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Understanding Cable & Antenna Analysis

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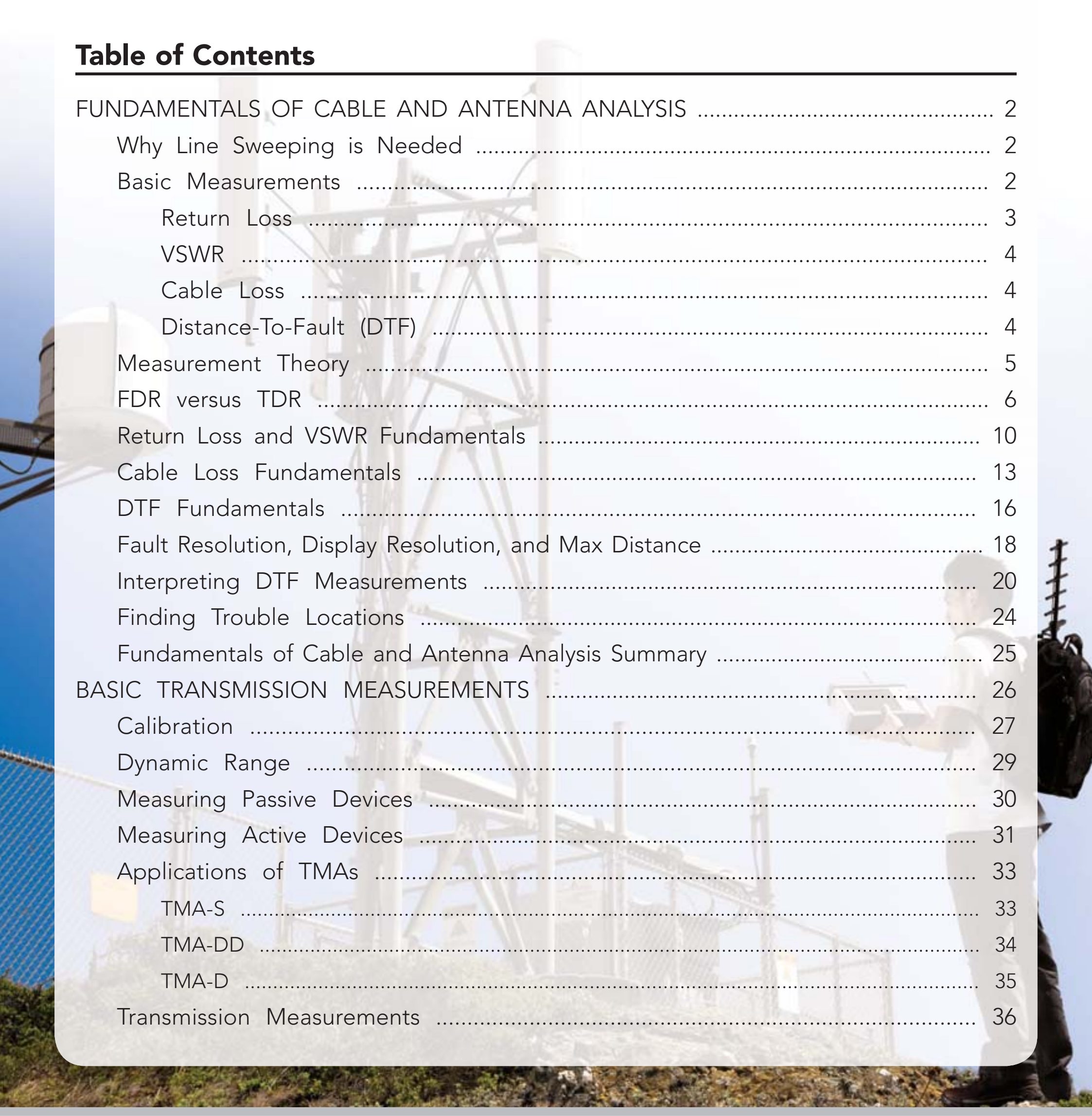
In this guide, the fundamentals of line sweeping cable and antenna systems are discussed. After reading this guide, the reader will understand what a line sweep is, why it is necessary, what affects its quality, how it is conducted, and how to best determine if a system is performing properly. Specific topics to be covered include Return Loss, Voltage Standing Wave Ratio (VSWR), Cable Loss, and Distance-to-Fault (DFT) measurements. Information on finding trouble locations will also be provided.



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1 - FUNDAMENTALS OF CABLE AND ANTENNA ANALYSIS

Why Line Sweeping is Needed

Wireless communication systems rely on good system integration and antenna performance at cell sites, repeaters and base stations. At a site, antennas are connected to the transmitter/receiver by coaxial cable or waveguide. When an issue occurs (e.g., a break, a crushed cable, moisture, or a bad connector splice in the transmission line), signal power is compromised and the site falls below specified performance limits, resulting in dropped call, loss of data or missed connections. The cable and antenna system is therefore crucial to the overall performance of a wireless communication system and must be properly maintained.

Because the cable and antenna system cannot simply be replaced when a problem occurs, troubleshooting the system to ensure it performs as expected and meets specification is a critical task for the contractor, field technician or engineer. Line sweeping—a technical method of measuring the quality of a transmission line and/or antenna system—offers the ideal means of accomplishing this goal.

Basic Measurements

When properly applied, line sweeping can accurately measure the losses in a line at any frequency and locate any faults in the line. In a cable system, a line sweep is performed to check the system's coaxial portion. Performing a line sweep when the transmission lines and antenna system have initially been installed can be very helpful when problems occur later.

When a problem does occur, the contractor, field technician or engineer is required to identify, locate, document and resolve all areas of the line sweep that do not meet specification. While this task may sound simple, it is not. The goal of a wireless communication system is to deliver RF signal energy as efficiently as possible, but transmission and antenna systems have a number of characteristics that can affect signal quality (e.g., RF signal frequency, type of transmission line, length of a transmission line, type of cable, size of cable, and quality of installation).

Two factors that affect the quality of the system are excessive reflections, caused by impedance mismatches, and excessive insertion loss (energy dissipated in the transmission line). Reflections are not desirable as they degrade the maximum transfer of electrical energy and therefore, are generally at the root of most problems in the cable and antenna system.

It should be noted that common faults in cable and antenna systems include antenna, cable and connector faults. Most faults are typically connector related and pertain to such things as loose and corroded connectors, as well as poorly installed connectors. The remaining faults are usually related to the cable portion of the system and are attributed to everything from water in the cable, loose weather wrap, pinched cables, poorly installed ground kits, and bullet holes, to nails in the cable. Antenna failures also happen but are much less common.

To better understand the problem with reflections consider that in a wireless communication system antennas are connected to the transmitter/receiver by means of a coaxial cable. Ideally, each of these system components would be set to exactly 50 ohms, allowing the system to transfer the maximum amount of signal energy. But, if one or more of the system's components are not properly matched, reflections will occur. If the level of reflections becomes excessive, the quality and performance of the cable and antenna system is greatly degraded.

All communications systems will have losses (e.g., reflections and insertion loss). The trick is to determine if they are excessive and if so, to find the problem. Handheld cable and antenna analyzers are the solution of choice for field technicians and engineers looking to analyze, troubleshoot, characterize, and maintain a cable and antenna system. By line sweeping the system, such instruments make a number of key measurements that are critical for cable and antenna analysis and can determine whether or not there are excessive losses in the system, including:

Return Loss

The Return Loss is the reflection of signal power resulting from the insertion of a device in a transmission line and measures the reflected power of the system compared to the input power. It is usually expressed as a ratio in dB relative to the transmitted signal power. Return Loss is caused by impedance mismatch between two or more circuits. For example, in a simple cable assembly, a mismatch will occur where the connector is mated with the cable. As a general rule of thumb, a high return loss denotes better quality of the system under test. A cable with a return loss of 21 db therefore, is better than a similar cable with a return loss of only 14 db.

VSWR

VSWR is a measure of the ratio of the minimum and maximum voltage in the transmission line. As an example, the VSWR value 1.2:1 denotes a maximum standing wave amplitude that is 1.2 times greater than the minimum standing wave value. High reflections cause a high ratio of minimum to maximum voltage. Note that the Return Loss and VSWR parameters are interrelated. Only one measurement is usually done, since both are methods of looking at system reflection.

Cable Loss

Insertion loss (Cable Loss) of the transmission line is a measure of the amount of energy that is absorbed by the transmission line as a signal travels down the cable. This loss is caused by the resistance of the cable and is measured in decibels (dB). The Cable Loss measurement includes losses of mated connectors from reference cables to both connectors on the cable under test, plus the loss of the fiber in the cable under test.

In general, a smaller diameter cable has more loss than larger diameter cable. For a specific cable type, the longer the cable length the greater the amount of energy it absorbs. Different cable types have different losses. Also, loss is specific to the frequency range—the higher the frequency range the greater the loss.

Distance to Fault (DTF)

DTF is another key measurement that the cable and antenna analyzer performs. It measures the distance-to-fault along the various system components of the transmission line in order to find locations of excessive reflections measured with Return Loss (DTF-RL) or VSWR (DTF-VSWR) and to predict future failure conditions. It displays RF Return Loss or SWR data versus distance to quickly identify the effects of poor connections, damaged cables or faulty antennas. Since DTF automatically accounts for attenuation versus distance, the display accurately indicates the Return Loss or VSWR of the antenna. DTF uses the Frequency Domain Reflectometry (FDR) measurement technique—a transmission line fault isolation method which precisely identifies signal path degradation for coaxial and waveguide transmission lines.

Measurement Theory

Before taking a more detailed look at the basic measurements necessary for cable and antenna system analysis, it's first critical to understand some of the fundamentals of TDR and FDR techniques. The more traditional technique, TDR, determines the characteristics of electrical lines by observing reflected waveforms. It begins with the propagation of a step or impulse of energy into a system and the subsequent observation of the energy reflected by the system. By analyzing the magnitude, duration and shape of the reflected waveform, the nature of the impedance variation in the transmission system can be determined.

The FDR measurement technique requires a swept frequency input to the transmission line. An inverse FFT (Fast Fourier Transform) is performed on the reflected signals, transforming this information into the time domain. By knowing the propagation velocity, the distance can be calculated using this information (Figure 2-1). Note that the relative propagation velocity of a coaxial transmission line is required for the distance calculation. The attenuation per foot or meter for the cable is also required in order to compensate for the attenuation versus distance. Likewise, the cutoff frequency and waveguide loss are required for DTF measurements of waveguide transmission lines.

FDR versus TDR

FDR and TDR techniques are used for similar purposes, but are very different in their technical implementation. First consider TDR techniques. TDR equipment sends pulsed DC or 1⁄2 sine wave signals into the transmission line and then digitizes the return response of reflected pulses. Pulse TDR was the original TDR methodology used to evaluate input impedance of components. Because it employs a fast rising DC pulse as the source, only a small amount of energy is sent. This technique is used for 50 Ω transmission lines and typically covers distances of less than 200 feet with an accuracy of ±1%. Some TDRs use a 1⁄2 sine wave source to test telecommunication transmission lines. Because the source services large amounts of energy, it is able to make measurements over a longer distance. For 50 Ω and 75 Ω transmission lines, for example, it can cover distances up to 50,000 feet with an accuracy of ±1%.

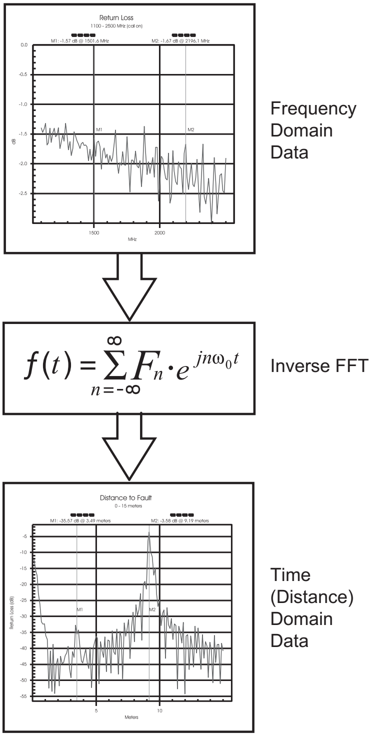


Figure 1-1. *This graphic depicts the actual Return Loss versus distance.*

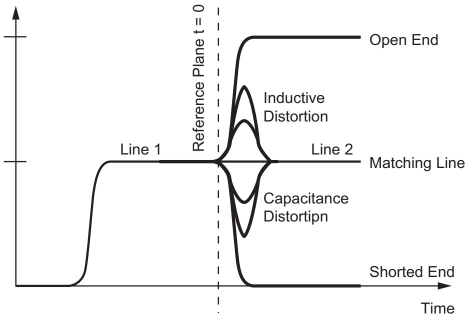


Figure 1-2. *DTF with impedance*

DTF with impedance information uses TDR pulse (Figure 1-2). This technique measures the impedance change of a cabling system versus distance using the cable propagation velocity (vp). It can identify the precise location of potential sources of DC level failures; however, no information regarding performance problems at actual operating RF frequencies is available.

In contrast to TDR, the FDR technique requires a swept frequency RF signal (Figure 1-3). The FDR principle involves vector addition of the sources output signal with reflected signals from faults and other reflective characteristics within the transmission line.

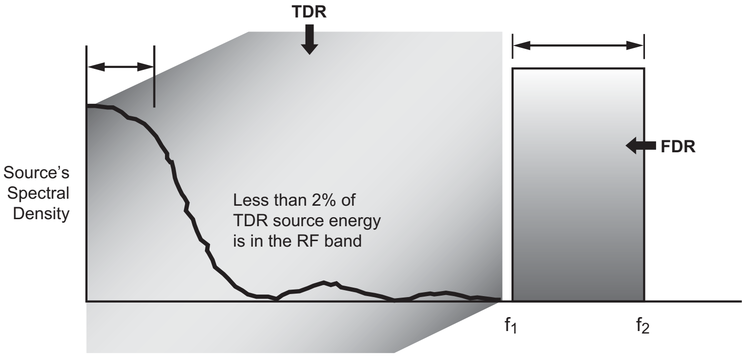
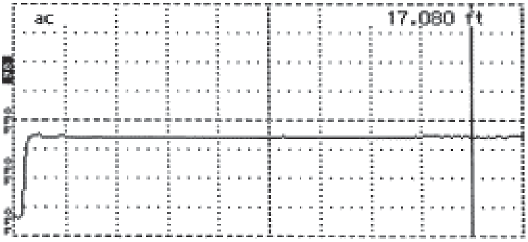


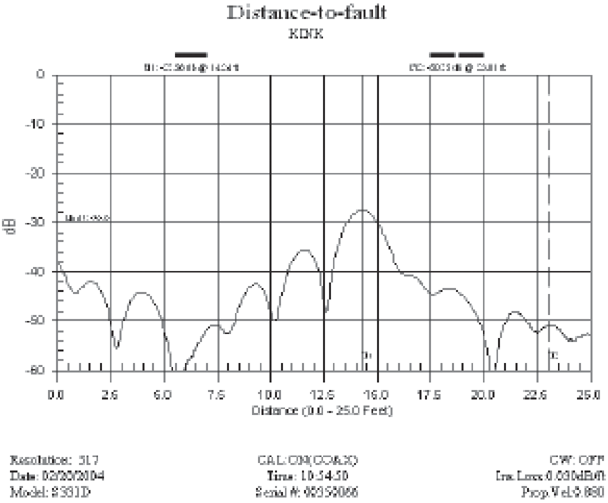
Figure 1-3. *A key benefit of analyzing a cable and antenna system using the RF sweeps made possible with FDR is that antennas can be tested at their correct operating frequency and the signal goes through frequency-selective devices like filters, lightning arrestors, high-pass filters, and duplexers, which are common to cellular antenna systems.*

Historically TDRs have been less expensive than FDR-based analyzers. While the price discrepancy no longer holds true today, the technical differences remain. For all practical purposes, TDRs do not measure RF performance. Rather, they identify opens or shorts in the conductors. Consequently, neither cables nor antennas can be tested to their RF specifications. FDR-based analyzers, on the other hand, can predict future failure conditions and precisely locate faults and degradation in system performance. As a result, many TDR devices have now become obsolete.

Figure 1-4 provides a visual comparison of a TDR versus FDR display, both measuring a kink in a coaxial cable at 14.2 feet. The cable anomaly can be clearly seen using FDR techniques. The same cannot be said for TDR, since TDR-based analyzers are limited by the fact that a corroded junction or over-crimped cable might easily pass a DC signal but cause large reflections of RF power. Despite commercial claims of high equivalent bandwidth, pulse TDRs do not provide sufficient effective directivity for accurate RF frequency tests such as Return Loss. Sensitivity is simply not adequate enough to identify small changes in Return Loss characteristics. Furthermore, TDRs frequently fail to measure in the presence of RF interference from nearby transmitters. They support only catastrophic open and short circuit failure conditions.



TDR Presentation



FDR Presentation

Figure 1-4. *Illustrated here is the graphic representation of a TDR versus FDR measurement.*

Because of these reasons, most modern analyzers used to characterize the cable and antenna system utilize the far more sensitive FDR measurement technique. Analyzing the data in the frequency domain, as opposed to the more traditional time domain, enables users to find small degradations or changes in the system, thereby preventing severe system failures.

Return Loss and VSWR Fundamentals

Return Loss and VSWR measurements are two key measurements for anyone making cable and antenna measurements in the field. They show the field technician or engineer the match of the system and whether or not it conforms to system engineering specifications. If problems show up during this test, the system is likely to have problems that will affect the end user. A poorly matched antenna, for example, will reflect costly RF energy that will not be available for transmission and will instead end up in the transmitter. The extra energy returned to the transmitter will not only distort the signal, but it will also affect the efficiency of the transmitted power and the corresponding coverage area.

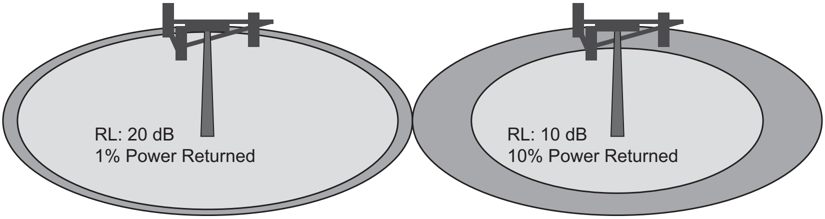


Figure 1-5. *This example shows that a poorly matched antenna can impact the Return Loss measurement and, in turn, affect the efficiency of the transmitted power.*

For instance, a 20 dB system Return Loss measurement is considered very efficient as only 1% of the power is returned and 99% of the power is transmitted (Figure 1-5). If the return loss is 10 dB, 10% of the power is returned. While different systems have different acceptable Return Loss limits, 15 dB or better is a common system limit for a cable and antenna system.

Return Loss and VSWR both display the match of the system but they show it in different ways. When a signal is sent through a transmission line to an antenna, most of the signal reaches the antenna. Some of the signal is reflected from various discontinuities in the system, such as links in the cable, loose connectors or jumper problems. These reflections are measured to give an idea of the integrity of the overall antenna system. Return Loss is a way to show the power, in dB, that doesn't reach the destination but rather is reflected back to the transmitter. In other words, it is the ratio of reflected power to reference power. The goal is to make the reflected power as small as possible. For a Return Loss measurement, a higher value is better than a smaller value.

The Return Loss view is usually preferred due to the benefits associated with logarithmic displays; one of which is that it is easier to compare a small and large number on a logarithmic scale. Note that the Return Loss scale is normally set up from 0 to 60 dB, with 0 being an open or a short and 60 dB being close to a perfect match.

In contrast to Return Loss, VSWR displays the match of the system linearly. It measures the ratio of voltage peaks and valleys. The greater this number is, the worse the match. In VSWR, the best possible value (perfect match) is 1:1, which means that all of the power generated by a transmitter is either radiated from the antenna, or absorbed by losses in the system, with none returning to the transmitter. A more realistic match for a cable and antenna system is in the order of 1.43 (15 dB). Antenna manufacturers typically specify the match in VSWR. The scale of a VSWR is usually defaulted to setup between 1 and 65.

Note that for systems with low reflections, it is often easier to understand performance variations when the results are displayed as Return Loss rather than SWR. For example, 26.44 dB Return Loss is an SWR of 1.10, while 23.13 dB Return Loss is an SWR of 1.15.

VSWR can be converted to Return Loss using the following equations:

$\text{VSWR} = 1+10^{-RL/20}/1-10^{-RL/20}$ Equation 1-1

$\text{Return Loss} = 20 \log |\text{VSWR}+1/\text{VSWR}-1|$ Equation 1-2

The trace in Figure 1-6 shows a Return Loss measurement of a cellular antenna matched between 806-869 MHz. The Return Loss amplitude scale is setup to go from 0.5 dB to 28 dB. The VSWR display in Figure 1-7 measures the same antenna and the amplitude scale has been setup to match that of the Return Loss measurement. The two graphs illustrate the relationship between VSWR and Return Loss, which in this case, can be stated simply as: 8.84 dB RL↔2.15 VSWR.

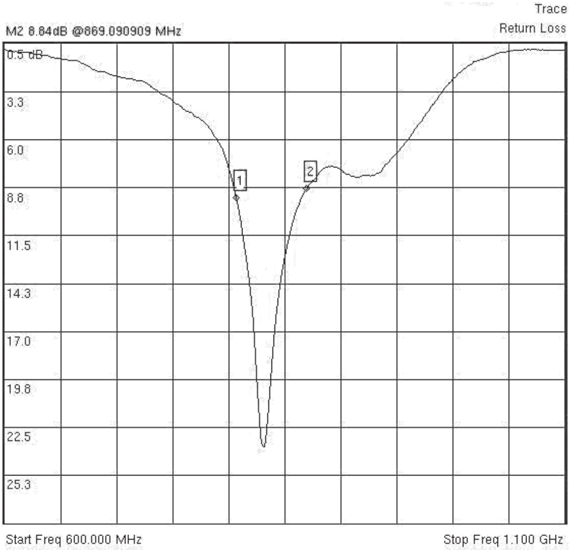


__Figure 1-6.__ Display of a Return Loss measurement.

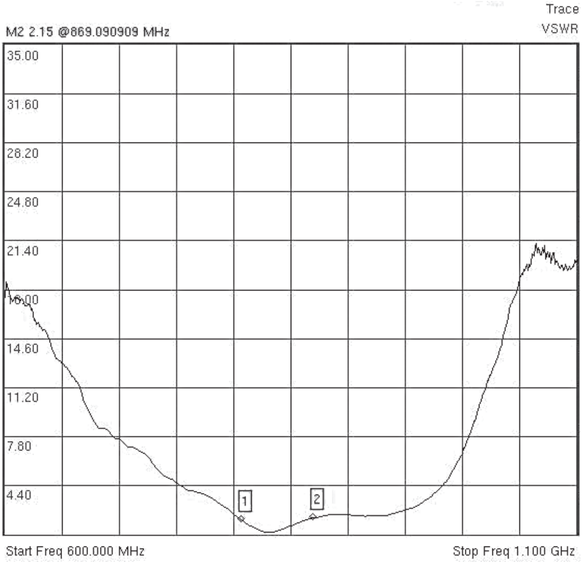


__Figure 1-7.__ Display of a VSWR measurement.

Cable Loss Fundamentals

As a signal travels through the transmission path, some of its energy is dissipated in the cable and the components. Different transmission lines have different losses, with the loss being frequency and distance specific. To account for this loss, a baseline Cable Loss measurement is typically made at the installation phase to ensure that the cable loss is within the manufacturer's specification and to show that the system has been installed correctly and is working properly. This measurement can be made with either a portable vector/scalar network analyzer or a power meter.

Cable Loss can also be measured using the Return Loss measurement available in a cable and antenna analyzer. For this measurement, a precision short circuit is placed at the end of the cable. A signal is then sent down the cable. When the signal is reflected back, the energy lost in the cable can be computed. The higher the return signal, the lower the Cable Loss. With coaxial cable, the higher the frequency or longer the cable, the greater the loss that will occur. Equipment manufacturers suggest that contractors, field technicians and engineers should use the average Cable Loss of the swept frequency range. This can be obtained by adding the peak of the trace to the valley of the trace and dividing by two in Cable Loss mode or, by dividing by four in Return Loss mode to account for the fact that the signal travels back and forth.

Most portable cable and antenna analyzers today are equipped with a Cable Loss mode that displays the average Cable Loss of the swept frequency range. This is usually the preferred method since it eliminates the need for any math. An example of a Cable Loss measurement made using a cable and antenna analyzer is shown in Figure 1-8. Note that, increasing the RF frequency and the length of the cable also increases the insertion loss. Cables with larger diameter have less insertion loss and better power handling capabilities than cables with smaller diameter.

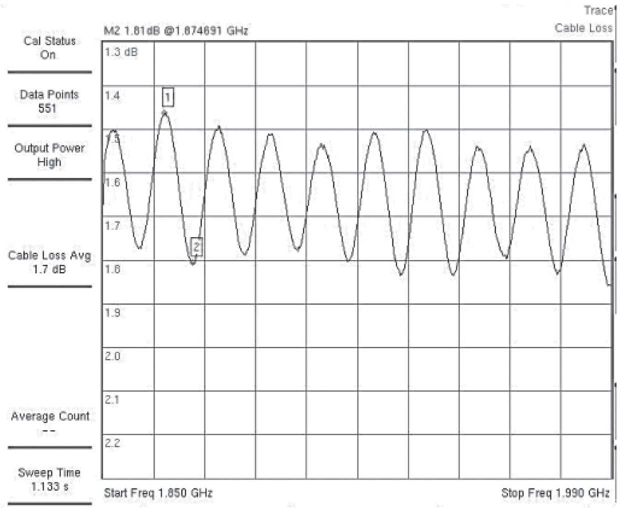


Figure 1-8. *Shown here is a Cable Loss measurement of a cable between 1850 and 1990 MHz that was made using a portable cable and antenna analyzer. The markers at the peak and valley can be used to compute the average. This particular handheld instrument has the ability to compute the average Cable Loss for the user, as can be seen in the left part of the display,*

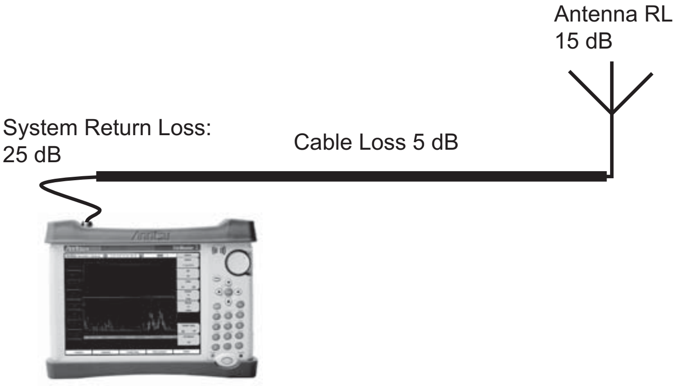


Figure 1-9. *Illustrated here is the setup for measuring system Return Loss.*

Since Cable Loss can have a significant effect on the cable and antenna system's Return Loss, it is vital to take in into consideration when making system Return Loss measurements. Figure 1-9 illustrates how the Cable Loss changes the perceived antenna performance. Here the antenna has a Return Loss of 15 dB, but the 5 dB insertion loss improves the perceived system Return Loss by 10 dB (5 dB-x-2).

While system designers generally take this information into consideration when setting up a site's specifications, it is important to be aware of the effects that the Insertion Loss and cable Return Loss can have on the overall system Return Loss. A very good system Return Loss may not necessarily be the result of an excellent antenna and therefore, might not always be a good things; it could be due to a faulty cable with too much insertion loss and an antenna that is out of specification. This would result in a larger than expected signal drop and once the signal reaches the antenna, a greater portion of it would be reflected since the match is worse than expected. As a result, the transmitted signal would be lower than needed and the overall coverage area would be affected.

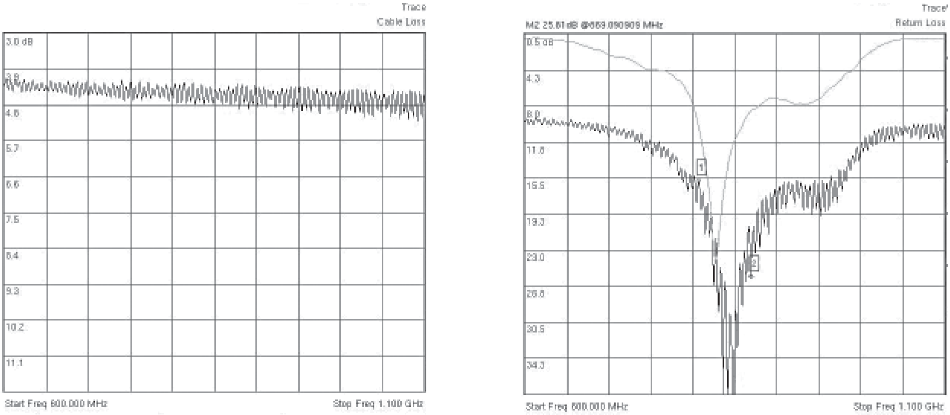


Figure 1-10. *The antenna Return Loss is shown on the left, while Cable Loss is on the right.*

As an example, consider the Cable Loss measurement of two 40 feet cables connected together, as shown in Figure 1-10. The combined Cable Loss averages about 4.5 dB. The graph on the left illustrates the differences between measuring the Return Loss at the antenna and measuring it for the entire system, including the 4.5 dB insertion loss of the cable. The graph on the right—the Cable Loss graph—shows how the insertion loss of the cable increases with frequency. Note that the delta in the graph on the left is proportional to 2-x-CL. Also, notice that the difference between the two traces in this graph is greater at 1100 MHz than it is at 600 MHz. The majority of this delta is a result of the Cable Loss increasing as the frequency increases. If both the Return Loss of the antenna and system Return Loss is known, the Cable Loss can be estimated from this information.

DTF Fundamentals

Return Loss/VSWR measurement characterizes the performance of the overall system. If either of these is failing, the DTF measurement can be used to troubleshoot the system and locate the exact location of a fault. It is a troubleshooting tool and best used to compare relative data and monitor changes over time with the main purpose of locating faults (e.g., with connector transitions, defective jumpers, kinks in the cable, and moisture intrusion or other similar defects that cause reflections) and measuring the length of the cable.

Using the DTF absolute amplitude values derived from the DTF data as a replacement for Return Loss or as a pass/fail indicator is not recommended. There are simply too many variables that affect the DTF readings (e.g., propagation velocity variation, insertion loss inaccuracies of the complete system, stray signals, temperature variations, and mathematical discontinuities), making it is very challenging for the engineer to come up with numbers that take all of this into consideration. When used correctly, the DTF measurement is by far the best method for trouble shooting cable and antenna problems.

The DTF measurement is based on the same information as the Return Loss or Cable Loss measurement. The measurement is done on a normal load, such as an antenna or a good quality 50 Ω load, connected to the far end of the transmission line. Usually the antenna is replaced with a load to avoid receiving interference from nearby sites. It sweeps the cable in the frequency domain and, with the help of the Inverse Fast Fourier Transform (IFFT), converts the data from the frequency domain to the time domain. In other words, if you forgot to do a DTF measurement but have the Return Loss and access to the magnitude and phase data of the 1-port measurement, you can use this data to create a DTF plot in software.

The dielectric material in the cable affects the propagation velocity which, in turn, affects the velocity of the signal traveling through the cable. The accuracy of the propagation velocity (vp) value determines the accuracy of the location of the discontinuity. A ±5% error in the vp value will affect the distance accuracy accordingly and the end of an 80 ft cable could show up anywhere between 76 and 84 ft. Even if the vp value is copied out of the manufacturer's data sheet, there could still be discrepancies between the interpreted and actual distance discontinuities, due to the adding of all the components in the system. Common base station systems can include a main feed line, feed line jumper, adapters, and top jumpers, and, even though the main feed line contributes with the largest amount, the velocity of the signal through the other parts of the system could be different.

The accuracy of amplitude values is usually of less importance because DTF is used solely to troubleshoot a system and find problems. Therefore, whether a connector is at 30 or 35 dB may not be as interesting as if the connector was at 35 dB one year ago and now is at 30 dB. While the propagation velocity value remains fairly constant over the entire frequency range, the insertion loss of the cable does not and this also affects the amplitude accuracy.

Most handheld instruments available today have built-in tables that include propagation velocity values and cable insertion loss values for different frequencies of the most commonly used cables (Table 1-1). This simplifies the task for the field technician as he/she can locate the cable type and obtain the correct vp and Cable Loss values.

Cable	Prop Velocity	1000 MHz	2500 MHz
Andrew LDF4-50A	**0.88**	**0.073 dB/m**	**0.120 dB/m**
Andrew HJ4.5-50	**0.92**	**0.054 dB/m**	**0.089 dB/m**

Table 1-1. *Different Cable Loss levels for two commonly used cables.*

Fault Resolution, Display Resolution and Max Distance

The term resolution can be confusing and its definitions can vary. For DTF, it is important to understand the difference between fault resolution and display resolution since the meanings are different.

The fault resolution is the systems' ability to separate two closely spaced signals. Two discontinuities located 0.5 ft apart from each other will not be identified in a DTF measurement if the fault resolution is 2 ft. Because DTF is swept in the frequency domain, the frequency range affects the fault resolution. A wider frequency range therefore means better fault resolution and a shorter maximum distance. Similarly, a narrower frequency range leads to wider fault resolution and greater maximum horizontal distance. The only way to improve the fault resolution is to increase the frequency range.

The MATLAB simulations shown in Figures 1-11 and 1-12, based on the DTF algorithm, show how two –20 dBm faults simulated to take place 2 ft apart at 9 ft and 11 ft, only show up when the frequency range has been widened from 1850-1990 MHz to 1500-1990 MHz. The 1850-1990 MHz sweep gives a fault resolution of 3.16 ft (vp=0.91), while the 1500-1990 MHz sweep gives a fault resolution of 0.9 ft. More data points in the example in Figure 1-11 would have given us finer display resolution, but it would only be a nicer display of the same graph. It would not matter if there were 20,000 data points, the two faults would still not show up unless the frequency range was widened.

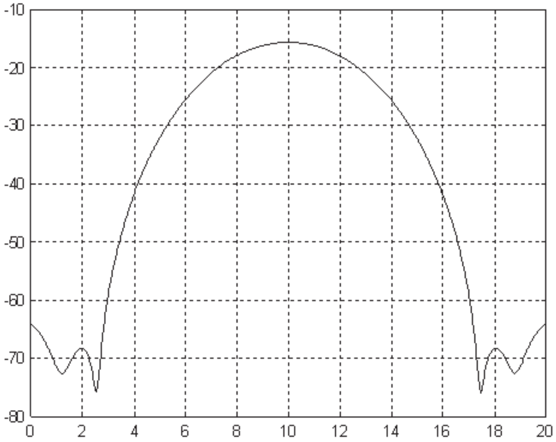


Figure 1-11. *DTF sweep 1850-1990 MHz.*

The curious observer will also note that the amplitude of the two discontinuities show up at –20 dBm in Figure 1-12. In the first example, the two amplitudes add up to create one fault with greater amplitude than the two individual faults.

To better understand these concepts, consider that:

Fault Resolution (m) = 150*vp/ΔF (MHz) Equation 1-3

Fault Resolution (ft) = 15000*vp/(ΔF*30.48) Equation 1-4

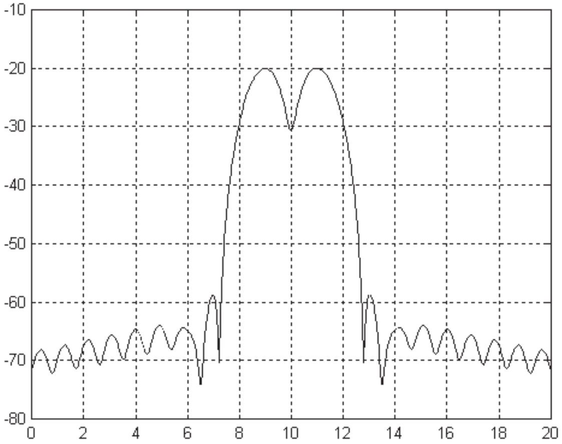


Figure 1-12. *DTF sweep 1500-1990 MHz.*

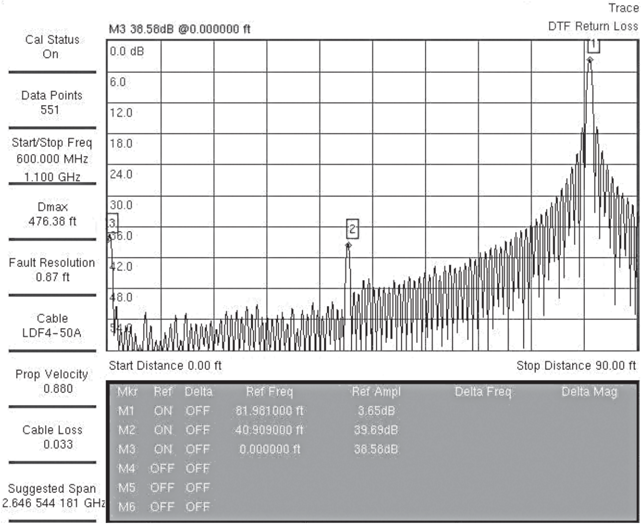
Now, consider the example in Figure 1-13:

Fault Resolution (ft) = 15000*0.88/((1100-600)*30.48) = 0.866 ft

Note that Dmax is the maximum horizontal distance that the instrument can measure. It is dependent on the number of data points and the fault resolution, and is calculated according to:

Dmax = (datapoints-1)*Fault Resolution Equation 1-5

Therefore (ft) = (551-1)*0.866 ft = 476.3 ft.



Cal Status
On

Data Points
551

Start/Stop Freq
600.000 MHz
1.100 GHz

Dmax
476.38 ft

Fault Resolution
0.87 ft

Cable
LDF4-50A

Prop Velocity
0.880

Cable Loss
0.033

Suggested Span
2.646 544 181 GHz

Mkr	Ref	Delta	Ref Freq	Ref Ampl	Delta Freq	Delta Mag
M1	ON	OFF	81.981000 ft	3.65dB		
M2	ON	OFF	40.909000 ft	39.69dB		
M3	ON	OFF	0.000000 ft	38.58dB		
M4	OFF	OFF				
M5	OFF	OFF				
M6	OFF	OFF				

Figure 1-13. *DTF measurement.*

Interpreting DTF Measurements

In the ideal world, the DTF measurement would be done with no frequency selective components in the path and just a termination at the end of the cable. Most of the time, this is not the case. Consequently, the contractor, field technician or engineer must be able to make the measurement with different components in the path and at the end of the cable.

Figures 1-14 and 1-15 depict graphs of DTF measurements with the same instrument setup. The two 40 ft LDF4-50A cables are connected together with an open at the end of the cable in Figure 1-14. In Figure 1-15, the two 40 ft LDF4-50A cables are connected together with a PCS antenna at the end of the cable. The only difference between the two graphs is the amplitude level of the peak that shows the end of the cable. Figure 1-16 shows the DFT PCS antenna measurement with the fault visible.

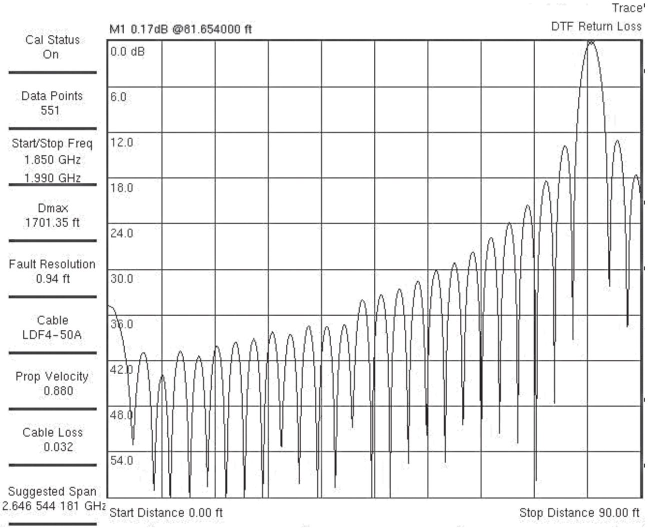


Figure 1-14. DTF open.

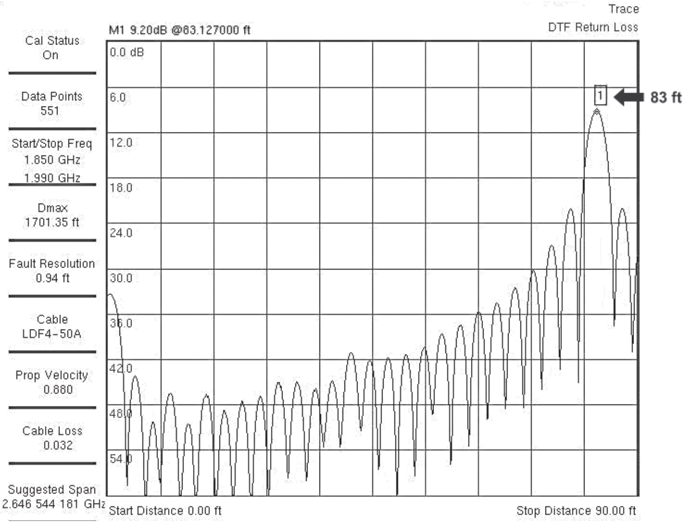
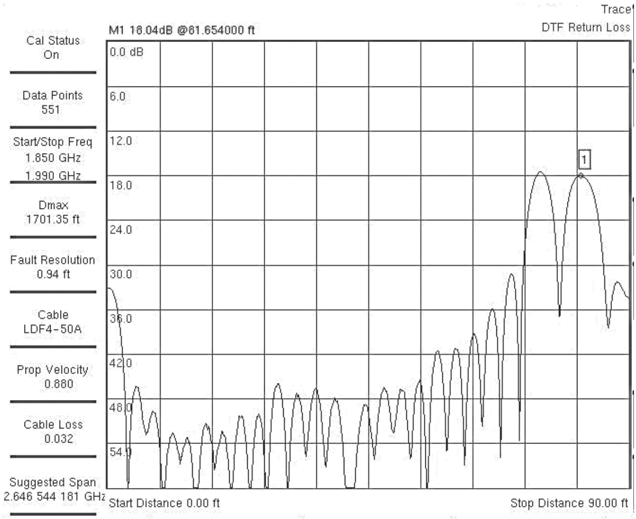


Figure 1-15. DTF PCS antenna.



Cal Status On

Data Points 551

Start/Stop Freq 1.850 GHz 1.990 GHz

Dmax 1701.35 ft

Fault Resolution 0.94 ft

Cable LDF4-50A

Prop Velocity 0.880

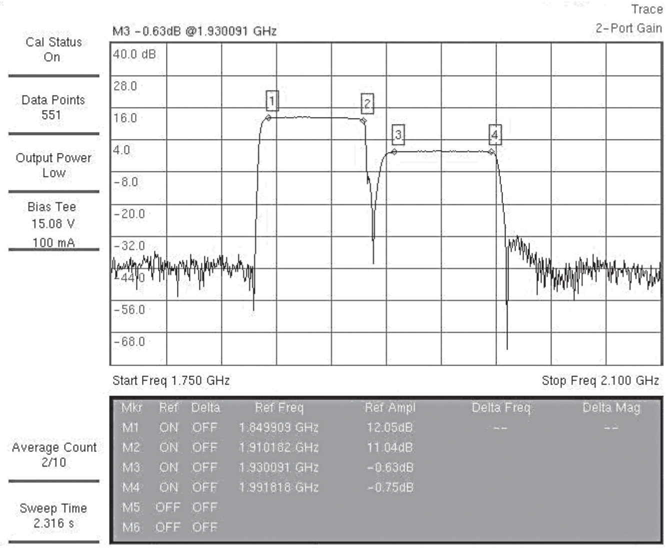
Cable Loss 0.032

Suggested Span 2.646 544 181 GHz

M1 18.04dB @81.654000 ft

Figure 1-16. *DTF PCS antenna with fault.*

Figure 1-18 shows how the electrical length of the Tower Mounted Amplifier (TMA) in Figure 1-17 affects the distance measurement of the system. The graph in Figure 1-17 shows a Transmission Measurement of a 2-port dual duplex LNA. Figure 1-18 shows the DTF measurement of this system swept with the TMA in the path. The end connection shows up at 106 ft because the TMA was swept over both the uplink and downlink bands of the TMA. The end of the same system without the TMA in the path shows up at 83 ft (Figure 1-15).



Cal Status On

Data Points 551

Output Power Low

Bias Tee 15.08 V 100 mA

Average Count 2/10

Sweep Time 2.316 s

M3 -0.63dB @1.930091 GHz

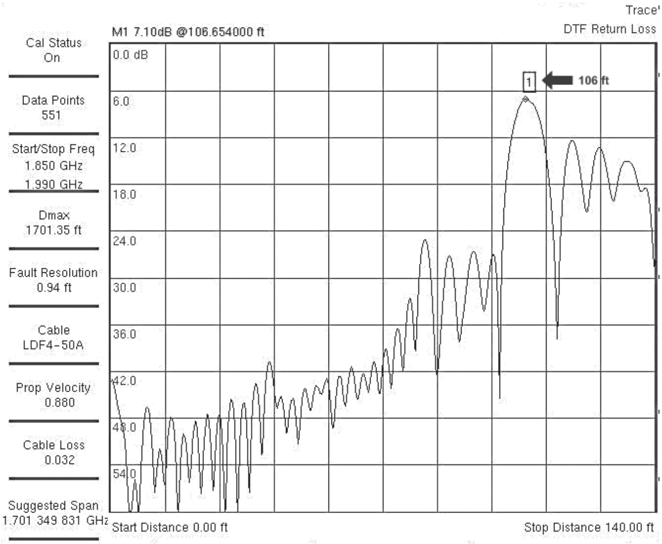
Trace 2-Port Gain

Start Freq 1.750 GHz

Stop Freq 2.100 GHz

Mkr	Ref	Delta	Ref Freq	Ref Ampl	Delta Freq	Delta Mag
M1	ON	OFF	1.849909 GHz	12.05dB	--	--
M2	ON	OFF	1.910182 GHz	11.04dB		
M3	ON	OFF	1.930091 GHz	-0.63dB		
M4	ON	OFF	1.991818 GHz	-0.75dB		
M5	OFF	OFF				
M6	OFF	OFF				

Figure 1-17. *2-port measurement of TMA.*



Cal Status On

Data Points 551

Start/Stop Freq 1.850 GHz 1.990 GHz

Dmax 1701.35 ft

Fault Resolution 0.94 ft

Cable LDF4-50A

Prop Velocity 0.880

Cable Loss 0.032

Suggested Span 1.701 349 831 GHz

M1 7.10dB @106.654000 ft

Trace DTF Return Loss

Start Distance 0.00 ft

Stop Distance 140.00 ft

Figure 1-18. *DFT measurement with the TMA in the path.*

Finding Trouble Locations

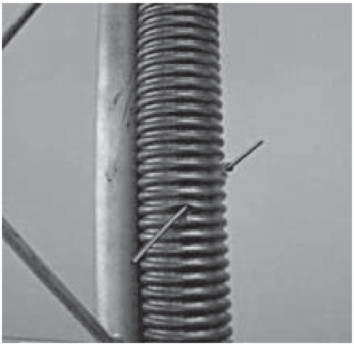


Figure 1-19. *While an antenna system could be faulty for any number of reasons, poorly installed connectors, dented/damaged coax cables and defective antennas tend to dominate the failure trends.*

In a cable and antenna system, there are many types of problems which can occur. In the cable, these problems include: cable discontinuities, damaged/dented ground shield, moisture and corrosion, and fasteners pinching cables. In contrast, problems with the antenna may include: performance out of specification, storm/shipping damage and a damaged lightning arrestor (Figure 1-19). While it easy to understand the types of faults that may occur, finding their exact location in the cable and antenna system can be difficult.

If there are problems in the cable and antenna, a DTF measurement provides the best insight regarding the locations of the problems (refer to DTF Fundamentals). Trace comparisons are often used for diagnostics because small changes in cables will have large effects on the DTF trace. Because of this, it is accepted practice to take reference sweeps of each cable using a cable and antenna analyzer at commissioning time for later comparison. Changes are often more significant than actual values. Even so, typical values with a good setup are:

- Open or Short: 0 to 5 dB
- Antenna: 15 to 25 dB
- Connectors: 30 to 40 dB

Propagation Velocity (vp) directly affects distance accuracy. When making DTF measurements, vp must be set either manually or by entering a cable type. Cable Loss also needs to be set accurately, either manually, or by selecting a cable type. False Cable Loss values can mask Return Loss or VSWR problems.

Another thing to keep in mind with DTF sweeps is the frequency range, which should be set to stay within the load's bandwidth. If an antenna is used for the load, any portion of the DTF sweep that goes outside of the pass band is mostly reflected, thereby reducing the accuracy of the vertical axis Return Loss or VSWR measurements. A wider frequency range improves distance resolution and lowers the maximum measureable distance. However, if an antenna is in place at the other end of the cable, the DTF frequency range should be restricted to the antenna's pass band.

Summary

The cable and antenna system is crucial to the overall performance of a wireless communication system and must be properly maintained. Line sweeping is a method of measuring the quality of a transmission line and/or antenna system. In an ideal world, the line sweep tells the contractor, field technician or engineer two things: the quality of the transmission system in question and its characteristics.

During the line sweep, Return Loss, VSWR, and Cable Loss measurements can be made to determine if there are excessive losses in the system. Once a problem is identified with either the Return Loss or VSWR measurement, the DTF measurement can be used to troubleshoot the system and locate the exact location of a fault. Each of these measurements is critical to ensuring the cable and antenna system operate according to specification.

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2 - TRANSMISSION MEASUREMENT BASICS

This section introduces the reader to basic transmission measurements. It underscores the importance of calibration to ensuring accurate, reliable measurements and provides practical tips for making transmission measurements on Tower Mounted Amplifiers (TMAs).

There are two fundamental scalar measurements—reflection and transmission. A scalar transmission measurement measures how much signal passes through the device under test (DUT) and can be used to determine its gain or insertion loss. Insertion Gain is defined as the gain that results from inserting a device in a transmission line. It is expressed in dB as the ratio of the signal power delivered to that part of the line following the device, to the signal power delivered to the same part of the line prior to insertion. Insertion Loss is the exponential decrease with distance, in the amplitude of an electrical signal traveling along a very long uniform transmission line, due to conductor and dielectric losses.

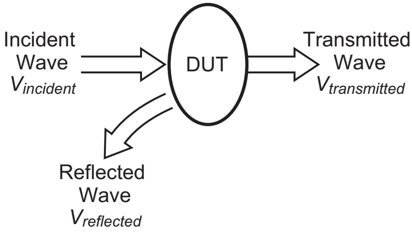


Figure 2-1. *This graphic depicts the transmission and reflection parameters that are important to know when making a transmission measurement.*

To better understand how to make a transmission measurement it's first necessary to learn a few basic transmission terms. The transmission coefficient, τ, is defined as the ratio of the transmitted voltage, $V_{transmitted}$, to the incident voltage, $V_{incident}$, as shown in Figure 2-1.

$$\tau = V_{transmitted}/V_{incident} \qquad \text{Equation 2-1}$$

Since typical spectrum analyzer displays are logarithmic, the transmission coefficient can be expressed in dB as:

$$20 \log [\tau] \text{ or } 20 \log [V_{transmitted}] - 20 \log [V_{incident}] \qquad \text{Equation 2-2}$$

This coefficient can be applied to all transmission measurements, with both passive and active DUTs.

Traditionally, transmission measurements have been made using a tracking generator (TG). The TG is a signal generator with an output that tracks or follows the tuning of a spectrum analyzer and allows a spectrum analyzer to perform scalar network measurements. It has an adjustable-level output that is used with a fixed-level input. While the TG can be a relatively inexpensive addition to a spectrum analyzer for making scalar frequency response measurements, it is not ideal for wireless measurement applications where the low-power, input device limits the source power that can be applied to the input of the DUT. Here, a low noise floor is required and nonlinear measurements must be made.

In this type of environment, a more appropriate measurement solution is the vector network analyzer equipped with a transmission measurement option that combines the capabilities of a TG with a spectrum analyzer to realize significant performance benefits. This alternative offers the ideal solution for verifying the performance (e.g., measuring the loss or gain) of two-port devices such as filter, cables, duplexers, attenuators, and amplifiers. It can also be used to verify antenna isolation between two sectors.

Calibration

Prior to making transmission measurements, the measurement instrument must be calibrated. Re-calibration is required whenever the temperature exceeds the calibration temperature range or when the instrument's test port extension cable is removed or replaced. The instrument must also be re-calibrated every time the setup frequency changes.

Calibrations are a vital part of ensuring accurate, repeatable transmission measurements, or any measurement for that matter, and are critical to establishing a reference baseline. Three types of errors that are associated with measurements include:

- **Systematic.** These types of errors are caused by imperfections in measurement equipment and accessories (e.g., cables and adapters). Because systematic errors do not change over time, they are both repeatable and predictable. Proper calibration can be used to mathematically eliminate these errors.
- **Drift**. These errors occur after a calibration has been performed and are most commonly associated with temperature changes. In some vector network analyzers, an error icon will display when the temperature has changed enough since calibration to cause excessive errors. Drift errors can be eliminated by properly recalibrating the vector network analyzer.
- **Random.** These types of errors are unpredictable and time varying. Common random errors are instrument noise floor and connector repeatability. Random errors cannot be removed by the vector network analyzer.

Performing accurate, repeatable measurements with a network analyzer requires precision calibration components. Such components allow the contractor, engineer or field technician to maintain measurement integrity and also remove both systematic and drift errors. Proper maintenance and care for these components is also critical.

Phase-stable test port cables provide the contractor, engineer of field technician with one way to ensure accurate, repeatable measurements. Phase stable means that after performing a calibration at the end of a test port cable, any subsequent measurements will be repeatable regardless of the cables' physical position. In contrast, when poor quality cables (e.g., those that are not phase stable) are moved, even slightly, they introduce large errors into the measurements. Note that phase-stable cables are reliable as long as they are well cared for and therefore, must be periodically examined for damage, especially at the connectors.

As an example, consider the measurement of a TMA-Dual Duplex (TMA-DD) using the basic setup shown in Figure 2-2. This is a typical measurement that can be taken before the TMA is installed. Here, the output of the measurement instrument transmits a signal (Tx) to the amplifier, while the receiver tracks the signal (Figure 2-3). The measurement is swept across the entire frequency range of the 1960 to 1990 MHz transmit and the 1880 to 1910 MHz receive (Rx) bands. Markers M1 and M2 highlight the signal level in the TMA's receive band where gain is measured. Note that in all TMA types, gain is measured between the antenna port and the Rx port of the amplifier.

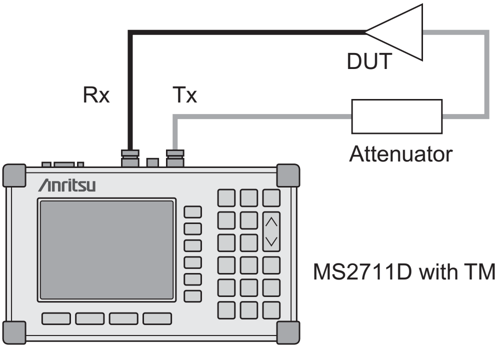


***Figure 2-2**. In this basic setup, the RF output of spectrum analyzer with transmission measurement is connected to the input of the DUT. The output of the DUT is connected to the Site Master input*

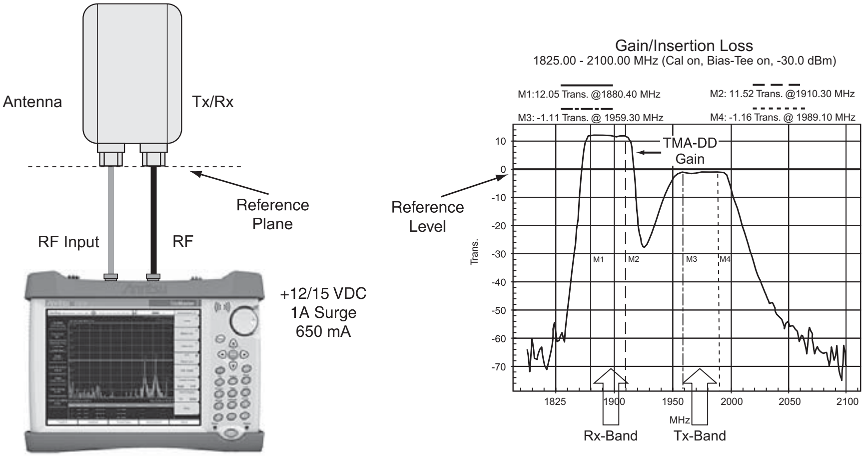
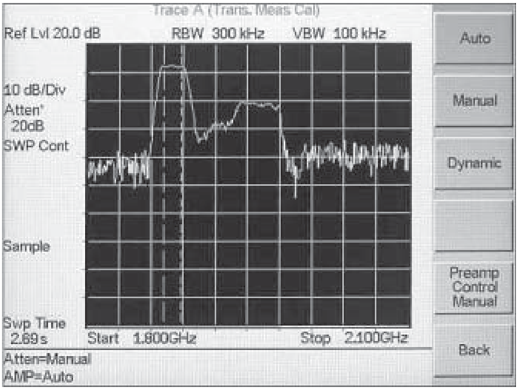


Figure 2-3. *The set-up for a TMA-DD gain measurement using a Site Master with transmission measurement option is illustrated here. Note that to prevent over-saturation of the receive signal or possible damage to the TMA, this test requires an external 30 dB attenuator.*

Dynamic Range

Dynamic range is a critical factor when making transmission measurements. Some applications like repeaters, for example, require additional dynamic range. It is also necessary for the accurate measurement of antenna-to-antenna isolation in the presence of high RF activity. Moreover, an excellent dynamic range allows the contractor, engineer or field technician to view and adjust the RF performance of critical RF devices including filters, duplexers, transmitter combiners, receiver multicouplers, and tower top amplifiers.


Trace A (Trans. Meas Cal)

Ref Lvl 20.0 dB   RBW 300 kHz   VBW 100 kHz

10 dB/Div

Atten' 20dB

SWP Cont

Sample

Swp Time 2.69s

Start 1.800GHz   Stop 2.100GHz

Atten=Manual

AMP=Auto

Figure 2-4. *Measurement of an amplifier with normal attenuation.*

Some measurement instruments offer a high dynamic range or dynamic attenuation mode (e.g., a fixed-level output with a dynamically-adjustable input) that can deal with this need, although using the mode generally slows down the instrument's sweep speed. The dynamic attenuation mode automatically tracks the input signal level and adjusts the input attenuator value to appropriately display gain at each measurement frequency (Figure 2-4 and 2-5). The reference level remains fixed at all times, regardless of dynamic attenuation changes. The result is a wider dynamic range display. Also, the power to the input mixer is always maintained in the linear region. This delivers excellent dynamic range in difficult measurement situations such as when external attenuation is needed to reduce the input level as a means of keeping the signal in the linear region of an amplifier.

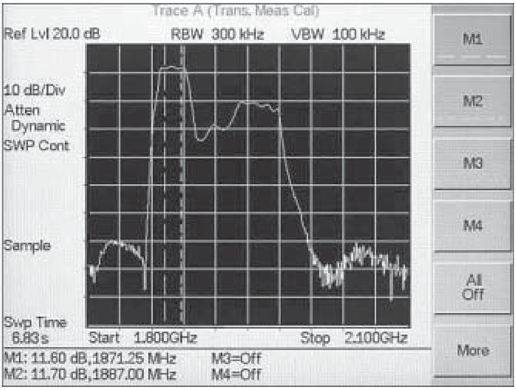

Trace A (Trans. Meas Cal)
Ref Lvl 20.0 dB
RBW 300 kHz
VBW 100 kHz
10 dB/Div
Atten
Dynamic
SWP Cont
Sample
Swp Time
6.83 s
Start 1.800GHz
Stop 2.100GHz
M1: 11.60 dB,1871.25 MHz
M2: 11.70 dB,1887.00 MHz
M3=Off
M4=Off

Figure 2-5. *Amplifier characteristics with the dynamic attenuation mode enabled.*

Measuring Passive Devices

The transmission measurement can be used to measure passive devices like filters (Figure 2-6). Depending on the TMA application, one of four basic filter types may be used. The filter types include:

- A low-pass filter which passes only those signals below a certain frequency. Low-pass filters are normally found in applications where the reduction of the harmonic content of a transmitter is desired. They are also used in the telephone and broadcast industry to limit the higher frequencies of a voice broadcast.
- A high-pass filter which passes only those signals above a certain frequency. A high-pass filter blocks the low-frequency signal

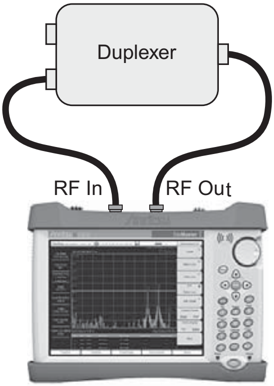


Figure 2-6. *Transmission measurement connections for a passive device.*

and allows high frequencies to pass. A good example of using both low-pass and high-pass filters to create a band-pass filter is the bass and treble controls on a stereo or car audio system.

- A band-pass filter which passes only those signals within the pass band. Band-pass filters are built into TMAs and duplexers.
- A band-stop or notch filter that attenuates a narrow slice of spectrum. A notch filter is typically used to reduce the amplitude of an off-frequency interfering signal at a receiver input. Often more than one notch filter is employed to mitigate odd-order intermodulation problems at high-level sites that are populated with many transmitters.

A duplexer allows simultaneous transmitter and receiver operation in a single antenna system. It isolates the receiver from the transmitter and reduces Tx noise. By comparison, a diplexer is a device that permits parallel feeding of one antenna from two transmitters at different frequencies, without the transmitters interfering with each other. Duplexers and diplexers are very similar and frequently confused. The duplexer separates two frequencies within the same band, while the diplexer separates two different bands.

Diplexers are three-port frequency-dependent devices that may be used as a separator or a combiner of signals. The device consists of two fixed, tuned band-pass filters sharing a common port. The common port and the output of the two filters (Rx and Tx) form the three terminals of the diplexer. Signals applied to the common port are combined in accordance with the passband frequencies of the filters. Signals applied to one uncommon port are isolated from the other uncommon port and are then combined at the common port.

Diplexers are the simplest form of a multiplexer. In contrast, duplexers allow a transmitter operating on one frequency and a receiver operating on a different frequency to share one common antenna with minimal interaction or degradation of the different RF signals.

Measuring Active Devices

In addition to measuring passive devices, the transmission measurement can be used to measure active devices like amplifiers. TMAs are active devices that are often installed at the top of cell towers, near the receiver antenna as a means of extending the receive coverage area, improving the reception of weak signals, increasing uplink sensitivity (Rx), and reducing dropped calls. Their use with any new installation is another way to provide better coverage and increase the number of subscribers without deploying new base stations in the same geographic area (Figure 2-7).

In a cell site, the TMA combines the receive/transmit signals to/from the antenna and provides pre-amplification of the signals received from cellular phones. It is mounted close to the antenna to derive the greatest benefit. Verifying the correct receive and transmit signal path is essentially a measurement of filter performance for the two distinct paths and the separation between them.

While a Return Loss or VSWR measurement of an antenna system provides the contractor, field technician or engineer with a clear indication of how well the antenna transmits power, the same cannot be said of an antenna system with a TMA. The addition of the TMA complicates the testing of the antenna system, requiring that the TMA itself be tested. An Insertion Loss/Gain Loss measurement is well suited for this purpose. The Insertion Loss measurement can also be used to perform antenna-to-antenna isolation measurements, which is crucial when more than one antenna is located on a tower.

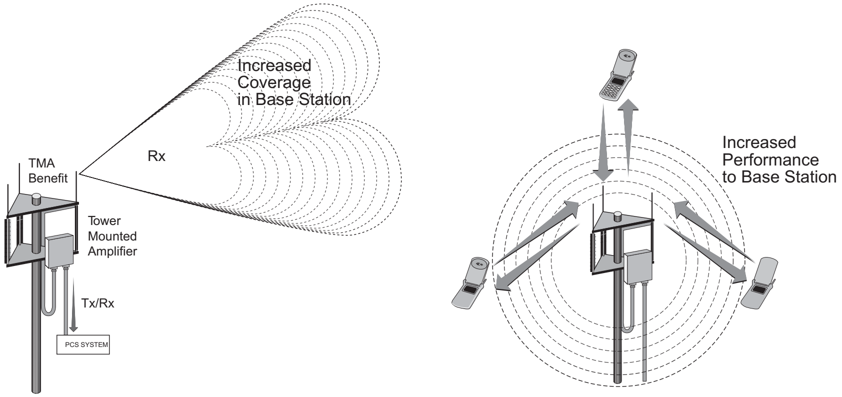


Figure 2-7. *Shown here is an example of how TMA usage increases coverage at the PCS base station. The low noise TMA, in the uppermost image, provides better coverage to the subscriber by minimizing fading in the communication system. The larger coverage area is depicted in the bottom image. This reduces call drop outs and extends battery life to the cell phone subscriber as the transmit power required is decreased because the base station becomes more sensitive to weaker signals.*

Applications of TMAs

Depending on the requirements of the base station, there are a number of different TMA configurations in use today. Three common configurations are:

- **TMA-S** - The TMA-Single is a Rx-receive only TMA that connects between the Rx-receive antenna and the radio (Figure 2-8). Its purpose is to boost weak signals from the subscriber. This configuration is specific to systems that use separate antennas for Tx-transmit and Rx-receive.

  The main components in the TMA-S are a band-pass filter which passes only signals at the receive bandwidth, a low noise amplifier (LNA) which provides the signal gain, and a bypass switch which opens when the TMA is powered up and closes when there is no power (Figure 2-9).

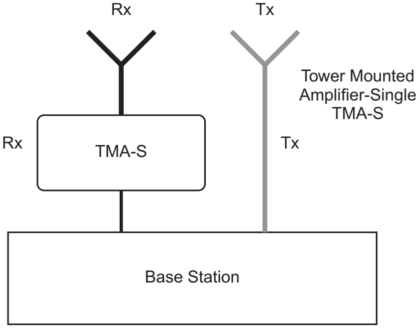


Figure 2-8. *Shown here is a TMA-S. This configuration is specific to systems that implement separate antennas for transmit and receive.*

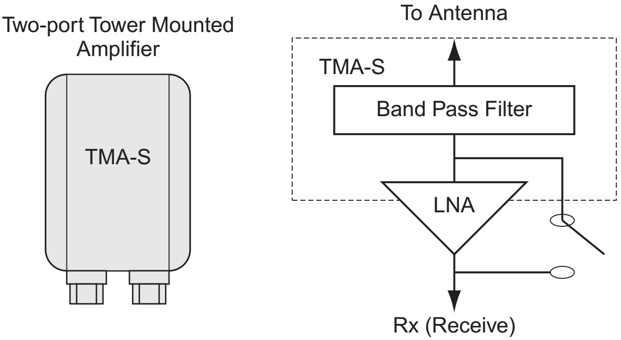


Figure 2-9. *Shown here is a receive-only TMA-S with bypass switch.*

- **TMA-DD -** The dual-duplex TMA (TMA-DD) is commonly called a transceiver as one port is connected to the antenna while the other connects to the base station. Unlike the TMA-S, the TMA-DD is used in systems where a single antenna is used to transmit AND receive (Figure 2-10). Also, there must be a single connection to the base station for both transmit and receive. Even though both transmit and receive signals pass through the TMA-DD, the receive signal is the only one that passes through the LNA. No gain is applied to the transmit signal.

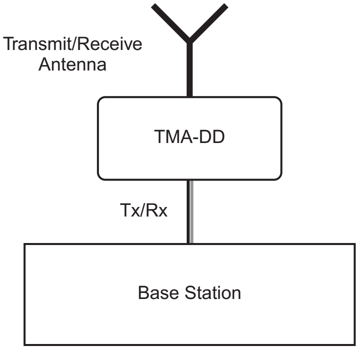


Figure 2-10. *Shown here is a TMA-DD configuration.*

The TMA-DD is composed of the same components as a TMA-S, with the addition of two duplex filters that provide isolation between the Tx and Rx at the antenna and the base station (Figure 2-11).

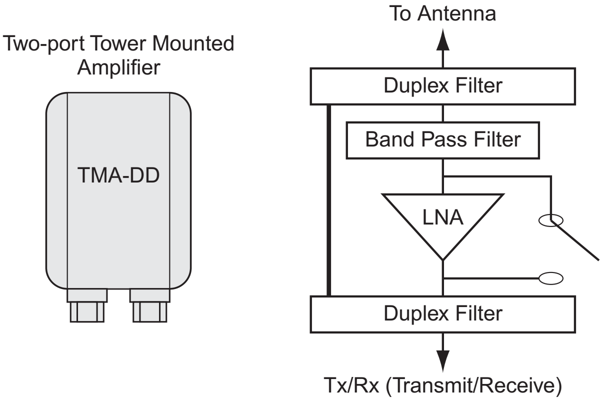


Figure 2-11. *Shown here is a two-port TMA-DD with bypass switch.*

- **TMA-D -** The duplex TMA (TMA-D) is used for radio systems with a single antenna port connection for transmit and receive (Figure 2-12). There are separate ports for transmit and receive (to/from the base station), and a third connection to the antenna. Even though both transmit and receive signals pass through the TMA-D, the receive signal is the only one that passes through the LNA. There is no gain applied to the transmit signal.

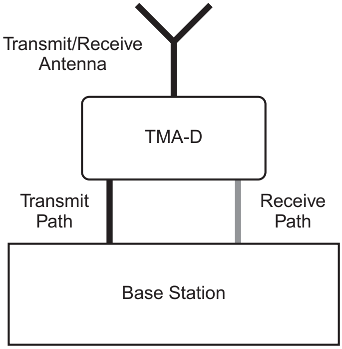


Figure 2-12. *Shown here is a TMA-D configuration.*

The TMA-D is comprised of the same components as a TMA-DD, with one exception. The TMA-D requires only one duplex filter to provide isolation between Tx and Rx at the antenna (Figure 2-13).

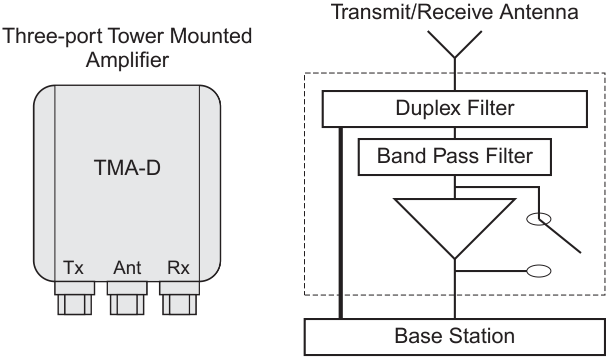
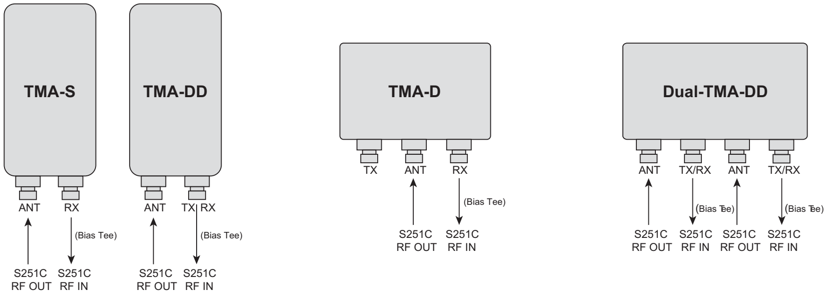


Figure 2-13. *Shown here is a three-port TMA-D with bypass switch.*

The various types of TMAs include a two-port TMA-S, two-port TMA-DD, three-port TMA-D, and four-port dual-TMA-DD (Figure 6-14). In a two-port TMA-S, for example, one port is connected to the receive antenna while the other is connected to the base station. Two antennas are required: one for transmit and one for receive. The transmit side is not connected to this type of TMA.



Two-Port Tower Mounted Amplifier

Three-Port Tower Mounted Amplifier

Four-Port Tower Mounted Amplifier
Dual-Duplex with Non Bypass

Figure 2-14. *Some of the various types of TMAs are pictured here.*

Tower Mounted Filters are used to limit and direct the correct signals coming from cellular and PCS phones. The two types of Tower Mounted Filters used with cellular antennas are a two-port band-pass filter and a three-port duplex filter. The filter is a frequency-selected device. In the TMA it passes signals with very little loss inside its frequency bands, while attenuating all signals outside its band.

Both filters and amplifiers affect the Return Loss measurement. Consider, for example, an antenna system that has a TMA-DD between its feed line and the antenna, and also includes bypass circuitry. Measuring the Return Loss with the bypass relay opened produces a different result than if the circuitry is closed. When opened, the performance inside the Rx and Tx frequency bands would not be affected, but outside these bands, the Return Loss would be much lower. This is caused by the filter's very low Return Loss at those frequencies, which dominates the performance of the antenna system.

Transmission Measurements

To measure the TMA before it is installed in the antenna system, the contractor, field technician or engineer must ensure that the input level on the antenna side of the TMA does not significantly exceed the maximum input level value specified

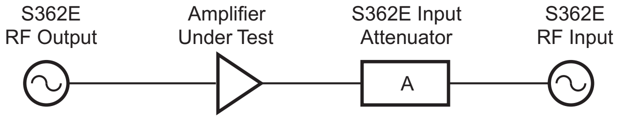


Figure 2-15. *Here, the two critical power levels that must be managed are the specified amplifier output power for 1 dB gain compression and the power level at the measurement instrument's input mixer.*

in the TMA data sheet (generally about –40 dBm). Most portable solutions provide a high power (0 dBm) and low power (–30 dBm) setting so that the power level can be optimized for both passive and active DUT's.

Since amplifiers increase power over a limited power range, care must be taken to manage the power levels at the input and output of the amplifier. If linear operating-power levels are exceeded, then the amplifier gain measurements may have errors (Figure 2-15).

If an overload occurs on the TMA, an invalid, low-gain value will be measured. To determine the gain of the TMA in this situation, the contractor, field technician or engineer will need to make a measurement with the supply voltage connected and then disconnected. The two test results must then be compared.

Note that most TMAs require a DC source, typically 18 volt DC, provided by the base station, to power them up. Also, since not all TMAs have a bypass switch installed, the TMA may need to be bypassed with a jumper.

Examples of the typical measured gain response from a TMA-S, TMA-DD and TMA-D are shown in Figure 2-16, Figure 2-17, and Figure 2-18, respectively.

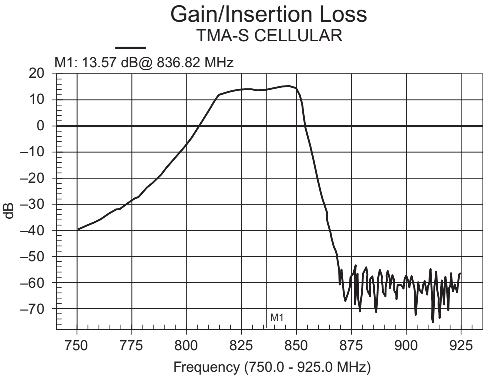


Figure 2-16. *This is the typical measured gain response from a TMA-S for a cellular system. A reference line has been placed at 0 dB after calibrating the Spectrum Master. Note that the gain is only in the Rx band.*

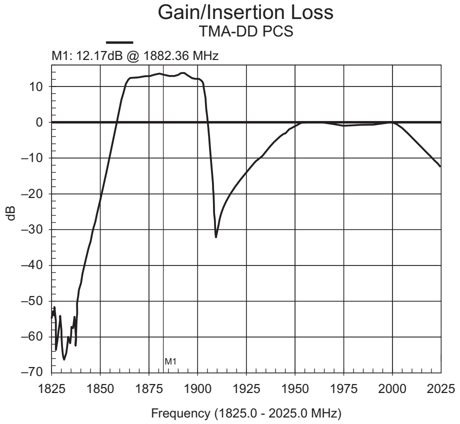


Figure 2-17. *This graph illustrates the typical gain response from a TMA-DD. The gain is only applied to the receive signal. A gain of about 12 dB above the reference line is achieved. Because the transmit signal also passes through the same cable as the receive signal, but no gain is added to it, the transmit band is at the 0 dB reference line.*

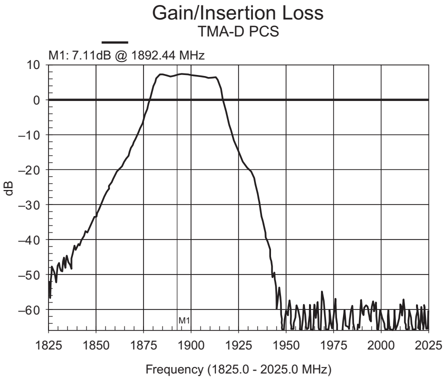


Figure 2-18. *This graph reflects the typical gain response from a TMA-D for a cellular system. A reference line was placed at 0 dB after calibrating the Spectrum Master. Note that the gain is only to the Rx band. The insertion gain trace for TMA-D looks similar to that of TMA-S. Only the receive band shows any gain. The transmit port is left disconnected for this measurement.*

Measuring System Gain

A system gain measurement can be used on a TMA after it has been installed on a tower, to verify the TMA and the installation—saving both the time and expense of hiring a tower crew to bring the TMA down. It requires the use of the system's Tx antenna to deliver a signal to the Rx antenna (Figure 2-19).

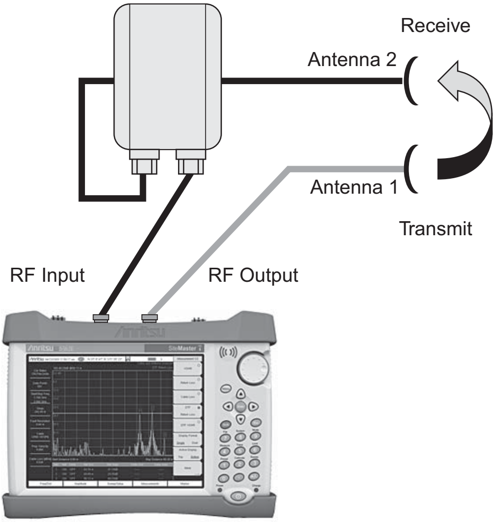


Figure 2-19. *Here is a typical system gain measurement setup for a TMA-D.*

When measuring TMA gain, the components in the receive path of the mobile-radio base station must be considered. The TMA should compensate for the receive Cable Loss. Also, the TMA may not be used for excessive level gain as this can make the defined Rx parameters (e.g., for detecting Rx level handover or for power regulation at the mobile station) impracticable or even dangerous.

Due to insertion losses in the system from such things as cables, connectors and antennas, the reference level used for measuring gain is not 0 dB. Rather, the gain is the difference between measurements taken with the bias tee turned off and then on (refer to Bias Tee Option). Be advised that the gain of a TMA without a bypass switch cannot be measured. However, by connecting and disconnecting the power, it is possible to determine whether the TMA is functional. While bias tee activation will not produce great accuracy, it will provide a good test for operation and verification of the TMA-DD, TMA-D, TMA-S or dual-TMA-DD.

Note that the relative gain measurement of the TMA, after installation, is very similar to other gain measurements, with the exception of signal-level offsets due to cable losses and the system isolation level.

Measuring Antenna Isolation

An antenna isolation test can be performed on systems with or without a TMA (Figure 2-20). It is used to determine the presence of any unwanted coupling between antennas in adjacent systems. If the transmit antenna were to transmit in a specific direction, then the amount of signal from it to the adjacent receive antenna would need to be minimized.

Typical antenna-to-antenna isolation shows results from –50 to –100 dB below the 0 dB reference line established by calibration. When the measured isolation level is more negative, there

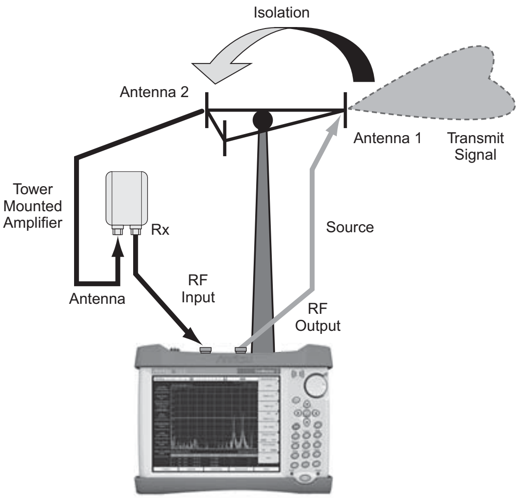


Figure 2-20. *Transmission measurement setup for measuring antenna isolation.*

is a better chance of co-location without system degradation. An isolation level of –89 dB is considered very good. The contractor, field technician or engineer must determine the "acceptable level" for their particular system. If the measured antenna-to-antenna isolation is closer to –60 dB, then re-alignment of the antennas may be necessary to improve isolation. In some cases, alternative channel plans must be used to ensure that all systems at the same location can operate successfully.

When conducting an antenna isolation test, make sure that the input level on the antenna side of the TMA does not significantly exceed the maximum input level value specified in the TMA data sheet (generally about –40 dBm). An example of typical antenna isolation measurement results is shown in Figure 2-21.

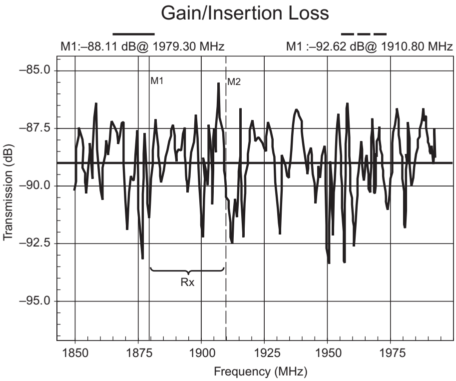


Figure 2-21. *Typical antenna isolation measurement results.*

Bias Tee Option

Some measurement instruments used for making transmission measurements will offer an integrated bias tee option (Figure 2-22). This can be especially useful when measuring applications where both DC and RF signals must be applied to a DUT and eliminates the need for external supplies.

In the Anritsu Site Master, for example, an optional bias tee can be installed inside the instrument. The bias arm is connected to a 12 to 32 VDC power source that can be turned on as needed to place the voltage on the center conductor of the instrument's RF In port. This voltage can be used to provide power to block down-converters in satellite receivers and can also be used to power some tower-

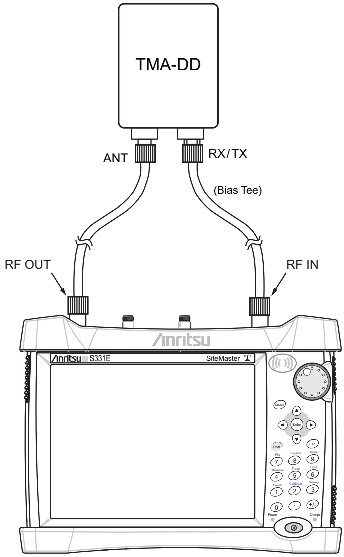


Figure 2-22. *A variable bias tee, shown here, can be very useful when conducting two-port transmission measurements.*

mounted amplifiers. The bias can be turned on when the instrument is in transmission measurement mode. When it is turned on, the bias voltage and current are displayed in the lower left corner of the display. The 12 to 32 VDC power supply is designed to continuously deliver a maximum of 6 Watts.

Summary

A transmission measurement measures the amount of signal that passes through a DUT and is used to determine its gain or insertion loss. It can be used to verify the performance of both passive (e.g., filters) and active devices (e.g, TMAs). It can also be used to verify antenna isolation. When making transmission measurements, dynamic range is a critical factor. Proper calibration is also important as it ensures the accuracy and repeatability of any measurements. Some transmission measurements will benefit greatly from the use of a bias tee—especially in applications where both DC and RF signals must be applied to a DUT.

3 - ADVANCED CABLE MEASUREMENTS

In This Section

At the start of this booklet, the theory and practice of cable and antenna testing was presented, along with a variety of standard test techniques. However, for some complex test parameters of modern systems, advanced cable measurement techniques are needed to provide the comprehensive test data used for field maintenance of those systems. This section will discuss phase-matching cables, S-parameter definitions as they apply to cable characterization and other cable parameters such as Phase Shift and Group Delay. Advanced Time-Domain measurements will also be presented as enhancements to the well-known Distance-to-Fault (DTF) techniques. In addition, diagnostic tools like the Smith Chart will be briefly described.

Advanced Cable Measurements

For the contractor, engineer or field technician burdened with bringing powerful instrumentation such as vector network analyzers or vector voltmeters—connected to a power cord—to a remote field site, the latest generation of handheld, portable tools offers an amazing array of performance, capabilities, and ease-of-use. The need for precision measurements in both magnitude and phase at RF and microwave frequencies is driving a trend toward more portable, field-friendly instruments. The benefit of portable instruments is in their ability to bring diagnostic tools to the Device-under-Test (DUT), instead of sending them back to the factory for maintenance or repair operation. Conducting measurements any time, anywhere is critical in deploying and maintaining the wireless applications we take for granted today.

Measuring and computing the most sophisticated cable parameters requires the full precision of a Vector Network Analyzer (VNA) because it provides both magnitude and phase of the test parameters. While phase measurements are important, the availability of phase information provides the potential for many new computed-measurement features, including Smith Charts, time domain and group delay. Phase information also allows greater measurement accuracy through vector-error correction of the measured signal. The Anritsu VNA Master, for example, corrects errors with a 12-term mathematical model for the utmost measurement accuracy.

VNA Fundamentals

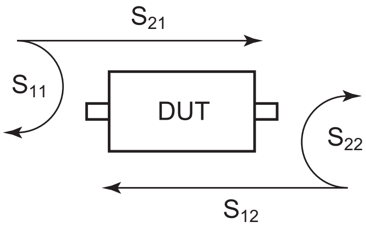


Figure 3-1. *Four scattering parameters describe the frequency-dependent transfer function of a 2-port device or cable under test.*

Any RF or microwave component (DUT), or cable with 2-ports can be functionally described by four complex, frequency-dependent parameters which are called S-parameters. Figure 3-1 shows that for Port 1, the S_{11} parameter reveals the forward reflected function, while S_{21} describes the forward transmission function. In turn, at Port 2, the S_{22} parameter is the "transfer function" of the reverse reflection and S_{12} is the reverse transmission function.

The Anritsu VNA Master has an architecture that automatically measures these four S-parameters with a single connection. There are three tuned receivers, all phase locked to the test generator and tracking its signal as it sweeps the frequency range set by the operator (Figure 3-2). The forward sweep from Port 1 simultaneously yields S_{11} and S_{21} and the reverse sweep from Port 2 simultaneously yields S_{22} and S_{12}. With a single connection, the VNA Master provides both precision measurements and hands-free operation.

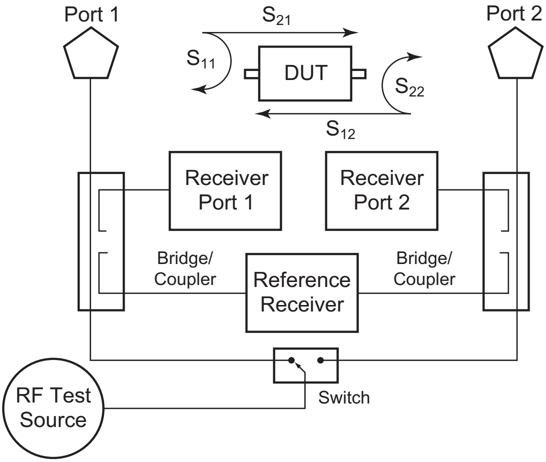


Figure 3-2. *The 3-receiver architecture of a modern VNA tracks the test signal and delivers magnitude and phase information on all 4 S-parameters with a single connection.*

Phase data and measurement in all three receivers is carefully maintained to great accuracy. The microwave test signal is down converted into the passband of the intermediate frequency (IF) of both test channels. To measure the phase of this signal as it passes through the DUT, the reference receiver provides the phase comparison. If the phase of the DUT test signal is 90 degrees, it is 90 degrees different from the reference signal. The VNA reads this as –90 degrees, since the test signal is delayed by 90 degrees with respect to the reference signal. The phase reference can be obtained by splitting off a portion of the microwave signal before the measurement.

A VNA automatically samples the reference signal so no external hardware is needed. A variety of complex mathematical computations then provide user-friendly parameters such as Group Delay or Smith Chart formats for display. The VNA is available as an economical 2-port, 1-path version or a full 2-port, 2-path version (Figure 3-3). Both furnish the all-important phase data for the user.

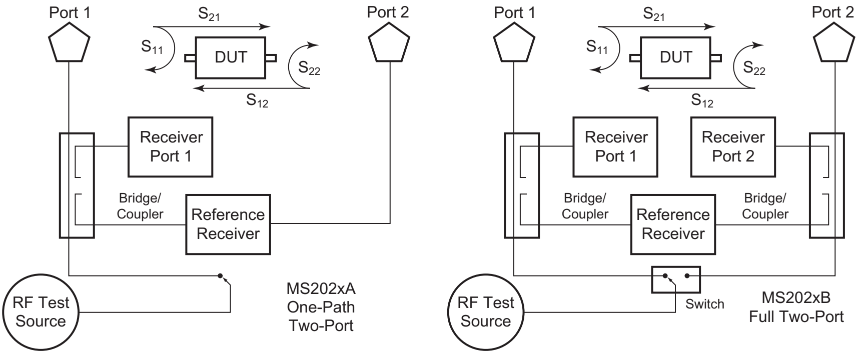


Figure 3-3. *Two versions of VNA instruments are available. On the left is an economical 2-port, 1-path, version, while the full 2-port, 2-path version that can measure all 4 S-parameters without reconnection is on the right. Either version provides accurate cable measurements.*

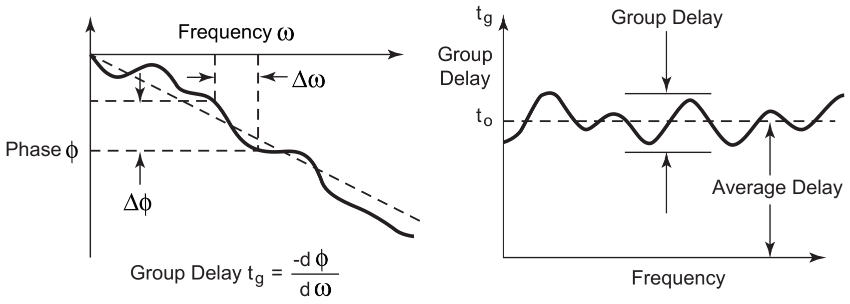


Figure 3-4. *Phase performance of a cable or component is crucial to its linearity versus frequency.[I] When phase linearity is mathematically differentiated, the parameter is called Group Delay (right). If the Group Delay of a component or cable is not flat, the signals within a frequency band will intermodulate.*

Phase and Group Delay Parameters

The phase characteristics of cables are fairly well behaved. Whether an air dielectric or a plastic, the phase shift of a signal traveling through a cable is generally linear versus frequency. Figure 3-4 shows a plot of phase shift versus frequency, although the lumpy phase behavior in this figure might be more typical of an active component such as an amplifier. The importance of a linear phase shift versus frequency is shown in the plot on the right, which is the differentiated results and is called Group Delay. If Group Delay is not flat, multiple signals within a transmitter band will intermodulate, causing serious distortion or bit errors in the case of digital modulations. If video pulses are being transmitted, the pulse shape will become distorted.

Smith Chart

Antenna technology and design are far more sensitive to phase considerations. Consequently, in field measurements, it is often crucial to characterize cables and antennas (or their combination) with a full magnitude and phase measurement. One of the most convenient display formats for field diagnostics is the Smith Chart. Originally conceived in the 1930s by a Bell Laboratories engineer named Phillip Smith, the Smith Chart is simply a plot of complex reflections overlaid with an impedance and/or admittance referenced to a normalized characteristic impedance, usually 50 Ω. It provides a convenient graphical representation of tedious and repetitive transmission line equations. Smith cleverly warped the rectangular grid by wrapping the infinity values for both reactive ±x values around to the right center, which was the infinity value for resistive value. In this manner, Smith allowed all numbers from 0 to ± ∞ to be plotted (Figure 3-5).

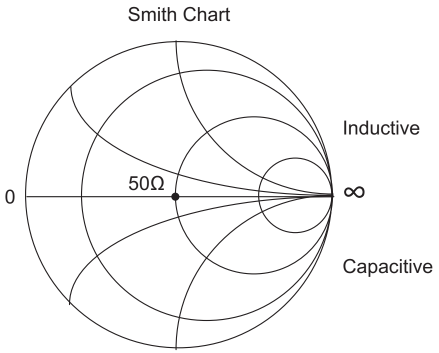


Figure 3-5. *The Smith Chart is a plot of r and x terms of the impedance of a DUT, where r is the real or resistive term (horizontal axis) and +/-x is the imaginary or reactive term of the impedance. By wrapping the normal plus and minus vertical axes around to the right infinity point, all values are easily viewed.*

The signal reflected from a DUT has both magnitude and phase. This is because the impedance of the cable or device has both a resistive and a reactive term, which is represented as r+jx, where r is the real or resistive term and x is the imaginary or reactive term. The j, which is sometimes denoted as i, is an imaginary number and is the square root of –1. If x is positive, the impedance is inductive. If x is negative, the impedance is capacitive. The size and polarity of the reactive component x is important in impedance matching.

The best match to a complex impedance is the complex conjugate. This complex sounding term simply means an impedance with the same value of r and x, but with x of opposite polarity. This term is best analyzed using a Smith Chart that is a plot of r and x, as shown in Figure 3-5. Depending on the format required, displaying all of the information on a single S-parameter requires one or two traces. A very common requirement is to view forward reflection on a Smith Chart (one trace), while observing forward transmission in log magnitude and phase (two traces). This dual display is crucial when tuning filters where there is a functional interaction between the reflection and transmission parameters caused by the tuning itself.

The Smith Chart is one of the most useful graphical aids available to the RF field engineer today and an advanced measurement capability available in handheld cable and antenna analyzers. In one glance, the user can see the reflection signal plotted versus frequency and, if the plot is clustered near the 50 Ω center point, the component is well matched. Using it, such problems can be solved in mere seconds, lessening the possibility of errors creeping into the calculations. Because Smith Chart graphically demonstrates how various RF parameters (e.g., impedances, reflection coefficients, S-parameters, noise figure circles, and gain contours) behave at one or more frequencies, it offers an alternative to using tabular information.

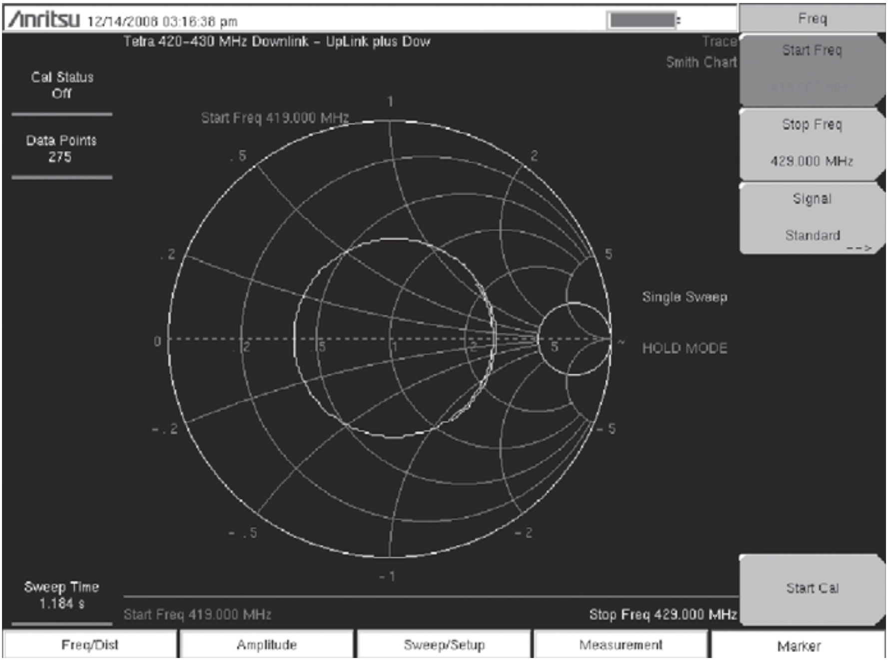


Figure 3-6. A typical Smith Chart display, such as the one pictured here, can be used to measure the match of an antenna.

In a handheld cable and antenna analyzer with this advanced measurement capability, 1-port measurements are displayed in a standard 50 Ω normalized Smith Chart (Figure 3-6). When markers are used, the real and imaginary components of the Smith Chart value are displayed. Some cable and antenna analyzers provide additional options and even a calculator to show the Return Loss, VSWR or reflection coefficient values of a specific Smith Chart value. Note that limit lines in a Smith Chart appear as circles (constant reflection coefficient) and can be entered in VSWR units.

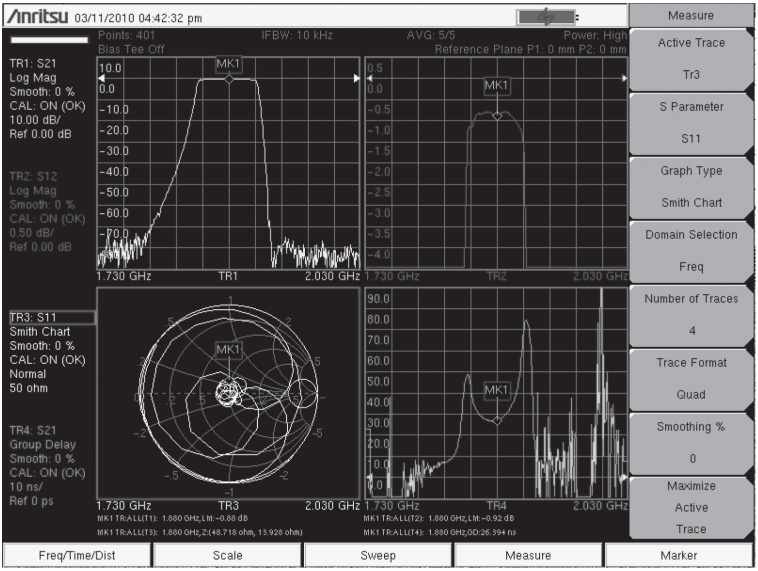
Figure 3-7 shows a typical combined quad-display of a Smith Chart and forward transmission parameters including Group Delay (lower right). Group Delay is the rate of change-of-phase versus frequency. If this rate of phase change versus frequency is not constant, the DUT is nonlinear. This nonlinearity can create distortion in communication systems. The result is the intermodulation of multiple signals which are transiting that particular amplifier or filter. Group Delay is a powerful diagnostic tool offered as a view on the cable and antenna analyzer trace, along with other advanced measurement capabilities like the Smith Chart. Both log magnitude and Smith Chart formats are user-defined.

Making Cable Phase Measurements in the Field

For measuring absolute insertion phase characteristics of a cable or comparing phase match between multiple RF/Microwave cables, especially in the field where access to AC power is limited, a portable VNA is the most appropriate tool. Some VNA models come with an optional built-in Vector Voltmeter (VVM) capability that enables a contractor, field technician or engineer to accurately measure or match the phase parameter in one or a multiple of cables with ease and high accuracy. A VNA with a VVM capability effectively replaces the functional ratio measurements of the now obsolete VVM and the signal generator.[1]

Many RF/Microwave systems depend on multiple antenna elements to create their transmitted beam, often with exceedingly precise requirements on the insertion phase or the phase match between the transmit cables. As an example, consider that precise directional characteristics are needed for the VHF Omnirange (VOR) navigation antenna systems at most airports. Detailed procedures are published for maintenance personnel to provide the exact phase match between cables. Glide slope antenna cables also require careful phase matching.

As shown in Figure 3-8, a VNA can be configured to make both 1-port and 2-port phase measurements at selected Continuous Wave (CW) frequencies. Figure 3-9 shows that unlike VVMs, the portable network analyzer permits close access to test cables and antennas.



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Points: 401 IFBW: 10 kHz AVG: 5/5 Power: High

Bias Tee Off Reference Plane P1: 0 mm P2: 0 mm

TR1: S21
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB

TR2: S12
Log Mag
Smooth: 0 %
CAL: ON (OK)
0.50 dB/
Ref 0.00 dB

TR3: S11
Smith Chart
Smooth: 0 %
CAL: ON (OK)
Normal
50 ohm

TR4: S21
Group Delay
Smooth: 0 %
CAL: ON (OK)
10 ns/
Ref 0 ps

MK1 TR:ALL(T1): 1.880 GHz,LM:−0.88 dB

MK1 TR:ALL(T3): 1.880 GHz,Z:(48.718 ohm, 13.928 ohm)

MK1 TR:ALL(T2): 1.880 GHz,LM:−0.92 dB

MK1 TR:ALL(T4): 1.880 GHz,GD:26.394 ns

Active Trace: Tr3

S Parameter: S11

Graph Type: Smith Chart

Domain Selection: Freq

Number of Traces: 4

Trace Format: Quad

Smoothing %: 0

Figure 3-7. *This image depicts a typical quad-display showing multiple characteristics of a filter, including: reject skirts (upper left), passband (upper right), S_{11} (lower left Smith Chart) and Group Delay (lower right).*

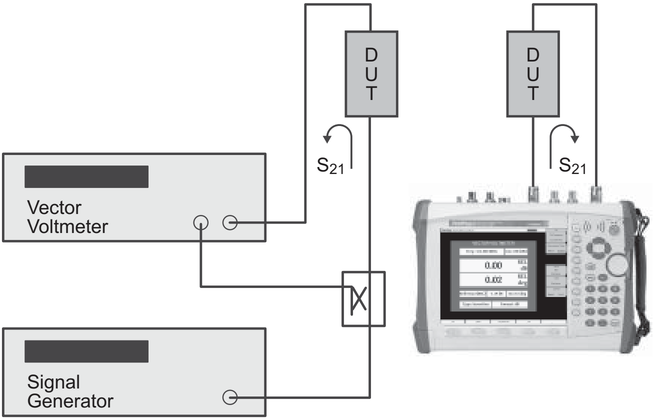


Figure 3-8. *With built-in test signal source and directional devices to detect forward and reverse power, the battery powered handheld VNA (on right) is self-configured for making field cable-phase measurements. The older VVM technique (left) requires an external signal generator.*

Insertion and Reflection are two common techniques employed by the VNA to obtain cable-phase measurements. Both are based on S-parameters. The preferred method, Insertion, utilizes the VNA's 2-port setup to make insertion phase measurements by measuring the S_{21} vector transmission from Port 1 to Port 2 through the cable. This allows the operator to determine the phase shift of the component or cable from its input connector to its output connector. Measured S_{21} data is displayed as cable insertion loss in dB, while insertion phase is displayed in degrees.

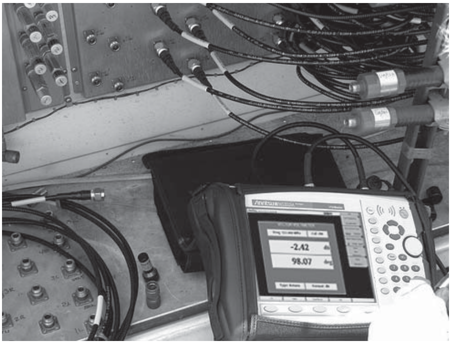


Figure 3-9. *In contrast to a bulky VVM system with power cords, the portable network analyzer moves in close to the test cables and antennas to streamline installation and maintenance of systems.*

Reflection, on the other hand, measures the reflected signal S_{11} on a test cable, and is dependent on the far end of the cable being deliberately mismatched—either shorted or left as an open circuit. With the deliberate mismatch, virtually 100% of the input signal is reflected and as a result, the phase delay of the measured reflected signal is equal to twice the one-way phase of the cable. Similarly, the cable measured return loss is twice the one-way loss.

This reflection technique is especially useful in situations where the operator must manually create multiple phase-matched cables using the "measure-and-snip" operation. This operation requires the contractor, engineer or field technician to carefully snip small amounts of cable with a diagonal cutter, perhaps 1/8th inch at a time, and re-measure the effect on the 2-way phase. The reflection technique is also useful on already installed cables where the far end cannot be brought near the VNA instrument.

Two-Port Measurements

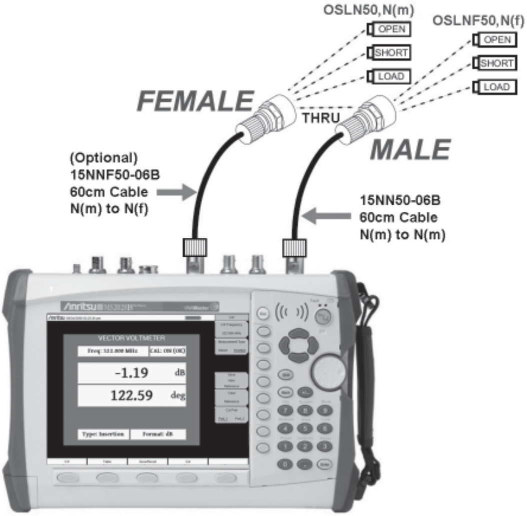


Figure 3-10. *This VNA calibration procedure provides the zero-phase reference out at the end of two extension test cables for later insertion-phase measurements. The calibration algorithm requires a through connection so it's important to setup a male-female interconnect scheme as shown to ensure a precise zero-phase reference.*

As shown above, phase measurements can be made in both reflection (S_{11}) and insertion (S_{21}) modes. The 2-port phase measurement can use both high (approximately 0 dBm) and low (approximately –35 dBm) power settings. However, prior to conducting a 2-port measurement with a network analyzer, the instrument must be calibrated as shown in Figure 3-10. To begin calibration, select a CW frequency and choose 2-port calibration. Set-up a 2-port connection to the DUT and then select "insertion" as measurement type prior to commencing the 2-port calibration process, which in this case uses Short, Open, Load and Thru (SOLT) standard components (Figure 3-11).

Note that when preparing system cables for precise match to other cables and the connectors of the cable under test are both the same gender (e.g., male-male), an extra female-female insert must be used in the calibration routine and its insertion effect on phase shift computed out of the final results.

Figure 3-11. *Convenient calibration components for the VNA provide the Open, Short and Load standards for the SOLT calibration procedure.*

For phase-matching cables, a good general practice is:

Step 1. Connectorize the first (reference) cable on both ends.

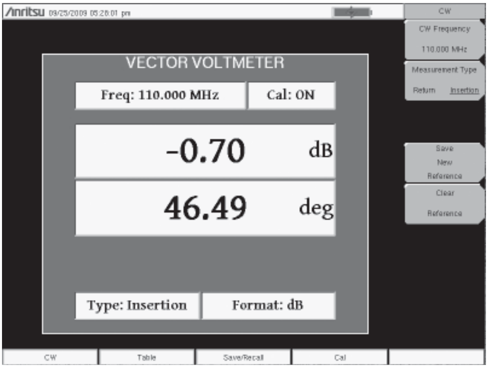
Step 2. Make an insertion phase measurement and store the data.

Step 3. Cut a second cable to length, being careful not to cut shorter than the reference cable, and connectorize it on both ends.

Step 4. Measure the second connectorized cable and compare it to the first (reference) cable.

From the difference observed, the user can estimate the trim required for the second cable. For more accurate trimming, one of the second cable's connectors must be removed and the center conductor trimmed. Re-connect the connector back for another measured comparison with the first cable. Although, it may be difficult to trim the cable correctly the first time, experienced users often achieve success in the first two or three tries. However, this practice of measure-and-cut varies with frequency. Lower frequencies (VHF) will likely be in the 1/16th to 1/8th inch range for final iterations, while at 1 GHz and above, the re-connecting might only involve unsoldering the center conductor and trimming it 1/32 the inch or less, and just letting the solder cool.

For example, at 118.5 MHz, 1.0 inch length of 1/4 inch diameter Andrew Heliax with a phase velocity Vp = 0.84, equals approximately 4.28 degrees, while at 332.3 MHz, it equals 12.05 degrees. Often times, trimming the cable precisely for the last few tenths of a degree can be very exacting. Nevertheless, with careful and clever attention to detail and data, users can establish their own learning curve. The 2-port measurements taken appear on the analyzer's display window as shown in Figure 3-12.



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VECTOR VOLTMETER

Freq: 110.000 MHz

Cal: ON

-0.70 dB

46.49 deg

Type: Insertion

Format: dB

CW Frequency 110.000 MHz

Measurement Type: Return Insertion

Figure 3-12. *The VNA's VVM display shows the insertion signal loss (-0.70 dB) and phase shift (46.49 deg) for the test frequency of 110 MHz. These quantities are derived from the VNA's measurement of* S_{21}.

One-Port Phase Measurements

The reflection or 1-port phase measurement is favored when one end of the cable cannot be brought up to the test instrument. Or, in cases where "measure-and-snip" operations must be performed to create cables of exactly the right phase length for a prescribed frequency. Prior to making these measurements, the VNA must be calibrated for 1-port measurements using the Open, Short, and Load setup shown in Figure 3-13.

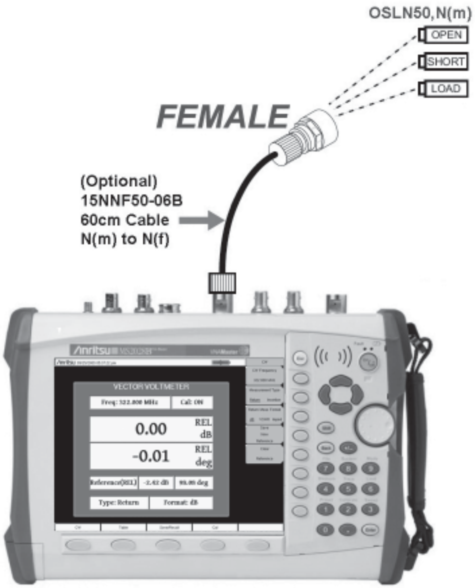


Figure 3-13. *The reflection or 1-port phase measurement is the preferred procedure for cable measurements when both ends of the test cable cannot be brought to the instrument. Prior to making these measurements, the VNA must be calibrated for 1-port measurements using the Open, Short and Load setup.*

When using this technique to measure a cable's phase length, it is assumed that the raw end of the cable reflects back 100% of the power. This condition is dependent on frequency. An open coaxial cable end will reflect virtually all of the power back at low frequencies (below 500 MHz), but might function as a non-efficient antenna at microwave frequencies. Thus, at higher frequencies the reflection is not complete. While in the VHF range, 100 to 500 MHz, an open end offers 100% reflection.

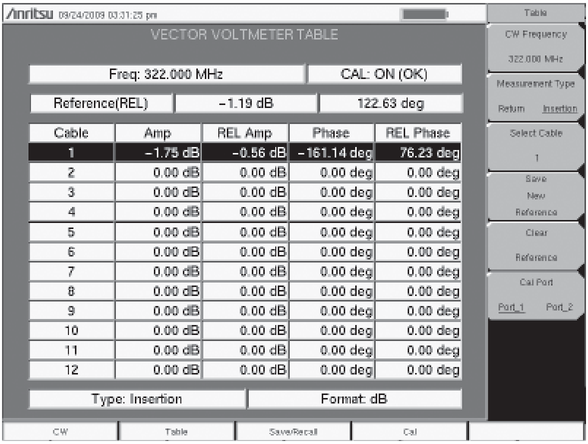
Depending on the model, the VNA is capable of measurements up to 4, 6 or 20 GHz. At these higher microwave ranges, users are advised to prepare the cable center conductor and braided shield to be electrically shorted, such as by soldering the two together to ensure a good short. This extra soldering step complicates the "measure-and-snip" technique since once the required phase is obtained by multiple snips, the final addition of the real connector starts with a slightly damaged cable end. Nonetheless, with a little experience, the user will understand and adapt to the process.

While interactively measuring and snipping cables for matched phase may be a tedious job, it is made faster by experience. Two tips that can help with this task include:

Tip 1. At any one frequency, cut the cable to be prepared several inches longer than the final length. Solder the raw end, creating a good short and take a measurement. Next, cut off exactly one inch of cable, solder it identically again and take another measurement. Note the change in phase from the removal of the one inch segment and calculate the amount of phase difference for, say, 1/8th inch. When the snip procedure brings you closer to the final desired value of the measured phase, you will have a good idea of how much more to snip.

Tip 2. Using the 1-port method, make a shorted-end phase measurement and note the value. Attach the final cable connector at that length using the normal connector attaching process. Next, make a 2-port connector-to-connector insertion phase measurement, as described above in Tip 1, and note the difference in phase. This correction value can be utilized in later steps when converting from the raw end measurements to the final connectorized configuration.

For comparing multiple cables for matched phase, the VNA can save measured phase and amplitude values of multiple cables in the memory of the portable cable and antenna analyzer as a convenient table. With this feature, the operator can save the first cable measurement as a reference, view the differences between the reference cable and other cables, and then output a final report showing both absolute and relative values of all cables. As an example, Figure 3-14 shows a display table with measured values of phase and amplitude for each cable. Their relative phase and amplitude, with respect to a chosen "golden standard cable," is shown in the top box as the REL standard.



VECTOR VOLTMETER TABLE

Freq: 322.000 MHz

CAL: ON (OK)

Reference(REL) -1.19 dB 122.63 deg

Cable	Amp	REL Amp	Phase	REL Phase
1	-1.75 dB	-0.56 dB	-161.14 deg	76.23 deg
2	0.00 dB	0.00 dB	0.00 deg	0.00 deg
3	0.00 dB	0.00 dB	0.00 deg	0.00 deg
4	0.00 dB	0.00 dB	0.00 deg	0.00 deg
5	0.00 dB	0.00 dB	0.00 deg	0.00 deg
6	0.00 dB	0.00 dB	0.00 deg	0.00 deg
7	0.00 dB	0.00 dB	0.00 deg	0.00 deg
8	0.00 dB	0.00 dB	0.00 deg	0.00 deg
9	0.00 dB	0.00 dB	0.00 deg	0.00 deg
10	0.00 dB	0.00 dB	0.00 deg	0.00 deg
11	0.00 dB	0.00 dB	0.00 deg	0.00 deg
12	0.00 dB	0.00 dB	0.00 deg	0.00 deg

Type: Insertion

Format: dB

Figure 3-14. *This screen capture displays results for multiple cables, showing both measured values of phase and amplitude for each cable. On the right is a typical soft key "Measurement Menu" cluster, showing the operator choices as the measurement progresses.*

Exploiting the Time-Domain Algorithm

For contractors, engineers and field technicians, the ability of time-domain analysis to separate impairments by time or distance is a powerful tool to analyze cables for faults. The instrument displays that provide DTF capture all the minor discontinuities that may occur due to a loose connection, corrosion, aging effects, or physical damage. Fundamentals for DTF were presented in Chapter 2. This section will discuss special variations of Time-Domain measurements as applied to cable characterization, and distributed transmission elements where the ability to separate S-parameters by distance or time is a very valuable tool.[2]

Frequency Domain Reflectometry

If you send a single-frequency test signal down the cable of Figure 3-15, with its distributed impairments, adapters, crushed cable, or end-short, you'll get back a single reflection made up of all the individual discontinuities, all added up in their random phases, depending on their position.

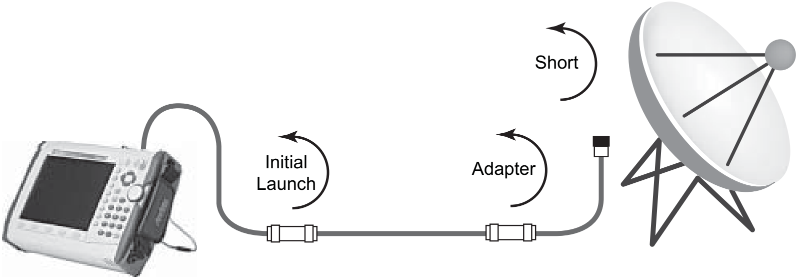
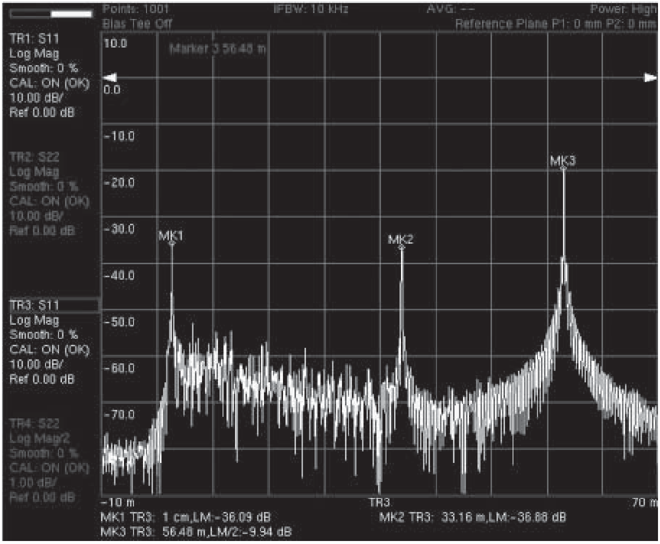


Figure 3-15. *Reflections from individual discontinuities add up in random phase at any one test frequency.*

If you set up for a swept frequency range of test signals, and store all the resulting magnitude and phase information, you have all the information needed for an extremely powerful diagnostic technique called the inverse Fast Fourier Transform. The measurement technique is called Frequency Domain Reflectometry (FDR) and the VNA Master is configured to use operational frequencies (instead of DC-based pulses from the classic TDR approaches) to more precisely identify discontinuities. When access to both ends of the cable is convenient, a similar time-domain analysis is available on transmission ($S_{21)}$ measurements too.[3], [4]



Points: 1001
IFBW: 10 kHz
AVG: --
Power: High
Bias Tee Off
Reference Plane P1: 0 mm P2: 0 mm

TR1: S11
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB

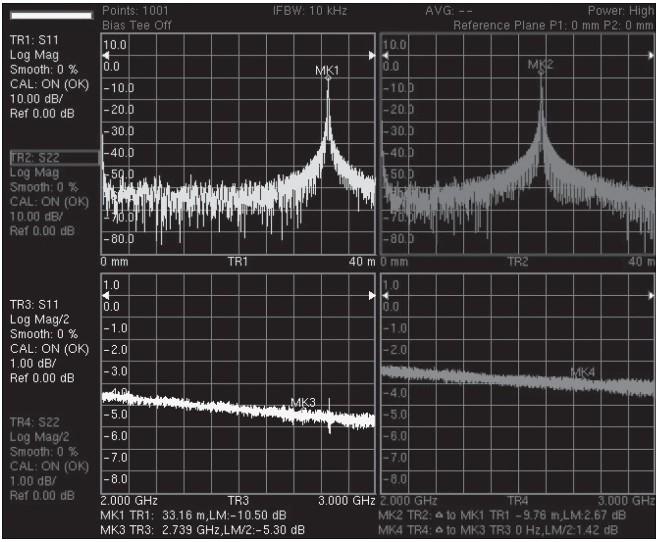
TR2: S22
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB

TR3: S11
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB

TR4: S22
Log Mag/2
Smooth: 0 %
CAL: ON (OK)
1.00 dB/
Ref 0.00 dB

MK1 TR3: 1 cm,LM:-36.09 dB
MK2 TR3: 33.16 m,LM:-36.88 dB
MK3 TR3: 56.48 m,LM/2:-9.94 dB

Figure 3-16. *This typical standard DTF display of discontinuities versus distance gives the technician a head start on tracking down faults.*



Points: 1001
IFBW: 10 kHz
AVG: --
Power: High
Bias Tee Off
Reference Plane P1: 0 mm P2: 0 mm

TR1: S11
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB

TR2: S22
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB

TR3: S11
Log Mag/2
Smooth: 0 %
CAL: ON (OK)
1.00 dB/
Ref 0.00 dB

TR4: S22
Log Mag/2
Smooth: 0 %
CAL: ON (OK)
1.00 dB/
Ref 0.00 dB

MK1 TR1: 33.16 m,LM:-10.50 dB
MK3 TR3: 2.739 GHz,LM/2:-5.30 dB
MK2 TR2: △ to MK1 TR1 -9.76 m,LM:2.67 dB
MK4 TR4: △ to MK3 TR3 0 Hz,LM/2:1.42 dB

Figure 3-17. *Optional time-domain analysis offers trace selections for the horizontal axis in frequency, distance or time scales. This screen simultaneously shows Distance-to-Fault and Cable Loss (Log Mag/2) for S_{11} and S_{22}.*

Figure 3-16 shows the resulting computations, plotted in terms of reflection magnitude in dB versus the distance from the reference plane of the test.

Experienced technicians often run a DTF sweep when the system is operating in proper performance, and store it as a reference. A current readout, during a fault outage, can then be compared against previous measurements in order to determine whether any degradations have occurred since installation (or the last maintenance activity). Marker functions can be utilized to help identify the precise location of those degradations. Moving left to right in the display, we can see the initial launch (MK1), the adapter (MK2), and the short at the far end of the cable (MK3). Using time-domain analysis, it is easy to interpret the discontinuities as normal or faults by simply looking at the location and amplitude of the peaks (Figure 3-17).

With the Time Domain Analysis (Option 0002), the VNA Master can also display the S-parameter measurements separated in the time or distance domain using this popular analysis mode. The broadband frequency coverage coupled with 4,001 data points means that you can measure discontinuities both near and far with unprecedented clarity for a handheld tool. With this option, you can simultaneously view S-parameters in frequency, time, and distance domain to quickly identify faults in the field.

Waveguide Transmission Lines

For microwave systems, with high power transmitters, the transmission line is often fabricated of waveguide. In the field, waveguide flanges can leak moisture and the condensation is a strong absorber. Also, the soft aluminum or brass waveguide is subject to physical damage in place. To handle waveguide lines in the field, the VNA Master also contains the mathematical functions which can compensate for the dispersion effect of the velocity of propagation in waveguide transmission lines.

One Way Versus Round Trip

With the ability to transform any S-parameter to the time domain, one question that arises is whether the time or distance that is plotted represents a one-way or a round-trip propagation. The one-way propagation represents the transmission (or 2-port) measurement, in which the signal is transmitted from one port, propagates through the DUT and is received on the second port. One-way propagation occurs when transforming S_{21} or S_{12}.

The round-trip propagation represents a reflection (1-port) measurement, in which the signal is transmitted from one port, propagates through the DUT, fully reflects at the end of the device, and is received back at the same port. One-way propagation occurs when transforming S_{11} or $S_{22.}$

The VNA Master handles one-way and round-trip propagation differently in the time and distance domains. In the time domain, the VNA Master plots the response against the actual time the signal travels from the transmission port to the receiving port without accounting for whether the measurement is transmission (2-port) or reflection (1-port). In the distance domain, however, the VNA Master compensates for the round-trip propagation by showing the actual length of the DUT (essentially dividing the distance by 2 for the reflection measurements).

For example, look at the results of measuring a cable that is 3.05 meters (10 ft) long. For a transmission measurement, approximately 14.4 ns are taken by a signal when traveling from one end of the cable to the other end of the cable. For a reflection measurement, twice as long (approximately 29 ns) are taken by a signal when traveling from one end of the cable, reflecting from the far end, and returning. Figure 9-18 shows a measured time-domain response of a cable of this length for both reflection (S_{11}) and transmission (S_{21}). The top trace is the S11 plot showing the reflections from both ends of the cable (MK1 at the near end and MK2 at the far end). You can see that the far end peak at MK2 is at approximately 29 ns. Looking at the bottom trace, you can see that the peak at MK3 (which represents the signal received at the end of the cable) is at approximately 14.4 ns.

Take a look at what happens in the distance domain for the same cable. As a user, you want the reflection and transmission measurements to show you where the end of the cable is located. Figure 3-19 shows a measured distance-domain response of this cable for both reflection (S11) and transmission (S_{21}). The top trace is the S_{11} plot showing the reflections from both ends of the cable (MK1 at the near end and MK2 at the far end). The bottom trace shows the transmission S_{21} measurement with the peak representing the signal received at the end of the cable (MK3). Looking at the signal at MK2 and MK3, you can see that the reflection and transmission measurements produced the same result for the length of the cable. The VNA Master compensated for the round-trip condition in the S_{11} measurement so that the distance information matches the physical length of the cable, just as it does in the S_{21} measurement.

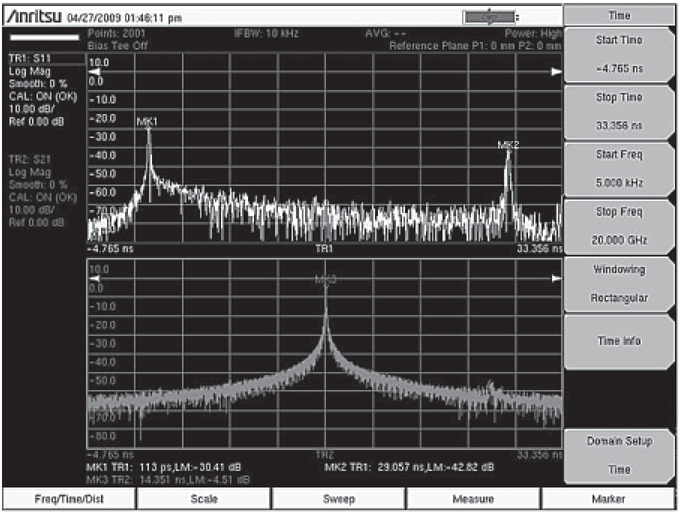

Anritsu 04/27/2009 01:46:11 pm
Points: 2001
Bias Tee Off
IFBW: 10 kHz
AVG: --
Power: High
Reference Plane P1: 0 mm P2: 0 mm
TR1: S11
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB
TR2: S21
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB
MK1 TR1: 113 ps,LM:-30.41 dB
MK2 TR1: 29.057 ns,LM:-42.82 dB
MK3 TR2: 14.351 ns,LM:-4.51 dB
Start Time -4.765 ns
Stop Time 33.356 ns
Start Freq 5.000 kHz
Stop Freq 20.000 GHz
Windowing Rectangular
Domain Setup Time

Figure 3-18. *Time-domain measurements of a 3.05 m cable shows S_{11} and S_{21}.*

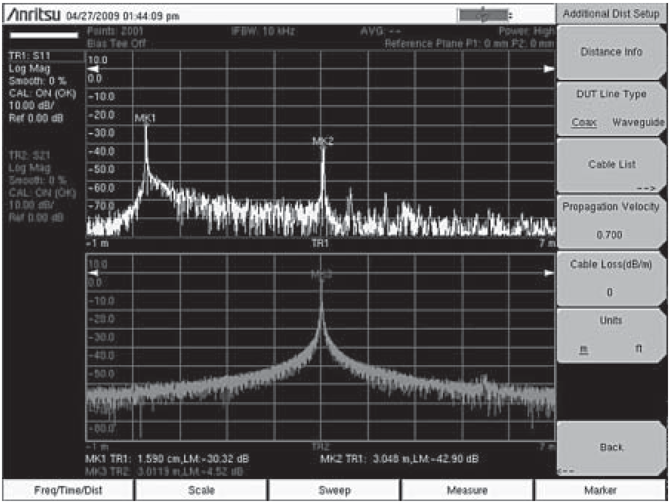

Anritsu 04/27/2009 01:44:09 pm
Points: 2001
Bias Tee Off
IFBW: 10 kHz
AVG: --
Power: High
Reference Plane P1: 0 mm P2: 0 mm
TR1: S11
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB
TR2: S21
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB
MK1 TR1: 1.590 cm,LM:-30.32 dB
MK2 TR1: 3.048 m,LM:-42.90 dB
MK3 TR2: 3.0119 m,LM:-4.52 dB
DUT Line Type Coax Waveguide
Propagation Velocity 0.700
Cable Loss(dB/m) 0
Units m ft

Figure 3-19. *Distance-domain measurements of a 3.05-m cable shows S_{11} and S_{21}.*

Note that the measured cable had a propagation velocity of 70%, which was entered into the VNA Master. Measurements in the distance domain use the entered propagation velocity value to calculate the actual physical length of cables. If the default value of 100% were used, then the measured cable length would be wrong (4.4 meters in the above example). Time-domain measurements are not dependent on the propagation velocity values.

Gated Time Domain

Gating is a popular technique for further analyzing discontinuities observed in the time domain. In the most popular scenario, one would highlight a desired discontinuity with a gate consisting of start and stop criteria. Once selected and enabled, the gate modifies measurements to show only the effect of the gate from start to stop in the swept frequency display. As an alternative, the gate can be configured as a notch to remove the effect of the gated portion from the current measurement. For closely spaced discontinuities, additional filtering options are provided to control how the gate is applied to further optimize the current measurement.

Anti-aliasing is an important consideration for time-domain analysis to ensure adequate distance/time is available for viewing discontinuities. For improved distance resolution, closely spaced discontinuities may require greater frequency spans. For greater maximum distance, more data points or narrower frequency spans will increase the maximum alias-free viewable distance (e.g., Dmax).

Measurement Readout and Interpretation

When gating is enabled, the trace readout in frequency domain is labeled with Frequency Gated with Time (FGT) to differentiate this applied post-processing from normal measurements. Verifying deployed cable is operating properly usually requires, at a minimum, the measurement of Cable Loss and Return Loss. In this typical field scenario, the far end of the cable is disconnected from the antenna and replaced by calibration devices: open/short for Cable Loss and load/termination for Return Loss. The following example shows how to use the new gating features to observe Cable Loss and Return Loss with a single connection.

Setup Considerations

Let's start by configuring the instrument to show Cable Loss and Return Loss on a single display. As a setup step, calibrate the instrument at Port 1 for 1-port measurements between 1 GHz and 2 GHz with 201 data points. Two traces are setup with S11 log magnitude displays as their assigned S-parameter: trace 1 (TR1) is Return Loss and trace 2 (TR2) is Cable Loss (e.g., Log Mag/2 graph type).

Following the 1-port calibration, we connect two 1.5 m cables in series, representing the DUT with propagation velocity (vp) of 0.7 for the sequence of measurements that follow.

In Figure 3-20, the Cable Loss is measured with the far-end short connection. Additionally, Return Loss can be measured with the far-end load connection. Note how the Return Loss results do not make sense when making Cable Loss measurements and vice versa. These results confirm that the cable has both good match and low loss, making it ideally suited for this transmission application.

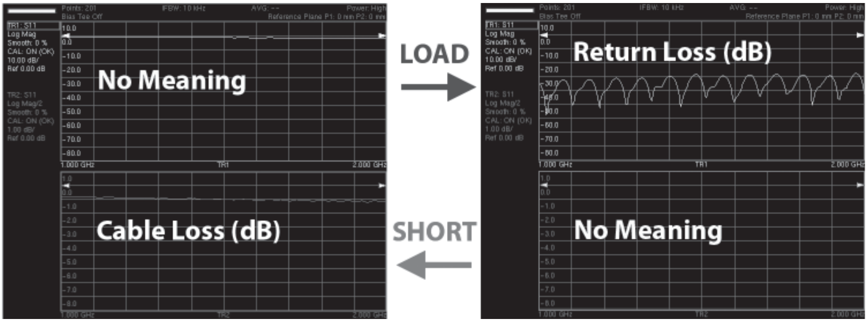


Figure 3-20. *These screen captures show Cable Loss on the left when the far-end connection is a short and Return Loss on the right when the far-end connection is a load. In these measurement scenarios, the results for Cable Loss do not make sense when measuring Return Loss (and vice versa) because both rely on different far-end physical connections.*

Gate Setup to Simultaneously Measure Cable Loss and Return Loss

For this next example, connect a far-end short for a Cable Loss measurement. Next, a gate must be set up at the calibration reference plane because we want to measure the Return Loss of the cable launch even though there are significant discontinuities farther down the cable. When we enable the gate, the VNA Master will essentially apply a filtering effect to the time-domain data as illustrated by the gate on the display (Figure 3-21).

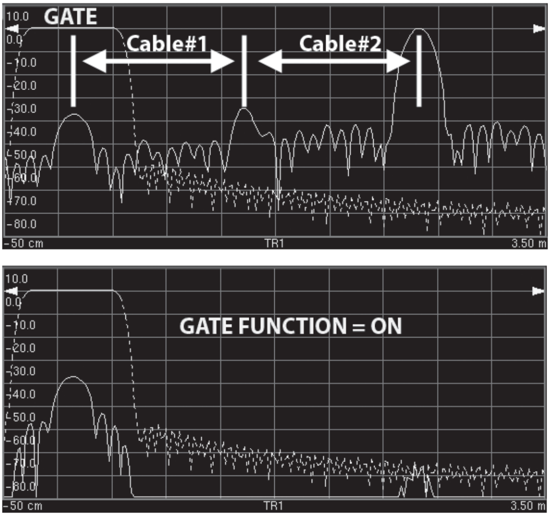
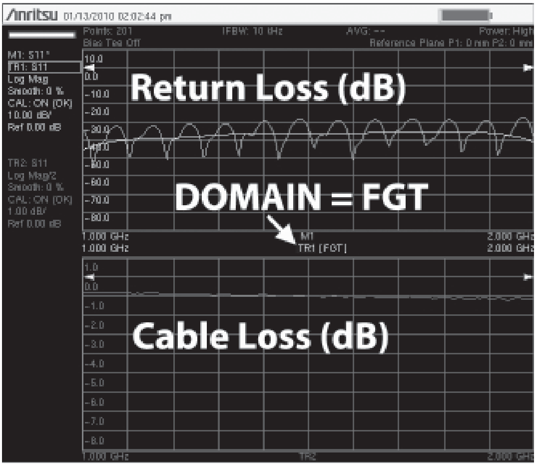


Figure 3-21. *These two screen captures illustrate how to set up a gate at the calibration reference plane to measure the Return Loss of the DUT. The top capture displays the gate as an overlay on the available distance (or time) measurement.*

FGT Reveals Return Loss and Cable Loss

As shown in Figure 3-22, the gate is enabled and the domain selection is changed from distance (or time) to FGT to view the updated S_{11} measurement of Return Loss with gating applied. The gating applied indicator is located under the trace with 'FGT.'



01/13/2010 02:02:44 pm

Points: 201
IFBW: 10 kHz
AVG: --
Power: High
Bias Tee Off
Reference Plane P1: 0 mm P2: 0 mm

M1: S11*
TR1: S11
Log Mag
Smooth: 0 %
CAL: ON (OK)
10.00 dB/
Ref 0.00 dB

TR2: S11
Log Mag/2
Smooth: 0 %
CAL: ON (OK)
1.00 dB/
Ref 0.00 dB

Figure 3-22. *This final screen captures shows the simultaneous measurement of Return Loss and Cable Loss with a far-end short using the VNA Master gate features.*

For comparison purposes, the original S_{11} Return Loss measurement using a far-end load is saved in memory to overlay with these updated FGT results. The ripple is caused by the mid-cable interconnect reflections; whereas, the gated response is able to effectively filter this contribution for easier to interpret results. This final screen capture shows one approach for simultaneous measurement of both Return Loss and Cable Loss using a far-end short and the VNA Master gate feature.

Gate Shape: Minimal, Nominal, Wide, and Maximum

The default gate shape is nominal to provide optimum results for most situations. Advanced users may want to optimize the gate shape for more resolution when multiple discontinuities are in close proximity to each other. Here, other gate shapes may be useful for further optimizing the final FTG results. As shown Figure 3-23, the overlay gate shape feature provides visual cues to further optimize the final FTG results.

Time Domain Diagnostics for Balanced/Differential Transmission Lines

Modern digital communications systems utilize pulse rates in the 10 Gbps range. Such pulses require frequency-response bandwidths of 25 GHz and more. When those extremely high data rate signals are to be cabled from one sub-system rack to another, simple shielded twisted pair wiring will not do. Yet, the signals must be designed to be immune to noise pickup. This leads system designers to specify balanced or differential coaxial transmission lines. The digital data stream is contained between the two center conductors of regular coaxial transmission lines. The terminology for the S_{11} parameter for such differential line set is S_{d1d1}.

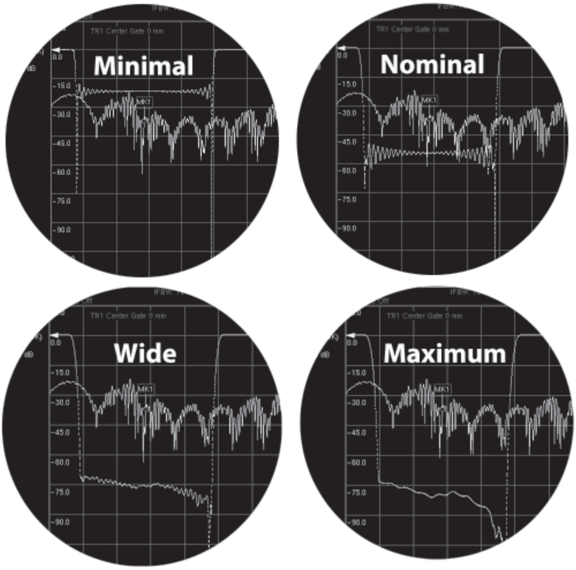


Figure 3-23. *The Anritsu VNA Master overlays the gate shape on the distance (or time) domain readout for optimized FGT results. These additional gate-shape selections (e.g., minimal, nominal, wide, and maximum) can be useful when dealing with multiple discontinuities in close proximity to each other. As shown in these screen captures, the gate shape differences are easily viewable on the display.*

The VNA Master, with Option 0077, reconfigures Ports 1 and 2 to act like one single balanced test port. It uses a full 2-port calibration to conduct 1-port differential measurements of S_{d1d1}. Similar to other S-parameters, S_{d1d1} can be viewed in the frequency, time or distance domain for signal-integrity measurements anytime, anywhere. This capability is especially valuable for applications in high data rate cables where balanced data formats are used to isolate noise and interference. Figure 3-24 shows a typical display of DTF for a balanced/differential line.

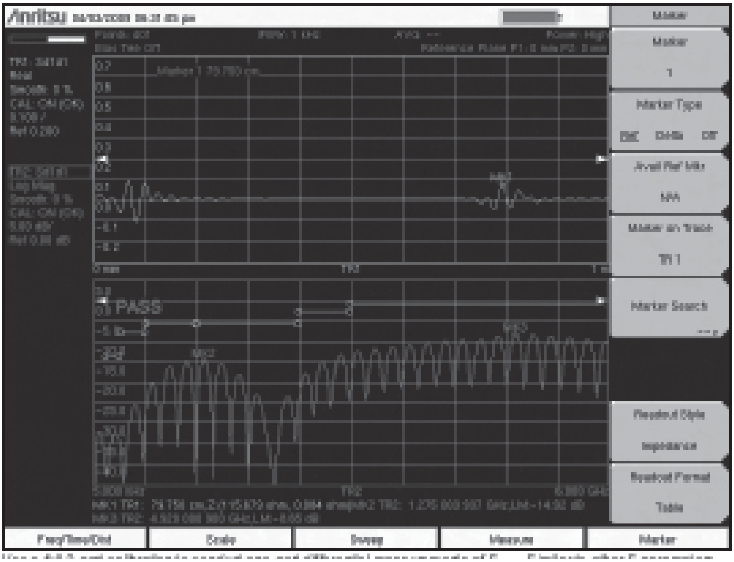


Figure 3-24. *By using Option 0077, the two test-ports are reconfigured into a balanced mode for measurement of* S_{d1d1}.

Time Domain Separation of S-Parameters

While not strictly a cable or antenna characterization, the following tuning procedures for highly-complex passband filters demonstrates the powerful ability of the Time Domain function to separate the S-parameters of a DUT in distance or time.[5] In the quest for superior filter performance, and the ability to create specific filter specifications, filter designers now utilize extremely complex architectures. This makes manufacturing and final test a difficult endeavor, not to mention the challenges associated with the field servicing requirement.

In this case, a number of different resonators can be used; lumped LC circuits are good for production on printed circuit type technology. Cavity resonators are good for high power. Waveguide models have used "waffle iron" type machining to develop filtering. Dielectric resonators tend to have higher Q factors. Producing more sophisticated filter parameters, sharper skirts and flatter passbands, multiple "poles" or resonators need to be used. Suppose you use 5 resonators designed to "cross-couple" certain individual effects, multiplying their features and producing sharper rejection skirts and deeper stop bands. Flat passbands are still maintained with the desired flat Group Delay.

A generic diagram of a tuned multipole LC filter is shown in Figure 3-25. Individual resonators may be tuned for the desired filtering performance. For filter characteristics with steeper slopes on the reject skirts, another wrinkle may be added, which is shown as "cross-coupling." The cross coupling can skip different numbers of resonators, even or odd, to achieve the selectivity that is needed for a given system. In many cases, it is the separation of transmit and receive frequency channels that determines the specific design. Since the resonators are physically distributed, the VNA Master's Time-Domain function can be used to display the tuning effect of each resonator individually.

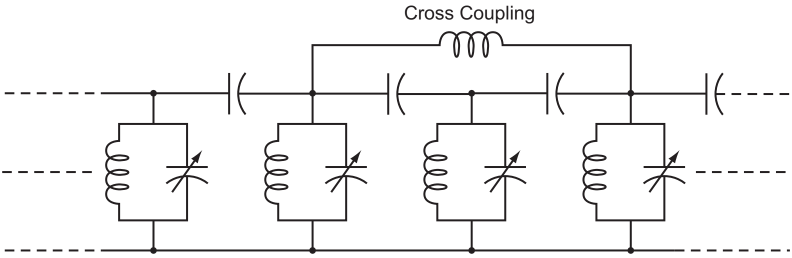
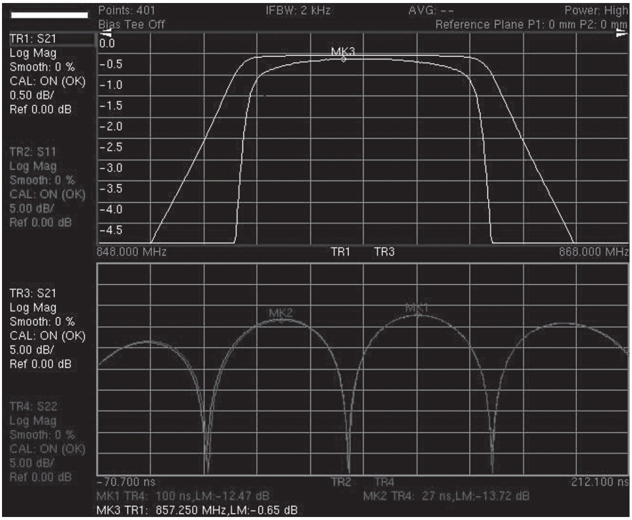


Figure 3-25. *Filter designers use as many resonators as necessary to create the desired passband. A technique for sharpening the reject skirt is to cross-couple some amount of signal between odd or even resonators, as required.*

While in general, the more poles or tunable resonant circuits used, the better the flatness, this is not completely true. More resonances also mean more loss across the passband, so practical filters might be 5 or 8 poles. But in the tuning stages, if the only measurement instrument shows a frequency versus attenuation plot, the tuning situation can be hopeless because of the extreme interaction between almost all tuning screwdriver slots.

One measurement answer is the ability to electronically separate the display of individual resonators by their physical position. This can be done with a powerful time-domain feature found in modern VNAs. Figure 9-26 shows a typical measurement display where the time domain separation assists in tuning bandpass characteristics. On the top overlay, two versions of the passband S_{21} are overlaid, one being 0.5 dB per division and the other (showing sharp skirts) is 5.0 dB per division. The lower display shows attenuation for the various resonators, separated by distance, with the markers MK1 and MK2 designating their physical distance.



```
Points: 401          IFBW: 2 kHz          AVG: --          Power: High
Bias Tee Off                  Reference Plane P1: 0 mm P2: 0 mm

TR1: S21
Log Mag
Smooth: 0 %
CAL: ON (OK)
0.50 dB/
Ref 0.00 dB

TR2: S11
Log Mag
Smooth: 0 %
CAL: ON (OK)
5.00 dB/
Ref 0.00 dB

TR3: S21
Log Mag
Smooth: 0 %
CAL: ON (OK)
5.00 dB/
Ref 0.00 dB

TR4: S22
Log Mag
Smooth: 0 %
CAL: ON (OK)
5.00 dB/
Ref 0.00 dB

MK1 TR4:  100 ns,LM:-12.47 dB        MK2 TR4:  27 ns,LM:-13.72 dB
MK3 TR1:  857.250 MHz,LM:-0.65 dB
```

Figure 3-26. *Powerful insights are now available with time-domain measurements of multiple resonator filters. This screen shot shows two views of S_{21} passband, one with 0.5 dB and the other 5.0 dB per division. The bottom trace shows the time-domain separated views of individual resonators, allowing the filter tuner person to have a better idea of what the tuning is doing.*

Finally, it should be noted that the Time Domain option for VNAs is not the traditional nanosecond-pulses-down-a-coaxial line of oscilloscope TDRs. Instead it is based on the use of a FDR technique, which captures data over a band-limited range of frequencies, and uses powerful inverse-Fourier transform data processing to develop and display a time separated view of transmission or reflection. The use of band-limited data also means it is also useful for waveguide lines which are band-limited by definition.

Summary

The insight and diagnostic power that the handheld VNA brings to field test and maintenance is stunning. For all the simple routines of characterizing components, cables and antennas, its accuracy and speed is expected. But, for the complex and sophisticated test routines of Time Domain and Precision Phase measurements, the specialized options of the VNA are crucial. Although not discussed herein, the ability of the contractor, field technician or engineer to add a powerful spectrum analyzer to the basic VNA takes a brand new test system on the road, anytime, anywhere.

References

1. Practical Tips on Making "Vector Voltmeter (VVM)" Phase Measurements using VNA Master (Opt 15), Anritsu Application Note 11410-00531.
2. Distance to Fault, Anritsu Application Note 11410-00373.
3. Reflectometer Measurements—Revisited, Anritsu Application Note 11410-00214.
4. Time Domain Measurements Using Vector Network Analyzers, Anritsu Application Note 114 10-00206.
5. Primer on Vector Network Analysis 11410-00387.

Handheld Cable & Antenna Analyzers - Site Master

Since 1995, the Site Master™ has been the leader in handheld Cable and Antenna Analyzers for installers, contractors, and wireless service providers worldwide. With its unsurpassed measurement uncertainty and best-in-class sweep speed, the Site Master gives you extremely accurate and fast measurements that you can totally trust, whenever and wherever.

The Site Master family includes seven models to meet a variety of needs. They all can make traditional line sweep measurements such as Return Loss, VSWR, Cable Loss, and Distanceto-Fault (DTF). To increase productivity, the Site Master completes sweeps quickly, performs calibrations quickly with InstaCal™, provides fast trace naming, and comes with automatic report generating capabilities.

The 2-port transmission measurement option with its excellent dynamic range allows you to measure gain, insertion loss, or isolation of critical RF devices including tower mounted amplifiers (TMA), repeaters and passive RF components such as filters and antennas. Models with Spectrum Analyzers can make RF channel measurements and hunt down interference. Get the most trusted name in cable and antenna analyzers – the worldwide standard – the Site Master.

Site Master	Frequency Range		Measurements
	Cable & Antenna Analyzer	Spectrum Analyzer	
S311D Cable and Antenna Analyzer	25 MHz to 1600 MHz	N/A	• Return loss • Cable loss • SWR • Distance-to-fault
S331E Cable and Antenna Analyzer	2 MHz to 4 GHz	N/A	
S361E Cable and Antenna Analyzer	2 MHz to 6 GHz	N/A	
S332E Cable and Antenna Analyzer	2 MHz to 4 GHz	100 kHz to 4 GHz	• Return loss • SWR • Cable loss • Distance-to-fault • PIM analysis • Adjacent channel power ratio • Interference analysis • Coverage mapping • AM/FM/PM analyzer • Transmission measurement • Channel power • S412E includes VNA
S362E Cable and Antenna Analyzer	2 MHz to 6 GHz	100 kHz to 6 GHz	
S412E Cable, Antenna, Spectrum, Interference, P25/NXDN Modulation Analyzer		100 kHz to 1.6 GHz	
S810D Broadband Microwave Transmission Line Analyzer	25 MHz to 10.5 GHz	N/A	• Return loss • 1-port cable loss • Distance-to-fault • 2-port cable loss • Coax and waveguide VSWR
S820D Broadband Microwave Transmission Line Analyzer	25 MHz to 20 GHz	N/A	

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