Searching for a Unicorn

Measuring Voltage Regulator Ripple Rejection, extra section

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This discussion was mostly omitted from the original article in AudioxPress due to space constraints. It is fully reproduced here.

Signal Generator

All the fixtures we've seen show an AC source input, what is that source? And what kind of measurement errors can it introduce? Several inexpensive and available sources were used, and here we examine the characteristics that make them better or worse for this measurement. As with the summing circuit, it turns out that at these low levels of measurement almost signal nuance is critical. There are so many variables that it's difficult to decide where to begin the discussion!

What is "Ground"?

A brief discussion on local power distribution

"Ground", or "earth", gets its name because, as a near–infinite current path, power line currents return to the electric generator via the earth, thus only half the length of wire is needed for power distribution. The term became a generic one to represent the conductive path for current returning to its power source.

Unlike the earth, wired return paths in our circuits are not near–infinite. As a common reference point for a circuit, ground impedance times return current equals voltage. To make things more complex, modern electrical distribution in our buildings has two paths to return current to the main "breaker box"—neutral and ground. Both return to the same point, one carries current and, in theory, one does not. Then the fused protection splits the circuit into multiple hot and neutral circuits for different power outlets. Ultimately this distribution setup makes it impossible to have a single clean, quiet return path for a group of measurement tools at a test bench. The best you can do is experiment with different power connections until the signals are as good as they can be.

In this search for the best possible ripple rejection measurement, it means plugging the various test instruments into one or another power outlet while staring at the spectrum analyzer until the measurements don't get any better. To illustrate, let's look at some baseline noise measurements for some signal generators.

Baseline Noise Floor

One of the big questions in determining the veracity of a measurement is "Does the result represent the device under test or the measurement apparatus?" A typical rule of thumb is to make the measurement system ten times better than the parameter being measured. As we're trying to measure a ripple component that's about a microVolt, across a range of frequencies, that's a difficult goal!

For this article, all the hard work has been done and we're analyzing the results, so first we'll take a look at the baseline noise floor to see the best we can measure.

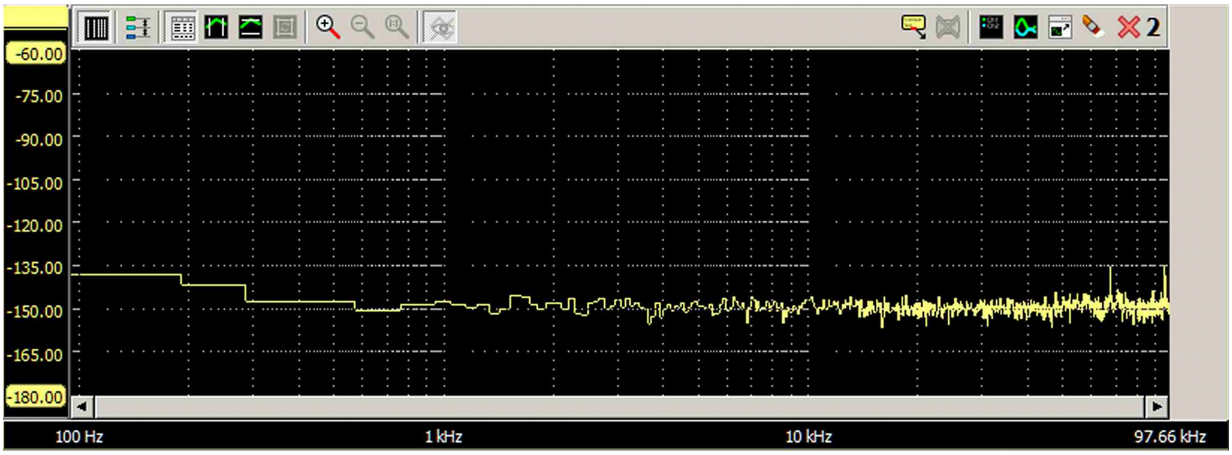

Figure 1 Baseline noise floor of measurement system, 100Hz to (almost) 100kHz

The spectrum in figure 1 represents the spectrum analyzer's lowest range of measurement while autoranged to ±200mV and boosted by an ultra–quiet gain of 1000 amplifier. Except for two artifacts that appear at about 68kHz and 95kHz, everything is below -135dBV, and beyond 1kHz at about -150dBV. So measurements down to at least -130dBV should be quite acceptable. Note that the 1000X amplifier precedes the analyzer so the vertical scale of figure graphs has been adjusted by -60dBV to account for that gain boost. Given this "best case", let's take a look at some potential error sources that can corrupt the measurements.

AC Source Errors via Ground

Note that spurs appearing in the spectra discussed here may be at the actual indicated frequency, or they may be aliased (demodulated) down into the visible spectrum from some higher frequency component such as a system clock signal. All ground signal errors shown in the spectra below are measured with the scope probe input and ground connected together at a common point that is connected to generator ground via BNC cables.

Wavetek Model 166

Wavetek is a company founded in 1963[i] and makes high quality, highly functional signal generators. Their Model 166 is a well regarded instrument from the 1970s and 80s that can be found used on eBay or at flea markets. Ours was almost resold but fortunately we kept it and it ultimately became the generator of choice for this ripple rejection measurement foray. The two spectra shown in figures 2 and 10 illustrate how lifting the AC earth connection at the power plug improves noise.

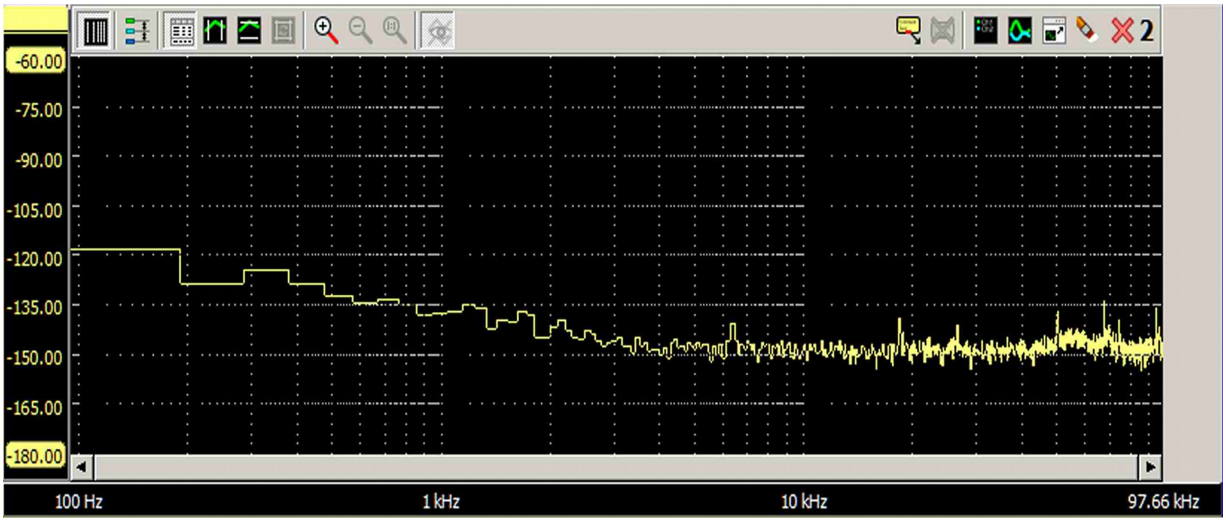

Figure 2 Wavetek ground noise, two prong AC

Conditions:

- WaveTek Model 166 as signal generator
- Analyzer in and return both connected to generator ground
- Generator 3rd prong ground wire isolated

Compared to the baseline noise floor, notice an increase in the power line components around 100Hz and higher noise floor out to 4kHz compared to baseline. Also notice artifacts at around 6.3kHz and 18kHz

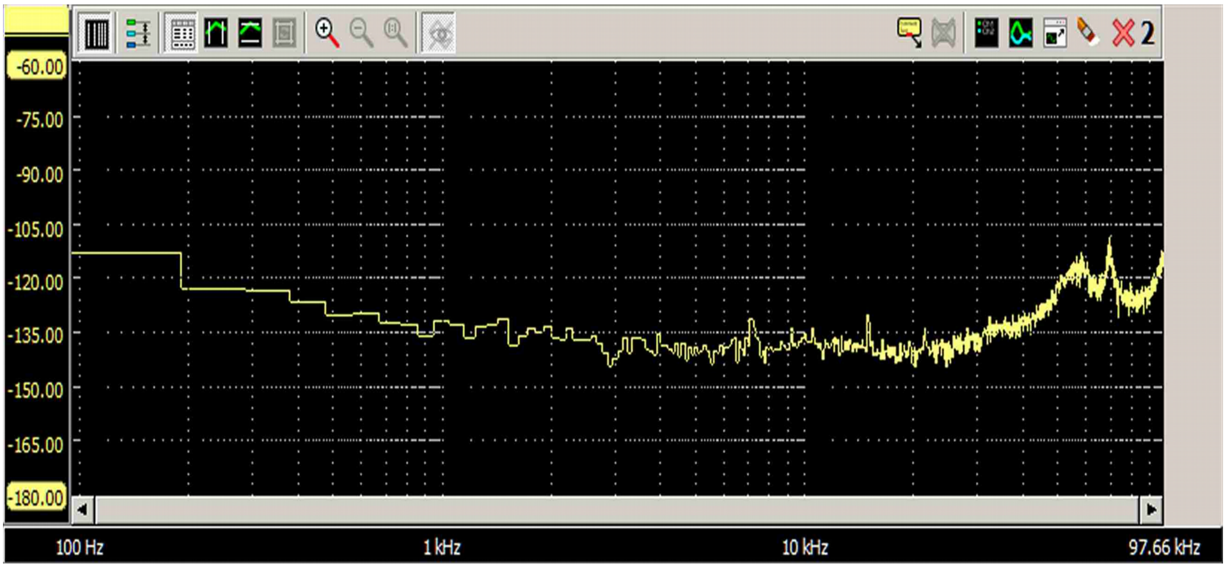

Figure 3 Wavetek ground noise, 3 prong AC

Conditions:

- Same as figure 2 *EXCEPT* AC 3rd prong ground wire connected

Compared to figure 2 notice an increase of garbage above 30kHz plus additional power line noise at 100Hz.

Tiepie HS3 AWG

Tiepie[ii] makes a line of USB oscilloscopes. Their HS3 model has an arbitrary waveform generator that's software programmable from a Windows PC interface in small amplitude and frequency increments.

It's accurate and easy to use. Using direct digital synthesis (DDS) to create its waveforms, it does have a small "skip" when the DDS cycle rolls over that makes a scope trace slightly unsteady.

We've configured it to create a sine wave as the AC source to the ripple rejection test fixture. In these spectral images of figures 4 and 7, the AWG is turned off and any noise above the baseline is from the internal operation of the HS3.

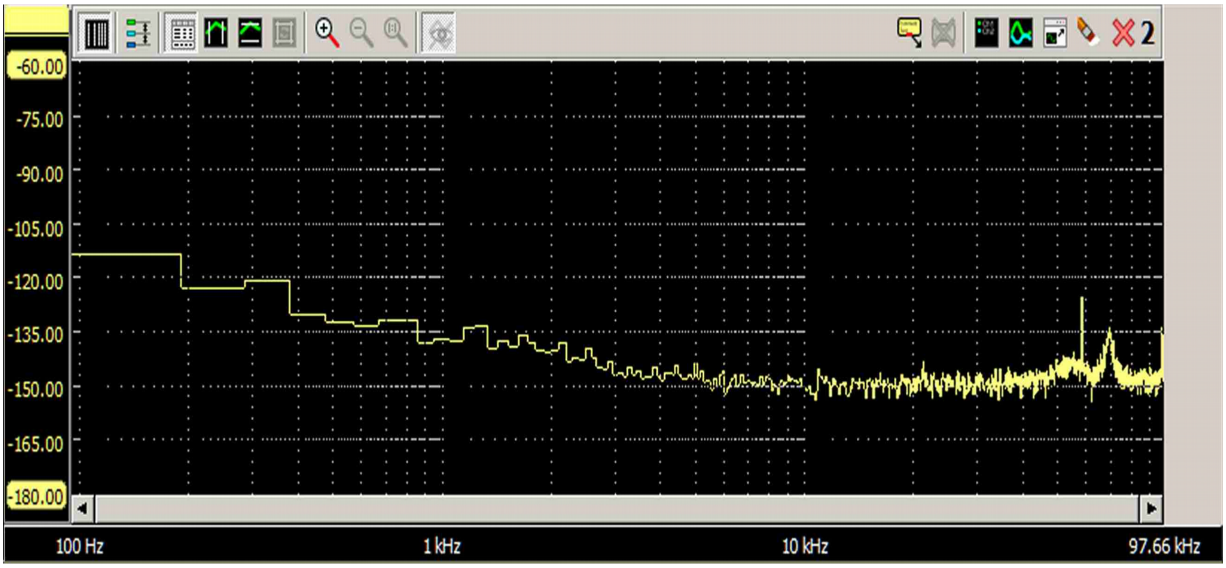

Figure 4 HS3 ground noise, USB power

Conditions:

- HS3 AWG as signal generator
- Analyzer and generator contained in the same USB powered case, on the same PCB.

Notice the *relatively* high (remember we're looking at microVolts!) power line component. Also notice artifacts near 60kHz and 70kHz.
This spectrum looks the same with generator on or off, so there is no ground feedthrough.

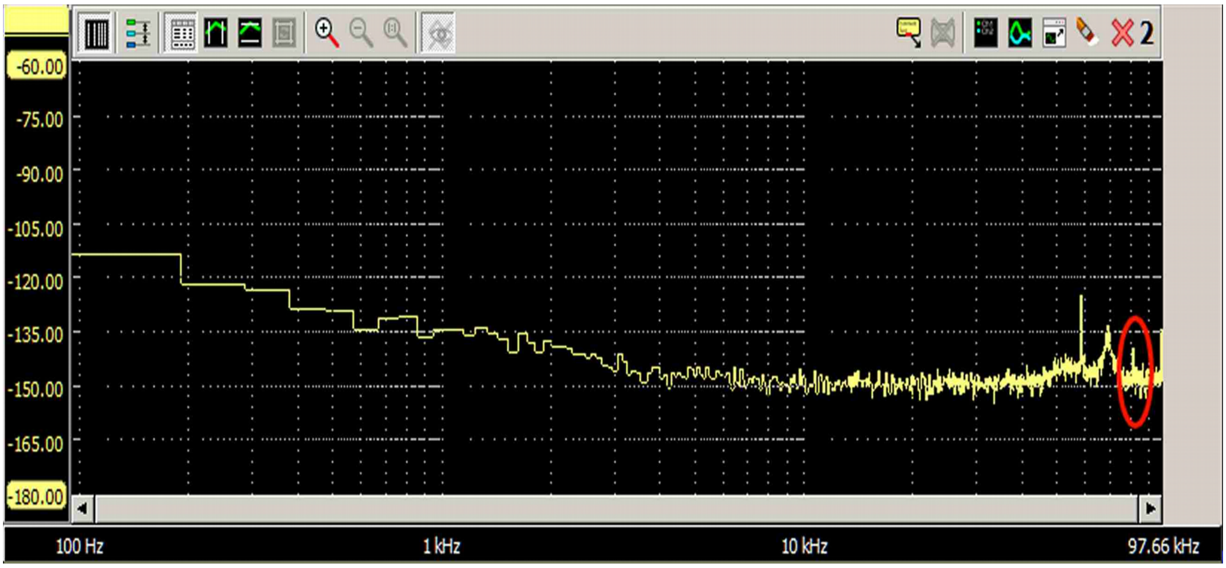

Figure 5 HS3 ground noise, USB with phone

Conditions:

- Same as figure 4 *EXCEPT* a cell phone was inserted into another USB outlet on the same computer.

Notice the additional component added at 80kHz (encircled). This appears even though the cell phone outlet is in a *separate self powered* USB extender!

HP200CD

The venerable HP200[iii] is the product that put Hewlett-Packard in business. It has a stable, low distortion sine wave from a differential output that's decoupled from earth and local ground. Beyond the inherent measurement error due to feedthrough shown in figure 6, there are practical difficulties with this generator for measurements across a range of frequencies:

- The amplitude changes with adjustment of frequency
- Manual frequency and amplitude adjustments are tedious and inaccurate
- Manual amplitude adjust is not accurate

This unit is very old (maybe 50 years?) and hasn't been calibrated in a long time, which could be the reason some of these issues exist.

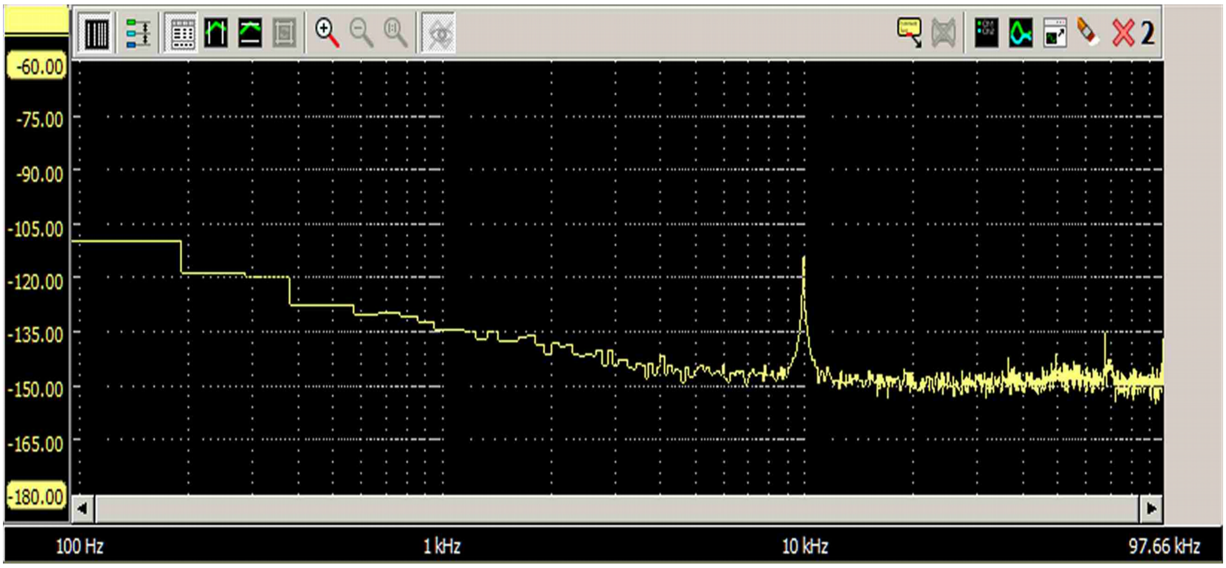

Figure 6 HP200CD internal feedthrough ,10kHz

Conditions:

- HP200CD oscillator as signal generator.
- Spectrum shows ground signal only.

While it has a very low noise floor, there is internal signal coupling to the ground return that causes feed–through error.

Digilent Analog Discovery Signal Source

Digilent Analog Discovery[iv] is a full function analog and digital excitation and measurement system originally developed as a teaching aid. It's great for high level excitation signals and even has a vector network analysis function. It's also moderately priced for its major functionality. The software is great, it has dual inputs and dual outputs. We use its sweep function on one channel with a sync pulse on the other to perform output impedance vs. frequency tests.

However, it's quite noisy, at least with regard to the *very* low level measurements we're making here. Because of its digitally induced noise and a significant DDS-induced skip in analog generator output, we're not including its performance as a signal source in this PSRR measurement expository.

Which Source Is Best?

Clearly we can exclude the Analog Discovery and the large ground–induced error of the HP200CD will distort any measurements. That brings the choice to HS3 and WaveTek 166. Let's examine ripple rejection measurements at 100Hz for each, to see which is more accurate.

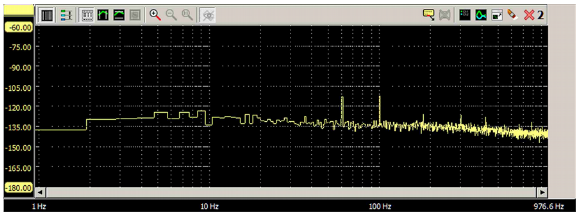

Figure 7 HS3 source at 100Hz, SPX

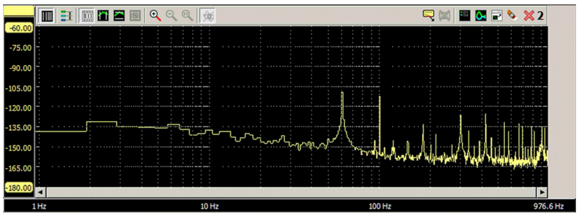

Figure 8 HS3 source at 100Hz, LT3045

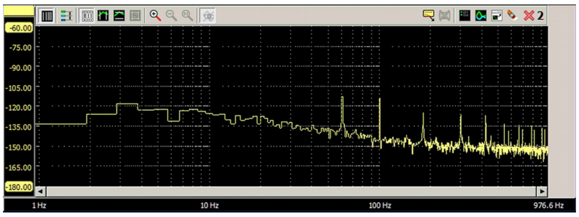

Figure 9 HS3 source at 100Hz, TPS7A4700

Figures 7,8,9 conditions:

- HS3 source at 100Hz
- Three voltage regulator brands

Two peaks are visible, one at 60Hz and one at 100Hz. Power line bleed within the 1000X amplifier is the source of 60Hz, although it's only a few μV. We have to decide if the 100Hz value is valid.

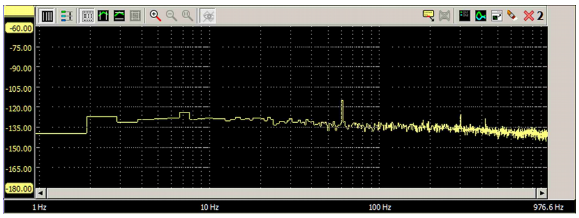

Figure 10 WaveTek source at 100Hz, SPX

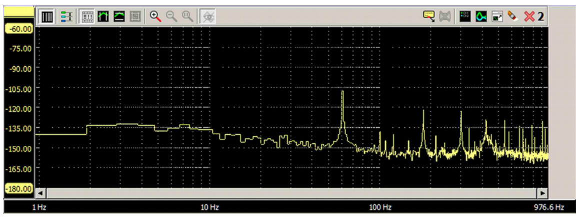

Figure 11 WaveTek source at 100Hz, LT3045

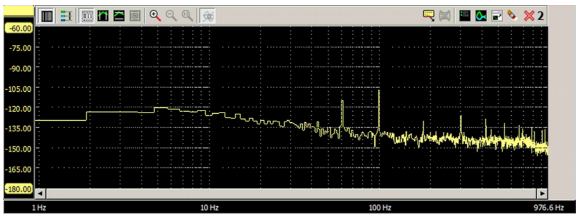

Figure 12 WaveTek source at 100Hz, TPS7A4700

Figures 10, 11, 12 conditions:

- WaveTek 166 source at 100Hz
- Three voltage regulator brands

Two or one peaks are visible, one at 60Hz and maybe one at 100Hz. Power line bleed within the 1000X amplifier is the source of 60Hz, although only a few μV.

We have to decide which 100Hz source is most valid. Notice in figures 7, 8 and 9 how all three regulators have approximately the same ripple at 100Hz? (Approx. 112dBV signal to ripple ratio) This indicates the source is causing most of the error signal. In contrast, figures 10, 11 and 12 show very different ripple values at 100Hz. SPX ripple is invisible below its -135dBV noise floor. TPS7A4700 and LT3045 both have very low noise across this low frequency band, yet LT3045 has a 138dBV signal-to-ripple ratio whereas TPS7A4700 is 107dBV.

Thus the jury rules in favor of the WaveTek 166 as the best signal source, but *only* if the AC plug has a ground isolator to disconnect the chassis from earth. The Tiepie AWG, while very good, internally injects some of the generator signal into the measurement system. In an attempt to improve its performance, I decoupled the generator ground from the oscilloscope ground by using a band saw to cut the face plate between the generator and 'scope. See figure 13.

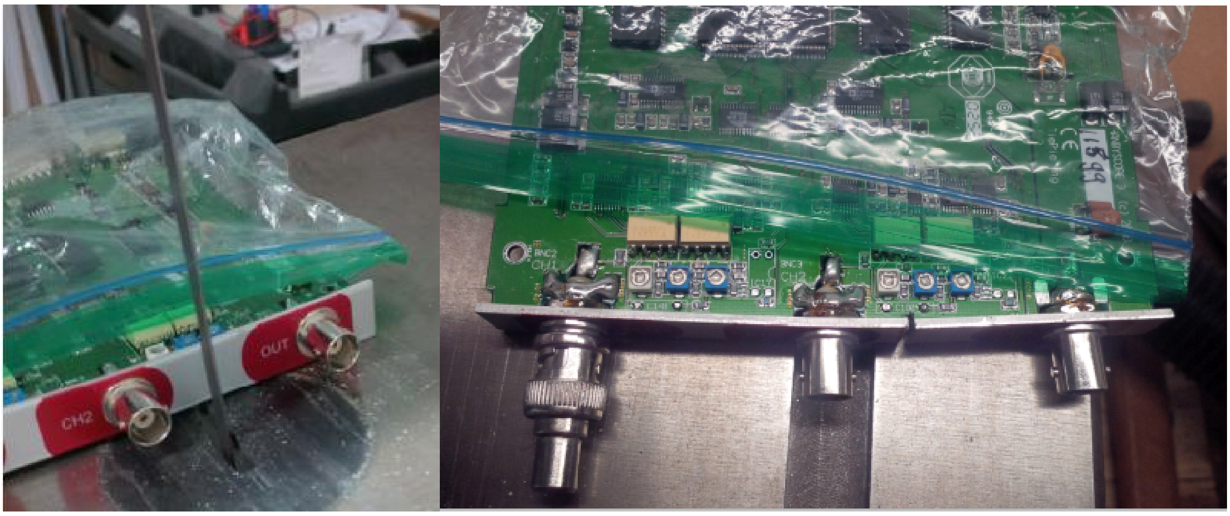

Figure 13: HS3 front panel cut with band saw (warranty has already expired)

It also involved removing a lot of solder from the generator BNC connector on the right, adding a ground wire from the BNC to the power supply entry point on the PCB and using a lot of hot glue to reinforce the mechanical integrity of the connector. It's not clear it helped much because the error is not ground induced; it appears only when a signal is being *generated and measured.* Again be aware that the performance of this device is exemplary, only not quite good enough for measurements of sub-microVolt ripple.

Author

Brian Lowe is founder and principle engineer at Belleson LLC[v]. His audio circuit design experience dates to 1971, when he designed a reverb unit using a ceramic phono cartridge, 4 ball point pen springs, a model car hub cap, a transistor amplifier kit and a speaker. In the 1980s, he was author of an article in issue 1 of *Glass Audio* called A Self-Bias Servo for Push Pull Amps, and in 1984 designed a diamond tester. He received U.S. patent 8294440 in 2012 for a novel voltage regulator. He's a proud father of two thriving teenagers and spouse of a very tolerant and patient wife.

i https://en.wikipedia.org/wiki/Wavetek
ii https://www.tiepie.com/en/usb-oscilloscope/handyscope-hs3
iii http://www.hpmuseum.org/garage/garage.htm
iv https://store.digilentinc.com/
v http://www.belleson.com/