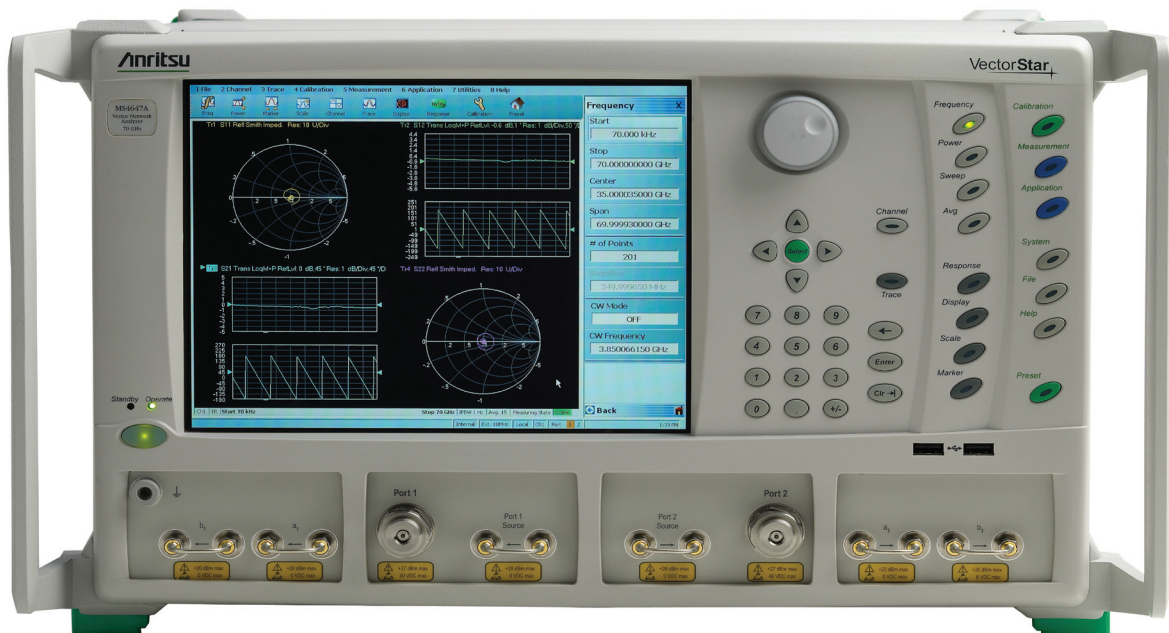# Time Domain Measurements Using Vector Network Analyzers

MS4640A
Vector**Star**™ VNA

Introduction

Vector Network Analyzers (VNAs) are very powerful and flexible measuring instruments. Their basic capability is to measure the S-parameters of an RF or microwave device and display the result in the frequency domain. This provides valuable data for the design engineer to develop a design and for the production engineer to substantiate the performance of the device or system. In addition to displaying performance in the frequency domain, Anritsu VNAs offer a Time Domain option to enhance the analysis capability by presenting data in the time (or distance) domain–valuable information for both the design and production engineer. Figure 1 provides the time and frequency response of a microstrip circuit as measured by the MS4640A VNA.

Note that port 2 of the DUT is left open and consequently the frequency plot of the device provides little information about the performance of the device. The benefit of the Time Domain response is in providing information of the device performance at specific locations. As a result, the VNA provides the overall S-parameter critical performance information for the device both as it appears when installed in a system and also at a specific location within the device.
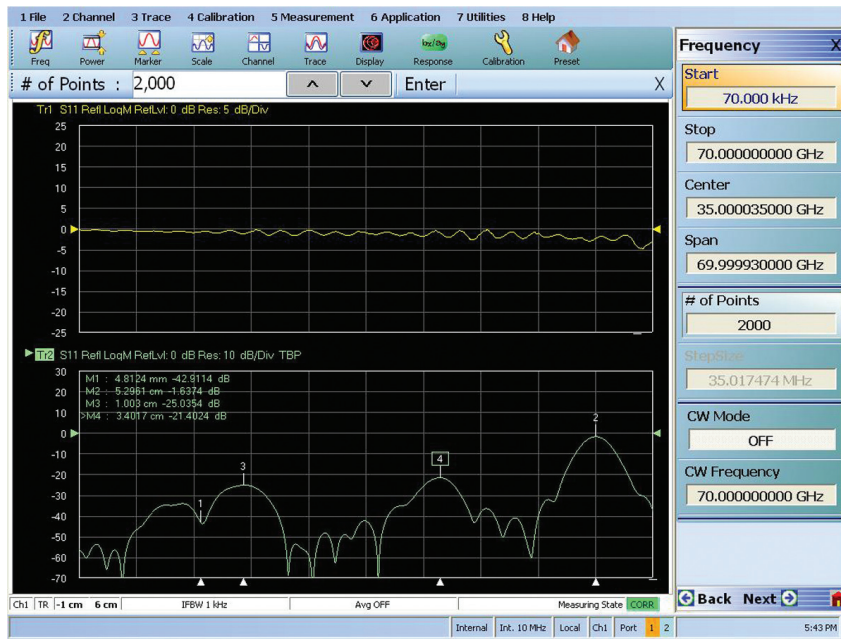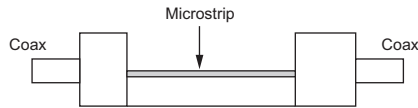
Figure 1. Time and Frequency Response of a Microstrip Circuit

Time Domain Fundamentals

The Fourier transform has been used in many technologies and in microwave measurements, provides a method for transforming frequency domain data, which is the VNA's basic capability, into the time domain. Microprocessors are fundamental to modern VNAs by providing an efficient method of computing error correction terms. In addition, microprocessing also permits convenient implementation of the Fast Fourier Transform (FFT) for additional advanced analysis.

Specifically, a variation of inverse FFT is used to transform from the frequency domain to the time domain. This permits the user to "zoom in" on a specific time (distance) range of interest for the data display. This application note addresses the properties of the transform process and shows how the various processing options are used to obtain optimum results for a given application. It will not address the algorithmic details of the FFT.

A convenient starting point is to consider the transform of frequency domain data obtained from the measurement of a short at the end of an airline as shown in Figures 2a and 2b. It is apparent that the time domain response is informative; but it is far from the ideal time domain response that is superimposed. This figure illustrates two of the fundamental properties (limitations) associated with the FFT: resolution and alias free range. Resolution is limited by the bandwidth of the measurement while aliasing is determined by the frequency step size.
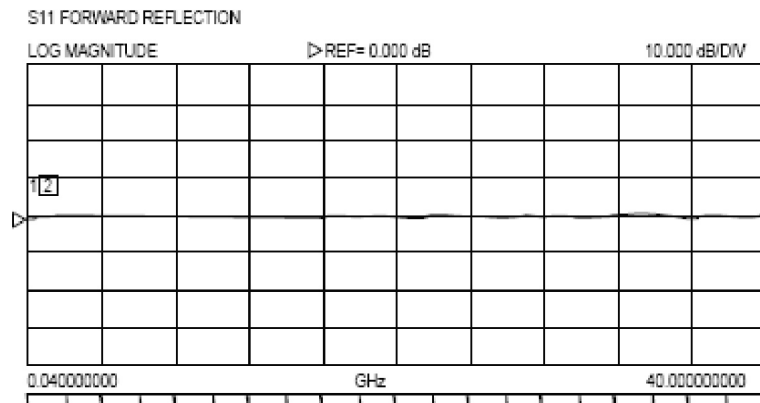
S11 FORWARD REFLECTION

LOG MAGNITUDE   ▷REF= 0.000 dB   10.000 dB/DIV

0.040000000   GHz   40.000000000

Figure 2a

S11 FORWARD REFLECTION   BP

LOG MAGNITUDE   ▷REF= 0.000 dB   20.000 dB/DIV

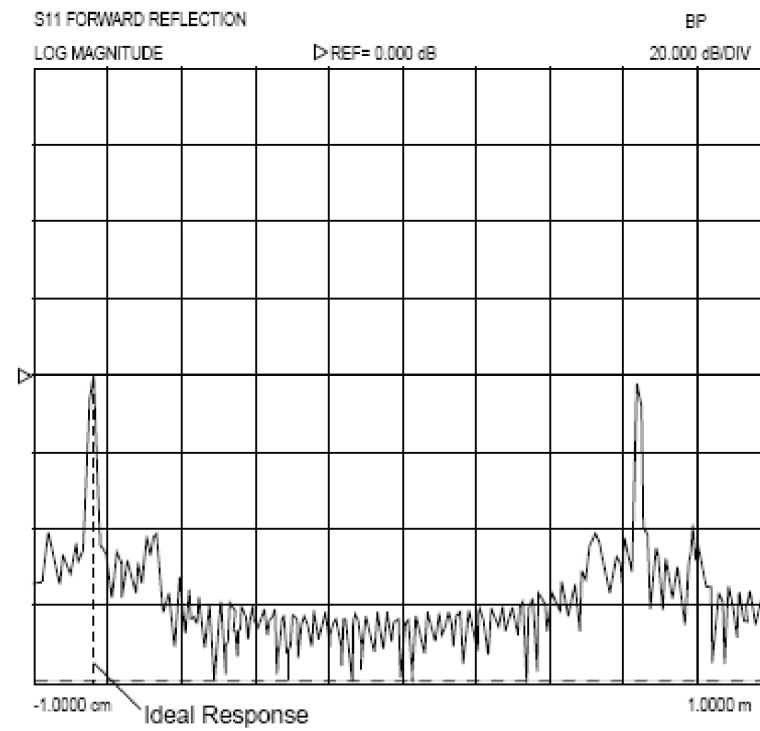-1.0000 cm   Ideal Response   1.0000 m

Figure 2b

The principal property of interest in time domain processing for most microwave applications is resolution; or the ability to resolve one location from another. In practice, the basic limitation is inversely related to data collection bandwidth in the frequency domain. A rule of thumb defines resolution on the order of 150 mm divided by Frequency Span (GHz) in air. For example, a 20 GHz frequency span will provide a resolution of about 8 mm while a span of 70 GHz will provide a resolution of about 2 mm. So the broader the frequency span, the more information presented during the time domain analysis. Figure 3 illustrates the importance of a wide frequency sweep if the application calls for identifying closely spaced reflections. Note that even though the DUT may not be required to perform up to 70 GHz, as long as the DUT doesn't completely fall apart out of band, the design engineer can still benefit from the 70 GHz span due to the increased resolution provided by the wide frequency range. A limitation to the frequency span rule is when measuring devices with limited bandwidth. Ideally, the device will pass the DC component, and as a result, the performance at higher frequencies will result in a gradual roll-off. If the DUT does not pass the DC component such as band pass or high pass filter, then resolution will degrade.
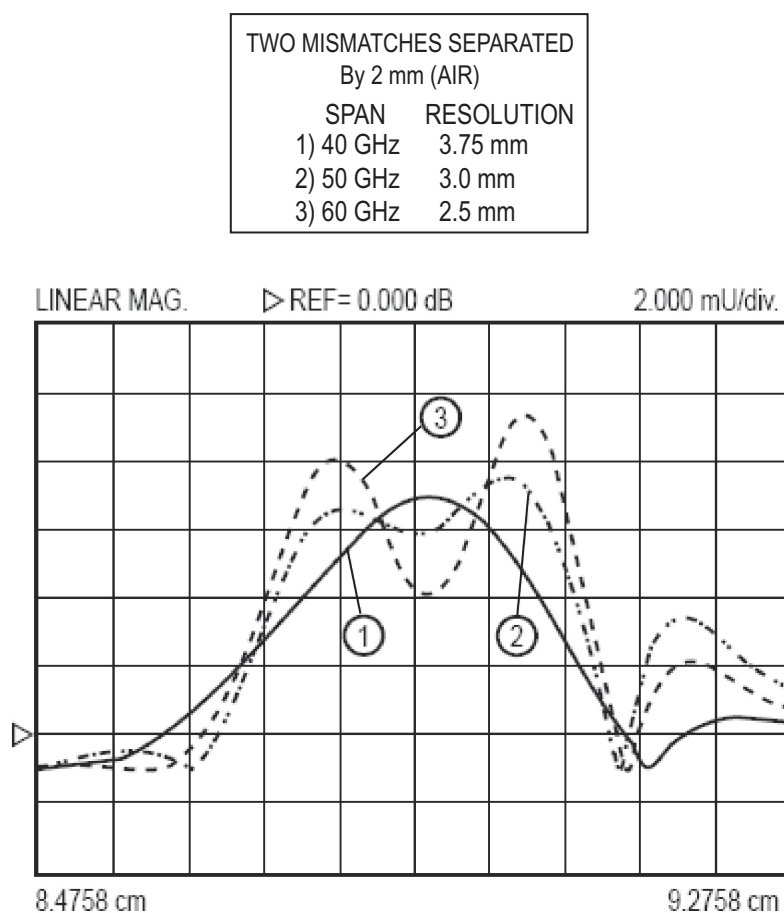
TWO MISMATCHES SEPARATED
By 2 mm (AIR)

SPAN	RESOLUTION
1) 40 GHz	3.75 mm
2) 50 GHz	3.0 mm
3) 60 GHz	2.5 mm

LINEAR MAG.　　▷REF= 0.000 dB　　　　　2.000 mU/div.

8.4758 cm　　　　　　　　　　　　　9.2758 cm

Figure 3. Wide bandwidth provides improved discontinuity resolution

4

Resolution is also influenced by the processing method and window selection options that are described below. Another important factor is the relative amplitude of the signals being processed. A large signal can swamp a smaller signal–where the greater the time (distance) separation between the two discontinuities the better the points of interest can be resolved.

Figure 4 represents a time domain plot of a device with two discontinuities separated by 4.8 mm. The discontinuities are located at marker 3 and the display is taken from a VNA whose maximum bandwidth is 26.5 GHz. Low pass processing, the highest resolution mode possible, is used. Note that the 26.5 GHz frequency span is unable to resolve the two discontinuities.

Figure 5 provides a low pass plot of the same device but with a VNA capable of covering a 65 GHz frequency span. Markers 2 and 4 on the 65 GHz display are at the same location as in the 26.5 GHz plot. Note the additional amount of information available from the wider bandwidth. Also note the difference in return loss value when compared to a narrow band sweep. This points out that for maximum resolution and accuracy, the widest frequency span available is best for optimum time domain analysis, especially when resolving two discontinuities in close proximity.
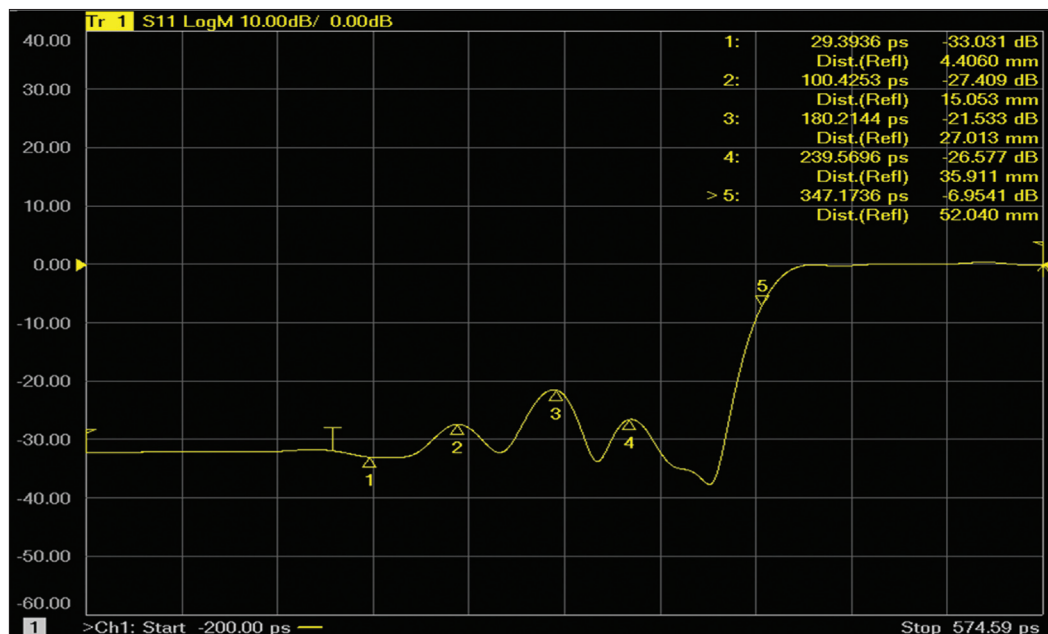

Figure 4. Low pass time domain plot of two discontinuities 4.8mm apart located at marker 3. VNA has an upper bandwidth limitation of 26.5 GHz
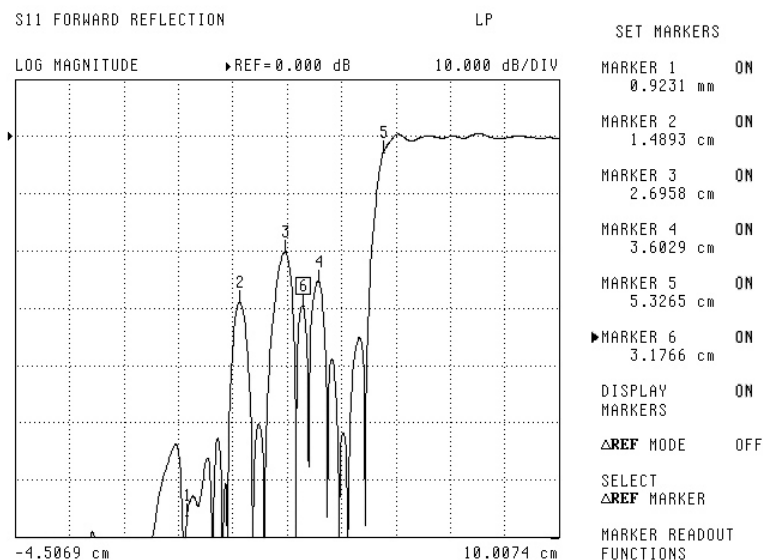

Figure 5. Same device measured with 65 GHz bandwidth. Second discontinuity now visible at marker 6. Note difference in return loss values.

Another property of the transform process is the Alias Free Range. The transform is a circular function and repeats itself outside of its inherent range of 1 divided by the Step Size (1/2x Step Size). The more data points available, the smaller the step size and the longer the time frame before the data starts to repeat. For example, with a 20 GHz frequency sweep and 401 data point collection, the Alias Free Range is:

1/2x 50 MHz = 10 nanoseconds

With the capability of providing 100,000 data points in a single channel sweep, the MS4640A can provide an Alias Free Range of:

1/2x 200 kHz = 2.5 µsec

Long range capability is especially valuable when analyzing long transmission cables such as optical cables or transmission lines with a high dielectric coefficient.

Processing Alternatives:

The Time Domain option offers a number of processing alternatives to the user. It is important that the user be aware of the feature set available as selection can have a significant effect on the end result.

These tools include:

- Processing Method – Lowpass or Bandpass.
- Response – Step or Impulse for Lowpass mode and Impulse or Phasor Impulse for Bandpass mode
- Window Shape – Rectangular, Nominal, Low Sidelobe, Min Sidelobe
- Gating – Frequency with Time Gate

Lowpass

This is the most powerful processing technique. It does require a special frequency plan consisting of: a harmonically–related set of frequencies that starts at the lowest frequency possible. Impulse or step response is available when using the lowpass mode. The step response provides a Time Domain Reflectometry-like display by integrating the impulse response. However, in order to provide a phase reference, a DC component must be included. Since VNAs cannot get all the way to DC, some additional information is needed to perform this integration. To see this, consider:

$$\text{ImpulseResponse} = \Im^{-1}\{X(DC)+X(\text{sweepRange})\}$$

$$\approx A{\cdot}X(DC)+ \Im^{-1}\{X(\text{sweepRange})\}$$

$$\text{StepResponse} = \int_{0}^{t} [A{\cdot}X(DC)+\Im^{-1}\{X(\text{sweepRange})\}]dt$$

A DC term is extrapolated thereby providing a reference so that the true nature of a discontinuity can be seen. The lower the start frequency, the more accurate the DC extrapolation calculation. With a start frequency of 70 kHz, the MS4640A offers the lowest available DC extrapolation point thereby minimizing the DC error. If additional information is available regarding the test environment, such as characterization of transmission cables, the DC term can be entered manually.

As mentioned above, lowpass offers two presentations: Step or Impulse response. The Step response permits the direct display of impedance versus time or distance similar to that obtained with a TDR. The Step response display is the integral of the Impulse response. The user can also obtain insight into the nature of a discontinuity: inductive, capacitive or resistive. Figure 6 shows ideal responses associated with various types of discontinuities. The default display graph type is real and shows impedance information (A scale of 20 mU per division is about 2 ohms per division). The user can choose Log Mag or a linear display format. Lowpass processing also offers the highest resolution for a given bandwidth and provides twice the resolution of Bandpass mode. If the instrumentation, transmission line, and DUT permit Lowpass processing, it should be used.
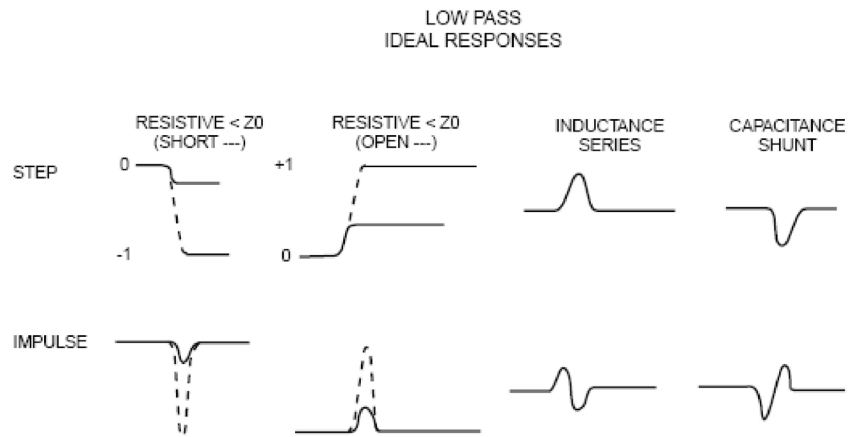
LOW PASS
IDEAL RESPONSES

Figure 6 Ideal responses associated with various types of discontinuities

Figure 7 shows a practical application of Lowpass Time Domain processing. An SMA line standard was constructed using solid Teflon® and precision connector interfaces, the response clearly shows the quality of the SMA "standard" that was used to evaluate SMA calibration performance. When considering time domain display, the most common method of display is in linear mode. So the display of Figure 7 is in terms of Reflection Coefficient, or Rho. One of the primary reasons for displaying the response in linear units is the ability to display the reactance component and better resolution of highly reflective devices. The standard line has a reflection coefficient of -2.679 mU or 51 dB (-20 log p) or an impedance of 49.73 ohms (R=Zo/VSWR).

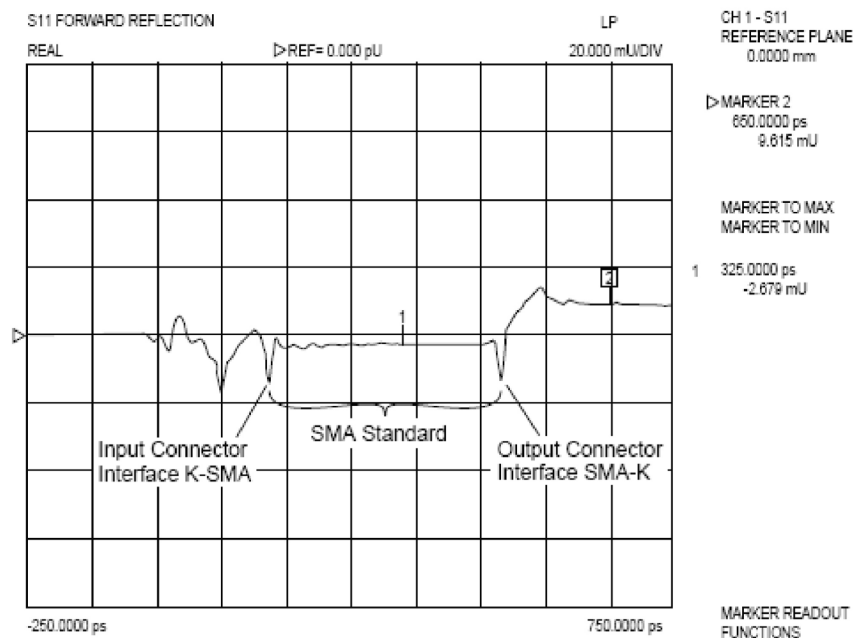*Figure 7. Practical application of Lowpass Time Domain processing*

Teflon is a registered trademark of the Dupont Company

Bandpass

Many situations such as waveguide or band limited DUTs preclude using a broadband harmonically related frequency plan. For these cases Bandpass processing should be used. In this situation, where there is a lack of a DC component, there is no phase reference so vector information is lost. However, useful magnitude information is still available and can be displayed in either log magnitude or linear form. Figure 8 shows the Bandpass response of the SMA "standard" that was used in Figure 7. This type of processing is common in fault location that can be used to test transmission lines. Figure 9 shows an example of this application: measuring a 2 m cable with imperfections.
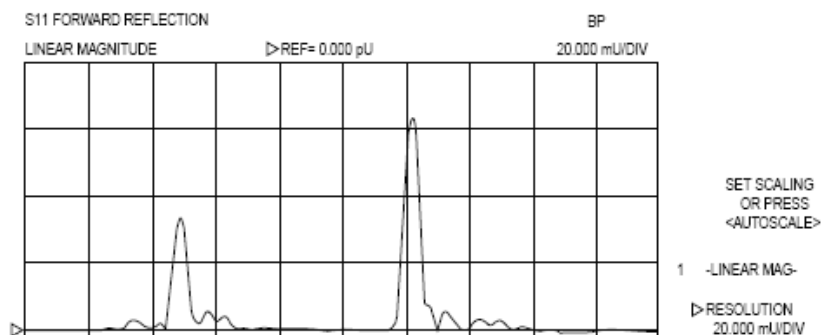

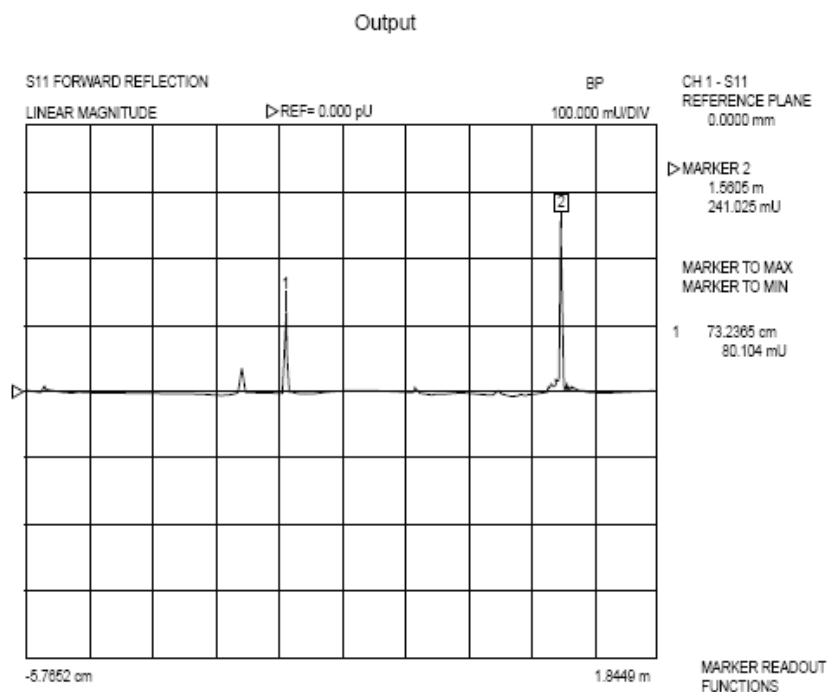*Figure 8. The Bandpass response of a SMA 'Standard'*

Figure 9. Measuring a 2m cable with imperfections

Phasor Impulse

This technique, exclusive to Anritsu VNAs, enables the user to extract impedance information for a specific discontinuity from a bandpass display. The discontinuity of interest is positioned in the center of the screen and should fill about 50% of the time range being displayed. When the Phasor Impulse processing is applied, the resulting display, usually Real, Imaginary, or Linear Polar, provides the desired impedance information.
Figure 10 shows the shunt capacitance associated with a waveguide iris.

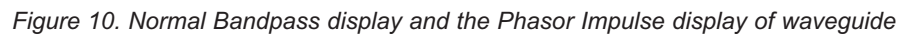*Figure 10. Normal Bandpass display and the Phasor Impulse display of waveguide*

Figure 11 is a summary of the processing types. As noted, Lowpass processing should be used whenever possible as it offers the highest performance and most versatile set of displays.
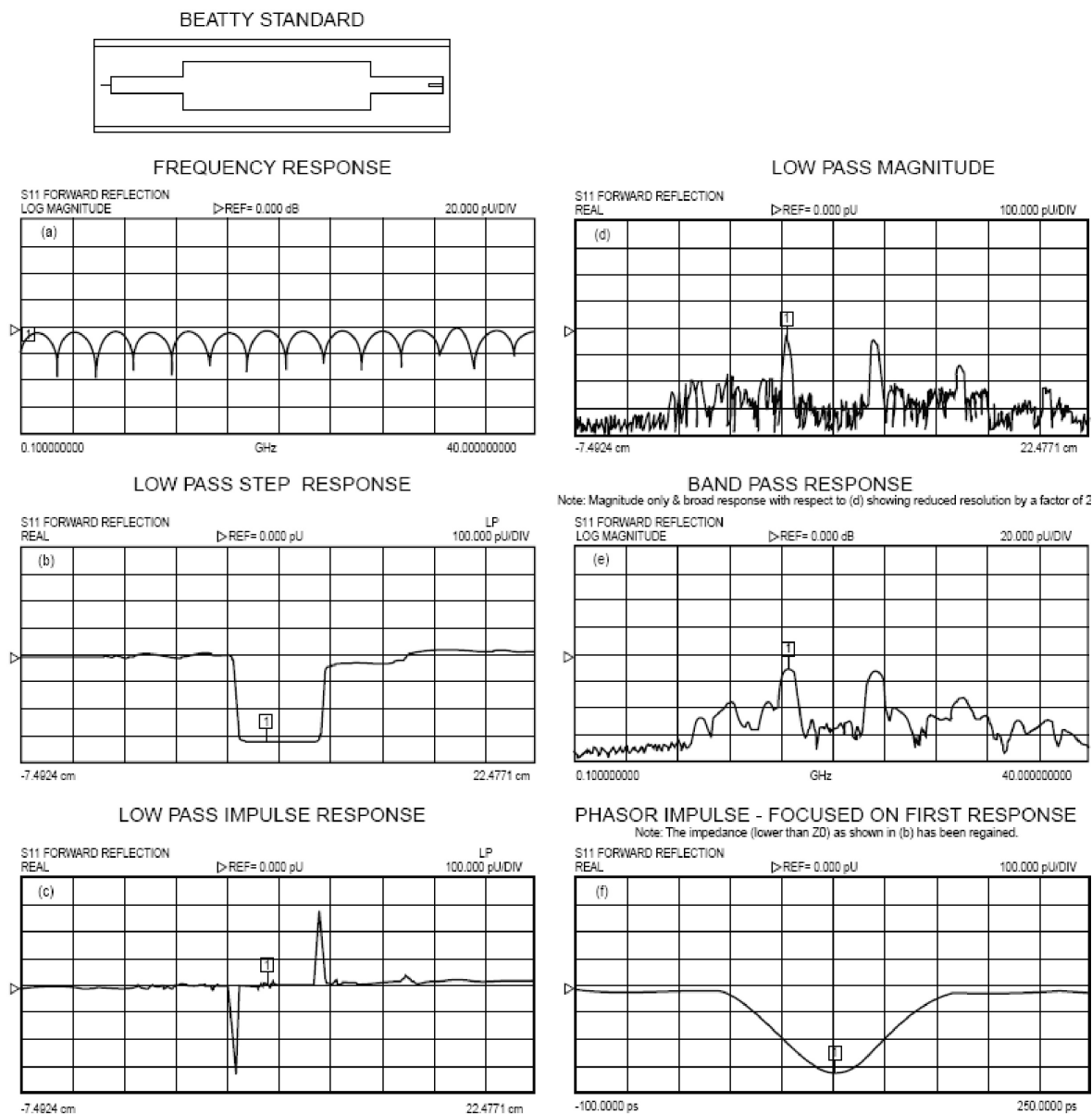

Figure 11. Summary of processing types

Windows

Windows are used to "condition" data prior to transformation. They are used to get around the Fourier transforms basic, but impractical, – to + form and they are used to mitigate edge effects associated with a finite data set. The application of what is called a "window" function to the frequency domain data will accomplish this. The window is a curve derived from a mathematical function (many are available–see reference 4) that tapers off from unity gain at the center of the frequency domain data to a low value at the ends. Figures 12a and 12b show the effect of applying the widely used two-term Hamming window to the data array obtained by measuring the short circuit shown earlier. The resulting time domain displays are shown in 13a and 13b. This is not without a price, since the window has the effect of widening the main lobe, thus decreasing the effective resolution. For this reason, it is good to have a range of different window types available so that multiple views between resolution and sidelobe effects, appropriate for the application, can be used. The Anritsu VNAs offer the window choices described in Table 1. Figure 14 provides a display of window effects on main and side lobes. Resolution has been normalized to the Default Nominal window that is adequate for most applications.
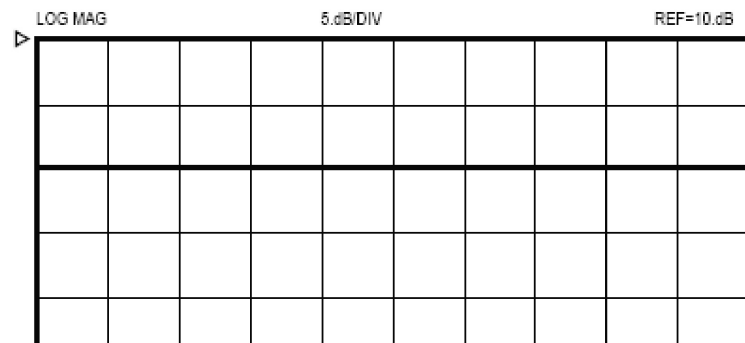

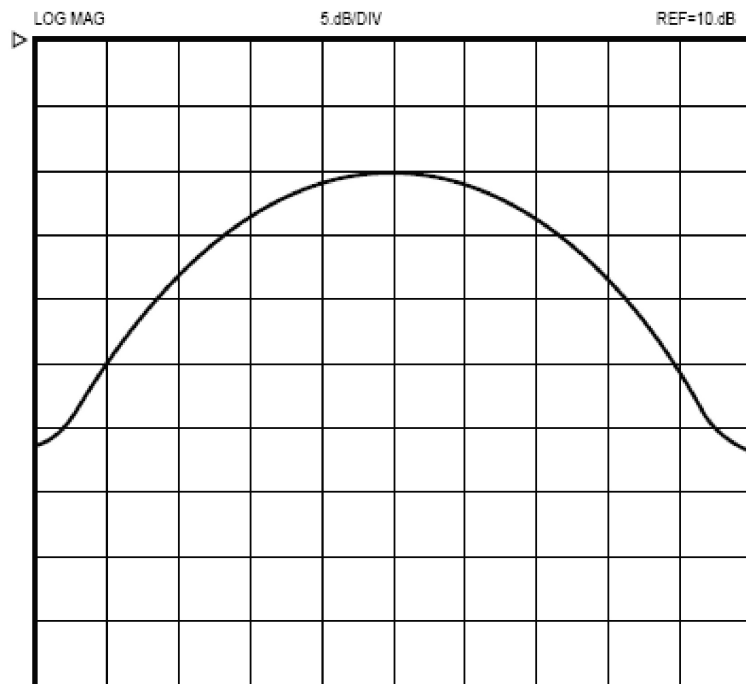*Figure 12a. Frequency domain data before application of Hamming Window*

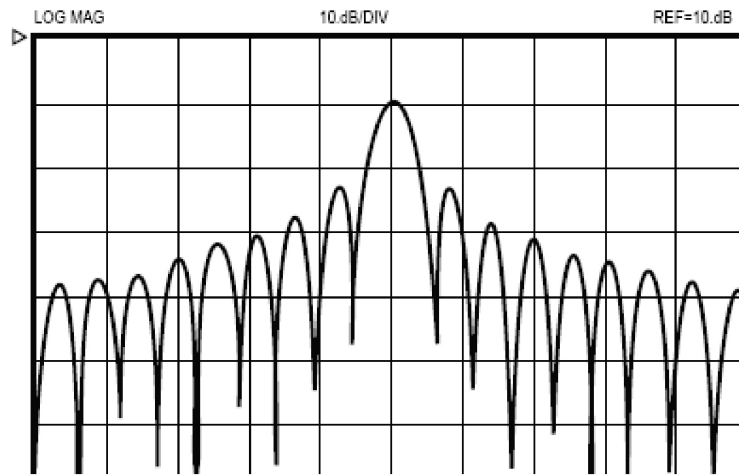*Figure 12b. Frequency domain data after application of Hamming Window*

Figure 13a. Time domain data before application of Hamming Window
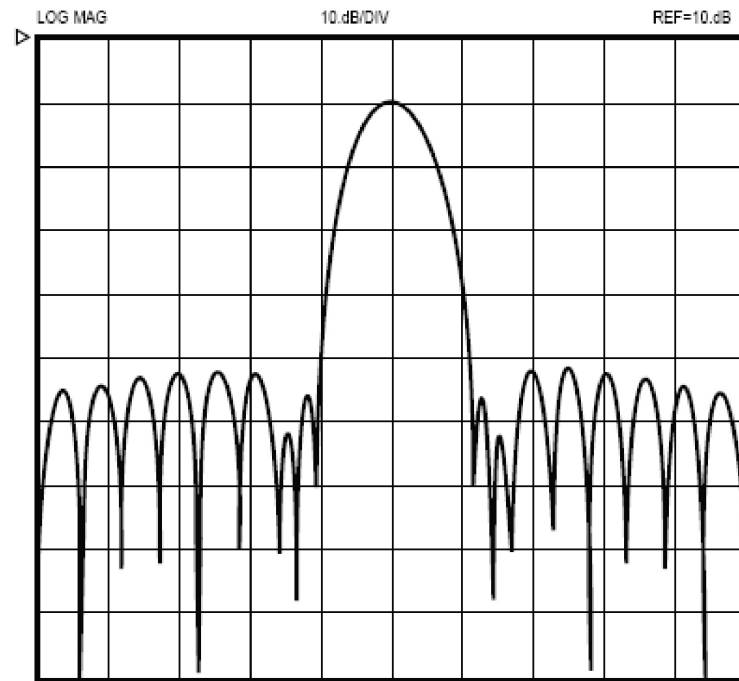

Figure 13b. Time domain data after application of Hamming Window

Window Type	Main Lobe Width Lowpass	Main Lobe Width Bandpass	Sidelobe Level (dB)
Rectangular	0.5/BW	1/BW	-13
Nominal	1/BW	2/BW	-42
Low sidelobe	1.5/BW	3/BW	-70
Min sidelobe	2/BW	4/BW	-90

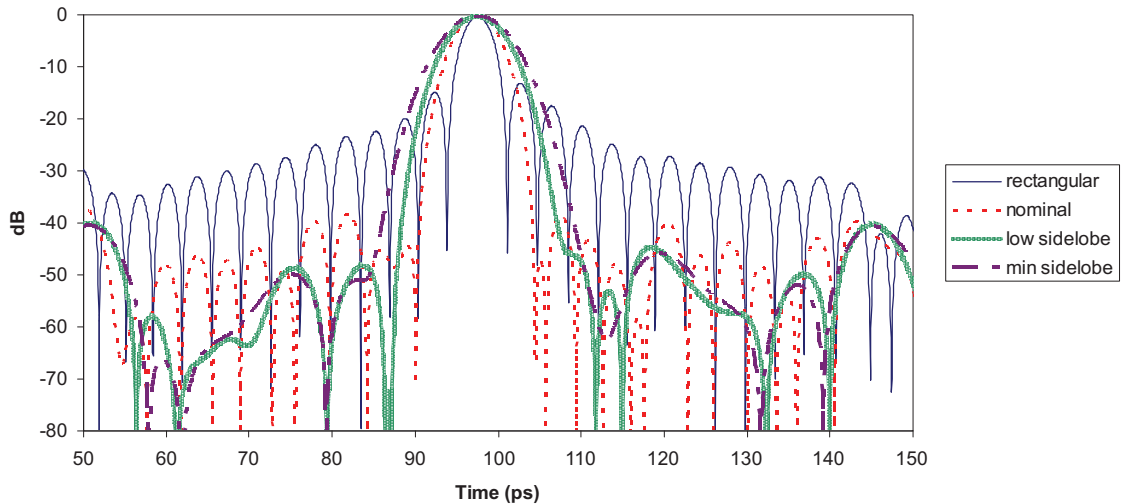*Table 1*

Lowpass time domain window effects

Figure 14. Window effects on main and side lobes.

In addition to the standard selection of window shapes, advance parameters unique to the MS4640A VNA are now available. The advanced control is available using the new selections, Kaiser-Bessel and Dolph-Chebyshev. Figure 15 provides an example of control possibilities using these choices. These two new window types allow for a finer selection of the trade-off between side lobe level and resolution. For the Kaiser-Bessel window, a larger Beta value leads to lower side lobes, and a wider main lobe width. For the Dolph-Chebysev window, the side lobe level is parameterized explicitly (in absolute dB) and a larger value leads to lower side lobes. The window for two parameter values for each of these windows is shown in Figure 15 along with the rectangular window for comparison.
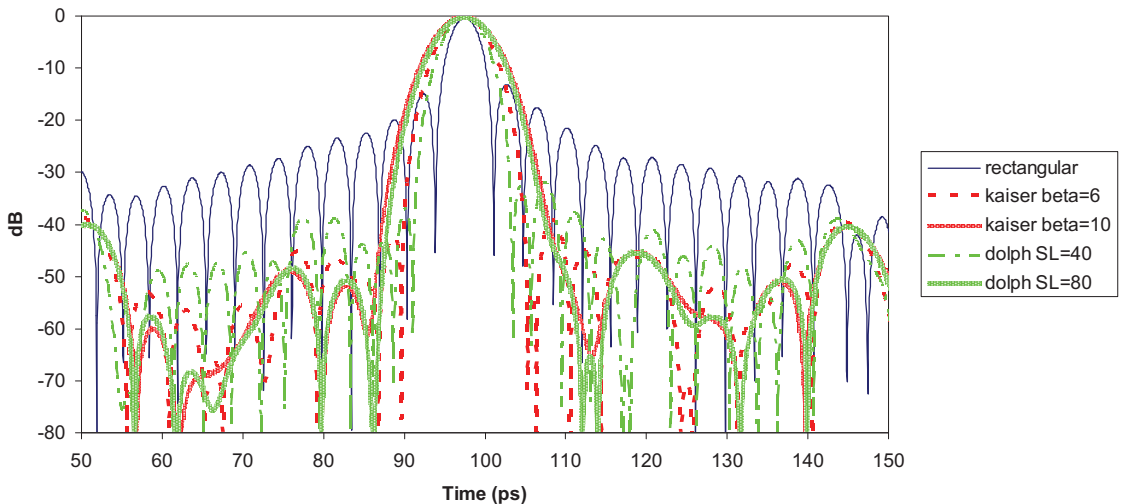
Lowpass time domain window effects

Figure 15. Advanced Time Domain controls on main and side lobe display.

The approximate relationship between these parameters and the main lobe width (null-to-null) is suggested in Figure 16. Here, everything is scaled relative to a rectangular window (a nominal window is at 2, a low side-lobe window is at 3, and a minimum side-lobe window is at 4 on this scale) and the y-axis is normalized relative to the lobe width of a rectangular window.
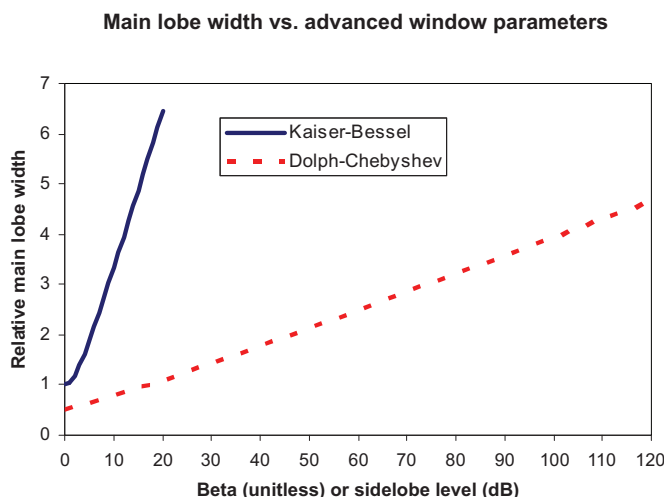
Main lobe width vs. advanced window parameters

Figure 16. Relative relationship of main lobe between Kaiser-Bessel and Dolph-Chebyshev parameters.

Gating – Frequency Gated by Time

The Gate is essentially a filter in the time domain. It is set by the operator while observing the time domain response to select a given discontinuity or in some cases to select those responses that can be attributed to a given DUT, such as a cable that has principal reflections at both ends. It can also be used to Gate out a specific discontinuity, such as a test fixture, thus observing the performance of a microwave circuit with an imperfection removed. This permits observing the selected range without the influence of unwanted elements, such as connectors or in the case of transmission measurements: multi-path signals. The Gating process also involves selecting a gate shape. This is similar, but not identical to the Window function. In looking at previous time domain displays, it is apparent that there are ripples associated with a specific reflection that extend over the time range. All of which are necessary to obtain a good representation of that reflection in the frequency domain. The gating process can eliminate some of this necessary data that can introduce errors or ripple in the frequency domain response. As in Windowing, the solution is to provide a selection of Gate functions so the user can obtain the best tradeoff of resolution versus ripple.

Figure 17 shows the application of a Gate and the Frequency Gated by Time display of the initial discontinuity of the Beatty standard used in Figure 11 above. This figure also illustrates the processing sequence that can be observed when a four trace display is available. Each trace is set to S11 and each is set up with a different process, the final in the lower right showing the frequency gated by time response of an impedance step that is reasonably flat with frequency as expected.
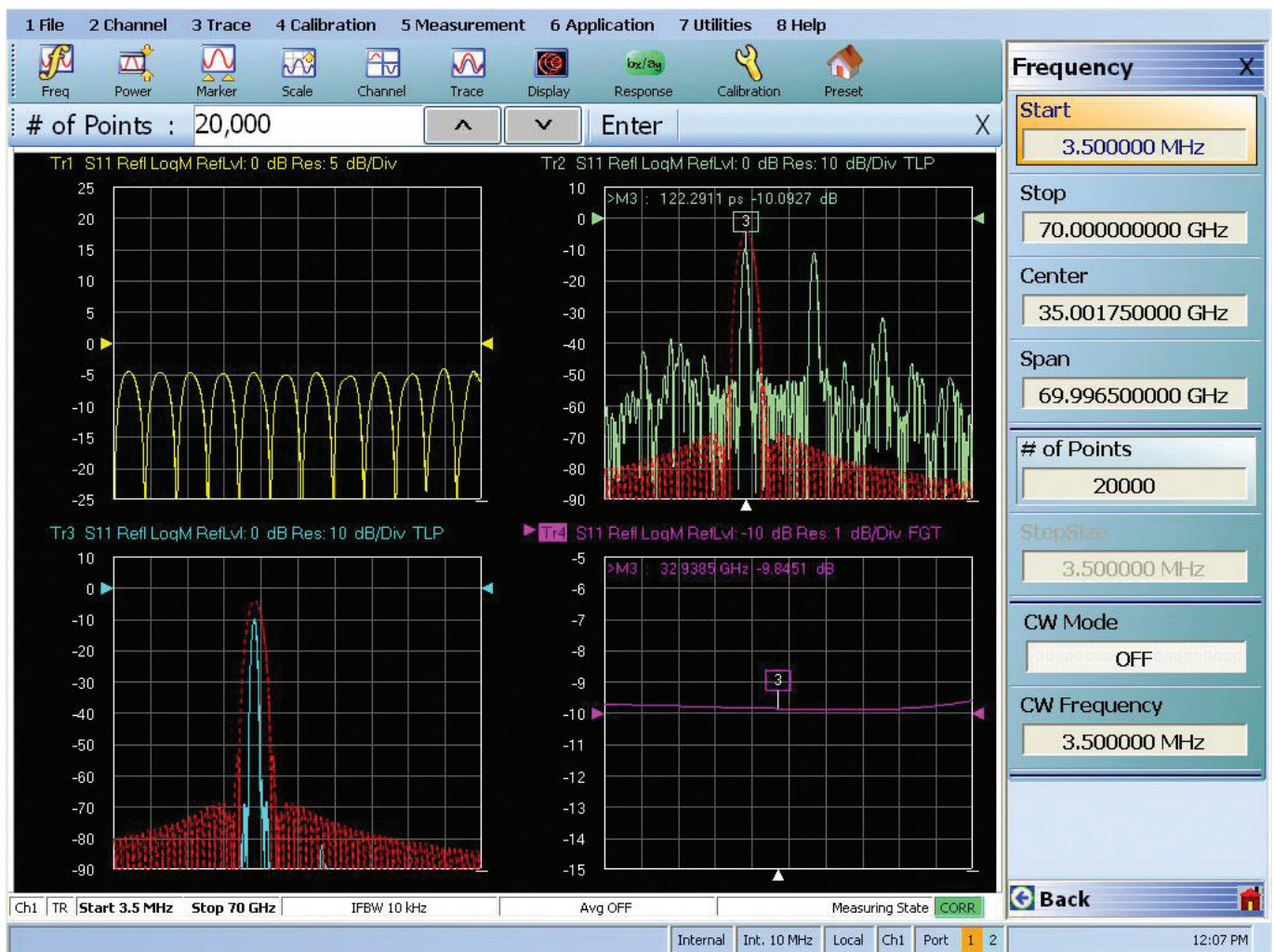
Figure 17. The application of a Gate and the Frequency Gated by Time display of the initial discontinuity of the Beatty Standard

Time Domain Applications

Time Domain is most useful when analyzing broadband low loss devices such as transmission lines, connectors, test fixtures and similar components. Narrowband devices such as filters, isolators or matching networks are not good candidates for Time Domain measurements.

A few "Helpful Hints":

- A harmonic frequency set is most desirable as this permits low pass processing. In any application, use the widest frequency range possible and start as low as possible for best DC extrapolation.

- When interpreting the return loss value of a Time Domain response, it must be noted that the response is the average of the return loss over the entire frequency range.

- When using frequency gated by time, it is important to center the gate around the discontinuity, or circuit being analyzed. In general, the gate should be as wide as possible, but not too close to the responses that the user wants to eliminate.

- The selection of Window and Gate shapes can have a significant effect on the result. A wide selection range provides the opportunity to optimize results. In these cases, if correlation with other measurements becomes an issue, it is important that the same Window and Gate shapes are used.

Utilizing Airlines

Time Domain work is greatly enhanced when the reflection to be studied is well separated from other reflections. This is readily accomplished if a high quality transmission line can be included in the system to be measured. In a coaxial system this would be an airline with connectors that interface to other components with minimum reflections. This performance can be realized by airlines with a beaded interface at one end, and a floating center interface at the other end. The bead insures an accurate pin depth at the precision interface, and also supports the center conductor so the airline can be easily installed.

The following examples show a number of practical applications for Time Domain processing:

Designing a Test Fixture

In test fixture design, it is often desirable to have an input coaxial connector and a launch to the microstrip medium being used for circuit design. This launch should be designed for minimum SWR so that it will be transparent when the device design is being evaluated. This can be accomplished by starting with a short length of microstrip line (several centimeters is a good choice) and connecting it to the initial launcher design, leaving the other end open. Figure 18 shows a coaxial to Duroid microstrip design. The reflection from the launch is clearly distinguished from the open end. The designer can make modifications to the launch design and easily see their effect until a satisfactory launch interface is obtained
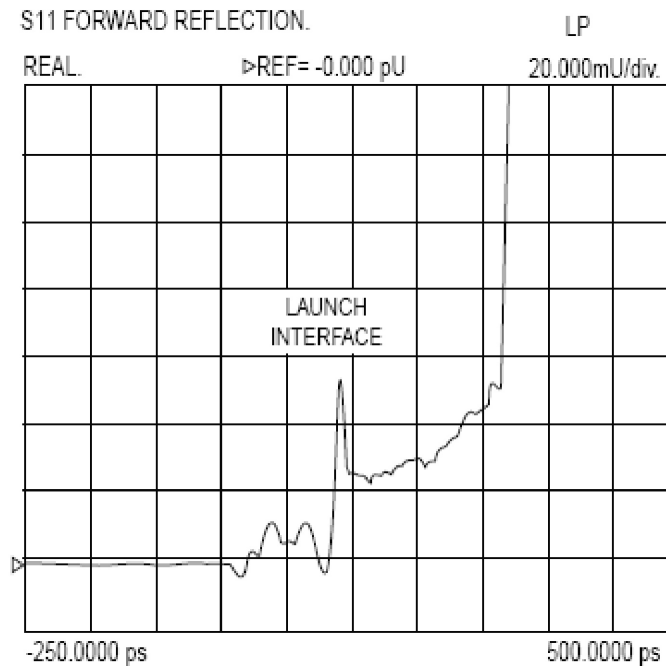

Figure 18. Coaxial to Duroid microstrip design

Measurement of VNA Directivity and Port Match

The accuracy of a VNA reflection measurement is primarily related to the effective directivity and port match after calibration. These parameters are usually specified in data sheets, but are dependent upon calibration standards and user technique. In some cases it would be important to know the value of these parameters. This information can be readily obtained if an Assurance Airline is available. It is installed at the calibrated test port and terminated with a short circuit. Figure 19 shows by diagram what is happening; the port match, directivity, and the short reflection are clearly separated in time and can be distinguished and evaluated quantitatively. The results show the result of an SOLT calibration using a broadband termination. Keep in mind the values displayed are a weighted average across the frequency sweep range.
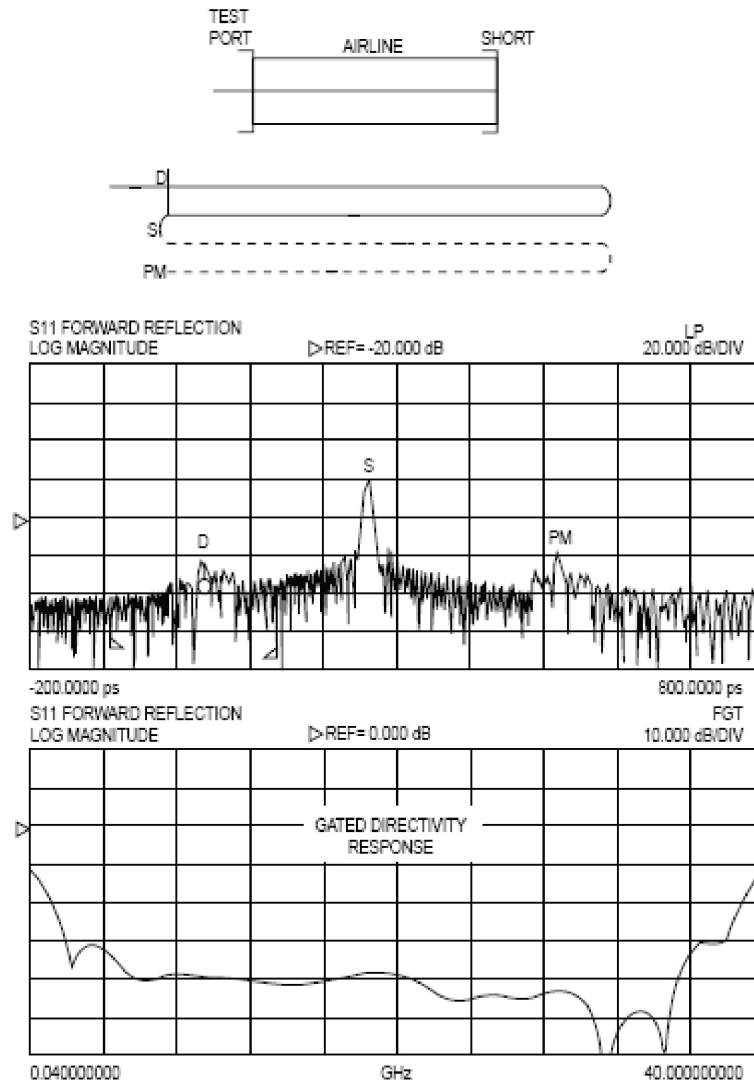
Figure 19. Port match, directivity and short reflection clearly separated in time.

Rise Time Measurements using Time Domain Transmission

The advent of data transfer rates in the tens of GHz region has created the need to measure the rise time and propagation delay of wide band devices such as coaxial cables, switches, and amplifiers used in optoelectronic systems. The use of sampling oscilloscopes in conjunction with fast rise pulse generators is a common technique for measuring rise time and delay. However, as VNA bandwidths have surpassed those of the scopes, the VNA provides an alternative means of performing the rise time and propagation delay measurements of these high speed devices.

These measurements require the use of Time Domain Transmission, that is an S21 Step response. The VNA performs these measurements with rise times as fast as 9 picoseconds (110 GHz system). The processing options; lowpass, bandpass, and the gating feature discussed earlier, apply to S21 Time Domain response as well.

In addition, the error correction techniques available on the VNA allow more accurate measurements of rise time, which may be obscured by the adapters and cables which are usually uncorrected in the oscilloscope method.

The Rise Time measurement of a 40 Gb/s driver amplifier using the 110 GHz VNA is discussed in this section. A measurement of the rise time of the VNA transmission response is required in order to make the amplifier measurement. In this case, a 12-term calibration is performed and with the thruline in place, the S21 time step response is measured as shown in Figure 20. The rise time, the time between the 10% and the 90% magnitude points, is measured to be approximately 9 ps.
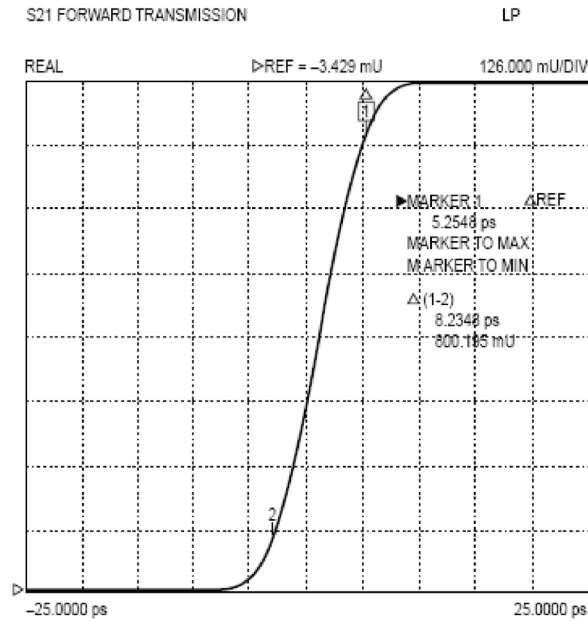
S21 FORWARD TRANSMISSION   LP

REAL   ▷REF = –3.429 mU   126.000 mU/DIV

▶MARKER 3   △REF
5.2548 ps
MARKER TO MAX
MARKER TO MIN

△:(1-2)
8.2348 ps
800.185 mU

–25.0000 ps   25.0000 ps

Figure 20. Corrected Step response of the 110 GHz VNA

The 40 Gb/s driver amplifier is then measured (Figure 21). The S21 Time Domain response in this case is the composite measurement of the VNA rise time and the Amplifier rise time. The 180° phase shift in the amplifier S21 response is displayed as an inverted step in Time Domain mode. The composite rise time measured is 12 ps.
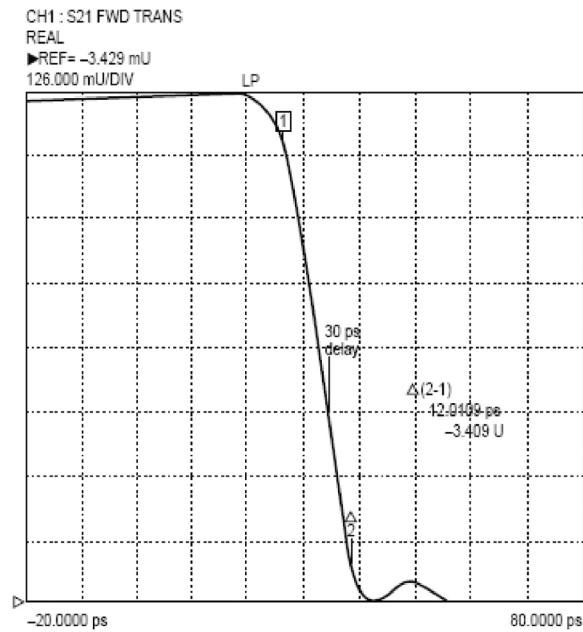

CH1 : S21 FWD TRANS
REAL
▶REF= –3.429 mU
126.000 mU/DIV   LP

30 ps
delay

△(2-1)
12.9409 ps
–3.409 U

–20.0000 ps   80.0000 ps

Figure 21. Inverted rise time and propagation
display response of the amplifier.

Rise time of the amplifier can then be calculated by using the root sum squares theorem:

T_{R2} *(DUT) =* T_{R2} *(total) -* T_{R2} *(input step)*

Or, T_R *(amplifier) =* $\sqrt{[(12)^2 - (9)^2]}$
= 8 ps

Similarly, the propagation delay through the amplifier can be measured from the 50% point of the step response.

Time Delay T_d *(amplifier) = 30 ps*

18

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Call for GSA quote and product information
1-888-665-2765 or www.anritsu.gsamart.com