The digital audio platform provides supply regulators for the most commonly used voltages, so that DAC/ADC modules do not need to provide their own regulators. There are four regulators, for ±15 V, +5 V, and +3.3 V. Of course, any amount of local supply regulation can be included on a module–the unregulated outputs of the rectifiers are also connected to the module. The unregulated supply voltages are approximately ±22 V and +7 V.

I constructed a test platform to evaluate the performance of these regulators and identify any design mistakes. This turned out to be quite a learning experience as the regulators' performance probed the limits of the measurement setup. These limits will be discussed below. (There were a few design mistakes also, so it was a useful exercise even if the measurements didn't turn out perfectly.)

The signal generator and analyzer was a PC with an Asus Xonar Essence STX sound card and Jensen CI-2RR isolation transformer for the input. The test bandwidth was 10 Hz to 20 kHz. Briefly, the regulators were exercised as follows:

- To inject an AC signal on the input, the sound card output was buffered and level shifted (via a Zener diode) to the ADJ terminal of an LM317/LM337 regulator. The regulator ensures the output voltage is 1.25 V above the voltage at the ADJ pin. This stimulus was fairly accurate if the capacitive load was kept small and the dropout voltage was sufficiently large. A stimulus of 100 mV RMS was used for all tests.
- To inject an AC current into the output, the sound card output was buffered and connected to an op amp based current source, regulating the voltage across a 25 ohm resistor. The DC current was 100 mA and an AC component of 4 mA was used for all tests.

The test board is shown in figure 1. The top side contains a rectifier and stimulus circuitry and the bottom contains the regulators. (In retrospect, it would have been better to put the rectifier on a separate board to reduce the ground errors introduced by ripple currents.) Jumpers are used to select which regulator is being tested. The four SMA connectors allow injecting input voltage and load current, and monitoring the input and output of the active regulator. The socketed Zener diodes set the DC input level (unless otherwise specified, a 16 V Zener was used, and the input was ±19.75 V.)

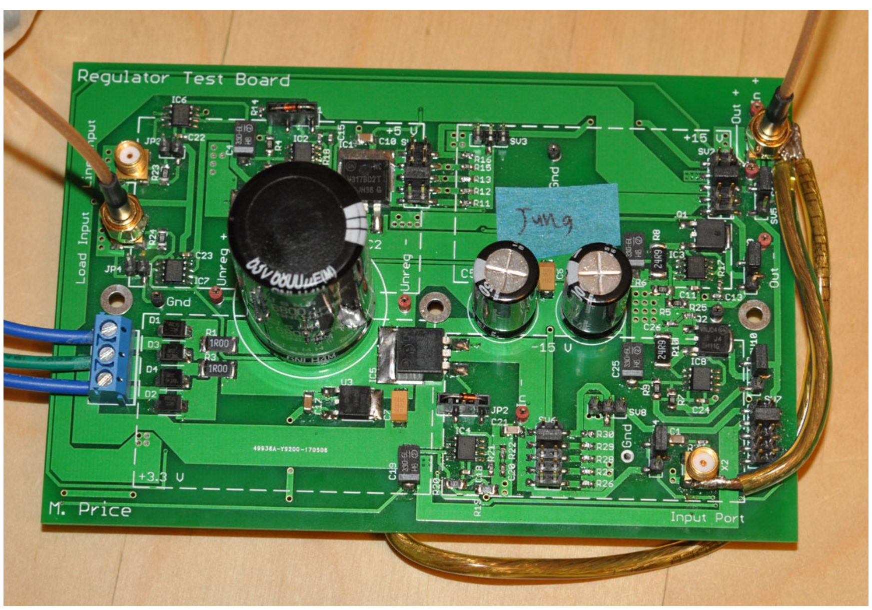

Figure 1: Regulator testing board

I assembled two boards. One was stuffed with components for Jung regulators [2] and one with lower cost LM317/LM337 regulators. In figure 2 you can see the Jung regulator option. D2PAK preregulators and pass transistors allow a rectangular heat spreader to be placed under the board. (Note that the +5 and +3.3 V versions of the

Jung regulator do not include preregulators, in order to reduce the required dropout voltage.) Figure 3 shows the LM317/337 option.

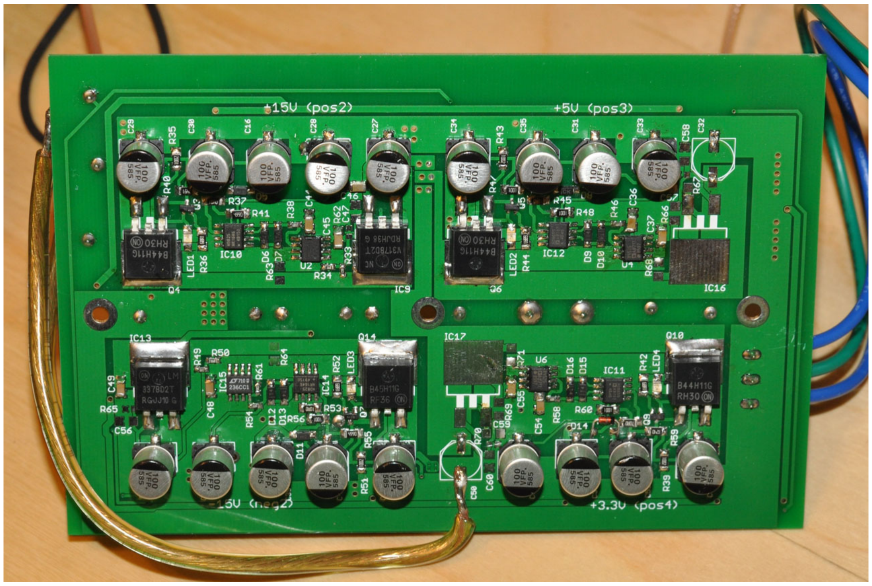

Figure 2: Regulators shown on bottom (Jung stuffing option)

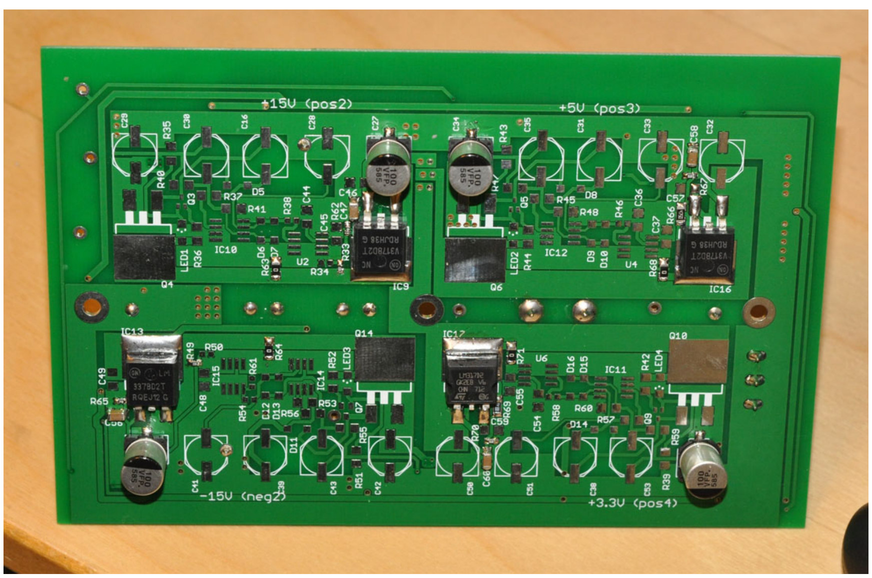

Figure 3: Regulators shown on bottom (LM317/337 stuffing option)

The first step in measuring was to measure the frequency response from the computer to the input port of the regulator; see figure 4. This looks about as you'd expect, with a low frequency rolloff from the soundcard and/or isolation transformer. There is some shelving at high frequencies, perhaps due to the limited slew rate of the LM317 driving the regulator input. (This device was driving a capacitive load of 11 μF.)

By observing the output of the regulator instead of the input, we can measure the line rejection. Figure 5 shows the line rejection of the LM317/337 regulators and figure 6 shows the Jung regulators.

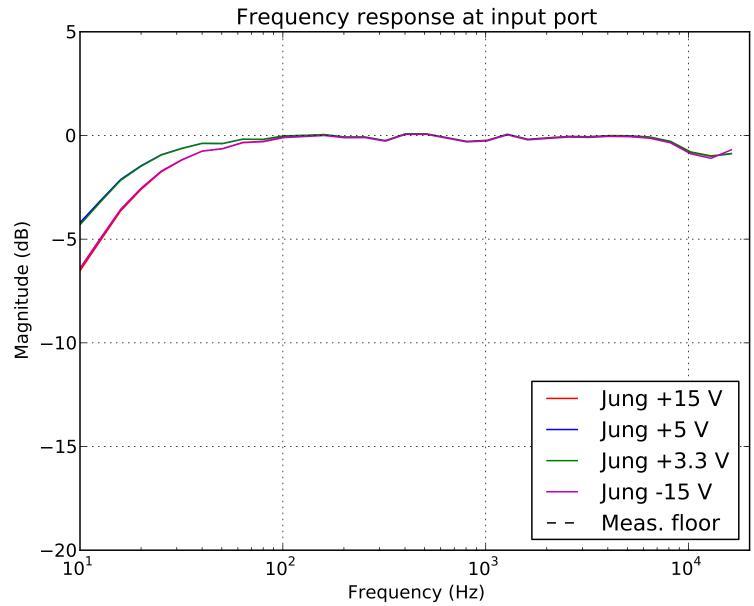

Figure 4: Input port calibration

The LM317 regulators offer good line rejection of more than -80 dB at moderate frequencies. The performance of the +5 V and +3.3 V regulators is similar to that shown in the datasheet (the ADJ pin was bypassed with 10 μF as recommended). The comparatively poor performance of the -15 V regulator is probably caused by the test setup; see below.

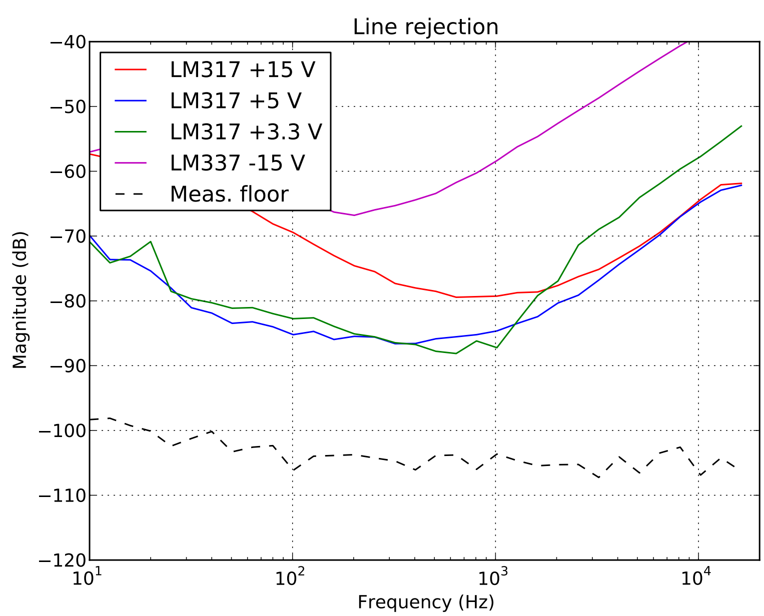

Figure 5: Line rejection of LM317/337 regulators

The line rejection of the Jung regulators is much better, as you would expect given that both the reference and error amplifier are supplied by the output voltage. The ± 15 V regulators, which include preregulators, are probably better than the measurement floor (around 105 dB) over most of the audio band. The +5 V and +3.3 V versions, without preregulators, still provide more than 100 dB of line rejection at low frequencies, but this seems to degrade faster as frequency increases.

It isn't clear how much of the high frequency degradation is caused by the test setup. Jung's measurements of the LM317 show line rejection of about 75 dB at 10 kHz, and 50 dB at 10 kHz for the LM337 [1]. This is about 10 dB better than what I measured.

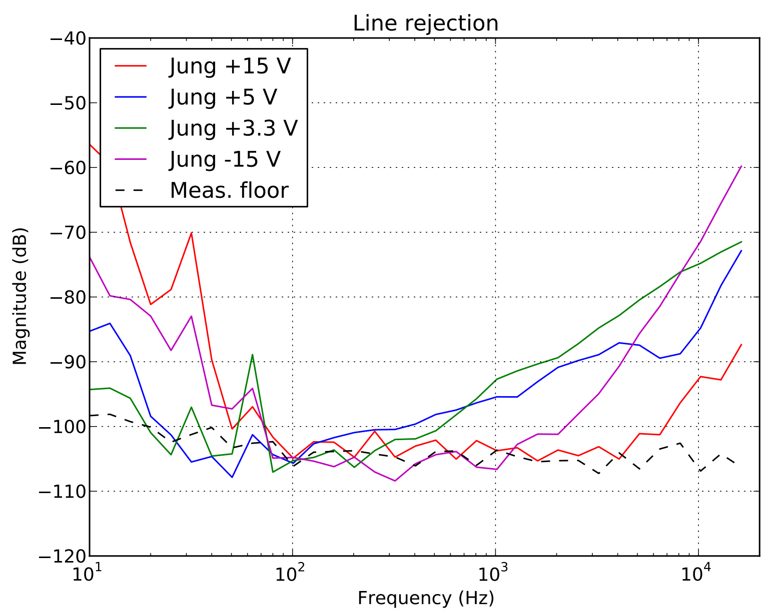

Figure 6: Line rejection of Jung regulators

Next, we look at the noise density of the regulators. This was obtained by simply monitoring the output of the regulator with a DC load of 100 mA. The LM317/337 results are shown in figure 7 and the Jung regulator results are shown in figure 8.

The LM317 regulators all have a noise floor of around 100 nV/$\sqrt{\text{Hz}}$ or 15 μV RMS over the audio band. You can see some harmonics of 60 Hz visible on the spectrum; this could be due to the finite line rejection of the regulators, or to ground errors introduced by the rectifier. Again, the -15 V regulator performance is much worse–I should investigate this. Jung measured 180 nV/$\sqrt{\text{Hz}}$ for the LM317 and 210 nV/$\sqrt{\text{Hz}}$ for the LM337 [1].

The Jung regulators exhibit lower noise. They are close to the noise floor (sorry, I should have done this with an extra LNA). The output of the +5 and +3.3 V regulators is indistinguishable from the measurement floor of about 3.7 μV RMS integrated over the audio band (24 nV/$\sqrt{\text{Hz}}$), so it's probably under 10 nV/$\sqrt{\text{Hz}}$. The ± 15 V regulators give about 5.1 μV, indicating that their actual noise contribution is about 3.5 μV; there is more noise at the lowest frequencies, but from 100 Hz to 20 kHz it looks like about 15 nV/$\sqrt{\text{Hz}}$. There are also some 60 Hz harmonics appearing in the output spectra, probably related to the grounding in the test setup.

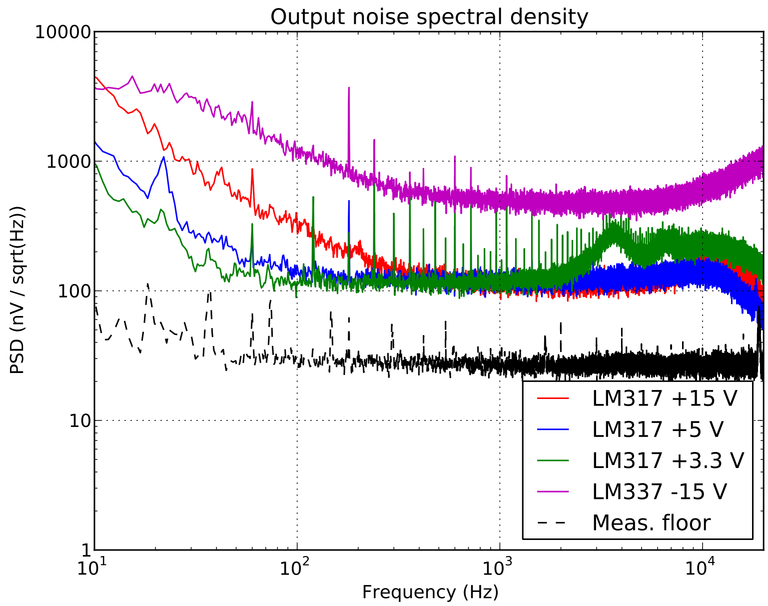

Figure 7: Noise density of LM317/337 regulators

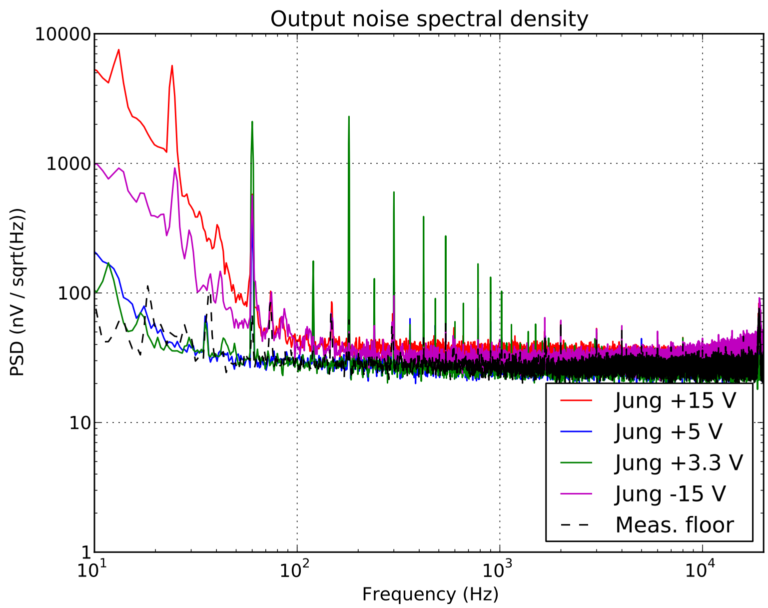

Figure 8: Noise density of Jung regulators

Output impedance measurements are shown in figures 9 and 10. The LM317 regulators have output impedance between 50–70 mΩ. Most of this is probably the resistance of the PCB traces and jumpers between the output pin and the current load.

The output impedance of the Jung regulators is lower, between 10–20 mΩ. This is probably caused by the addition of separate sense traces (for feedback) that go most of the way to the load on the test board. However, the parasitic resistances still swamp the output impedance of the regulator (expected to be in the $\mu\Omega$ range). The lesson here is that to exploit the low output impedance of a regulator, you need the feedback sense connections (both positive and negative) to be connected very close to the load. This is not possible with a 3-terminal regulator, and is not the case in most implementations I've seen with discrete regulators.

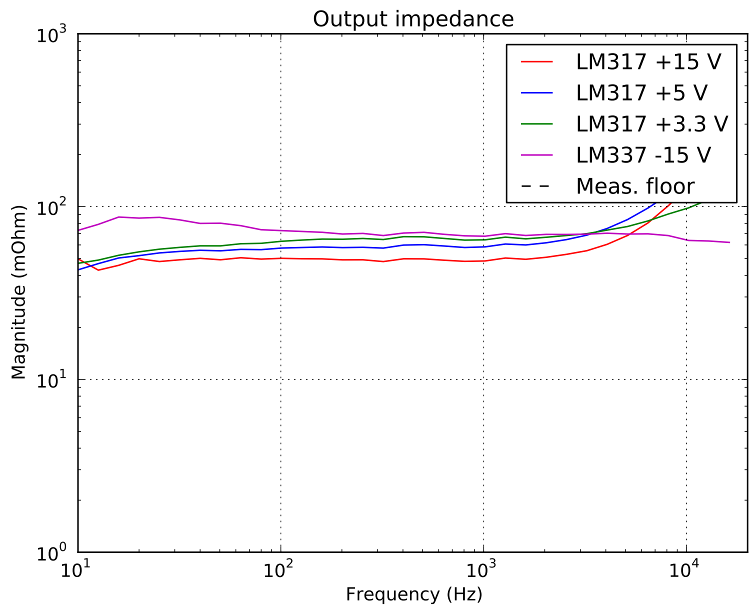

Figure 9: Output impedance of LM317/337 regulators

The main finding of this study was that my implementation of the Jung regulators is probably competent, but to properly measure such good regulators is a non-trivial task. So we may never know for sure.

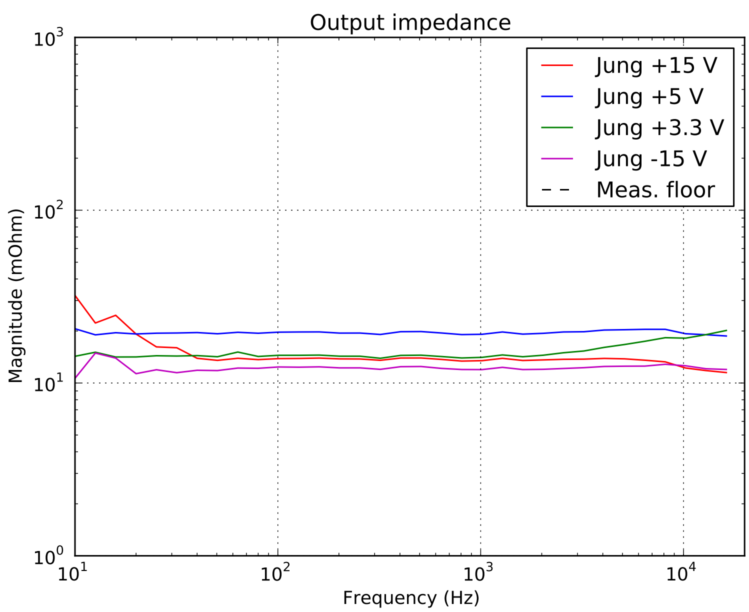

Figure 10: Output impedance of Jung regulators

Addendum: example measurement problems

Please see figure 11 for an illustration of the challenges in performing these measurements. The regulator circuit was not changed. Instead, I added a 12 awg wire to reduce the impedance between the regulator ground and the ground of the output connector. This wire also bypasses some sources of ground current (stimulus circuits and rectifier).

After this change, the line rejection improves by 10–20 dB. The declining line rejection at high frequencies is still suspicious. Not only do the 60 Hz harmonics disappear from the noise spectrum, but the overall noise level improves by 6 dB. Why does changing a ground connection affect the broadband noise? I'm not sure.

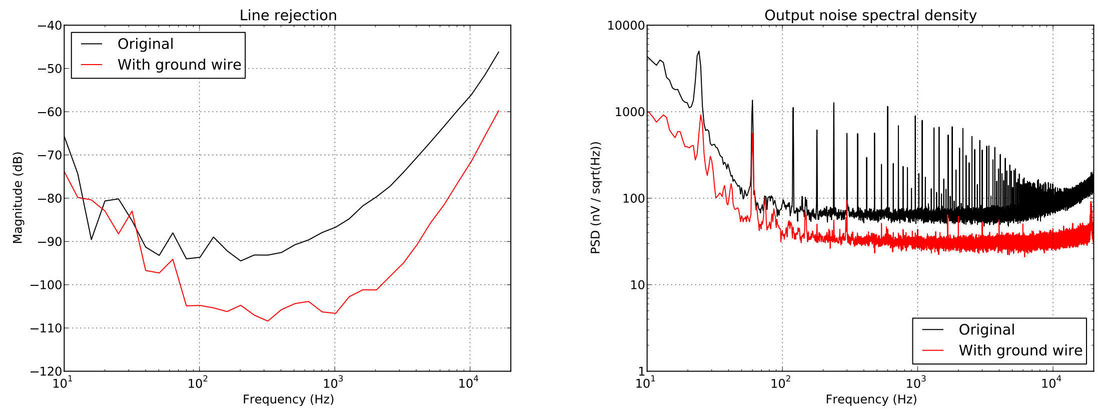

Figure 11: Line rejection and noise density of Jung -15 V regulator before and after adding an additional ground wire to the PCB.

Adding another wire to the ground on the +3.3 V regulator improved the high-frequency line rejection by around 5 dB, but made the noise spectrum slightly worse.

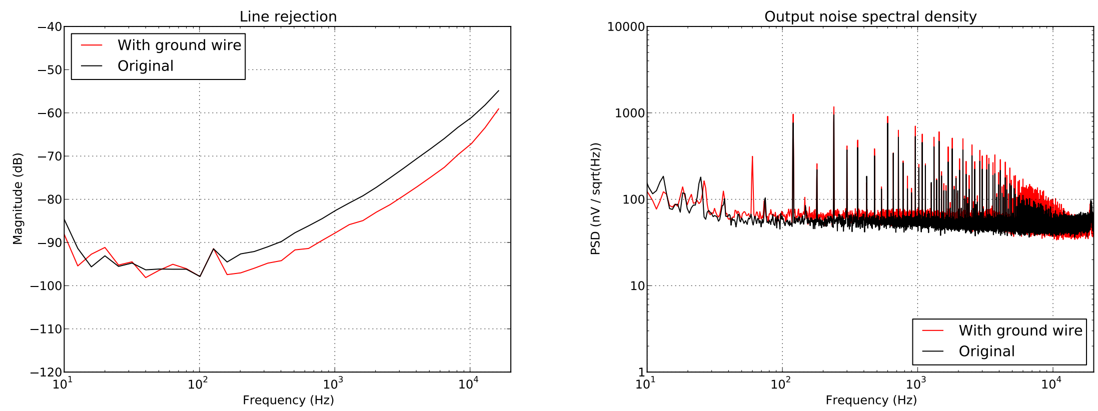

Figure 12: Line rejection and noise density of Jung +3.3 V regulator before and after adding an additional ground wire to the PCB.

Another change that made an impact was to try powering the board with a DC supply, in other words to keep the rectifier on a separate board. This seemed to help with line rejection, and reduced the amount of 60 Hz-related spuriae in the output. However, I was only able to use this setup for the +5 and +3.3 V regulators because the DC output of my other supply wasn't high enough. One thing to note was that I also tried removing the filter caps, and this degraded the line rejection.

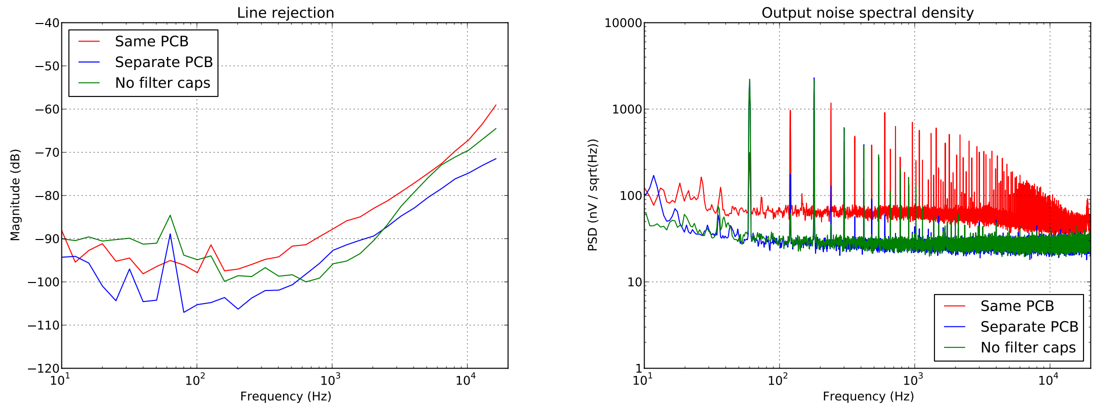

Figure 13: Line rejection and noise density of Jung +3.3 V regulator using different unregulated supplies.

Note that I did not perform any of these performance-enhancing experiments with the LM317/337 test board. It's likely that those regulators perform better than the above graphs would indicate.

References

[1] Walt Jung. Regulators for high-performance audio: part 2. *The Audio Amateur*, (2):20–35, 1995.

[2] Walt Jung. Improved positive/negative regulators. *Audio Electronics*, (4):8–19, 2000.