How to Minimize Measurement Uncertainty in RF Vector Signal Generators

Introduction

Test equipment characterizes design performance and verifies devices under test function as expected. To be effective, test equipment must outperform the device under test. Minimizing measurement uncertainty attributed to test equipment requires careful consideration of all components in the testbed.

This application note helps you minimizing measurement uncertainty attributed to test stimuli in a test system.

Discover how to achieve the best signal quality for vector modulated signals using RF vector signal generators.

Minimizing your measurement uncertainty starts with knowing which signal generator capabilities, features, and performance levels you require.

With the right equipment, you can generate the signals required to effectively test your DUT. Select the signal generator and measurement software that unleash your insight, experience, and creativity while meeting your design objectives.

Vector Signal Generators

A great deal of systems test has shifted to vector signal generators (VSG), driven by the popularity of digital modulation schemes in today's communications systems. VSGs, equipped with dual arbitrary waveform generators (AWG), generate complex baseband I/Q waveforms as shown in Figure 1.

Dual AWGs control the playback sequence of waveform segments, which are downloaded into the random-access memory (RAM) in the internal baseband generator. The baseband generator output I/Q signals travel to the I/Q modulator and upconvert to an intermediate frequency (IF) and RF. The RF output section includes amplifiers, attenuators, and an automatic leveling control (ALC) circuit to maintain precise control of the output level. In the next section, we explore common sources of error from these sub-systems and how to overcome these problems.
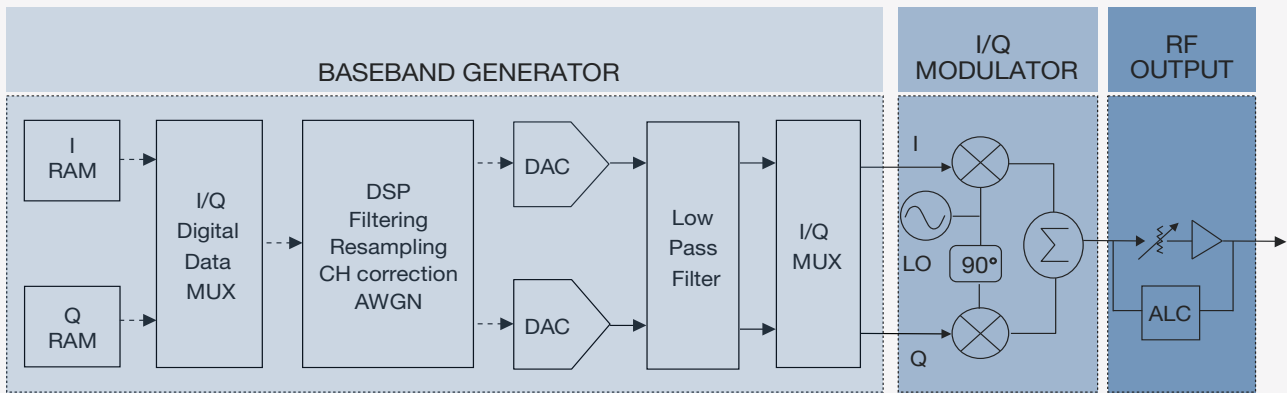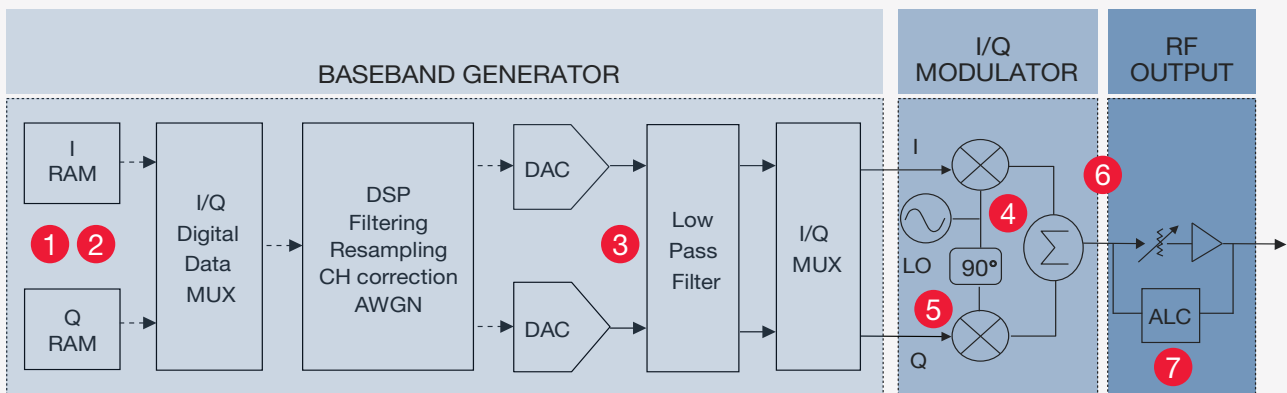

Figure 1. A simplified block diagram of a vector signal generator

Common Sources of Error

Baseband Generator
1. Phase Discontinuity
2. Interpolation Overshoot
3. Sampling Images

I/Q Modulator
4. I/Q Impairments
5. Phase Noise

R/F Output
6. Frequency Response
7. Output Level Errors with ALC

Baseband Generation

Waveform Phase Discontinuity

Arbitrary waveform generators are frequently used to repeatedly play back a previously sampled waveform. A side effect of waveform playback is spectral regrowth and distortion, caused by phase discontinuity between the end of a waveform and the start of the next repetition.

For example, the sampled waveform in Figure 2 does not cover the entire period of the sinewave. When playing back the waveform repeatedly, a phase discontinuity appears at the transition point between the end of the waveform and and beginning of the next retransmission. This phase discontinuity results in periodic spectral regrowth and distortion. Figure 3 shows the impact with and without phase discontinuity.
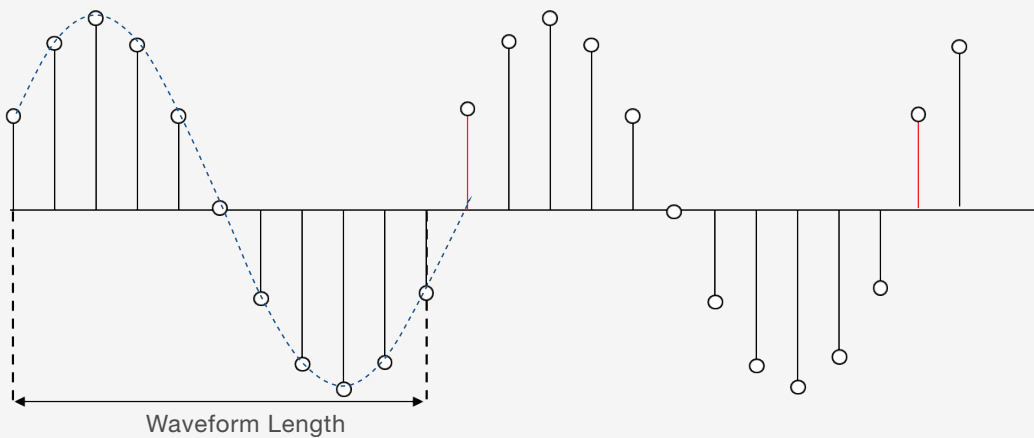

Figure 2. A sampled sinewave waveform with phase discontinuity

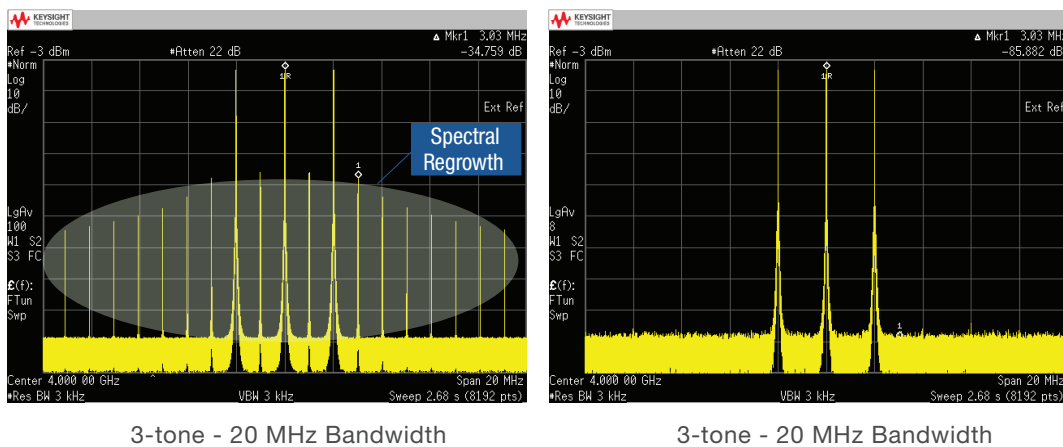3-tone - 20 MHz Bandwidth   3-tone - 20 MHz Bandwidth

Figure 3. The impact of a waveform with and without phase discontinuity

Avoiding Phase Discontinuities

Simulating an integer number of periods when creating your waveform segment can avoid phase discontinuities for periodic waveforms shown in the top of Figure 4.

For time division multiple access (TDMA) or pulsed periodic waveforms, resolve phase discontinuity by adding off-time at the beginning of the waveform, and by subtracting an equivalent amount of off-time from the end of the waveform as shown in the button of Figure 4. Making this adjustment can avoid spectral regrowth.
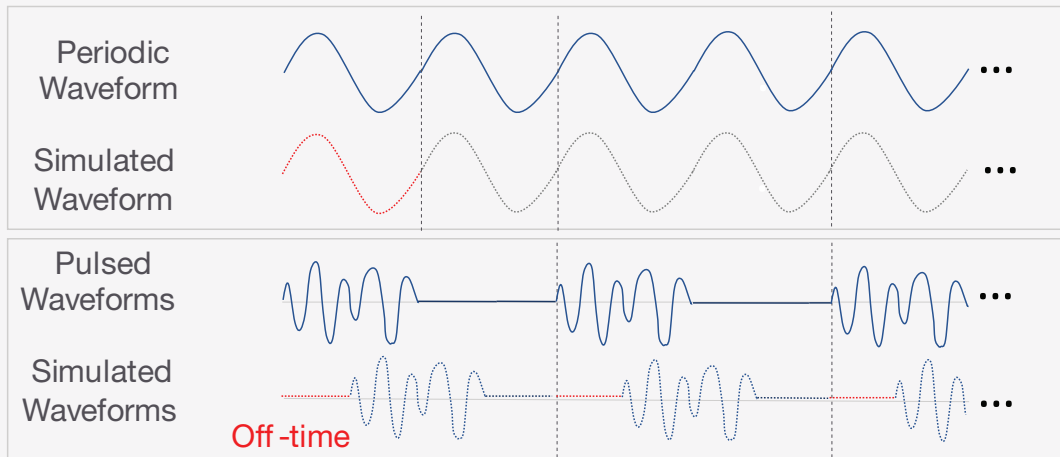

Figure 4. Simulate periodic and TDMA waveforms

- If there are N samples in a periodic waveform, but only the first N-1 samples are stored in the waveform segment as shown in Figure 5.

- If the waveform period exceeds the waveform playback memory available in the AWG, a periodic phase discontinuity may be unavoidable. Select a option with larger size of playback memory for a long period of waveform.
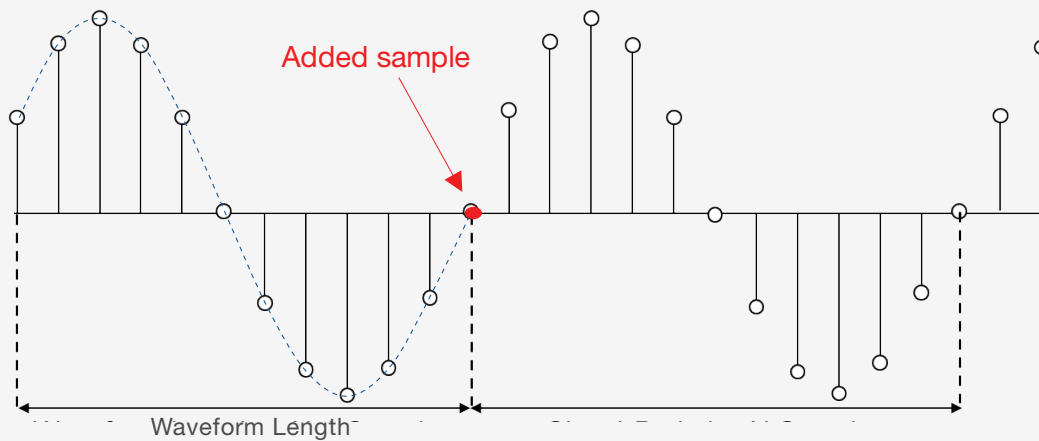

Figure 5. Add a sample for a signal period

Interpolation Overshoot

Dual AWGs provide flexibility when generating modern complex modulation signals. You can simulate your design and create the waveform files on a PC, then use the AWGs to convert the waveform files into analog signals. However, you must be cautious about introducing unexpected errors due to interpolation overshoot during digital-to-analog conversion.

Digital-to-Analog Conversion Over-Range

Baseband generator uses an interpolation algorithm to resample and reconstruct a waveform. However, interpolation can cause overshoots which result in digital-to-analog converter (DAC) over-range errors.

For example, if a baseband waveform has a fast–rising edge, the interpolator's filter overshoot becomes a component of the interpolated baseband waveform as shown in Figure 6. This response causes a ripple or ringing effect at the peak of the rising edge. This ripple overshoots the upper limit of the DAC output range (red line), causing the signal generator to report a DAC over-range error.
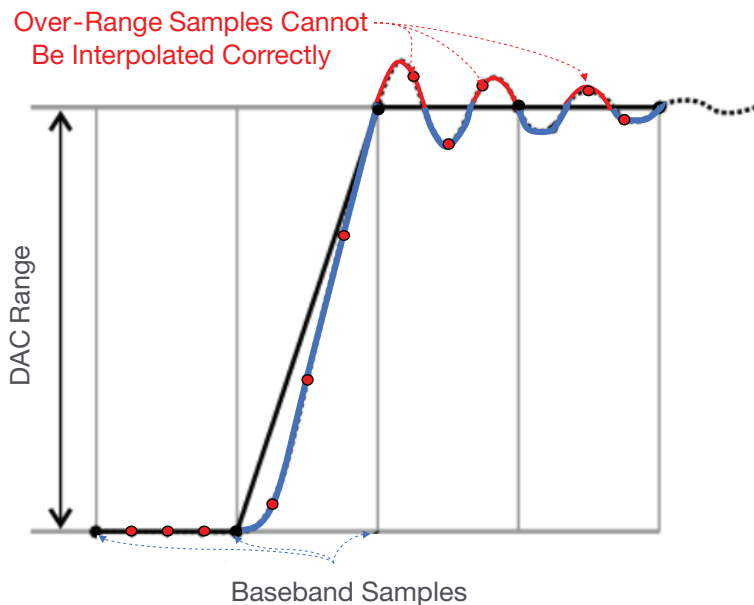

Figure 6. The interpolation filters in the DAC overshoot the baseband waveform

Scaling a Waveform to Eliminate DAC Over-Range Error

To avoid the DAC over-range problem, you must scale the I and Q input values, so that any overshoot remains within the DAC range. Scaling reduces the amplitude of the baseband waveform while maintaining its basic shape and characteristics, such as peak-to-average power ratio (PAPR) as shown in Figure 7. To achieve the maximum dynamic range, select the largest scaling value that does not result in a DAC over-range error.
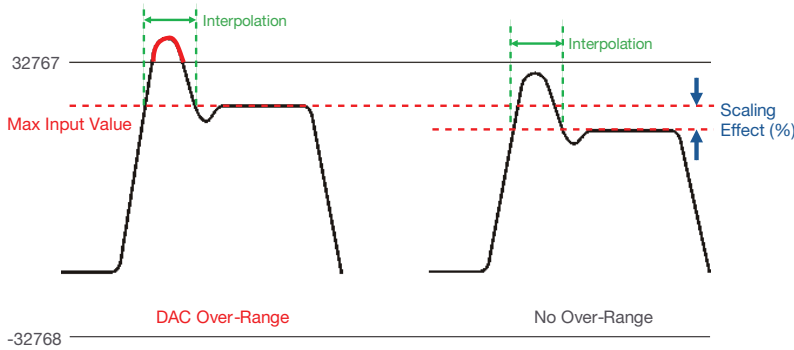

Figure 7. Waveform scaling to avoid DAC over-range

Accelerate the Evaluation with Runtime Scaling

New vector signal generators, such as the Keysight MXG N5182B and Keysight EXG N5172B provide runtime waveform scaling, so that the tradeoff between distortion performance and dynamic range can be evaluated in real-time. This feature does not impact stored data, and you can apply runtime scaling to either to a waveform segment or waveform sequence.

In Figure 8, you can see an example of evaluating distortion performance by adjusting the waveform scaling from 100% to 70%. The scaling reveals a 5-dB improvement in the third order intermodulation distortion (IMD3).
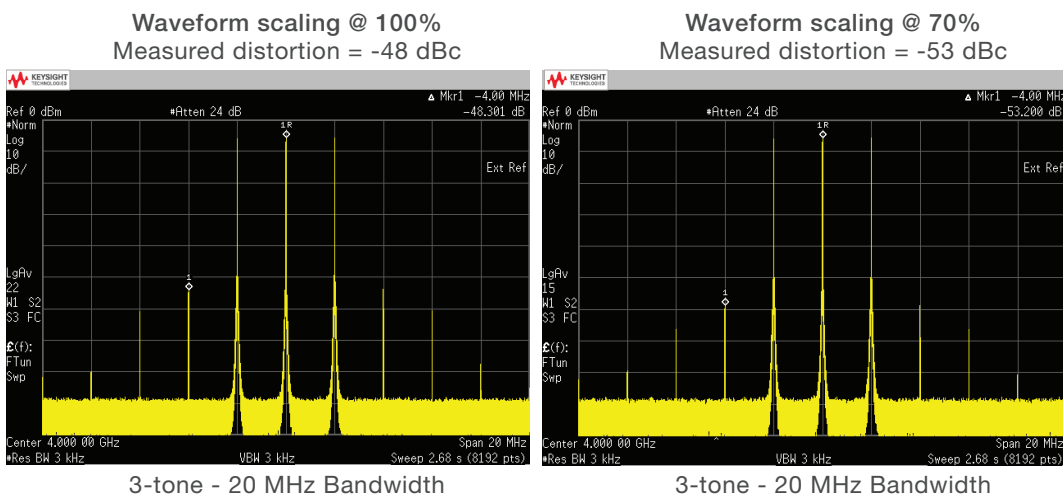

Figure 8. Two-tone test stimulus is achieved by changing the waveform scaling

Sampling Images

A digital-to-analog converter (DAC) playing back a sampled waveform creates both the signal of interest, and higher-order images, known as aliases of the signal. These aliases are located at multiples of the sampling frequency (fs) as shown in Figure 9.

We can use a low pass filter (LPF) to remove these higher order images. This LPF, which is also commonly referred to as an "anti-aliasing filter" or a "reconstruction filter", is frequently used to reconstruct the original, desired signal.

To successfully isolate the desired signal, The filter cutoff frequency must be low enough to reject the images and high enough to cover the full bandwidth of the signal of interest.

The filter in Figure 9 cannot reject the images completely. To be successful, you need to know the reconstruction filter bandwidth before you decide the waveform sample rate. This will ensure all the images can be rejected by the filter.
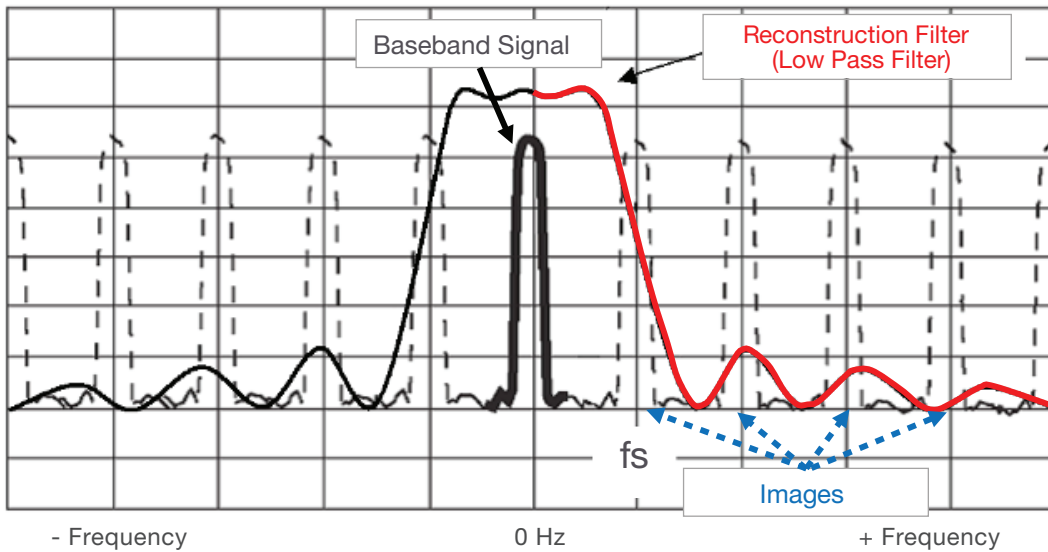

Figure 9. Remove sampling images with a reconstruction filter

DSP Waveform Resampling Benefits

R&D engineers usually implement oversampling in software when creating a waveform. Oversampling lets them move the images far away from the cutoff frequency of the reconstruction filter, as shown in Figure 10. However, this technique also increases the size of the waveform file, and memory can be a constraining factor when designing waveforms for playback.

New vector signal generators support hardware resampling to remove sampling images with a single wideband reconstruction filter. The resampling process happens in the digital signal processing (DSP) before sending waveform data to the DACs. The interpolation resampling process matches the signal to the DAC's clock rate using a combination of oversampling, filtering, and signal decimation.

Hardware resampling lets you focus on waveform creation, while the DSP implements resampling and sampling rate matching for the DACs.
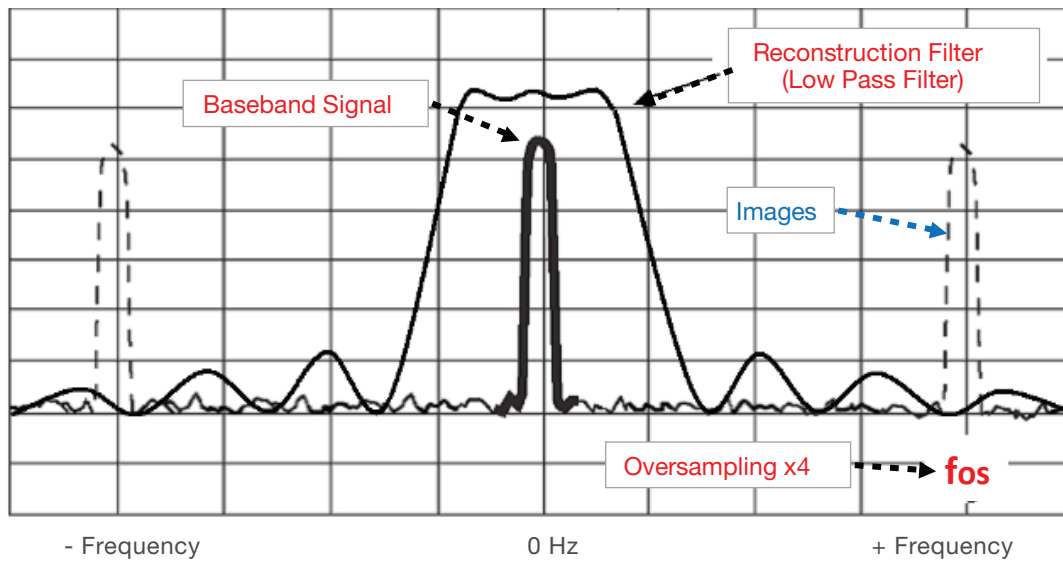

Figure 10. Move sampling images far away with 4 times of oversampling ratio

⚡ I/Q Modulators

Baseband I/Q Impairments

In a digital transmitter, I (in-phase) and Q (quadrature) signals mix with the same local oscillator (LO), but a 90-degree phase shifter is placed in one of the LO paths, as shown in Figure 11. This 90-degree phase shift makes the I and Q signals orthogonal to each other, so they do not interfere with one another. I/Q impairments leading to measurement uncertainty can be caused by unmatched components in the separate I and Q signal paths.
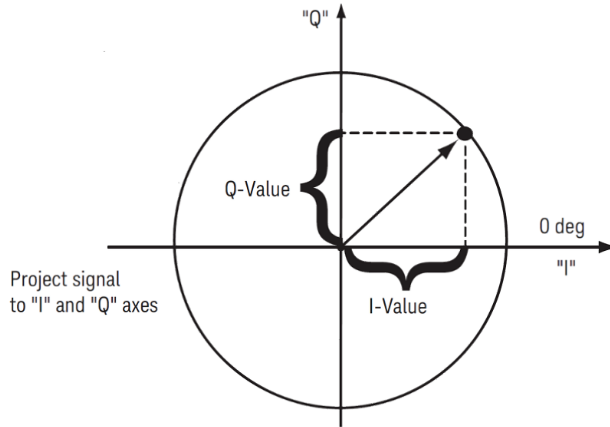

Figure 11. I/Q diagram

> Learn about how to identify the most common impairments in transmitter designs "Testing and Troubleshooting Digital RF Communications Transmitter Designs"

I/Q Gain Imbalance
I/Q gain imbalance is characterized by comparing the gain of the I signal with the gain of the Q signal.

I/Q Quadrature Skew
A quadrature error occurs if the phase shift is not 90 degrees between I and Q channels.

I/Q Offset
The I/Q offset (also called I/Q origin offset) indicates the magnitude of carrier feedthrough signal or baseband DC offsets in dB.

I/Q Timing Skew
The modulator, digital-to-analog converter (DAC), or different electrical lengths in the I and Q paths can all cause unwanted delay between I and Q signals.
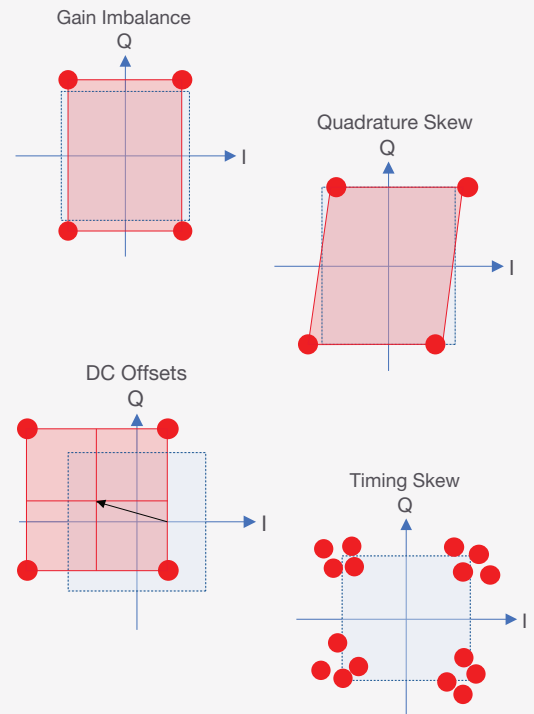

Figure 12. Common baseband I/Q impairments

Baseband I/Q Adjustments

Baseband I/Q impairments can occur in a baseband generator, an I/Q modulator, or an RF section. It is not always necessary or desirable to minimize I/Q impairments. Some applications and tests require a specific amount of impairment to accurately simulate the signal, or for tolerance testing.

Vector signal generators allow you to use I/Q Adjustments to compensate for, or add impairments to, the I/Q signal. Table 1 is summary of I/Q effects and impairments available through I/Q Adjustments.

Table 1. Baseband I/Q adjustments

I/Q Adjustment	Effect	Impairment
Offset	Carrier feedthrough	DC offset
Quadrature Angle	Error vector magnitude (EVM) error	Phase skew
	I/Q images	I/Q path delay
I/Q Skew	EVM error	High sample rate phase skew
		I/Q path delay
I/Q	I/Q amplitude difference	I/Q gain ratio

Baseband I/Q Calibration

Calibration routines compensate for measurement uncertainly resulting from calibration drift related to temperature changes. When you perform I/Q calibration, that calibration data takes precedence over factory–supplied calibration data.

I/Q calibration routines allow you not only to correct the impairments of the internal baseband generator, but also the external I/Q input signals. You can select the instrument's entire frequency, or specify the calibration start and stop frequencies to shorten calibration period.

Run an I/Q calibration when ambient temperature and the latest calibration temperature have changed by more than ±5 degrees Celsius.

Phase Noise

Phase noise describes the frequency stability of an oscillator. It measures the noise spectrum around the oscillator's signal in the frequency domain.

Phase noise is usually measured as the single-sideband (SSB) power within one hertz bandwidth at a specific frequency away from the carrier frequency power. Figure 13 shows SSB phase noise measurement results.

Figure 13. SSB phase noise measurements
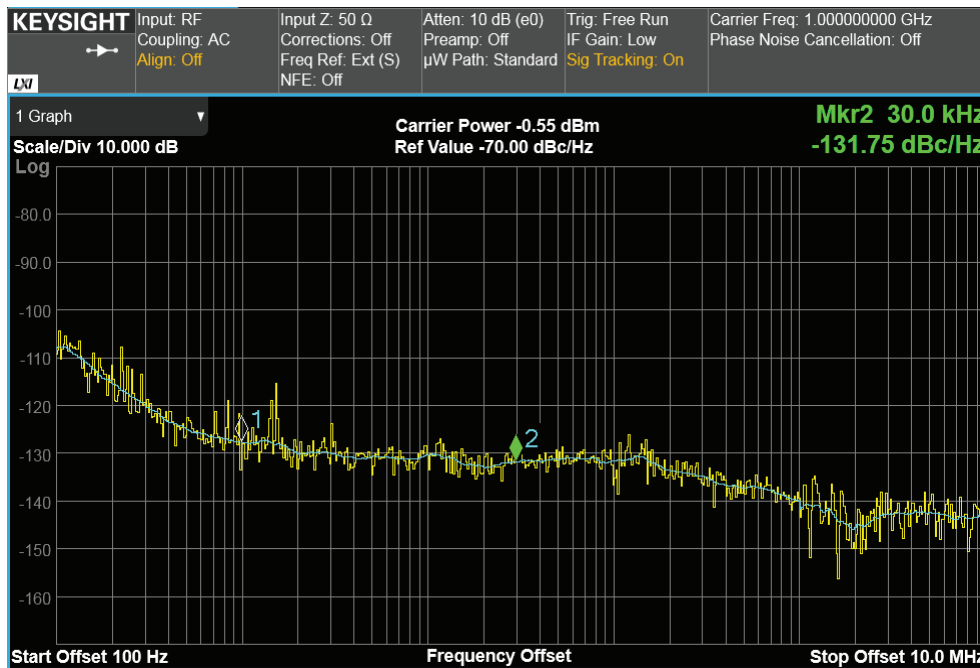
Learn more about the impact of phase noise and how to optimize a signal generator's phase noise profile by downloading the white paper "Making Noise in RF Receivers"

When Phase Noise Matters

Signal source phase noise performance can be a limiting factor for specific applications in aerospace and defense, as well as in digital communications.

Radar Applications: The radar receiver cannot identify the moving object if the downconverted signal of interest is masked by the phase noise.

Digital Modulation: The effect of phase noise on the constellation diagram is the radial smearing of symbols.

Orthogonal Frequency-Division Multiplexing: The sub-carrier with phase noise spreads into other sub-carriers as interference.

Optimize Phase Noise Performance

Optimizing phase noise performance is not always necessary or desirable. Some applications and tests require a specific amount of phase noise for accurate signal substitution or tolerance testing.

The Keysight N5182B/N5172B RF signal generator allows users to adjust synthesizer phase noise impairment. Using this feature, you can introduce phase noise into a signal generator by controlling two frequency points (f1 and f2) and amplitude values (Lmid), as shown in Figure 14.

Figure 15 shows a CW signal with phase noise impairment. The start frequency f1 is 1 kHz; the stop frequency f2 is 30 kHz; amplitude values Lmid is -90 dBc/Hz.
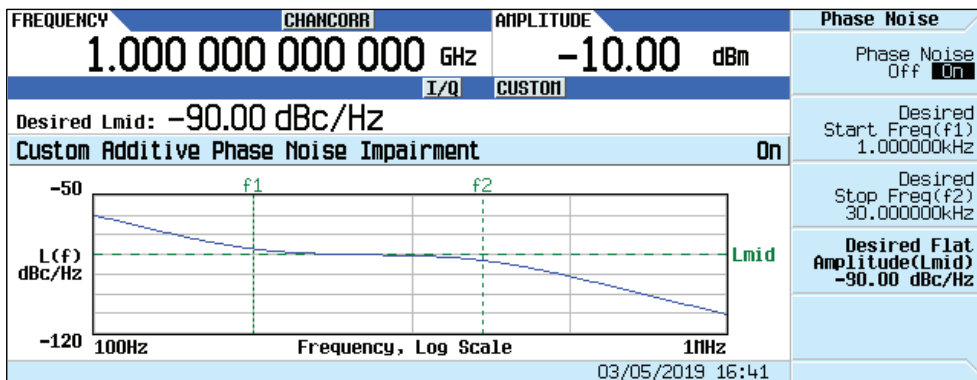

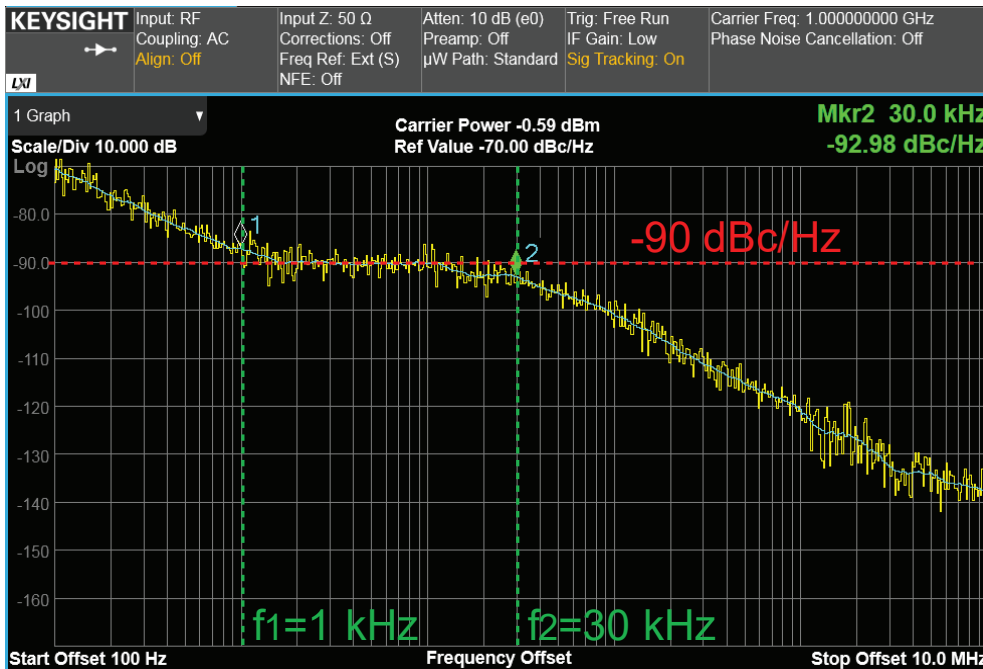**Figure 14. Applying real-time phase noise impairment on a signal generator**

Figure 15. A CW signal with phase noise impairment

Internal algorithms produce customized phase noise using the signal generator's real-time baseband ASIC and processor accelerator. With this feature, you can simulate a more realistic signal which is helpful in evaluating and troubleshooting your devices under test.

Figure 16 illustrates a 64-QAM demodulation analysis at a 30 MHz symbol rate. The demodulation measurement of the signal with the phase noise impairment setup OFF (upper) and ON (lower) as shown in Figure 14. The RMS phase error increases from 1.85° to 2.20°, and the error vector magnitude (EVM) increases from 1.73% to 1.99%.
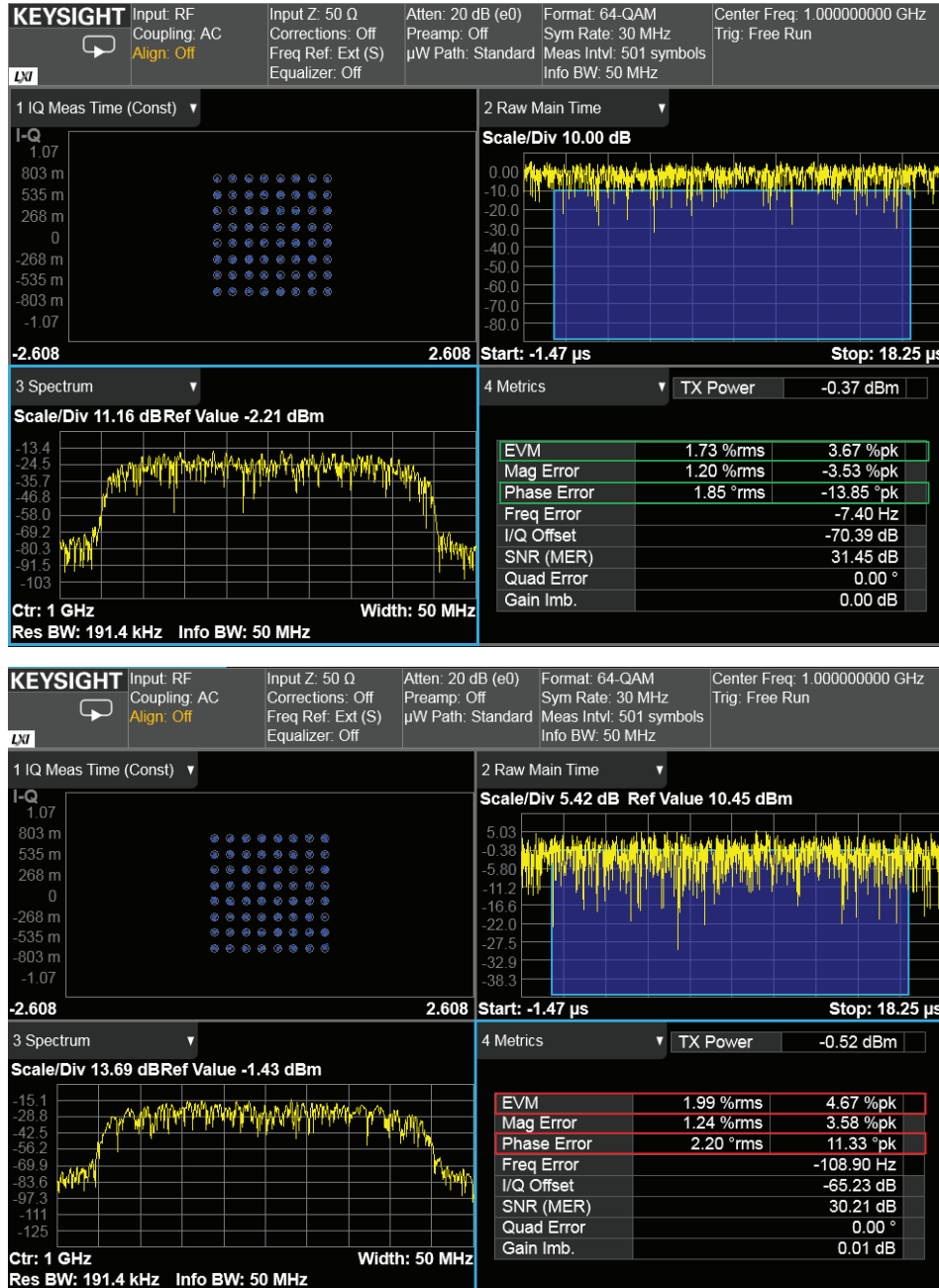

Figure 16. Demodulating a signal without (upper) and with phase noise impairment (lower)

RF Output Section

Frequency Response

When a signal generator outputs a modulated signal, the components inside the signal generator, such as mixers, filters, and amplifiers, contribute frequency responses which degrade modulation quality. These responses occur at different frequencies and output levels, and include both amplitude and phase response.

Figure 17 illustrates a 64-QAM demodulation analysis at a 100 MHz symbol rate. The I/Q constellation is chaotic due to the wide bandwidth frequency response, and the signal cannot be demodulated correctly.

With adaptive equalization enabled on the signal analyzer, you can see the signal's both amplitude and phase responses, as shown in the upper-right and lower-right diagrams of Figure 18.

Adaptive equalization removes linear errors from modulated signals by dynamically creating and applying a FIR (feed-forward) compensating filter. The errors include group-delay distortion, frequency-response errors, and reflections or multipath distortion.
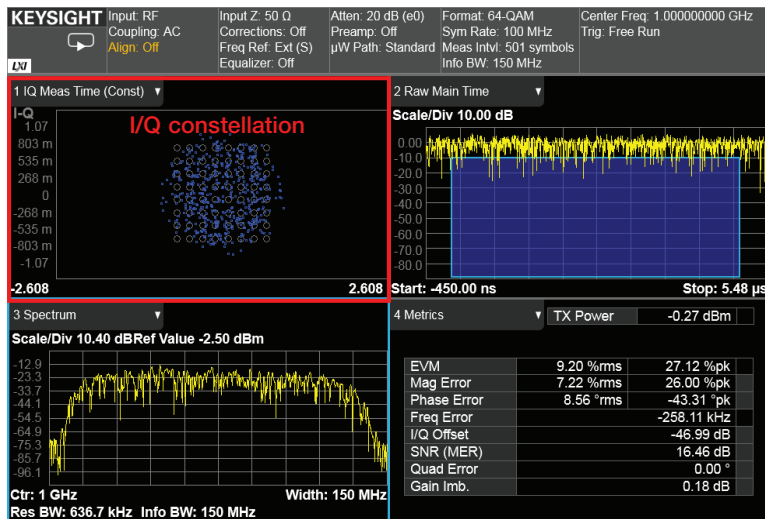

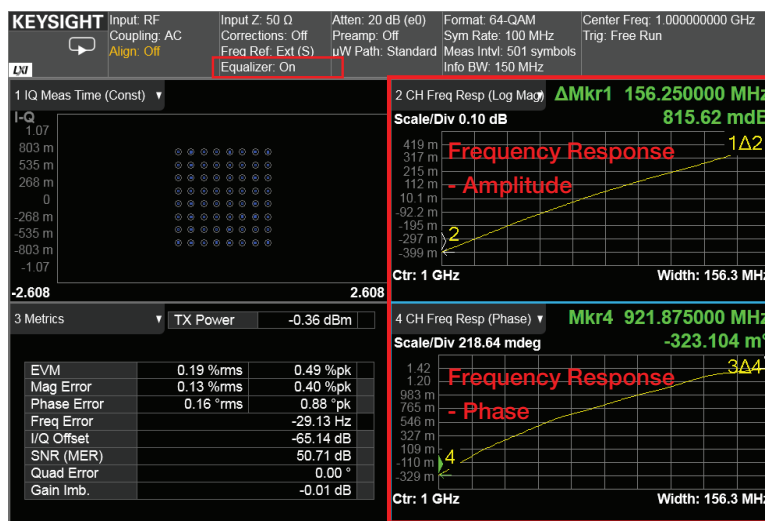Figure 17. Frequency response impacts on signal modulation quality

Figure 18. Signal's amplitude and phase responses

Internal Channel Correction

Vector signal generators support an internal calibration routine. This routine collects correction data for both baseband and the RF magnitude and phase errors. These measurements are performed over the entire RF frequency and across all power level ranges. The correction data includes parameters of the correction filter, applied to baseband waveforms in real time.

DSPs process the data to implement real-time channel correction, which is especially important for wide bandwidth signal generation.

In Figure 19, you can see the demodulation analysis of the 64-QAM signal with Internal Channel Correction on. You can see that the symbols are concentrated in the constellation diagram (upper-left), and EVM is down to 0.82%.

Learn how to improve amplitude accuracy for your measurements by downloading the white paper "Improving Amplitude Accuracy with Next-Generation Signal Generators"
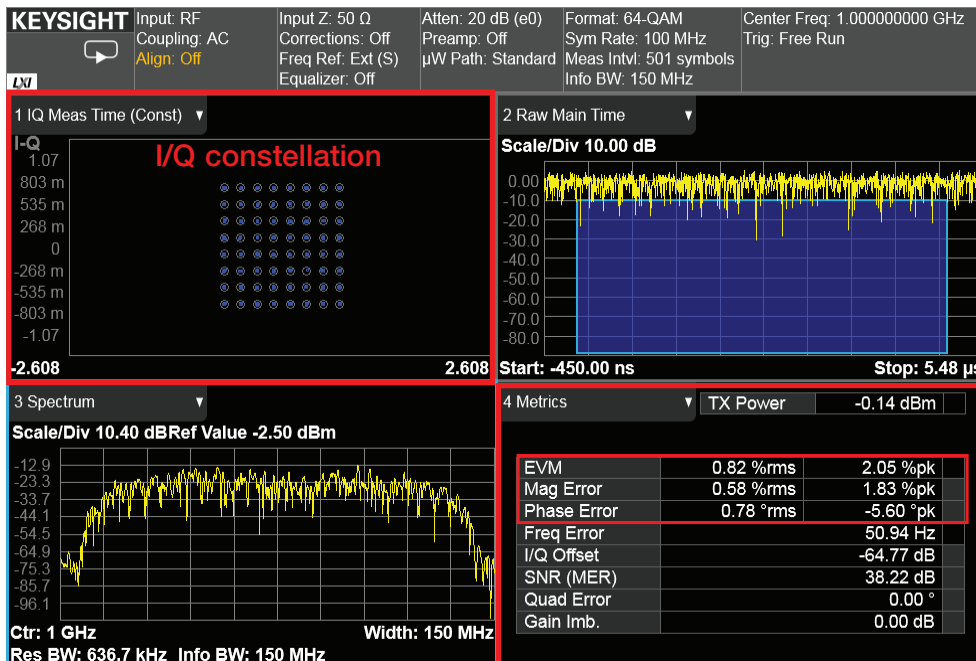

Figure 19. Signal generator with Internal Channel Correction On

When the correction feature is on and you change frequency, the firmware will calculate a channel correction filter. This process requires additional time, and depends on the frequency switch type.

Output Level Errors

A step attenuator and an automatic leveling control (ALC) circuit determines the signal generator output power range, shown in Figure 20. The step attenuator provides coarse power attenuation, in 5-dB steps, to achieve low power levels. The ALC circuit provides fine power level adjustment within the attenuator hold range, resulting in very accurate amplitude levels at the signal generator RF output port.

With some modulations, it is not possible to use the ALC circuit, which can lead to output level errors. In these conditions, power level accuracy can be achieved by turning the ALC off and using the Power Search feature.
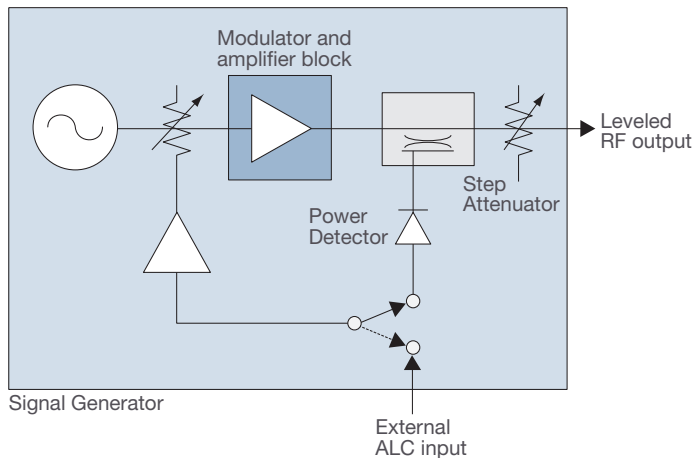

Figure 20. A simplified block diagram of an ALC feedback circuit

ALC Off and Power Search

In cases where the RF level cannot be accurately determined by the ALC circuit, the ALC can be switched off. When off, the signal generator has no source of closed-loop feedback to detect RF levels and correct for errors. In these cases, the Power Search feature can be used to calibrate the RF level.

The following use cases are suitable for power search:

- Non-repetitive pulse modulation
- Repetitive pulse modulation with pulse widths less than 1 μs
- High peak-to-average power modulation signal
- Applications requiring the lowest amplitude modulation (AM) noise
- I/Q modulation at low symbol rates with the best spectral re-growth
- Pulse modulation with low symbol rate I/Q modulation

Learn more about how to improve the amplitude accuracy for your measurements by downloading the white paper "I/Q Modulation Considerations for PSG Vector Signal Generators".

What is ALC?
The ALC circuit maintains output power at the desired level, despite drift caused by temperature variation. A directional coupler and power detector measure the output RF power. The detected power level feeds back to ALC, and this input is used to adjust the ALC modulator, helping maintain a precisely controlled output level.

What is Power Search?
Power Search is a calibration routine used to set an accurate RF level with automatic levelling control off. A power-search cycle starts with modulation temporarily switched off. Then, the ALC system is switched on, just long enough to determine the ALC modulator value. This lets the algorithm determine the correct RF level. Finally, the modulation is switched back on. The gain of the RF system is then held constant, delivering an accurate RF level even with no closed-loop feedback.

Conclusion

Minimizing your measurement uncertainty starts with knowing which signal generator capabilities, features, and performance levels you require.

With the right equipment, you can generate the signals required to effectively test your DUT. Select the signal generator and measurement software that unleash your insight, experience, and creativity while meeting your design objectives.

Discover more measurement best practices at the RF Test blog. For more information about Keysight signal generators, visit www.keysight.com/find/sg.

Learn more at: www.keysight.com

For more information on Keysight Technologies' products, applications or services, please contact your local Keysight office. The complete list is available at: www.keysight.com/find/contactus

KEYSIGHT
TECHNOLOGIES