



WHITE PAPER

Improving Amplitude Accuracy with Next-Generation Signal Generators

Generate True Performance

Signal generators offer precise and highly stable test signals for a variety of components and systems test applications. In an RF test system, you extend the measurement accuracy from the signal generator's output to the device under test (DUT). The nature of the cables, components, and switches in the paths between the instruments and the DUT can degrade the measurement accuracy.

This whitepaper will help you improve the amplitude accuracy of your measurements that involve signal generators. Before learning why amplitude accuracy matters and how to optimize amplitude accuracy, let's start with the fundamentals of RF power measurements.



What is “Power”?

The International System of Units defines the watt (W) as a unit of power; one watt is one joule per second and is used to quantify the rate of energy transfer. At DC and low frequencies, voltage and current measurements are simple and straightforward. Power (P) is the product of voltage (V) and current (I).

For low-frequency signals, both voltage and current vary with time. The energy transfer rate (instantaneous power) also varies with time. In Figure 1, instantaneous power (P) shifts around cycles (blue curve). Averaging is done by integrating the area under the P curve.

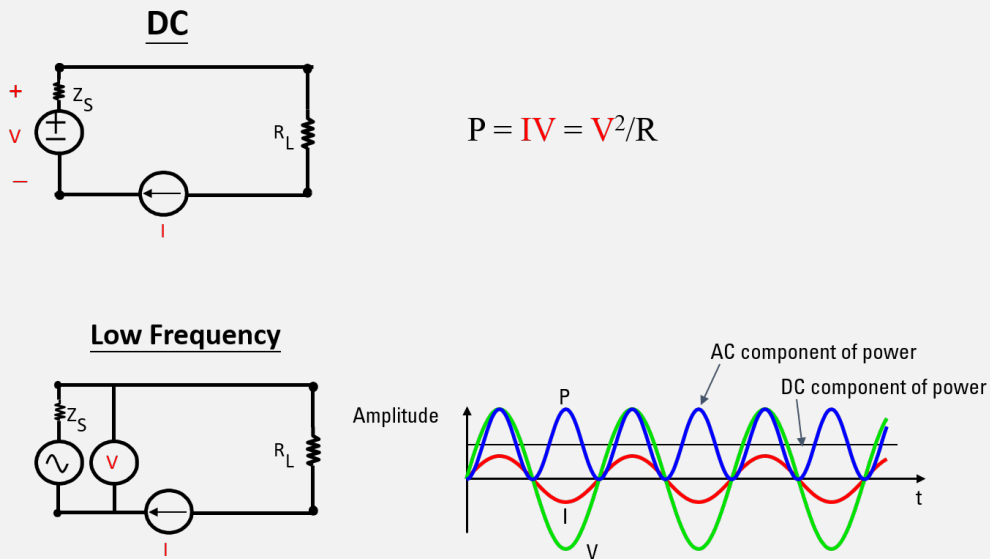
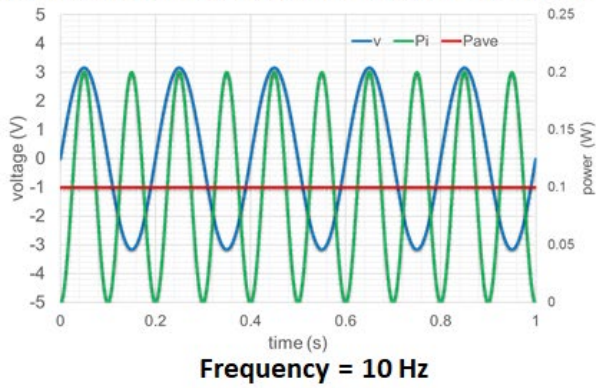


Figure 1. DC and low frequencies power measurements

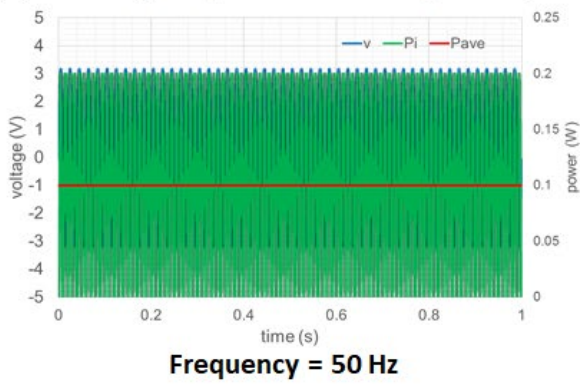
However, as frequency increases, voltage and current measurements become difficult to obtain and impractical. In most applications, direct power measurements are made instead. Figure 2 illustrates three continuous waves with the same voltage level but different frequencies. Pi (in green) is instantaneous power and it varies with time. Pavg (in red) represents average power.

You can see that average power remains constant and independent of frequency. Average power is a good quantity for high-frequency signals. Let's clarify different definitions of power for RF measurements.

(A) Low frequency sinusoidal voltage and power



(B) Low frequency sinusoidal voltage and power



(C) High frequency sinusoidal voltage and power

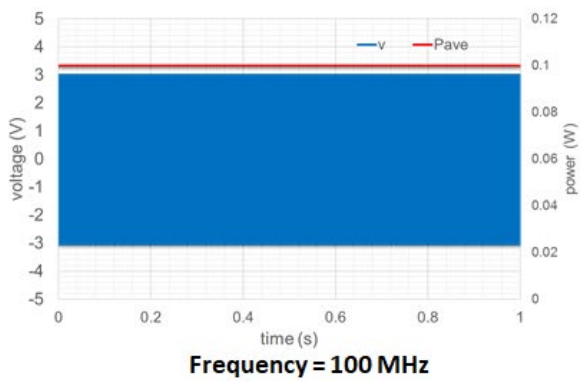


Figure 2. From low to high frequencies power measurements

Average Power

As frequency increases, the impedance will vary. The term “average power” is very popular and is used to specify almost all RF and microwave systems, as the instantaneous power variations are too fast to be meaningful. Average power is the averaged energy transfer rate across many time periods of the lowest frequency. For a continuous wave (CW) signal, the lowest frequency and the highest frequency are the same, so “average power” and “power” are the same. For an amplitude modulation signal, the power must be averaged over many periods of the modulation component of the signal.

Envelope Power and Peak Envelope Power (PEP)

For some applications, engineers examine the effects of modulation or transient conditions without looking at the details of the RF carrier waveform. Figure 3 below shows high-frequency modulated signal power measurements. The upper graph is the voltage envelope of the modulated signal. The lower left graph shows the instantaneous power of the signal in green and the average power in red.

The envelope power is measured by averaging the power over a long-time period compared to the period of the highest modulation frequency, but short compared to the period of the carrier. Figure 3 on the lower right shows the envelope power in red. The maximum envelope power is called “peak envelope power” PEP and it is an important parameter for specifying RF transmitters.

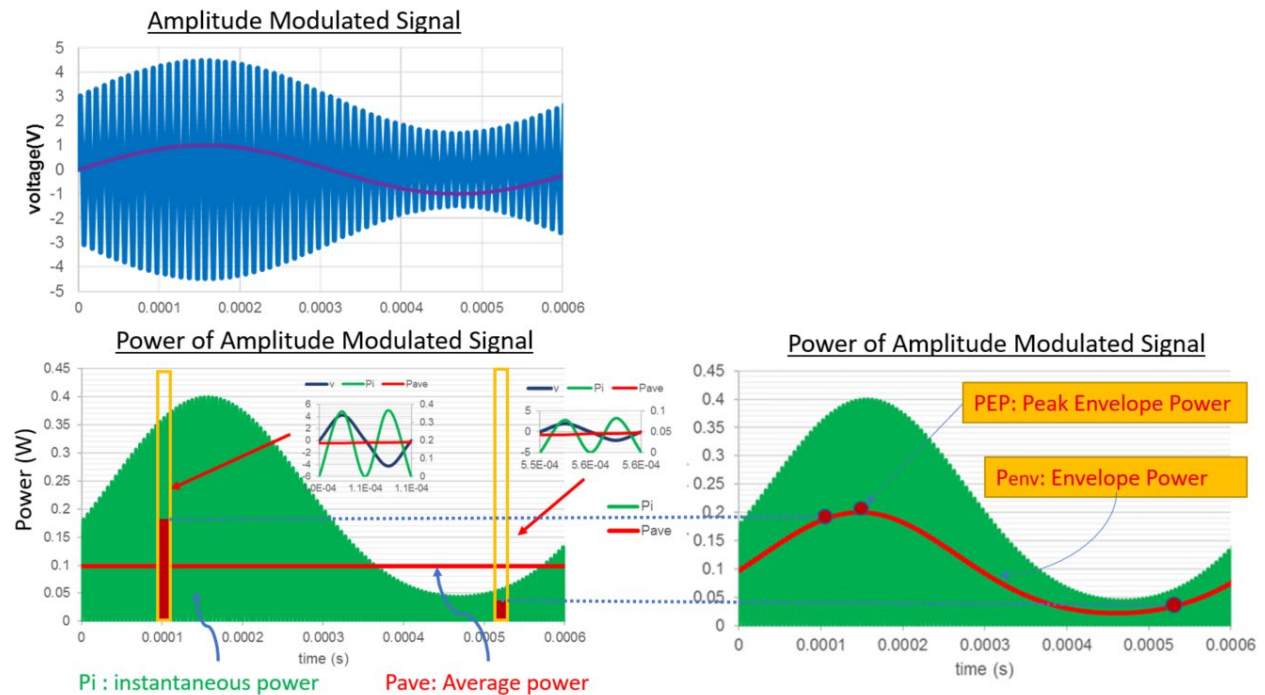


Figure 3. Voltage envelope and power envelope of a high-frequency modulated signal

For more details on RF and microwave power measurements, download the application note [“Fundamentals of RF and Microwave Power Measurements Parts 1-4.”](#)

Power Statistics - Complementary Cumulative Distribution Function

Many digitally modulated signals appear noise-like in the time and frequency domain. Power complementary cumulative distribution function (CCDF) curves help characterize the higher-level power statistics of a digitally-modulated signal. You may use the CCDF plot of a signal generator to identify the peak-to-average ratio (PAR) of a signal waveform as shown in Figure 4. The signal waveform is a 64 QAM, symbol rates at 1 Msps, and with RRC (root-raised-cosine) baseband filter waveform. The PAR is 5.95 dB. If the output amplitude is set to 0 dBm (average power), the PEP is equal to output amplitude plus PAR, i.e. +5.95 dBm.

$$PEP = P_{out} + PAR$$

where P_{out} is the amplitude setting on a signal generator (average output power).

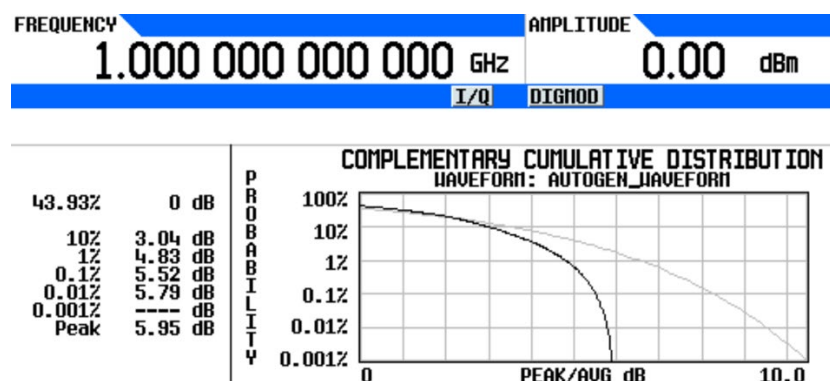


Figure 4. CCDF plot from waveform utility of Keysight's N5182B signal generator

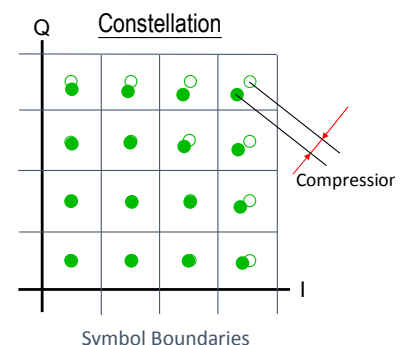
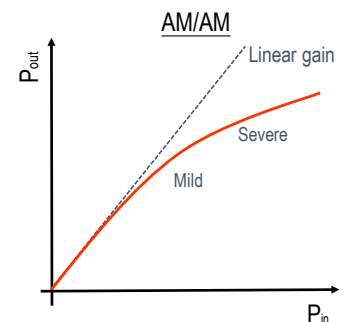
Gain Compression of a Signal Generator

If the output power of a signal generator is saturated, it impacts not only the output power level accuracy but also the modulation quality due to AM-to-AM compression. For a high PAR signal, the amplitude level setting on a signal generator cannot be greater than the maximum output power (i.e. PEP) of the signal generator minus the peak-to-average ratio. For example, the maximum output power of the signal generator is +18 dBm. The PAR of the signal is 10 dB. The maximum amplitude setting (average power) you can use with the signal generator is +8 dBm (18 - 10 = 8). This prevents the signal generator's power amplifier from being saturated.



What is AM-to-AM compression?

Ideally, amplifiers have constant gain, so P_{out} is linearly related to P_{in} . At high input levels, saturation or compression sets in (also called AM-to-AM). It will cause compression in baseband IQ constellation.



When is CCDF Used?

CCDF curves are excellent tools for characterizing the power distributions of digital modulation signals and they apply to many design applications.

- Visualizing the effects of modulation formats.
- Combining multiple signals via system components.
- Evaluating spread-spectrum systems (e.g. CDMA).
- Designing and testing RF components.

To learn more about CCDF, download the application note “**Characterizing Digitally Modulated Signals with CCDF Curves**”.

What Does Specification Say about Power?

In RF testing, the maximum output power is an essential attribute of every signal generator. The signal generator must be capable of maintaining spectral purity and level accuracy while delivering high output power. Let’s take a closer look at the amplitude specification of a signal generator.

Maximum Output Power

Table 1 below illustrates the maximum amplitude specifications of Keysight’s MXG/EXG signal generators. There are several points you need to be aware of when reading this table:

1. The settable range is not the actual output range of the signal generator. Using an output offset, the signal generator can output an amplitude that is offset (positive or negative) from the entered value. This means that you can extend output range with external amplifiers or attenuators.

Displayed (Settable) Amplitude Level = Output Level + Amplitude Offset

2. The output amplitude is affected by frequency ranges and operating temperatures.
3. The step attenuator (in 5-dB step) provides coarse power attenuation to achieve low power levels. The ALC (automatic leveling control) circuit fines power level adjustment within the attenuator hold range.

| Output parameters | |
|-------------------|-------------------------------------------|
| Settable range | +30 to -144 dBm |
| Resolution | 0.01 dB |
| Step attenuator | 0 to 130 dB in 5 dB steps electronic type |
| Connector | Type N 50 Ω, nominal |

| Max output power1 () = typical | | |
|--------------------------------|----------|-------------------|
| Frequency | Standard | Option 1EA |
| 9 kHz to 10 MHz | +13 dBm | +17 dBm (+18 dBm) |
| > 10 MHz to 3 GHz | +18 dBm | +24 dBm (+26 dBm) |
| > 3 to 5 GHz | +16 dBm | +19 dBm (+20 dBm) |
| > 5 to 6.0 GHz | +16 dBm | +18 dBm (+19 dBm) |

Note 1: Quoted specifications between 20 °C and 30 °C. Maximum output power typically decreases by 0.01 dB/°C for temperatures outside this range.

Table 1. Amplitude specifications of output parameters and maximum output power

Amplitude Accuracy

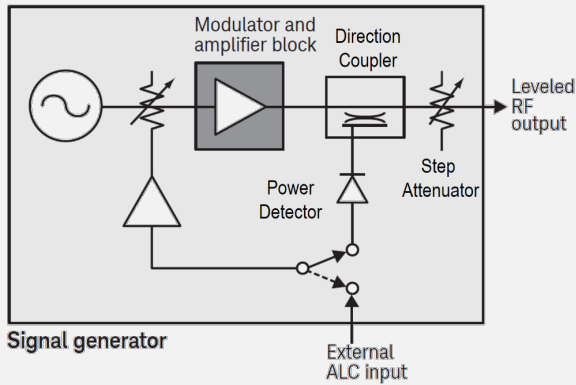
Amplitude accuracy of a signal generator is the degree to which the signal generator's output amplitude conforms to its set amplitude. Amplitude accuracy is often specified within a frequency and temperature range. The temperature range is specified because a signal generator is often calibrated within a temperature-controlled environment. The further the operating temperature is from the temperature at which the signal generator was calibrated, the more compromised the amplitude accuracy becomes.

As mentioned previously, the output range of a signal generator is decided by attenuators and an ALC circuit. The lower output power is, the more attenuators are required. Each attenuator contributes some uncertainties. Table 2 shows that amplitude accuracy is affected by frequency ranges and amplitude levels.

There are some modulation conditions the ALC circuit cannot handle properly which can lead to output level errors. In these conditions, power level accuracy can be achieved by turning the ALC off and using power search. The ALC off function is helpful when used with pulse modulation where the pulse width is narrower than two microseconds and with certain external I/Q modulation.

| Absolute level accuracy in CW mode ¹ (ALC on) () = typical | | | |
|------------------------------------------------------------------------------------|----------------------|-------------------|--------------------|
| | Standard | | Option 1EQ |
| Range | Max power to -60 dBm | < -60 to -110 dBm | < -110 to -127 dBm |
| 9 to 100 kHz | (± 0.6 dB) | (± 0.9 dB) | |
| 100 kHz to 5 MHz | ± 0.8 dB (± 0.3) | ± 0.9 dB (± 0.3) | |
| > 5 MHz to 3 GHz | ± 0.6 dB (± 0.3) | ± 0.8 dB (± 0.3) | ± 1.5 dB (± 0.5) |
| > 3 to 6 GHz | ± 0.6 dB (± 0.3) | ± 1.1 dB (± 0.3) | ± 1.6 dB (± 0.6) |
| Absolute level accuracy in CW mode (ALC off, power search run, relative to ALC on) | | | |
| 9 kHz to 6 GHz | ± 0.15 dB, typical | | |
| Absolute level accuracy in digital I/Q mode (N5182B only) | | | |
| (ALC on, relative to CW, W-CDMA 1 DPCH configuration < +10 dBm) | | | |
| 5 MHz to 6 GHz | ± 0.25 dB, (0.05 dB) | | |

Table 2. The absolute level accuracy of Keysight MXG signal generator



What is ALC?

The purpose of ALC circuit is to maintain the output power at the desired level despite drift caused by temperature variation. A direction coupler and power detector are used to measure the output RF power. The detected power level is fed back to ALC system to adjust the ALC modulator to maintain a precisely controlled output level.

Figure 5: A simplified block diagram of an ALC feedback circuit

Why Amplitude Accuracy Matters

Receiver sensitivity test determines if a receiver is able to detect weak signals at or below a specified power level. In this scenario, the measurement result is sensitive to the signal generator level and the signal generator amplitude accuracy specification is critical.

For example, a receiver has a specified sensitivity level of -110 dBm. The receiver sensitivity test will only accept receivers that are sensitive enough to detect transmissions with a signal strength of -110 dBm or less. There are six DUTs with different receiver sensitivity levels as shown in Figure 6. To ensure that no failed unit will pass the sensitivity test, you need to set the output level lower and consider the amplitude accuracy of the signal generator.

Case 1: The amplitude accuracy of the signal generator is ± 5 dB. The output amplitude needs to be set to -115 dBm. The actual output level is 1 dB higher, -114 dBm. You can see five of the six DUTs failed.

Case 2: The amplitude accuracy of the signal generator is ± 1 dB. The output amplitude needs to be set to -111 dBm. The actual output level is 1 dB less, -112 dBm. You can see only two DUTs failed in this case.

In fact, six DUTs tested in the example, and only one failed. When signal generators offer better amplitude accuracy, fewer retests are required.

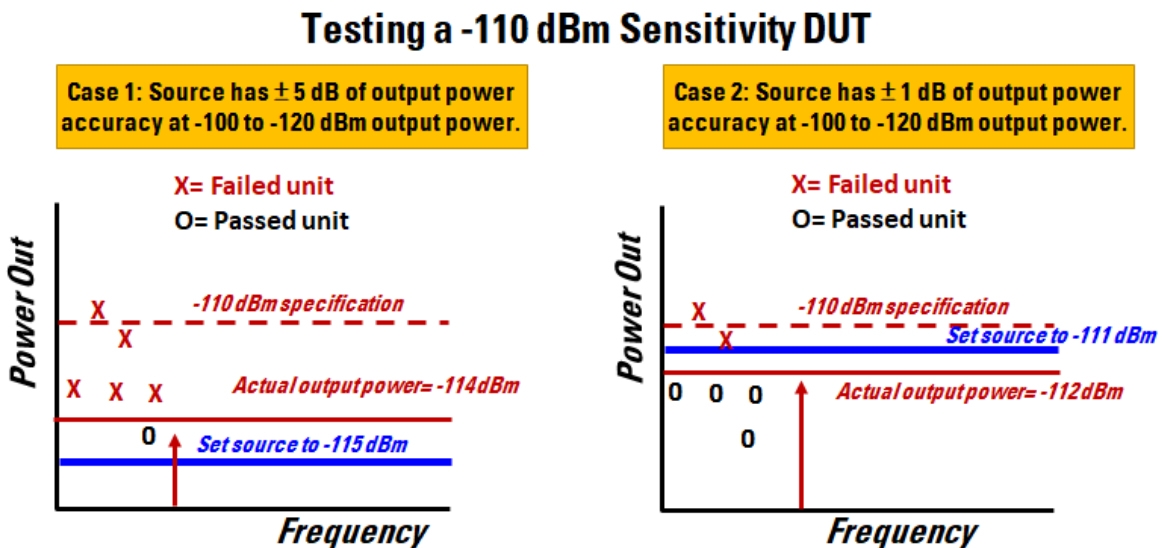


Figure 6. Receiver sensitivity test results compare different levels of amplitude accuracy

Measurement Applications

High Output Power

While you can increase output power by adding a high-power amplifier, the high-power amplifier degrades spectral purity and the distortion performance of a signal generator.

Spectral purity

Adding a high-power amplifier to a signal generator will increase the broadband noise floor. While you measure the phase noise of the signal generator, the broadband noise appears at offsets greater than 1 MHz from the carrier frequency. In addition, the amplifier also affects spurious performance due to gain flatness and impedance changes. For a digital modulation signal, broadband noise degrades modulation quality.

Distortion performance

Power amplifiers are a major contributor to non-linear distortion in RF signal generators. This includes harmonic and intermodulation distortion. These two types of distortion create in-channel, in-band, and out-of-band unwanted spectral signals. These non-linear distortions degrade the signal generator's performance in areas such as spurious, modulation quality, and spectral regrowth.

To learn more about creating a more effective high-power signal generator, download the application note **“Generating and Applying High-Power Output Signals.”**

Low Output Power

For low output power, attenuator accuracy is the most important characteristic. The lower the output power level, the lower the amplitude accuracy. This is because a combination of several attenuators is needed to achieve higher attenuation, but each attenuator introduces errors.

When you output extremely low amplitude signals, the internally-generated noise of a signal generator becomes critical. The lower the system noise floor, the higher the signal-to-noise ratio (SNR). Lower SNR results in a poor receiver sensitivity measurement.

In addition to the system noise floor, interfering signals are an important source of error for extremely low amplitude signals. It is a common practice to place the DUT in a shielded environment to block the interference signals.

Beyond the Output Range

RF signal generators are capable of outputting as high as +25 dBm and as low as -120 dBm. If you need to go beyond the specified range, you can use an amplifier to increase the output power or an attenuator to decrease it. When you extend the output range of the signal generator, there are two important factors to be aware of.

1. Amplifier gain uncertainty affects the output amplitude level.
2. Attenuator flatness and accuracy performance.



Reduce distortion

To deliver high output power, selectable harmonic filters are used to reduce the level of harmonics, and an ALC circuit corrects the mismatches and frequency response. A high-performance power amplifier with low distortion is most important.

Best Practices for Optimizing Amplitude accuracy

There are several ways to optimize amplitude accuracy while you use an external amplifier, an attenuator, or other passive accessories with a signal generator. A common method is to use a vector network analyzer (VNA) to measure the entire signal path and enter correction values into the signal generator. There are ways you can improve amplitude accuracy by using built-in capabilities of new signal generators.

Using Flatness Correction

User flatness correction allows the adjustment of RF output amplitude to compensate for external losses in cables, switches, or other devices. Using a power meter/sensor to calibrate the measurement system, a table of power level corrections can automatically be created.

The USB power sensor can connect to the signal generator directly. The signal generator works like a power meter and measures the power at the test plane. The correction values can be saved in the signal generator's memory. You can recall and apply the correction values the next time you use the same test configuration. Figure 7 below illustrates the flatness correction setups using a signal generator and a USB power sensor.

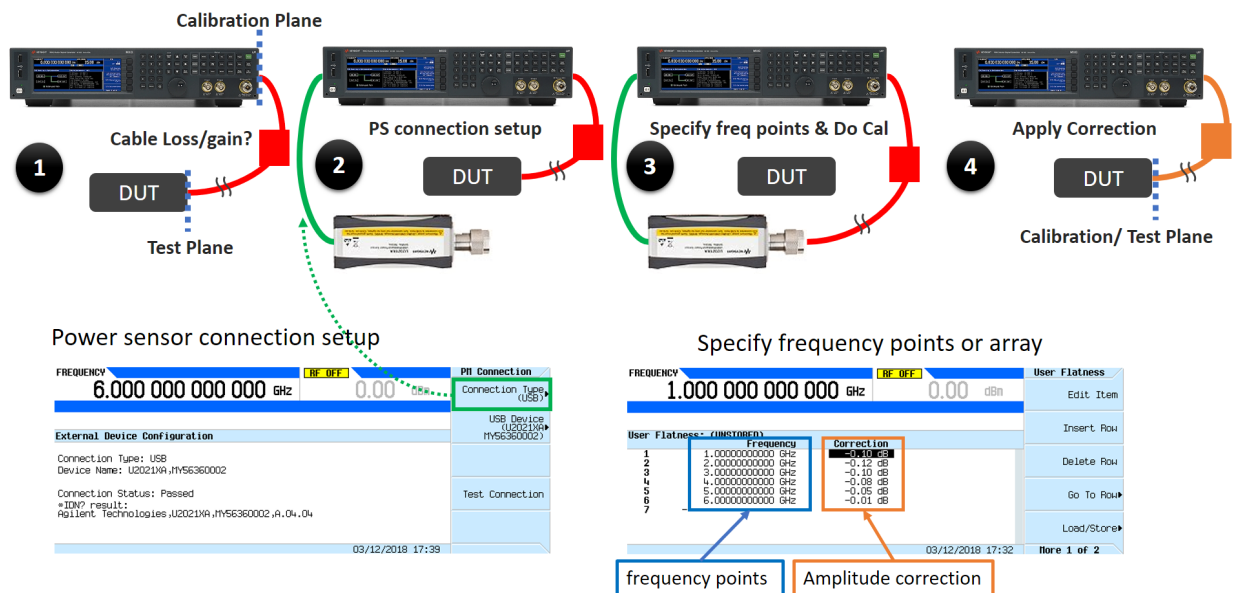


Figure 7. Flatness correction using USB power sensor

Using External Leveling

External leveling lets you move the ALC feedback source closer to the DUT so that it accounts for most of the power uncertainties inherent to the cabling and components in a test setup.

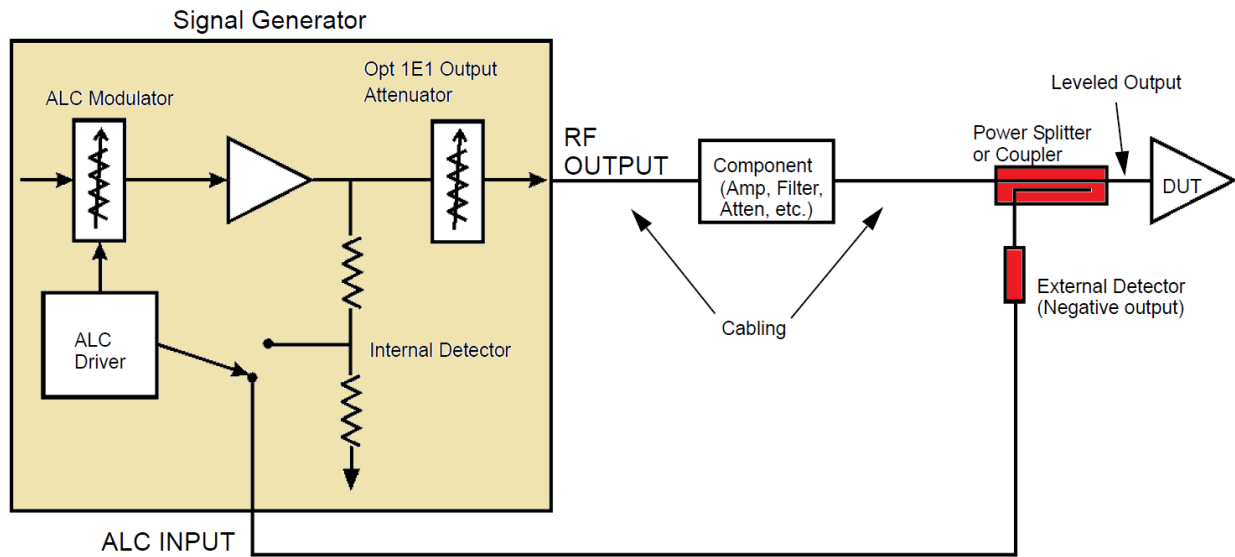


Figure 8. Test Setup for external leveling

As the RF power level at the input of a power coupler/splitter changes, the external detector returns a compensating negative voltage. The ALC circuit uses this negative voltage to level the RF output power by raising or lowering the signal generator's power. This ensures a constant power level at the input of a power coupler/splitter.

Understand, Characterize, and Correct RF Signal Paths

RF signal generators are used for testing RF components, receivers, transmitters, and systems. Amplitude accuracy is frequently a critical factor for RF test systems. This paper outlined RF power basics and why amplitude accuracy is important and offered tools to characterize the signal and correct amplitude flatness.

The best solutions will come from your experience, insight, and creativity, combined with signal generators and measurement software that enable you to generate the signals required to effectively test your DUT.

For more best practices to help you make better measurements, visit the **RF Test blog**. For more information about Keysight signal generators, visit www.keysight.com/find/sg.

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