

Agilent Extending Vector Signal Analysis to 26.5 GHz with 78 MHz Information Bandwidth

Product Note

The Agilent 89600 series vector signal analyzers provide unmatched signal analysis capabilities including traditional spectrum analysis, transient analysis, analog and digital demodulation, high-speed spectrum monitoring, phase noise analysis and more. They are used in applications as wide ranging as surveillance, signal monitoring, digital communications, radar signal analysis and underwater acoustics.

For some applications, the vector signal analyzer's information bandwidth and frequency coverage has been a limitation. Instruments such as the Agilent 89640A are limited to frequencies below 2.7 GHz and information bandwidths of 36 MHz. This precludes the analysis of several spread spectrum, radar and satellite signals that typically occupy more than 36 MHz bandwidth and may exist only at microwave frequencies.

By combining two Agilent products--the 89610A vector signal analyzer and the 71910A wideband receiver--into a single measurement system, the unique capabilities of the vector signal analyzer can be used on signals with 78 MHz bandwidth at frequencies from 2.7 GHz to 26.5 GHz.

This product note describes how to configure, calibrate and operate a measurement system capable of wide-bandwidth vector signal analysis.



Figure 1. 89610A vector signal analyzer and 71910A wideband receiver together form a wideband vector signal analyzer system

System description

The wideband vector signal analyzer system consists of two major components: an 89610A two-channel vector signal analyzer and a 71910A wideband receiver with a wideband IF and quadrature outputs. The vector signal analyzer provides the user interface and display, and performs all of the signal processing. The 71910A is basically a microwave spectrum analyzer with additional features to optimize surveillance and signal monitoring applications. In this application, the analyzer converts the RF or microwave signal into a baseband signal that can be further processed by the vector signal analyzer. As the front end of the measurement system, it also provides the necessary gain or attenuation.

The vector signal analyzer has two input channels, each with a bandwidth of 39 MHz. Normally this would represent the maximum bandwidth of the signal to be analyzed. However, the 89610A is capable of treating the signals on each channel as two parts of the same signal. That is, the signal going into channel one represents the real part of a complex signal, and the signal going into channel two represents the imaginary part. These two signals are usually referred to as the in-phase and quadrature-phase components, or simply as I and Q. The vector signal analyzer digitizes the I and Q signals which are, by themselves, real signals. It then combines them internally into a single complex signal of the form $I+jQ$ or $CH1+jCH2$, where j represents the square root of negative one. This new complex signal, which exists only in digital form, has a maximum bandwidth of 78 MHz, or twice the input bandwidth of the vector signal analyzer.



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In the wideband vector signal analyzer system, the analog I and Q signals are generated in the wideband IF module of the microwave receiver as shown in figure 2. The IF has a bandwidth of >100 MHz, which ensures a relatively flat frequency response over the center 78 MHz used in this system. A flat IF is important in vector signal analysis. An IF with a significant amount of amplitude unflatness or group delay distortion would produce significant errors. This is especially true for modulation analysis where the IF characteristics would introduce distortion in the time domain characteristics of the signal. For example, group delay distortion in the IF would result in increased inter-symbol interference in a digitally-modulated signal. In this system, the microwave receiver is always used at its widest bandwidth to obtain the highest level of accuracy. The vector signal analyzer is responsible for reducing the measurement bandwidth to 78 MHz and below.

When the microwave receiver is used at frequencies below 12.8 GHz, the spectrum obtained using I+jQ is mirrored about the center frequency. There are two ways to compensate for this mirroring. The first is to simply swap the I and Q outputs. While this works, it's inconvenient and makes calibration more difficult. A simpler way to compensate for the mirroring is to conjugate the complex signal. In other words, I-jQ instead of I+jQ. The vector signal analyzer has a spectral mirror key that conjugates the CH1+jCH2 data. This corrects both time and frequency domain results without affecting the I and Q calibration.

As a measurement system, there is an obvious need for software that can link the two instruments. This software should provide a user interface, as well as provide for system calibration. An example program which provides these functions is available. The primary purpose of the example program is calibration. However, it also provides for simple control of center frequency and reference level. Once the system is calibrated and the center frequency

and reference level are properly adjusted, the program is paused or terminated to provide access to all the measurement and analysis features of the vector signal analyzer. The example program is written in the Agilent VEE visual environment. This program requires an external controller with GPIB. Contact your local Agilent sales representative for information on how to obtain the example program.

System configuration

This section describes the necessary components, the physical connections between components, and the software required to create a wideband vector signal analysis system. The minimum requirement is described, but additional options are available, including the link to the Agilent Advanced Design System (ADS). These additional options and capabilities are not described here. Consult your local Agilent sales representative for more information. (See table 1).

To support measurements of the complex (I+jQ) output signal of the 71910A, the 89610A vector signal analyzer must have Options 288, 289 (second 39 MHz channel), and Option AYA (vector modulation analysis) installed. Additional information on configuring the 89610A can be found in the *Agilent 89600 Series Vector Signal Analyzers Configuration Guide*, literature number 5968-9350E.

The 71910A wideband receiver contains all the MMS components which make wide bandwidth vector signal analysis possible. Minimally, Option 004 (analog I/Q outputs) must be ordered. Depending on the other measurements you may want to make with the system, additional output options are available. The 71910A wideband receiver has bandwidth >100 MHz above low-band (above 2.7 GHz). The low-band bandwidth is 48 MHz. Option 70910A H05 (150 MHz low-band bandwidth) is available if the 78 MHz system bandwidth is required in the low-band frequency range (below 2.7 GHz).

Connections are straightforward. Connect BNC cables from the 71910A I and Q outputs on the front panel of the 70911A wideband IF module to the two inputs on the front of the 89610A vector signal analyzer and 89606A input module. Connect the 10 MHz external frequency reference using a BNC cable and SMA and SMB adapters. Connect the GPIB cables from the controller (PC) to the 71910A and 89610A.

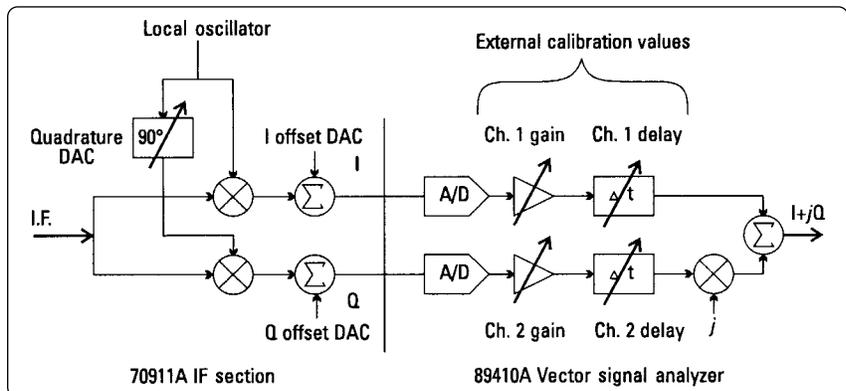


Figure 2. IF module generates I and Q signals using quadrature mixer. Calibrations compensate for imperfections such as dc offset, gain errors and delay mismatch. Vector signal analyzer combines I and Q signals into single, complex digital signal.

Calibration methods

The 89610A vector signal analyzer and the 71910A wideband receiver are both capable of self calibration. To obtain the best system performance, the instruments must be calibrated together. The system calibration compensates for system-induced errors, such as unequal cable lengths for the I and Q signals. It also fine tunes factory calibrations, such as quadrature, for optimal performance. The calibration affects more than just amplitude accuracy. As shown in figure 3, calibrations also improve the dynamic range of the system. Refer to Appendix A for a description of how errors in the signal path can affect the spectrum.

To perform the calibrations, the example software uses the 300 MHz calibrator, which is built into the 71910A wideband receiver. The software measures the magnitude and phase of the calibration signal while adjusting the center frequency of the wideband receiver. It also measures the amount of residual dc in the I and Q signals. From these measurements, the software determines IQ gain imbalance, IQ magnitude error, IQ delay mismatch, IQ quadrature error and the dc offset. It then adjusts both instruments to minimize the effects of the errors. These adjustments are indicated in figure 2.

DC offset

Residual dc limits the dynamic range of the measurement by introducing a spurious term in the center of the spectrum (zero hertz). The dc offset calibration measures the amount of residual dc in both the I and Q channels and determines the optimal settings for the offset DACs in the 70911A IF module. For dc offset, the two channels are independent of one another and are calibrated separately. The following procedure describes the calibration for the I channel. The same procedure is also performed on the Q channel.

At the start of the dc offset calibration, the 89610A is instructed to perform an internal offset calibration. This calibration removes dc from the vector signal analyzer inputs without consideration of the input signal. This is done so that subsequent internal calibrations, which are performed automatically by the vector signal analyzer, will not affect the system calibration. After the vector signal analyzer's offset calibration, the software records the amount of dc remaining

in the I channel, along with the current setting of the I channel offset DAC in the 70911A. The DAC is then slightly adjusted, and the amount of dc in the channel is measured again. The two dc measurements (y_1 and y_2) and the two DAC values (x_1 and x_2) are combined to determine the slope and offset of a line $y = Ax + B$ where A is the slope and B is the offset. The optimal setting for the DAC is then $-B/A$. This is the value that drives y, the residual dc, to zero.

Table 1. Recommended minimum system configuration

Agilent 89610A vector signal analyzer

Option 288	Additional RAM
Option 289	Second 40 MHz input channel
Option AYA	Vector modulation analysis

Agilent 71910A wideband receiver

Option 004	Analog I/Q outputs
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Controller and accessories

Controller (PC) with GPIB and Agilent VEE (rev. 5.01 or greater)
50 ohm BNC (M) - BNC (M) cable, 36" (three required)
50 ohm BNC (F) - SMB snap-on (M) adapter (one required)
50 ohm BNC (F) - SMA (M) adapter (one required)
Agilent 10833A GPIB cable, 1 meter (one required)

The following option is only required if bandwidth greater than 48 MHz is needed in low-band:

Extended 71910A low-band bandwidth (below 2.7 GHz)

70910A Option H05, 150 MHz IF bandwidth in low-band

Channel match

Channel match is also important for preserving the dynamic range of the measurement. System errors that cause mismatch include gain imbalance, delay mismatch and frequency response differences between the I and Q signals.

A frequency response mismatch can occur in both the IF module and the vector signal analyzer input channels. Only the center 78 MHz of the IF module's >100 MHz bandwidth is used (I and Q each have 50 MHz bandwidth), so the mismatch there is relatively small. The mismatches in the vector signal analyzer are compensated by the instrument's built-in calibration routines.

IQ gain, delay match

The system calibration software only attempts to match gain and delay. The software determines the gain and delay parameters by measuring the I and Q signals generated when the 300 MHz calibrator is connected. To simplify the measurement, the vector signal analyzer is taken out of the channel combine mode (CH1 + jCH2) and put into two-channel mode. The center frequency of the spectrum analyzer is adjusted to 291 MHz. With a 300 MHz signal and a center frequency of 291 MHz, the I and Q outputs are both 9 MHz sine waves. In a perfect system, these 9 MHz sine waves would have a phase difference of 90 degrees and would have identical amplitudes. In a real system, the amplitudes will probably be different, and the phase difference will be something other than 90 degrees. As shown in figure 4, the phase error has two components: error due to quadrature error and error due to IQ delay mismatch. Quadrature error in the IF module produces a phase error that is inde-

pendent of the relationship between the calibrator frequency and the center frequency of the measurement. Delay mismatch produces a frequency-dependent phase error term that is zero when the center frequency and the calibrator frequency are the same. (That is, the difference frequency is zero, and I and Q have no ac component.) To determine the delay and quadrature error, the center frequency is adjusted in 2 MHz steps from 261 MHz to 339 MHz, and the phase differences between I and Q are recorded. Then, using a least-mean-square algorithm, a line is fit to the phase error versus frequency data. The slope of the line corresponds to the delay mismatch, and the offset to the quadrature error.

The absolute signal level and gain match are measured at the same time as the phase. At each center frequency, the magnitude squared of the signal ($I^2 + Q^2$) is computed, as is the ratio between I and Q. The square root of the average magnitude squared is used to set the overall gain adjustment. This minimizes the absolute error across the 78 MHz bandwidth rather than the error at the center frequency. The average ratio is used to determine the gain mismatch. The gain and delay parameters are used to configure the external calibration parameters of the vector signal analyzer. It is worth noting that the errors are quite small. For example, the delay mismatch is usually less than 100 psec.

Quadrature

The final calibration is for quadrature error. Although a value for quadrature error was obtained in the channel match calibration, the number cannot be used by itself to set the quadrature adjustment DAC in the IF module, as the mapping from DAC setting to phase is not known. The DAC setting for the quadrature is determined much like the DAC setting for the residual dc. First, the phase difference between the channel one and channel two signals is measured and the current DAC setting recorded. A second measurement of the phase difference is made after the DAC has been adjusted by a small amount. The two DAC values and the two phase difference values can then be used to compute how far to adjust the DAC to compensate for the quadrature error observed in the delay calibration. The example software performs this calibration with the center frequency adjusted to 309 MHz. Although the frequency is not critical, the center frequency should be different than the calibrator frequency to avoid potential problems with errors introduced by residual dc in I and Q.

The example software was designed to work with a 300 MHz calibrator. Any frequency can be used, provided the calibrator frequency variable in the software reflects that frequency. This might be desirable if better absolute amplitude accuracy is desired at some frequency other than 300 MHz. Other parameters, such as delay, are not greatly affected by the center frequency of the microwave spectrum analyzer.

Operation

The vector signal analyzer provides for all signal processing, display and analysis. With the exception of scalar analysis, all 89610A features are available in the wideband vector signal analyzer system. The system software only needs to provide control over center frequency, input attenuation, spectral mirroring and system calibration. As a convenience, it also initializes both instruments for wideband vector signal analysis. This includes, but is not limited to, changing instrument modes, setting inputs to dc coupling and adjusting RBW settings.

The center frequency and reference level can be adjusted on the 71910A wideband receiver. While this may seem more convenient, there are good reasons for using the features found in the example program to control the receiver from the vector signal analyzer. For example, when changing the center frequency, the example program will label the traces on the vector signal analyzer to reflect the center frequency of the measurement. This is useful since the x-axis annotation will always show a center frequency of zero hertz whenever the receiver mode is set to CH1+jCH2. Another important function that the example program handles is the setting of the mirror frequency key, used to flip or invert the spectrum of the signal at approximately zero hertz. This operation may be necessary depending on the center frequency. In the microwave spectrum analyzer, center frequencies below 12.8 GHz will produce an output spectrum that is inverted. The frequency inversion is due to the mixing scheme used in the instrument. When setting the center frequency, the example program will check to see if the spectrum will be inverted (based on center frequency) and will set the mirror frequency key to compensate.

The mirror frequency key actually causes the time data to be conjugated; that is, the sign of the Q channel data is negated. Conjugating the time data will not only mirror the spectrum, but it will also correct the time data for modulation analysis.

The example program is even more useful for changing the reference level (input attenuation). When the input attenuation is adjusted in the 71910A wideband receiver, the gain of the signal path may change. If it does, the absolute level displayed on the vector signal analyzer will be wrong. When changing the reference level, the example software will also change the gain calibration to reflect any nominal changes in the gain of the signal path. This ensures that the reference level can change without affecting the level of the result. With two instruments, there are actually two sets of input attenuators that need to be adjusted. Obviously, the input to the 71910A wideband receiver will be adjusted based on the level of the signal to be measured. The vector signal analyzer

inputs are adjusted to reflect the I and Q signal levels at the output of the IF module. This setting is fixed and has been chosen as a compromise between noise and distortion performance. A variable in the example program can be adjusted to provide different levels of performance.

The system calibration described earlier is very easy to perform using the example program. Once the instruments are properly connected, the example program is started, automatically configuring the instruments for wideband vector signal analysis. Pressing the calibration soft key will initiate the calibration. Unless the example program has been modified, it will prompt the user to connect a 300 MHz, -10 dBm signal to the input. Once connected, the calibration only takes a few moments to perform. After calibration, the user can adjust the center frequency and reference level or exit the program to operate the vector signal analyzer.

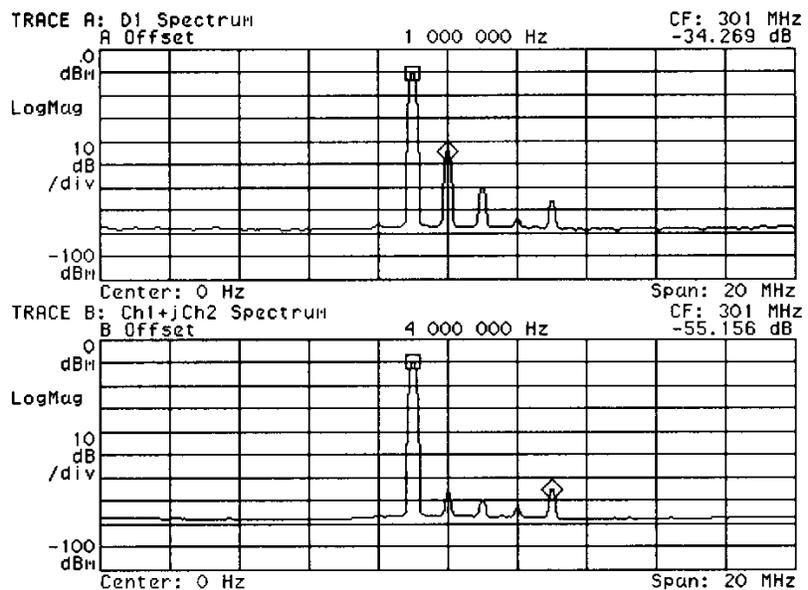


Figure 3. Calibrations provide better accuracy and improve dynamic range. Upper trace shows spectrum of 300 MHz calibrator as measured before system calibrations. Lower trace shows measurement of same signal after system calibration.

Summary

Vector signal analyzers provide measurement and analysis features not found in other types of instrumentation. These features have generally not been available for analyzing wide bandwidth signals or signals at microwave frequencies.

A vector signal analyzer system can be built which provides vector signal analysis capabilities at microwave frequencies to 26.5 GHz and with information bandwidths to 78 MHz. This system is based on the 89610A two-channel vector signal analyzer and the 71910A wideband receiver. The two channels in the vector signal analyzer are used to digitize the I and Q signals from the wideband receiver and combine them internally into a complex digital signal of the form $I+jQ$.

To get the best performance from the vector signal analyzer system, it must be calibrated. Without calibration, IQ gain and delay imbalance, quadrature error and residual dc result in spurious signals that reduce the dynamic range of the system. No special equipment beyond the 300 MHz calibration signal built into the wideband receiver is required for calibration.

An example program is available which performs the calibrations described in this product note. It also provides features that simplify operation of the system by controlling the center frequency of the receiver, controlling the input attenuation, adjusting the vector signal analyzer to ensure correct data scaling, and adjusting the frequency mirror key to ensure proper orientation of the spectrum.

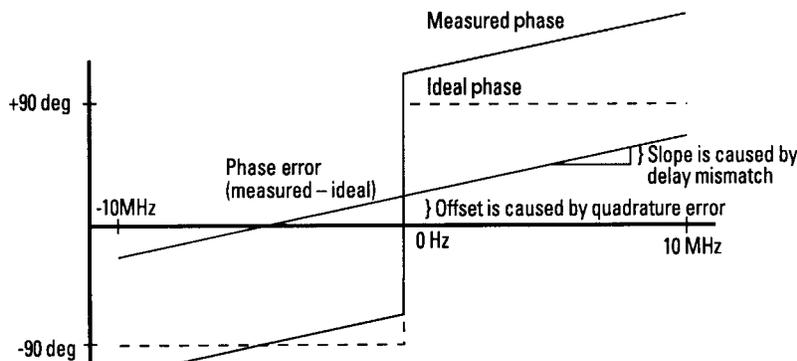


Figure 4. For a sinusoidal input, I and Q outputs should also be sinusoidal and should have a phase difference of exactly ± 90 degrees. Quadrature error and delay mismatch between channels introduce a phase error that is a function of the relationship between the center frequency of the measurement and the frequency of the input signal.

Appendix A: Complex signals

In this section, we will use simple example signals to show how the use of complex signals allows a doubling of bandwidth relative to real-only signals and how the spectrum can be mirrored simply by conjugating the complex time data. We will also show how measurement errors can produce spurious signals which reduce the dynamic range of a measurement. A more thorough and general description of complex signals can be found in textbooks on signal processing and communications.

Consider the following real-only sinusoidal signal:

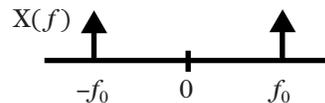
$$x(t) = \cos(2\pi f_0 t)$$

Using the Fourier transform

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft} dt$$

and solving for $X(f)$, we get

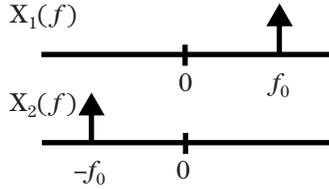
$$X(f) = \frac{1}{2} [\delta(f-f_0) + \delta(f+f_0)]$$



From this result, we see that the spectrum contains two elements: a discrete spectral line at f_0 and another at $-f_0$. In general, real signals will have the property that $X(f) = X^*(-f)$. That is, the negative side of the spectrum is the complex conjugate of the positive side. This spectrum would be described as being conjugate symmetric.

Although the spectrum extends from $-f_0$ to f_0 , only one side of the spectrum is unique. The usable bandwidth extends from 0 to f_0 .

If we start with the spectrum that is not conjugate symmetric and take the inverse Fourier transform, we get a complex signal. Consider two different signals with the following single-sided spectrums. We will choose these signals to represent the upper and lower frequency limits of our analysis bandwidth.



$$X_1(f) = \frac{1}{2}\delta(f-f_0) \text{ and } X_2(f) = \frac{1}{2}\delta(f+f_0)$$

Taking the inverse Fourier transform, we get:

$$x_1(t) = \frac{1}{2}[\cos(2\pi f_0 t) + j\sin(2\pi f_0 t)]$$

$$x_2(t) = \frac{1}{2}[\cos(2\pi f_0 t) - j\sin(2\pi f_0 t)]$$

Looking at $x_1(t)$ and $x_2(t)$, we see that the individual bandwidths of the real and imaginary components are the same as for the real-only example. In fact, $x(t)$ can be obtained by simply adding $x_1(t)$ and $x_2(t)$. Since the inverse Fourier transform of a single-sided spectrum resulted in a complex signal, it should be obvious that a *complex signal is not constrained to having a conjugate symmetric spectrum and can therefore uniquely represent signals over a bandwidth extending from $-f_0$ to f_0 which is twice the bandwidth of a real-only signal.*

Another important point in this example is that the spectrums, $X_1(f)$ and $X_2(f)$, are mirror images of each other. Looking at the time domain representation of the signals, we see that the only difference between them is that one is the complex conjugate of the other. This is a characteristic of all complex signals, not just the one used in this example. The spectrum of a complex signal can be mirrored about zero hertz by simply conjugating the time data.

In the wideband vector signal analyzer system, the microwave receiver performs a frequency translation to dc. Signals above the center frequency of the measurement appear as signals above dc in the vector signal analyzer; signals below the center frequency appear as negative frequency signals. The highest frequency I and Q signal that can be measured is 39 MHz. So, on the vector signal analyzer display, the frequency axis starts at -39 MHz and stops at 39 MHz (providing that the span is set to 78 MHz).

In a real measurement system there will be—among other impairments—a residual dc term in each channel and a gain mismatch between channels. Recall the single-sided spectrum $X_1(f)$ and its corresponding time representation.

$$x_1(t) = \frac{1}{2}[\cos(2\pi f_0 t) + j\sin(2\pi f_0 t)]$$

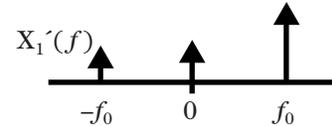
We can modify the previous equation to include a gain error a and dc error term b on the real part of the signal. This would represent errors in the I (channel one) portion of the signal.

$$x_1'(t) = \frac{1}{2}[(a\cos(2\pi f_0 t) + b) + j\sin(2\pi f_0 t)]$$

This equation can be rewritten as:

$$x_1'(t) = \frac{1}{2}[\cos(2\pi f_0 t) + j\sin(2\pi f_0 t)] + \frac{1}{2}[(a-1)\cos(2\pi f_0 t)] + \frac{b}{2}$$

The first component in this equation is the original signal which has a single spectral component at f_0 . The second component in the equation is a real-only component that we know has spectral components at both f_0 and $-f_0$. The final component is the dc term that produces a spectral component at zero hertz. The result of the gain mismatch and the dc term is a spectrum with two extra elements as shown below. The gain error also produces a change in the level of the signal at f_0 .



A similar approach can be used to show the effects of a quadrature error ϕ on the previous signal:

$$x_1''(t) = \frac{1}{2}[\cos(2\pi f_0 t + \phi) + j\sin(2\pi f_0 t)]$$

Using

$$\cos(x+y) = \cos(x)\cos(y) - \sin(x)\sin(y)$$

the equation can be rewritten as:

$$x_1''(t) = \frac{1}{2}[\cos(2\pi f_0 t) + j\sin(2\pi f_0 t)] + \frac{1}{2}[(\cos(\phi) - 1)\cos(2\pi f_0 t) - \sin(\phi)\sin(2\pi f_0 t)]$$

As before, the first term of the equation is the desired result. The second term is real-only with frequency components at both f_0 and $-f_0$. This shows that quadrature error can also limit the dynamic range of the measurement through the creation of spurious signals.

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Printed in USA December 28, 2000
5988-0257EN**

