SCORPION® AND LIGHTNING™

APPLICATION NOTE

Primer on Vector Network Analysis

Introduction

Anritsu Vector Network Analyzers (VNAs) measure the magnitude and phase characteristics of networks that include passives (e.g., diplexers, cables, filters, antennas, SAW devices, balanced and unbalanced); Integrated amplifiers, ICs, LNAs; mixers; power amplifiers; and tower mounted amplifiers.

They function by comparing 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.

Figures 1 and 2 illustrate the types of measurements that Anritsu VNAs can make.

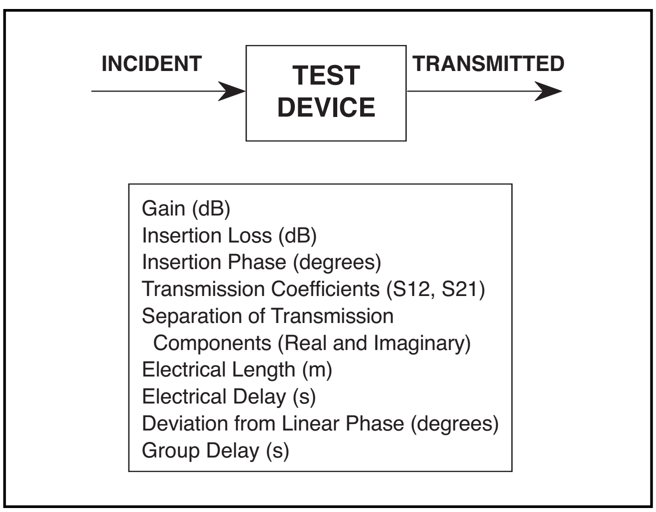

Figure 1. Transmission Measurements

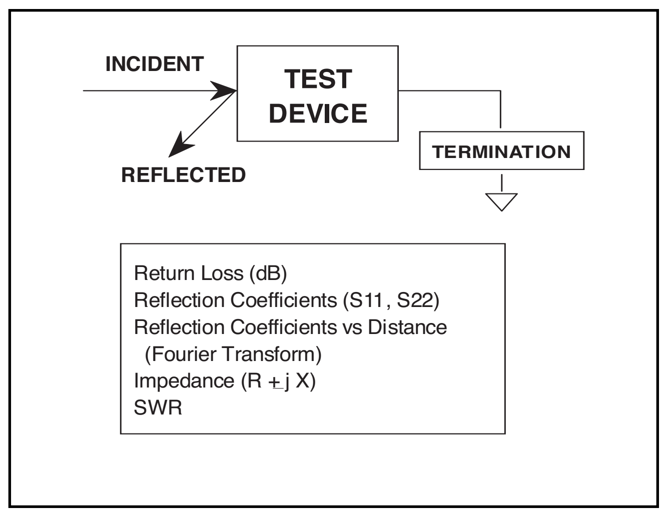

Figure 2. Reflection Measurements

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 67XXB, 68X/ 69X or MG369X Series Synthesizers as Additional Sources

Anritsu VNAs contain internal system modules that perform the following functions:

Source Module or Modules
This module provides the stimulus to the device under test (DUT). The frequency range of the source and 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, the VNA always phase locks the source to an internal (or optional external) 10 MHz crystal reference.

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 used is important, as is the "Auto Reversing" feature. Auto Reversing means that it applies the stimulus signal in both the forward and reverse direction. The direction is reversed automatically. This saves you from having to reverse the test device physically to measure all four scattering parameters (S-parameters). Frequency conversion occurs in the analyzer.

Analyzer Module
The analyzer module down-converts, receives, and interprets the IF signal for phase and magnitude data. It then displays the results of this analysis on a color display. This display can show all four S-parameters simultaneously. In addition to the installed display, you can also view the measurement results on an external color monitor.

Vector Network Measurement System Basics
The network measurement system is a tuned receiver (Figure 3). The microwave signal is down converted into the passband of the IF.

This phase reference can be obtained by splitting off some of the microwave signal before the measurement (Figure 4).

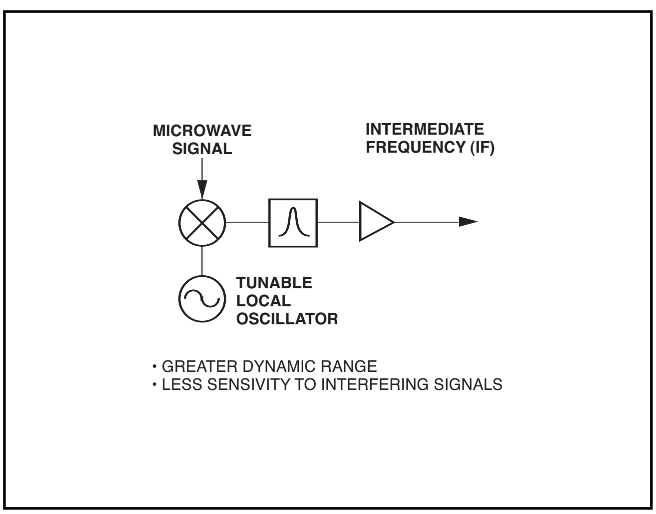

Figure 3. Network Analyzer is a tuned receiver

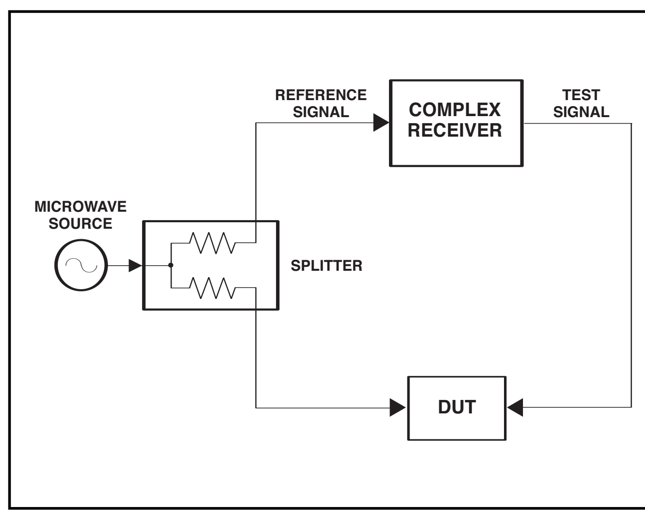

Figure 4. Splitting the Microwave Signal

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

Let us consider for a moment that you remove the DUT and substitute a length of transmission line (Figure 5). Note that the path length of the test signal is longer than that of the reference signal. Now let us see how this affects our measurement.

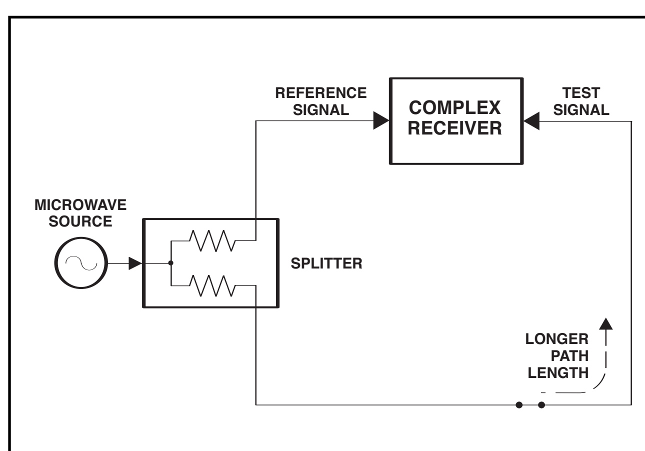

Figure 5. Split Signal where a length of line replaces the DUT

Assume that we are making a measurement at 1 GHz and that the difference in path-length between the two signals is exactly one wavelength. This means that test signal is lagging the reference signal by 360 degrees (see Figure 6). 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.

Now consider that we make this same measurement at 1.1 GHz. The frequency is higher by 10 percent so therefore the wavelength is shorter by 10 percent. The test signal path length is now 0.1 wavelength longer than that of the reference signal (see Figure 7). 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.

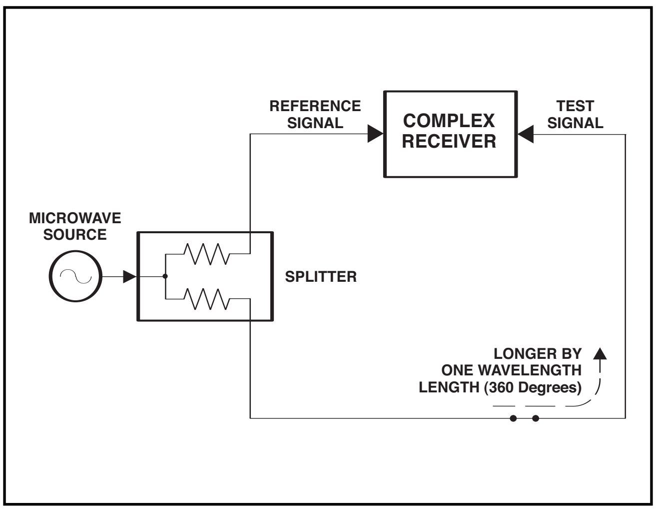

Figure 6. Split signal where path length differs by exactly one wavelength

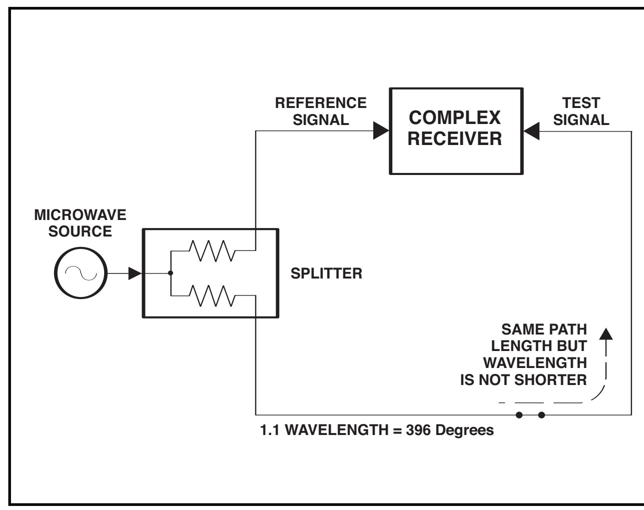

Figure 7. Split signal where path length is longer than one wavelength

You can see that if the measurement frequency is 1.2 GHz, we will get a reading of –72 degrees, –108 degrees for 1.3 GHz, etc., as shown in Figure 8. There is an electrical delay 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 you had to equalize the length of the reference arm with that of the test arm to make an appropriate measurement of phase vs. frequency.

To measure phase on a DUT, we want to remove this “phase-change-vs.-frequency-due-to-changes” in the electrical length. This will allow us to view the actual phase characteristics. These characteristics may be much smaller than the “phase-change-due-to-electrical-length” difference.

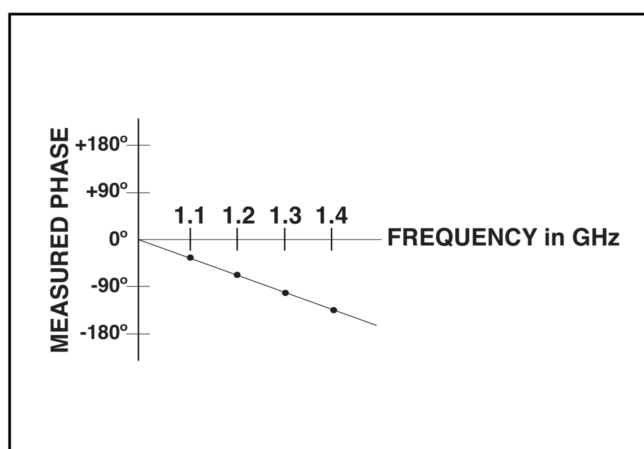

Figure 8. Electrical delay

There are two ways of accomplishing this. The most obvious way is to insert a length of line into the reference signal path to make both paths of equal length, as shown in Figure 9. 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.

Another approach is to handle the path length difference in software. Figure 10 displays the phase-vs-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.

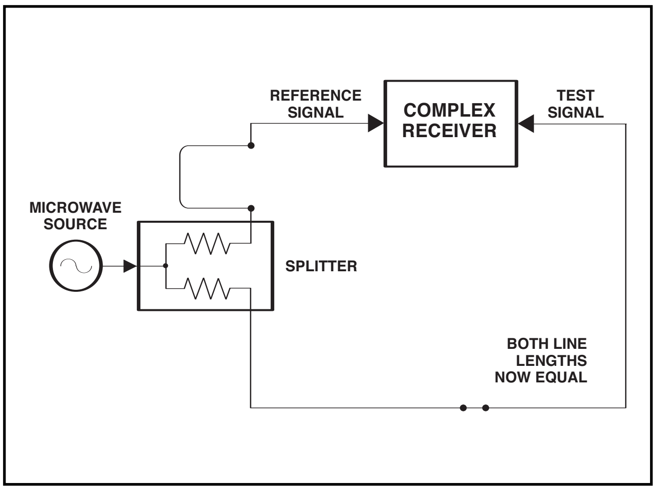

Figure 9. Split signal where paths are of equal length

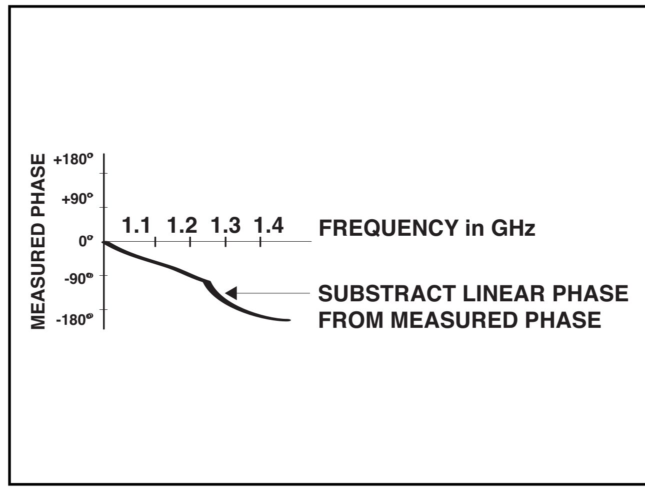

Figure 10. Phase difference increases linearly with frequency

Anritsu VNAs offer automatic reference delay compensation with the push of a button. Figure 11 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.

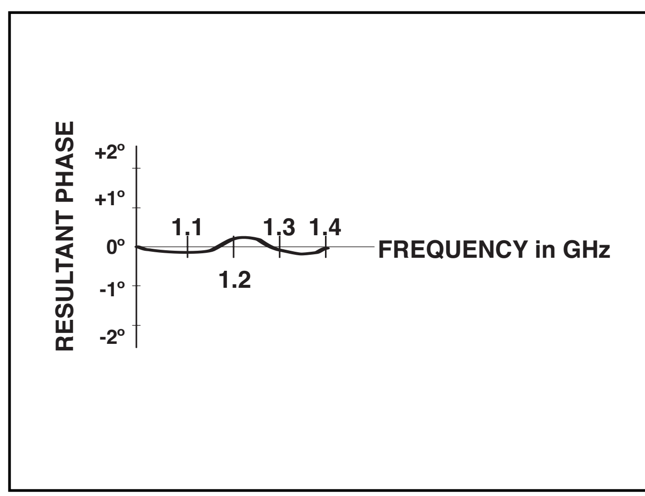

Figure 11. Resultant phase with path length compensation in place

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 other end terminated into 50 ohms. If we designate one end as the normal place for the input that gives a reference. We can then define the reflection characteristics from the reference end as forward reflection, and those from the other end as reverse reflection as shown in Figure 12.

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, a shorthand! The “S” stands for scattering. The second number is the network analyzer port that the signal is being injected into, while the first is the network analyzer port that the signal is leaving. S_{11}, therefore, is the signal being injected into Port 1 relative to the signal leaving Port 1. The four scattering parameters are (see Figure 13):

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

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.”

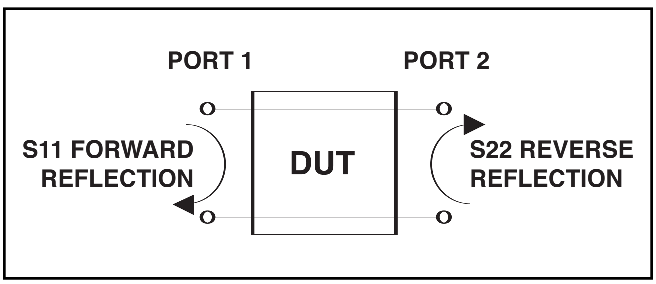

Figure 12. Forward and reverse measurements

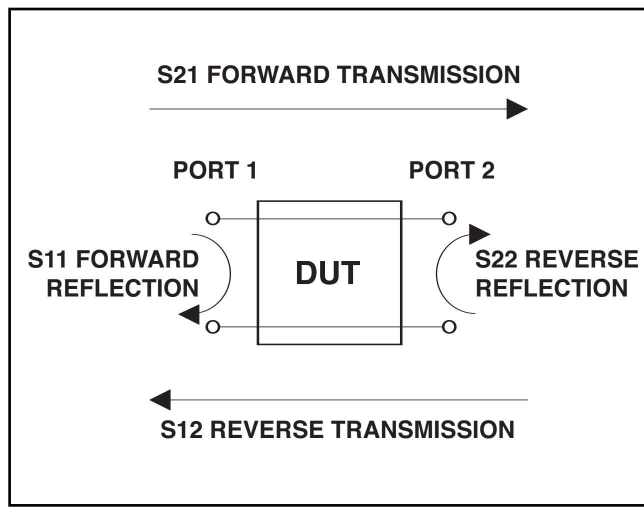

Figure 13. S-parameters

We can display phase as “linear phase,” see Figure 14. As discussed earlier, we can’t 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. The –180 to +180 approach is more common. It keeps the display discontinuity Figure 12. Forward and reverse measurements removed from the important 0 degree area used as the phase reference.

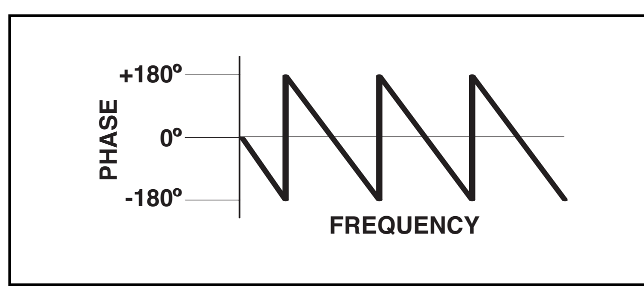

Figure 14. Linear phase with frequency waveform

There are several ways in which all the information can be displayed on one trace. One method is a polar display (shown in Figure 15). 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 log magnitude (dB) information of each device's 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.

The size and polarity of the reactive component x is important in impedance matching. The best match to complex impedance is the complex conjugate. This complex-sounding term simply means impedance with the same value of r and x, but with x of opposite polarity. This term is best analyzed using a Smith Chart shown in Figure 16, which is a plot of r and x. Figure 15. Polar display 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.

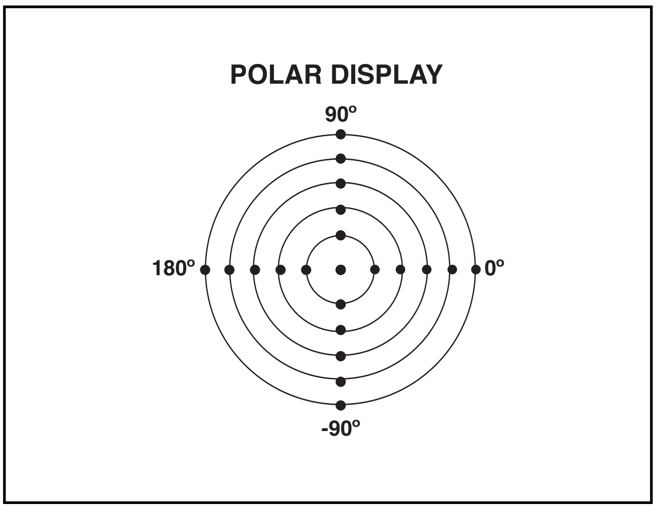

Figure 15. Polar display

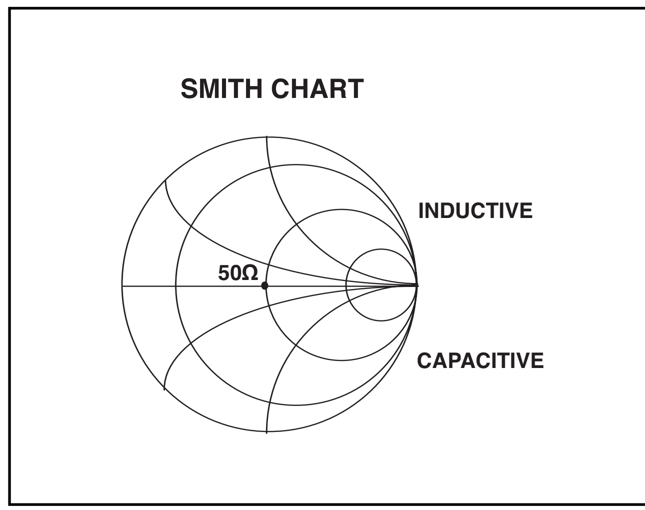

Figure 16. Smith chart

Anritsu VNAs have four channels. Each channel can display a complete S-parameter in any format on either one or two traces. All four S-parameters can be seen simultaneously in any desired format. A total of eight traces can be viewed at the same time. While this is a lot of information to digest, the Anritsu VNAs offer a large LCD color display to make recognizing and analyzing the data surprisingly easy.

Another important parameter we can measure when phase information is available is group delay. 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-vs.-frequency (group delay). If the rate of phase-change-vs.-frequency is not constant, the DUT phase is nonlinear with frequency. 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:

- ❑ Source Test Port Match
- ❑ Load Test Port Match
- ❑ Directivity
- ❑ Isolation
- ❑ Transmission Frequency Response
- ❑ Reflection Frequency Response

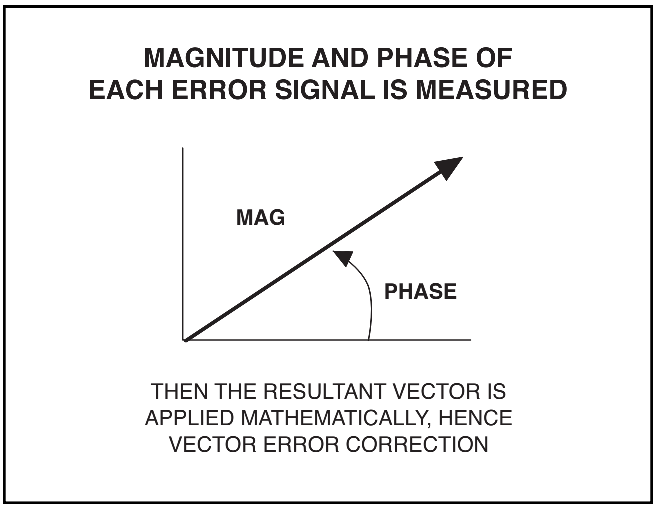

Figure 17. Magnitude and Phase Measurements

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 either the forward or reverse direction.

To accomplish this error correction, we measure the magnitude and phase of each error signal (Figure 17). Magnitude and phase information appear as a vector that is mathematically applied to the stimulus signal. This process is termed “vector error correction.”

Summary

Anritsu VNAs 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 uncertainty is minimized. Phase measurements also add the capability for measuring group delay, which is the rate of “change-of-phase-vs.-frequency” (group delay). All in all, using a network analyzer provides for making a more complete analysis of your test device.

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