# RESISTOR TEST PROJECT:

# PART 3 - RESULTS USING AP515

Developed with support from:

Audio Builders Workshop

https://www.audiobuildersworkshop.com/

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## CONTENTS

Please see the Summary document for a list of abbreviations and revision notes. Please see part 1 for references.

## SUMMARY

This document records the measurements made with an AP515 to determine the excess noise in a variety of resistors. A second set of measurements was originally proposed to be made with an AP555; it offers potentially better results due to lower input noise but measurement (see Part 2) showed that it's 1/f noise was actually higher than the AP515. The AP555 wideband noise is better than the AP515. Measuring the noise index of the best resistors will require a LNA.

For details of the test fixture please see Parts 1 and 2.

Unless noted otherwise AP515 setup as per the discussion in Part 2 - TEST JIG VERIFICATION RESULTS:

- input set to 100 k ohms (200 k ohms for balanced)
- 96K sample rate (45 kHz BW as specified by AP)
- Input filter: DC for FFT, AC for RMS measurements
- Weighting & EQ: None
- Blue Jeans (Canare) cables unless noted otherwise[1]
- FFT 128K points AP-equiripple window. 128 averages. 1/24 octave smoothing. ASD plotted.

Unless noted otherwise CH1 is the DUT and CH2 is the reference resistor (2.5 K wirewound), designated by RREF.

The applied voltage is nominally 18 V across the bridge, or 9 V across each resistor. The battery voltage was observed to drop over the course of the tests[2] in the Rev 1 version so voltage is reported with the measurements. Fresh batteries were used for the Rev 2 update, the starting voltage was 19.25V.

The thermal noise from the 2.5K RREF resistors is calculated as 1.35 uV RMS (45K BW).

The AP input noise is 1.6 uV RMS. For the RREF reference channel the expected ideal noise of the 2.5K ohm resistor plus the AP noise is 2.1 uV RMS

The RREF channel is simply to validate that the test setup produces consistent results, it does not affect the DUT measurement in any way.

## AP515 MEASUREMENTS

[1] Some initial measurements were done with the Talent cables, whose lower capacitance will give a slightly higher noise reading with higher source impedance values.
[2] In part due to accidentally shorting them at one point in testing.

RMS levels measured with recording smoothed (5 sec/.2 Hz) data using AP Recorder at 16 readings/sec. 30 seconds of data were captured, the data exported to excel and the average calculated.

The tests were performed over several days, with gaps of a few weeks between revisions where additional parts were tested. The results are divided by resistor type and increasing value and not reflective of the testing order. All parts tested for Rev 1 of the documents were retested for Rev 2 to ensure more consistency with the data reduction. Parts tested for Rev 3 generally have shorter analysis as results were becoming consistent and the test methodology robust.

Rev 1 plots were generally left in the document for comparison with the Rev 2 version. Note the rev 1 plots generally plotted noise voltage and not ASD, so a conversion process was needed. The results were presented unsmoothed for rev 1; subsequent results are always presented with 1/24 octave smoothing.

Unless noted otherwise values are read from the plot data using the AP's cursors. For interpreting ASD plots of noise some of the data is not quite a flat line the cursor was placed at the visual average. Some quick comparisons with exporting the data to Excel showed that values were typically within 5% of the calculated Excel value. As the frequency bins of the FFT are linear and the contribution to noise power in logarithmic the Excel average is not a actually the value needed to calculate RMS noise – that value would need to be determined by integration. More precision in a the RMS noise voltage isn't particularly helpful as the shape of the spectrum will also be important for determining audibility.

## WIREWOUND PARTS

The 2.5K parts had a much higher noise index (NI) than the other two values. As there was just one sample of each wattage type there's not enough data at present to indicate what difference is causing this.

### 1K WW (NON INDUCTIVE, 1W)

Retested for Rev 3.

Ohmite WNB1K0FET

#### REV 1 ORIGINAL TEST

RMS level with no voltage applied is:

- DUT 1.83 uV RMS
- REF 2.17 uV RMS

RMS level with 17.6 volts applied

- DUT 1.84 uV RMS
- REF 2.22 uV RMS

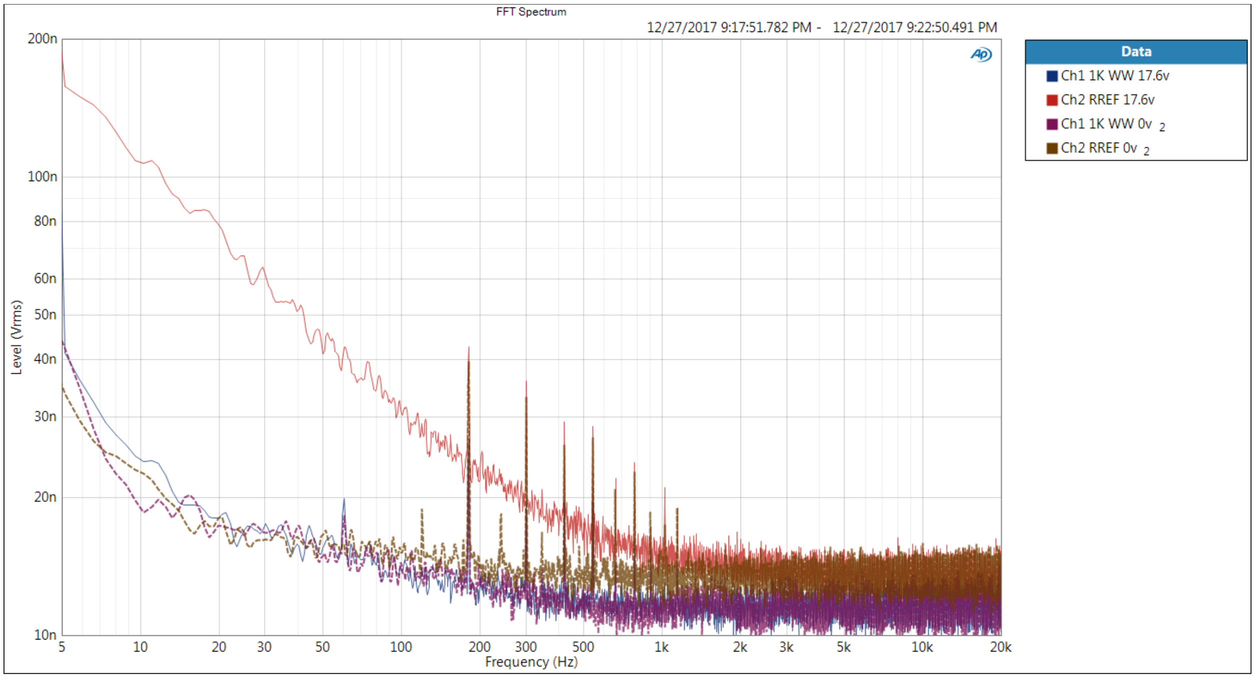


**Figure 1 1K WW vs. reference (128K pt FFT with 128 averages) (Rev 1).**

## ANALYSIS: 1K WW

The NI is calculated as:

- At 10 Hz the level is 25 nV RMS (from the FFT plot)
- Correcting for the FFT and window (.761) the spectral density is 19 nV/rt-Hz at 10 Hz
- 11.5 nV for the Johnson noise level from the FFT, the spectral level is 8.75 nV/rt-Hz
- Plugging 10Hz to 100 Hz and 19 nV/rt-Hz at 10 Hz to the spreadsheet and calculate the 1/f noise in a frequency decade, yielding 0.12 uV RMS.

With 17.6 V applied this is 0.0068 uV/V, or a NI of -43 dB. The calculated RMS noise voltage is 1.87 uV, basically the same as the 1.84 uV RMS that was measured.

## REV 3 RETEST

RMS levels were observed to be the same as the Rev 1 test.

For the rev 2 data:

- At 10 Hz the level is 16.5 nV /rt-Hz (from the ASD plot in Figure 2)
- The Johnson noise level is 8.4 nV/rt-Hz
- Plugging 10Hz to 100 Hz and 16.5 nV/rt-Hz at 10 Hz to the spreadsheet and calculate the 1/f noise in a frequency decade, yielding 0.323 uV RMS.

With 17.8 V applied this is 0.0168 uV/V, or a NI of -47 dB. The calculated RMS noise voltage for a 45 kHz BW is 2.19 uV.

Looking at the plot it can be seen that the 1/f noise contribution is at the same level as the AP515's 1/f noise (purple trace); the difference being that of the Johnson noise.

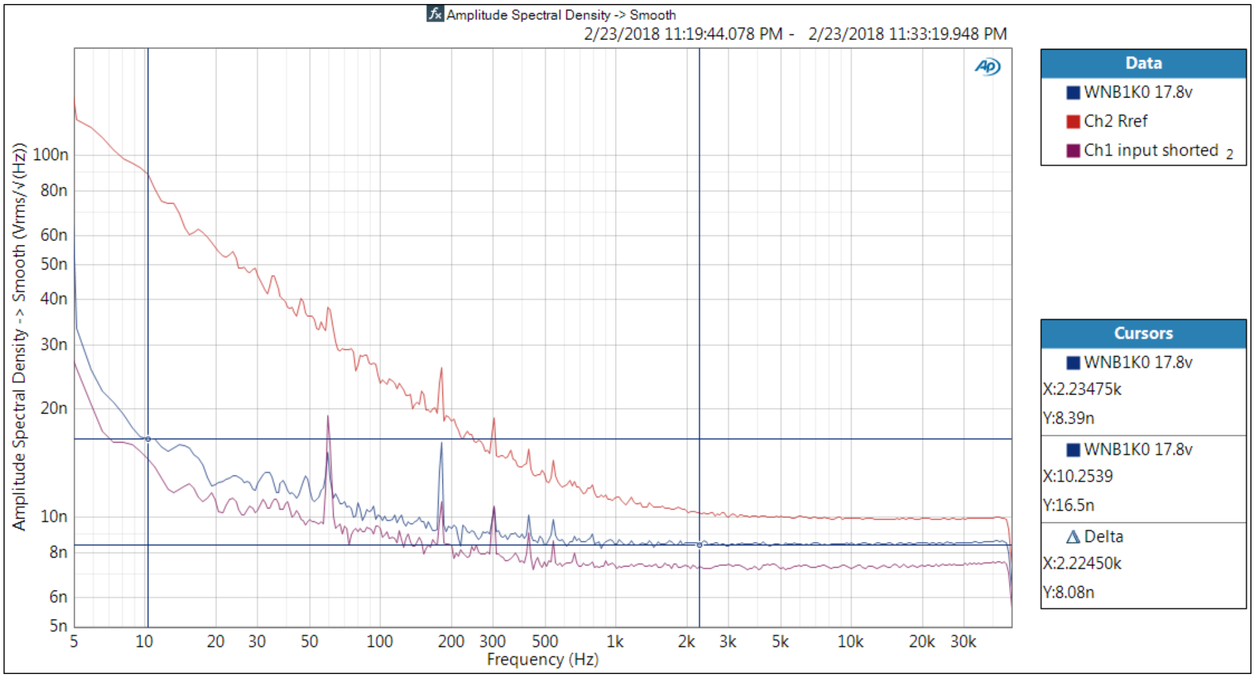


**Figure 2 1K WW vs. reference (128K pt FFT with 128 averages) (Rev 3).**

## 2.5K WIREWOUND (3W, NON-INDUCTIVE)

The original results obtained for the Rev 1 version of this paper are retained for the plots in Figure 2 and Figure 3 as they show the raw data for an unexpected result.

### REV 1 ORIGINAL TEST

This test compared the same resistors used for the reference to using them as the DUT. The same readings would be expected from both since the parts are the same. With no power applied both the REF and DUT show 2.1 uV RMS noise and about the same residual noise spectrum as shown in Figure 2. The input cables were then swapped at the AP and test rerun for excess noise to produce the result in Figure 3. As can be seen the higher 1/f curve is associated with RREF and not the AP input.

This is not due to an unexpected DC offset error as the RDUT measured 38 mV and the RREF 9 mV, both should be well within the AP's capability to ignore for measurements. In revision 2 testing an additional raw FFT capture was made with AC input coupling to confirm the DC offset error was not a factor. The plot in Figure 4 confirms this hypothesis.

It was expected that the two bridges built with the same values would produce very nearly identical results vs. about the 20% difference seen here. Another difference is the RREF value changed when the channels were swapped. The 10 Hz intercept for RREF in Figure 2 is 95 nV, in Figure 3 (with RREF on ch1) it's 115 nV.

Testing with more samples might determine if there's a large variation in the NI for the 2.5K ohm parts, but the apparent measurement shift between the two channel for RREF is unexplained.

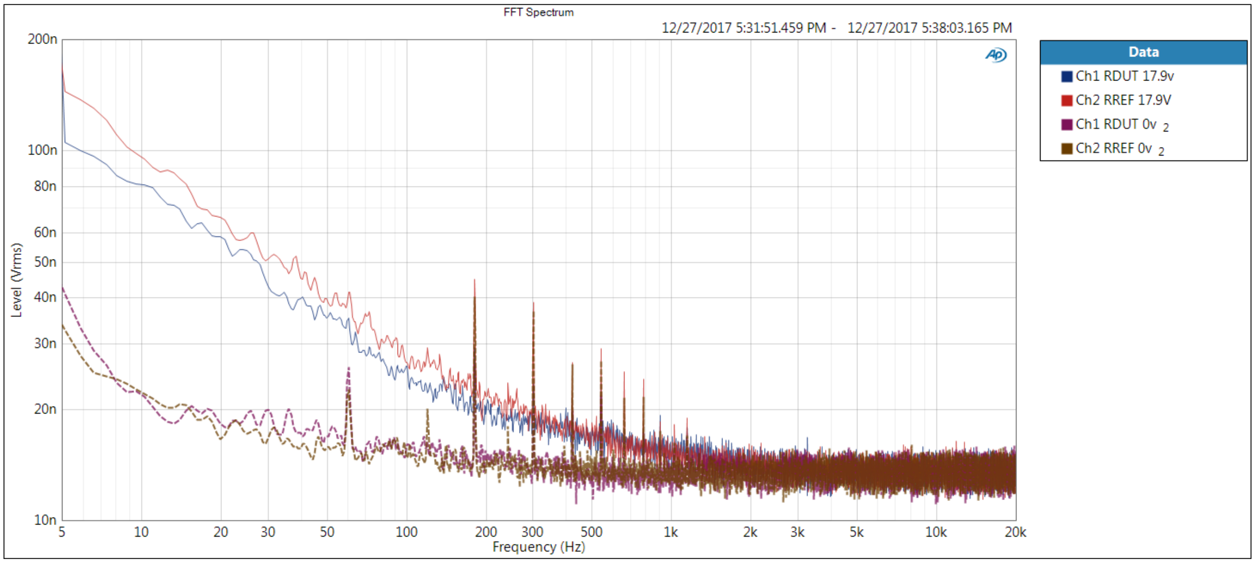


**Figure 3 2.5K WW excess and residual noise (128K pt FFT 128 averages) for DUT and REF. Unprocessed 128K point FFT with 128 averages. (Rev 1).**

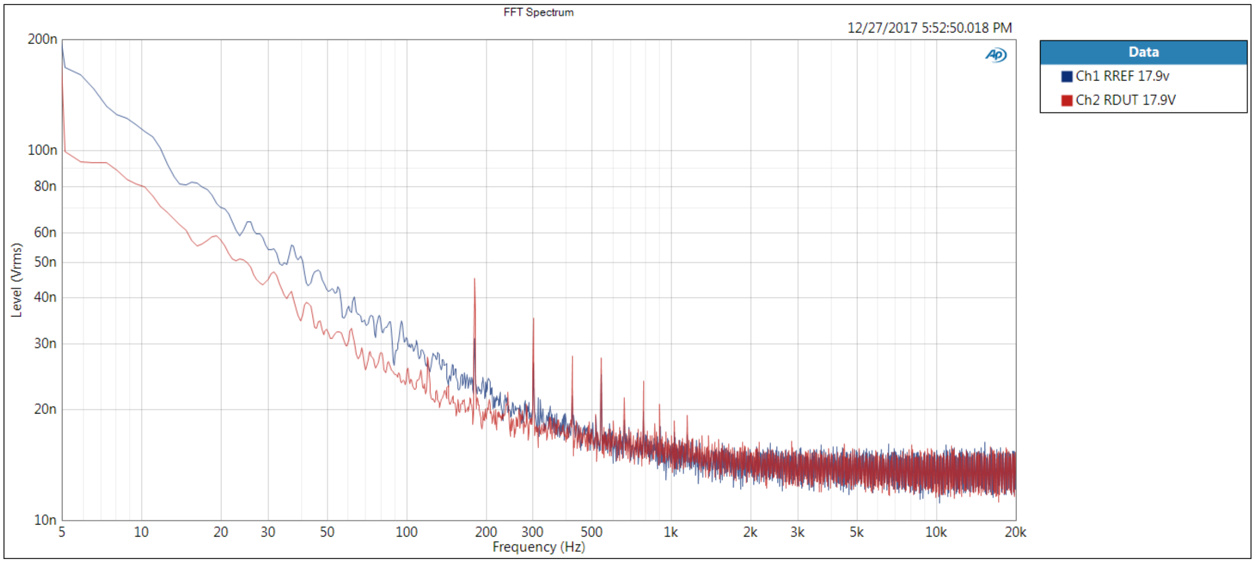


**Figure 4 Same as prior plot but with inputs swapped (Rev 1) to show RREF has higher 1/f noise. Unprocessed 128K point FFT with 128 averages. (Rev 1)**

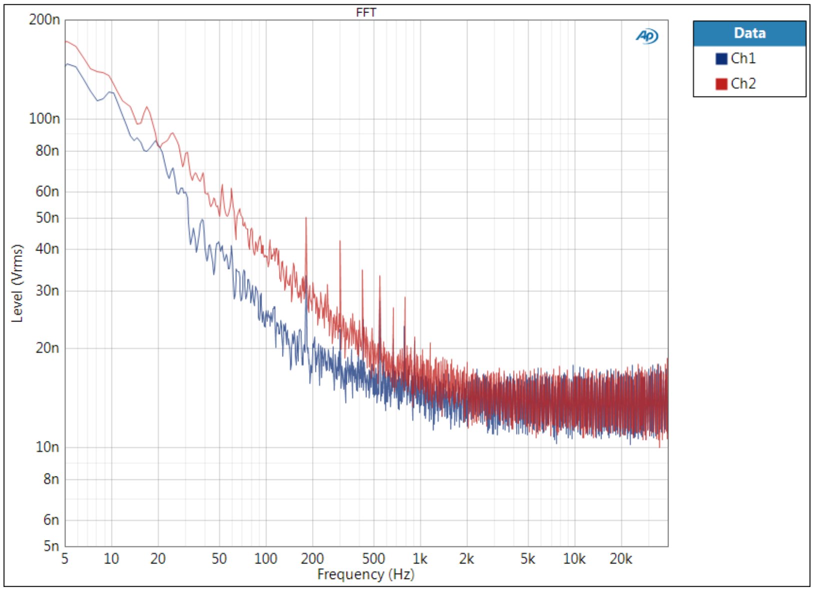


**Figure 5 Checking that the differing input DC offset doesn't contribute to the differences between DUT ch1 and RREF ch2 by AC coupling the input. Unprocessed 128K point FFT with 32 averages. (Rev 2)**

## REV 2 RESULTS

The test performed in Rev 1 was run again, the resulting smoothed ASD plot is shown in Figure 5. As with the earlier test the RREF bridge shows higher 1/f noise that as of yet does not have a good explanation.

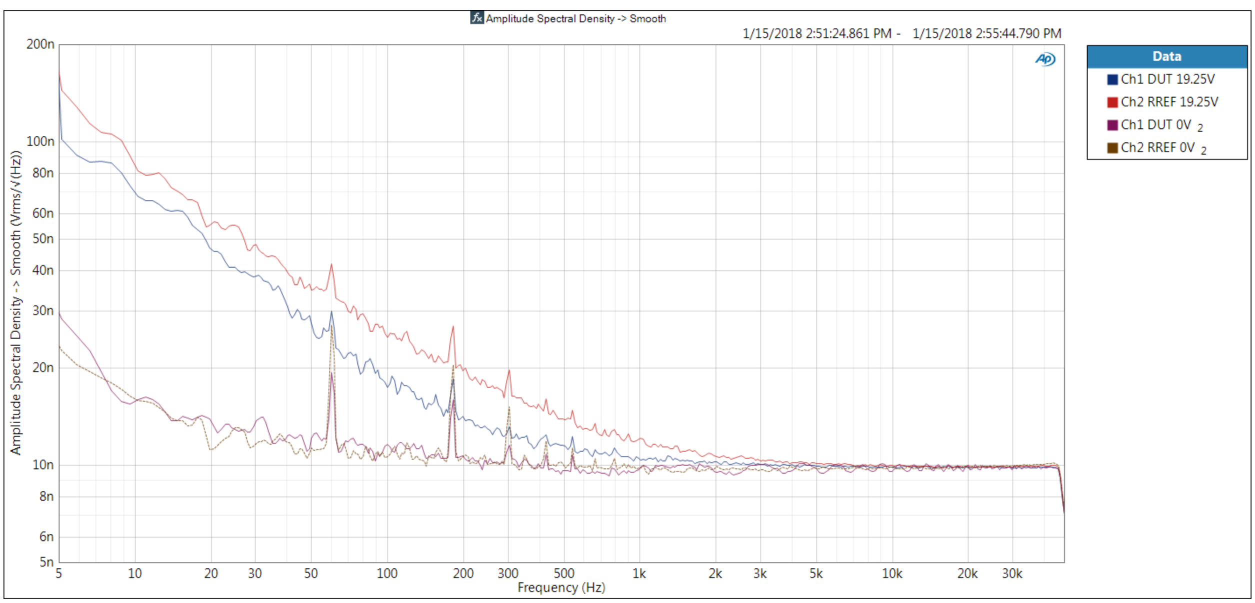


**Figure 6 Smoothed ASD plot of 2.5K WW DUT versus RREF with 19.25V applied. (Rev 2)**

## ANALYSIS: 2.5 K WW

See part 2 for the analysis of the 2.5K WW noise in RREF which gave a NI of -34 dB.

The NI for the DUT is calculated from the Rev 1 data as:

- At 10 Hz the level is 80 nV RMS (from the raw FFT plot inFigure 2 )
- Correcting for the FFT and window (.761) the spectral density is 60.9 nV/rt-Hz at 10 Hz
- 13.5 nV for the Johnson noise level from the raw FFT in Figure 2, the spectral level is 10.2 nV/rt-Hz
- Plugging 10Hz to 100 Hz and 60.9 nV/rt-Hz at 10 Hz to the spreadsheet and calculate the 1/f noise in a frequency decade, yielding 0.292 uV RMS.

With 17.9 V applied this is 0.0163 uV/V, or a NI of -36 dB. The calculated RMS noise voltage for a 45 kHz BW is 2.23 uV.

For the rev 2 data:

- At 10 Hz the level is 67.4 nV /rt-Hz (from the ASD plot in Figure 5)
- The Johnson noise level is 9.9 nV/rt-Hz
- Plugging 10Hz to 100 Hz and 67.4 nV/rt-Hz at 10 Hz to the spreadsheet and calculate the 1/f noise in a frequency decade, yielding 0.323 uV RMS.

With 19.25 V applied this is 0.0168 uV/V, or a NI of -36 dB. The calculated RMS noise voltage for a 45 kHz BW is 2.19 uV.

There is good consistency between the results of the Rev 1 method of using the raw FFT and the Rev 2 method of reading the values off of the smoothed ASD plots.

## 10K WIREWOUND (5W, NON INDUCTIVE)

Ohmite WNE10KFE.

### REV 1 RESULTS

Original test with Talent cables. Retest with Blue Jeans cable which have higher capacitance, leading to some attenuation of the higher frequencies of the noise and therefore lower readings.

RMS level with no voltage applied is:

- DUT 3.14 uV RMS (retest: 2.97 uV)
- REF 2.16 uV RMS (retest: 2.15 uV)

RMS level with 18 volts applied (17.8 for the retest):

- DUT 3.15 uV RMS (retest 2.97 uV)
- REF 2.25 uV RMS (retest 2.23 uV)

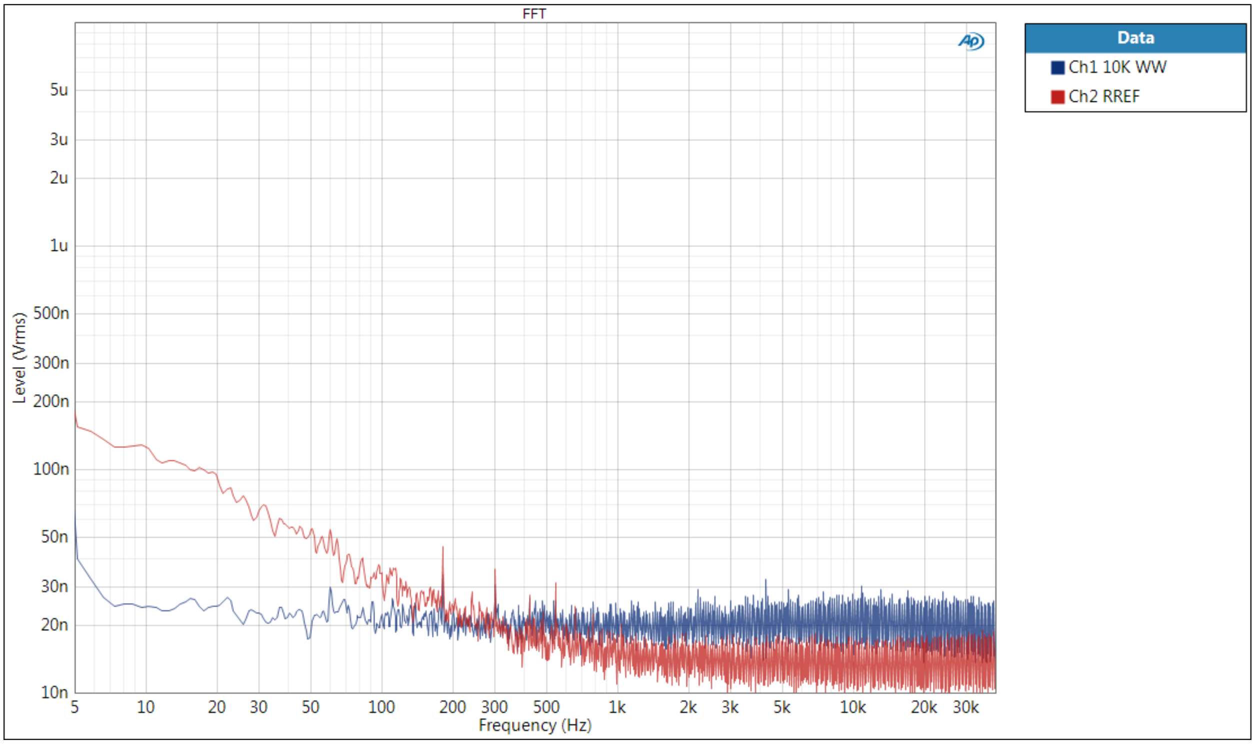


**Figure 7 10K WW RDUT vs. RREF with 18 V applied**

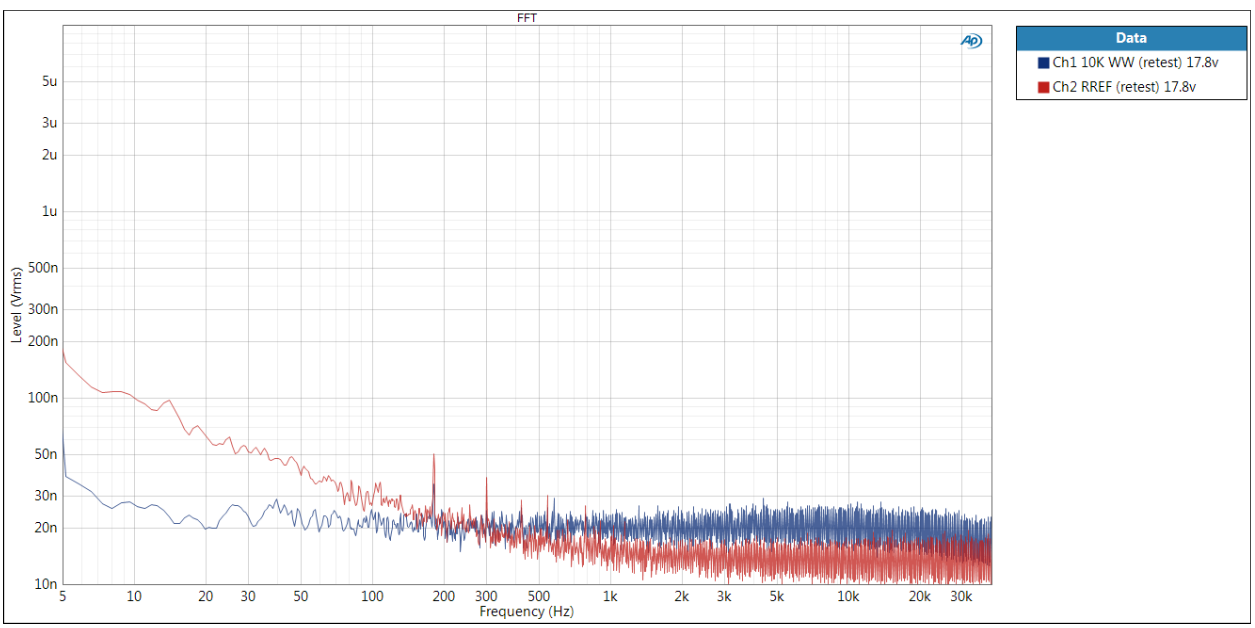


**Figure 8 Retest of 10K WW using Blue Jeans cable (Canare wire, higher capacitance).**

## REV 2 TEST

A new plot was captured as shown in Figure 8 that includes the noise floor of the AP in the plot.

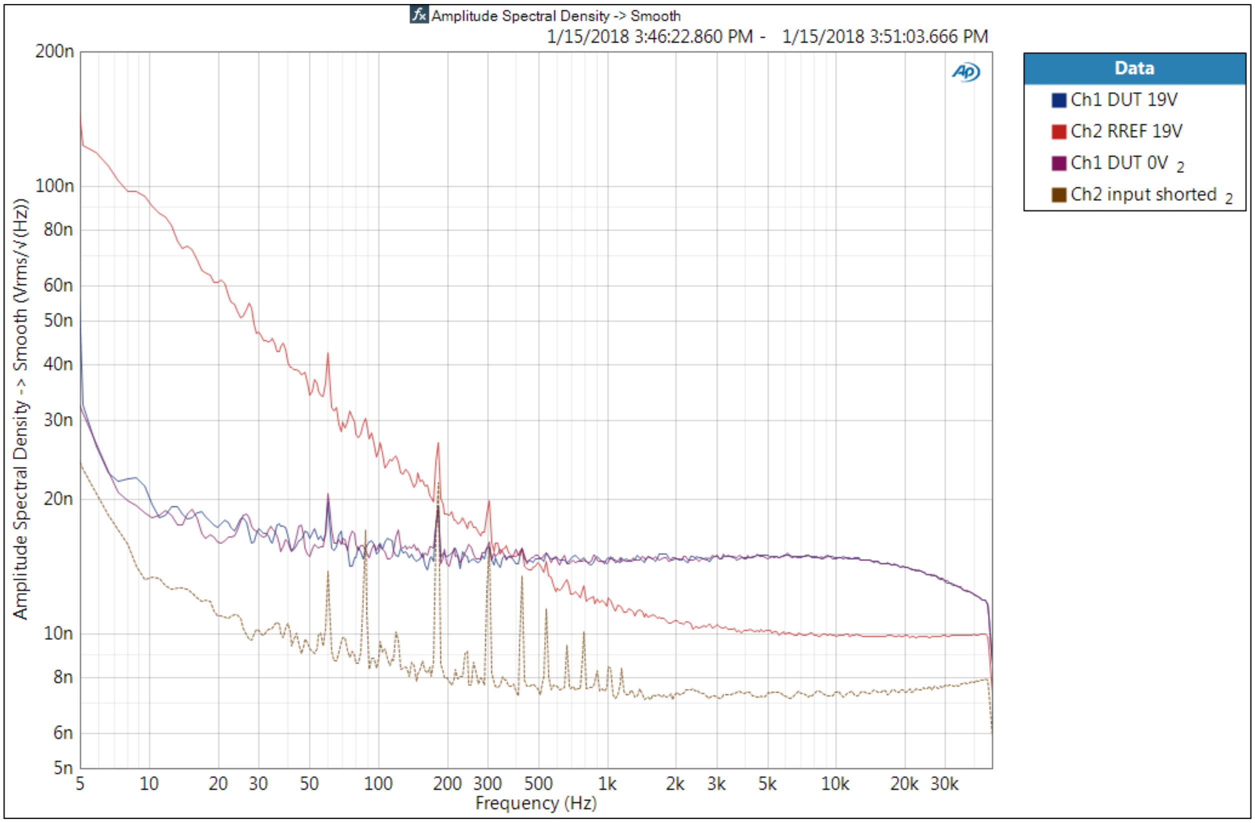


**Figure 9 Smoothed ASD result on 10K WW. Dotted line is AP residual noise on ch 2. (Rev 2)**

### ANALYSIS: 10K WW

The excess noise for the 10K part is very low so it's difficult to make an accurate decision about the value at the 10 Hz point used for the 1/f calculation. There is no obvious difference for the DUT between the powered state and the unpowered state. The resistor's Johnson noise and the AP's own 1/f noise dominate the plot. From the analysis in part 2 of the AP we can only say that the NI is < -48 dB.

## 5K WIREWOUND (5W, NON INDUCTIVE)

Ohmite WNE5K0FE. As with the other wirewounds, excepting the 2.5K value, the part's 1/f noise is below the AP515's floor.

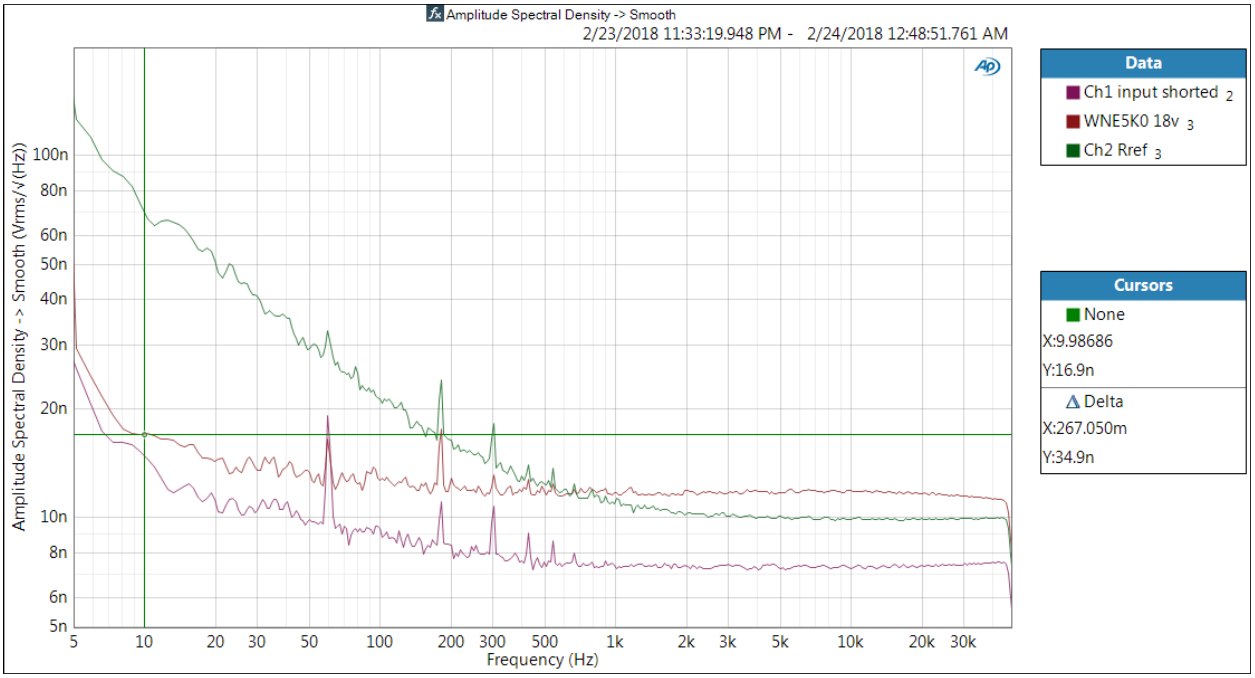


**Figure 10 Smoothed ASD result of 5K WW. Purple line is AP residual noise on ch 1. (Rev 3)**

## CARBON RESISTORS (AXIAL)

This includes both carbon film and carbon composition styles.

### 2.2K CARBON FILM 1/4 W (AXIAL) LEADED

Manufacturer unknown. This part was believed to be a carbon film part but the noise levels are not indicative of that.

#### REV 1 TESTING RESULTS

RMS level with no voltage applied is:

- DUT 2.10 uV RMS
- REF 2.17 uV RMS

RMS level with voltage applied

- DUT 2.13 uV RMS
- REF 2.27 uV RMS

The expected noise level for 2.2K alone is 1.27 uV RMS, with the AP noise the total expected would be 2 uV RMS, very close to the measured value.

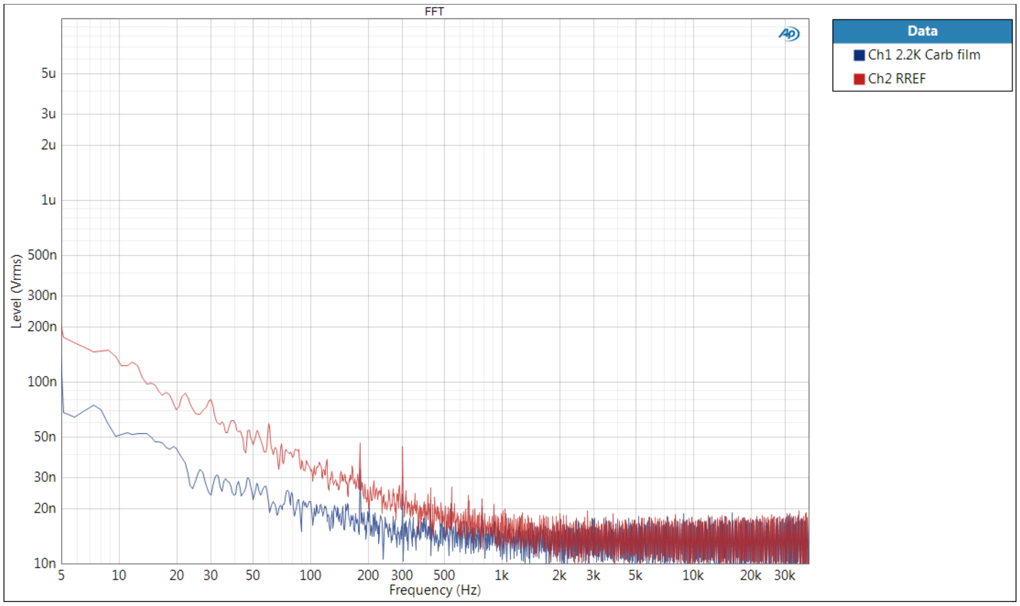


**Figure 11 2.2K (assumed to be) carbon film excess noise (18V applied) raw 128K point FFT for 128 averages result (rev 1)**

## REV 2 RESULTS

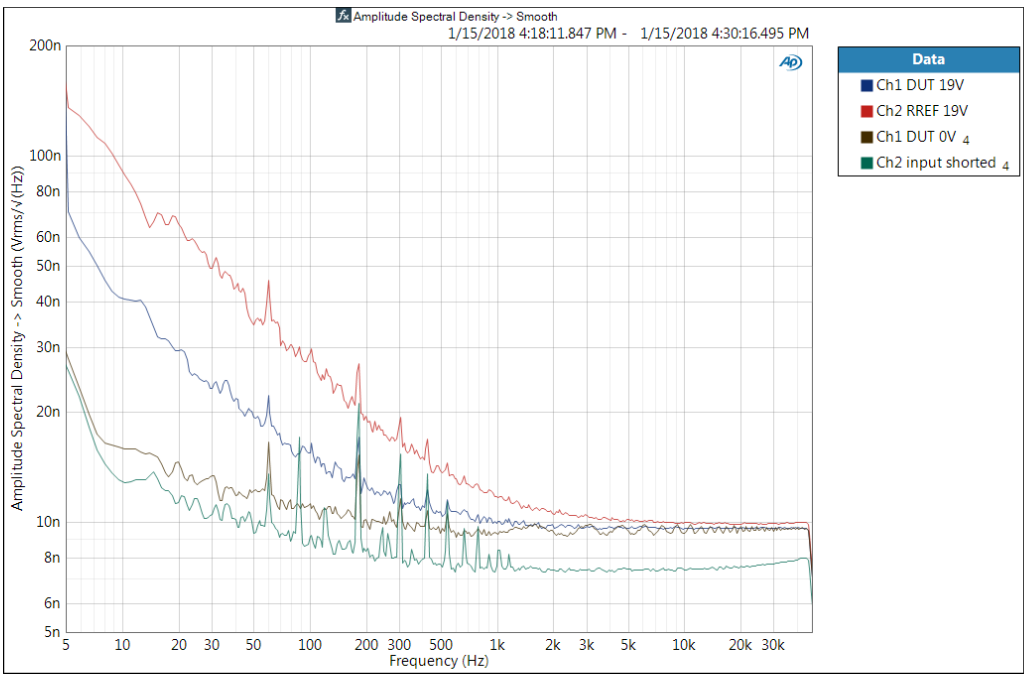


**Figure 12 Assumed 2.2K carbon film smoothed ASD plot for 19V applied, include AP input shorted (rev 2)**

## ANALYSIS: 2.2K CF

Figure 10 is interesting in that it shows even the slight difference in Johnson noise between 2.2K (DUT) and 2.5K (RREF) can be observed.

The NI for the DUT is calculated from Figure 10 as:

- The spectral density from Figure 10 is 40 nV/rt-Hz at 10 Hz
- The Johnson noise spectral density is 9.7 nV/rt-Hz
- Plugging 10Hz to 100 Hz and 40 nV/rt-Hz at 10 Hz to the spreadsheet and calculate the 1/f noise in a frequency decade, yielding 0.192 uV RMS.

With 19 V applied this is 0.010 uV/V, or a NI of -40 dB. The calculated RMS noise voltage is 2.09 uV which is very close to the (rev 1) measured value of 2.13 uV RMS.

A retest with known carbon film parts is called for as the expectation was they would have a much higher NI. This may be partially accounted for by the part being an axial leaded component and not SMT.

## 22K CARBON COMP 1/8W (AXIAL) LEADED

Manufacturer unknown as this was another set of parts out of the spare parts bins. The initial test had one resistor not seated well in the connector leading to unusual readings so a lesson was learned about making positive contact everywhere. The effect of the cable capacitance with the higher value part can be seen in the DUT Johnson noise plot.

### REV 1 TEST

RMS level with no voltage applied is:

- DUT 3.50 uV RMS
- REF 2.15 uV RMS

RMS level with 17.7 volts applied

- DUT 5.86 uV RMS
- REF 2.21 uV RMS

The rolloff in the plots is due to the AP’s input impedance and is expected for a 22K ohm value. The total noise results are therefore not quite directly comparable with the other parts as the last octave is attenuated.

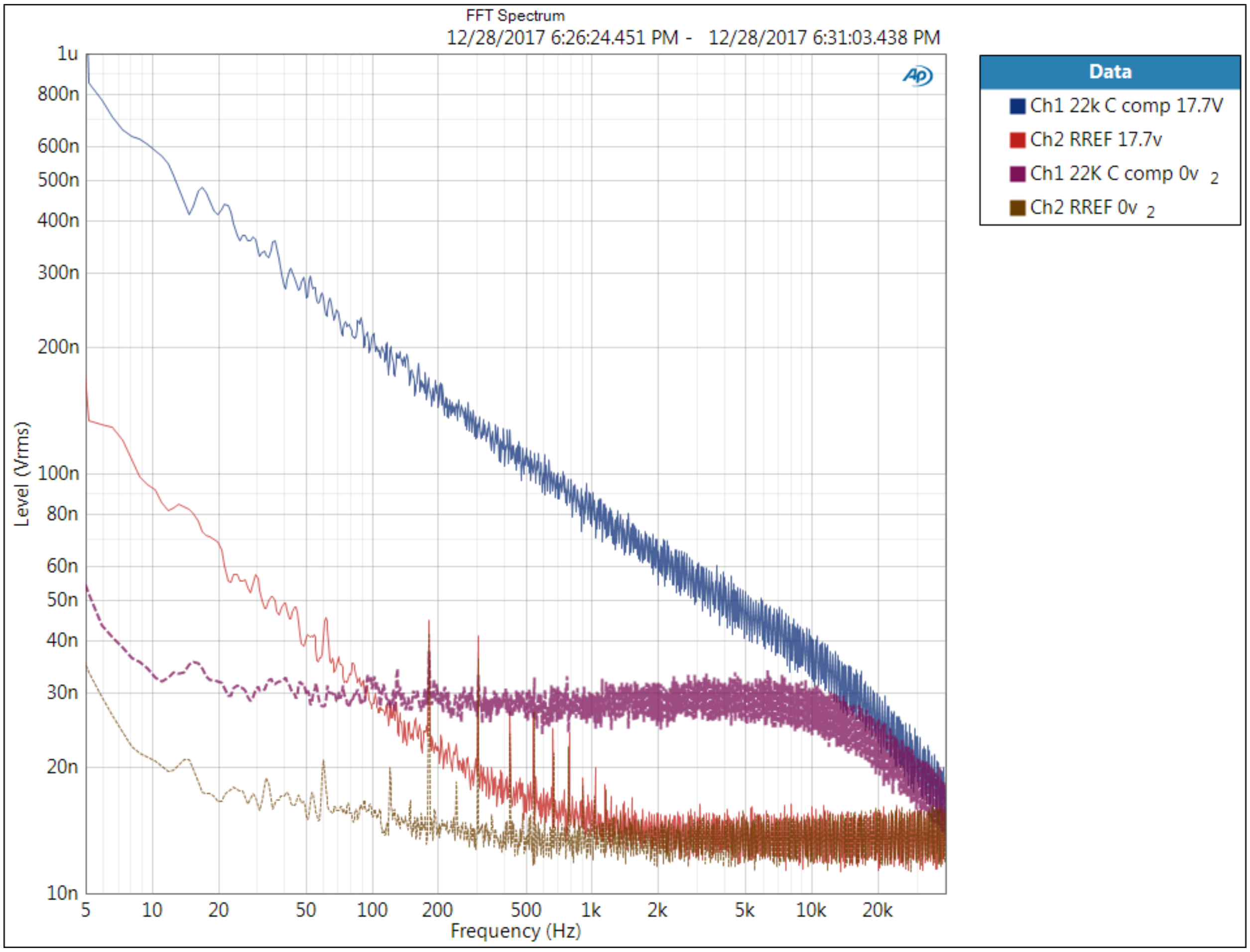


**Figure 13 22K carbon comp DUT with 17.7V and 0V applied vs. RREF (128K point FFT, 128 averages) (rev 1)**

## REV 2 RESULTS

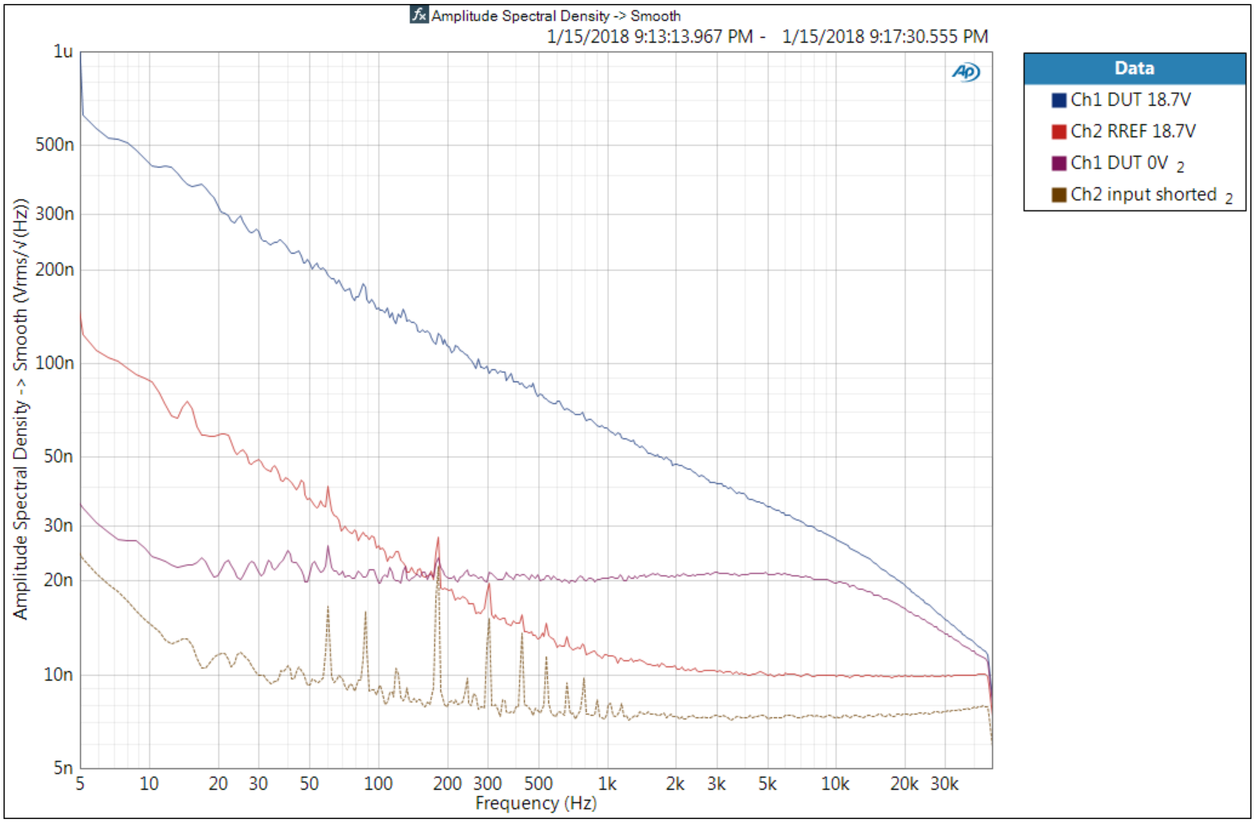


**Figure 14 22K carbon comp DUT with 18.7V and 0V applied vs. RREF and input shorted. Smoothed ASD. (Rev 2)**

Note the scale for Figure 12 is different than the other plots.

### ANALYSIS: 22K C-COMP

The NI for the DUT is calculated as:

- At 10 Hz spectral density is 452 nV/rt-Hz (Figure 12)
- 30 nV for the Johnson noise the spectral level is 21 nV/rt-Hz (vs. a theoretical value of 19 nV/rt-Hz)
- Plugging 10Hz to 100 Hz and 452 nV/rt-Hz at 10 Hz to the spreadsheet and calculate the 1/f noise in a frequency decade, yielding 2.2 uV RMS.

With 18.7 V applied this is 0.12 uV/V, or a NI of -18 dB. The calculated RMS noise voltage is 6.1 uV using the full BW, but that is not correct here due to the cable related rollof. For a 20 kHz bandwidth the noise is calculated as 4.9 uV RMS. The measured value of 5.8 uV RMS falls reasonably well in that range.

## FILM RESISTORS

### PANASONIC 0603 SMD 2K 1/10W 0.1% 25 PPM TCR

ERA-3AEB202V Thin Film, High reliability.

Manufacturer's page: https://industrial.panasonic.com/ww/products/resistors/chip-resistors/high-precision-chip-resistors/thin-film-chip-resistors-high-reliability-type/ERA3AEB202V

### REV 1 MEASUREMENTS

RMS level with no voltage applied is:

- DUT 2.05 uV RMS
- REF 2.15 uV RMS

RMS level with 17.7 volts applied

- DUT 2.06 uV RMS
- REF 2.21 uV RMS

After running the capture it was observed that the noise spectrum was pretty close to the AP's floor, so a second plot, Figure 13, was made and included the AP noise floor. From that it's difficult to say that the DUT is much different than the noise floor. This observation led to the inclusion of the noise floor in the Rev 2 captures.

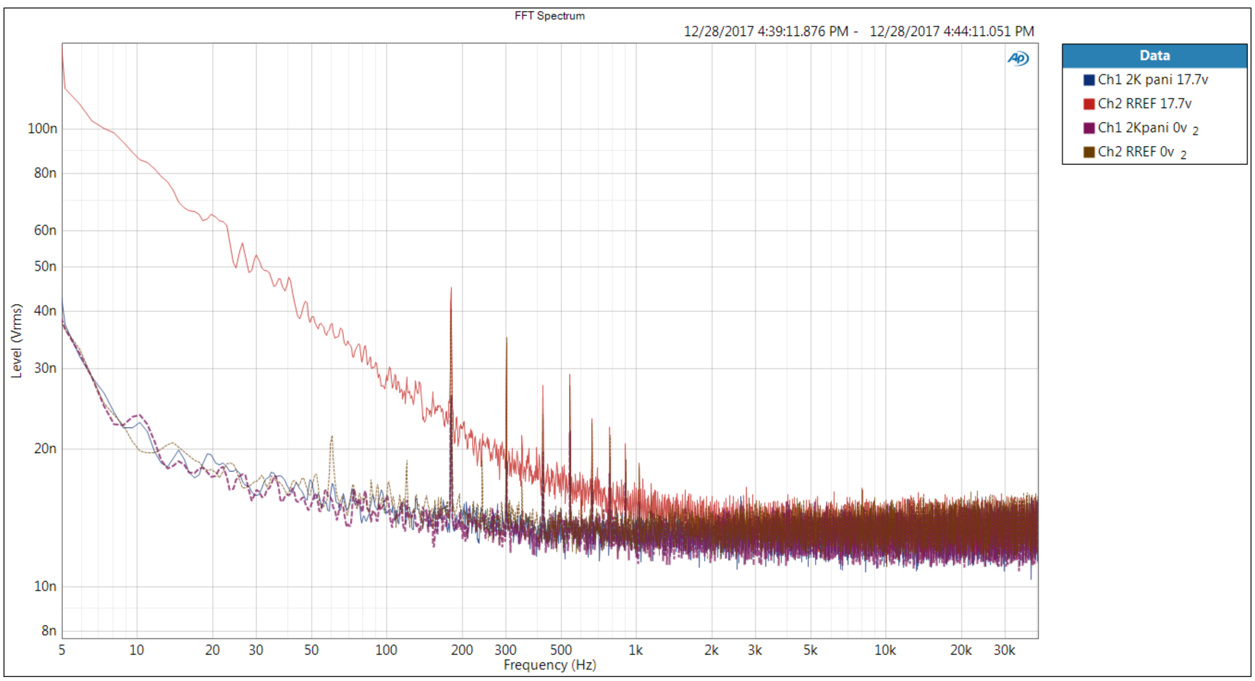


Figure 15 Panasonic 2K ohm thin film (ch1) and RREF spectrum (128K pt FFT, 128 averages) (Rev 1)

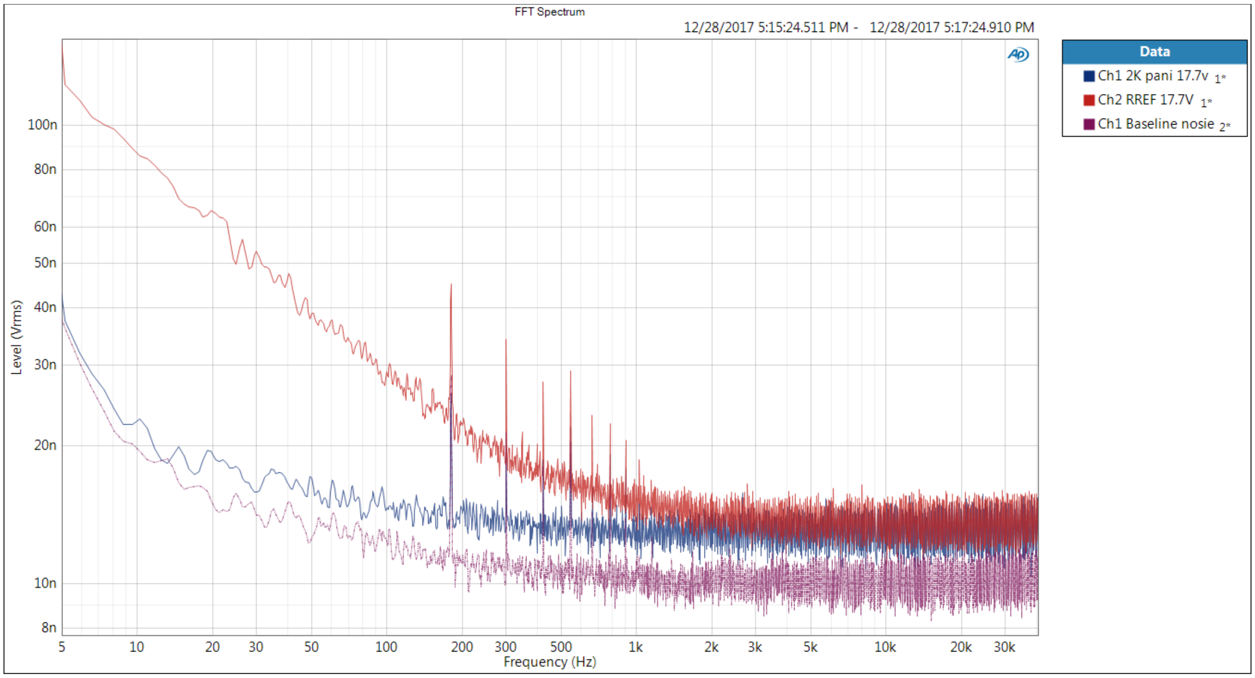


**Figure 16 as above but including baseline noise data for ch1 (128K pt FFT, 128 averages) (Rev 1)**

## REV 2 MEASUREMENT

The measurements was repeated with the AP set for plotting the smoothed ASD response, which is presented in Figure 15. Note the top of the scale in the figure has been reduced from 200 nV/rt-Hz to 100 nV/rt-Hz to better see the lower values.

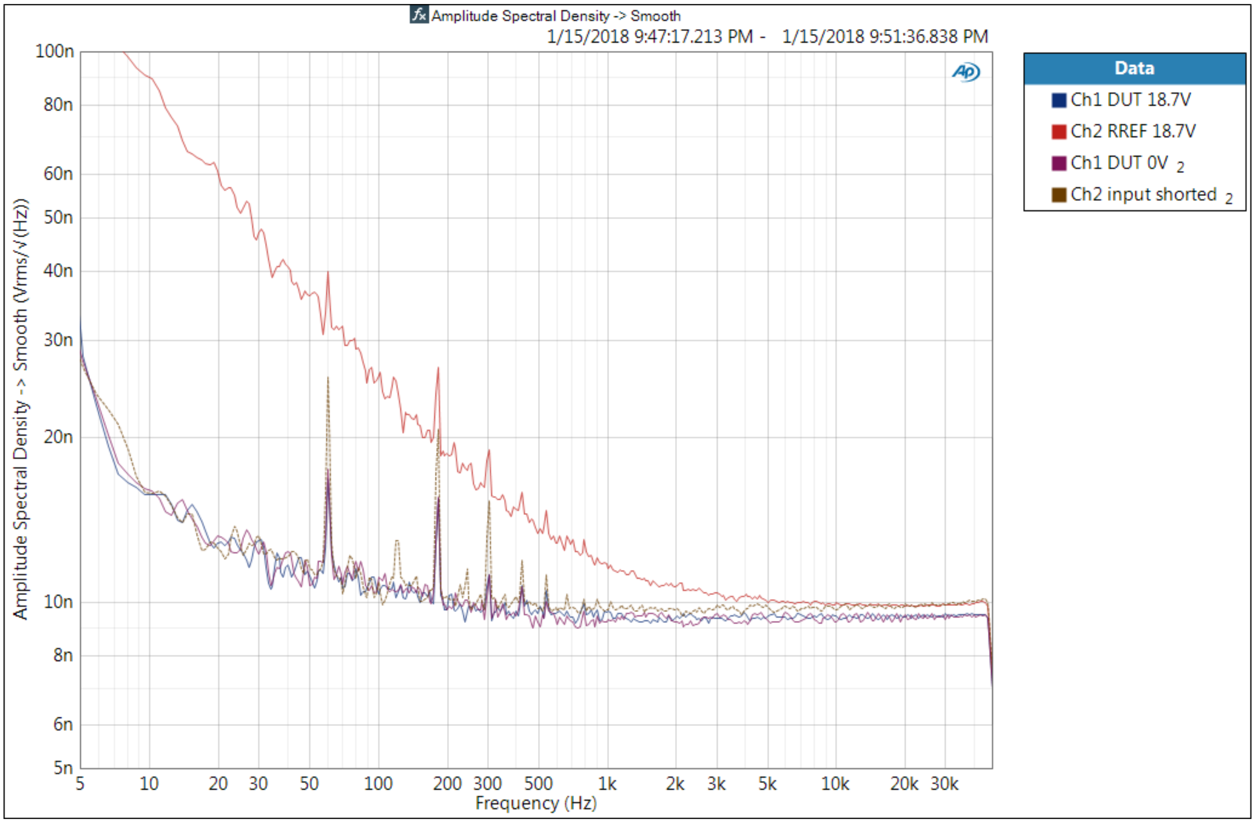


**Figure 17 Panasonic 0603 SMD 2K with 18.7V and 0V vs. DUT and input shorted. Smoothed ASD. (Rev 2)**

### PANASONIC 0603 SMD 2K THIN FILM ANALYSIS

The low level of excess noise does not make it possible to determine a NI for these parts beyond the floor of the AP515's measurement noise.

## PANASONIC 0603 SMD 10K 1/10W 0.1% 25 PPM TCR

ERA-3AEB103V Thin Film, High reliability.

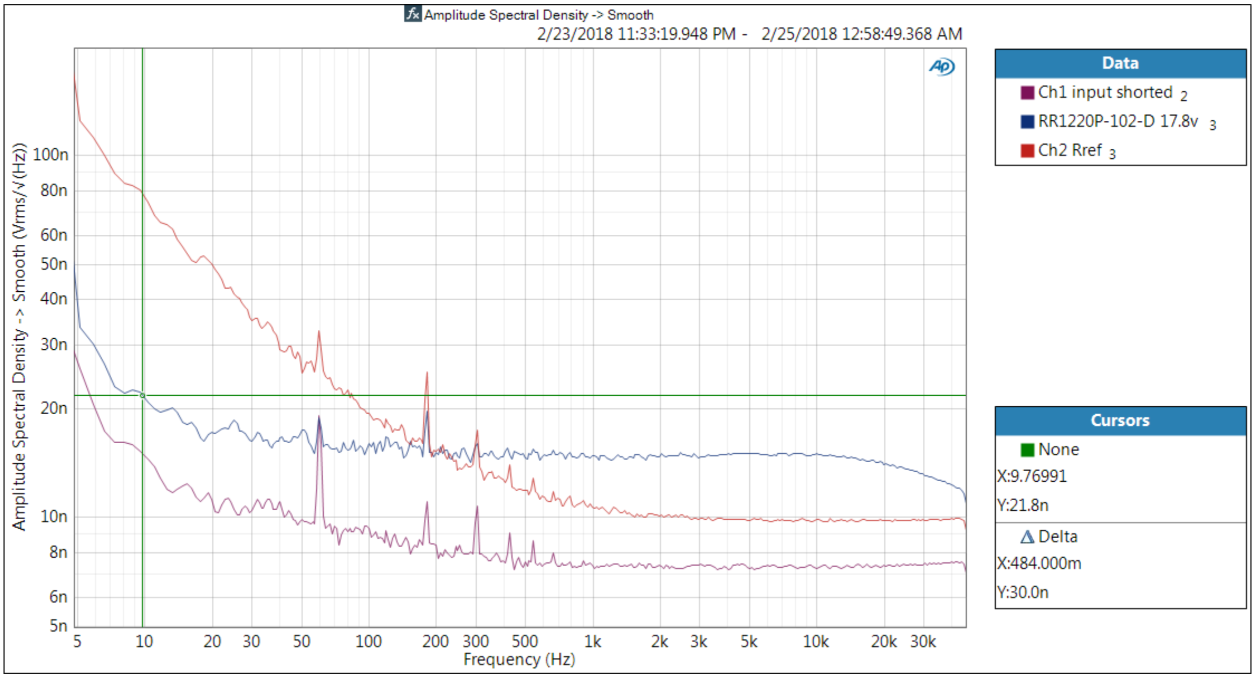


**Figure 18 Panasonic 0603 SMD 10K with 17.8V. DUT. RREF. and input shorted.**

## SUSUMU 2.2K RS SERIES 0805 SMD 0.5% 25 PPM TCR

Susumu part RS2012P-222-D-T5-3

Manufacturer's page:
http://www.susumu.co.jp/dl/?filename=n_catalog_partition23_en.pdf&type=application/pdf

### REV 1 MEASUREMENTS

RMS level with no voltage applied is:

- DUT 2.06 uV RMS
- REF 2.14 uV RMS[3]

RMS level with 17.6 volts applied

- DUT 2.08 uV RMS
- REF 2.19 uV RMS

[3] This is lower than previous values. Among plausible explanations is that the ambient temperature is 5 deg. F lower than some of the earlier measurements. There's also the variability in the current setup that isn't well controlled such as the cables and physical location of the fixture.

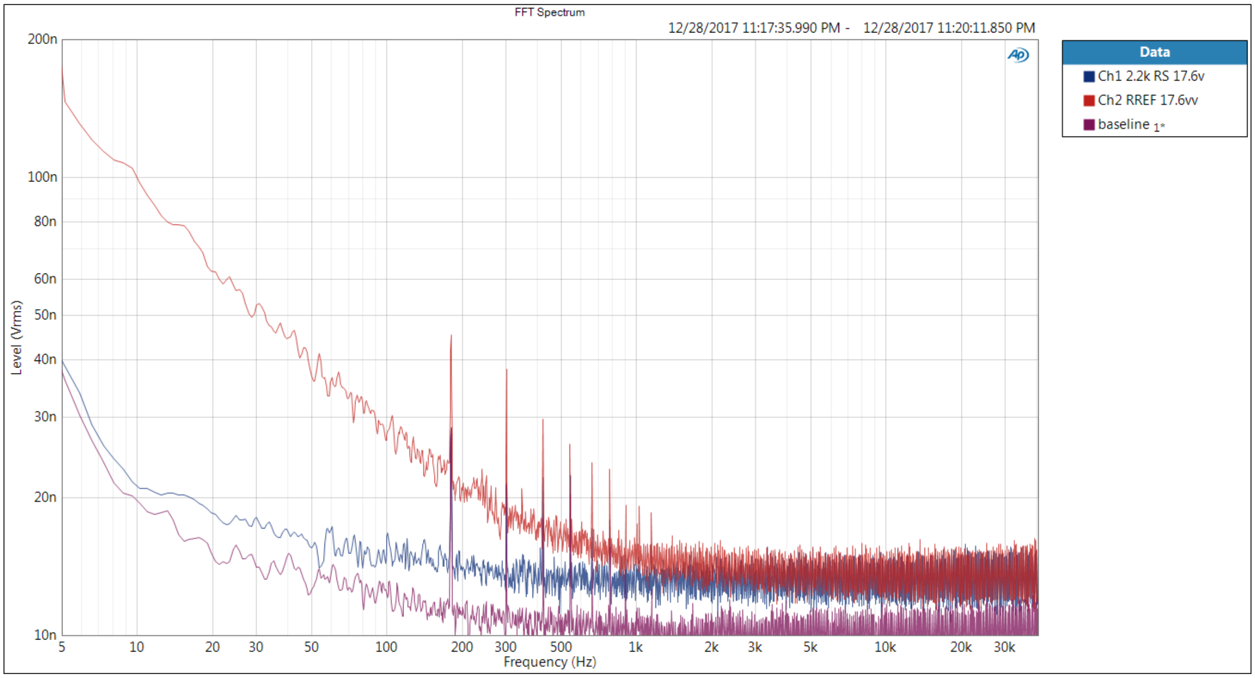


**Figure 19 FFT with 17.6v applied to 2.2K ohm Susumu RS part, 128K pt FFT 128 averages. Baseline (AP input shorted) noise in purple. (rev 1)**

## REV 2 MEASUREMENTS

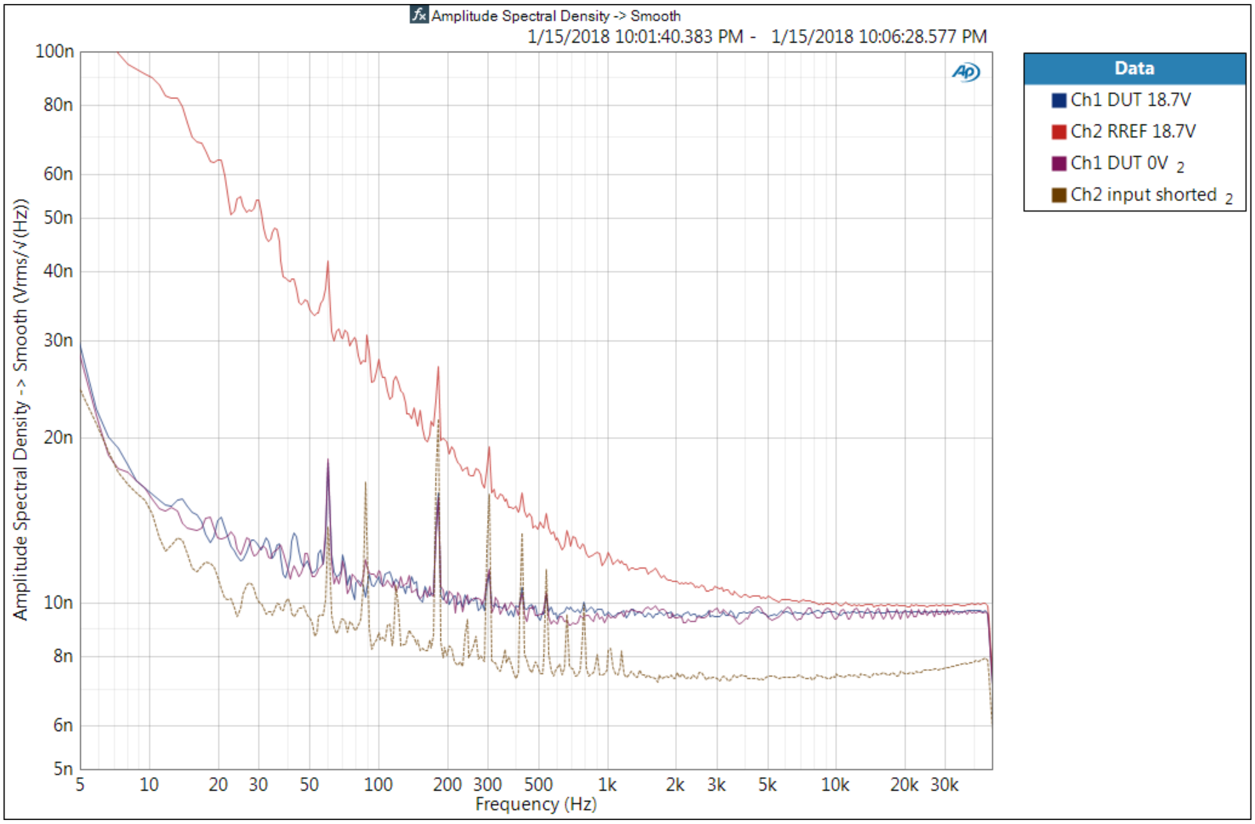


**Figure 20 Susumu 0805 RS 2.2K with 18.7V and 0V vs. DUT and input shorted. Smoothed ASD. (Rev 2)**

## SUSUMU RS 2.2K ANALYSIS

The low excess noise levels relative to the AP515 do not allow a determination of the NI.

## SUSUMU 1.0K RG SERIES 0805 SMD 0.5% 25 PPM TCR

Susumu part RG2012P-102-D-T5

Manufacturer's page:
http://www.susumu.co.jp/dl/?filename=n_catalog_partition23_en.pdf&type=application/pdf

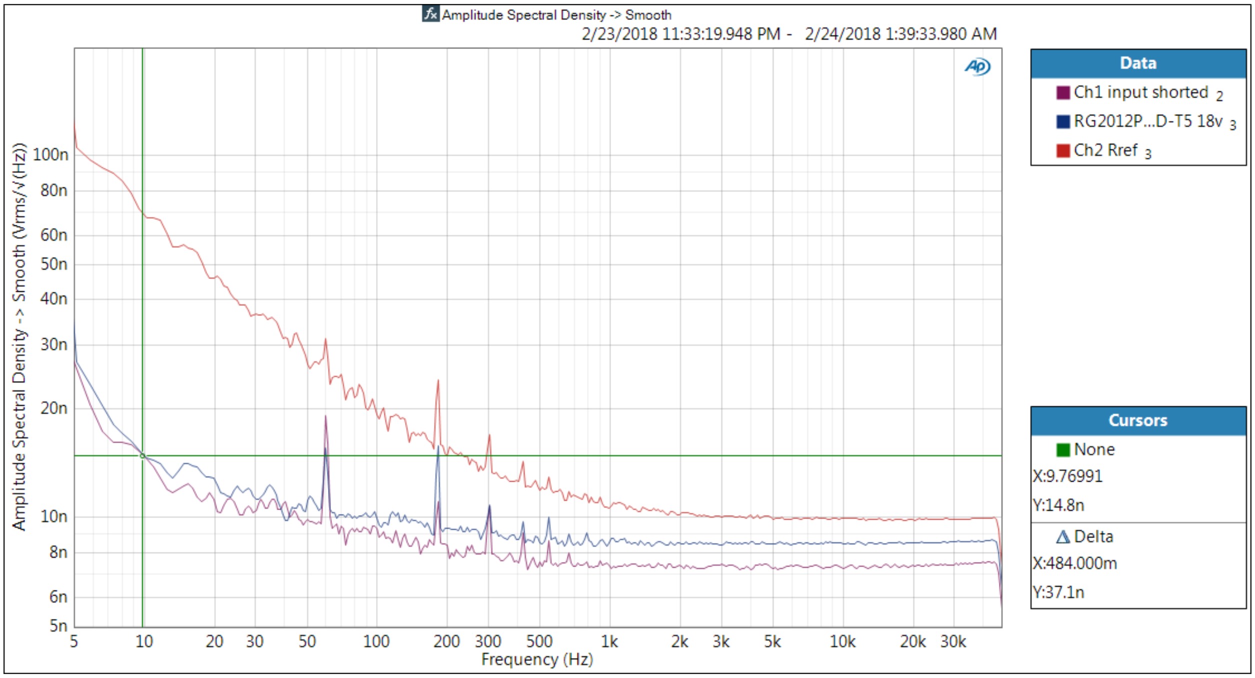


**Figure 21 Susumu 1K RG series and baseline noise (rev 3)**

## SUSUMU 10K RG SERIES 0805 SMD 0.5% 25 PPM TCR

Susumu part RG2012P-103-D-T5.

As with the 1K version of the RG part the 1/f noise of the part is masked by the AP515 noise. The calculated NI is -45 dB.

The slight drop off above 20 kHz is from the higher capacitance of the cables being used (Blue Jeans cables using Canare wire).

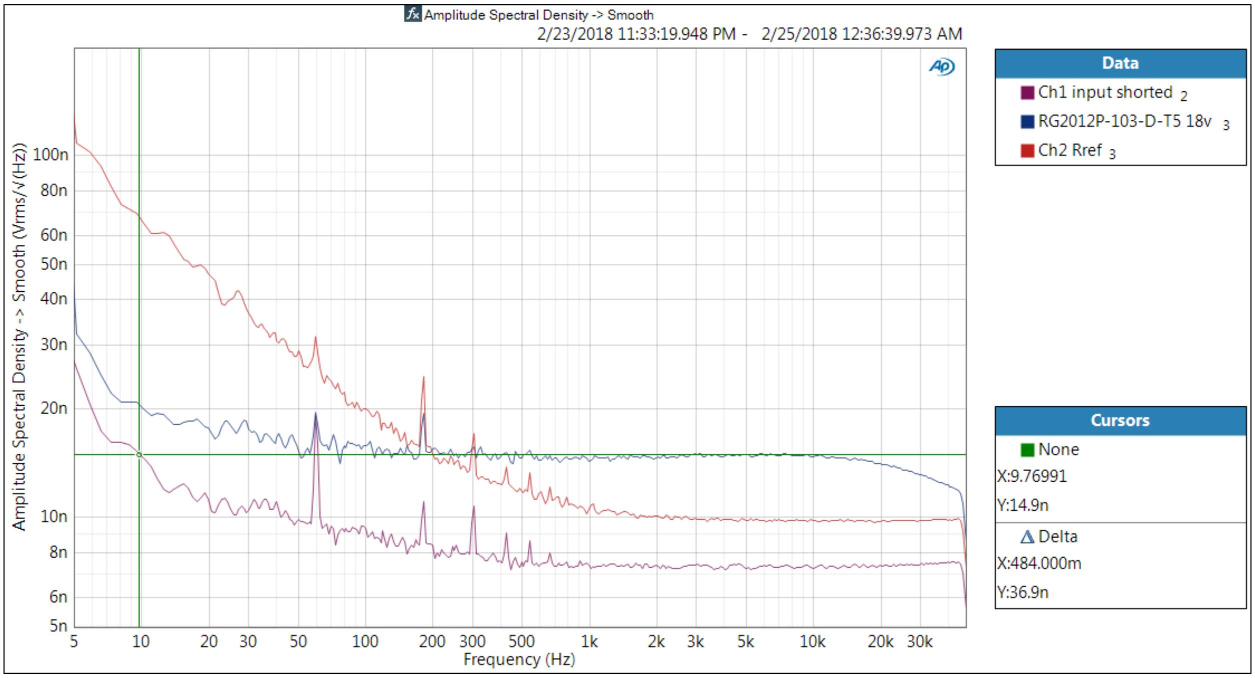


**Figure 22 Susumu 10K RG series and baseline noise (rev 3)**

## SUSUMU 1K RR SERIES 0805 SMD 0.5% 25 PPM TCR

Susumu part RR1220P-102-D.

The 1/f noise is indistinguishable from the AP515 noise.

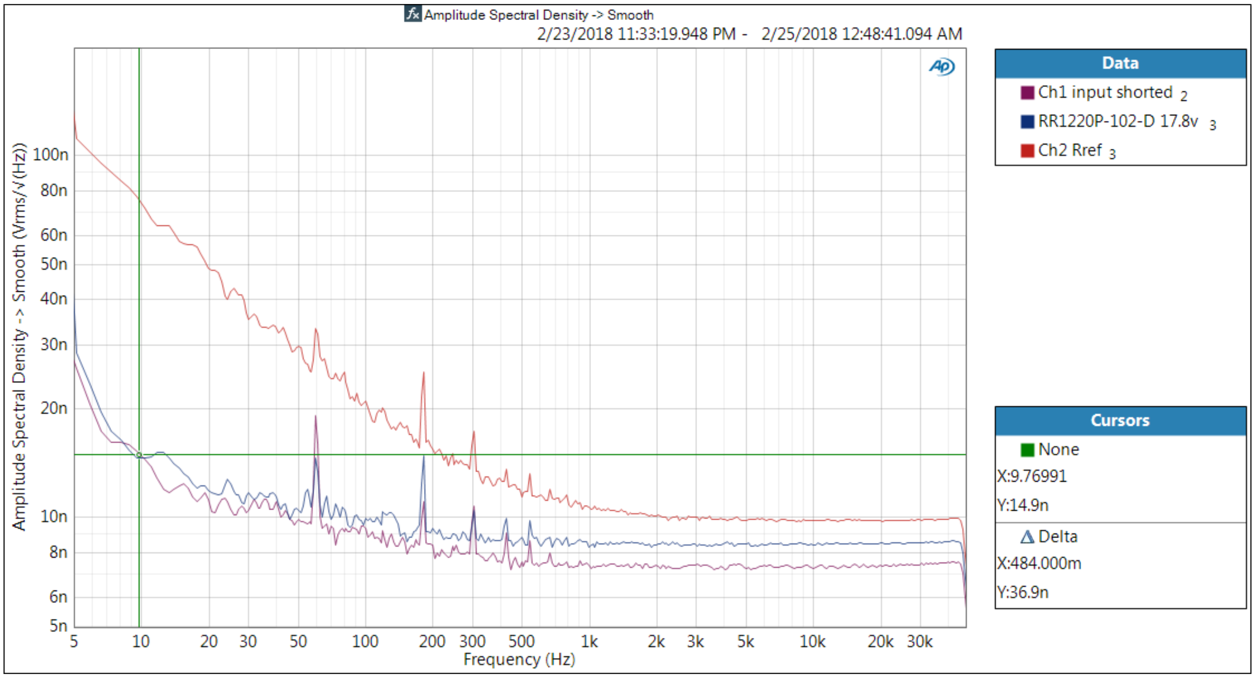


**Figure 23 Susumu 1K RR series and baseline noise (rev 3)**

## SUSUMU 10K RR SERIES 0805 SMD 0.5% 25 PPM TCR

Susumu part RR1220P-103-D.

Though the 1/f noise looks more dramatic than the other plots, the difference from the AP baseline is mostly from the Johnson noise of 15 nV rt-Hz. 37 nV at 10 Hz at 18V applied yields a NI of -40 dB. This is 8 dB worse than the measurement floor of -48 dB but can’t be attributed exclusively to the resistor due to the AP’s own 1/f noise.

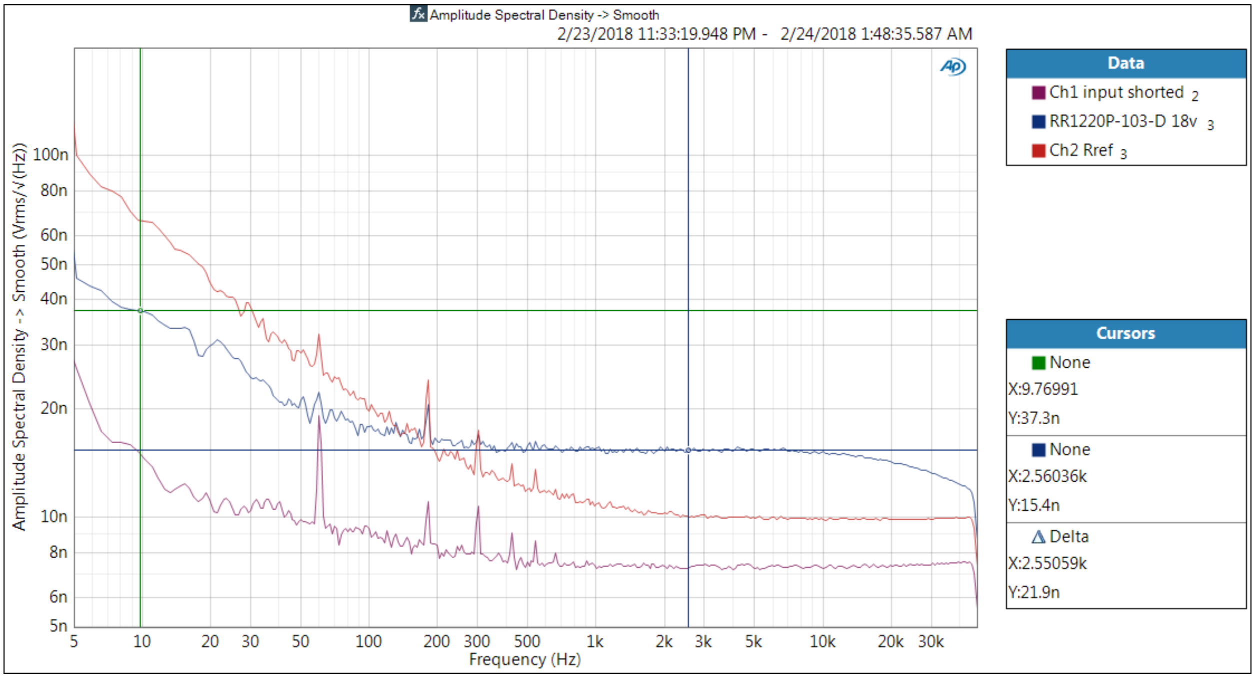


**Figure 24 Susumu 10K RR series and baseline noise (rev 3)**

## STACKPOLE 2K AXIAL 1/4W 1% METAL FILM 100 PPM TCR

Stackpole RNF14FTD2K00

Manufacturer's page: https://www.seielect.com/Catalog/SEI-RNF_RNMF.pdf

RMS noise measurements were not made.

## REV 1 MEASUREMENT

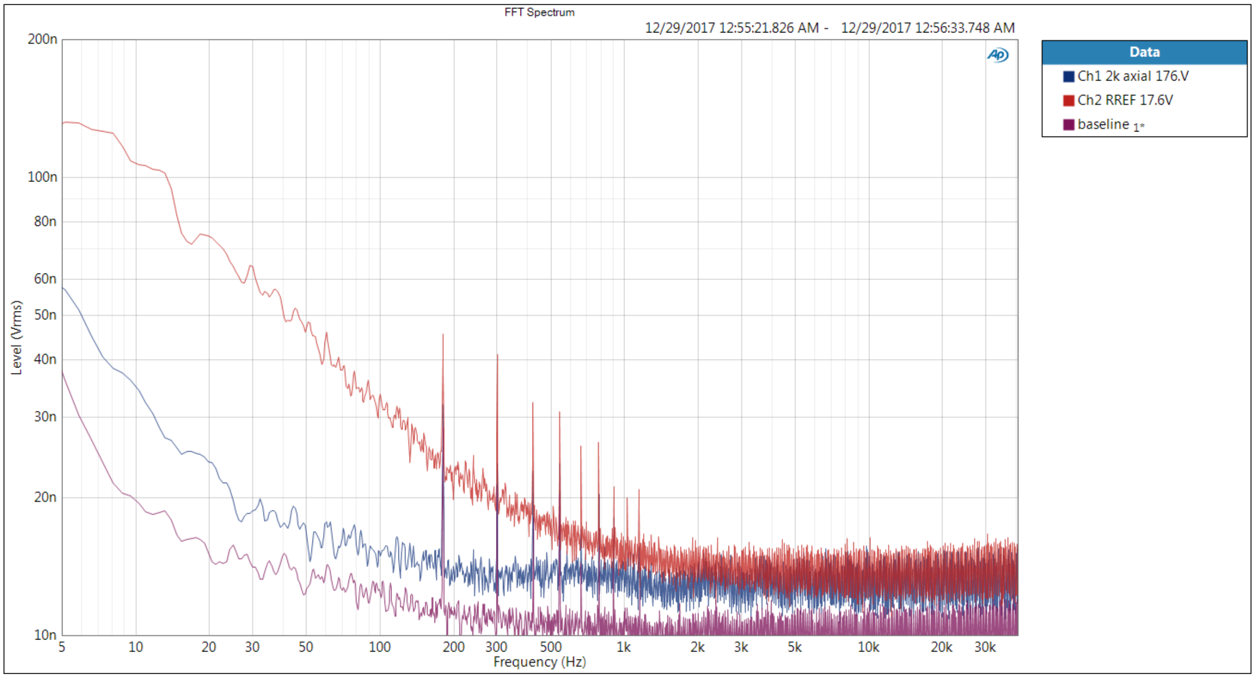


**Figure 25 2K 1/4W 1% axial excess noise plot. Instrument baseline in purple (128K point FFT 128 averages) (rev 1)**

## REV 2 MEASUREMENT

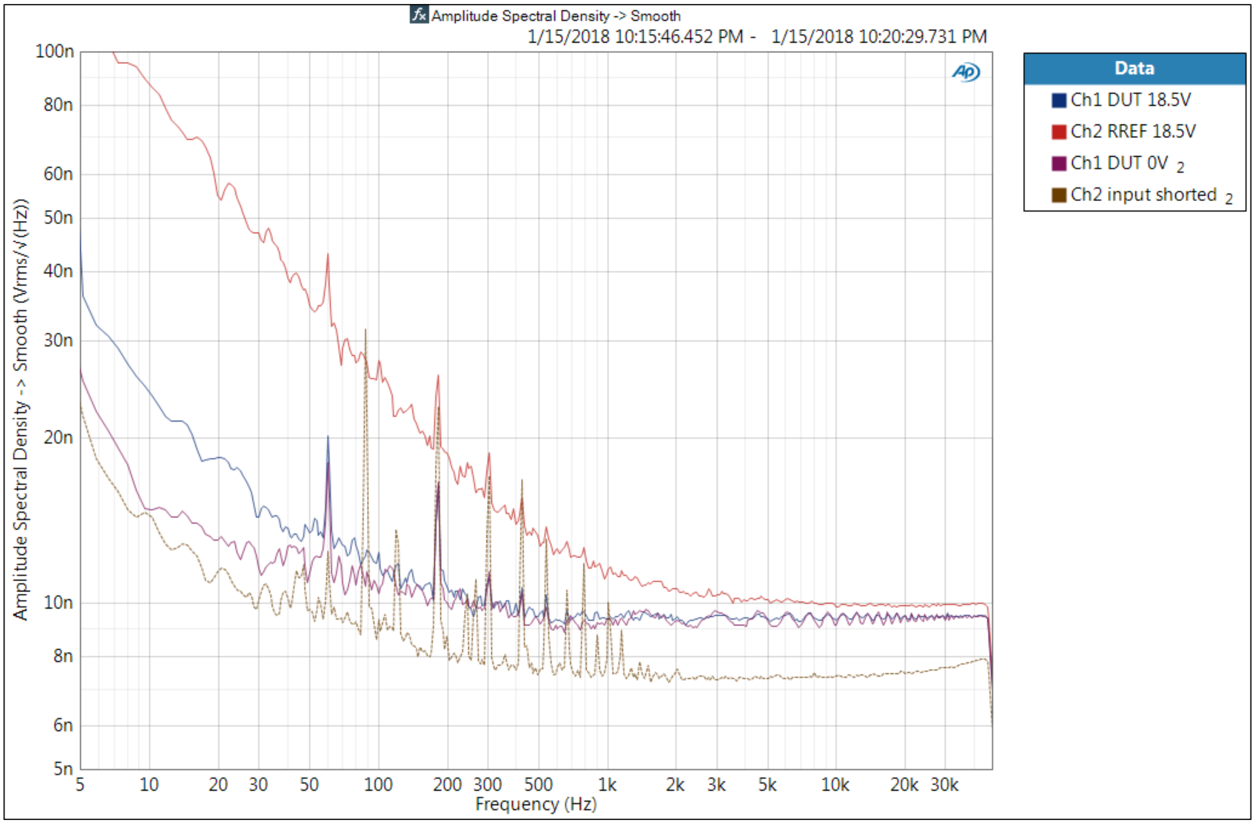


**Figure 26 Stackpole 2K metal film 1/4W with 18.5V and 0V vs. DUT and input shorted. Smoothed ASD. (Rev 2)**

### ANALYSIS: 2K METAL FILM 1/4W AXIAL

The NI for the DUT is calculated as:

- The spectral density from Figure 19 is 24.7 nV/rt-Hz at 10 Hz
- The Johnson noise spectral density is 9.5 nV/rt-Hz
- Plugging 10Hz to 100 Hz and 24.7 nV/rt-Hz at 10 Hz to the spreadsheet and calculate the 1/f noise in a frequency decade, yielding 0.12 uV RMS.

With 18.5 V applied this is 0.0065 uV/V, or a NI of -44 dB.

## STACKPOLE 10K AXIAL 1/4W 1% METAL FILM 100 PPM TCR

Stackpole RNF14FTD10K0. As with the 2K value the 1/f noise is dominated by the AP515's inherent noise. The plot is shown in Figure 21

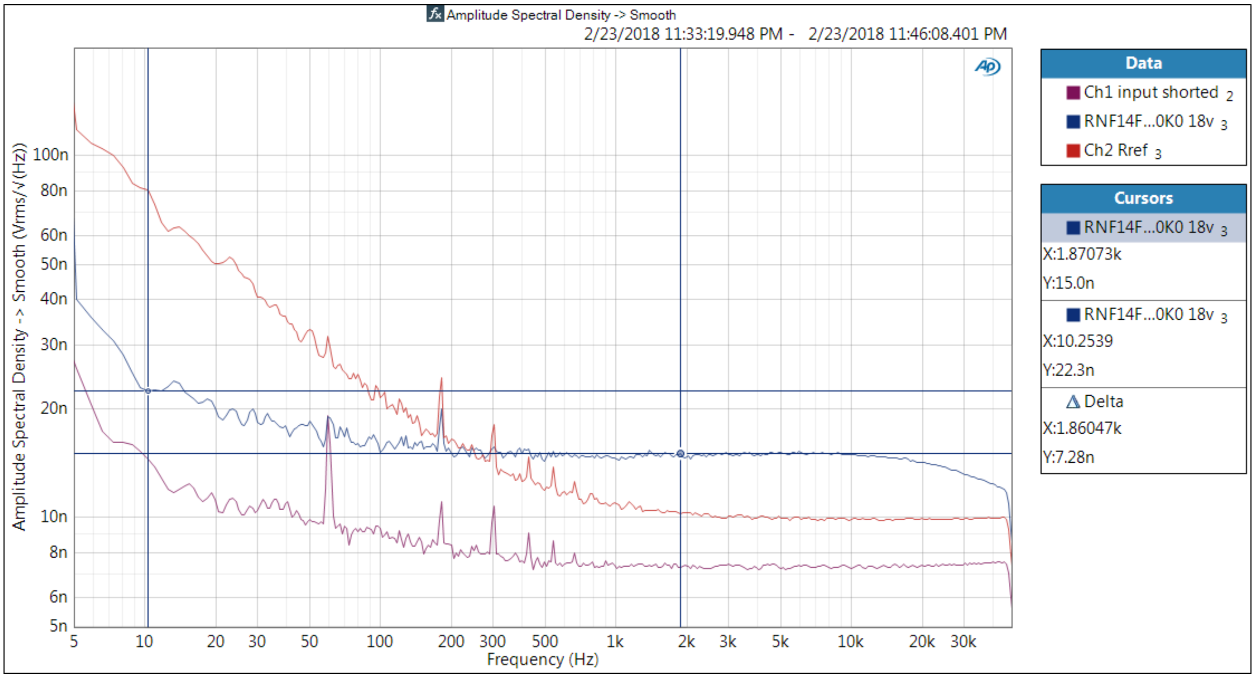


**Figure 27 Stackpole 10K metal film 1/4W with 18.5V and 0V vs. DUT and input shorted. Smoothed ASD. (Rev 3)**

## YAGEO 2K 0603 SMD 1% 100 PPM TCR

RC0603FR-072KL thick film resistor

Manufacturer's data: http://www.yageo.com/documents/recent/PYu-RC0603_51_RoHS_L_4.pdf

Add as part of rev 2 so no older testing data,

With the unusually high noise the total noise was checked from the AP meters and read as 2.1 uV RMS for the DUT with 0V and 5.5 uV RMS with 18.5V applied.

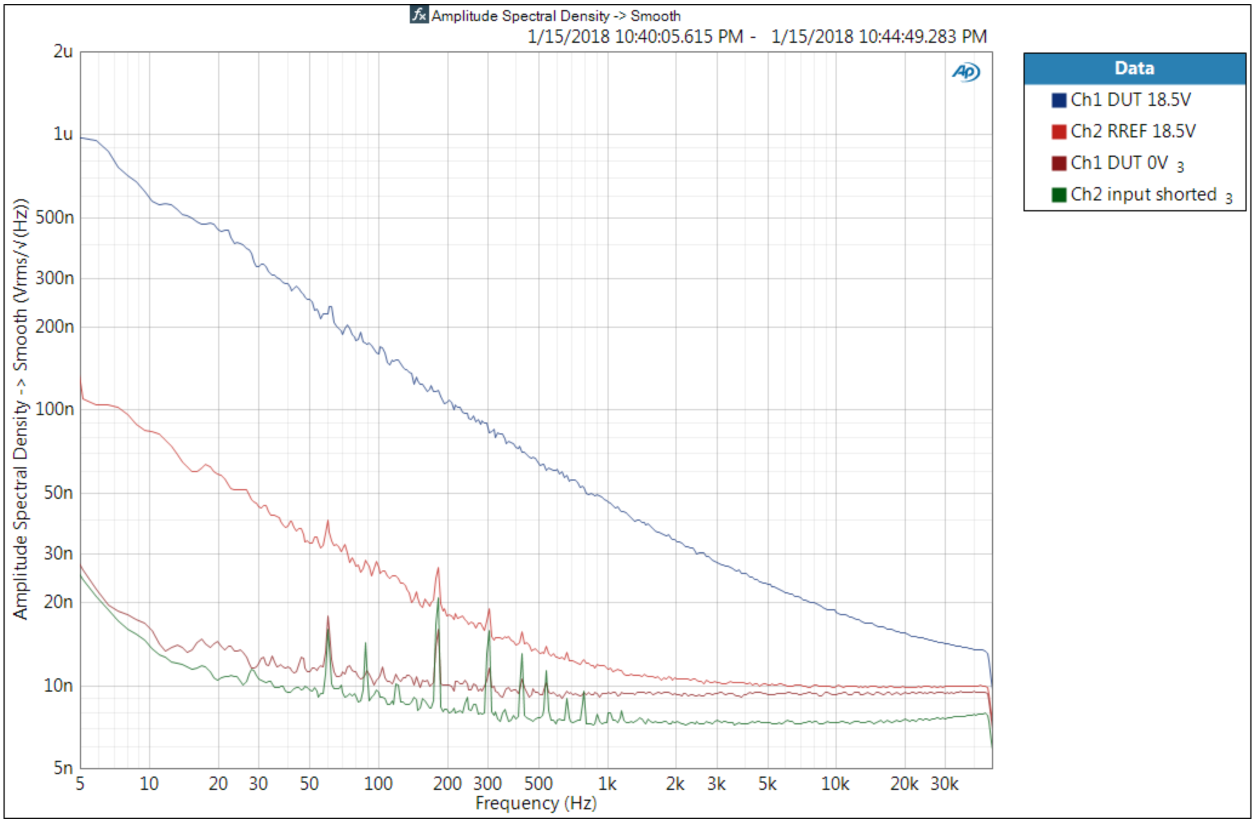


Figure 28 Yageo 2K thick film 0603 SMD with 18.5V and 0V vs. DUT and input shorted. Smoothed ASD. (Rev 2)

Also interesting for this part is that the RMS noise level versus time plot wanders by a significant amount, as shown by the ch 1 (blue) trace in Figure 21.

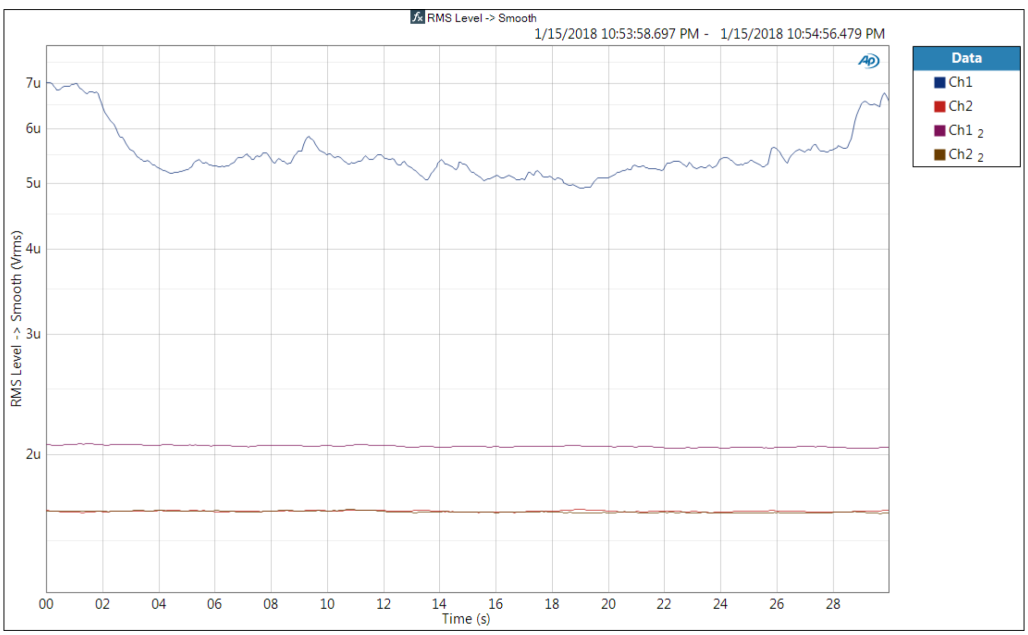


Figure 29 RMS noise vs. time. ch 1 = Yageo with 18.5V and 0V. Ch 2 is AP input shorted. AC coupled.

### YAGEO 2K THICK FILM ANALYSIS

- The spectral density from Figure 20 is 571 nV/rt-Hz at 10 Hz
- The Johnson noise spectral density is 9.3 nV/rt-Hz
- Plugging 10Hz to 100 Hz and 571 nV/rt-Hz at 10 Hz to the spreadsheet and calculate the 1/f noise in a frequency decade, yielding 2.7 uV RMS.

With 18.5 V applied this a NI of -17 dB. The total calculated noise is 5.1 uV RMS.