RESISTOR TEST PROJECT:
PART 1- TEST DESIGN

Developed with support from:

Audio Builders Workshop

https://www.audiobuildersworkshop.com/

Rev 3.0 24-Feb-18

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Please see the Summary document for a list of abbreviations and revision notes.

SUMMARY

This project came out of a discussion among some members of the ABW (Audio Builders Workshop[1]) as a result of visiting a resistor vendor (Susumu) at the exhibits at the 143rd AES convention in New York City.

This project has ended up with several related goals:

- Develop a simple test fixture to test resistors for excess noise and distortion that would affect audio products
- Test the components individually as well as in a representative circuit
- Outline other analysis work that could be done in future installments of this project
- Develop summarized material for use as an ABW video[2]
- Offer student AES[3] members the opportunity to be involved with hands on engineering and/or develop a paper for presentation at an AES event

The report has been split in to multiple parts. At present the parts are:

1. Test Design – this document. Describes the design of the system
2. Test jig verification results. Tests the jig to validate that it is working as planned and serve as initial trial at measurements
3. Initial results using AP515. A test of a wide range of parts to decide on the final set of tests for the AP555
4. (to be performed) Results using AP555
5. Create summary report/paper, post results

The first 4 parts are mainly documentation of the raw data and thus quite long. There is also a level of tutorial material included in the first two parts as no assumptions are being made about the reader's background beyond a general understanding of audio system design. Those familiar with audio hardware design can skip over the discussions.

While this work and analysis seeks to be useful to a wide range of audio hardware developers, it is being done as a side project in volunteers' spare time and with no budget beyond donated items. It therefore lacks full scientific rigor but it is everyone's hope that you, the reader, will find value in this work to make more informed decisions in your next audio design project.

[1] See https://www.audiobuildersworkshop.com/ or https:/www.facebook.com/groups/AudioBuildersWorkshop/
[2] https://www.youtube.com/channel/UCL2QPbpqc7WbapSZI18CsWg
[3] ABW is part of the Boston section of the Audio Engineering Society http://bostonaes.org/

THE QUESTIONS

What we hope to answer with this work: A lot of these items have been addressed in other work listed in the references, our goal is to replicate those results.

- Verify the idea that resistor noise by technology generally goes as follows (worst to best):
  - Carbon comp
  - Carbon film
  - Thick film
  - Thin film
  - Wirewound
- Verify that distortion for small surface mount resistors increases with decreased package size.
- Generally, the view is that 0805 is the smallest size package to use in high performance audio applications.
- Verify that parts advertised as “better for audio” have better noise and/or distortion performance than those not marketed as such.
- Define under what circuit topologies and system applications the component differences will have an audible effect.

A set of properly conducted double blind listening tests to confirm the measurements have not overlooked something would be the ideal final question; that experiment remains outside of the currently planned work. It is hoped that this can be performed in the future.

BACKGROUND

The normal figure of merit for resistors noise is the excess noise, i.e. noise over the theoretical Johnson noise. This is mostly 1/f noise, though there are several other types of self-generated noise.

The figure of merit is described by a noise index, which is the measured RMS noise with a voltage applied to the resistor. 0 dB is referenced to the value of 1 uV/Volt. This noise voltage is only measured across one decade of frequency. See *Smith* or *Vasilescu* for more background (or just web search for *excess noise*).

The resistor test follows the design discussed in *Seifert* and that document is assumed familiar to the reader. **If you haven’t read that yet, do it now**!

The general ideas for the test fixture was taken from multiple places on the web and too numerous to list here (though see the REFERENCES section for sources) – the idea of using cookie tins for shielding certainly predates the internet.

Distortion testing is somewhat more straightforward than noise testing as only harmonics are of interest versus a number of possible noise types.

PEOPLE

A number of people have contributed to this effort (listed in alphabetical order):

- Kelly Clifford. Clifford Consulting. Advice/review on setup and measurements.

- Owen Curtin. Boston AES president. Facilities and logistics support.
- Dan Foley. Audio Precision. Arranged for loan of AP 515 and AP555 test equipment and support for their use.
- Debora Grosse. Momentum Data Systems. Advice/review on setup and measurements.
- Matthew McGlynn. Micparts. Advice/review on setup and measurements.
- Monte McGuire. Advice/review on setup and measurements.
- Kazuo Morishita. Susumu USA. Provided resistor kits and (unpublished) materials on resistor tests

BUT DON'T BLAME THEM…

The lead author/developer for this project is Brewster LaMacchia. Clockworks Signal Processing. http://clk.works

COMPONENT TESTING

Before working on the test jig two small fixtures were developed to plug directly in to the unbalanced (BNC) jacks of the AP, as shown in the next set of diagrams and pictures.

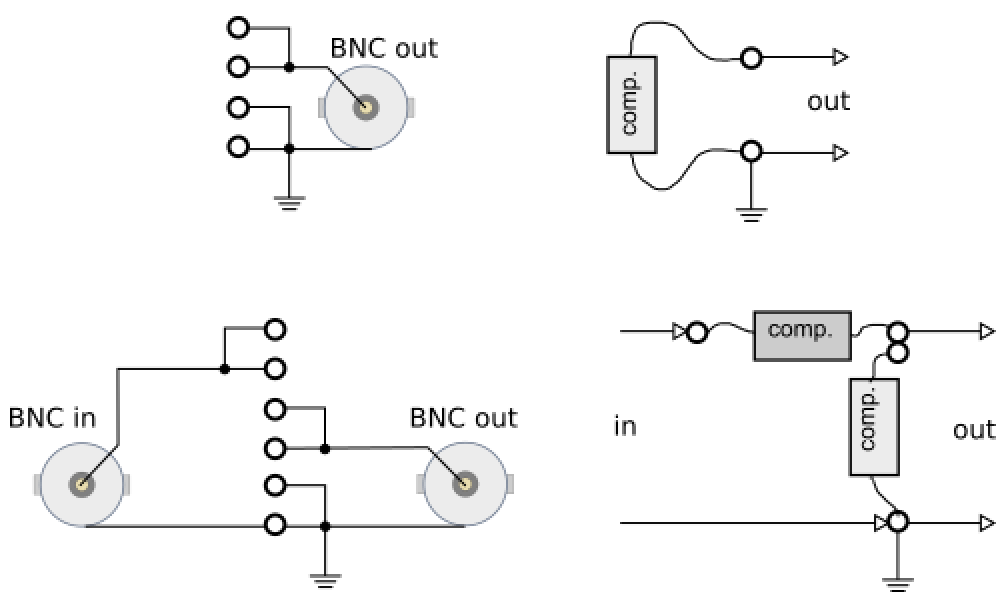

Figure 1 Component test fixture diagram

Figure 2 Component test fixtures.

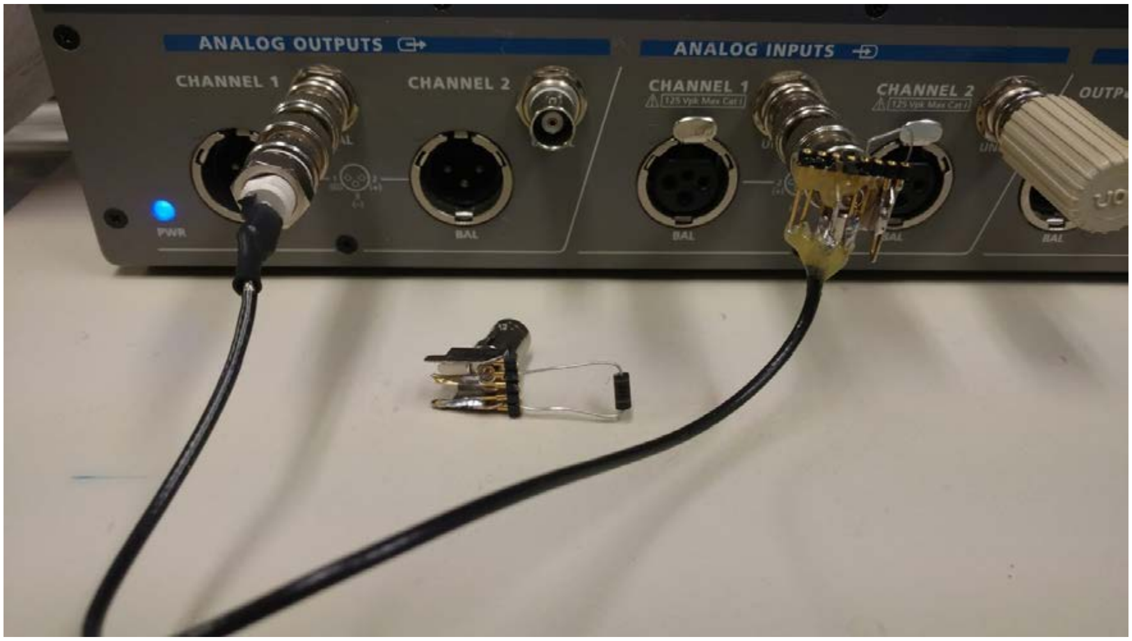

Figure 3 Component test jig on AP

The small fixture shown on the table just places the component across the connector's input.

The second fixture provides three terminals: In, Out, and ground (common) to allow placing components between the generator output and the analyzer input. Multiple pins allow parts to be arranged in a divider arrangement.

A 50 ohm terminator was used to measure an “input shorted” reference, which was compared to the small fixtures’ input shorted (via the small jumper wire shown in the picture in the fixture connected to input 1).

The particular AP515 unit being used had different baseline noise floors for each of the two inputs, with input 1 generally being quieter.

For SMD resistors they were soldered on to small PCB strips and wires attached to allow them to be plugged in to the component test component test jig. See Figure 22 for an example.

FIXTURE CONSTRUCTION

Originally an aluminum chassis was planned for the construction of the test jig, but as more capability was added it outgrew the available box so instead a cookie tin (with appropriate places sanded to ensure good contact) was used instead.

Please see the schematics and pictures in the Appendices at the end of this document for more details. A list of suggestions for the next version can be found on page 20.

SUMMARY

As there was minimal funding for this experiment as many aspects as possible were constructed from parts on hand at the time of development. A “rev 2” is contemplated where the system is built on a custom PCB to increase robustness; the use of connectors in between the various portions did allow for flexibility with experimentation but also proved to be possible sources of noise.

The breadboard PCBs were previously obtained from Amazon. MTA-100 series connectors from TE were used – for any subsequent revision a better choice would be something like Molex’s KK series as the MTA series need a lot of force to unmate them.

9V batteries were used for convenience as well as eliminating concerns about an external supply being noise or introducing ground loops. It’s recognized that +/- 9V somewhat low for typical op-amp supplies for audio, but most testing is being done at 1V RMS and there should be little performance variation between +/-9V and +/-15V supplies.[4]

One restriction that the battery use does place is the values that can be tested in the resistor bridge, i.e. lower values would discharge the batteries quickly.

The bridge can also be connected to the input XLR to allow measuring excess noise using an AC waveform instead of DC.[5]

[4] Another project for a different day.

[5] There are IEC documents that describe resistor testing for both excess noise and distortion. Given the project’s $0 budget purchasing an expensive “public” specification was not possible. US military standards offer an equivalent set of specifications and are free. For audio applications it is not clear that measurements made following those standards would yield the most helpful material for designing low noise audio applications.

RESISTOR BRIDGE

A Wheatstone bridge configuration was used for the excess noise measurement (see *Seifert*). The CM rejection of the AP is high enough to not have to deal with nulling. As will be shown in Part 2 the AP AC input filter added 1/f noise so spectrum measurements were done with the AP515 input DC coupled.

This effect will need to be investigated on the AP555 to determine if the same considerations exist there. These subtle measurement effects do illustrate why measuring the equipment in different scenarios is needed before trusting specific results.

In these experiments the goal is a qualitative "these parts are better than those parts" versus an absolute measurement of the components, and therefore systematic errors created by the test setup are of less concern if they can be quantified relative to the desired measurements.

Since the AP has two inputs the test fixture design for the bridge measurements as proposed to include a "reference" bridge that could validate that the test setup was operating correctly. There are a number of ways that errors can creep in – loose connectors, unexpected noise sources[6], and pilot error on the measurement systems.

Previous research had indicated that wirewound resistors can act as almost ideal resistors with almost no 1/f noise. Their high inductance though could make them unsuitable for audio bandwidth applications. There is a subset of wirewound resistors that are wound non-inductively. A quick bandwidth test of these using the AP515 showed that they will work well in the audio band (> 30 kHz BW) in the planned test circuits.[7]

The *Märki* paper also used a bridge configuration, though there are differences from *Seifert's* approach. The concept of using a header to plug in resistors was directly borrowed from *Märki*.

OP-AMP CIRCUIT

A reasonably priced (5 for $20) experimenter's board from http://www.pmillett.com/opamp_pcb.html was used for testing resistors in an actual circuit.[8] A validation board with inverting and non-inverting topologies was built with the non-inductive wirewound resistors. For more information about noise in op-amp circuits see Texas Instruments' *Noise Analysis in Operational Amplifier Circuits.*

Resistor values of 1K and 10K were chosen as those values are being tested for excess noise and provide a gain value (10 for non-inverting, 11 for inverting, or 20 and 21 dB respectively) that is reasonable for a real system as well as reasonable impedance values.[9] Since non-inductive wirewound parts are used to create a low noise comparison, 10 kOhm is also a practical upper value for resistors used.

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[6] The only reliably random noise source observed was the Dell laptop used to operate the AP with. Running off of battery seemed to ensure that it wouldn't be the source. Remembering to unplug it though proved to be a source of "oops, need to redo the measurement" more than expected.
[7] The highest value used was 10 kOhms – larger values might have higher residual inductance.
[8] Available for purchase here https://www.ebay.com/itm/DIY-PCB-5x-Dual-opamp-experimenter-PCB-/161630980345?hash=item25a1f508f9
[9] The inverting configuration usually provides lower distortion, but this does come at the expense of lower input impedance compared to the non-inverting configuration. In most audio applications input impedance of at least 10 kOhms is required, and 47 kOhms is a typical value.

Higher gain and/or differential input circuits like those used for microphone or phono cartridge applications would also be of interest to use for resistor tests but open up a wide range of design variables and circuit topologies that is better suited to a future investigation.

The bandwidth of the validation design is a nominal 70 kHz so as to not affect the presumed desire for a system that operates at a 96 kHz sample rate having flat response and minimal phase shifts through the audio band. Other designs would be assumed to use the same bandwidth values so total noise can be directly compared.

The validation board (Figure 17) has single ended input and outputs. NE5532 are used as a representative op-amp found in many audio product designs. OPA1612 were also used as low noise/low distortion part.

It is assumed that for the resistor tests the boards will be built up in just one configuration with two different types of resistors used in each half.

ADDITIONAL ANALYSIS

The amplifier configurations do not generate a DC voltage across the resistors. It was assumed that AC voltages would generate 1/f noise though in hindsight the total energy per unit time would be less. As will be discussed in Part 2 AC measurement didn't produce the expected excess noise measurements. This needs further investigation as it may be a measurement issue.

Regardless it raises a question about what op-amp topology would show excess noise and/or if op-amp circuits are that relevant for evaluating the impact.

SPECTRUM MEASUREMENTS

As was noted previously spectrum measurements were performed DC coupled to reduce instrument noise contribution. DC offsets will show up as a 0 Hz component. The window filter must be considered as this affects the bin spreading. Available filters for the AP are described at https://www.ap.com/technical-library/fft-windows/.

The AP-equiripple filter produces a 12 bin wide peak, and insignificant (< -140 dB) side ripples. The 128K point FFT and 96 kHz sample rate results in a bin size of 0.732 Hz/bin. DC will therefore show up below 4 Hz.

For audio the primary range of accurate low frequency reproduction is taken to be those frequencies above 20 Hz. For nominally flat performance (0.5 dB[10]) down at 20 Hz would place a practical cut off (Fc at the – 3dB point) in the 5 Hz area.

Looking at it from a practical design aspect any sane audio system is going to block/filter DC so that again puts the Fc at at least a few Hz.[11] Therefor the effect of DC and FFT/windows functions won't contaminate the 1/f portion

[10] The question of just noticeable differences in volume level, particularly for bass frequencies could be debated but half a dB seems more than reasonable for the electronics given the huge variations from the transducers. Phase shift at these frequencies is likewise taken to be a non issue.

[11] The author is aware of systems using fans to get the air volumes needed for reproduction at a few Hz but there's also the issue of recorded content below 20 Hz to consider. An interesting side project would be to look at the LFE (Low Frequency Effects) channel on surround sound content and determine a meaningful expectation of content in the bottom octaves.

of the noise curve that our experiments are interested in. This pragmatic limit of a few Hertz applies both with the measurements and the first few Hz in any real system.

Noise, being random, must be averaged to obtain a spectrum plot that is meaningful. In most cases 16 averages was sufficient, though for parts with low noise 128 averages were used.

With the AP515, using the AP's **Recorder** mode there was sometimes a 1% variation in the RMS noise measurement across periods of 0.5 to a few seconds even when using the AP's smoothing filter at its lowest bandwidth (0.2 Hz). (This is with the AP's input high pass filter engaged, so it should not be from low frequency noise.)

This will be looked at again with the AP555 to see if the source if this variation is from the instrument, the test setup, or the resistors themselves. Keeping in mind this variation is on the order of 20 nV so that even if it's associated with the components it is unlikely to factor in to any issue in a real audio system.

NOISE DENSITY FROM THE FFT PLOTS

The plots presented are the output of the AP software which has the ability to plot the amplitude spectral density directly. Other measurement systems may only provide level.

This section provides background about converting spectra obtained by FFT in to an amplitude spectral density plot. The normal FFT results have the Y axis units in volts and normal noise density plots are in V/rt-Hz on the Y axis. Furthermore the FFT size (and window function) scale the noise level.[12] See the Audio Precision technote: *FFT Scaling for Noise* for more information.

To convert the values from FFT results to ones that can be used for calculations (like in *Trump* and the associated spreadsheet) there needs to be two corrections:

- FFT bin size: With 128K FFT the bin size is 0.732 Hz, so values are scaled by 1/0.732 (= 1.37) for 1 Hz bandwidth.
- Window function: The AP-Equiripple noise power bandwidth correction is 2.36.

The net scaling factor for amplitude is 1/sqrt(0.732 * 2.36) = 0.761 (where the units of the result are in V/rt-Hz).

In the spreadsheet the frequency decade from 10 to 100 Hz was used as it was interesting to see the ratio of 1/f to Johnson noise in that region for the various parts. The actual decade used to calculate the Noise Index (NI) technically doesn't matter as ideal 1/f noise is constant/decade. Calculating it in a range that was observed in the spectrum seemed more likely to catch errors.

[12] The author remembers more than one semiconductor company's ADC or DAC chip datasheets using FFT results to claim a low noise floor (i.e. the flat line across the bottom) but failing to provide any information about the FFT, making it impossible to determine any meaningful information.

SPICE MODELS

Using TINA-TI as the SPICE system, some models were made of the resistor bridge and op amp circuits to provide a set of theoretical numbers to compare the actual system against. The .TSC files will be made available along with the other files associated with this project.

RESISTOR BRIDGE

Resistors in SPICE do not include any noise other than the ideal Johnson noise. A macro was added for 1/f noise to evaluate its effect on the measurements. The circuit model is shown in Figure 2. The Va and Vb measurements allowed evaluation of noise with and without the 1/f macro. The model examples shown here use the following parameters for the 1/f macro:

```
* NV/RHZ AT 1/F FREQ
.PARAM NLF=150
* FREQ FOR 1/F VAL
.PARAM FLW=10
```

While the bridge uses 4 resistors, as explained in the *Seifert* paper, it acts from the noise perspective for excess noise like single resistor with the voltage applied across the bridge. The model therefor just adds one 1/f noise source.

The total noise plot in Figure 4 is computed through 45 kHz to match the measurement bandwidth. The total noise calculated is 1.95 uV RMS. As will be presented in Part 2, the 2.5K wirewound reference bridge resistors have higher 1/f noise than the other wirewound values tested.

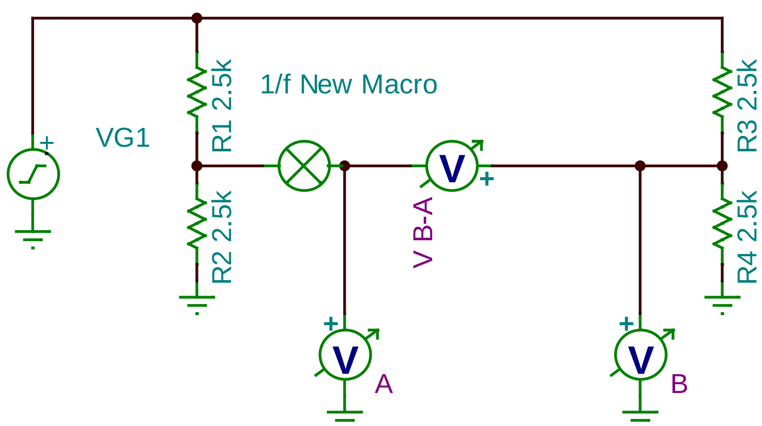

Figure 4 TINA-TI model for bridge with 1/f noise added

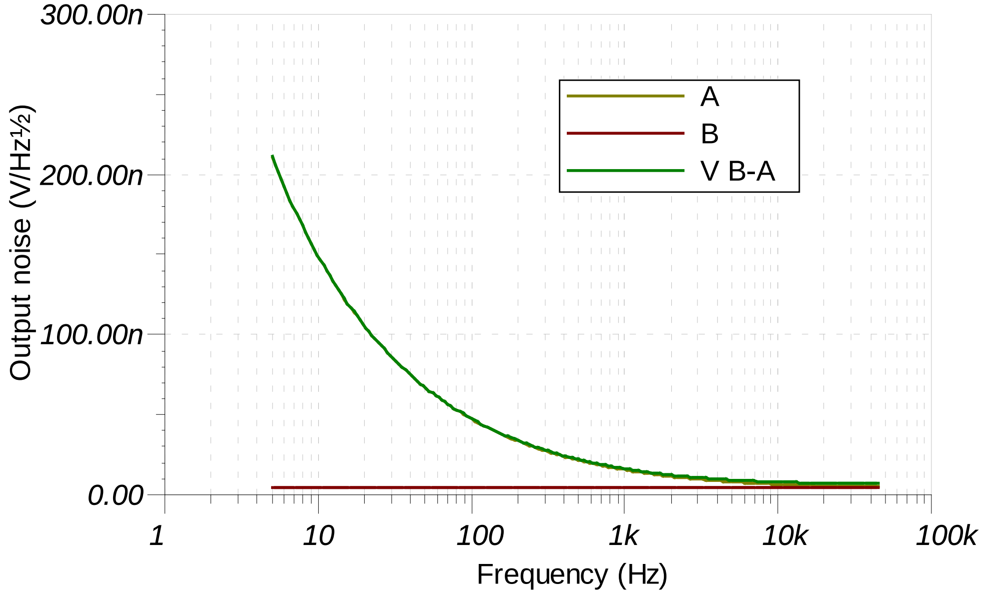

Figure 5 Output noise for the above model

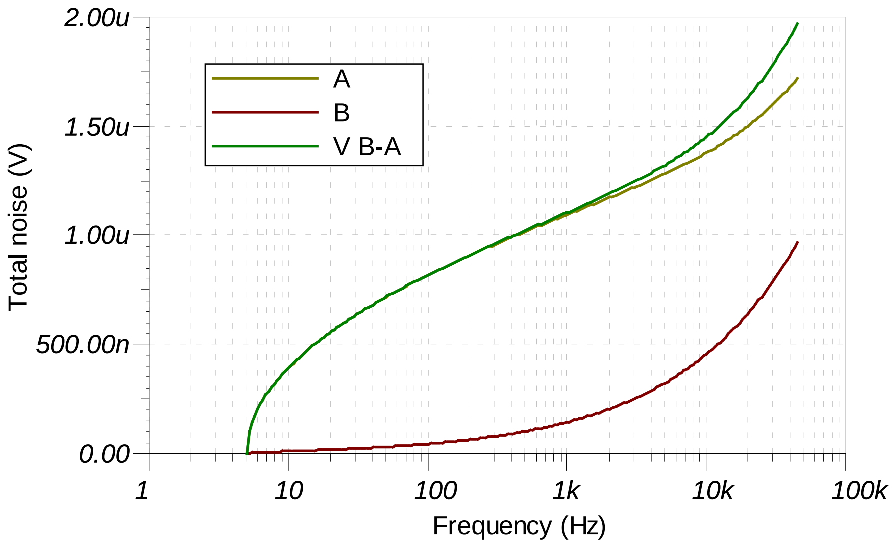

Figure 6 Simulation results for total noise for the bridge system

OP AMP CIRCUIT - IDEAL

A TINA-TI model using ideal op-amps was built to allow estimation of noise from an ideal system where the only noise is the Johnson noise from the resistors. With this as a baseline the effects of real op-amps and resistors with 1/f noise can be compared.

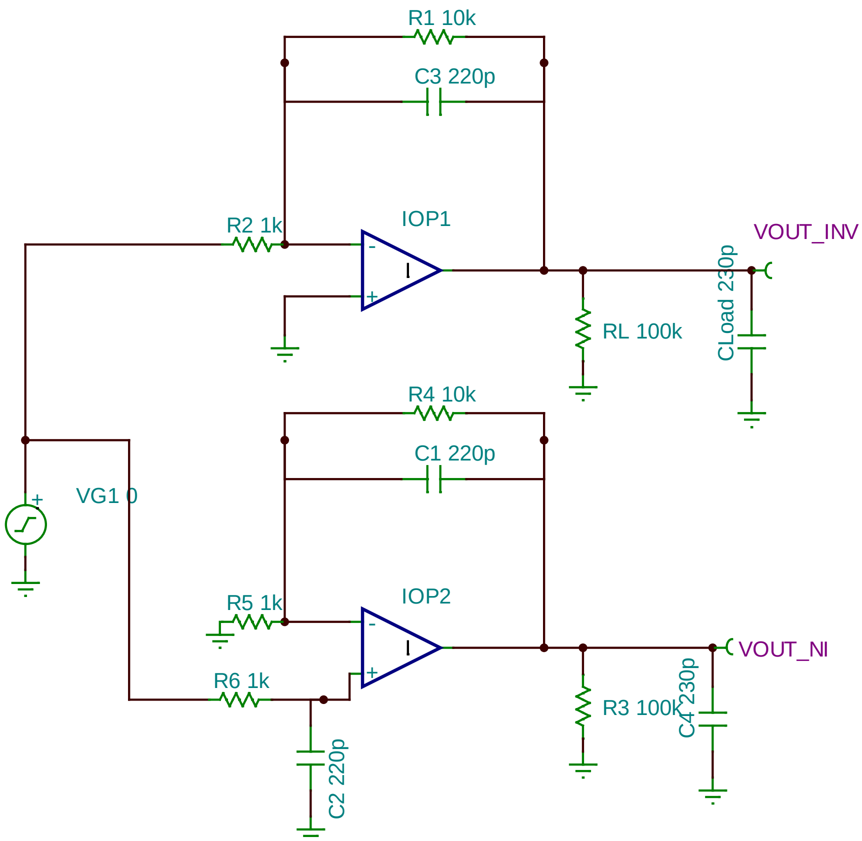

Figure 7 Ideal op-amp circuit model

The AP515 input (100 kOhm||230 pF) is included in the model, though it has no effect on the ideal circuit. In the non inverting configuration R6 is suggested by certain manufacturers to avoid a potential destructive latchup from input voltage applied before the op-amps are powered up. C2 was added to model the finite input bandwidth but isn't critical to the ideal simulation. R6 increases noise by 30% as can be seen in Figure 7 and Figure 8, so it's not a desirable thing to add to the actual circuit.

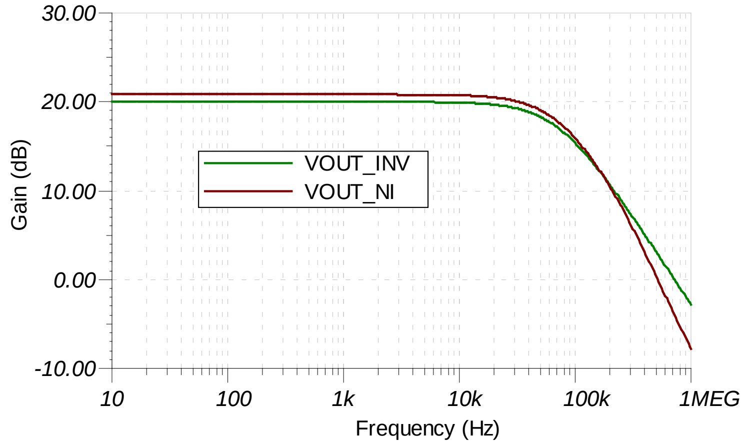

Figure 8 op-amp circuit bandwidth

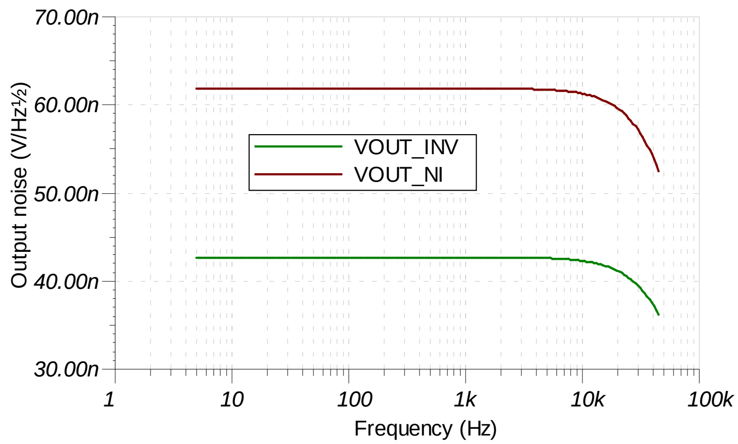

Figure 9 Output noise plot for ideal op-amp circuit

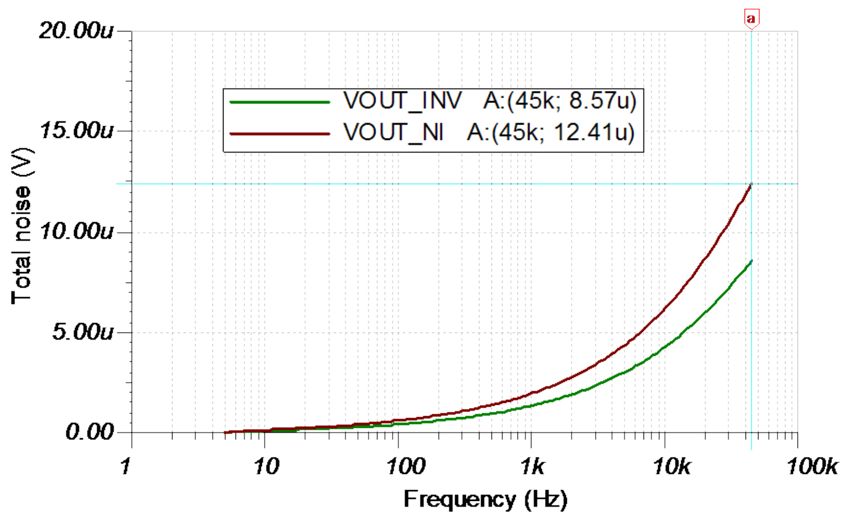

Figure 10 Noise contribution from ideal resistors

The calculated total noise (Figure 8) could be viewed as overly pessimistic as:

- The measurement bandwidth is 45 kHz and the noise contribution above 20 kHz is going to be inaudible
- An A-weighting curve[13] should be applied as human hearing sensitivity to low level sound drops off over 10 kHz even with young listeners and below 60 Hz on the low frequency end.

If used in a system with 1V RMS (0 dBV) as the nominal full scale output then the non-inverting noise would represent a SNR of 98 dB (45 kHz bandwidth). With a 20 kHz bandwidth the SNR would be 101 dB, the inverting configuration SNR is 104 dB. These are mediocre SNR performance numbers; the 0 dBV output level is a low assumption – most systems are probably designed for at least 10 dBV (12 dBU) output and sometimes more. While this yields a more respectable datasheet SNR of 114 dB, the actual system probably operates where 0 dBV is the nominal program content peak and the 10 dB is left as headroom.

The only way to improve the SNR is to lower the resistor values – everything else in the model described are ideal components with no noise. The real world will not be so kind.

XLR CABLES

A concern before starting the project was that the XLR cables used to connect the test jig to the AP would introduce noise that would swamp the measurements. Testing showed that this was not a concern if the cables were not subject to any mechanical forces. Touch them though and electro-mechanical effects come in to play.

Two different XLR M to F cables were compared:

- Talent brand 5' 22AWG microphone cables (Parts Express) SKU # MC05

[13] For low level broadband noise being masked by musical content A-weighting is a reasonable estimation of the audibility. Despite its continued use in SPL meters A-weighting is not useful for other types of noise (tones, music, mechanical) nor at louder levels.

- Blue Jeans cable 6’ cable with Neutrik connectors and Canare L-4E6S cable

With two cables connected end to end (for 10’ or 12’ total length) connected to the AP input and the far end not connected the following levels were observed at the measurement location (the cables were placed side by side and then coiled together on the floor):[14]

- Talent: 8.1 uV RMS noise
- Blue Jeans: 4.5 uV RMS noise

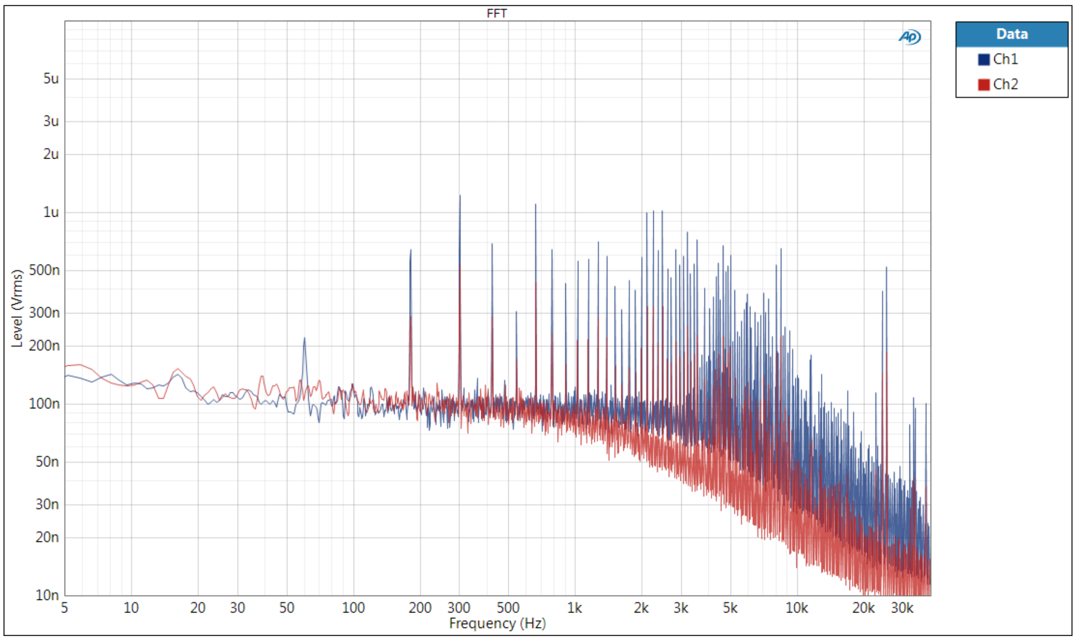

Figure 11 Ch1: Talent cable Ch2: Bluejeans “coiled on the floor” test (some of the peaks are AP noise)

The cables were swapped between the two AP inputs to verify that the measurements correspond to the cable and not the inherent differences in the AP515 inputs on this particular unit.

The Canare wire is most likely higher capacitance than the Talent cable (no data is available for Talent) and most likely results in a lower equivalent bandwidth and therefor the lower RMS noise measurement. With 1.25K ohm connected to the cable far end the noise measured is that of the AP and resistor noise (see part 2).

A tap test using a ruler was then performed. While there is no doubt significant variation in the force applied for this test, the AP measurements speak for themselves about the differences between the two cables. The Talent cable shows about 5 times the voltage level as the Blue Jeans (Canare wire) cable.

[14] 96K sample rate on AP, 45 kHz BW. 128K pt FFT (AP-equiripple window) with 16 averages (note 128 averages is used in a lot of the actual data gathered)

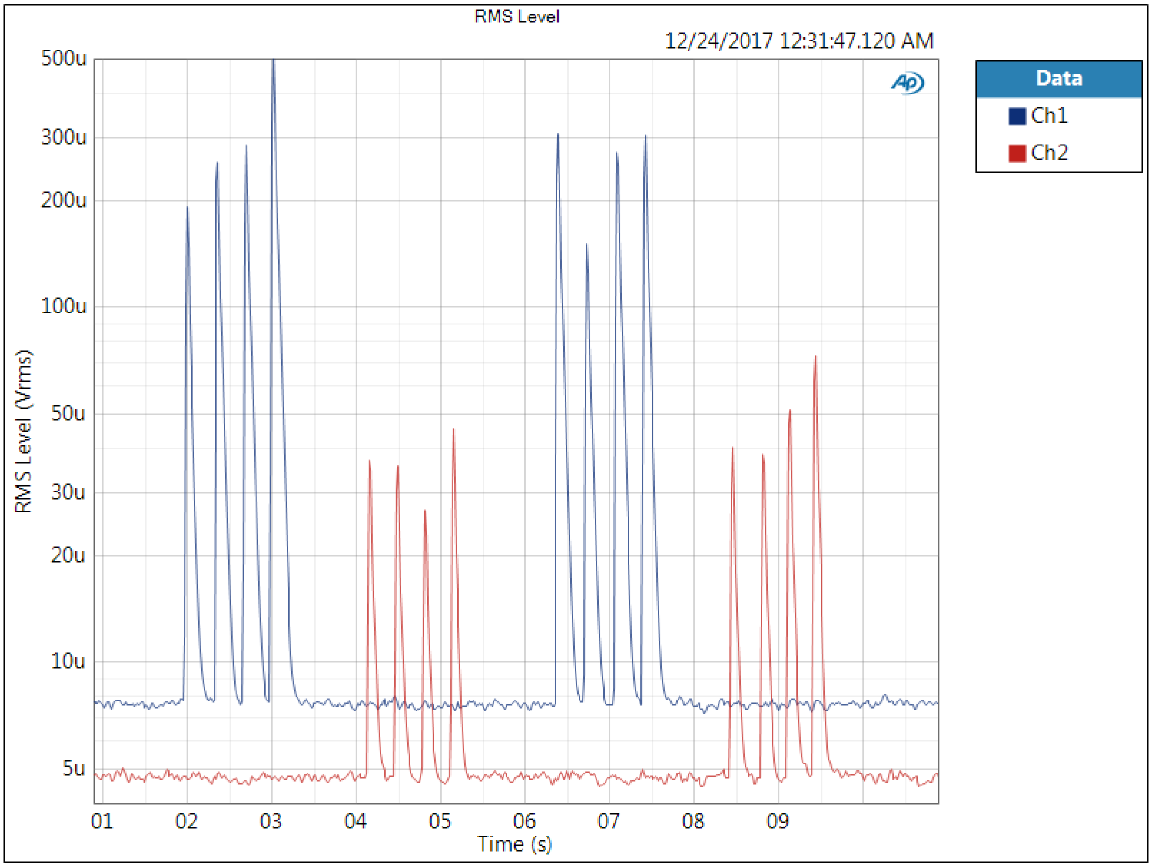

Figure 12 1 Ch1: Talent cable Ch2: Bluejeans (Canare wire) "tap test" (note the log scale)

An obvious question is if this is a meaningful indication that the cables are important. With the far end of the cable shorted the input noise is the same as that measured with the AP input shorted, and no electro-mechanical effects are observed.

With the cables connected to the test jig, the Canare cable shows only a very small (< 1 uV) effect of tapping on the cable (Figure 11).

Some general conclusions from this limited testing is that with sources with normal driving impedances the short length of cable is not going to be a factor in noise pickup from minor mechanical effects. EMI interference effects could not be readily ascertained; there was only a short length of cable involved in this test.

If the application had high source impedances then perhaps the differences observed would translate in to real world performance differences. Certainly the higher capacitance could come in to play.

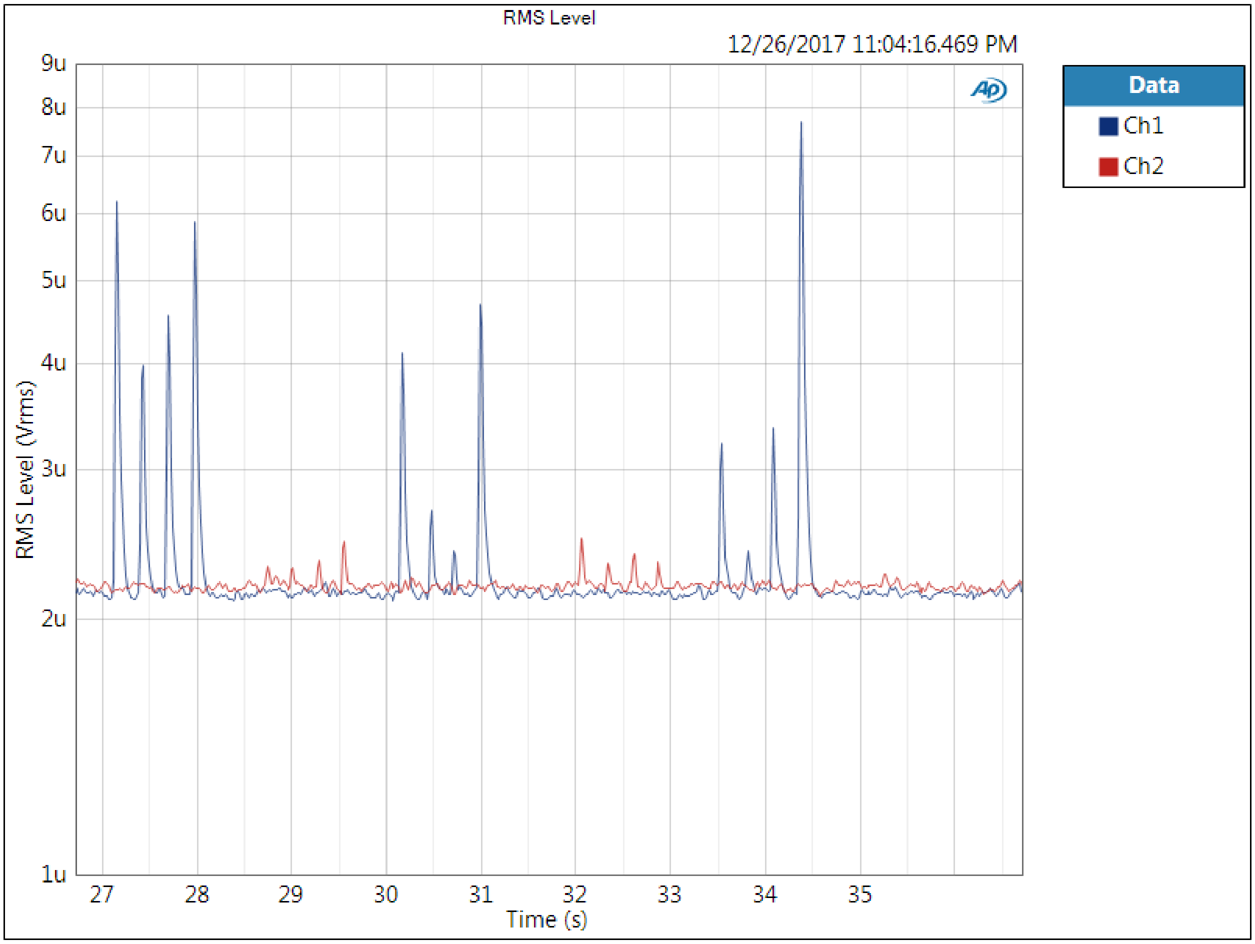

Figure 13 Talent cable tap test (ch1) vs. Blue Jeans (ch 2) with far end connected to 2.5 K ohm differential (1.25K to ground) impedance.

MEASUREMENT BANDWIDTH

Professional audio has settled on 96 kHz sampling for most recordings, and among the high end audio community interest in 96 kHz and above sampling rates has a small but growing following as more content is released. To not overlook issues in these applications the AP was operated with a 96 kHz sample rate, yielding a 45 kHz equivalent bandwidth.

With high impedance sources and the Blue Jeans XLR cables the bandwidth is somewhat less than 45 kHz. The change in total RMS noise changed only slightly: < 10%, or 200 nV RMS worst case.

OTHER TEST STRATEGIES

The AP515 has the ability to add DC offset and tests of individual components could be performed that way. This requires a second resistor to act as a divider (see *Self* Figure 2-9).

As little 1/f noise was detected using an AC waveform (which remains an issue to investigate at the time of writing) it suggests that the current op-amp approach for component evaluation will not show differences in parts. This is a huge result if that really is the case. OTOH there are op-amp circuits which do create a DC voltage across resistors

(ADC input offset is an obvious one) which might be more representative. Or perhaps a discrete (transistor) amplifier with its multitude of biasing resistors is an even better real world way to see what effect 1/f noise has in a real design?

For the best parts the AP instrument noise is of the same order as the effects being measured. For the 1/f noise calculations the noise level at 10 Hz was used as higher frequencies will be dominated by the Johnson noise. More averaging might allow for better resolution, but also would require further analysis that there isn't some systemic error at those frequencies that would confound the use of averaging to improve the estimate.

HIGH VALUE PARTS

The passive nature of the test bridge and the AP input impedance, as well as cable capacitance, limits the parts that can be tested to 10K ohms (though some 22K parts were tried to see the issues). Adding a low noise would lift that restriction for values up to a few megohms.

The question of noise from high value parts used to bias microphone capsules was raised. Evaluating noise from 1G ohm parts seems like an interesting issue for addressing in a separate effort.

ITEMS FOR IMPROVEMENT AND/OR FURTHER STUUDY

This was generated as the result of the work using the AP515 and documenting Parts 1, 2, and 3. These improvements would be for a rev 2 design and/or incorporated for testing with a LNA to measure parts with very low noise.

- Combine the main and bridge boards in to a single PCB: Eliminates the connector between the two, as well as a PCB will have less concerns about failure points than the protoboard version.
    - It may make sense to move the op-amp board to a separate enclosure, as it ultimately didn't share anything with the op-amp test
    - If a Low Noise Amplifier (LNA) is needed for the Wheatstone bridge output then there would be an op-amp section on the main board which could also be built with alternate resistors to see what impact that has on performance. This though would entail unsoldering parts vs. the small op-amp boards that can be unplugged/swapped out.
- Investigate metal foil resistors as the bridge reference for establishing the noise floor of the complete system measuring something other than input shorted. They're pricey but are considered the best choice.
    - At the moment thin film and wirewound noise is already below the AP515 measurement floor, so this might entail building some low noise preamps
- Investigate other brands of wirewound resistors as the reference. Standard wirewounds might be OK despite their inductance.
    - See if the high excess noise from the 2.5 K parts are related to that particular wattage (3W) and/or case size.
- Control for ambient temperature and measure it as part of the test protocol
- The observation of no obvious increase in 1/f noise with an AC stimulus needs further investigation
    - Some comments about AC generated excess noise were seen in some of the materials gathered but seen as a complicating factor best saved for a later investigation.
        - See for example research *chopper stabilized amplifiers* or *AC excitation of measurement bridges* for the theory behind what happens with non-DC application to the parts.

  - The op-amp circuits planned don't include a DC offset so in hindsight probably aren't the best way to show an effect.
  - OTOH they are typical of many applications, which raises the question of exactly when to be concerned about excess noise.
- Record and listen to the noise for the DUT to determine if the averaging process is hiding differences from ideal 1/f+Johnson noise. For example popcorn noise might be expected at some level.
- Synthesize various levels of 1/f noise and listen to just noise as well as noise+content over a high quality reproduction system to determine audibility. Presumably this is best done with a mono set up?
- Add reference noise index lines to the captured plots (like -40 and -20 dB)
  - RREF's unexpectedly high 1/f does provide a reasonable reference line of -34 dB, so perhaps that is good enough.
- Develop an AP script to average 30 seconds of RMS readings instead of having to export to a spreadsheet.
- Allow for an external supply. The 9V batteries can't power lower impedance bridges. 12V sealed batteries are cheap and might be an option. Or a bench supply if it doesn't introduce noise. A center off DPDT power switch, with one side for the 9V battery and the other to a set of binding posts for an external supply?
- The AP515 THD+N floor was above the expected values for most of the resistor types for THD measurement. The AP555 should provide the needed resolution (-102 dB vs -117 dB)
- Variation of about 20% in the low frequency 1/f noise spectrum between the two AP515 channels was noted when measuring a DUT made from the same 2.5 K ohm wirewound parts as the RREF.
  - Develop some sort of calibration method to determine if there is a real difference in the AP; it's possible that the variation is mostly explained by the parts behaving differently.
- Instrument 1/f noise on the AP515 must be considered for the measurements for the low noise thin film resistors, though the general noise floor of the AP515 is of equal level for measuring excess noise for low noise resistors.
  - After measuring an AP555, it was determined a low noise preamp is needed even with the AP555.
- The NE5532 op-amp is not specified for THD+N. *Self* indicates different manufacturer's parts perform differently. Characterizing that would be interesting.
- Investigate other (lower cost) XLR cables and/or define a test to determine if they generate noise.
  - Shorter cables with lower capacitance might be helpful; one of the reasons for the longer cables was to place the test jig away from the AP, laptop, etc., to reduce the chance of pickup of stray EMI.
- If hardware is redesigned then where internal connectors are used consider Molex KK series or similar
- The shrouded 10 pin header used for mounting the DUT bridge (see Figure 20) made it possible to mis plug the header in to the socket without realizing it. Non shrouded headers were obtained for subsequent use.
- Determine if a low noise preamp would allow for a wider range of test gear for the analysis portion
  - This would only help with the noise measurement, not distortion measurement, unless the amplifier was very special
  - Connecting to a PC soundcard exposes the system to all sorts of possible contaminating noise sources

COMMENT ON THE TEST FIXTURE GOAL

While the test fixture is simple and proven to be flexible enough for the purposes of this evaluation, it does rely on an Audio Precision or other similar instrument with a low noise, low distortion sensitive balanced input and extensive software for data capture and analysis.

While businesses and research facilities would have such instruments around, they are usually only found on the benches of the most dedicated independent developers.

Use of a high quality USB ADC/DAC with balanced analog I/O would be possible by adding a low noise preamp to the test fixture (see *Siefert* for discussion). Software supporting the spectrum and RMS measurements would be needed; there are several free and low cost packages that might work well for this.

Adding the ability to not require an AP would make an excellent task for follow on work to expand testing to a wider audience.

ABW considers itself very privileged to have had the support of loaned equipment from Audio Precision in developing this report.

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For all parts of this study.

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APPENDIX A – SCHEMATICS

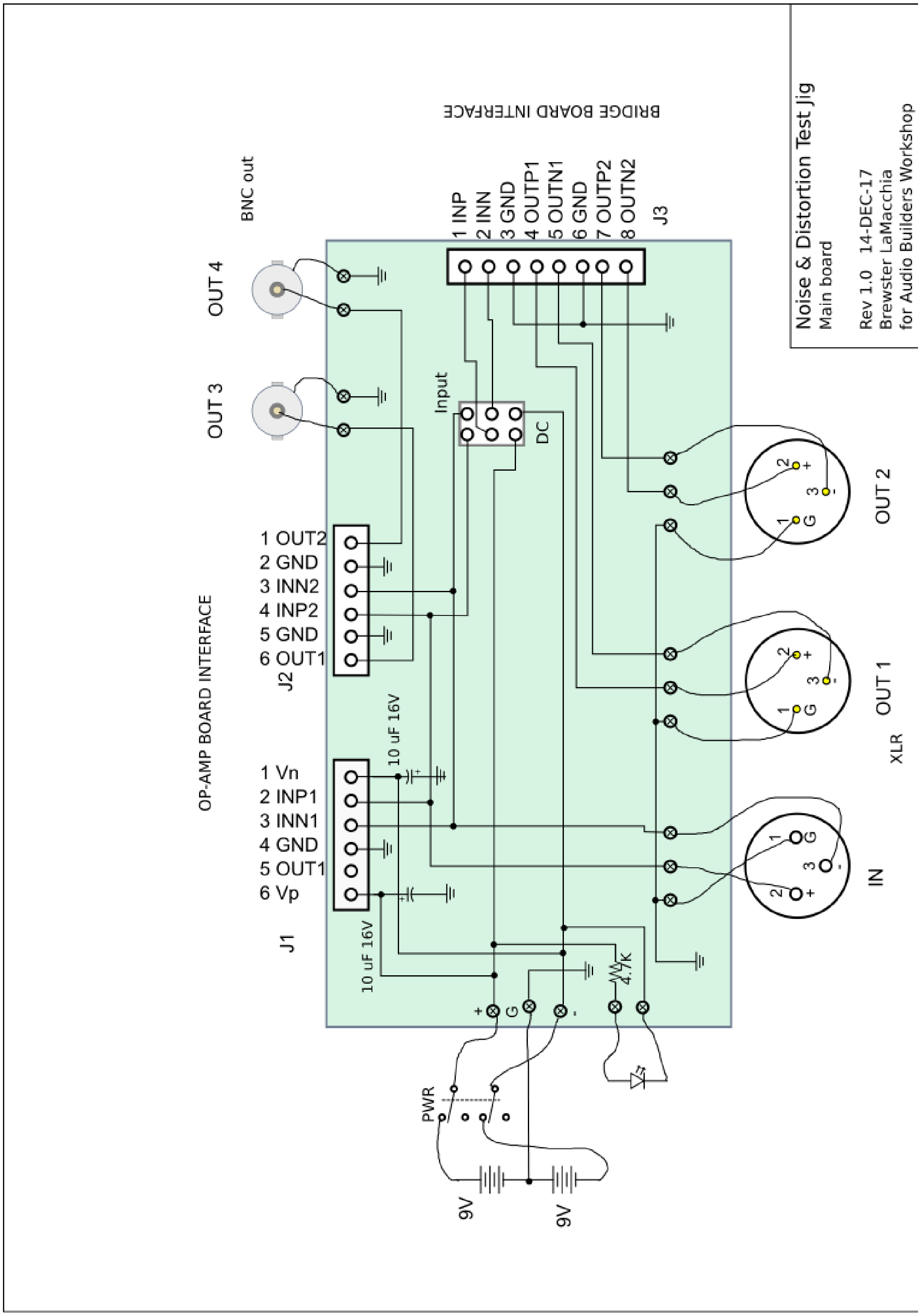

Figure 14 Main board schematic

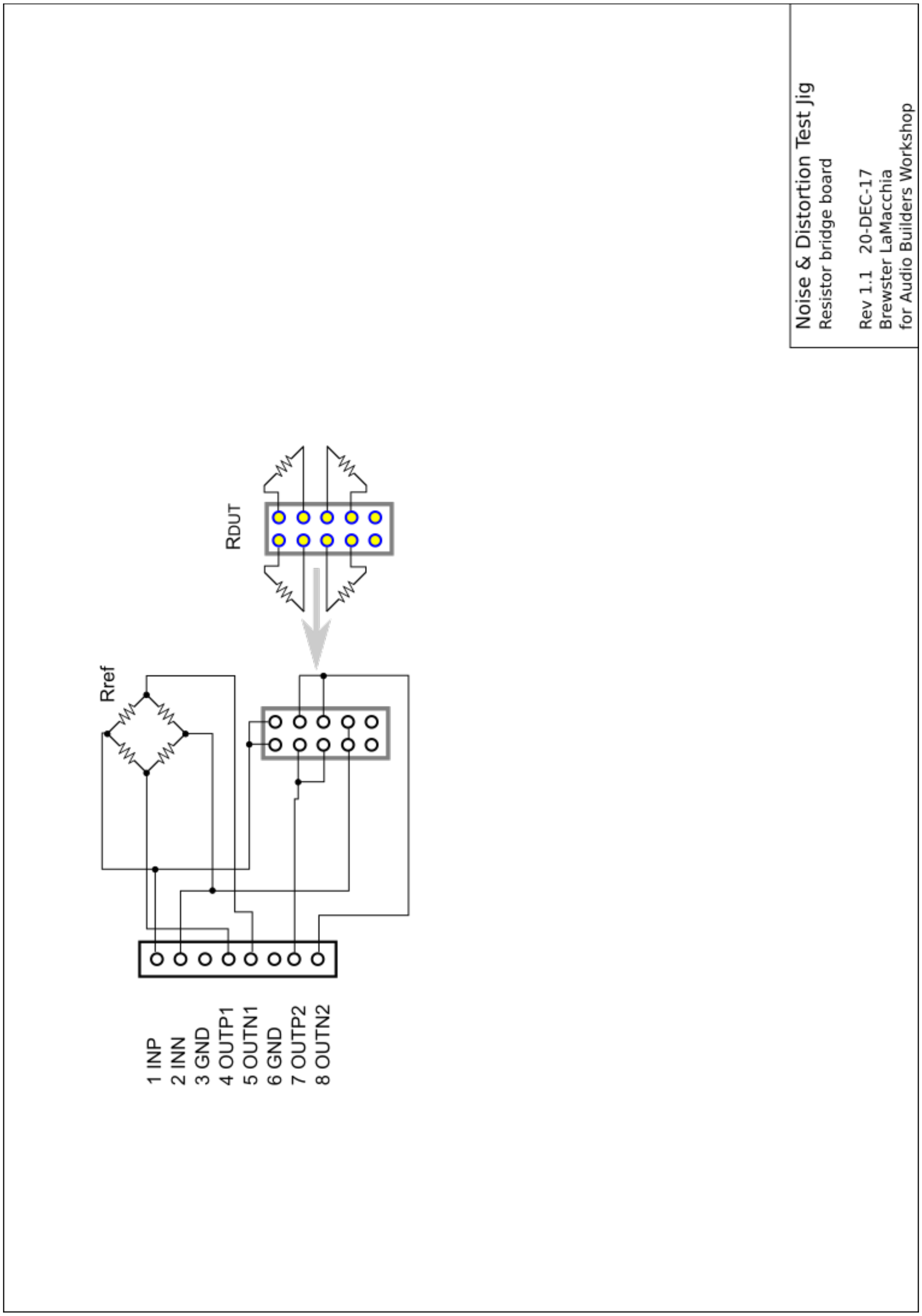

Figure 15 Bridge board schematic

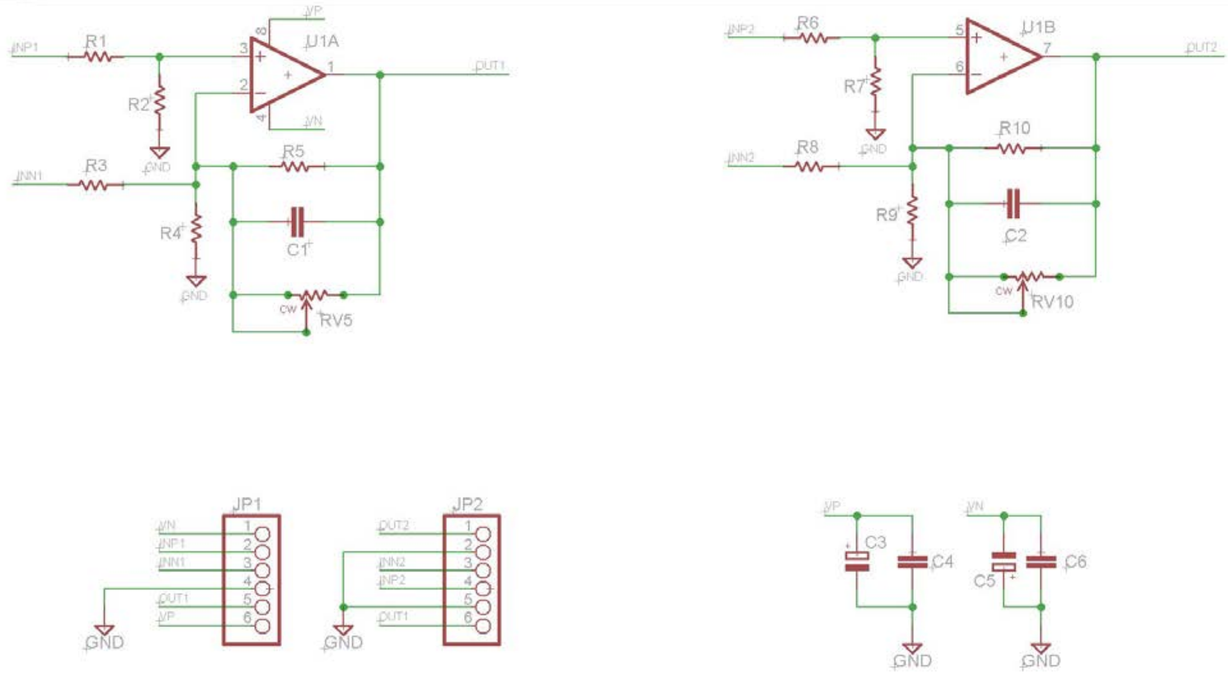

Figure 16 Op-amp eval board schematic

APPENDIX B – PICTURES

Figure 17 System construction (rear panel, prior to op amp board connection)

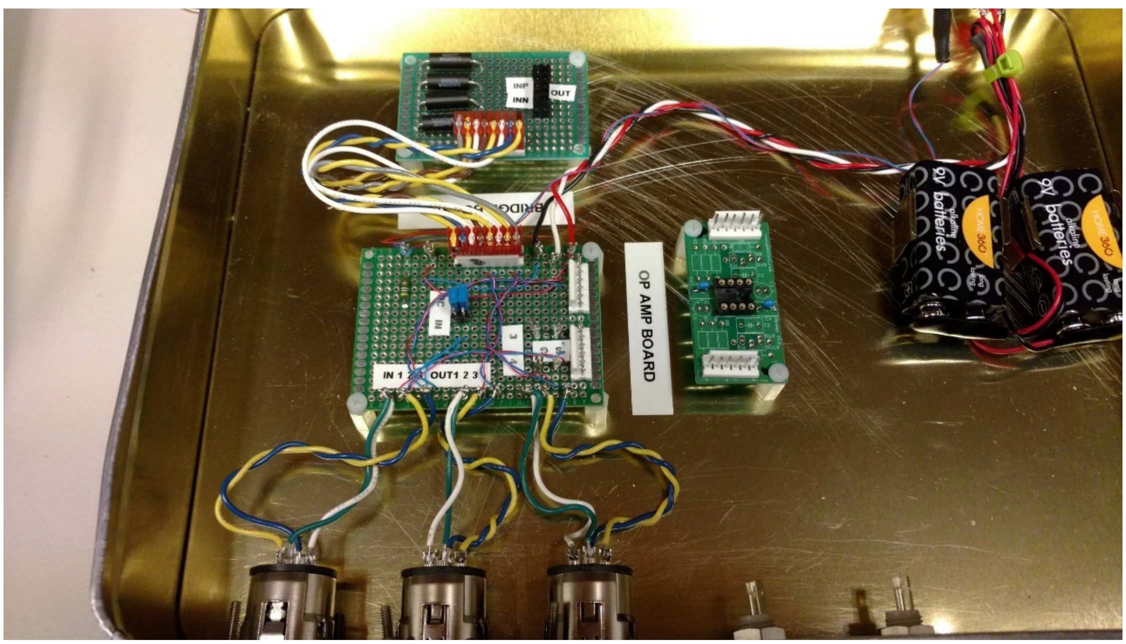

Figure 18 Top view. Resistor test (bridge board) at top

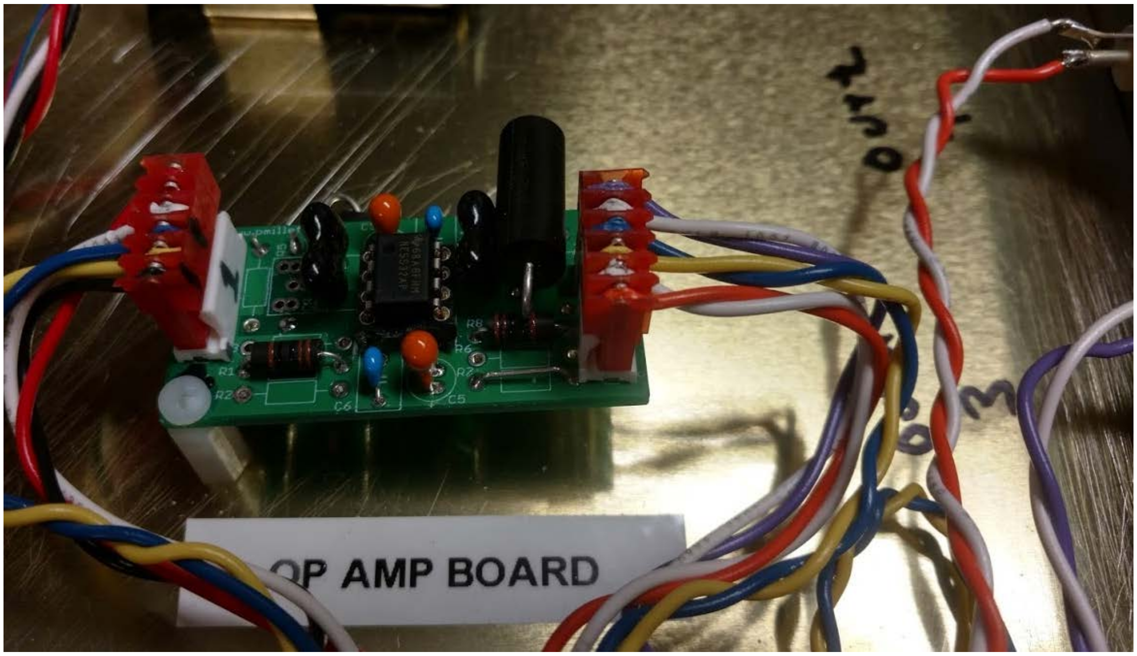

Figure 19 Op amp board configured for circuit evaluation with wirewound resistors

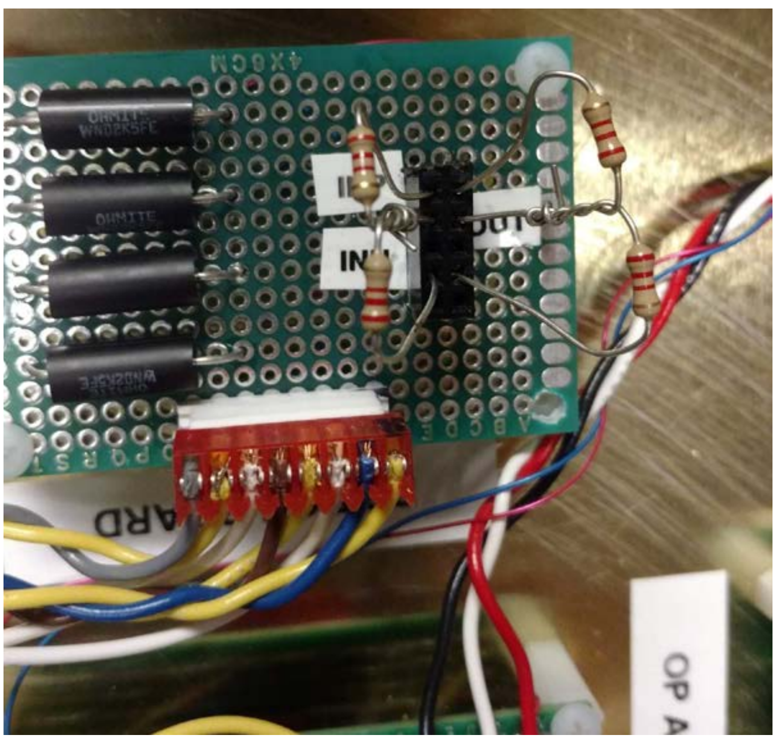

Figure 20 Testing axial resistors in the bridge configuration

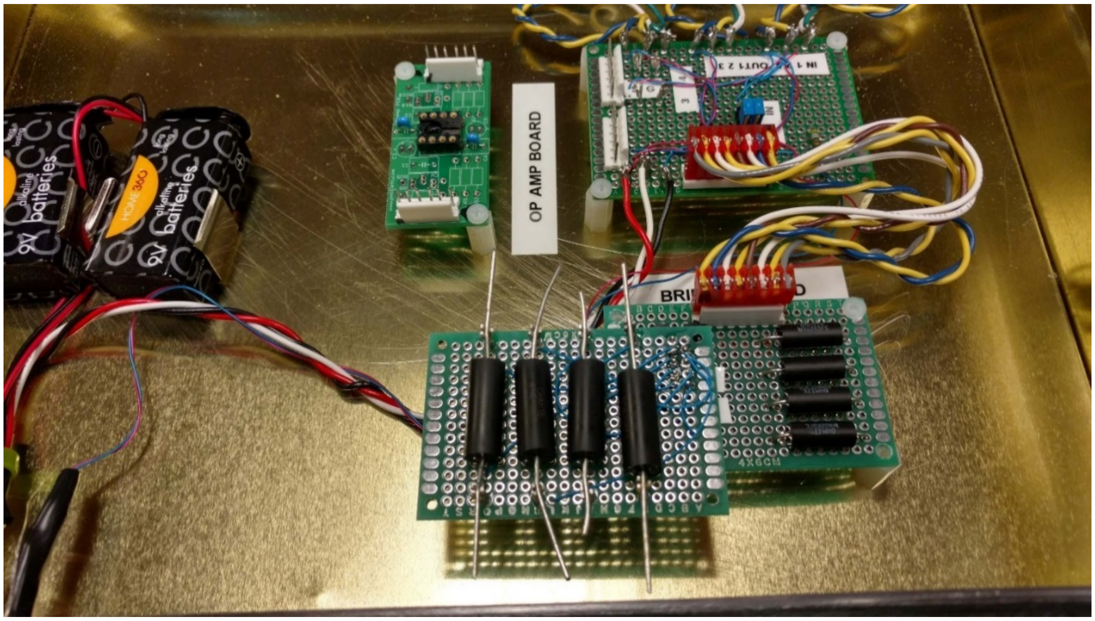

Figure 21 Testing oversize 10K 5W wirewounds with a plug on board. Leads were not trimmed so parts could be reused.

Figure 22 Header with 0603 resistors

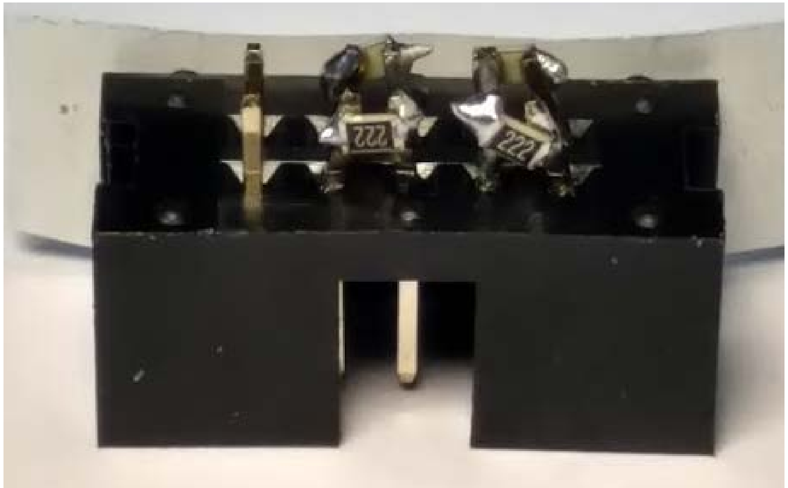

Figure 23 Header with 0805 resistors

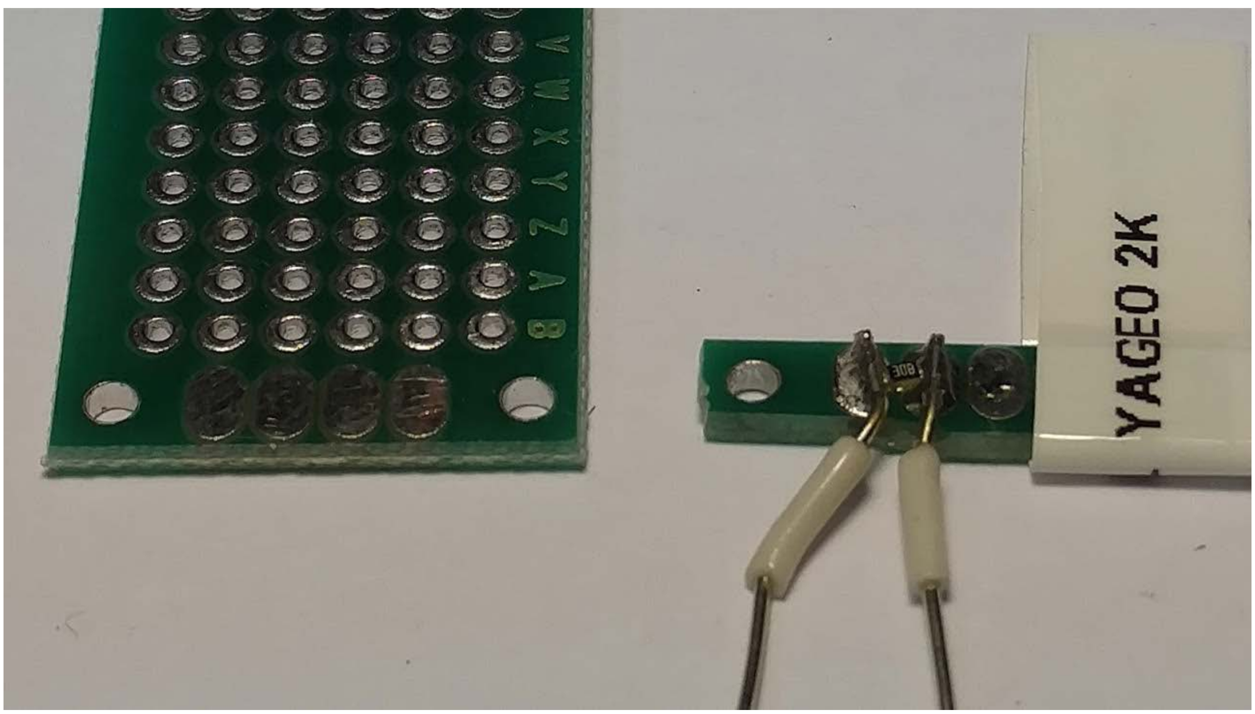

Figure 24 Single resistor holder (on right) made from proto PCB (on left)

Figure 25 Unshrouded header for resistors. A little fragile but is easier to mate correctly than the shrouded one