

# Keysight Technologies

## Making Your Best Power Integrity Measurements

Application Note

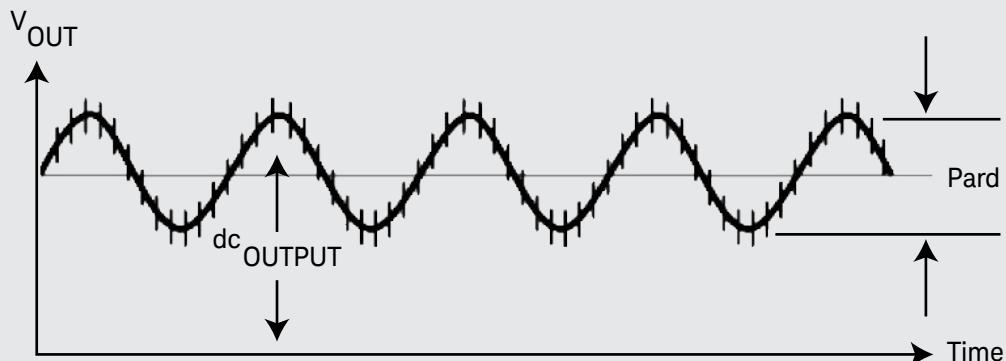
# Introduction

Thanks to the continued fulfillment of Moore's Law, we all enjoy a wide variety of electronic products packed with ever-increasing functionality and features. The explosion of the affordable micro-controller means that more and more devices are experiencing improved performance and richer features by relying on micro-controller controlled operations (ex: household appliances, automobiles, medical devices, wearables, the Internet of Things, smartphones, the cloud). One of the burdens that designers of these products face is providing "clean" power to the devices and circuits in their products. Significant resources of time, people and equipment are dedicated to designing the power distribution networks (PDN) of modern products. Real-time oscilloscopes are commonly used to measure DC power supplies in these products. This application note covers helpful techniques for measuring and analyzing DC power supplies and discusses selection and evaluation of tools for DC power supply measurements.

## PDN's and power integrity

Power integrity (PI) is a broad term used in the electronics industry that refers to the analysis of how effectively power is converted and delivered from the source to the load within a system. The power is delivered through a power distribution network (PDN) that consists of passive components and interconnects from the source to the load including packaging up to the semiconductor. It typically includes measurements from DC to multi-gigahertz. Some common PI measurements are:

- PARD—periodic and random deviation, a term used widely in the industry, is the deviation of the DC output from its average value with all other parameters constant. It is a measure of the undesirable AC and noise components that remain in the DC output after the regulation and filtering circuitry. It is measured in RMS or peak-to-peak, the latter being more common, over a bandwidth range of 20 Hz to 20 MHz. PARD-like variations occurring below 20 Hz are usually called drift.



- Load response—this can refer to a static or transient load, and is a measure of a supply's ability to remain within specified output limits for a predetermined load. This usually includes a measurement of the transient recovery time of the supply to settle within a predefined settling band in response to a load.
- Noise—deviations of the DC supply from its nominal value. This can include random noise, like thermal noise, and spurious signals such as switching coupling in from adjacent circuits or PARD and load response.

## The Problem

The importance of “clean” power has increased proportional to the density and speed of the successive generations of products being designed. DC power rail deviations can be the single biggest source of clock and data jitter in digital systems. A drop in the power supply to a digital device can decrease the propagation delay through gates in that device, resulting in reduced timing margin or even bit failures. To combat this, supply tolerances have shrunk to 5% or less.

As the switching speeds and slew rates of digital devices have increased, so has the probability that switching noise will be induced into the power supply. The resulting noise happens at the bandwidth of the switching current and can easily exceed 1 GHz.

Reduced signal amplitudes in digital systems enable faster switching speeds. Reduced signal amplitudes also create a need for reduced noise margins on power supplies.

Improving efficiency or reducing power consumption is another reason to place tighter tolerances on power supplies. If a supply once had a 10% tolerance and that tolerance is reduced to 5%, the design can experience up to 5% reduction in power consumed.

The challenge facing designers then is to measure ever smaller and faster AC signals riding on top of their DC supplies.

### DC power supply noise

Ideally, there wouldn’t be any noise on your DC power supplies. How did it get there?

There is the simple Gaussian noise on the supply that is a result of unavoidable thermal noise—the electronic noise generated by the thermal agitation of electrons. Typically, this is not the largest source of noise.

The dominant sources of noise on DC power supplies are switching noise from the supply itself and noise induced by the switching currents of devices in the circuit, which create transient current demands. The noise created by the switching events may appear random in time; however, they tend to be coherent with clocks in the system.

Thinking about the noise on the DC supply as being a combination of “signals,” like supply switching noise and switching current noise, being superimposed on the DC supply will make their measurement and analysis easier.

### Measurement challenge

Because of the wide bandwidth of DC power supply noise, individuals measuring this noise often prefer to use an oscilloscope because of its wide bandwidth, ease-of-use and availability. Oscilloscopes can also provide unique insights into the cause of noise, as will be illustrated below.

Real-time, wideband oscilloscopes and their associated probes have noise of their own. This can complicate measuring DC power supply noise if the noise of the oscilloscope and probes is similar in magnitude to the noise of your DC supply.

Dynamic range presents another challenge to measuring DC supply noise. Your supply of interest is at some DC level, and the small AC signals (noise) riding on it that you want to measure are only a tiny fraction of the DC level. The desire is to zoom-in on the AC noise—place the scope in a more sensitive range to observe the details of the noise while also at a lower scope noise level (see sidebar “A brief lesson in scope noise”). Depending on the oscilloscope and probe being used, it may prove impossible to be able to offset them enough to accomplish this.

## Tip 1. Choose the Lowest Noise Oscilloscope Measurement Path

This may seem obvious: If you are about to measure the noise riding on your DC supply, you want the noise of your oscilloscope measurement system to be as small as possible so as to not overshadow your results. Unfortunately, many users stumble here, not knowing they may have even better options available to them. The oscilloscope measurement path consists of the oscilloscope being used and the scope input termination— $50\ \Omega$  or  $1\ M\Omega$ .

For many oscilloscopes, the  $50\ \Omega$  input is a lower-noise path than the  $1\ M\Omega$  path. Figure 1 below shows the baseline noise of the  $50\ \Omega$  input and  $1\ M\Omega$  input of a Keysight DSOS054A high-definition oscilloscope (500 MHz, 4 channels).

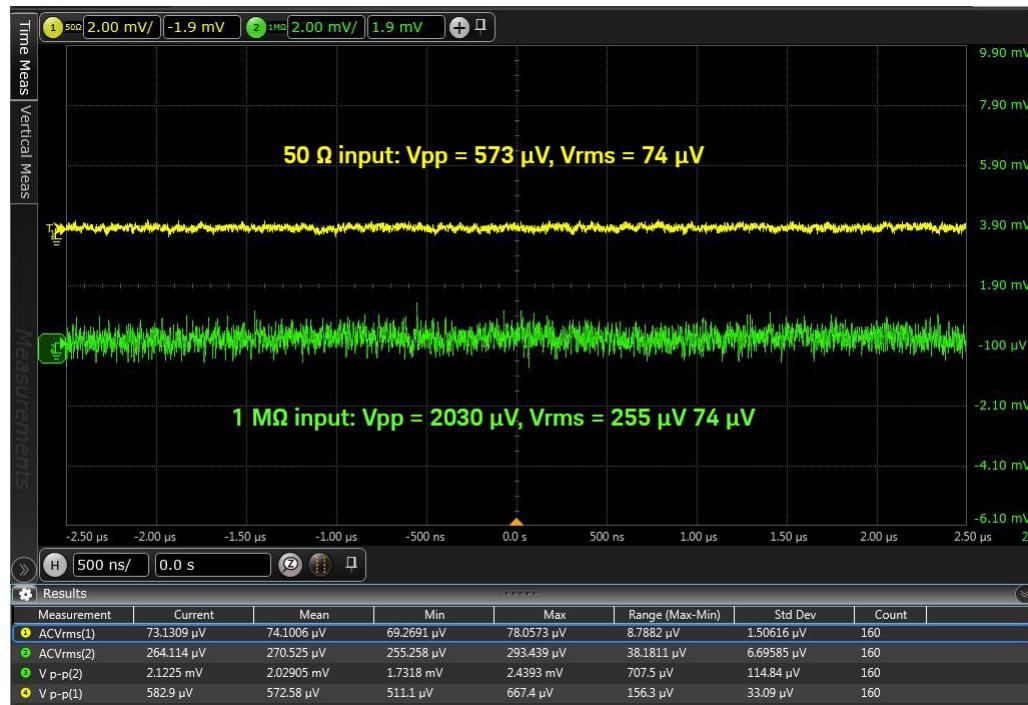


Figure 1. Baseline noise comparison of  $50\ \Omega$  and  $1\ M\Omega$  scope input of a Keysight DSOS054A.

This type of measurement is commonly called a null measurement and is a measure of the baseline noise of your oscilloscope measurement system. It is a sanity check similar to shorting the leads together on a DMM before making a continuity or resistance measurement. It is a good practice to perform a null measurement on your complete oscilloscope measurement system—including probe—so as to be confident that your scope and probe are appropriate for the power supply noise measurements you are about to make. To make a null measurement, simply configure your oscilloscope and probes as you intend to use them when making your supply noise measurement, then short the input to ground (or short the inputs together on a differential probe) and measure the noise.

## Tip 2. Bandwidth Limit to Reduce Measurement System Noise

More bandwidth is better, right? Not always. The noise voltage of an oscilloscope and probe is a function of frequency. By limiting the bandwidth used to only the amount necessary for the given measurement, we can reduce the amount of oscilloscope and probe noise that shows up in the measurement. Consider the measurements shown in Figure 2. For these measurements, we performed the null measurement described above using a Keysight MSOS804A oscilloscope (8 GHz, 10 bit ADC, 20 GSa/s) with a N7020A power rail probe (2 GHz, 1:1 attenuation). The results are summarized in Table 1.

Table 1. Null measurement noise results at various bandwidths

Null measurement		
Bandwidth	Vpp	Vrms
2 GHz	1,040 $\mu$ V	110 $\mu$ V
1 GHz	860 $\mu$ V	90 $\mu$ V
500 MHz	800 $\mu$ V	80 $\mu$ V
20 MHz	460 $\mu$ V	60 $\mu$ V



Figure 2. Baseline noise at various bandwidth limits with the N7020A power rail probe and S-Series oscilloscope.

## Tip 3. Use 1:1 Attenuation to Reduce Measurement System Noise

Oscilloscope probes come in a variety of attenuation ratios. You are probably most familiar with the 10:1 passive probe. One benefit of using a 10:1 probe is that it allows you to measure signals that otherwise would exceed that maximum input to the scope. The down side of attenuation is that the size of the scope noise relative to the size of the signal being measured increases proportional to the attenuation ratio. See the side bar, "A brief lesson in scope noise," for details.

Consider the measurement result shown in Figure 3. Both a 10:1 probe and a 1:1 probe are measuring the same signal, simultaneously—a 20 MHz 50 mV p-p sine wave. The only difference between the two measurements is the attenuation ratio. The 1:1 measurement is 52 mV p-p while the 10:1 measurement is 65 mV p-p. The higher attenuation ratio overstates the measurement by at least 25% due to the reduced signal-to-noise ratio resulting from the higher attenuation ratio. From this, we can see that when measuring small signals where oscilloscope and probe noise can be problematic, it is best to use as small an attenuation ratio as possible or available.

### A brief lesson in scope noise

Refer to the block diagram below. There are two primary sources of noise in an oscilloscope and probe system. The input amplifier and buffer circuits in the scope contribute some noise, and the probe amplifier of an active probe has its own noise.

Scopes use an attenuator to vary the vertical scale factor. The scope's noise arises after this attenuation occurs. When the attenuator is set to something greater than 1:1 (the most sensitive scope hardware ranges) the noise will appear to be larger relative to the signal at the input connector of the scope. For example, consider a scope that has a basic sensitivity of 5 mV/division with no attenuation inserted (1:1). For this example, we will say this scope has a noise floor of 500  $\mu$ Vrms at 5 mV/division. If we change the sensitivity to 50 mV/division the scope inserts a 10:1 attenuation in series with the input. The noise then appears as if it were 5 mVrms relative to the input ( $500 \mu$ V\*10). The same thing happens when a probe with attenuation is attached to the scope. The scope noise appears larger relative to the signal at the input to the probe by the amount of the attenuation.

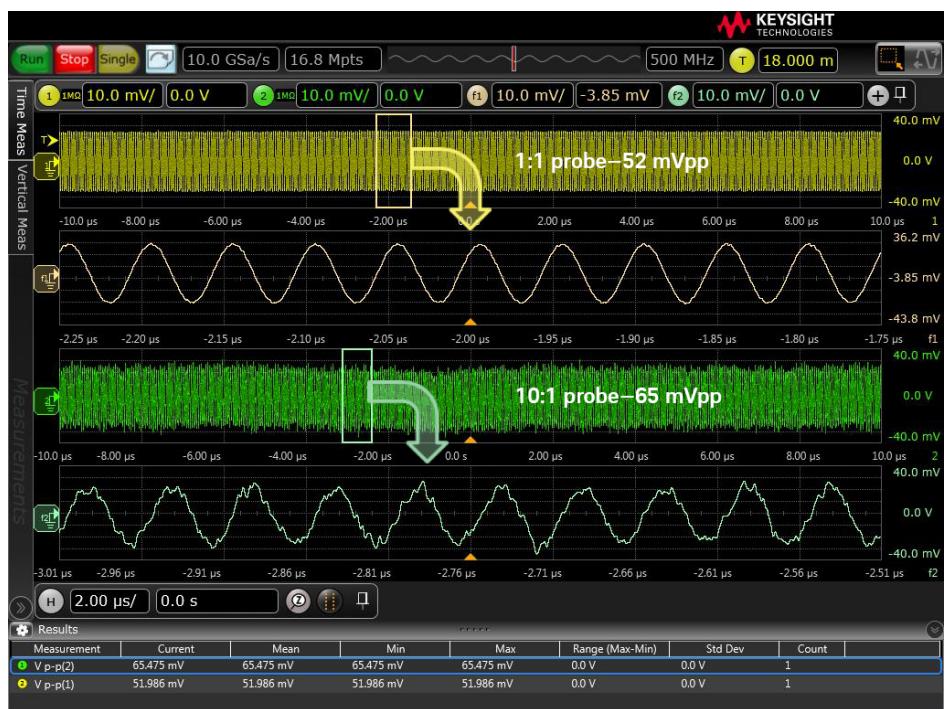
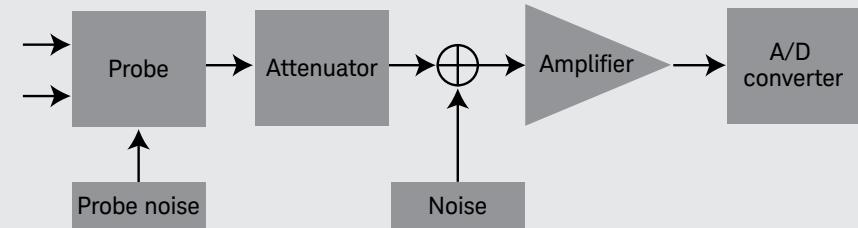


Figure 3. Noise comparison of a 1:1 and 10:1 probe measuring a 50 mVpp sine wave.

## Tip 4. Use Probe Offset to Increase Dynamic Range

Probe offset is a feature of active probes that enables the user to remove DC content from signals being measured. This is especially useful when there is a small AC signal riding on a DC signal, as is the case when measuring power rail noise. Figure 4 shows the noise measurement results on a 1.5 V supply with and without the use of probe offset. The difference is due to the attenuation applied by the oscilloscope at the larger V/div settings.

A word of caution: most active probes that provide offset also have large, non-1:1 attenuation ratios, which works against the goal of reducing oscilloscope measurement system noise. There are some probes available, such as the Keysight N7020A power rail probe, which provide offset capabilities and a 1:1 attenuation ratio. In the case of the N7020A, the offset range is  $\pm 24$  V.

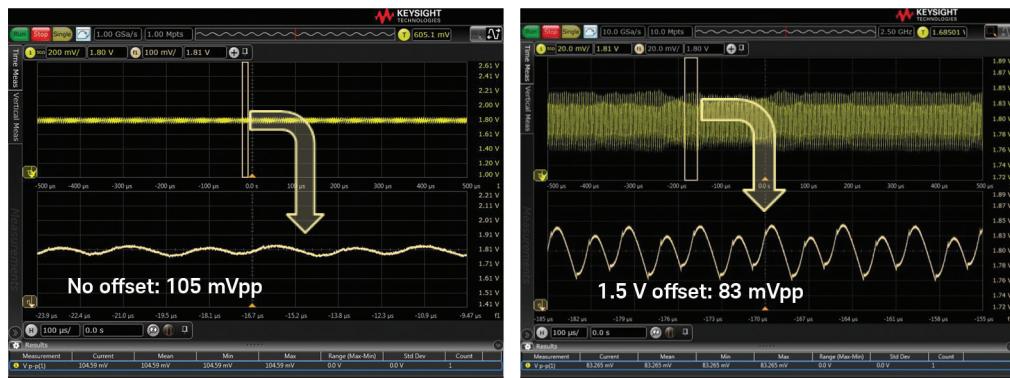


Figure 4. Measuring the noise on a 1.5 V DC supply with no offset and with the use of probe offset.

## Tip 5. Understand the Limitations of DC Blocks

A DC block is a specialized large value capacitor that can be placed in series with the signal before the input to the oscilloscope. The benefit of a DC block is that it blocks, or removes, the large DC component so the scope can be placed in a more sensitive range—same measurement principal as mentioned above with regards to the use of probe offset. The limitation of a DC block is that it blocks low frequency AC content, such as drift or supply compression, in addition to the DC content. Figure 5 shows measurement of a 5 V DC supply using a DC block compared to using the N7020A power rail probe with probe offset. From this example, you can see that measurements made with a DC block would exclude the low frequency supply drift and could be misleading. Additionally, because the DC information is blocked, it is not included in the measurement, so it cannot be determined from the scope what DC value the supply noise is riding on. Obtaining this information would require the additional use of a DMM or similar measurement. Illustrating this point, Figure 6 compares measurements made on a 1.5 V DDR3 supply using a DC block and an N7020A power rail probe with offset.

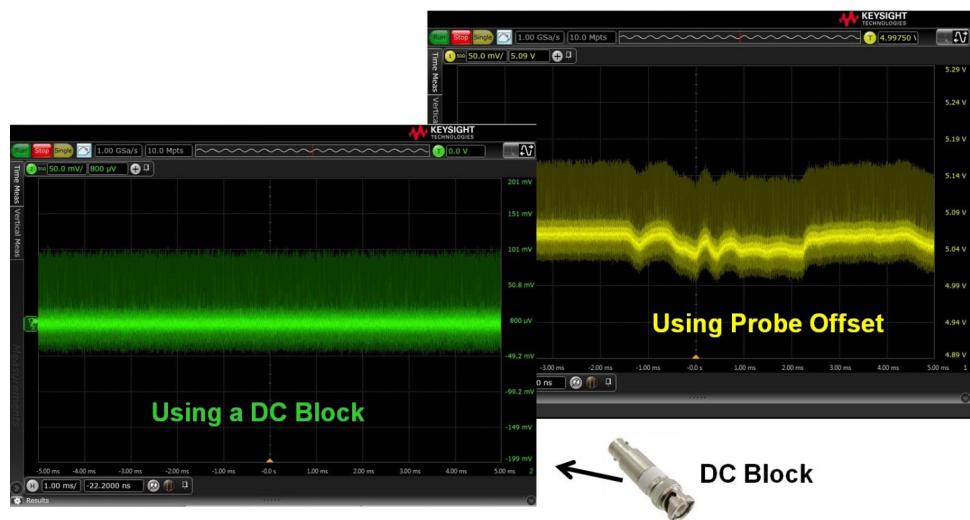


Figure 5. Illustrating the loss of low frequency content, such as supply drift or compression, when using DC block to measure DC supply noise.

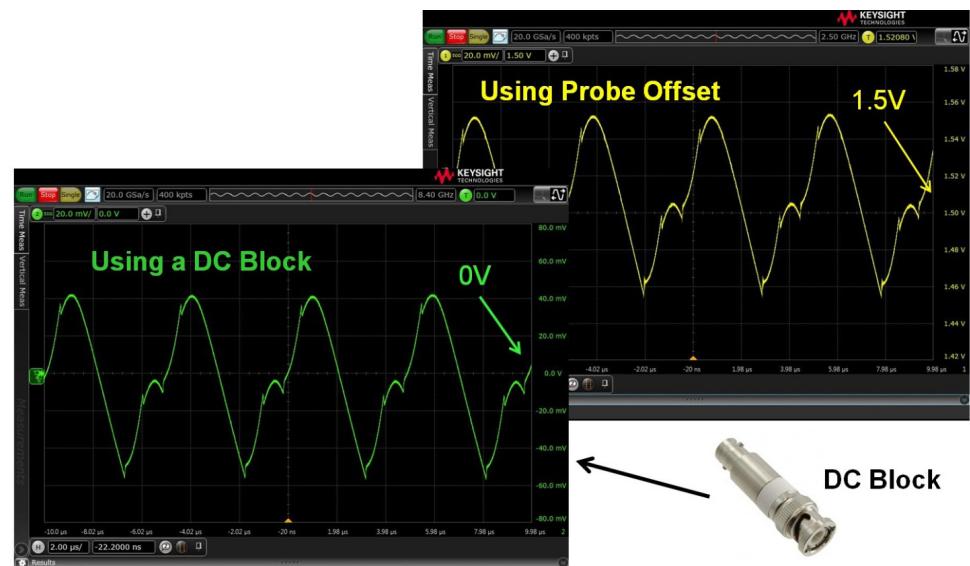


Figure 6. Illustrating the loss of DC content from the oscilloscope measurements when using a DC block. Additional steps, such as measuring the DC value with a DMM are thus needed to understand what DC value the noise is riding on.

## Tip 6. Minimize Oscilloscope and Probe Loading of the Supply

Any time an oscilloscope probes a system, it becomes part of that system due to the electrical contact being made, and this changes the behavior of the system being measured. This is referred to as loading, and the goal is to minimize it as much as possible. In the context of measuring DC supplies, a common source of excessive loading happens when a user attaches a  $50\ \Omega$  coax to the supply and the  $50\ \Omega$  input of the scope. The user is well meaning when they do this because they have chosen the  $50\ \Omega$  scope input for its low noise and the coaxial cable for its shielding and low ground inductance, but the  $50\ \Omega$  termination of the scope will load the supply  $20\ \text{mA}/\text{V}$ . For example, a  $3.3\ \text{V}$  rail probed this way will experience a  $66\ \text{mA}$  load from the oscilloscope. A better approach would be to use a probe like the N7020A power rail probe, which has a DC input impedance of  $50\ \text{k}\Omega$ . Figure 7 shows a comparison of these two approaches. First, the supply was measured with a DMM, and the result was  $3.31\ \text{V}$ . Next, the supply was probed with the N7020A power rail probe, and there was no change to the supply—still  $3.31\ \text{V}$ . Finally, the supply was probed by connecting directly to the  $50\ \Omega$  scope input, and the supply dropped from  $3.31\ \text{V}$  to  $3.25\ \text{V}$ . Not all supplies will be adversely affected in this way. Some supplies will have enough excess capacity to drive this additional load while other supplies may not have enough excess capacity to drive this load, or this additional load may affect the behavior of the PMIC (power management IC) in systems that contain one, so beware.

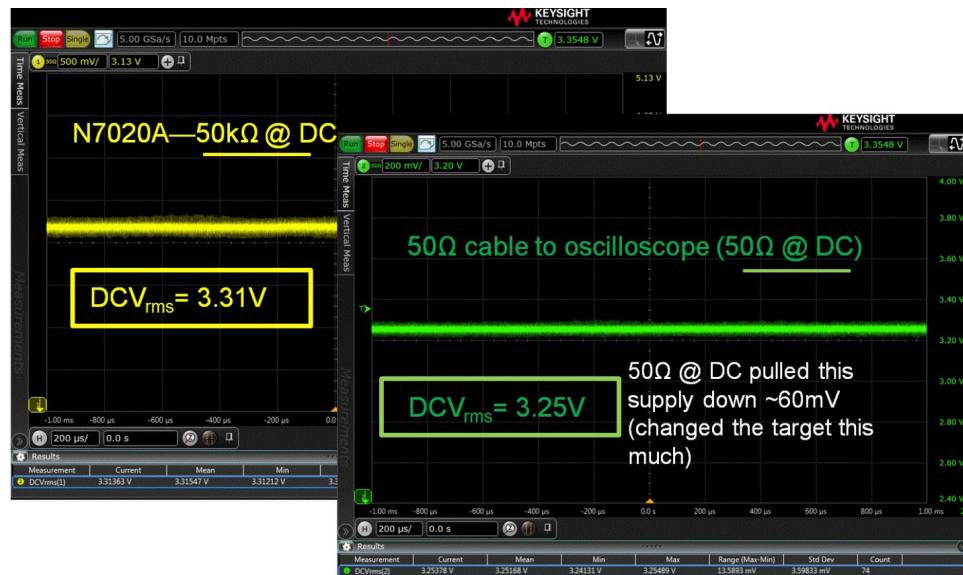


Figure 7. The effects of probe loading on a supply. A  $3.3\ \text{V}$  supply probed with the N7020A power rail probe with its  $50\ \text{k}\Omega$  impedance at DC and the same supply probed by direct connection to the  $50\ \Omega$  input of the scope.

## Tip 7. Use the Frequency Domain for Analysis

Using an oscilloscope's FFT capabilities to view signals in the frequency domain can be helpful in identifying sources that contribute to the noise on a supply.

In this example we have a switching DC/DC converter converting 5 V to 3.3 V. The switcher operates at 2.8 MHz. Elsewhere on the PC board there is a 10 MHz clock and 125 MHz clock running. We will make use of the previous Tips and use the 1:1 attenuation ratio of Keysight's N7020A power rail probe, apply 3.3 V of probe offset and limit the bandwidth to 500 MHz to measure the noise on the 3.3 V supply. The probe is connected to a Keysight S-Series oscilloscope. Figure 8 shows the results of this measurement in the time domain. From the time domain view, we can see a signal of ~360 ns period, which is the remnants of the 2.8 MHz, but it is not obvious that the 10 MHz and 125 MHz clocks are creating noise on the 3.3 V supply.

Figure 9 shows the same data in the frequency domain. Here, using FFTs, we have set up two different windows covering two different frequency ranges, and we can clearly see a peak at 2.8 MHz, which correlates to the frequency of the switching converter and spikes at 10 MHz and 125 MHz, representing noise coupling in from the two clocks. Viewing the noise in the frequency domain in addition to the time domain has given us additional insight into the source of the noise.

### FFT considerations in scopes

An oscilloscope will capture a finite amount of time on each trigger based on the amount of memory and the sampling rate. The FFT cannot "see" frequencies in the incoming signal that are below the inverse of the scope's time capture window. The lowest frequency that can be analyzed by the FFT is  $1/[1/(sampling\ rate) \times (memory\ depth)]$ . To see a suspect source in the FFT, be sure to set the depth to capture enough samples. For example, if your switching supply operates at 33 kHz, you would need to capture  $1/(33\ kHz)$  or 30 microseconds of signal activity in order to see it in the FFT. For a sampling rate of 20 GSa/s, this would require 600,000 points in memory. The FFT typically operates only on the data that is on the screen.

## Tip 7. Use the Frequency Domain for Analysis (Continued)

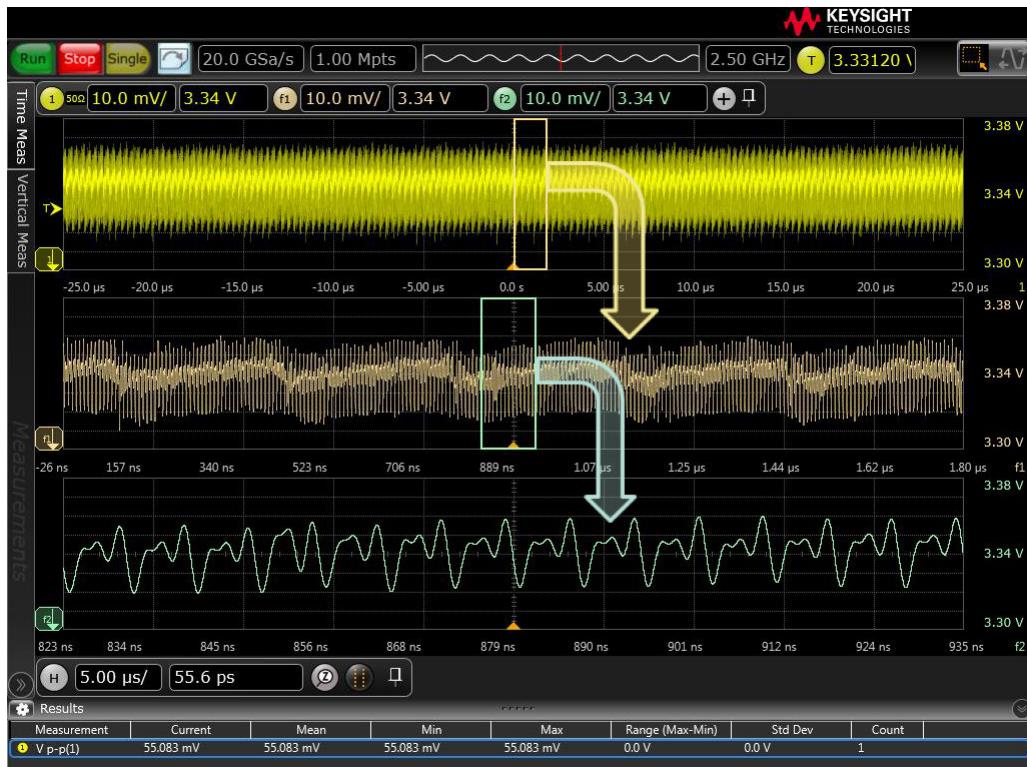


Figure 8. Time domain view of 3.3 V DC supply. Remnants from 2.8 MHz switcher can be seen in the middle, zoomed-in, trace. It may not be obvious that the 10 MHz and 125 MHz clocks are sources of noise in the bottom, zoomed-in, trace.

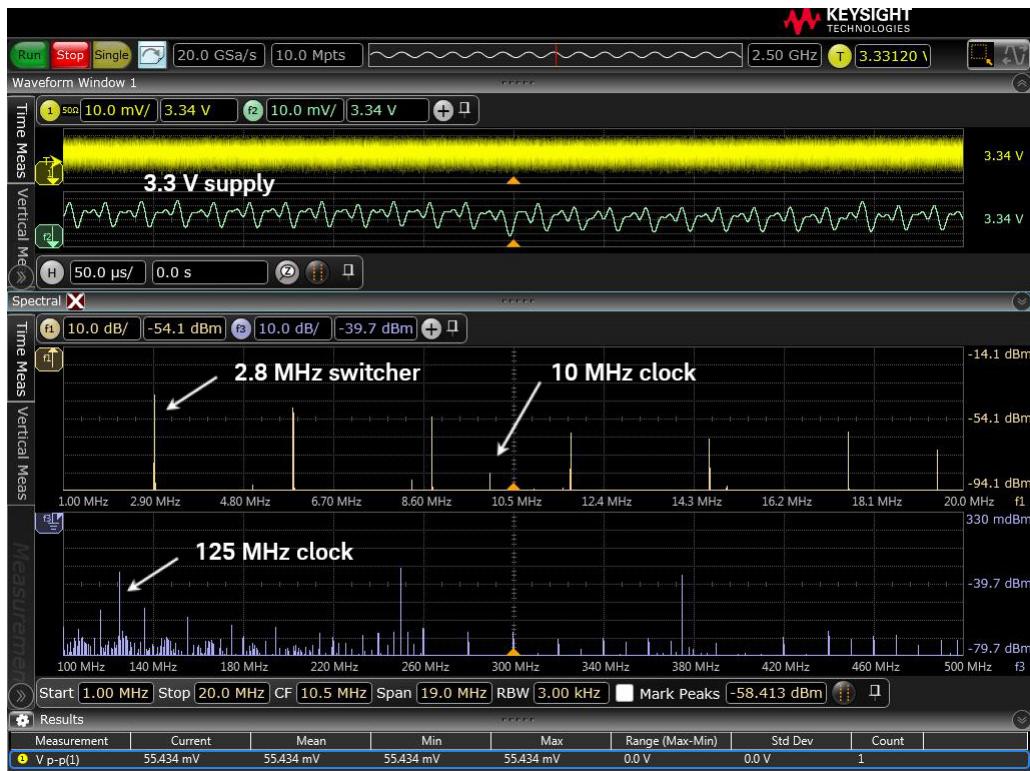


Figure 9. Making use of FFT's to confirm that noise from the 2.8 MHz switcher and 10 MHz and 125 MHz clocks are on the 3.3 V supply.

## Tip 8. Use Triggering to View and Measure Signal Components in the Supply Noise

Triggering can help to visualize and measure components of supply noise that are coupling into the supply from, and are phase-coherent to, other elements in the system. To demonstrate this, we will use the same measurement system as Tip 5 (N7020A probe with offset and bandwidth limiting connected to an S-Series oscilloscope) and target with a 2.8 MHz switching regulator delivering 3.3 V and a 10 MHz clock in the system. Figure 10 shows the measurement results. We can see the 2.8 MHz clock and its harmonics in the FFT along with a spike at 10 MHz that represents the clock. From this we know that the clock is coupling noise into the 3.3 V supply. Now we will trigger on the clock and turn on averaging. By doing this, averaging will eliminate all of the random noise and other signal components that are not coherent with the clock. The end result will be those portions of the supply noise that are correlated to the 10 MHz clock. This is illustrated in Figure 11.

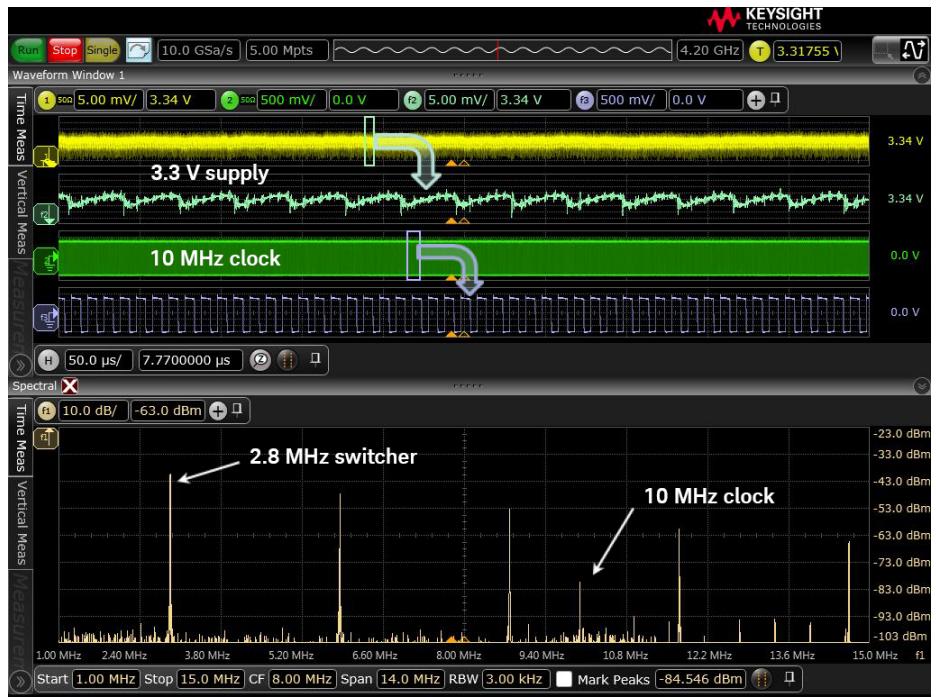


Figure 10. Measurement results of a 3.3 V supply and a 10 MHz clock in the target system. Using an FFT, we verify that the 10 MHz clock is creating noise on the 3.3 V supply.



Figure 11. Triggering on the 10 MHz clock and enabling averaging removes all random noise and signals that are not coherent with the clock. The resulting view is of the noise on the supply that is related to the 10 MHz clock.

## Tip 9. Have Enough Bandwidth

In Tip 2, we discussed the value of limiting the bandwidth of the measurement to only that needed to minimize noise for the task at hand. A similar but opposite pitfall can await users who do not have enough bandwidth for the task—they may miss high frequency noise and transients that can adversely affect clocks and data in their systems. Switching currents from things like clocks and data can create high-frequency supply noise. Likewise, these same devices are susceptible to this high-frequency supply noise. In many modern systems, this noise can require  $> 1$  GHz of bandwidth to observe, so choosing a probe with enough bandwidth is important. Figure 12 shows a side-by-side comparison using a common 35 MHz 1:1 probe and the 2 GHz N7020A probe measuring the noise on a 1.5 V DDR3 memory supply. This illustrates the ability of the higher bandwidth probe to capture the high-frequency noise that can be troublesome in many modern digital systems.

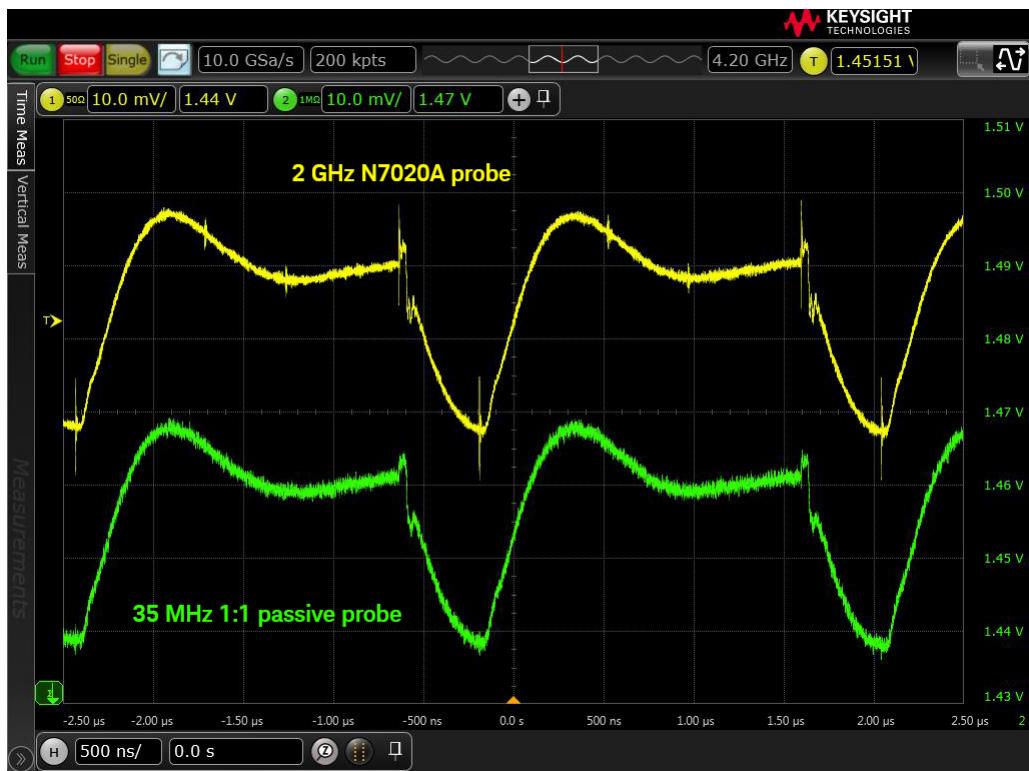


Figure 12. Comparison of a 35 MHz 1:1 passive probe and the 2 GHz N7020A power rail probe measuring the noise on a 1.5 V DDR3 memory supply. The lower bandwidth probe misses the high frequency noise and spikes that are troublesome in high-speed digital system.

## Tip 10. The N7020A Power Rail Probe

The previously mentioned tips will help to minimize oscilloscope measurement system noise when measuring power supply noise and help to identify sources of noise in the power supply. These techniques work even better when they are used with specialized tools that are designed to measure power supply noise. For example, the N7020A power rail probe, shown in Figure 13 (and used in some of the previous examples), is the first probe that is specifically designed for measuring noise on DC power supplies. This probe has a 1:1 attenuation ratio (Tip 3),  $\pm 24$  V of offset (Tip 4), and connects to the  $50\ \Omega$  scope input (Tip 1). It has 2 GHz bandwidth to capture the high-frequency noise and transients that can cause clock and data jitter (Tip 7). When used with an oscilloscope like the Keysight Infiniium S-Series, it can be bandwidth-limited (Tip 2) to reduce noise when the full 2 GHz bandwidth is not needed.

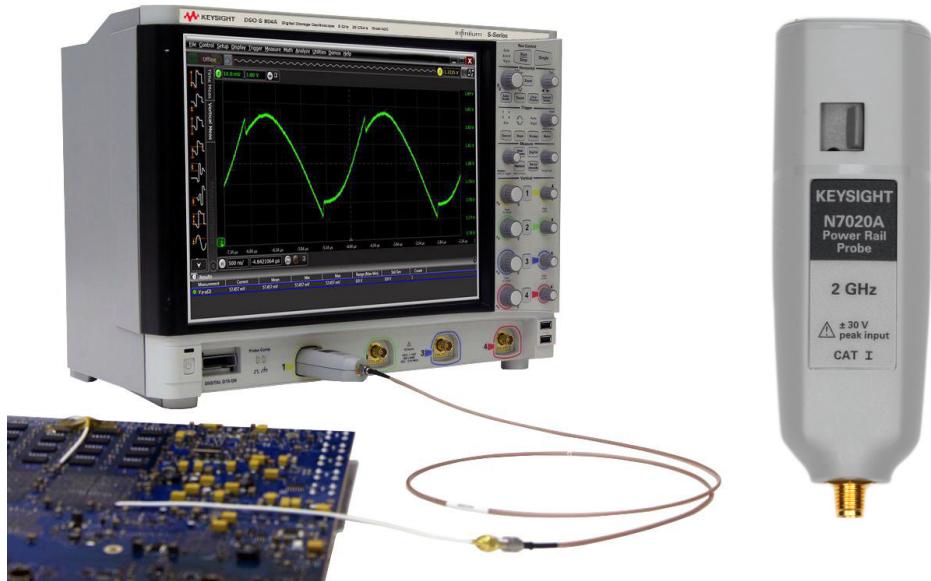


Figure 13. N7020A power rail probe (R) was designed specifically for measuring power supply noise and can be used with a variety of Keysight oscilloscopes including the S-Series high-definition oscilloscopes (L).

## Characteristics and Specifications: N7020A Power Rail Probe

Description	
(Tip 9) Probe bandwidth (-3 dB)	2 GHz
(Tip 3) Attenuation ratio	1:1
(Tip 4) Offset range	$\pm 24$ V
(Tip 6) Input impedance at DC	$50 \text{ k}\Omega \pm 2\%$
Active signal range	$\pm 850$ mV about offset voltage
Probe noise	10% increase to the noise of the connected oscilloscope
Probe type	Single-ended
Included accessories	N7021A – Coaxial probe head N7022A – Main cable
Maximum non-destructive input voltage	$\pm 30$ V (DC + peak AC)
(Tip 1) Output impedance	$50 \Omega$
Ambient operating temperature	Probe pod: 0 to 40°C N7021A main cable, N7022A coaxial probe head: 0 to 85°C

### Summary of Tips and Techniques

**Tip 1:** Use the  $50 \Omega$  scope input – it usually has the lowest noise, and begin your power supply noise measurements with a null measurement so you know how much noise your oscilloscope measurement system has.

**Tip 2:** Don't use more bandwidth than necessary.

**Tip 3:** Stick with smaller attenuation ratio probes when possible – ideally a 1:1 probe.

**Tip 4:** Use probe offset to zoom-in on the signal.

**Tip 5:** If you choose to use a dc block, use it wisely.

**Tip 6:** Beware of loading your supply through the scope's  $50 \Omega$  termination ( $50 \Omega$  at dc).

**Tip 7:** Use FFT for analytical insight.

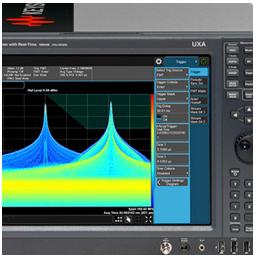
**Tip 8:** Trigger on suspect sources of noise and use averaging to eliminate uncorrelated noise.

**Tip 9:** Use enough bandwidth to capture troublesome transients and noise.

**Tip 10:** Make use of the N7020A power rail probe.

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