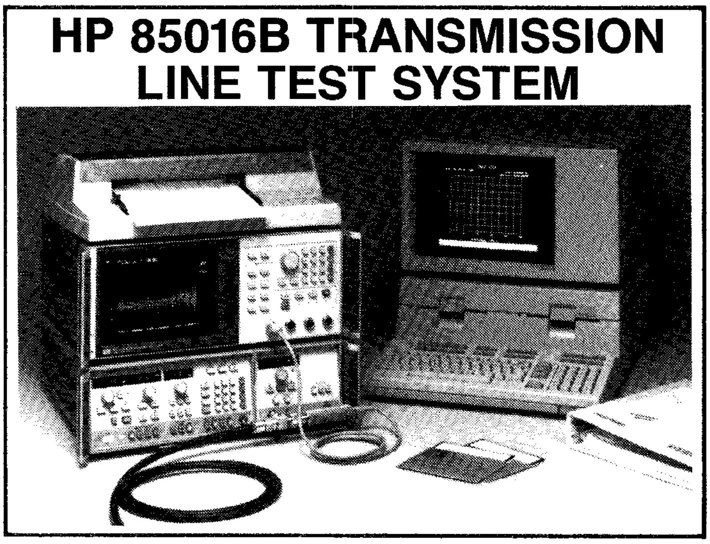
This HP 8510A Time Domain display is in seconds, with the trace marker providing amplitude and distance data. The flexibility in generating this data in a real-time fashion is unprecedented.



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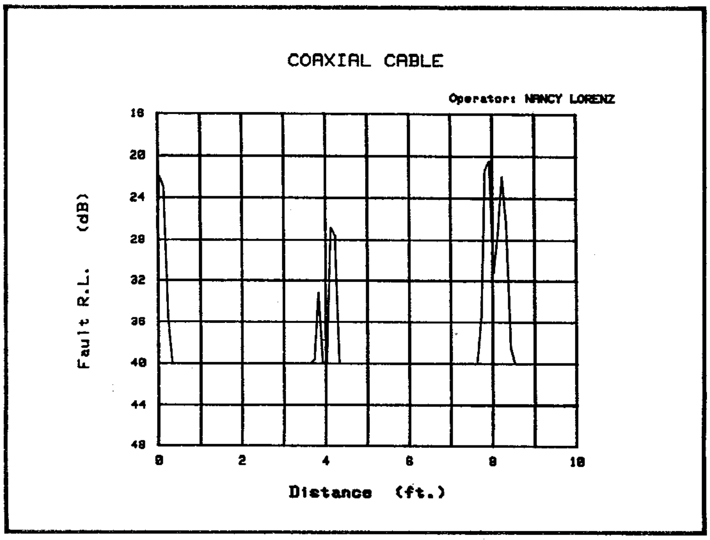
The HP 85016 Transmission Line Test Software augments the HP 8756A and 8757A Scalar Network Analyzers. Using an HP 9000 Series 200 or 300 computer, the FFT is performed and data displayed on either the computers' CRT or the CRT of the HP 8757A. The system is dedicated to fault location and frequency response testing, plus compensates for common errors in coax and waveguide line testing.

This system is also available in a transportable cart-based approach as the HP 8328A Transmission Line Test System. The HP 8328A is a complete system providing the same capabilities and packaged for quick accessibility.



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This HP 85016 fault return loss display is provided directly in physical length for the line under test. The system includes limit testing and completely turnkey measurement test capability.

Let's take a look at how an FDR system is used. All systems follow this 4 step sequence.

MEASUREMENT SEQUENCE

- **Calibrate**
- **Connect and Measure**
- **Compute and Correct Data**
- **Display**

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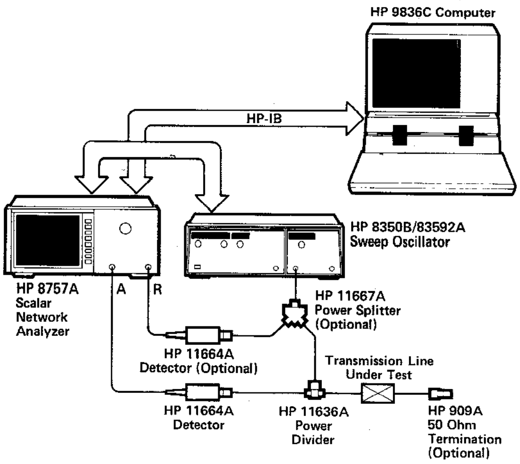
The HP 85016 system is a computer enhanced scalar network analyzer system. The basic system uses a single detector and a power divider. For tests on lines removed from the source, a ratio technique must be used as shown here with the optional equipment.



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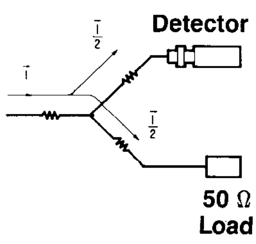
The first step is calibration. We do this by measuring a perfect termination at the test port. Here the power divider splits the incident signal and we measure the residual reflections and frequency response of the system.

CALIBRATION



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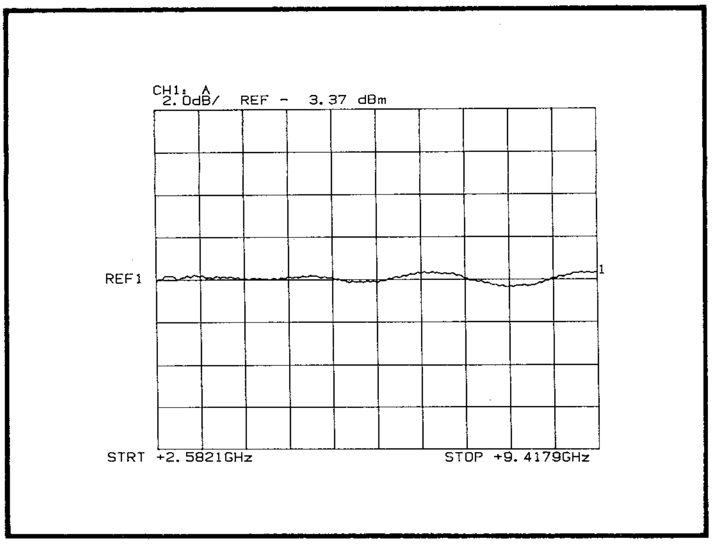

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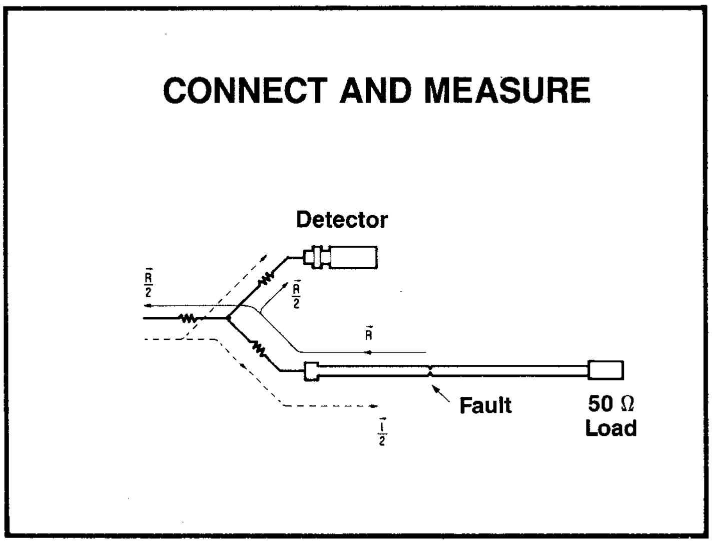
The calibration trace typically is flat, since there are only residual reflections in the system. These are completely removed by the system, but do limit how low a reflection we can accurately measure. Thus the terminations' return loss is critical when measuring low-level reflections.



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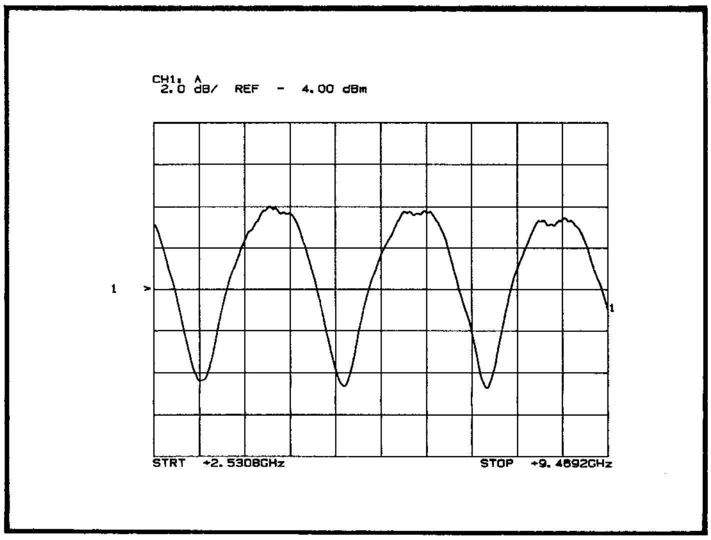
When measuring the line under test, the other end of the line can either be terminated or left open circuited. Here the power divider splits the incident signal plus combines it with the reflected signal. Terminating the end of the line let's us look for smaller faults within the line. If it were open circuited, this reflection could affect the accuracy of other faults before it.



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For a single fault, this is the swept return loss display. Now we must convert from the frequency domain to the time domain.

The time domain information must be converted into distance domain data for physical length. In the process, we must correct for losses in the system due to the line characteristics such as attenuation and dispersion, plus multiple mismatches.

COMPUTE AND CORRECT FOR

- Time to Distance
- Attenuation of Cable
- Multiple Fault Mismatch
- Waveguide Dispersion

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Calibrating the time domain to physical distance requires the line velocity of propagation (Vp). This allows us to scale the equivalent electrical length into physical length.

TIME TO DISTANCE

Need:

- Velocity of Propagation
- Coax or Waveguide?

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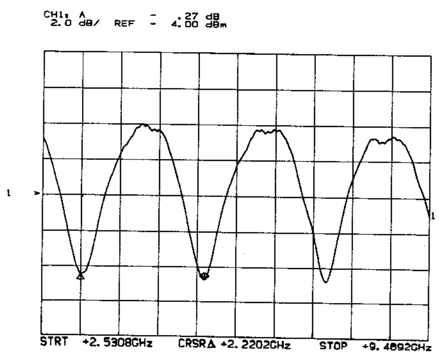
The distance to the fault can be determined by the velocity of propagation and the ripple period. For this example, the Vp is approximately 0.7 being coax. This indicates a fault at 3 inches, which happens to be the end of a Type-N to SMA adapter attached to the test port of the power divider (no test cable was attached).



$$d_{fault} = \frac{V_p}{2 \times \text{Ripple Period}}$$

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LINE ATTENUATION

Need:

- **Loss per 100 feet/meters**

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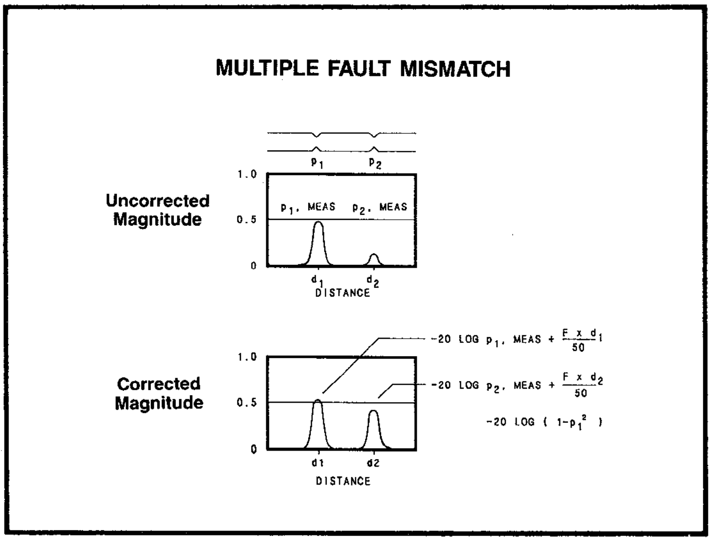
Since the line has some loss vs. distance, we must correct for the round trip path loss of each reflected signal. This is achieved by using the line attenuation for the line under test.



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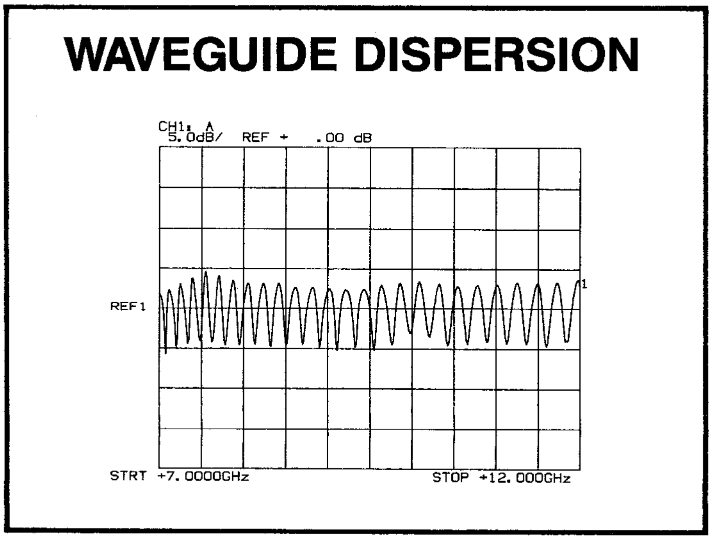
If more than one fault exists, the first (and closest) fault reduces the signal incident to the following faults. This affects the return loss measured at each of these faults. Once the positions of each fault are known, we can correct for this mismatch loss and make more accurate readings.



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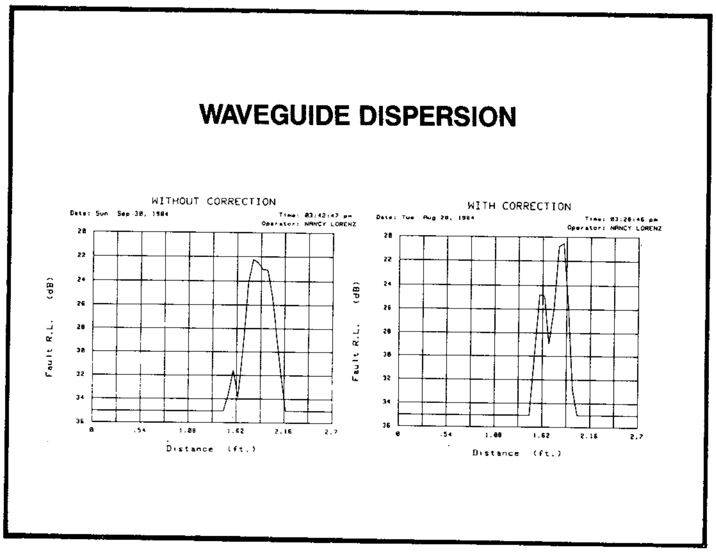
When measuring waveguide, the test algorithm must be modified to account for the guides' non-linear phase characteristics. As seen in this example, the ripple frequency changes going from the low end of the band to the high end. This is because the group delay of the guide is decreasing with higher frequencies. If we operate over a narrower portion of the band, we can ignore this effect. If not, special processing must be used.

To see the effects of dispersion, here is a measurement with the dispersion correction first disabled, then enabled. The plot on the right accurately identifies two close faults. The uncorrected plot on the left has smeared the data, plus affected the return loss levels. We can correct for this non-linear phase characteristic by using frequency points that are not linear frequency steps, but rather non-linear in order that they produce linear phase increments. In coax testing, it is easier to use linear frequency steps since the measurement can be made much quicker.



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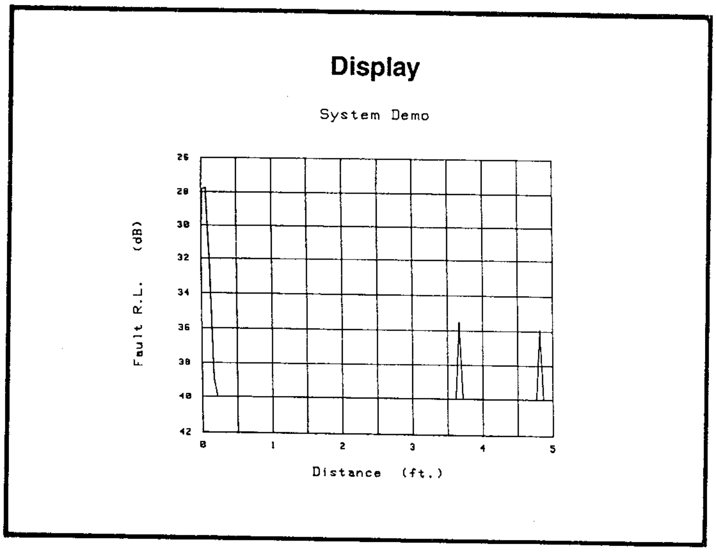
After all the corrections are performed, we can view the fault return loss data vs. distance. A plot provides the most helpful information. Here we see a mismatch caused by an adapter, then an SMA barrel connecting two semi-rigid cables, and finally, a termination.



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A tabular printout can provide a good mismatch summary. Here we can list just the major mismatches found, focusing on the largest and then fixing it.

MISMATCH SUMMARY

Cable or Waveguide Type: RG-141/U
Relative Velocity: .695
Loss/100 ft: 41.534
Length (Range): 5 ft
Center Frequency: 6 GHz
Distance Resolution: .05 ft
Current Window is : Normal

Measurement 1:

System Demo

Distance (ft)	FLT. R.L. A (dB)	% OF TOTAL MISMATCH
4.920	27.73	100.000

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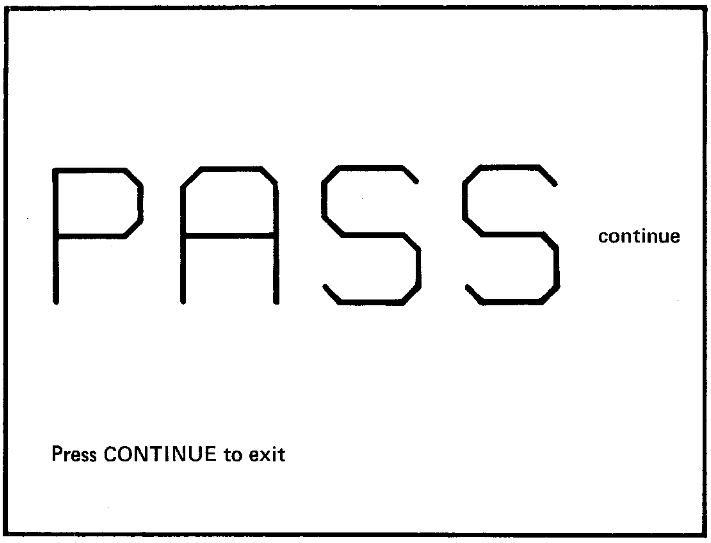

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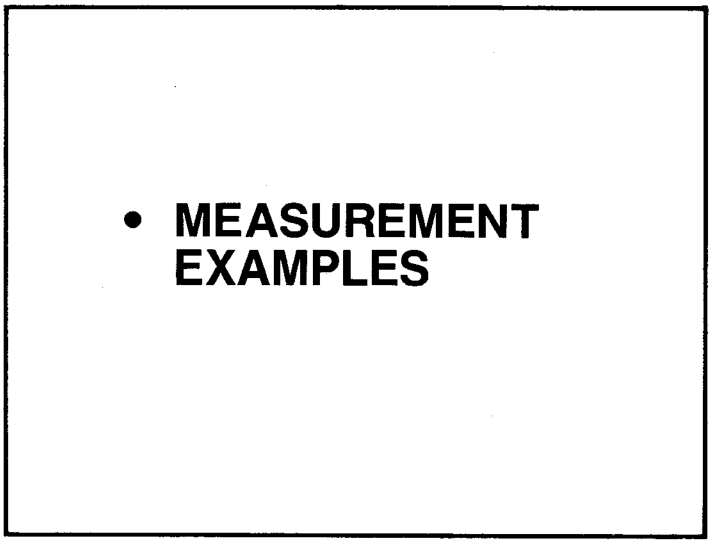
Better yet, if we could use our test specifications and let the computer determine if it passed or failed, we can speed up the measurement. Using limit tests and a visible pass/fail indication, we can proceed to our next test if our test line passes. If it fails, then we can resort to the plot and/or printout to locate the fault.



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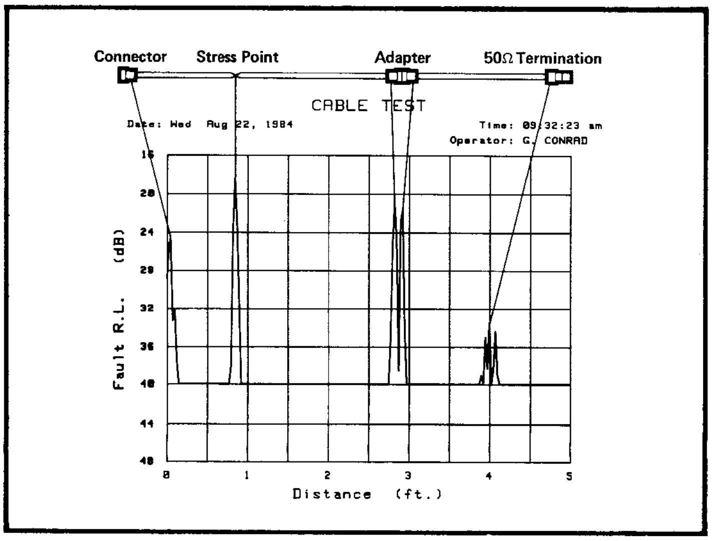
Now that we've seen that the system can produce the results we're looking for, let's look at how to interpret the measurements on a few test cases.



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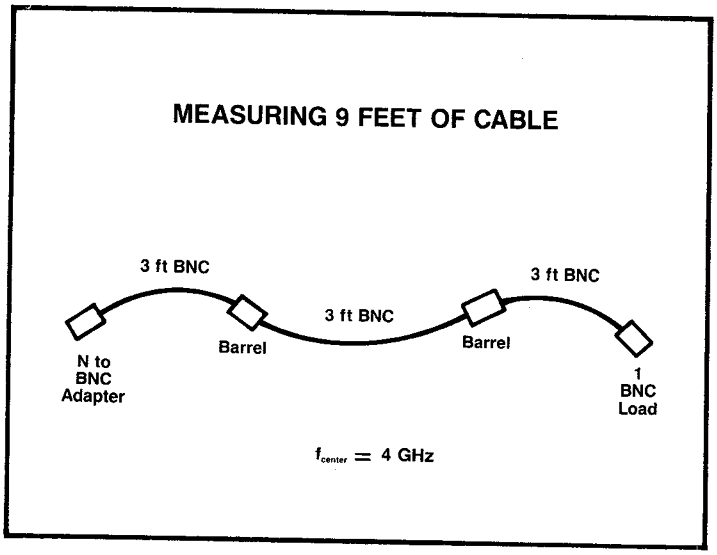
The resolution capability of an FDR system allows us to find numerous mismatches quickly. Using two semi-rigid SMA cables (0.141") as a test line, we can easily determine the reflections contributed by the initial adapter/connector, a stress point caused by a pair of pliers, the barrel adapter, and the termination. In this high resolution measurement, we can even see the reflection of each side of the SMA barrel!

Many transmission lines are long, like antenna feeds or interconnects winding in and out of bulkheads. In attempting to simulate this, we'll test 3 BNC cables connected together. While the connector match of standard BNC cables is not good, we can determine if a cable is good or bad by testing it at 4 GHz.



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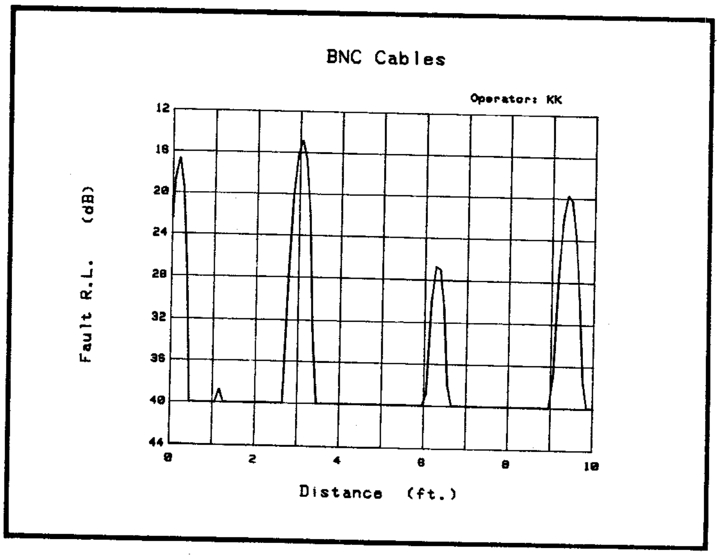
Here we inspect this 9 foot test line. Notice we can see the initial Type-N to BNC adapter, and each successive BNC connection. Interestingly, the first BNC cable exhibits a low-level reflection (39 dB) at about 1 foot in. This could indicate a bend or crimp inside.



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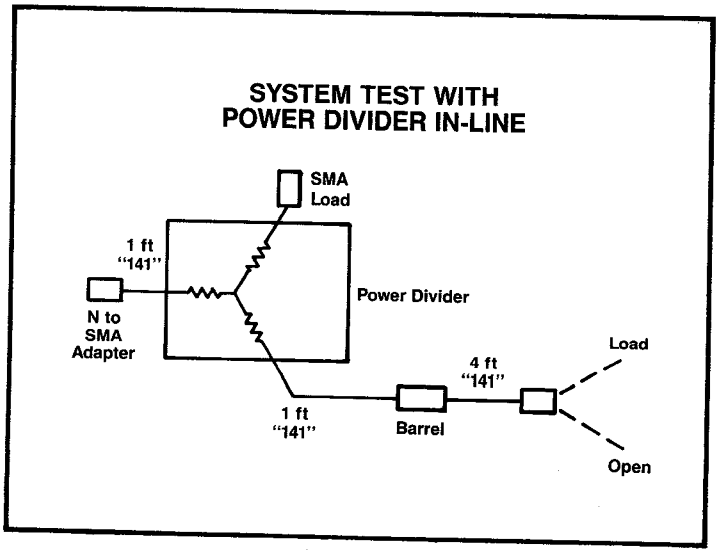
Many lines are a combination of cables, bulkhead adapters, connectors, power dividers, switches, etc. How do in-line attenuators affect our one-end test? Let's measure this system, as it exemplifies what most of us want to determine -- are there any bad connections -- without tearing apart the system.



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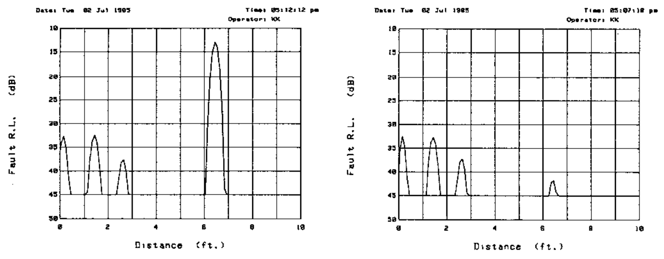

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Let's look at measuring first with the other end open circuited, then with it terminated. In both we can see the initial adapter, the input to the power divider, and the SMA barrel between the outer two semi-rigid cables. However, the open circuit at the end appears as a 12 dB return loss and the termination as a 42 dB return loss. This measurement was made at a center frequency of 4 GHz. Both return loss values have been attenuated by 12 dB -- the roundtrip insertion loss through the power divider. Hence, one is really a 0 dB return loss (the open), the other 30 dB (the termination). Thus, we must compensate for in-line attenuation ourselves, realizing that it will limit our measurement dynamic range.

- **MEASUREMENT CONCERNS**

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Now that we've seen what the system can do for us, let's discuss some hidden operational concerns.

CONCERNS

- **Distance Range**
- **Distance Resolution**
- **Frequency Span Required**
- **Connection Hardware**

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These include how well we can determine distance, what source requirements we'll need, and the rest of the system connections.

The Inverse FFT converts the swept return loss data into swept time domain data. To convert from time to distance, we must scale the data by the velocity of propagation (Vp). Notice that the distance resolution and range are inversely proportional to the frequency span swept. Thus the minimum resolution is limited by our ability to measure one period of ripple. The total range is determined by the number of cycles measurable.

DISTANCE vs. FREQUENCY

$$\text{Resolution} = \frac{V_p}{2 \times \text{Span}}$$

$$\text{Range} = (N-1) \times \text{Resolution} = \frac{(N-1) \times V_p}{2 \times \text{Span}}$$

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Hence the frequency span swept determines how well we can resolve two mismatches and at what distance. Since frequency span and distance are inversely proportional, to measure long line lengths requires small frequency spans. Here the source stability will be critical, maybe requiring a synthesized sweeper. For short lengths, broad frequency coverage is required, forcing the source to very broadband.

FREQUENCY SPANS REQUIRED

Range and Span for 201 Distance Points

Range (FT)	Resolution (FT)	Frequency Span (GHz) (Relative Velocities Given Below)					
		0.6	0.66*	0.7**	0.8	0.9	1
2	0.01	14.8	16.2	17.2	19.7	22.1	24.6
5	0.025	5.9	6.49	6.88	7.87	8.85	9.84
10	0.05	2.95	3.25	3.44	3.93	4.43	4.92
20	0.1	1.48	1.62	1.72	1.97	2.21	2.46
50	0.25	0.59	0.649	0.688	0.787	0.885	0.984
100	0.5	0.295	0.325	0.344	0.393	0.443	0.492
200	1.0	0.148	0.162	0.172	0.197	0.221	0.246
500	2.5	0.059	0.0649	0.0688	0.0787	0.0885	0.0984

* polyethylene ** teflon

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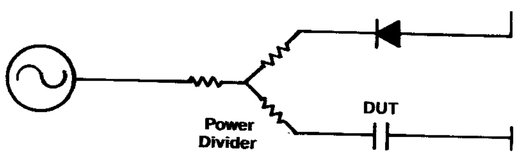
Measuring coaxial cables requires a simple instrument setup. Coaxial power dividers and sources are available from 10 MHz to 26.5 GHz.

CONNECTION HARDWARE: COAX



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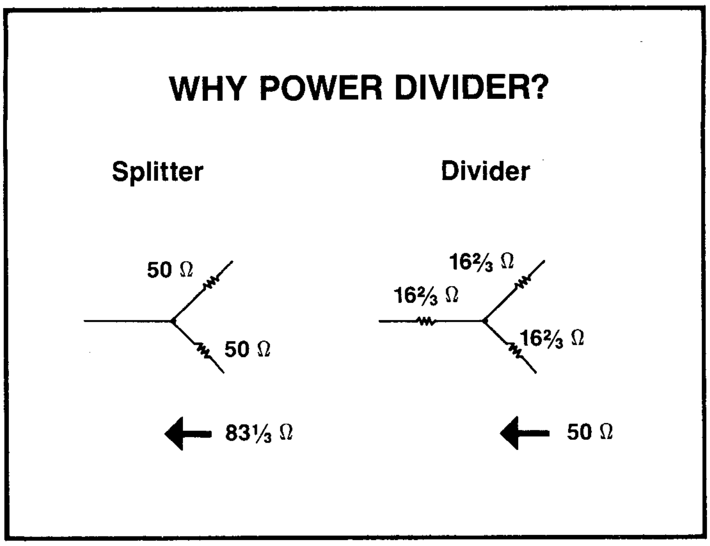
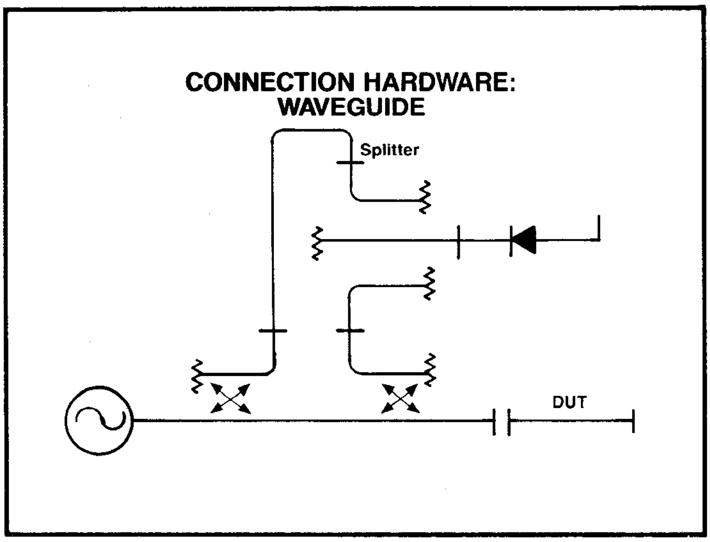


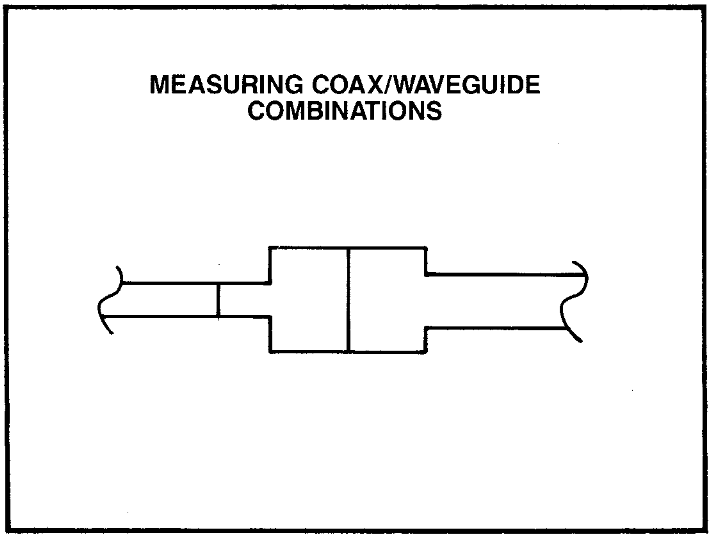
3601

A power divider is necessary for fault location tests, since it is needed to both combine and divide power. Normal swept frequency response testing uses a power splitter not a divider. A splitter is designed for ratio measurements and leveling purposes. Comparing the two devices, we can see that the power divider provides a good 50 ohm source match to the line under test -- critical in minimizing residual system reflections. The power splitter has a poorer match, which causes more reflections and uncertainty in this application. However, it is superior to the divider in a ratio measurement.



3602

Waveguide can be tested in two ways. For measurements below 26.5 GHz, it is preferrable to use a coax-to-waveguide adapter and a coaxial test setup. For measurements above 26.5 GHz, we use the waveguide analog to a coaxial power divider/combiner. Here we combine via couplers the incident and reflected signals at one port to form the needed standing wave.



3995

Many systems are a combination of coax and waveguide. Since both have different velocities of propagation, this is a very difficult measurement in computation. The best approach is to select a velocity of propagation that is the average of the two individual velocities, realizing that the measured distances will be approximate, not exact. The dispersion due to the waveguide will also not be compensated for, thus the user must inspect these test results more carefully.

In summary, there are two types of network analyzer systems available using FDR. Each aids the user in analyzing distance and time related mismatches. Let's review the benefits of each system.

SUMMARY

- HP 8510A Opt. 010
  HP 8753A Opt. 010
- HP 85016B with 8756A/8757A
  HP 8328A

3603

The HP 8510A and 8753A vector network analyzers with the optional Time Domain firmware are high performance vector analyzers. The precision time domain analysis is ideal for short transmission lines. For example, analyzing fixtures, leads, launches, and connectors. Its' use is optimized for the analysis of a design and verification of performance.

HP 8510A APPLICATIONS

- Component Design
- Precision Analysis
- Fixture/Launch Analysis
- Vector Error-Corrected Network Analysis

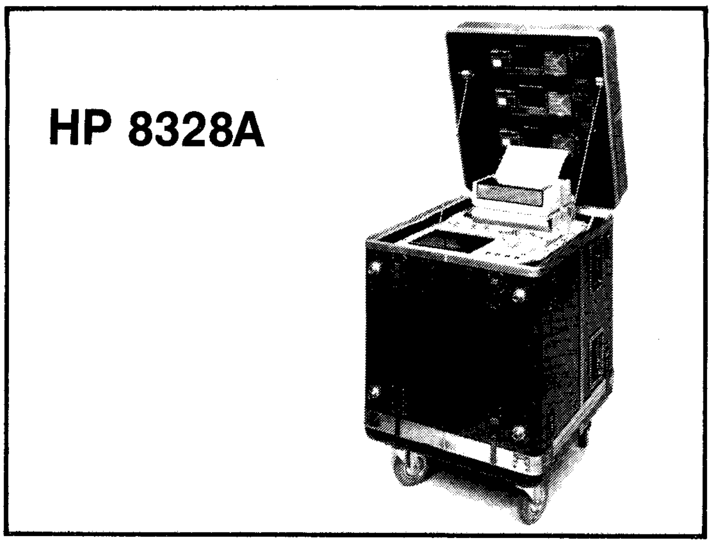
3604

The HP 85016 software for use with the HP 8756A and 8757A scalar network analyzers forms a dedicated transmission line test system. The system offers swept frequency response and distance measurements. The return loss vs. distance capability allows measurements of both coax and waveguide, with lengths over 500 ft. possible. With the limit tests, the user can configure a measurement sequence where a line can be tested and a simple pass/fail message displayed. This system is ideal for production and maintenance areas where a simple, dedicated test system is desired.

HP 85016B APPLICATIONS

- Production
- Maintenance
- Incoming Inspection
- Quick Pass/Fail Dedicated System

3605



3606

The HP 8328A Transmission Line Test System shown is a variation of the HP 85016 based scalar system. In its transportable case, you have easy access to difficult to reach lines. To reduce complexity, the analyzers' CRT and keyboard are used to interact with the software, virtually hiding the fact that the system is computer driven.

REFERENCES

1. HP 8510A Operating Manual (1984).
2. HP 85106B Operating Manual (1986).
3. HP 8510A User's Course (1984).

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