Application Note

# Vector Network Analyzer Primer

## MS4640A and 37000D

### Vector**Star**™ and Lightning™ VNAs

## Introduction

This application note provides a summary description of the operation and capabilities of a Vector Network Analyzer (VNA), including general considerations of front panel operation and measurement methods. Included in this paper are discussions on the following topics:

- System description
- General discussion about network analyzers
- Basic measurements and how to make them
- Error correction
- General discussion on test sets

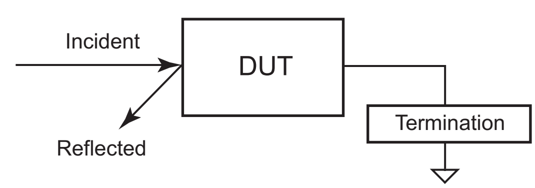
For detailed information regarding calibration techniques, accuracy considerations, or specific measurement applications, pleaser refer to additional Anritsu application notes and technical papers.

## General Description

Anritsu Vector Network Analyzers measure the magnitude and phase characteristics of networks, amplifiers, components, cables, and antennas. They compare the incident signal that leaves the analyzer with either the signal that is transmitted through the test device or the signal that is reflected from its input. Figure 1 and Figure 2 illustrate the types of measurements that the Anritsu VNA performs.


- Gain (dB)
- Insertion Loss (dB)
- Insertion Phase (degrees)
- Transmission Coefficients (S12, S21)
- Separations of Transmission Components (Real and Imaginary)
- Electrical Length (m)
- Electrical Delay (s)
- Deviation from Linear Phase (degrees)
- Group Delay (s)

*Figure 1. Transmission Measurements*




- Return Loss (dB)
- Reflection Coefficients (S11, S22)
- Reflection Coefficients vs Time (Fourier Transform)
- Impedance (R ± jX)
- SWR

*Figure 2. Reflection Measurements*

Anritsu VNAs are self contained, fully integrated measurement systems that include an optional time domain capability. The system hardware consists of the following:

- Analyzer
- Precision components required for calibration and performance verification
- Optional use of Anritsu synthesizers used as a second source
- Optional use of Anritsu power meters for test port power leveling and calibration

The Anritsu VNA internal system modules perform the following functions:

*Source Module*

This module provides the stimulus to the device under test (DUT). The frequency ranges of both the source and the test set modules establish the frequency range of the system. The frequency stability of the source is an important factor in the accuracy (especially phase accuracy) of the network analyzer. Hence, Anritsu VNAs always phase lock the source to an internal crystal reference for a synthesized, step sweep mode of operation. Anritsu VNAs avoid the use of unlocked, analog sweep modes because of the sacrifices in measurement stability, phase performance, and group delay accuracy.

*Test Set Module*

The test set module routes the stimulus signal to the DUT and samples the reflected and transmitted signals. The type of connector that is used is important, as is the “Auto Reversing” feature. Auto Reversing means that the stimulus signal is applied in both the forward and reverse directions. The direction is reversed automatically. This saves you from having to reverse the test device physically in order to measure all four scattering parameters (S-parameters). It also increases accuracy by reducing connector repeatability errors. Frequency conversion to the IF range also occurs in the test set module.

*Analyzer Module*

The analyzer module receives and interprets the IF signal for phase and magnitude data. It then displays the results of this analysis on a high resolution display screen. This display can show all four S-parameters simultaneously as well as a variety of other forms of displayed information such as Group Delay, Time and Distance information, and complex impedance information. In addition to the installed display, you can also view the measurement results on an external monitor.

## Network Analyzers

We will begin this discussion with a subject familiar to most microwave test equipment users: scalar network analysis. After showing comparisons, we will proceed to the fundamentals of network analyzer terminology and techniques. This discussion serves as an introduction to topics that are presented in greater detail later in this section. This discussion will touch on new concepts that include the following:

- Reference Delay
- S-parameters: what they are and how they are displayed
- Complex Impedance and Smith Charts

## Scalar Analyzer Comparison

Vector Network Analyzers do everything that scalar analyzers do, plus they add the ability to measure the phase characteristics of microwave devices over a greater dynamic range and with more accuracy.

If all a vector network analyzer added was the capability for measuring phase characteristics, its usefulness would be limited. While phase measurements are important in themselves, the availability of phase information provides the potential for many new features for complex measurements. These features include Smith Charts, Time Domain, and Group Delay. Phase information also allows greater accuracy through vector error correction of the measured signal.

First, let us look at scalar network analyzers (SNAs). SNAs measure microwave signals by converting them to a DC voltage using a diode detector (Figure 3). This DC voltage is proportional to the magnitude of the incoming signal. The detection process, however, ignores any information regarding the phase of the microwave signal. Also, a detector is a broadband detection device, which means that all frequencies (the fundamental, harmonic, sub harmonic, and spurious signals) are detected and simultaneously displayed as one signal. This, of course, adds significant error to both the absolute and relative measurements.

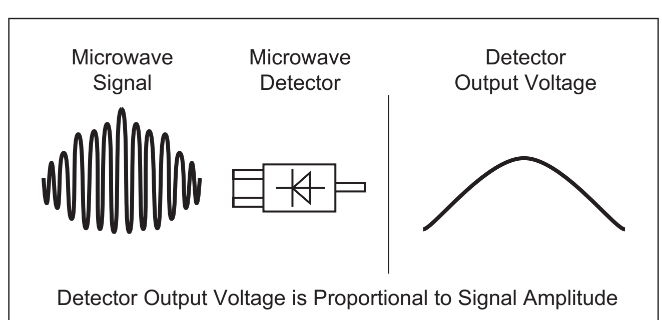



*Figure 3. Scalar Analyzer Detection*

In a vector network analyzer, information is extracted of both the magnitude and phase of a microwave signal. While there are different ways to perform the measurement, the method the Vector**Star** VNA employs is to down convert the signal to a lower intermediate frequency (harmonic sampling). This signal can then be measured directly by a tuned receiver. The tuned receiver approach gives the system greater dynamic range due to the variable IF filter bandwidth control. The system is also much less sensitive to interfering signals, including harmonics.

## Vector Network Analyzer Basics

The vector network analyzer is a tuned receiver (Figure 4). The microwave signal is down converted into the passband of the IF. To measure the phase of this signal as it passes through the DUT, we must have a reference to compare. If the phase of a signal is 90 degrees, it is 90 degrees different from the reference signal (Figure 5). The vector network analyzer would read this as –90 degrees, since the test signal is delayed by 90 degrees with respect to the reference signal.

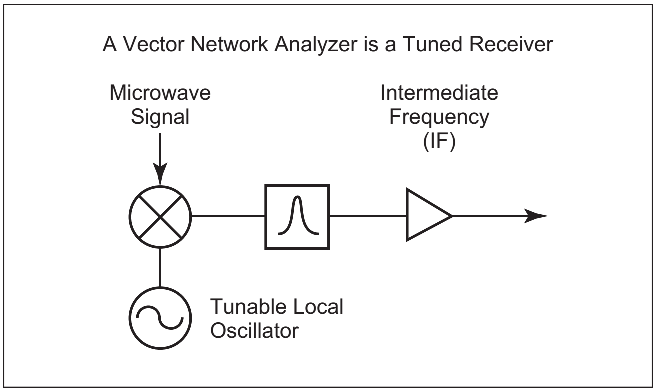



*Figure 4. Network Analyzer is a Tuned Receiver*

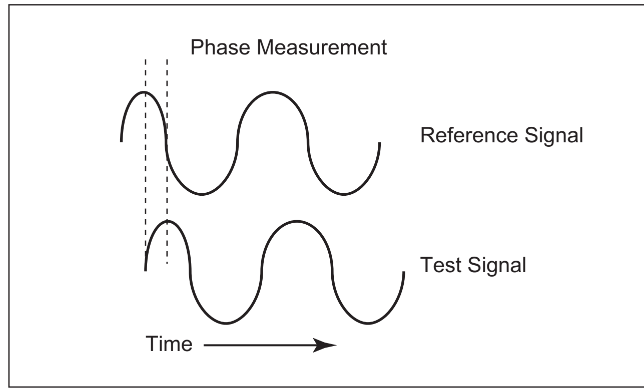



*Figure 5. Signals with a 90 Degree Phase Difference*

The phase reference can be obtained by splitting off a portion of the microwave signal before the measurement (Figure 6).

The phase of the microwave signal after it has passed through the DUT is then compared with the reference signal. A network analyzer test set automatically samples the reference signal, so no external hardware is needed.

Let us consider the case when the DUT is removed, and a length of transmission line is substituted (Figure 7). Note that the path length of the test signal is longer than that of the reference signal. Let us see how this affects our measurement.

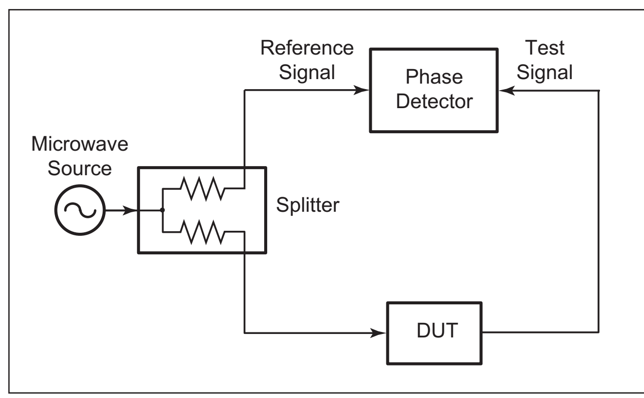



*Figure 6. Splitting the Microwave Signal*

Assume that we are making a measurement at 1 GHz, and that the difference in path length between the two signals is exactly 1 wavelength. This means that test signal is lagging the reference signal by 360 degrees (Figure 8). We cannot really tell the difference between one sine wave maxima and the next (they are all identical), so the network analyzer would measure a phase difference of 0 degrees.

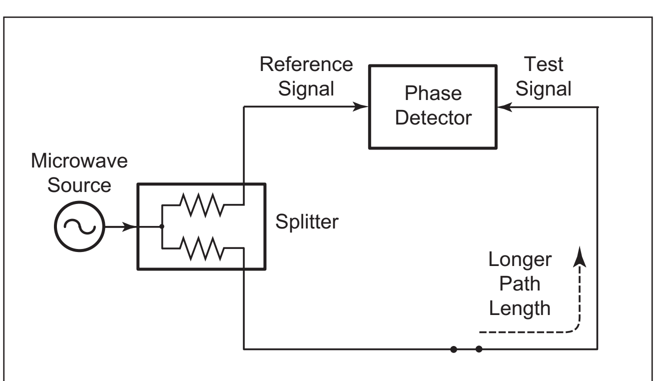



*Figure 7. Split Signal where a length of line replaces the DUT*

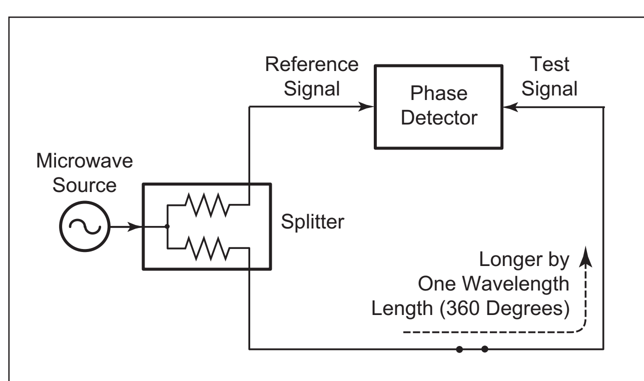



*Figure 8. Split Signal where Path Length Differs by Exactly One Wavelength*

Now consider that we make this same measurement at 1.1 GHz. Since the frequency is higher by 10 percent, the wavelength of the signal is shorter by 10 percent. The test signal path length is now 0.1 wavelength longer than that of the reference signal (Figure 9). This test signal is:

1.1 X 360 = 396 degrees

This is 36 degrees different from the phase measurement at 1 GHz. The network analyzer will display this phase difference as –36 degrees.

The test signal at 1.1 GHz is delayed by 36 degrees more than the test signal at 1 GHz.

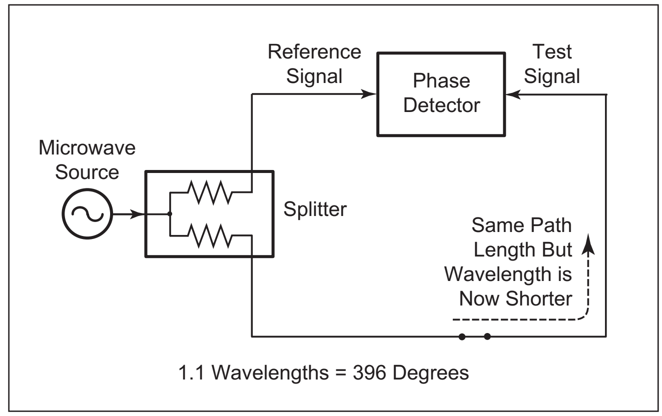



*Figure 9. Split Signal where Path Length is longer than One Wavelength*

You can see that if the measurement frequency is 1.2 GHz, then we will get a reading of –72 degrees, –108 degrees for 1.3 GHz, and so forth. (Figure 10). An electrical delay occurs between the reference and test signals. For this delay, we will use the common industry term of reference delay. You also may hear it called phase delay. In older network analyzers, the length of the reference path had to be constantly adjusted relative to the test path in order to make an appropriate measurement of phase versus frequency.

To measure phase on a DUT, we need to remove this phase change versus frequency due to changes in the electrical length. This will allow us to view the actual phase characteristics of the device, which may be much smaller than the phase change due to electrical length difference of the two paths.

This can be accomplished in two ways.. The most obvious way is to insert a length of line into the reference signal path to make both paths of equal length (Figure 11). With perfect transmission lines and a perfect splitter, we would then measure a constant phase as we change the frequency. The problem using this approach is that we must change the line length with each measurement setup.

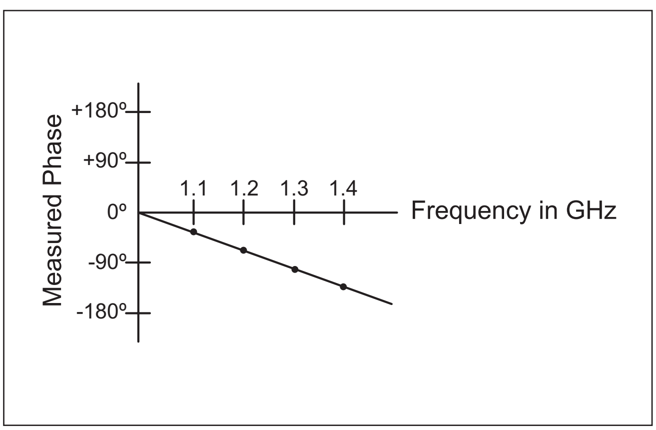



*Figure 10. Electrical Delay*

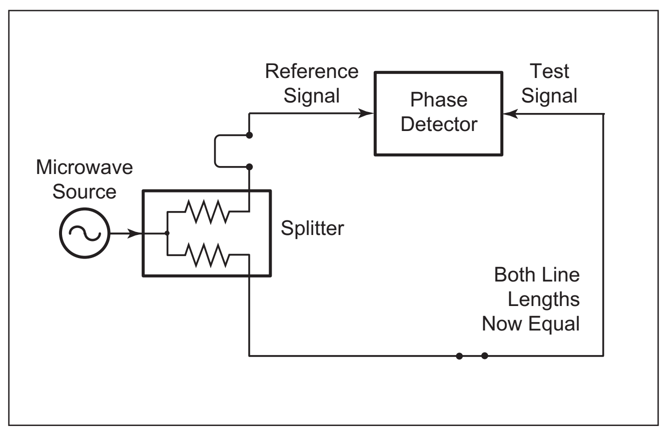



*Figure 11. Split Signal where Paths are of Equal Length*

Another approach is to handle the path length difference in software. Figure 12 displays the phase versus frequency of a device. This device has different effects on the output phase at different frequencies. Because of these differences, we do not have a perfectly linear phase response. We can easily detect this phase deviation by compensating for the linear phase. The size of the phase difference increases linearly with frequency, so we can modify the phase display to eliminate this delay.

Anritsu VNAs offer automatic reference delay compensation with the push of a button. Figure 13 shows the resultant measurement when we compensate path length. In a system application, you can usually correct for length differences; however, the residual phase characteristics are critical.

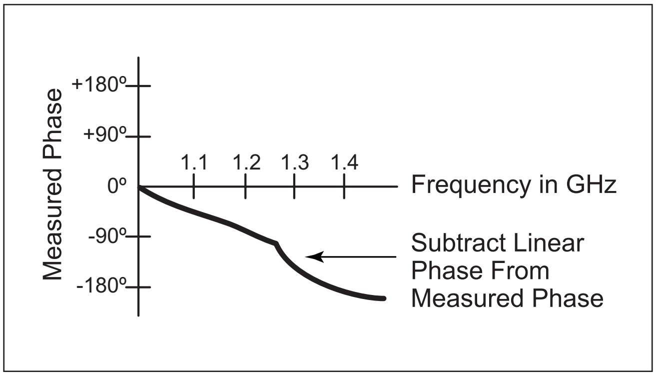



*Figure 12. Phase Difference Increases Linearly with Frequency*

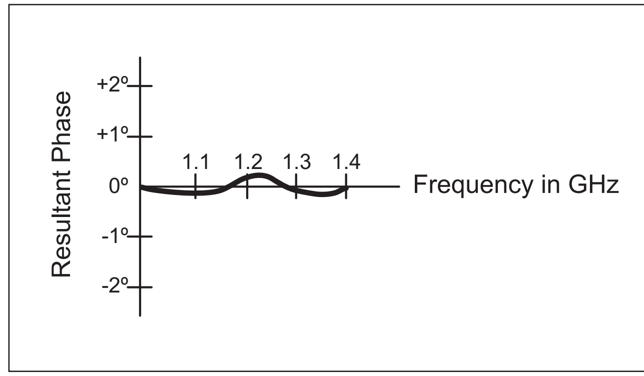



*Figure 13. Resultant Phase with Path Length*

## Network Analyzer Measurements

Now let us consider measuring the DUT. Consider a two port device; that is, a device with a connector on each end. What measurements would be of interest?

First, we could measure the reflection characteristics at either end with the opposite end terminated into 50 ohms. If we designate one of the inputs as Port 1 of the device, then we have a reference port. We can then define the reflection characteristics from the reference end as forward reflection, and those from the other end as reverse reflection (Figure 14).

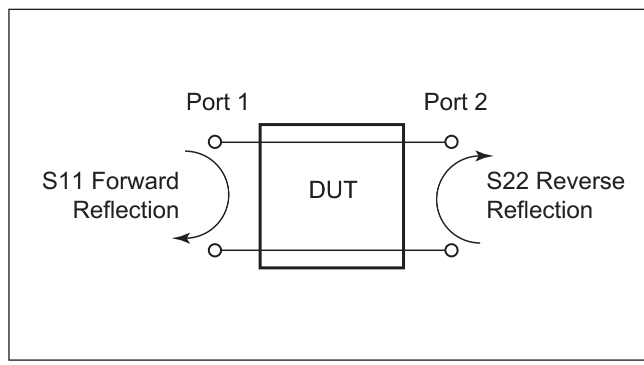



*Figure 14. Forward and Reverse Measurements*

Second, we can measure the forward and reverse transmission characteristics. However, instead of saying “forward,” “reverse,” “reflection,” and “transmission” all the time, we use a shorthand. That is all that S-parameters are, shorthand! The “S” stands for scattering. The second number is the device port that the signal is being injected into, while the first is the device port that the signal is leaving. S11, therefore, is the signal leaving port 1 relative to the signal injected into port 1. The four scattering parameters (Figure 15) are:

- S11 Forward Reflection
- S21 Forward Transmission
- S22 Reverse Reflection
- S12 Reverse Transmission

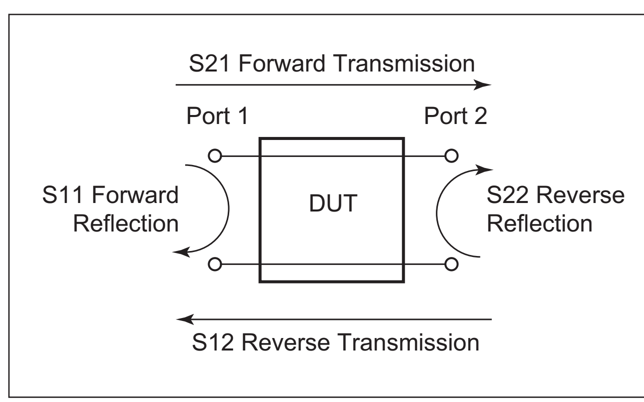



*Figure 15. S-Parameters*

S-parameters can be displayed in many ways. An S-parameter consists of a magnitude and a phase. We can display the magnitude in dB, just like a scalar network analyzer. We often call this term log magnitude. Another method of magnitude display is to use Units instead of dB. When displaying magnitude in Units, the value of the reflected or transmitted signal will be between 0 and 1 relative to the reference.

We can display phase as “linear phase” (Figure 16). As discussed earlier, we cannot tell the difference between one cycle and the next. Therefore, after going through 360 degrees, we are back to where we began. We can display the measurement from –180 to +180 degrees, which is a more common approach. This method keeps the display discontinuity removed from the important 0 degree area that is used as the phase reference.

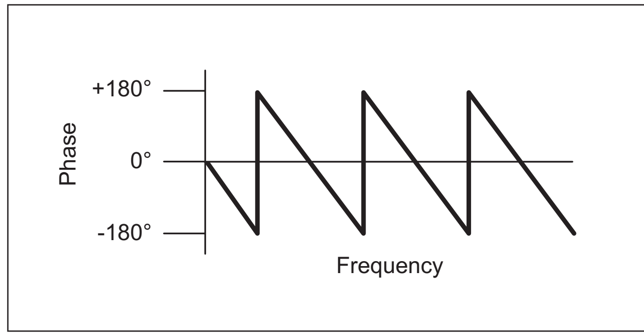


*Figure 16. Linear Phase with frequency Waveform*

Several methods are available to display all of the information on one trace. One method is a polar display (Figure 17). The radial parameter (distance from the center) is magnitude. The rotation around the circle is phase. We sometimes use polar displays to view transmission measurements, especially on cascaded devices (devices in series). The transmission result is the addition of the phase and the log magnitude (dB) information in the polar display of each device.

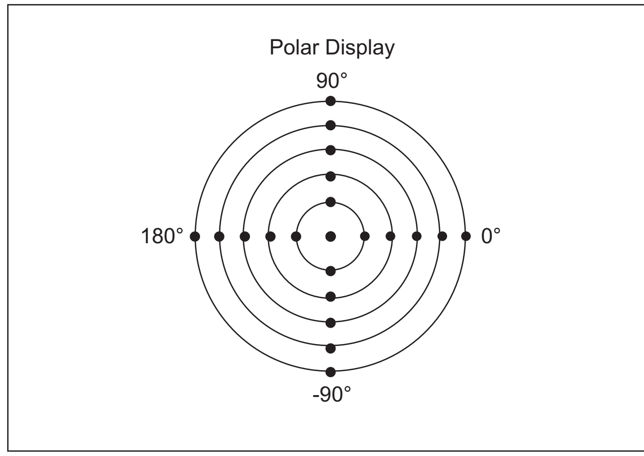


*Figure 17. Polar Display*

As we have discussed, the signal reflected from a DUT has both magnitude and phase. This is because the impedance of the device has both a resistive and a reactive term of the form r+jx. We refer to the r as the real or resistive term, while we call x the imaginary or reactive term. The j, which we sometimes denote as i, is an imaginary number. It is the square root of –1. If x is positive, the impedance is inductive; if x is negative, the impedance is capacitive.

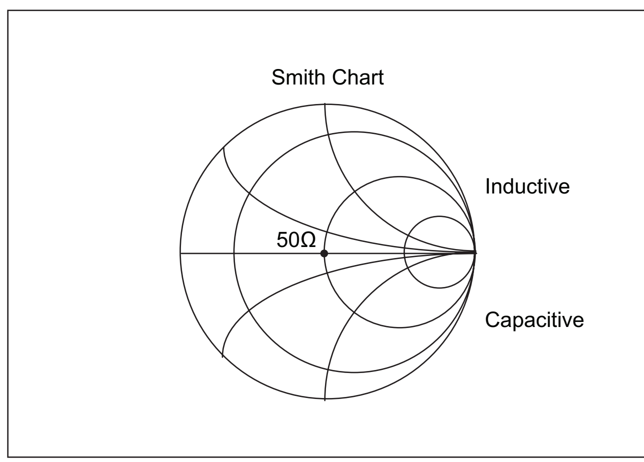


*Figure 18. Smith Chart*

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 (Figure 18), which is a plot of r and x. To display all the information on a single S-parameter requires one or two traces, depending upon the format we want. 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). Let us see how to accomplish this in the MS4640A Vector**Star** VNA.

The MS4640A Vector**Star** has the ability to configure one to sixteen channels. Each channel can be thought of as an independent VNA. For example, a channel in the Vector**Star** can be configured for a specific frequency range, calibration type, power level and IF filter bandwidth setting. Additional channels can then be configured within the Vector**Star** to help facilitate testing in multiple setup parameters, up to the 16 available channels. And the Vector**Star** can be configured to display all of the active channels in a pattern that is most useful to the user. With multiple channels configured, the Vector**Star** VNA can sequentially sweep from one calibrated setup and measurement condition to the next. Additionally, each of the channel displays can be configured to accept up to 16 traces. All of the traces in each channel can likewise be configured for the most beneficial display pattern. Finally, each of these traces can be configured for an appropriate graph type depending on the data being displayed. For instance, Trace 6 can be set up to provide S11 performance of the device displayed on a Smith Chart, Trace 7 can be set up for S11 with a Time Domain display, and Trace 12 can be set up for an S21 display on a Log Magnitude and Phase graph.

Another important parameter we can measure with phase information is group delay (Figure 20). In linear devices, the phase change through the DUT is linear with frequency. Thus, doubling the frequency also doubles the phase change. An important measurement, especially for communications system users, is the rate of change of phase versus frequency (group delay). If the rate of phase change versus frequency is not constant, then the DUT is nonlinear. This nonlinearity can create distortion in communications systems.

## Measurement Error Correction

Since we can measure microwave signals in both magnitude and phase, it is possible to correct for six major error terms:

1. Source Test Port Match
2. Load Test Port Match
3. Directivity
4. Isolation
5. Transmission Frequency Response
6. Reflection Frequency Response

We can correct for each of these six error terms in both the forward and reverse directions, hence the name 12 term error correction. Since 12 term error correction requires both forward and reverse measurement information, the test set must be reversing. "Reversing" means that it must be able to apply the measurement signal in the forward or reverse direction automatically without having to disconnect the calibration components or DUT.

To accomplish this error correction, we measure the magnitude and phase of each error signal (Figure 21). Magnitude and phase information appear as a vector that is mathematically applied to the measurement signal. This process is termed vector error correction. For more information on the techniques and choices of calibration methods using a VNA, please refer to the Measurement Guide for the Vector**Star** VNA.

## Summary

A vector network analyzer is a much more powerful analyzer than a scalar network analyzer. The major difference is that a VNA adds the ability to measure phase as well as amplitude. With phase measurements comes scattering, or S-parameters, which are a shorthand method for identifying forward and reverse transmission and reflection characteristics. The ability to measure phase introduces two new displays, Polar and Smith Chart. It also adds vector error correction to the measurement trace. With vector error correction, errors introduced by the measurement system are compensated for, and measurement accuracy is increased. Phase measurements also add the capability for measuring Group Delay, which is the rate of change of phase versus frequency (group delay). When you use a vector network analyzer, you can make a more complete analysis of your test device.

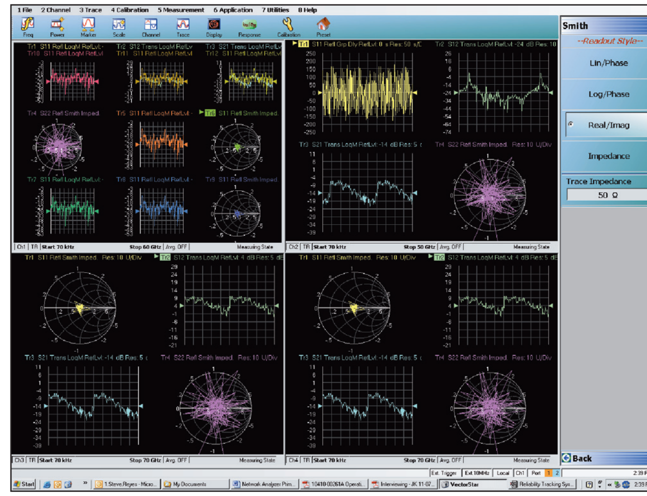


*Figure 19. Vector**Star** Multiple Channel and Multiple Trace Display*

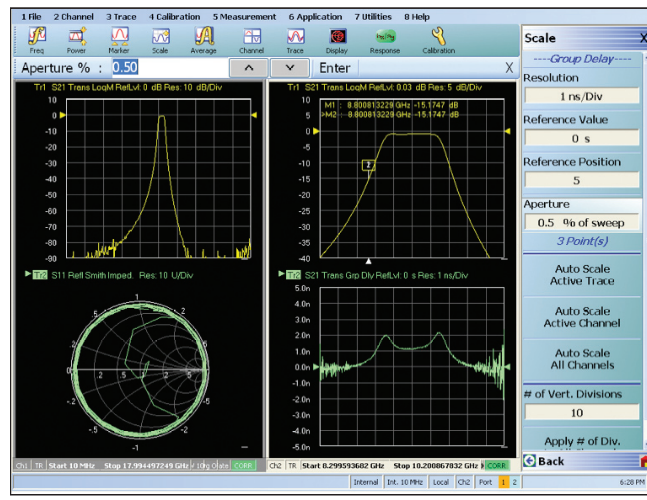


*Figure 20. Vector**Star** Display of Group Delay measurement of a wireless communication filter*

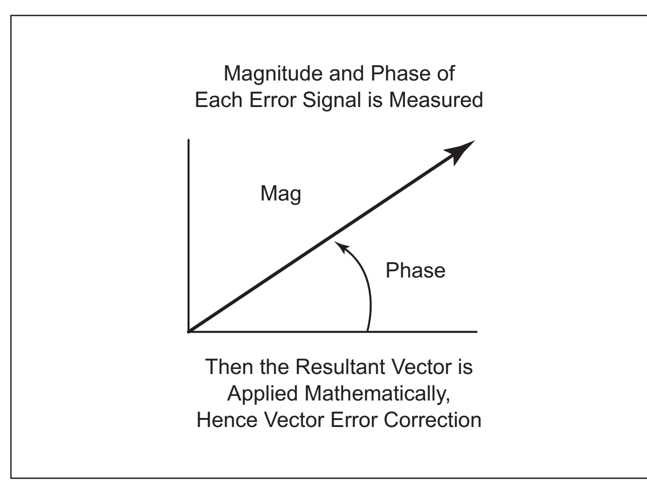



*Figure 21. Magnitude and Phase information of each error signal is measured and available for removal during the measurement.*

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