My resistors are better than your resistors

BUT DOES IT MAKE A DIFFERENCE?

Presented by:
Brewster LaMacchia

Clockworks Signal Processing

http://clk.works

Notes for pdf version

- Based on presentation at the Boston AES meeting held 27-Feb-2018
- This slide deck contains some backup slides not presented in the original slides
- Media files can't be included in a pdf, so they have been posted to:
  - http://clk.works/2018/02/resistor-noise-presentation/
- There is a corresponding paper that this PPT was based on, search here: http://clk.works/blog/
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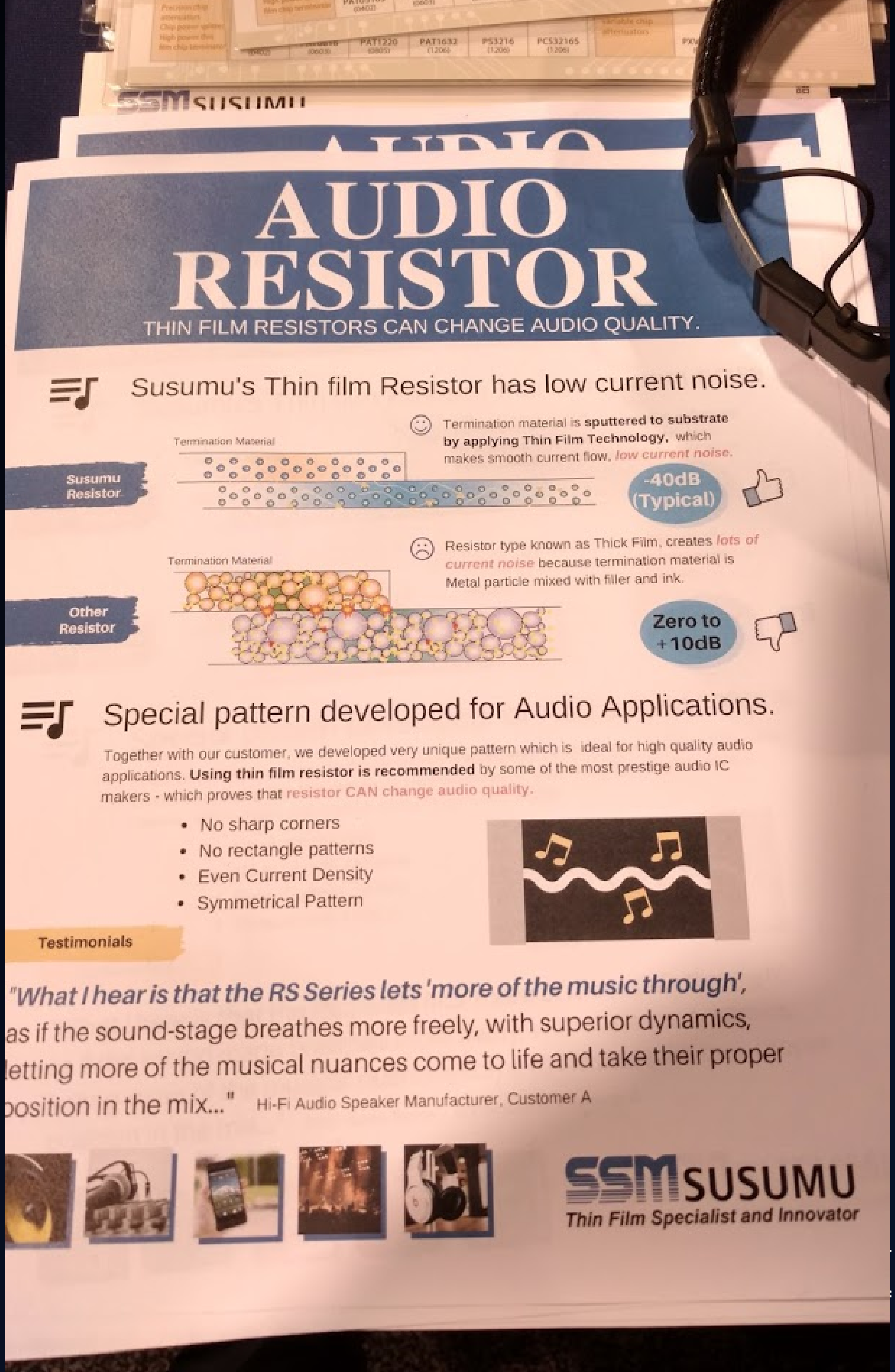
One day at AES



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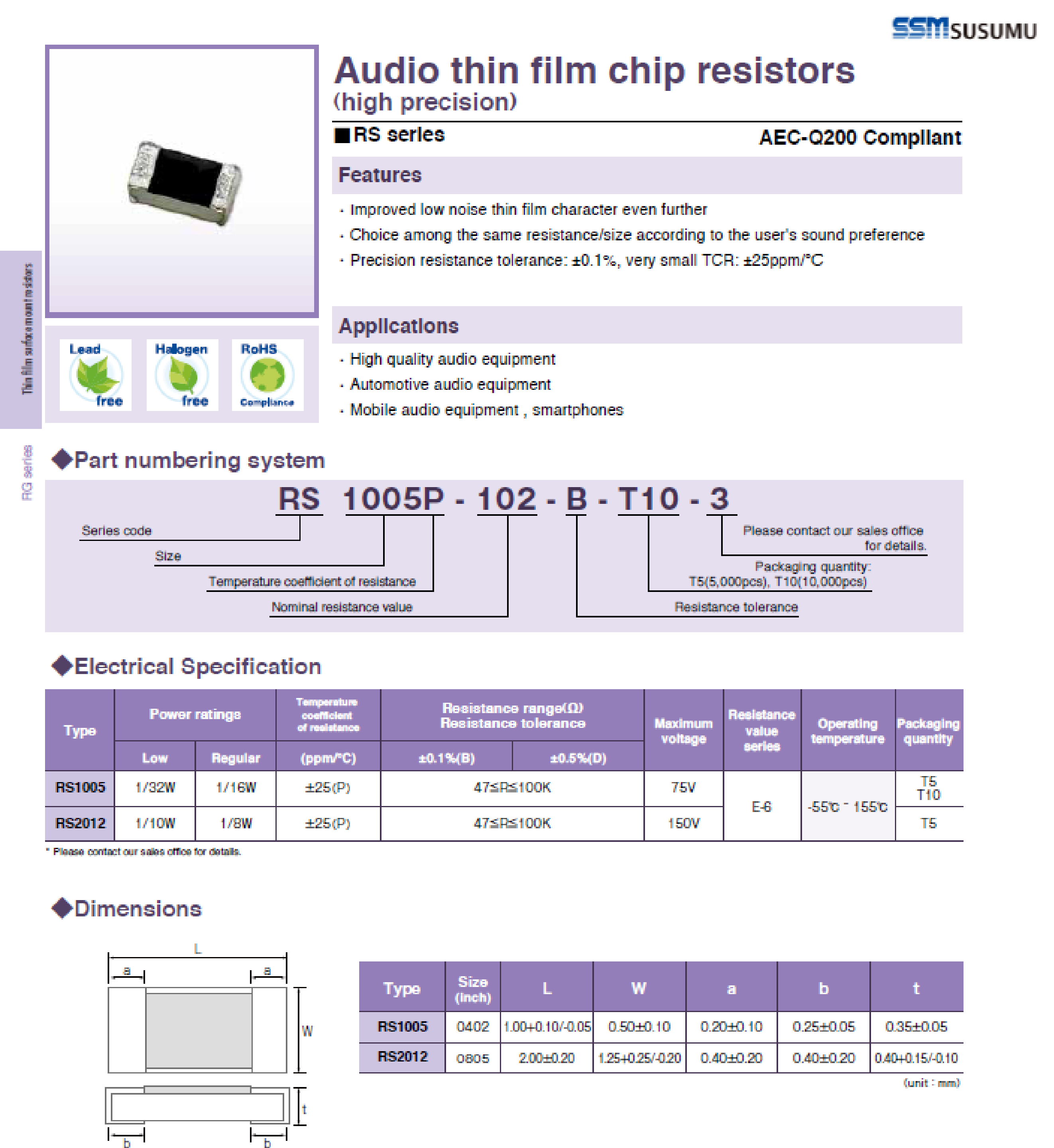
Hmm, datasheet isn't helpful!



SSM SUSUMU

Audio thin film chip resistors
(high precision)

■RS series AEC-Q200 Compliant

Thin film surface mount resistors

RG series

Lead free · Halogen free · RoHS Compliance

Features
- Improved low noise thin film character even further
- Choice among the same resistance/size according to the user's sound preference
- Precision resistance tolerance: ±0.1%, very small TCR: ±25ppm/°C

Applications
- High quality audio equipment
- Automotive audio equipment
- Mobile audio equipment , smartphones

◆Part numbering system

RS 1005P - 102 - B - T10 - 3

- RS: Series code
- 1005: Size
- P: Temperature coefficient of resistance
- 102: Nominal resistance value
- B: Resistance tolerance
- T10: Packaging quantity: T5(5,000pcs), T10(10,000pcs)
- 3: Please contact our sales office for details.

◆Electrical Specification

Type	Power ratings		Temperature coefficient of resistance	Resistance range(Ω) Resistance tolerance		Maximum voltage	Resistance value series	Operating temperature	Packaging quantity
	Low	Regular	(ppm/°C)	±0.1%(B)	±0.5%(D)				
RS1005	1/32W	1/16W	±25(P)	47≦R≦100K		75V	E-6	-55℃ ~ 155℃	T5 T10
RS2012	1/10W	1/8W	±25(P)	47≦R≦100K		150V			T5

* Please contact our sales office for details.

◆Dimensions

Type	Size (inch)	L	W	a	b	t
RS1005	0402	1.00+0.10/-0.05	0.50±0.10	0.20±0.10	0.25±0.05	0.35±0.05
RS2012	0805	2.00±0.20	1.25+0.25/-0.20	0.40±0.20	0.40±0.20	0.40+0.15/-0.10

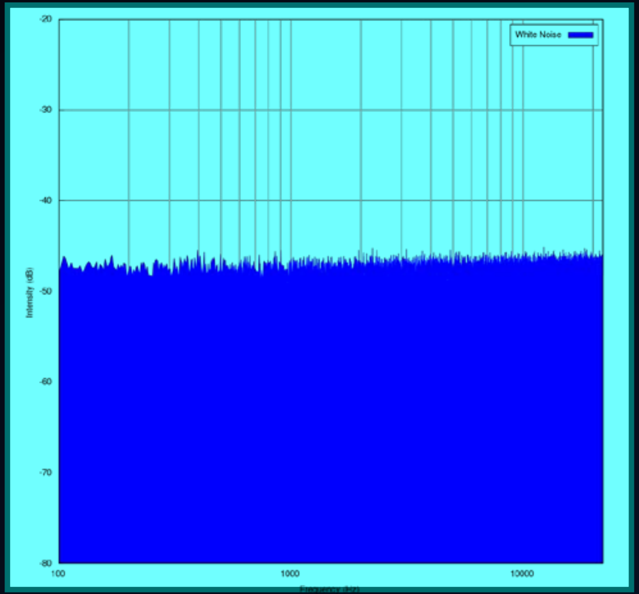
(unit : mm)

Noise

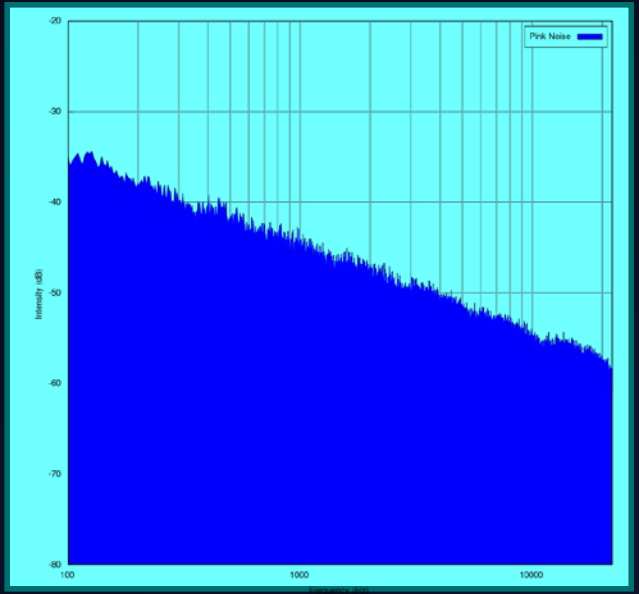
ONLY CONSIDERING THE MAJOR SELF GENERATED NOISE SOURCES FOR PASSIVE COMPONENTS

Noise…

- White
  - Equal energy at all frequencies
    - Flat spectrum



- Pink
  - Equal energy per octave
    - 3 dB falloff per octave
      - Or 10 dB/decade



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1/f noise

$$S(f) \propto \frac{1}{f^{\alpha}}$$

- For what we're interested in $\alpha \approx 1$
- Which is the same as pink noise
  - Also called flicker noise
- 1/f spectrum occurs in nature
  - Earthquake magnitudes, ocean currents, physics, etc.
  - Causes are not always well understood

Shot noise

- To fully explain have to include quantum effects of charge carriers (electrons in our case) moving through conductors
  - Versus white noise, which is from random thermal motions of the carriers
- Mostly a concern in very sensitive electronics where the number of charge carrier per unit time (i.e. current) is small
  - Only a function of current; the higher the current the lower the noise value

1/f + Johnson noise are the most common sources in resistors

Note the Y axis is noise density in units of

$$\frac{V}{\sqrt{Hz}}$$

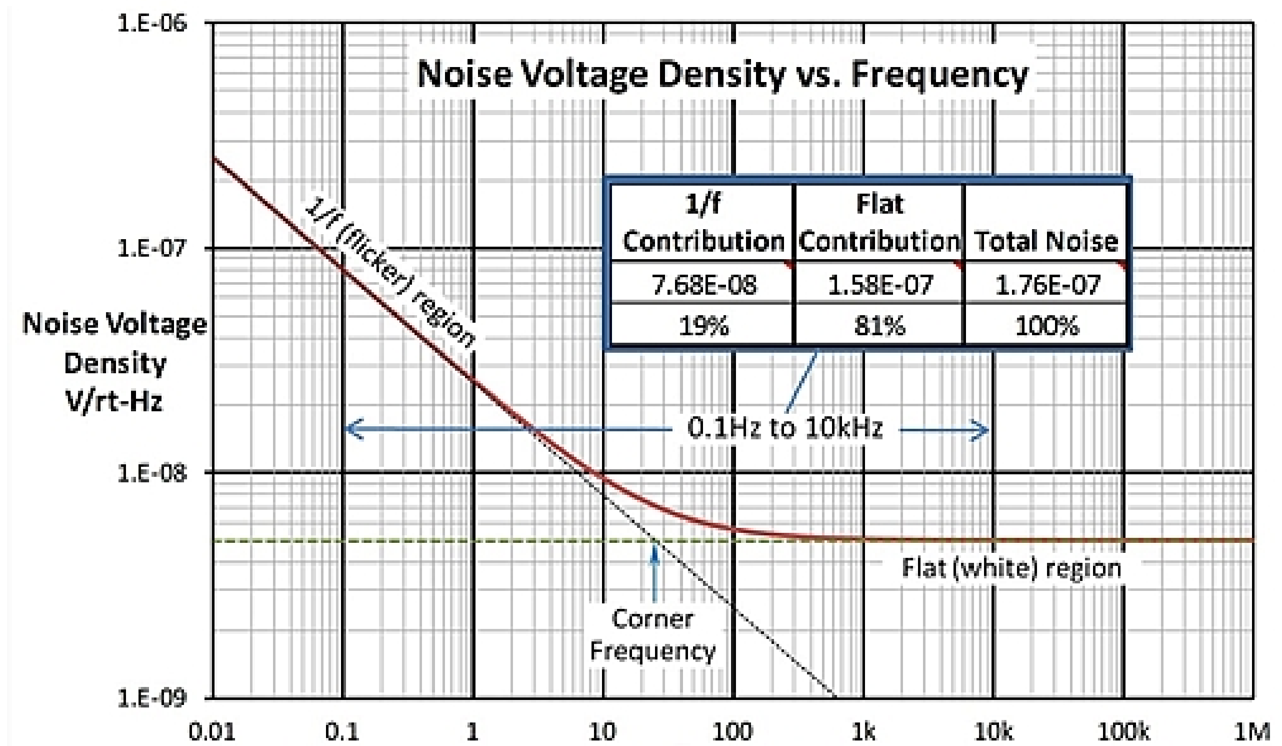

Figure 2.

Bruce Trump, *1/f Noise—the flickering candle*, from: https://www.edn.com/electronics-blogs/the-signal/4408242/1-f-Noise-the-flickering-candle-

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Resistors

- An essential component in any electronic circuit
- All generate White noise

- Formal name is Johnson-Nyquist noise
- $v_n = \sqrt{4\, k_B\, T\, R\, \Delta f}$

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Resistor noise sources

- Johnson noise is only a function of resistance and temperature
- 1/f noise is a function of current and material/component design
- Shot noise is a function of current and material /component design

Defining excess noise

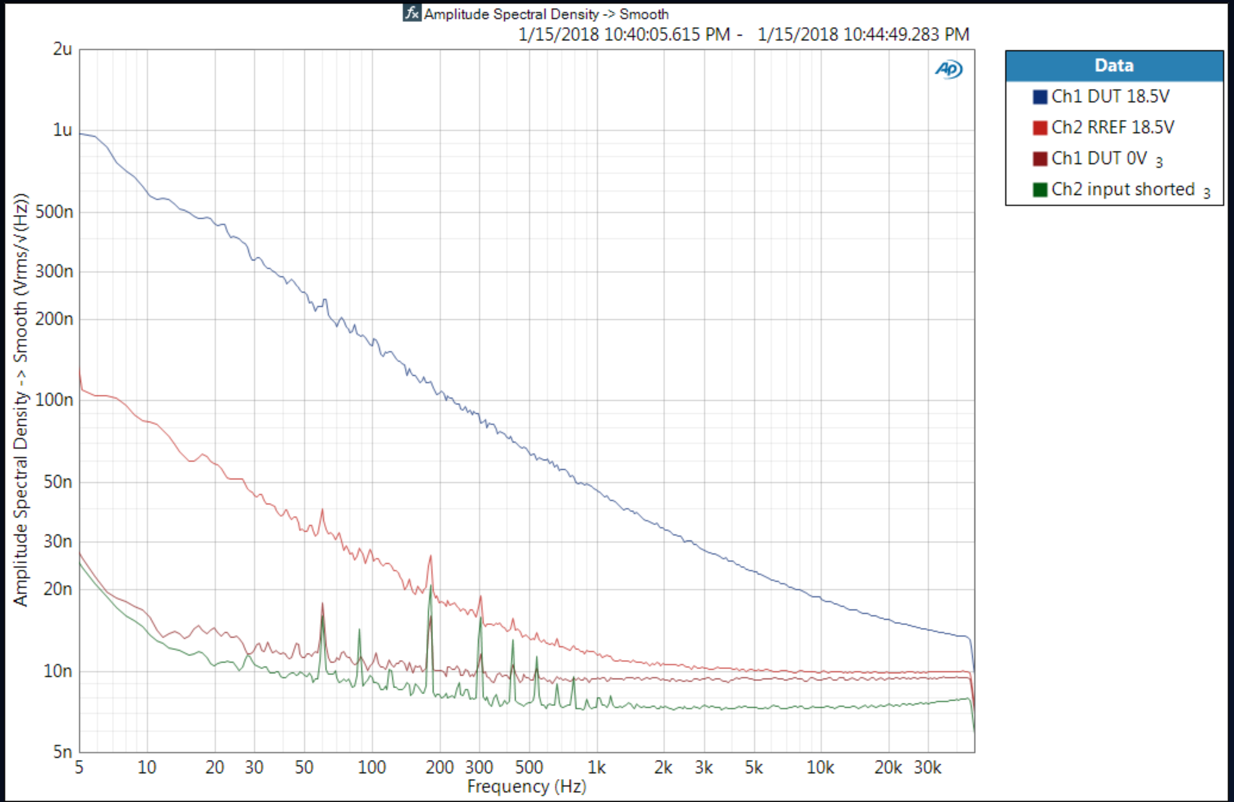
- There are some standards for this, but they aren't always helpful for low noise parts in the audio band
  - See for example MIL-STD-202G
- The excess noise index (NI) measured in dB:

$$NI = 20\log_{10}\left(\frac{v_{\text{rms}}}{V_{\text{DC}}}\right)$$

  - Where
    - *V*rms total noise power in a decade in uV (micro volts)
    - VDC is the applied DC voltage (in volts)
  - For 1/f noise it doesn't make a difference which decade you use!
    - If you can get clear measurements…

Examples

- Instrument noise [equiv to NI of -48 dB]
- 2K resistor noise, no voltage applied
- 2K resistor with 18V DC applied [NI -18 dB]
- RREF with 18V DC applied [NI -34 dB]



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Resistor noise based on technology

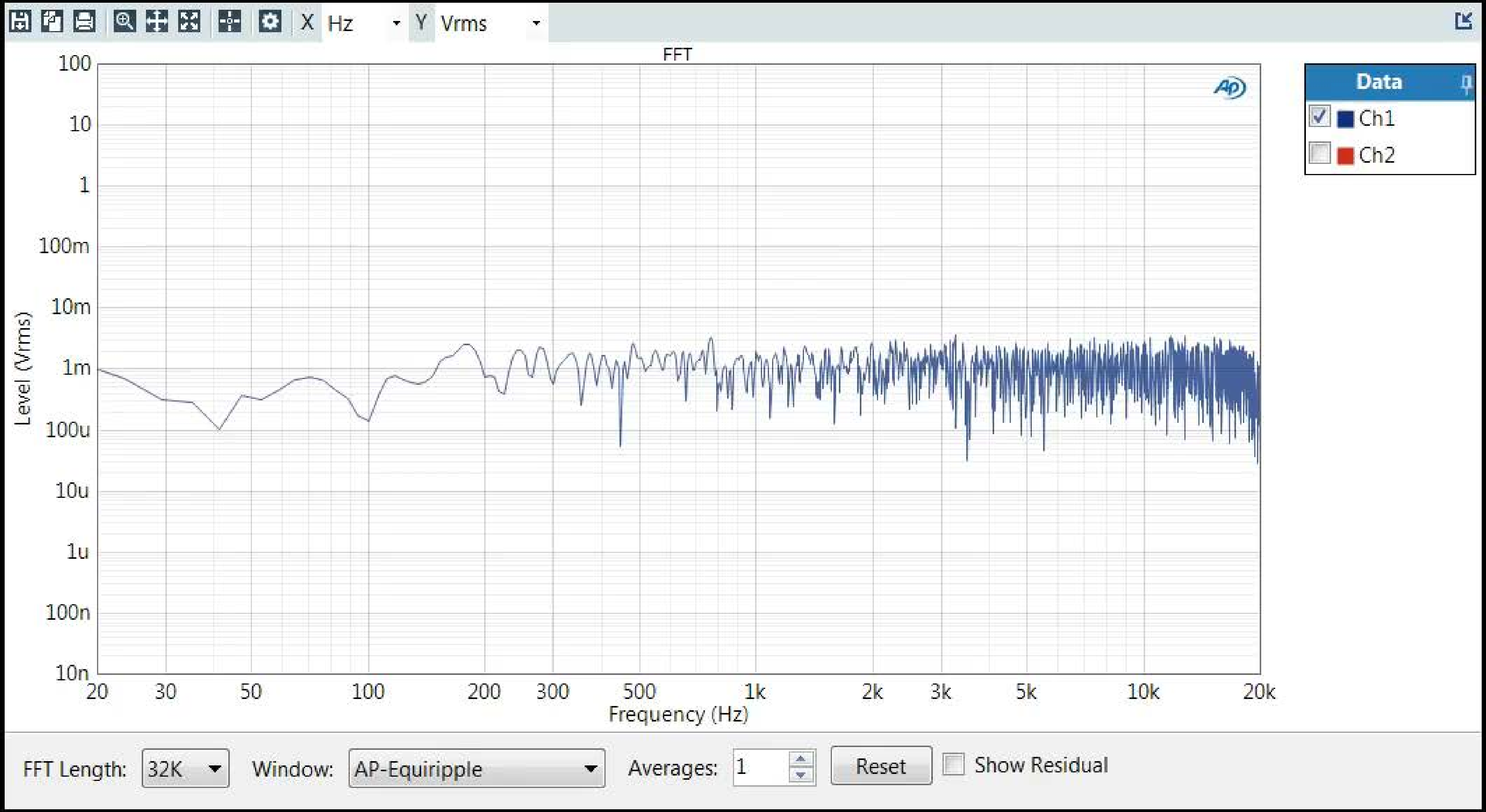
- Mostly a function of the technology used
  - Carbon resistors: Very high noise and other nasties associate with that "old time warm sounding tube stuff"
    - Johnson noise way above theoretical values
    - High 1/f noise, potential for shot noise
  - Thick film resistors (< $0.01)
    - Not as bad as carbon resistors, but not good
  - Thin film resistors ($0.10 - $0.50)
    - Way better, limited excess noise
  - Wirewound ($1-$5, very large)
    - Theoretically almost ideal
  - Metal foil (> $10 unless they are very low value)
    - As close to perfect as you can get…if you don't care about $$$

Measuring excess noise

UNDERSTAND YOUR TOOLS

Spectrums

- Created by transforming time domain data to the frequency domain using the Fourier transform
- In sampled systems the Fast Fourier Transform is typically used
  - Finite sample windows creates spectral artifacts
  - Window functions can reduce this but introduce other issues
    - One way to lessen some issues is to use large FFT sizes, like 128K sample points
- When measuring noise – the data is noisy!
- Averaging and smoothing helps to make the plots easier to interpret



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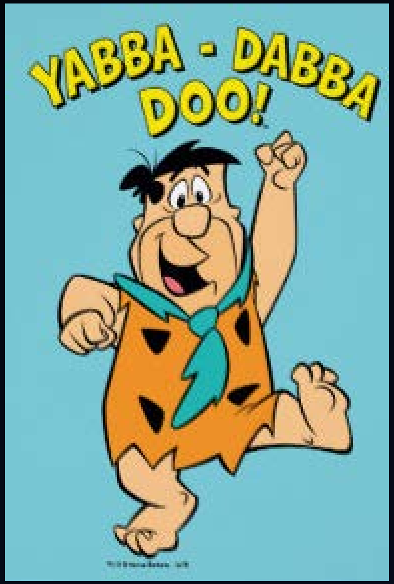
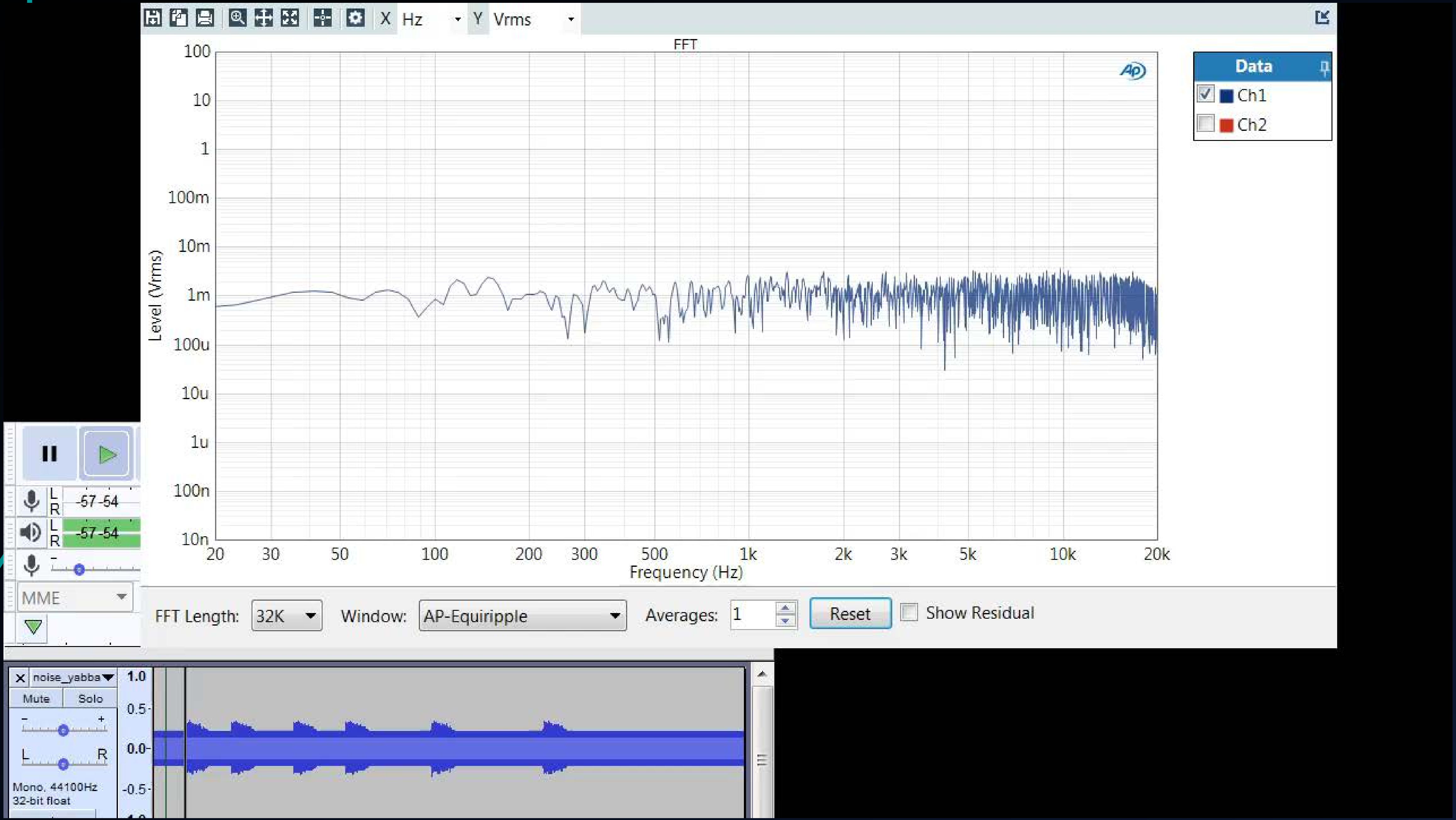
Spectrum looks perfect?



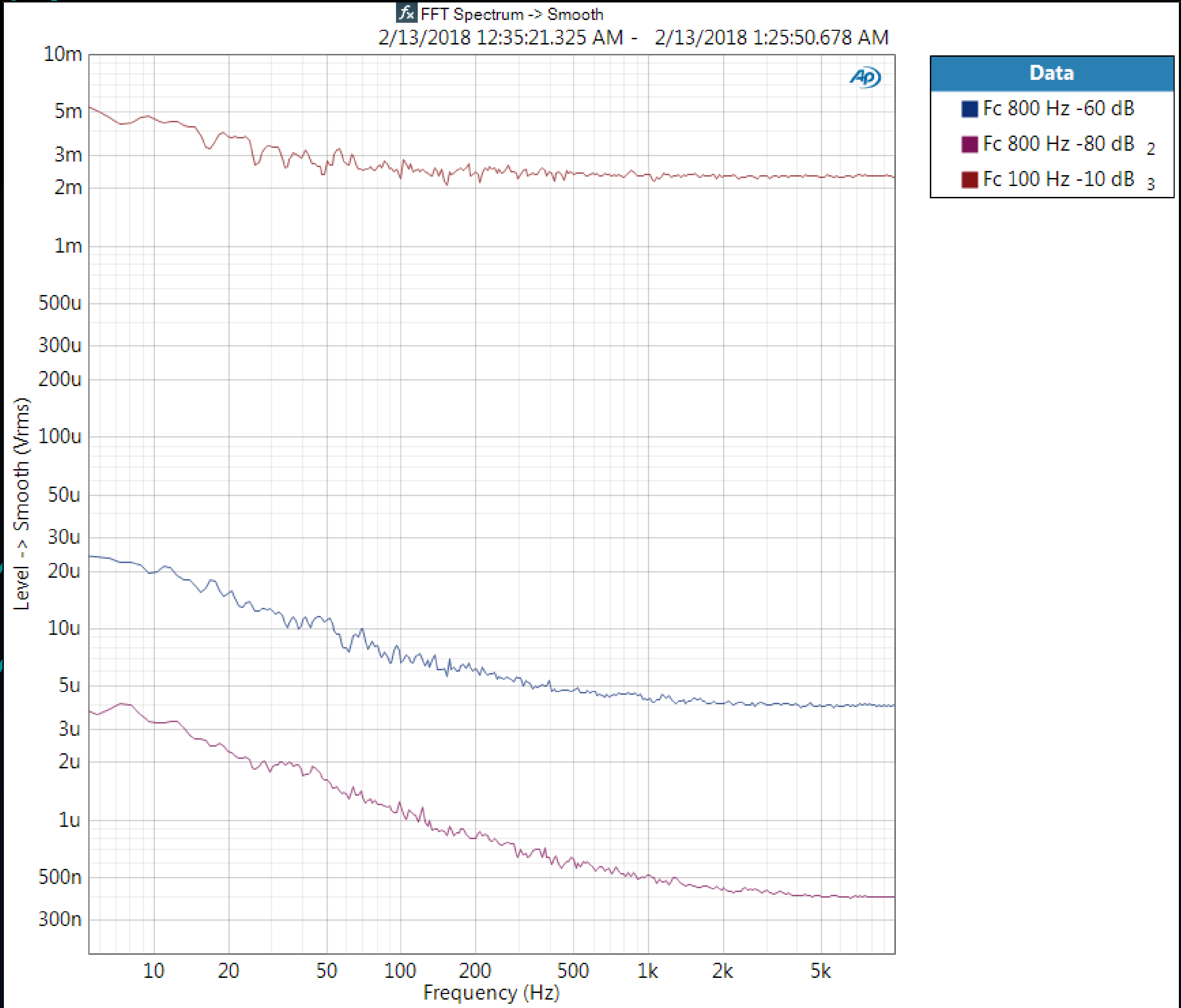
- Might not sound perfect…


X Hz Y Vrms
FFT
100
10
1
100m
10m
1m
100u
10u
1u
100n
10n
Level (Vrms)
20 30 50 100 200 300 500 1k 2k 3k 5k 10k 20k
Frequency (Hz)
Data
Ch1
Ch2
FFT Length: 32K
Window: AP-Equiripple
Averages: 1
Reset
Show Residual
-57 -54
-57 -54
MME
noise_yabba
Mute
Solo
L R
Mono, 44100Hz
32-bit float
1.0
0.5
0.0
-0.5


the noise
"Can you hear me now?"

White + pink noise

- Example using Audacity to mix pink and white noise to emulate resistor sources
- Fc (frequency from where transition from white to pink happens) determined by measurement
- Create initial full scale track and then reduce its gain for mixing



Playback spectrums captured with AP 515 128K pt FFT, AP-Equiripple window. 1/24 octave smoothing.

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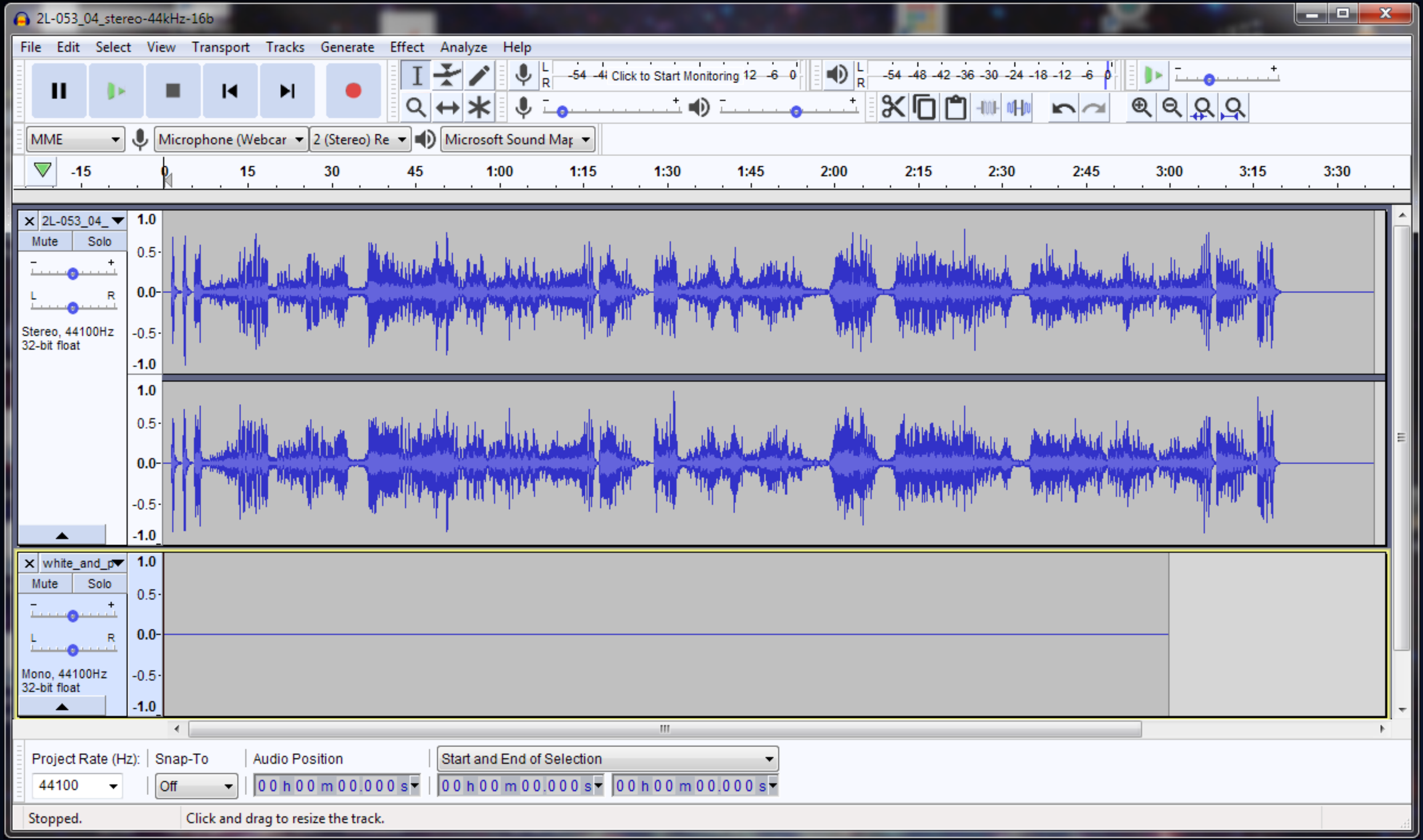
Using Audacity to play different music + noise mixes



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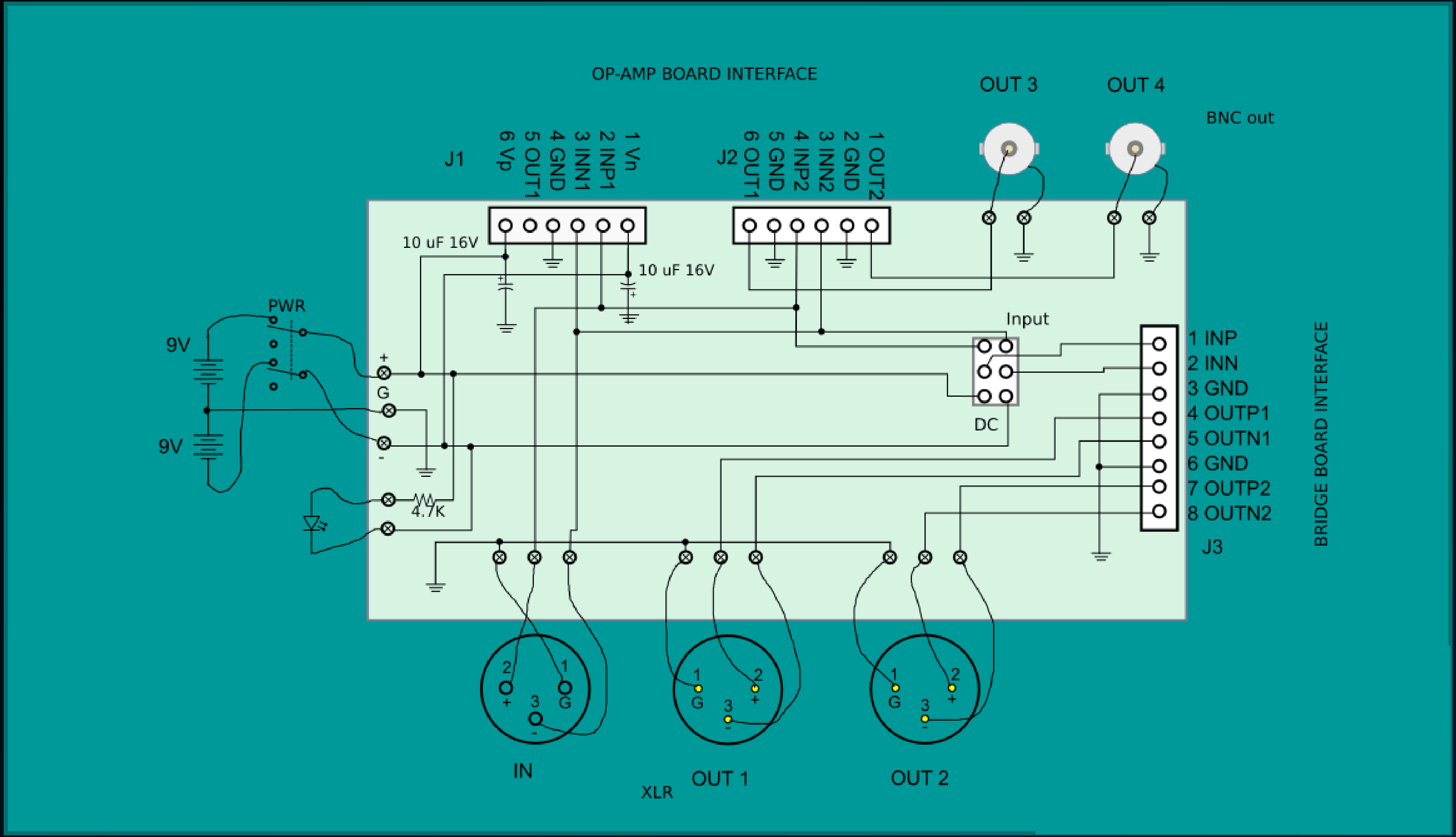
What resistors really do

WE HAVE THE TECHNOLOGY TO MEASURE THIS STUFF

Test fixture

- Provides two ways to measure
  - Wheatstone bridge configuration for determining the Noise Index (NI)
    - The *Seifert* paper (LIGO) is the primary guide
      - He already answered our questions!
      - But that is NOT what science is about…
  - Op-amp circuit for real world measurements in an actual application
- Needs a low noise measurement system
  - AP 515 used for initial validation
    - Good enough to draw some opinions on the questions posed
    - High accuracy 1/f noise will need a LNA (Low Noise Amplifier)

Test fixture diagram



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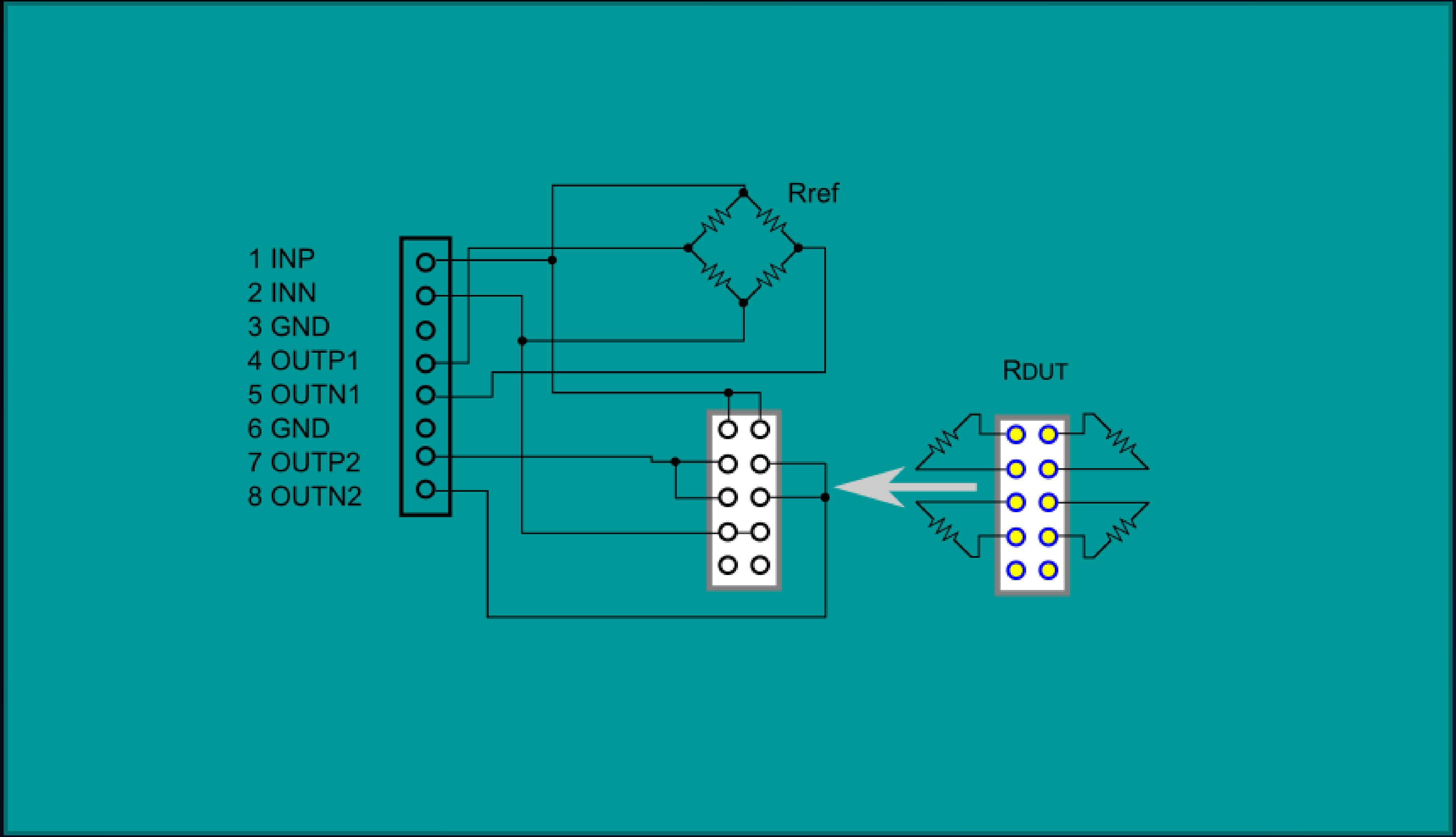
Resistor bridge board



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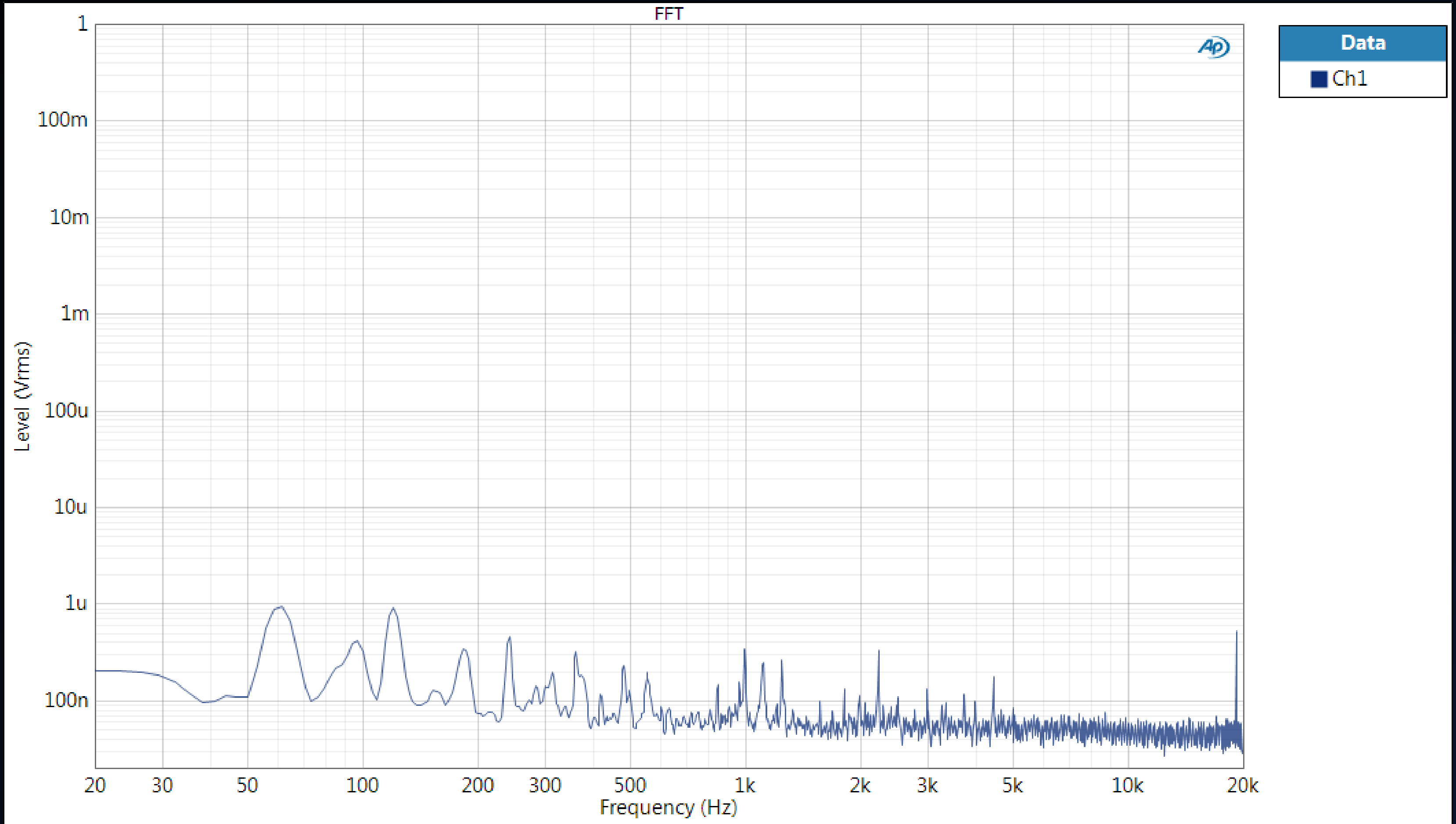
Test the Test Fixture

GARBAGE IN, GARBAGE OUT

Houston, we have a problem?



Before

After

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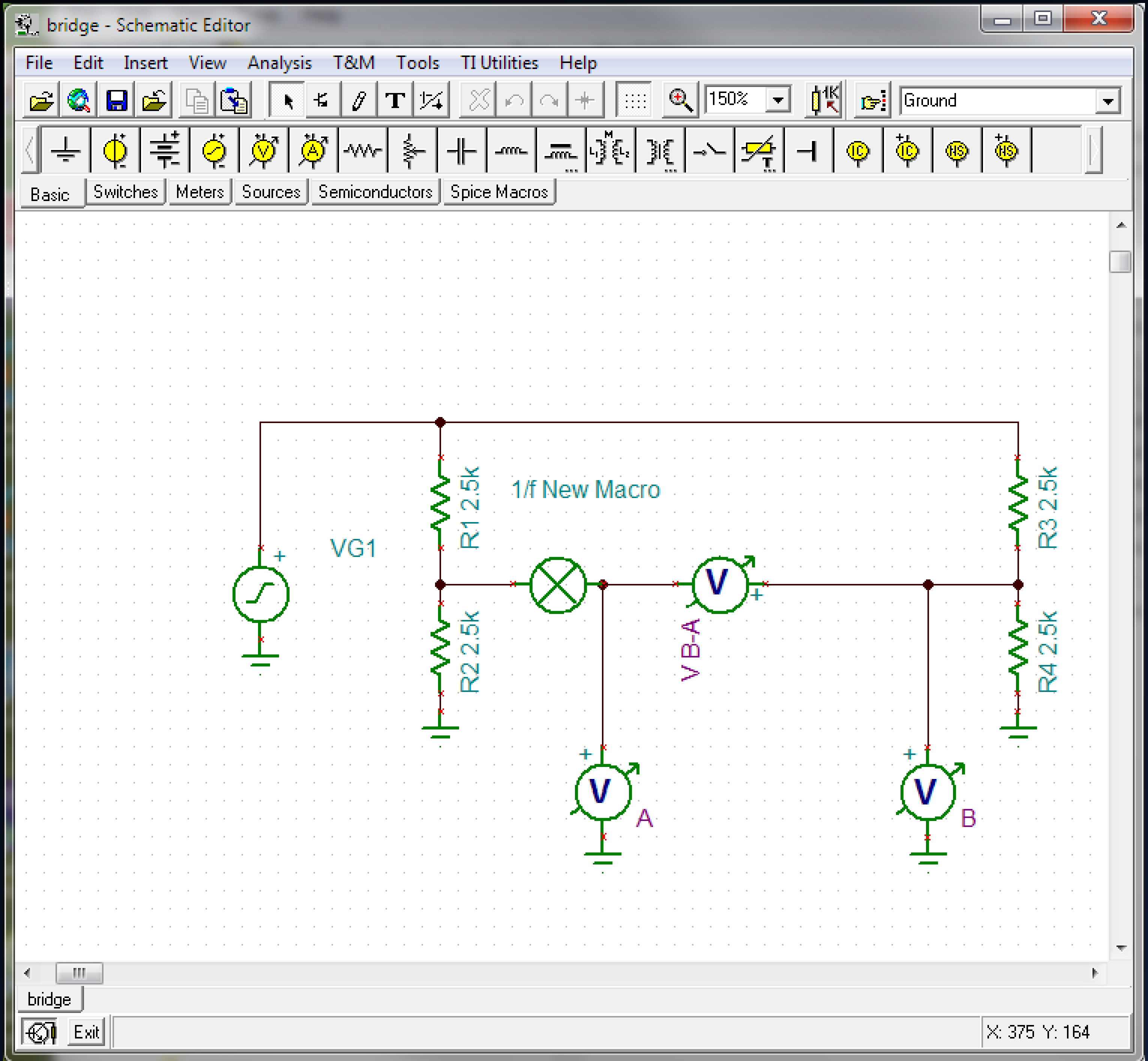
Putting it all together

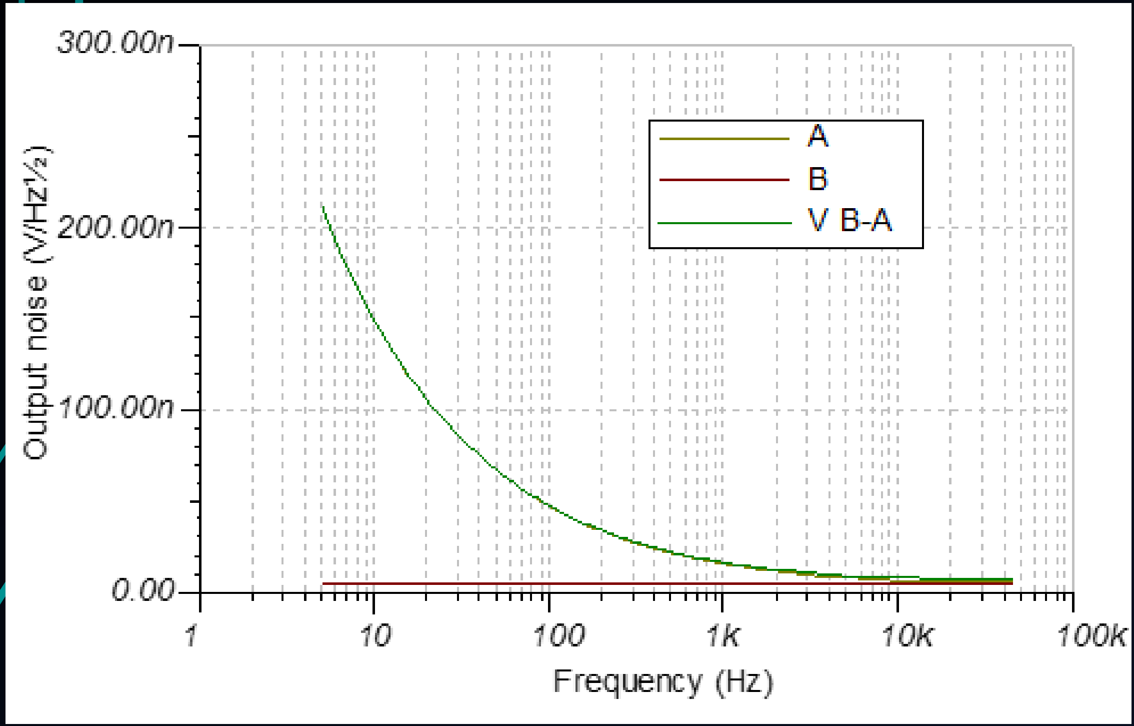
- Use test fixture to measure excess noise of proposed resistors in critical circuits
  - For example: have seen “perfect” wirewound resistors not be perfect
- Determine if the measured noise creates a performance issue
  - Do the math
  - Use a SPICE tool
    - Note that 1/f noise is not always modeled in component libraries
  - Consider the noise floor and headroom for the whole signal chain

SPICE

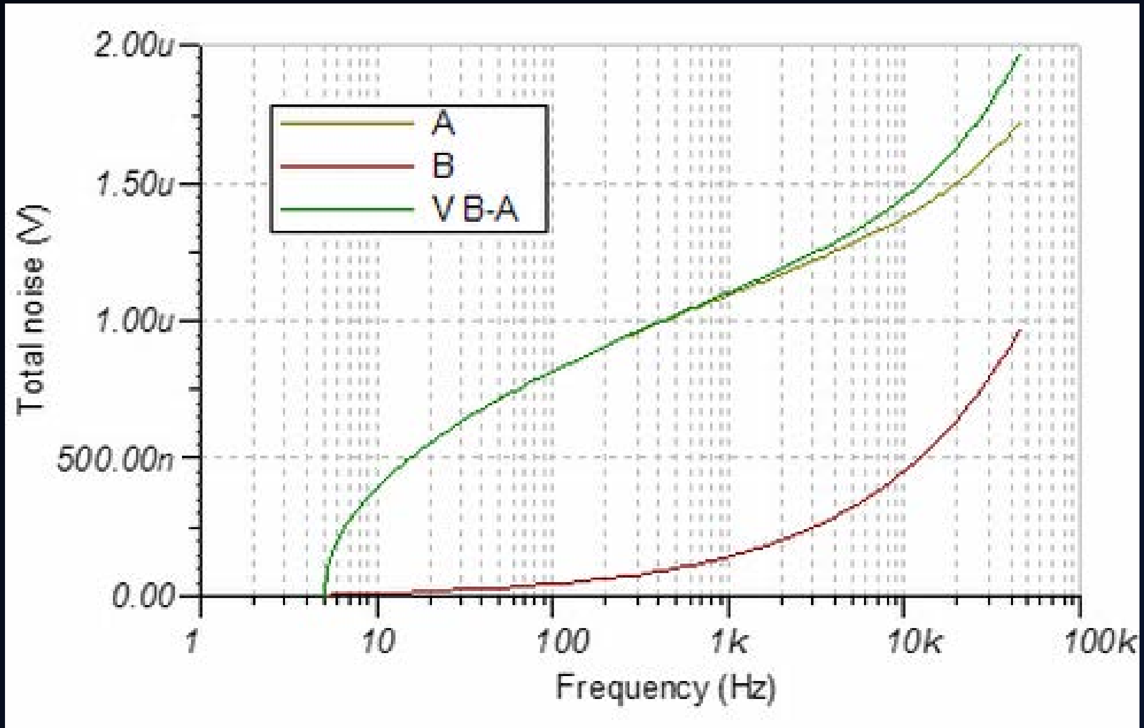
- TINA-TI
- LTSPICE
- Many others



SPICE results



Noise density



Total noise

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Prices of parts

- Susumu
  - RG series [NI at measurement limit -45 to -48 dB]
    - $0.04489 in 5K volume (0.1%)
    - $0.33495 in 1K volume (0.05%)
    - $2.05538 Q500 (0.01%) (special order, Q500 min)
  - RR series [NI -40 dB]
    - $0.01162 in volume (0.5%)
  - RS series (audio specific parts from AES) [NI at measurement limit]
    - $0.14500 in volume (0.5%)
- Panasonic
  - ERA-3A series [NI at measurement limit]
    - $0.03422 in volume (0.1%)

And the answer is?

- TOO MANY PARTS TO MEASURE!
- TOO MANY DIFFERENT USE CASES FOR ONE SINGLE ANSWER!
- NEED BETTER INSTRUMENTATION FOR THE LOWEST NOISE PARTS
  - If it matters!

Next step(s)

- Test some more part types
  - Identify ones that might be problematic
  - Decide what might be gained from the op-amp circuit as a test
- Update the “things to look at” list
- Post summary and detailed results
  - Look in the Audio Builders Workshop Facebook page for a link
    - Files will be posted under http://clk.works/?page_id=35

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Some future work ideas

- Test fixture improvements – make it easier for others
  - Design a PCB instead of the perf board to make it easier to use/build
  - Add a LNA (Low Noise Amplifier) to get better data for low NI (noise Index) parts
  - Better power source than 9V batteries
- Investigate excess noise in the presence of large AC signals
  - Theory says it won't be present in the low end – but exactly where does it end up and what's the impact?
- Repeat the investigation but measure THD instead
  - Claim is the better parts are better here too
    - Unless in small surface mount package size?

Some future work ideas (cont)

- Repeat noise and distortion investigation on
  - Capacitors
  - Op-amps
    - Particularly the 5532 op-amp is reported to vary across manufacturers
- Conduct controlled listening tests on 1/f noise audibility
- Investigate cable quality
  - Standard mechanical noise test?
  - EMI/RFI susceptibility