How to measure LDO noise

Texas Instruments

Kyle Van Renterghem
System Engineer
LDOs and Supervisors
Texas Instruments

Because measuring noise can be a difficult task, pay particular attention to the hardware setup and analyzer configuration before taking any measurements.

Low-dropout regulators (LDOs) are used to regulate a higher input voltage down to a lower output voltage. Unlike switching regulators, LDOs are easy to implement and do not create high levels of switching noise. Many applications use a switching regulator to efficiently convert one voltage to another, and then use an LDO to filter and clean up the voltage before it goes to the actual load device.

Device noise is a physical phenomenon due to the resistors and transistors in a circuit. The bandgap is the largest internal noise source in an LDO.[1] This explains why low-noise LDOs have a noise reduction pin which filters the bandgap noise using an external capacitor, referred to as the NR cap. The customer attaches a capacitor to this pin which creates a low-pass filter in conjunction with a large internal resistor. While the NR capacitor offers bandgap noise filtering, it also slows the rise of the bandgap (and therefore the output voltage) during startup.

The input voltage, output capacitor, and load current have little effect upon the LDO's output noise. The noise can be reduced by connecting a capacitor from the LDO's output to the LDO's feedback node (assuming the device is not being used in a unity-gain configuration). [2] This capacitor is known as a feed-forward cap, CFF. At high frequencies this capacitor looks more like a short, thereby reducing the LDO's closed-loop gain, preventing the error amplifier from amplifying high-frequency noise. Like the noise reduction capacitor, a CFF increases the start up time.

Noise is often shown in a datasheet in two different ways: 1) showing a plot of the spectral noise density (in μV/√ Hz) versus frequency; and 2) including a line in the electrical characteristics table stating the root-mean-square (RMS) noise voltage in μVRMS. The RMS noise voltage equals the spectral noise density integrated over a specific frequency range (often 10 Hz-100 kHz or 100 Hz-100 kHz). This gives a quick way of comparing the noise performance of various LDOs, assuming the frequency range aligns with your application's needs. Most datasheets report RMS noise with the LDO in a unity-gain configuration because the output noise is typically proportional to the gain. So if you know the unity-gain RMS noise voltage and the gain needed for your output voltage, you can quickly estimate what the RMS noise voltage for your application will be. When comparing various LDOs, it is important to compare the RMS noise at the actual output voltage you plan to use in your application.

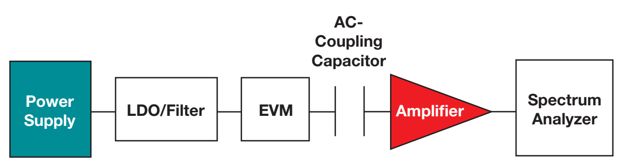

Figure 1. Block diagram of noise measurement setup.

Noise measurement block diagram

The block diagram in **Figure 1** represents the noise measurement setup, which we will discuss later in more detail. The power supply powers the evaluation module (EVM), which is the printed circuit board (PCB) on which the LDO is placed.

The LDO or filter before that is optional and reduces the noise coming from the power supply. The AC-coupling capacitor only allows the AC signal to be transmitted to the subsequent circuitry. The amplifier is also optional and allows the spectrum analyzer to measure the signal more easily. The amplifier is only needed if the noise floor (noise measured without an EVM connected) is too high relative to the LDO's noise output.

Be sure that your resolution bandwidth (RBW), which sets the width of the spectrum analyzer's bandpass filter, is at least a decade smaller than your measured frequency. The smaller the RBW, the more resolution you will see on specific frequency content; however, a smaller RBW will also increase the measurement time. Many analyzers have an AUTO feature that will increase the RBW as frequency is increased to reduce the total measurement time. You may need to set the minimum or maximum RBW to use this feature effectively. The video bandwidth (VBW) sets the amount of smoothing shown on the screen and it usually should be set equal to the RBW.

Finally, since we are measuring noise, who's magnitude fluctuates due to noise's random properties, it is important to use the spectrum analyzer's built-in averaging function, which will make multiple measurements of each point and average the results. Note this is not a rolling average, which averages adjacent points, but an average of multiple measurements at each frequency. As a general rule, we usually set the sample average somewhere between 25 and 50.

Noise floor

All measuring equipment has a finite resolution. For a spectrum analyzer, this limitation is often referred to as the noise floor. Any signal below the noise floor cannot be resolved by the analyzer. If the noise of the LDO is close to the noise floor of the analyzer, you will need to gain up the LDO's output in order to properly measure the LDO's output noise. Keep in mind that the noise density with multiple noise sources is calculated by taking the root-sum-square of the noise sources (1):

$$\text{Noise density} = \sqrt{x_1^{\,2} + x_2^{\,2} + \ldots + x_n^{\,2}} \qquad (1)$$

There are other noise sources that need to be considered when making noise measurements, including noise internal to the spectrum analyzer as well as external noise sources present in the lab where the measurement is taking place. However, you can lump all these noise sources together, which becomes the effective noise floor, NNF. This is the lowest noise measurable on your equipment in your lab.

To find the noise floor for your measurement, mimic your actual setup as closely as possible without actually inserting the device to be tested. Once you have the noise floor of the test setup, compare that to the expected output noise of the device under test, NDUT, to ensure that you can measure it properly. As a general rule of thumb, the noise density of the measured device should be ten times larger than the noise floor of the setup. This will keep the contribution of the noise floor to your measurement to about 0.5%. Equations 2 and 3 are used for determining the percent error due to the noise floor, so you can determine what is acceptable for your situation.

$$\text{If } N_{OUT} = x \bullet N_{NF} \qquad (2)$$

where N_{OUT} is the noise density of the LDO, N_{NF} is the noise floor, and x is the proportion of $\dfrac{N_{OUT}}{N_{NF}}$

$$\begin{array}{l}\text{The percent}\\ \text{error due to}\\ \text{the noise floor}\end{array} = \left(\frac{\sqrt{x^2+1}}{x} - 1\right) \bullet 100\% \qquad (3)$$

Amplifier

If the noise floor of your spectrum analyzer is too high and causes an unacceptable amount of error in your measurement, you can do one of two things: 1) buy a better spectrum analyzer; or 2) buy a low-noise, high-speed amplifier and use it to create a non-inverting gain circuit. Option two may take more time to implement correctly. You have to choose the right operational amplifier (op amp), layout a board, and have that board fabricated and assembled. However, it will be significantly less expensive than buying a piece of high-performance test equipment.

If you decide to use an amplifier, make sure that the gain bandwidth product (GBP) is suitable for your needs. Ideally you want the gain to be flat over the range of frequencies where you'll be measuring the output noise. For example, if you need a gain of 40 dB (100 V/V) to get far enough above the noise floor of your spectrum analyzer, and you want to measure the noise out to 10 MHz, your op amp should have a GBP of at least 1 GHz. If you can obtain such an amplifier, you can simply divide your measured results by its gain. If, on the other hand, your amplifier exhibits high-frequency rolloff, you can measure its gain versus frequency, and then divide your measurement at each point by the amplifier's gain at that frequency.

The op amp's input-referred noise should be as low as possible, as this noise will be amplified by the circuit's gain. Be careful not to let the self-generated noise of the op amp obscure the signal from the LDO as this would defeat the purpose of the amplifier. Another noise contributor is the resistors used to set the gain of the non-inverting amplifier. Resistors produce thermal noise that is proportional to the square root of their resistance, so choose the smallest resistance values that will not overload the amplifier (remember that the amplifier must also drive the input impedance of the spectrum analyzer).

AC-coupling capacitor

Most spectrum analyzers have input terminals that are 50 Ω terminated and cannot sink much current. To keep from damaging them, the impedance of the input terminal you need to increase. Some manufacturers offer high-impedance active probes; however, these will introduce their own noise into the measurement since they are active components. A better way to create a high-impedance input is to use an AC-coupling capacitor. Usually capacitors are used in a bypass configuration with one terminal connected to the signal of interest and the other terminal connected to ground. Assuming an ideal capacitor with infinite capacitance, in a bypass configuration the DC signal passes through while the AC signal is shorted to ground. However, if we connect one terminal of the capacitor to the output of the LDO and the other terminal to where we make our measurement, the capacitor will block the DC signal while allowing the AC signal to pass through, thus the name AC-coupling capacitor. In our case the DC is the nominal output voltage and the AC signal is the noise voltage, which is what we want to measure.

Since the AC-coupling capacitor has a finite capacitance, it creates a high-pass filter that attenuates signals below its cutoff frequency, fc. The cutoff frequency is inversely proportional to the product of the coupling capacitance and the resistance of the spectrum analyzer's input terminal. Since the impedance of the spectrum analyzer is a fixed value, usually 50 Ω, the capacitance of the AC-coupling capacitor determines how low of a frequency can be accurately measured. Equation 4 can be used for calculating the capacitance of the AC-coupling capacitor.

$$C_{AC} = \frac{1}{2\pi R_{IN} f_c} \tag{4}$$

Since the cutoff frequency is the point where the filter has already started attenuating the signal by 3 dB, select a cutoff frequency that is approximately an order of magnitude lower than the lowest frequency you will be measuring. As an example, if you want to accurately measure down to 10 Hz with an analyzer with a 50 Ω input terminal, you will need approximately 3 mF of capacitance. Remember to account for capacitor tolerances, voltage derating, and even temperature derating, if your testing will be performed at a temperature other than room temperature. **Figure 2** shows one of our first AC-coupling caps made to measure down to 10 Hz. We simply soldered a bunch of caps in parallel onto a protoboard and then soldered a wire to each end. This works, however, when measuring very low-noise LDOs, environmental noise can become an issue.

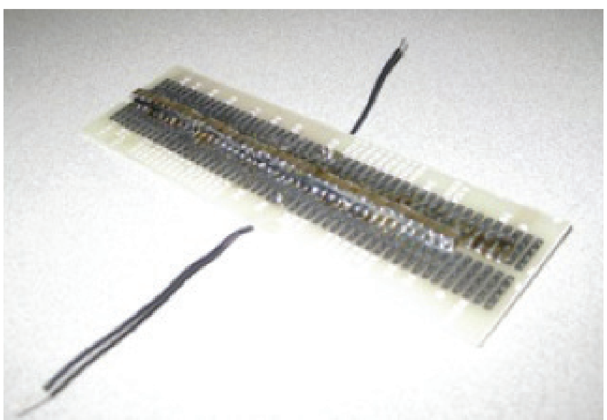

Figure 2. *Our first unshielded 4000 μF AC-coupling capacitor for making noise measurements.*

Figure 3 shows an AC-coupling capacitor we made later that was shielded from environmental noise and used subminiature version A (SMA) connectors so all connections can be made using shielded cables. This helped to minimize any noise pickup that was not coming from the device being measured.

Figure 3. *Our shielded 5100 uF AC-coupling cap which is used for making low noise measurements.*

Power supplies

One way for noise to sneak into your measurement is through the power supply. This includes both the power supply for the LDO and the power supply for any amplifiers used to gain up the LDO's output. If available, use batteries to power both the LDO and any gain circuitry; however, this can be a challenge with high-current LDOs. The battery voltage may require the voltage to be stepped down to the desired supply voltage for the measurement. Benchtop power supplies are convenient because their outputs can be easily adjusted and they don't run out of charge; however, they tend to be rather noisy.

The output of most benchtop power supplies have large spikes in the spectral noise density at the line cycle frequency (typically 50 or 60 Hz) and the switching frequency of the internal converter. Some bench top power supplies operate as linear supplies, but the majority of most modern benchtop supplies contain switching converters and should not be used without addressing the additional noise spikes at the switching frequency and its harmonics.

There are two ways to reduce power supply noise. The first is to use brute-force passive filtering: you simply build a low-pass pi filter with a cutoff frequency below the line cycle frequency. Such a filter will be very large in physical size due to the large value inductors and capacitors. The second approach for filtering supply noise is to use a low-noise, high-power supply rejection ratio (PSRR) LDO as a filter. This results in a much smaller and cheaper solution. Note that many LDOs lack high levels of PSRR at higher frequencies which is where many switching regulators operate.[3] The TPS7A47xx family of devices may be a good choice for filtering high-frequency switching noise due to its low output noise and wide-bandwidth PSRR. If a suitable LDO cannot be found, use a small LC filter to filter the switching noise.

Shielding

No unshielded environment is free of environmental noise. This noise can appear at various points in the measurement setup. One area most likely to pick up environmental noise is the cabling being used to make the measurements. The wires connecting the positive and negative terminals of any supply or measurement line are extremely susceptible to noise pickup as they create large inductive loops. Magnetic fields present in the measurement environment can induce undesired high-frequency currents in these inductive loops. To minimize these induced currents and the noise associated with them, use shielded cables and either Bayonet Neill-Concelman (BNC) or SMA connectors whenever feasible.

If shielded cables are not available, keep the wires divide as short as possible and twist the positive and negative wires together to minimize the inductive loop they create. Another good practice is to put the device being measured and any other boards into a grounded metal box. This box acts as a shield for the boards used in making the measurement, much like the shielding on shielded cables reduces the noise picked up by the wires. **Figure 4** shows an example of a test setup in a shielding box (with the top open); note the foam on the bottom which prevents any shorts to ground.

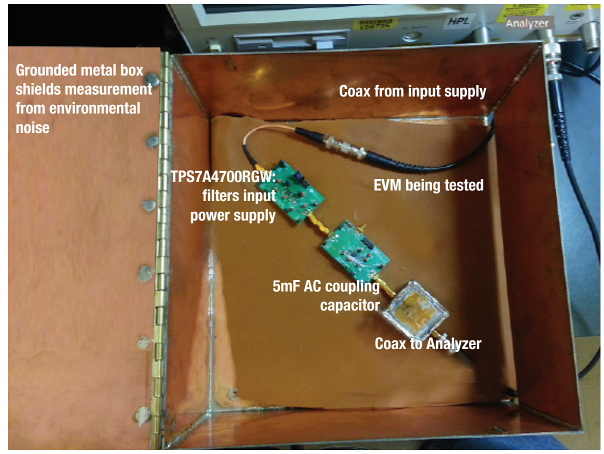

Figure 4. *Test setup in shielded box.*

Loading the LDO

The last noise source to consider is the one associated with the load. For a lot of automated testing, electronic loads are used because they are easily configurable to any value. However, when measuring noise always use resistive loads. Electronic loads generate their own noise profile due to the active circuitry they contain, and their use will negatively affect the measurement.

What to do with all this data?

Most spectrum analyzers record the measured noise in dBμV/√Hz. You will need to convert these values into μV/√Hz. If an amplifier is being used, these values by the amplifier gain, in V/V. After doing this for all the measured data points, you can graph that data versus frequency to generate the spectral noise density plot as shown in many LDO datasheets. Equation 5 shows how to convert from dBμV/√Hz to μV/√Hz.

$$\frac{\mu V}{\sqrt{Hz}} = 10^{\left(\frac{dB\mu V}{\sqrt{Hz}} / 20\right)} \tag{5}$$

Once you have the spectral density in µV/√Hz, you can calculate the RMS noise by calculating the area under the graph across the bandwidth of interest (industry standards are 10 Hz-100 kHz and 100 Hz-100 kHz). To calculate this area, integrate the noise across the chosen bandwidth. If you have your data in a spreedsheet and have converted it to µV/√Hz, then you can graphically integrate the data using a method such as the midpoint Riemann sum which follows: select two adjacent points, square each number individually and then add them together and divide by two to get the average noise voltage for these two points. Multiply the average noise voltage by the change in frequency between these points. Repeat this process for every point in the frequency band of interest, sum all of the calculations, then take the square root of that summation. Equation 6 is the mathematical representation of all of the above steps:

$$RMS\ Noise = \sqrt{\sum\left(\left(\frac{N_{n-1}^{\ 2} + N_n^{\ 2}}{2}\right) * \left(f_n - f_{n-1}\right)\right)}$$

$$\text{where } N_n \text{ is the spectral noise in } \frac{\mu V}{\sqrt{HZ}} \qquad (6)$$

$$\text{and } f_n \text{ is the frequency}$$

Measuring noise in an application

To measure the noise that a system will see due to its power supply, the LDO should be powered by whichever circuitry will be used in the actual application. This shows the noise that the downstream components see and is really a combination of the internally generated noise of the LDO, plus the noise of the LDO's power supply, which is attenuated by the LDO's power supply rejection ratio. So if the LDO is going to be powered by a switching regulator, it is best to use the exact same switching regulator used to measure the noise. You can use two separate EVMs wired together to represent the switcher and the LDO, but ideally this measurement should be made on either the final production board, or one that is as similar as possible. This gives a more accurate picture of the noise that the load device sees at its input supply since high-frequency noise can easily couple through various parasitic paths to either the ground plane, supply plane, or both.

Place the measurement connection as close to the load device as possible as this will give a more accurate picture of the actual noise seen by the load. If the board to be used does not have a SMA or BNC connection at the output, one trick is to solder a SMA connector across the terminals of either the input capacitor of the load device, or the output capacitor of the LDO. Note that this can be a bit tricky to accomplish, therefore, be careful with the connecting wires as they can put enough mechanical torque on the capacitor to rip it off the board (and may take the pads with it).

Pre-production noise benchmarking

To compare various LDOs without putting them on the production board, use evaluation modules (EVMs) to measure their output noise. It is possible for the EVM to give different results than a production board using the same circuit because of the differences in parasitic coupling caused by different component placements and routing. To test an LDO on an EVM, remember to use a resistive load instead of an electronic load to minimize the load's noise contribution. Ground this load resistor as close to the negative terminal of the input power supply as possible to avoid generating excessive noise on the ground plane. Large ground currents on the relatively small ground plane of an EVM can affect the noise measurement. See **Figure 5** for an example.

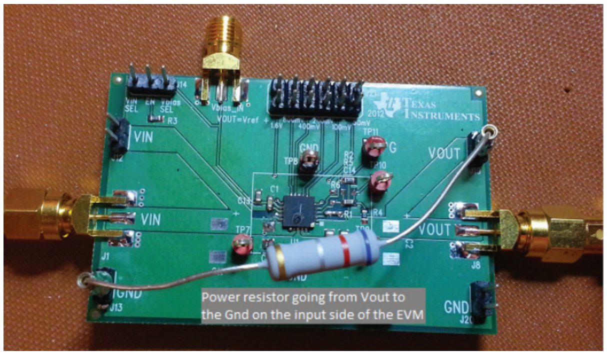

Figure 5. *Grounding the load resistor near the input supply.*

Use shielded connections whenever possible to limit the size of any inductive loops. If the EVM does not have a SMA or BNC connection at the output, try soldering a SMA connector across the terminals of the LDO's output cap. As noted before, this can prove tricky to accomplish and the resulting arrangement is fragile.

Quick setup guide

1. Set up the LDO and the board in preparation for testing.
2. Connect required load to VOUT using a resistive load, preferably grounded close to the input supply.
3. Place the EVM in a metal (or metal-coated) box and ground it at the input supply to shield it from environmental noise.
4. Connect required VIN, VOUT, Venable, and so on, using shielded coax cables.
5. Connect one side of the AC-coupling capacitor to the output of the EVM. Then connect the other side of the AC-coupling capacitor to the analyzer used for measurement.
6. Run the measurement.

Additional pointers

- Make sure that the noise floor of the measurement equipment is lower than the noise floor of the LDO.
  - If the noise floor is larger than or close to the noise of the LDO, use a low-noise op amp to gain up the noise
  - Keep the gain resistors small to limit their noise contributions
  - Check to see that the gain you are using is flat across the frequency range you are measuring.
    - if it's not flat, either lower the gain or make sure you account for the gain's roll off when converting the noise data.
    - Once you have the noise data in uV/√Hz, divide by the gain of the amplifier in V/V.
- The AC-coupling capacitor should be large (3-10 mF for measuring 10 Hz) to ensure that the low-frequency noise is adequately captured.
- Keep all connections and wires as short as possible and/or shielded to reduce environmental noise pick up.

References

1. John C. Teel. Understanding Noise in Linear Regulators, Texas Instruments Analog Applications Journal (slyt201), 2Q 2005
2. Masashi Nogawa. LDO Noise Examined in Detail, Texas Instruments Analog Applications Journal (slyt489), 4Q 2012
3. Masashi Nogawa and Kyle Van Renterghem. Wide Bandwidth PSRR of LDOs, Bodo's Power Systems, pp. 46-49, Mar 2011
4. Product Folders: TPS7A47, TPS7A35, TPS7A83

IMPORTANT NOTICE FOR TI DESIGN INFORMATION AND RESOURCES

Texas Instruments Incorporated ('TI") technical, application or other design advice, services or information, including, but not limited to, reference designs and materials relating to evaluation modules, (collectively, "TI Resources") are intended to assist designers who are developing applications that incorporate TI products; by downloading, accessing or using any particular TI Resource in any way, you (individually or, if you are acting on behalf of a company, your company) agree to use it solely for this purpose and subject to the terms of this Notice.

TI's provision of TI Resources does not expand or otherwise alter TI's applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such TI Resources. TI reserves the right to make corrections, enhancements, improvements and other changes to its TI Resources.

You understand and agree that you remain responsible for using your independent analysis, evaluation and judgment in designing your applications and that you have full and exclusive responsibility to assure the safety of your applications and compliance of your applications (and of all TI products used in or for your applications) with all applicable regulations, laws and other applicable requirements. You represent that, with respect to your applications, you have all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. You agree that prior to using or distributing any applications that include TI products, you will thoroughly test such applications and the functionality of such TI products as used in such applications. TI has not conducted any testing other than that specifically described in the published documentation for a particular TI Resource.

You are authorized to use, copy and modify any individual TI Resource only in connection with the development of applications that include the TI product(s) identified in such TI Resource. NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information regarding or referencing third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of TI Resources may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI RESOURCES ARE PROVIDED "AS IS" AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING TI RESOURCES OR USE THEREOF, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY YOU AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS EVEN IF DESCRIBED IN TI RESOURCES OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF TI RESOURCES OR USE THEREOF, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

You agree to fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of your non-compliance with the terms and provisions of this Notice.

This Notice applies to TI Resources. Additional terms apply to the use and purchase of certain types of materials, TI products and services. These include; without limitation, TI's standard terms for semiconductor products http://www.ti.com/sc/docs/stdterms.htm), evaluation modules, and samples (http://www.ti.com/sc/docs/sampterms.htm).

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265