APPLICATION NOTE

Measuring High Output Voltage Regulator Noise

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Introduction

Electric-Vehicles, 48V telecom/data centers, 240W USB power delivery, and so on… these electronics applications utilize higher voltage power supplies than the 3.3V, 5V and 12V rails that we are more used to. These supplies often need to have very low output ripple and noise voltage to avoid degradation of the performance of the end load circuitry. Since many of these application circuits modulate input power supply noise into the output of phase noise or clock jitter, it is most useful to measure the power supply noise using a spectral noise density plot.

In this article, we focus on output noise measurement of 48V-range voltage regulators (VRs), up to a maximum of 65V. We propose a noise measurement setup and evaluate the accuracy of the results obtained.

This is a full-length engineering report, corresponding to the same titled article from the Signal Integrity Journal.

Challenges

It is common knowledge how to measure regulator output noise at low voltages, such as 3.3V and 5V. We just hook up the regulator output to a spectrum analyzer and the job is done.

The input ports of most spectrum analyzers are terminated in 50Ω, so with no DC blocking, connecting the output of a 5V regulator would, for example, result in 100mA/0.5 W of current flow/power. Usually, a maximum DC input voltage limit is set at 5V for a 50Ω terminated port and if a 50VDC supply were directly connected, the port would sink 1A and dissipate a damaging 50W.

Some analyzers and pre-amplifiers include an internal DC-blocking capacitor, eliminating the DC voltage offset and associated loading current. However, 50V DC is often the limit for this capacitor, too close to 48V and certainly insufficient for 54V or 60V VR outputs.

It is possible to add an external in-line DC-blocking capacitor, but this involves a risk of damage to an expensive analyzer input port by accidental over-shoot events after VR overloads or short circuits, for example. Any DC blocking components can also mask the regulator's true noise performance; ceramic DC-blocking capacitors have significant variation of capacitance with DC Bias, making noise difficult to measure at low frequency. Ceramic DC-blocking capacitors also become ferro-resonant at higher bias voltages, contributing additional external noise into the measurement.

For power electronics engineers, there is not a complete, readily available solution for measurement of VR noise with a DC bias at a reasonable cost, so a method is now proposed using a combination of commercially available equipment.

Goal

The goal of this paper is to establish a suitable noise measurement setup for 48VDC nominal output voltage regulators. The target regulator voltage range is up to 65V with a 10Hz to 100kHz RMS noise measurement, based on spectral noise density plots.

A Qorvo prototype *RFPoL ACT43850* with programmable output voltage is used as a ‘Device Under test’ (DUT) and an Agilent 33220A waveform generator as a known broadband noise source. **Figure 1: An overview of the measurement set up** shows the bench arrangement.

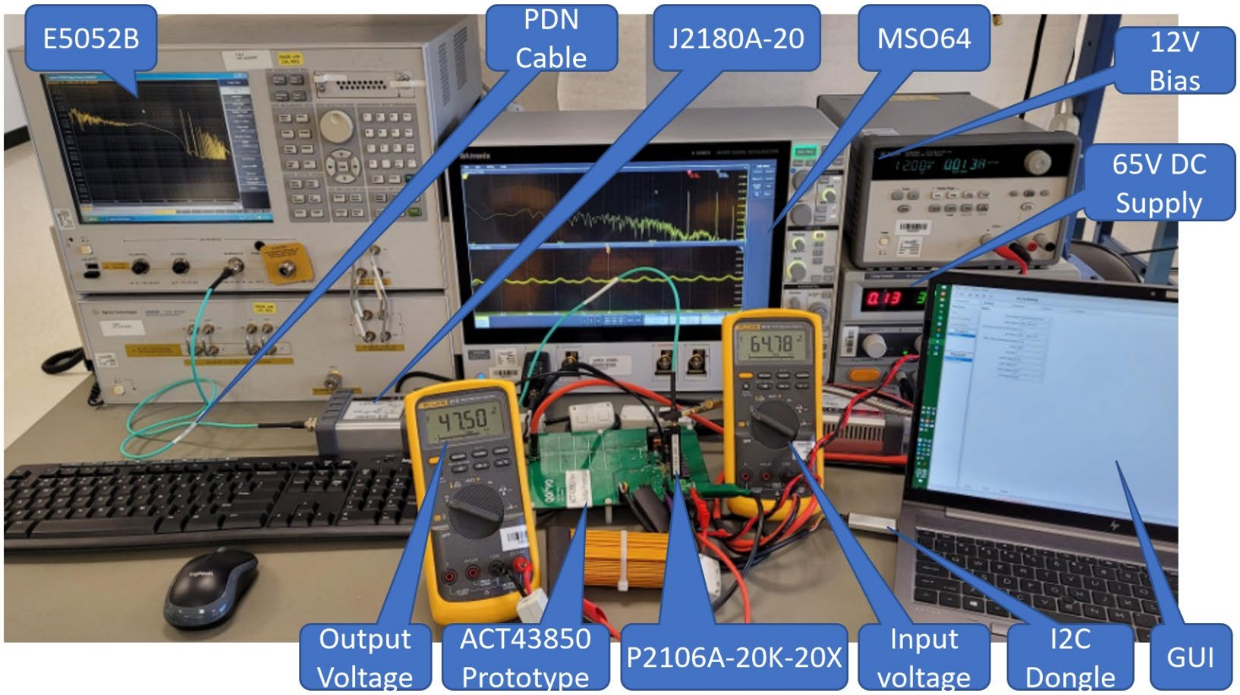


Figure 1: An overview of the measurement set up

In the tests, the following measurement equipment was used:

- Agilent E5052B Signal Source Analyzer (SSA) as a noise density meter
- Tektronix MSO64 oscilloscope in ‘Spectrum View’ mode as an alternative noise density meter
- Picotest High Voltage Noise Bundle (bundle ID: HV-NOISE)
    - Picotest J2180A-20 pre-amplifier, with the “Shielded” option as a noise pre- amplifier and to convert the high input impedance probe to the 50Ω input impedance analyzer. J2180A would be preferable for better low frequency fidelity, but was not readily available to us for this testing
    - Picotest P2106A-20K-20X 1-port browser probe as a noise probe. This is a near-zero capacitance probe to avoid noise peaking due to probe resonance
    - Picotest SMAJ/SMPMK-500, BNCJ/BNCJ-1000 PDN (Power Delivery Network) cabling for high shield attenuation coaxial connections
- Off-the-shelf SMA to BNC conversion adapters
- Picotest custom differential amplifier (to be released as P2103A) prototype for a double confirmation of the final measurement and noise comparison

High voltage noise measurement outline

The target procedure for the high voltage noise measurement method evaluated is as follows:

- Probe the DUT with the P2106A high impedance probe
- Amplify the P2106A signal and interface to the 50Ω analyzer port using the J2180A pre-amplifier
- Measure the probe and the J2180A-amplified noise signal with a Keysight E5052B Signal Source Analyzer (SSA) using its baseband input port

The Picotest J2180A is a high performance, ultra-low noise ×10 gain (20dB) preamplifier, with a high impedance input to 50Ω output conversion, for sensitive signal measurement. The internal J2180A DC blocking capacitor is rated for 50V and applying 65V would overstress it, but also would add noise due to its ferro-resonance. So, we use the Picotest P2106A probe to divide down the entire signal (AC and DC together) of the regulator output by the attenuation of ×1/20. With a combination of ×1/20 P2106A and ×10 J2180A, we have total ×1/2 gain into the E5052B, keeping the noise gain almost unaffected, compared to a direct measurement.

Measurement method validation

The first rule of test is to validate measurements against a known standard.

We start our validation by measuring a known, broadband, noise signal generated by the Agilent 33220A, with no DC bias. Then, we keep cross-comparing known signal(s) and new signal(s) from the voltage regulator output noise measurements, approaching our goal of measurements with 50V bias and up to 65V.

Noise floor of the E5052B SSA

First, we always record the noise floor of the measurement setup. This is essential to ensure high quality, accurate and repeatable data. Below table shows the detailed setup.

The noise floor as measured is shown in **Figure 2: Noise floor of the E5052B SSA.**

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	(open)
DUT Contact	(open)
Probe	(open)
Cable between Probe and Pre-Amplifier	(open)
Pre-Amplifier	(open)
Cable between Pre-Amplifier and Analyzer	1-meter, BNC to BNC, PDN cable
Analyzer	E5052B, Baseband Port, IF gain = 0dB

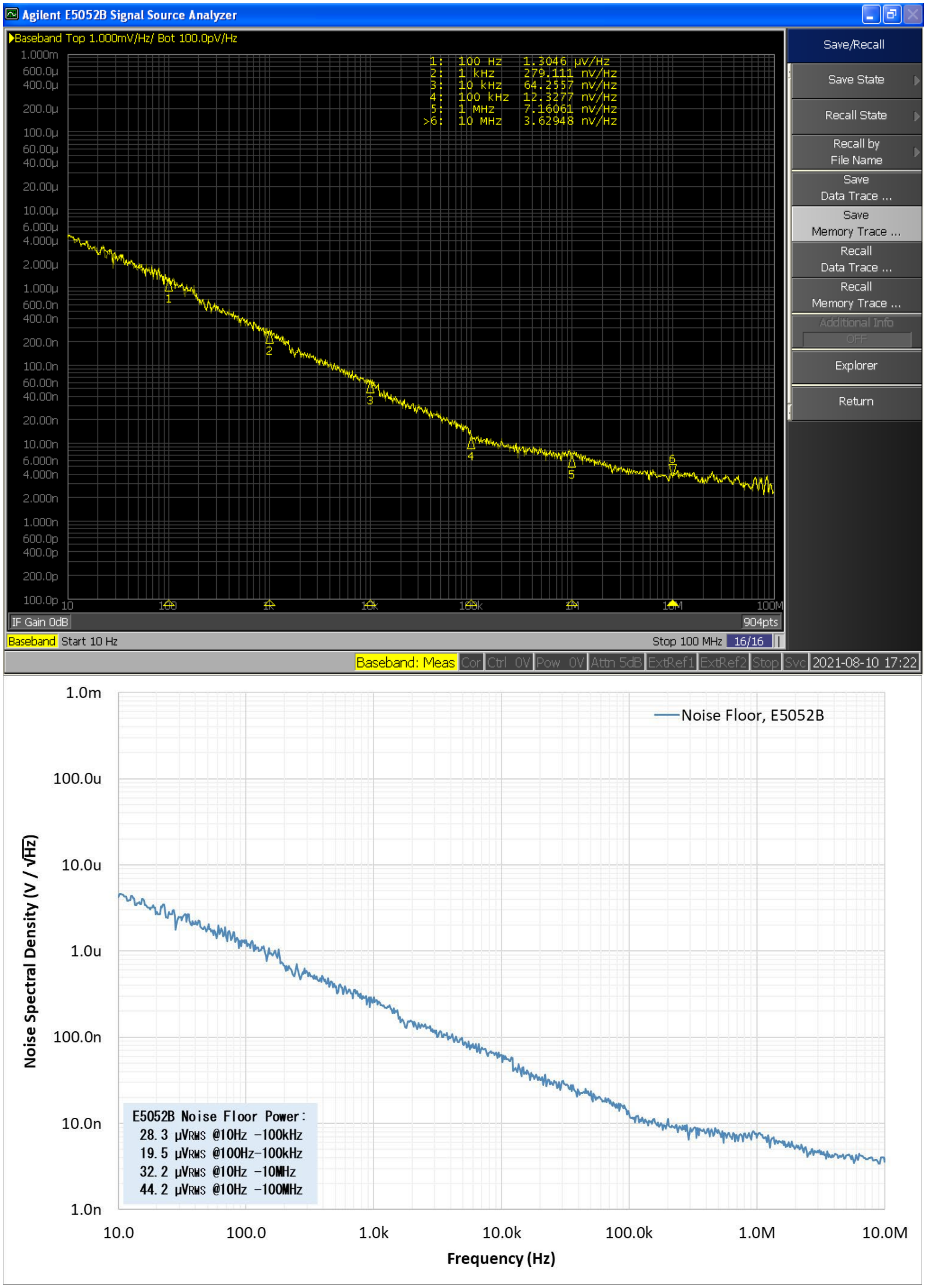


Figure 2: Noise floor of the E5052B SSA

Noise floor of P2106A + J2180A + E5052B

Now, the noise floor of the complete measurement system is evaluated, by the setup in below where high performance, shielded, PDN fixed-length cables are used.

The results, in **Figure 3: Noise floor of the P2106A probe + J2180A amplifier + E5052B SSA**, show the minor broadband noise and harmonics from the switching power supply powering the pre-amplifier. This is one reason why the shielding of the cables is important.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	(open)
DUT Contact	(open)
Probe	P2106A
Cable between Probe and Pre-Amplifier	0.5-meter, mini-SMP to SMA, PDN cable,
	SMA to BNC adapter
Pre-Amplifier	J2180A-20 “Shielded”
Cable between Pre-Amplifier and Analyzer	1-meter, BNC to BNC, PDN cable
Analyzer	E5052B, Baseband Port, IF gain = 0dB

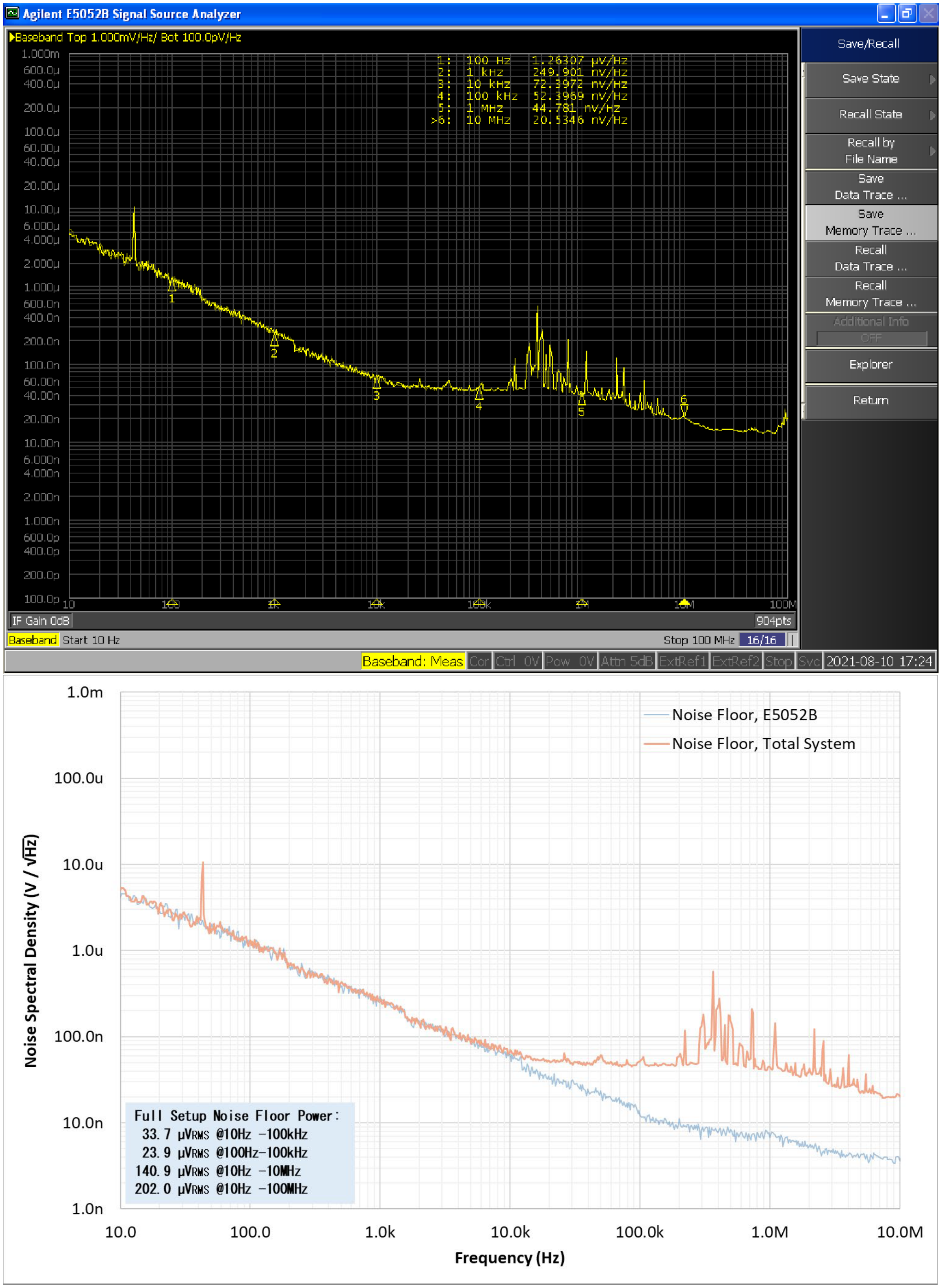


Figure 3: Noise floor of the P2106A probe + J2180A amplifier + E5052B SSA

Known noise from the Agilent 33220A

Next, we use the Agilent 33220A signal generator “noise” output mode as a known noise source. The 33220A generates white noise with fixed amplitude vs. frequency up to 10 MHz, and the generator output noise level can be programmed in units of mV_{RMS}. When we see an equivalent noise reading at the E5052B, we can use this measurement as our first correlation point and we can use this data to verify the measurement bandwidth and the scaling of the pre-amplifier and probe.

Applying 50mV_{RMS} direct to the spectrum analyzer - the first correlation step

As a first correlation step, we connect the Agilent 33220A noise source directly to the E5052B analyzer baseband input port, by the setup below. The noise amplitude is set to 50mV_{RMS}. The noise source 50Ω output matches the analyzer 50Ω input, so the analyzer should read exactly the set output of the noise source with no amplification or attenuation. Note that the E5052B does not measure amplitude, but rather noise density. The amplitude is computed from the measurement bandwidth and the noise density. **Figure 4: Known noise level from the Agilent 33220A: 16µV noise density = 50mVRMS in 10MHz bandwidth** shows the resulting plot.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	**33220A, Noise-mode: 50mV_{RMS}, 50Ω Output**
DUT Contact	**↓ (bypass)**
Probe	**↓ (bypass)**
Cable between Probe and Pre-Amplifier	**↓ (bypass)**
Pre-Amplifier	**↓ (bypass)**
Cable between Pre-Amplifier and Analyzer	**1-meter, BNC to BNC, PDN cable**
Analyzer	**E5052B, Baseband Port, IF gain = 0dB**

The precise (Excel) calculation result is shown in Figure **4** but we can easily hand-calculate this flat white noise power from the 10MHz signal bandwidth and the noise density, as 50mVRMS = 16µV × sqrt(10MHz). From the plot, it is confirmed that the entire applied noise curve stays above the noise floor of the E5052B analyzer.

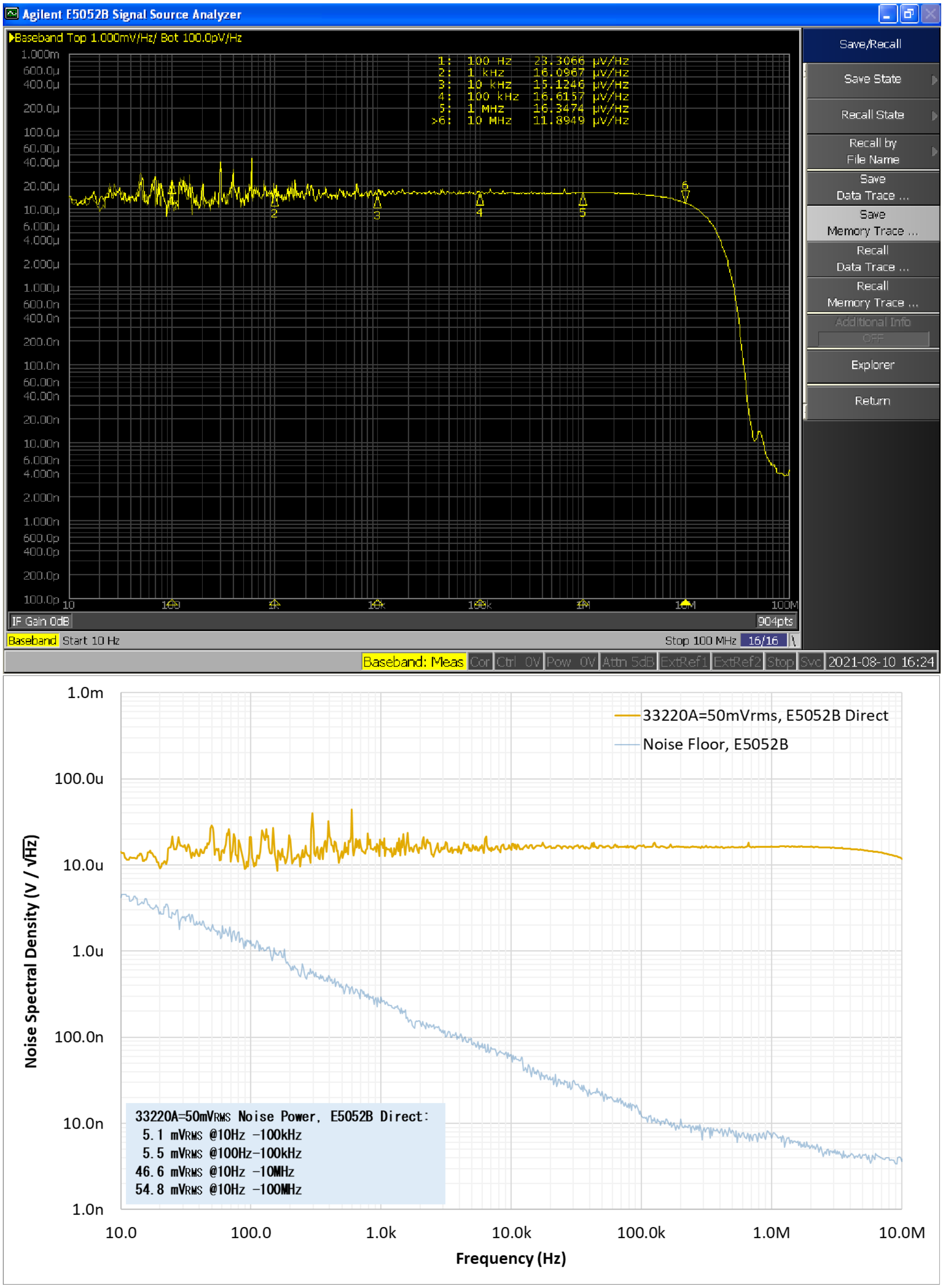


Figure 4: Known noise level from the Agilent 33220A: 16µV noise density = 50mV$_{RMS}$ in 10MHz bandwidth

100 mV_{RMS} noise to J2180A + E5052B

In this step, we use the Agilent 33220A noise source but add the J2180A pre-amplifier between the noise source and analyzer as the detail shown below.

The Agilent 33220A always has 50Ω output impedance, but can be set in its utility menu to expect a high impedance or 50Ω load. The display automatically changes from 50mV_{RMS} with a high impedance load to 100mV_{RMS} with 50Ω load, to produce the same voltage to the high impedance J2180 pre-amplifier input, without manually adjusting the amplitude setting. This means that the noise source output driver amplifier electrical conditions stay the same, while toggling the output termination setting.
See Error! Reference source not found. for the detail.

The J2180A pre-amplifier has ×10 gain, so our expected result on the E5052B input is 100 mV_{RMS} ×10 or 1V_{RMS}, shown in **Figure 5: Known noise level from the Agilent 33220A with the pre-amp: 100mVRMS target**. Only one factor/element is changed at a time during this series of correlations and we can also confirm that we get the same expected total of ×20 gain at this step, compared with connecting 50mV directly to the analyzer.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	**33220A, Noise-mode: 100mV_{RMS}, Hi-Z Output**
DUT Contact	**↓ (bypass)**
Probe	**↓ (bypass)**
Cable between Probe and Pre-Amplifier	**1-meter, BNC to BNC, PDN cable**
Pre-Amplifier	**J2180A-20 “Shielded”**
Cable between Pre-Amplifier and Analyzer	**1-meter, BNC to BNC, PDN cable**
Analyzer	**E5052B, Baseband Port, IF gain = 0dB**

Figure 5 confirms that the source noise is shifted by 20dB (×10) with the addition of the pre-amplifier but, with the pre-amplifier, we hit the noise ceiling of the E5052B analyzer by judging from the RMS calculation result of 86mV_{RMS} which is short for our target 100mV_{RMS}.

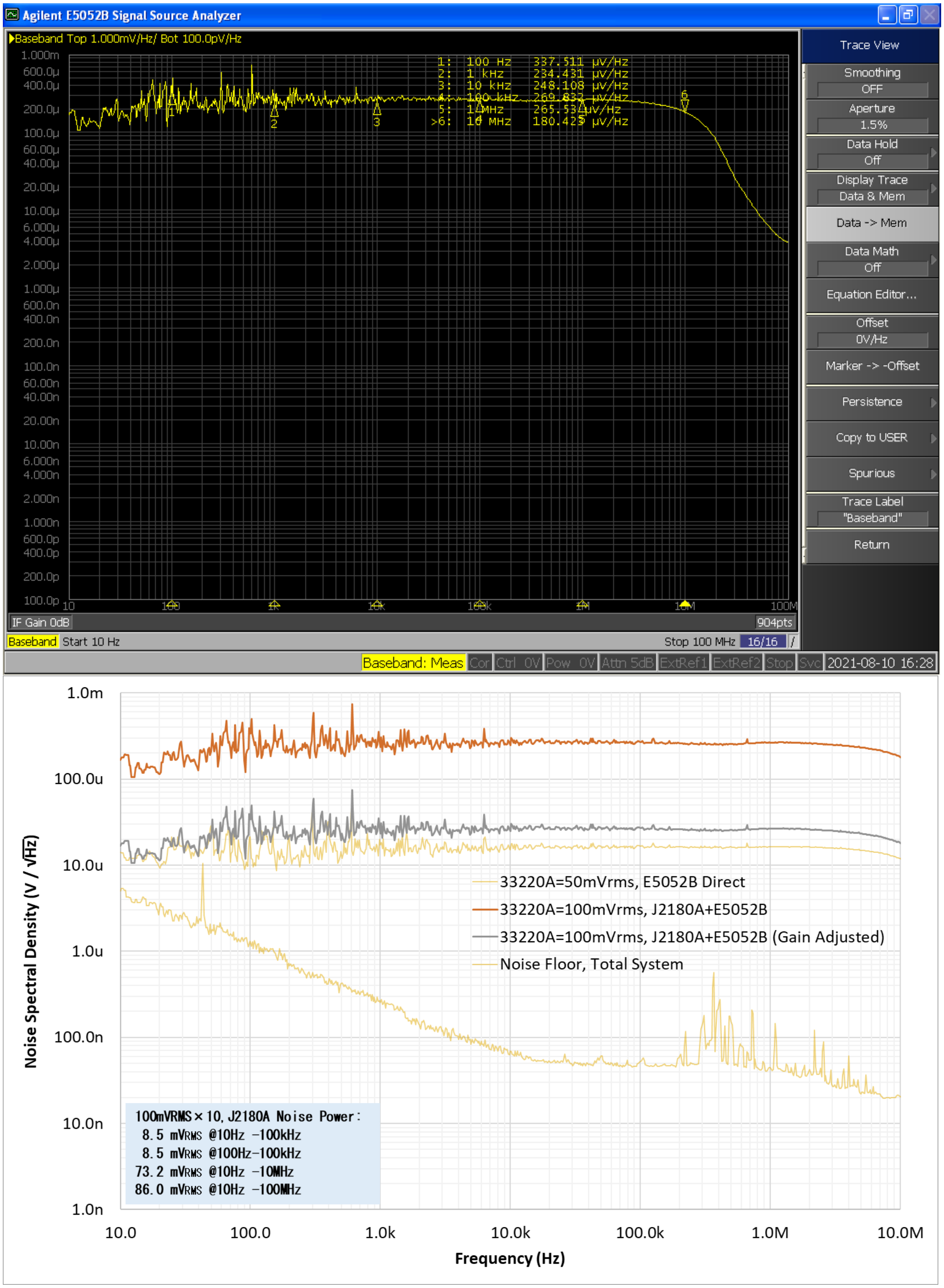


Figure 5: Known noise level from the Agilent 33220A with the pre-amp: 100mVRMS target, hitting the measurement ceiling

50 mV_{RMS} noise to J2180A + E5052B

As we hit the noise ceiling in the previous step, we repeat the same measurement for the $50mV_{RMS}$ target, by following the detailed setup below.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	**33220A, Noise-mode: $50mV_{RMS}$, Hi-Z Output**
DUT Contact	**↓ (bypass)**
Probe	**↓ (bypass)**
Cable between Probe and Pre-Amplifier	**1-meter, BNC to BNC, PDN cable**
Pre-Amplifier	**J2180A-20 “Shielded”**
Cable between Pre-Amplifier and Analyzer	**1-meter, BNC to BNC, PDN cable**
Analyzer	**E5052B, Baseband Port, IF gain = 0dB**

Figure 6: Known noise level from the Agilent 33220A with the pre-amp: 160μV noise density confirms that the entire noise curve stays above the noise floor.

By reducing the source noise signal by half, the RMS calculation comes to the target $50mV_{RMS}$. This “Gain Adjusted” curve perfectly overlays the “E5052B Direct” curve with $50mV_{RMS}$ input, providing correlation and confirming the measurement is below the measurement ceiling and well above the noise floor.

We also see the low frequency gain roll off of the J2180A-20 at 20Hz. The J2180A (without the -20 suffix) has a much lower frequency cutoff at 0.1Hz and so is preferred. Either pre-amplifier should be a shielded type.

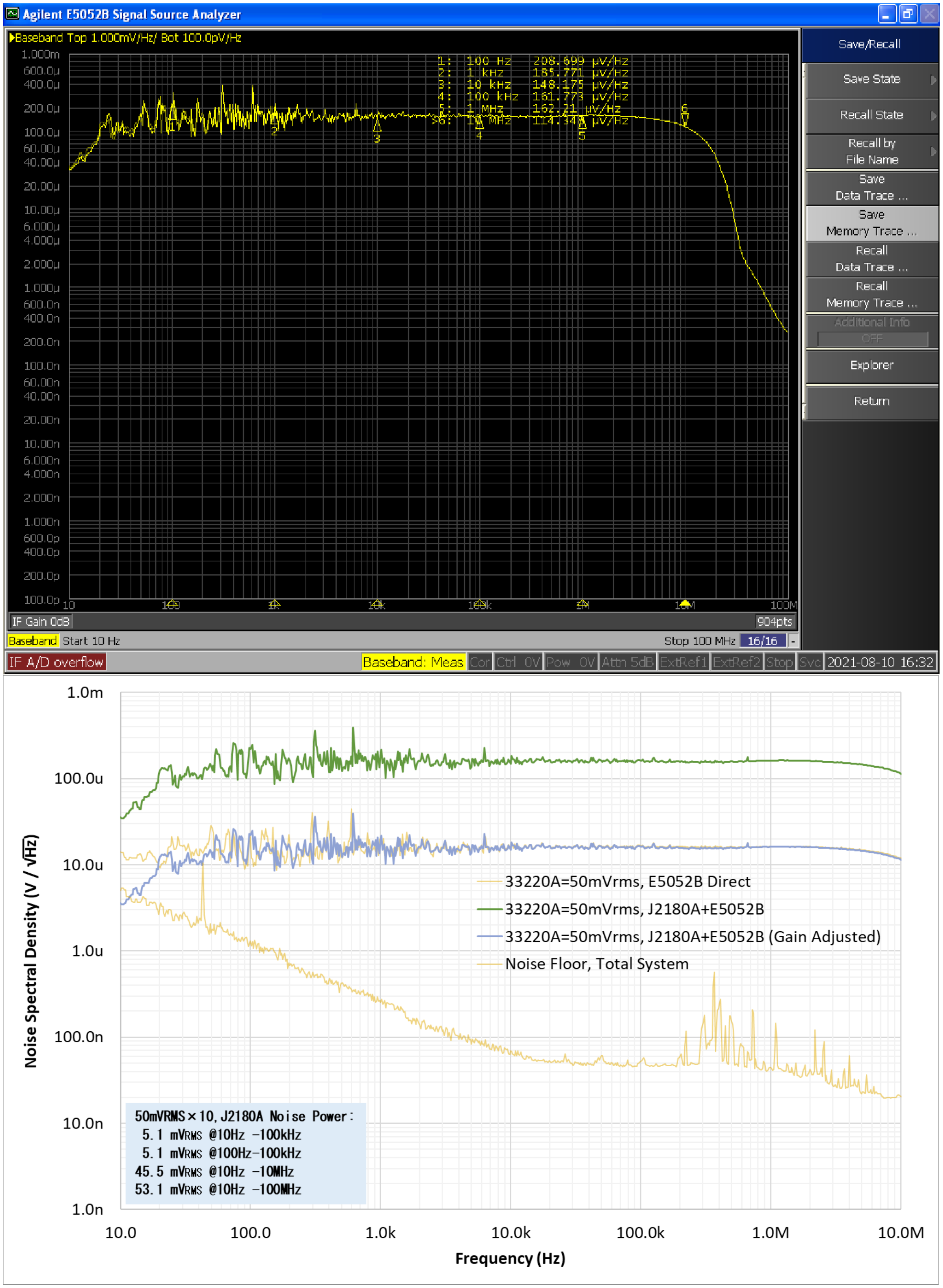


Figure 6: Known noise level from the Agilent 33220A with the pre-amp: 160µV noise density target

50mV$_{RMS}$ noise into the full system

In this step, we insert the P2106A probe, which has a gain of ×1/20, as the detailed setup shown below.

Knowing that the input resistance of the P2106A probe is 20kOhms, we can terminate the 33220A output immediately at its output BNC port with a 50Ω termination resistor and probe this 50Ω resistor with the P2106A. Since the noise generator is terminated into a 50Ω termination resistor, we toggle the output setting of the 33220A to expect 50Ω termination, so it displays the noise level correctly.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	**33220A, Noise-mode: 50mV$_{RMS}$, 50Ω Output**
DUT Contact	**BNC Card-edge connector**
	50Ω termination resistor
Probe	**P2106A**
Cable between Probe and Pre-Amplifier	**0.5-meter, mini-SMP to SMA, PDN cable,**
	SMA to BNC adapter
Pre-Amplifier	**J2180A-20 "Shielded"**
Cable between Pre-Amplifier and Analyzer	**1-meter, BNC to BNC, PDN cable**
Analyzer	**E5052B, Baseband Port, IF gain = 0dB**

The total gain of this measurement system is ×1/2 from the 33220A's display to the analyzer shown in **Figure 7: 50mVRMS noise into the full test setup**.

The gain-adjusted measurement result is well matching to the direct measurement up to about 2MHz, where the signal begins to roll off. Because of this high frequency gain roll off, the RMS value in Figure **7** is not 50mVRMS since the bandwidth is no longer 10MHz. See more comments in the next step.

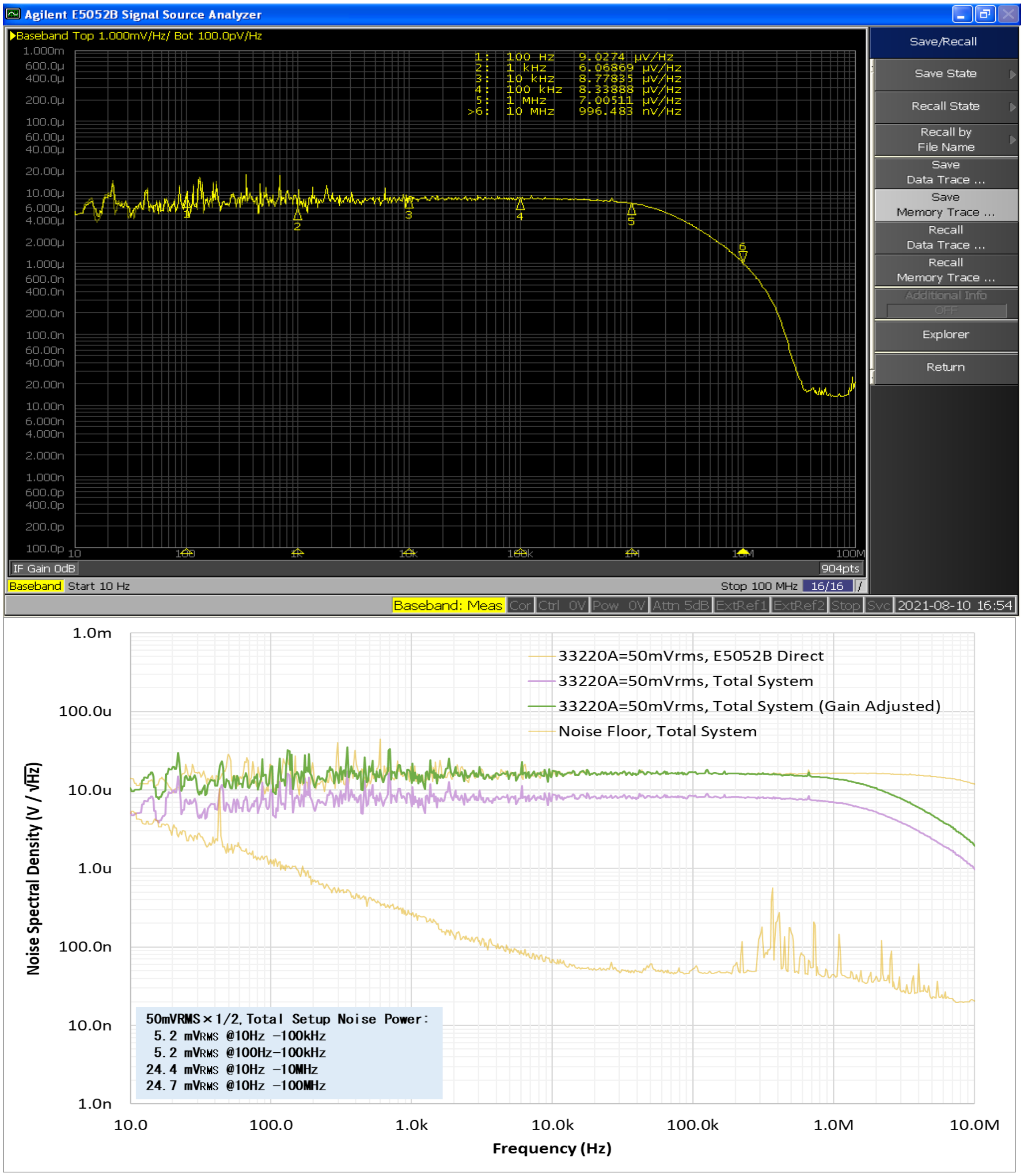


Figure 7: 50mVRMS noise into the full test setup

$100mV_{RMS}$ noise into the full system

As a final step for full system measurement confirmation with the known noise source, we adjust the Agilent 33220A's noise output to $100mV_{RMS}$ so that we can do an apple-to-apple comparison with our first measurement earlier of the noise floor of the Analyzer. This gives the plot in **Figure 8: 100mVRMS noise into the full test setup**.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	**33220A, Noise-mode: $100mV_{RMS}$, 50Ω Output**
DUT Contact	**BNC Card-edge connector**
	50Ω termination resistor
Probe	**P2106A**
Cable between Probe and Pre-Amplifier	**0.5-meter, mini-SMP to SMA, PDN cable,**
	SMA to BNC adapter
Pre-Amplifier	**J2180A-20 "Shielded"**
Cable between Pre-Amplifier and Analyzer	**1-meter, BNC to BNC, PDN cable**
Analyzer	**E5052B, Baseband Port, IF gain = 0dB**

When we compare this pre-gain-adjust result with the measured noise floor of the analyzer in Figure **2**, we see the gain roll off in this measurement, but we can also confirm it is good for our target of up to 100kHz RMS noise evaluation, and even up to 2MHz. This bandwidth is mostly controlled by the P2106A probe resistance, the capacitance of the probe cable and the input capacitance of the J2180A pre-amplifier.

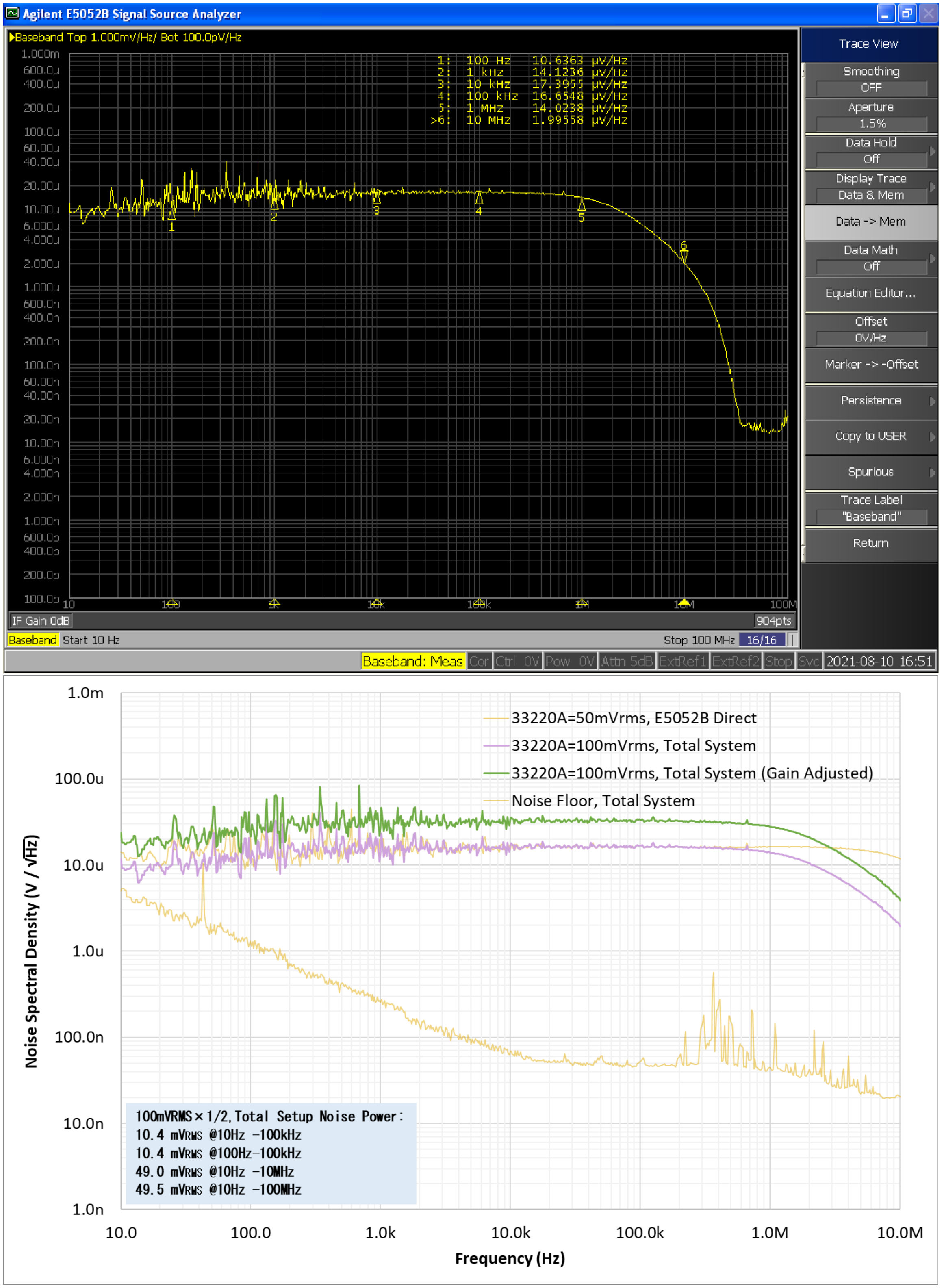


Figure 8: 100mVRMS noise into the full test setup

Measuring DUT RFPoL ACT43850 VR

In the previous sections, we validated our noise measurement setup with the P2106A + J2180A + E5052B.

Now, we measure the noise output of our DUT, a prototype of Qorvo RFPoL ACT43850 DC-to-DC voltage regulator

ACT43850 set at 25V$_{DC}$ output, connected directly to the E5052B

Before jumping to the target 50V measurement, we run one more step of correlation. The E5052B is specified for a maximum 35V baseband signal input. So, we program the ACT43850 regulator to the 25V target and connect directly to the E5052B analyzer.

We are confident that this DC-DC regulator has an output impedance much lower than 1Ω, in the 1mΩ range (this will be covered in a future application notes where we measure the output impedance). So, this VR fully drives the 50 Ω terminator at the input port of the E5052B (through the DC-blocking capacitor, also inside the E5052B) and no attenuation is observed. It actually doesn't matter if the E5052B port is high impedance or 50Ω input, because the VR output impedance is so low.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	**ACT43850 programmed at 25V**
DUT Contact	**Mini-SMP surface mount connector, across the ACT43850 output capacitors**
Probe	**↓ (bypass)**
Cable between Probe and Pre-Amplifier	**↓ (bypass)**
Pre-Amplifier	**↓ (bypass)**
Cable between Pre-Amplifier and Analyzer	**1-meter, mini-SMP to SMA, PDN cable**
	SMA to BNC adapter
Analyzer	**E5052B, Baseband Port, IF gain = 0dB**

The **Figure 9: ACT43850 noise at 25V output with direct connection to the E5052B** shows the result. Up to 100kHz, we see the curve is above the system noise floor.

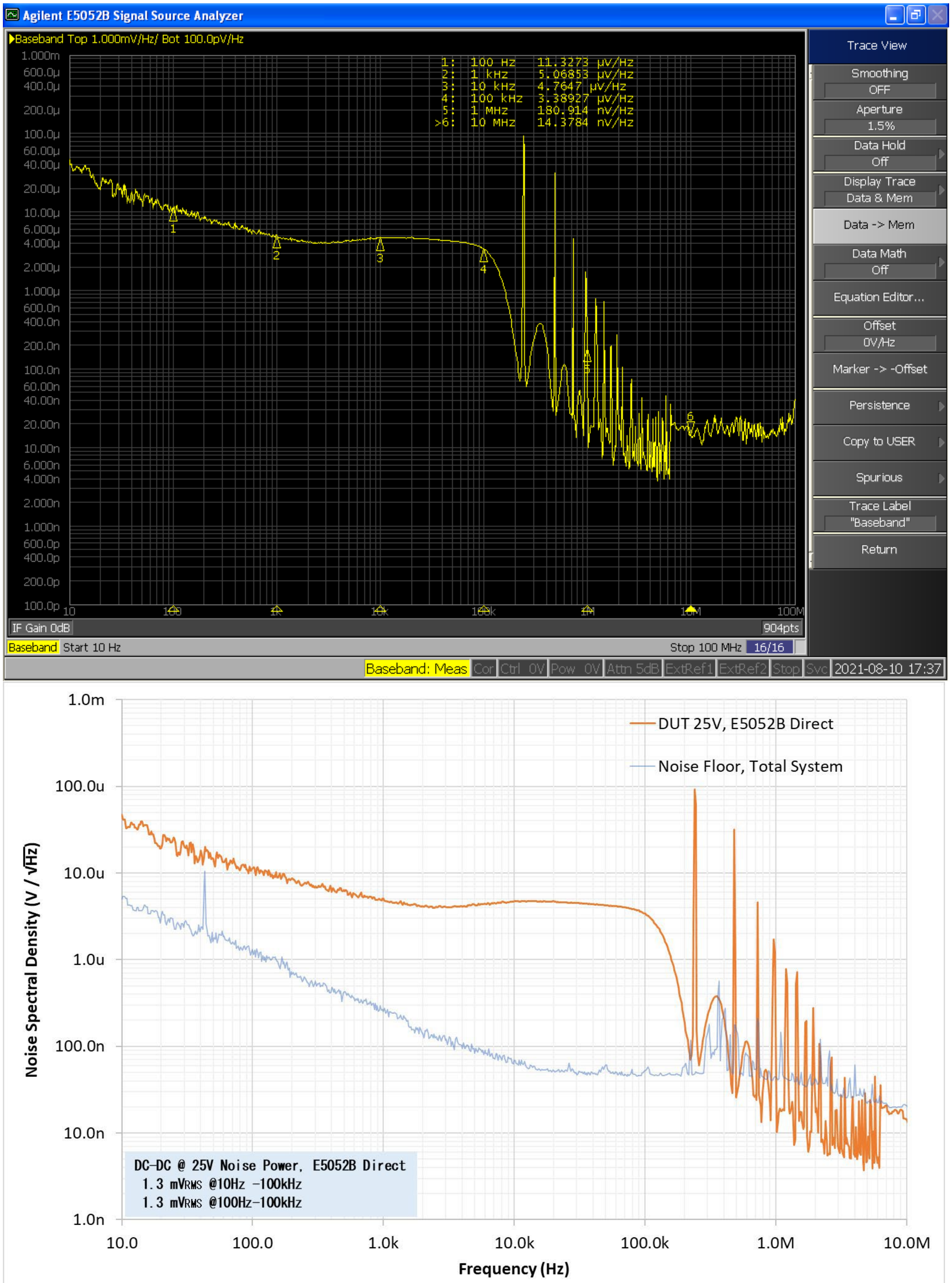


Figure 9: ACT43850 noise at 25V output with direct connection to the E5052B

ACT43850 set at 25V_{DC} with the full measurement setup

We repeat the same ACT43850 25V output with the full measurement setup as below.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	ACT43850 programmed at 25V
DUT Contact	↓ (bypass)
Probe	P2106A, across the ACT43850 output capacitors
Cable between Probe and Pre-Amplifier	0.5-meter, mini-SMP to SMA, PDN cable,
	SMA to BNC adapter
Pre-Amplifier	J2180A-20 “Shielded”
Cable between Pre-Amplifier and Analyzer	1-meter, BNC to BNC, PDN cable
Analyzer	E5052B, Baseband Port, IF gain = 0dB

With the probe and pre-amplifier interposed between the DUT and analyzer, the total gain is x1/2 and we see the result in **Figure 10: ACT43850 noise at 25V output with the full measurement setup**.

We see the curve is above the system noise floor and when we compare this result with a direct connection to the analyzer, allowing for the gain difference of x1/2, we can confirm it is very good result for our target of noise evaluation up to 100kHz RMS.

We see the slight gain roll off of this measurement system in the low frequency region, below 20Hz. When using the J2180A “Shielded” option (not J2180A-20), this low frequency performance is improved with the roll off reduced to 0.1Hz.

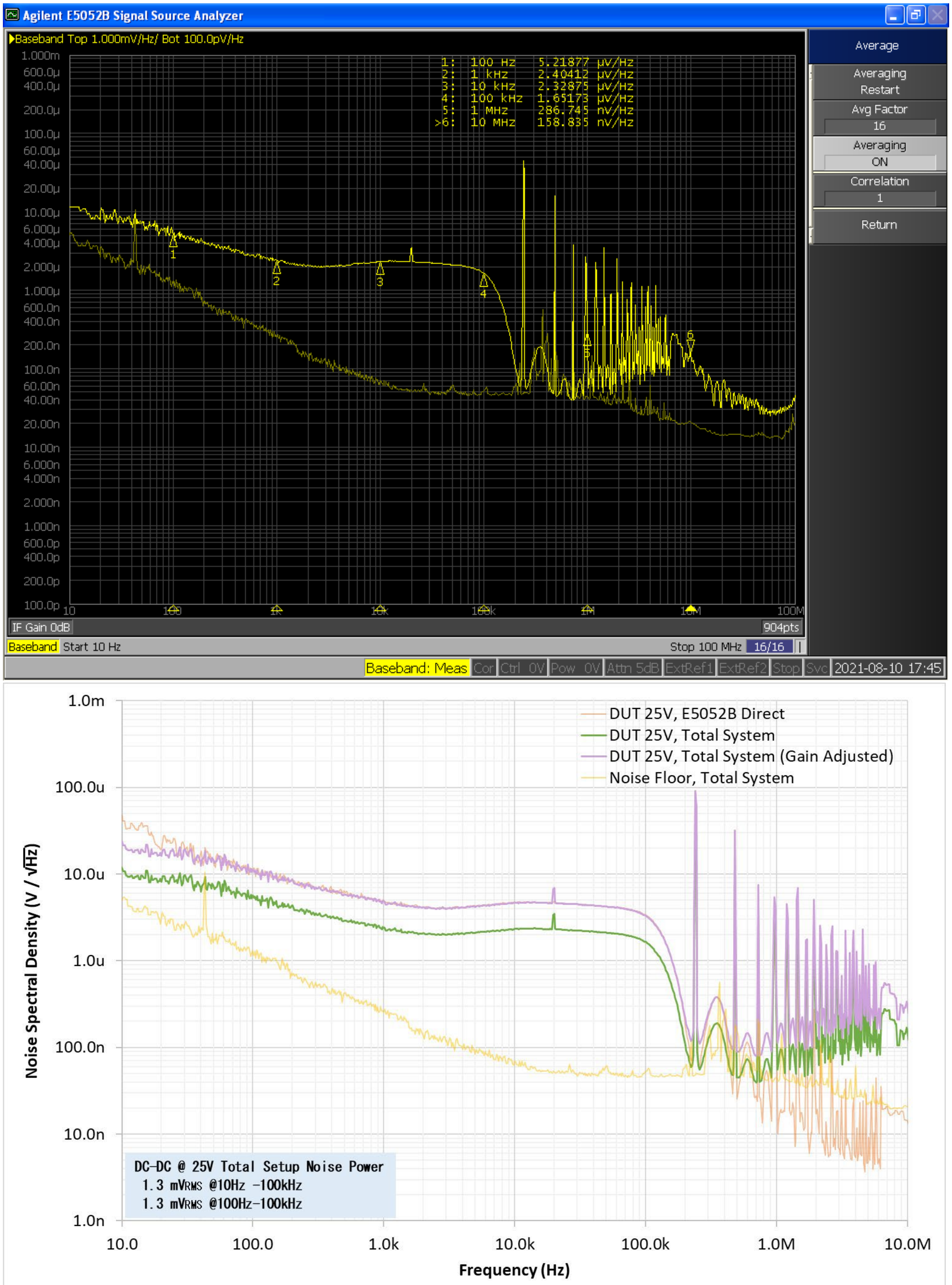


Figure 10: ACT43850 noise at 25V output with the full measurement setup

ACT43850 set at 50V$_{DC}$ with the full measurement setup

Now, we measure our target ACT43850 VR at 50V output, as the details below.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	ACT43850 programmed at 50V
DUT Contact	↓ (bypass)
Probe	P2106A, across the ACT43850 output capacitors
Cable between Probe and Pre-Amplifier	0.5-meter, mini-SMP to SMA, PDN cable,
	SMA to BNC adapter
Pre-Amplifier	J2180A-20 “Shielded”
Cable between Pre-Amplifier and Analyzer	1-meter, BNC to BNC, PDN cable
Analyzer	E5052B, Baseband Port, IF gain = 0dB

Figure 11: ACT43850 noise at 50V output with the full measurement setup shows the result. We have combined comments and observations in the next step.

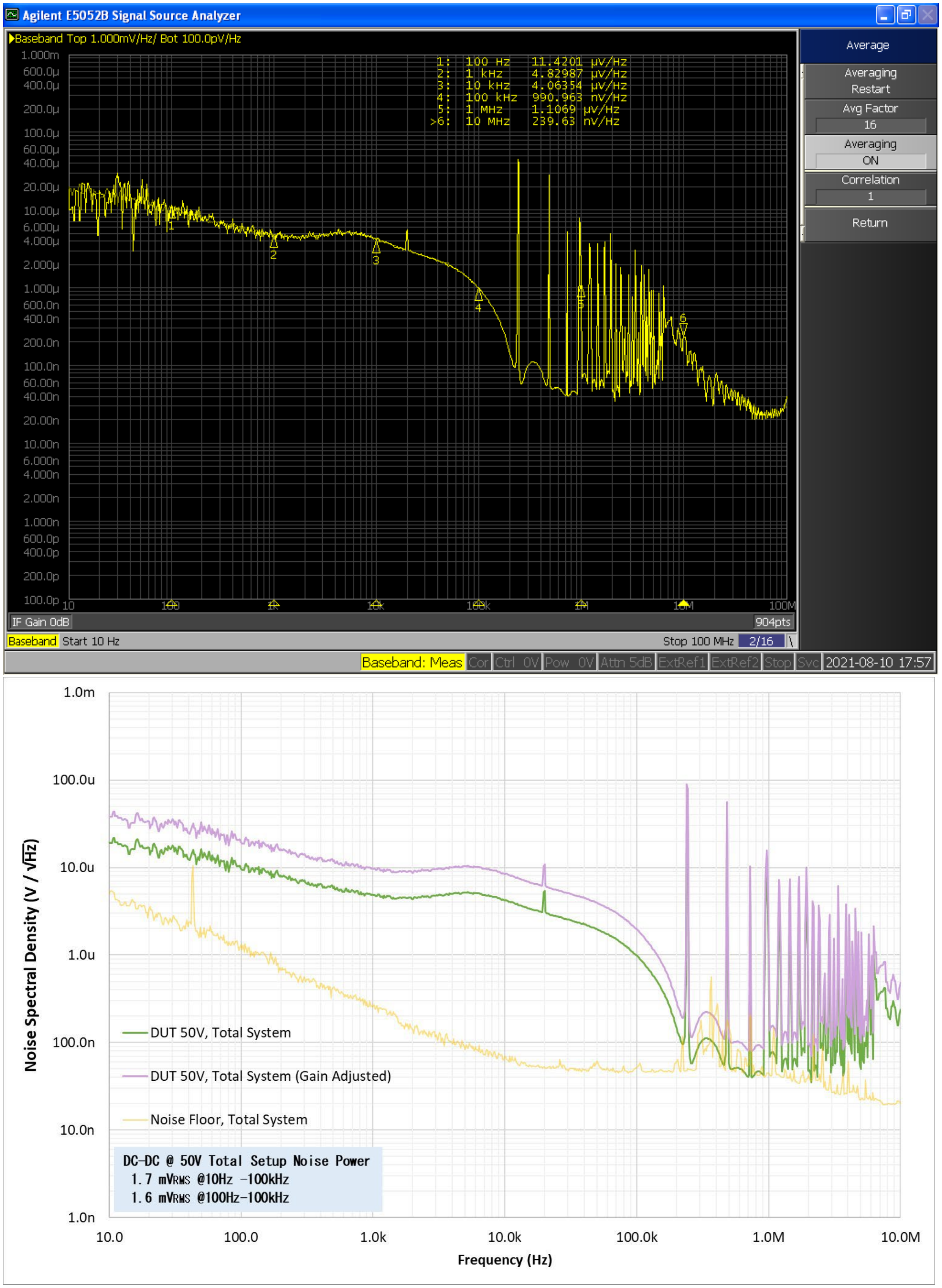


Figure 11: ACT43850 noise at 50V output with the full measurement setup

ACT43850 set at 50VDC, using an alternative method

Though we hit our target, we run one final correlation, we use one other measurement setup and see if the two 50V regulator noise measurements are aligned, as the details shown below. As this is not our main proposed system test setup, we will skip the details but, in this final step, we use a high input impedance ×1/6 gain prototype Picotest differential amplifier in place of the P2106A probe and J2180A pre-amplifier.

POSITION FROM DUT TO ANALYZER	ELEMENT USED
DUT	ACT43850 programmed at 50V
DUT Contact	Mini-SMP surface mount connector, across the ACT43850 output capacitors
Probe	↓ (bypass)
Cable between Probe and Pre-Amplifier	0.5-meter, mini-SMP to SMA, PDN cable,
	SMA to BNC adapter
Pre-Amplifier	Picotest (P2103A) prototype differential amplifier
Cable between Pre-Amplifier and Analyzer	1-meter, BNC to BNC, PDN cable
Analyzer	E5052B, Baseband Port, IF gain = 0dB

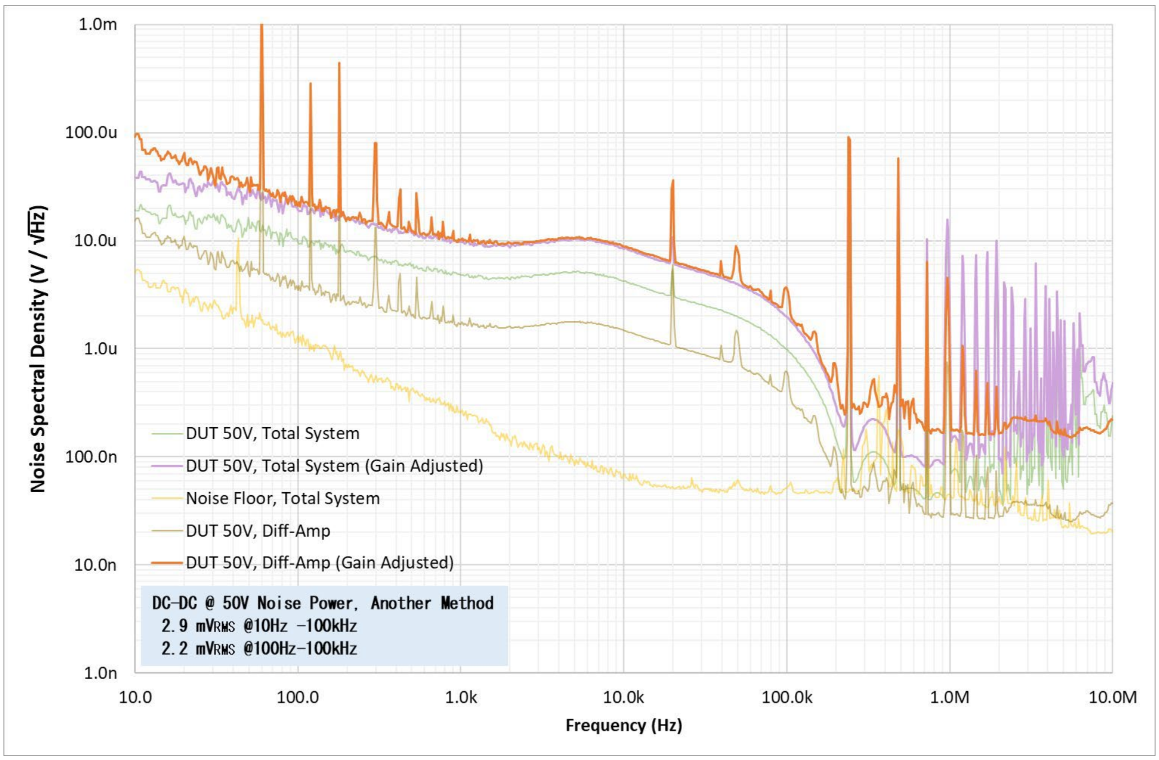


Figure 12: ACT43850 noise at 50V output, alternative, using Picotest differential amplifier

The **Figure 12: ACT43850 noise at 50V output, alternative, using Picotest differential amplifier** shows the result.

The comparison of the two different methods (the previous step and this step) agree very well with some spurs and gain roll off. The differential probe is noisier than the P2106A and J2180A proposed solution, mostly due to the differential probes onboard switching regulators.

Using an oscilloscope as a spectrum analyzer

Finally, to demonstrate our proposed setup is compatible to any 50Ω-input equipment, we repeat the step of **100mV$_{RMS}$ noise into the full system** but replacing the E5052B SSA with a Tektronix MSO64 oscilloscope, using its "Spectrum View" analyzer function.

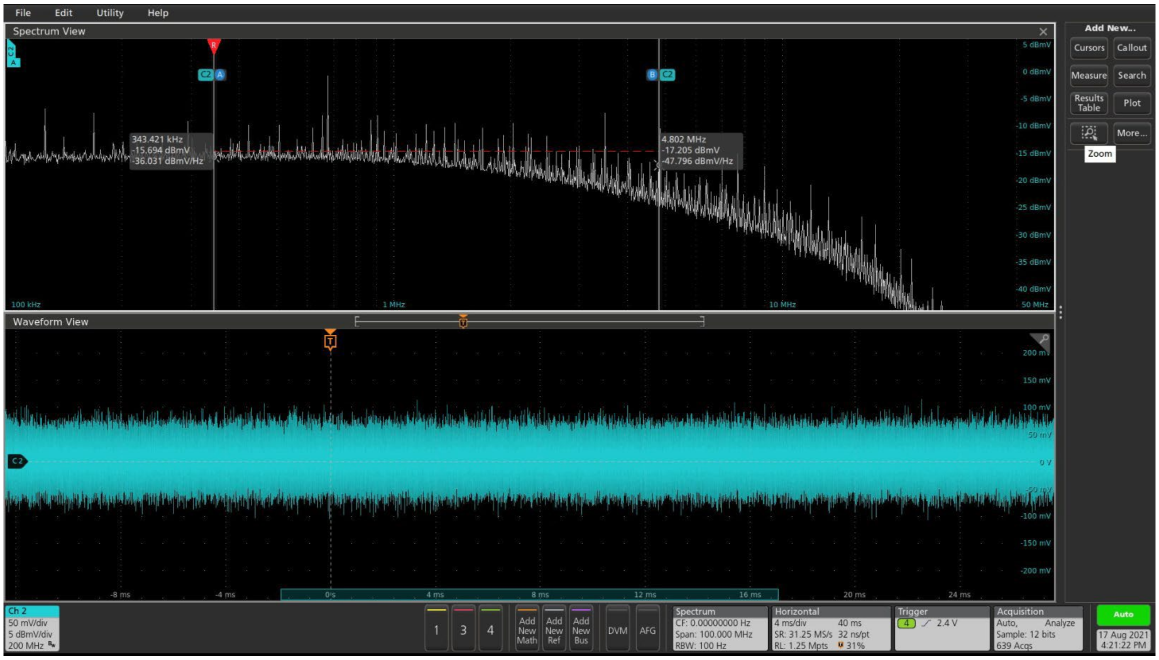


Figure 13: MSO64, Spand to 100MHz / RBW = 100Hz

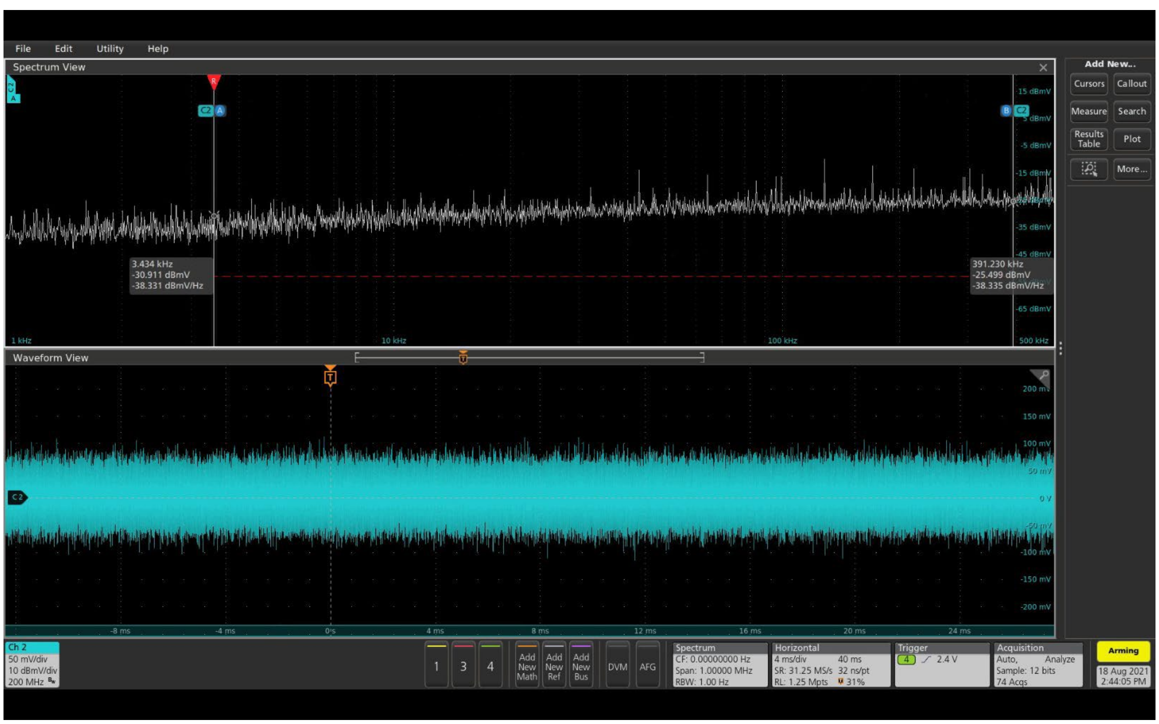


Figure 14: MSO64, Spand to 1MHz / RBW = 1Hz

The plots in **Figures 13** and **Figure 14** are displayed, the first with 100MHz span and a resolution bandwidth of 100Hz, the second with a span of 1MHz and with 1Hz resolution bandwidth.

On the excel, the data is then analyzed, converting the MS064 dBmV output to noise power density, factoring-in the receiver bandwidth and x1/2 gain adjustment as shown in **Figure 15**.

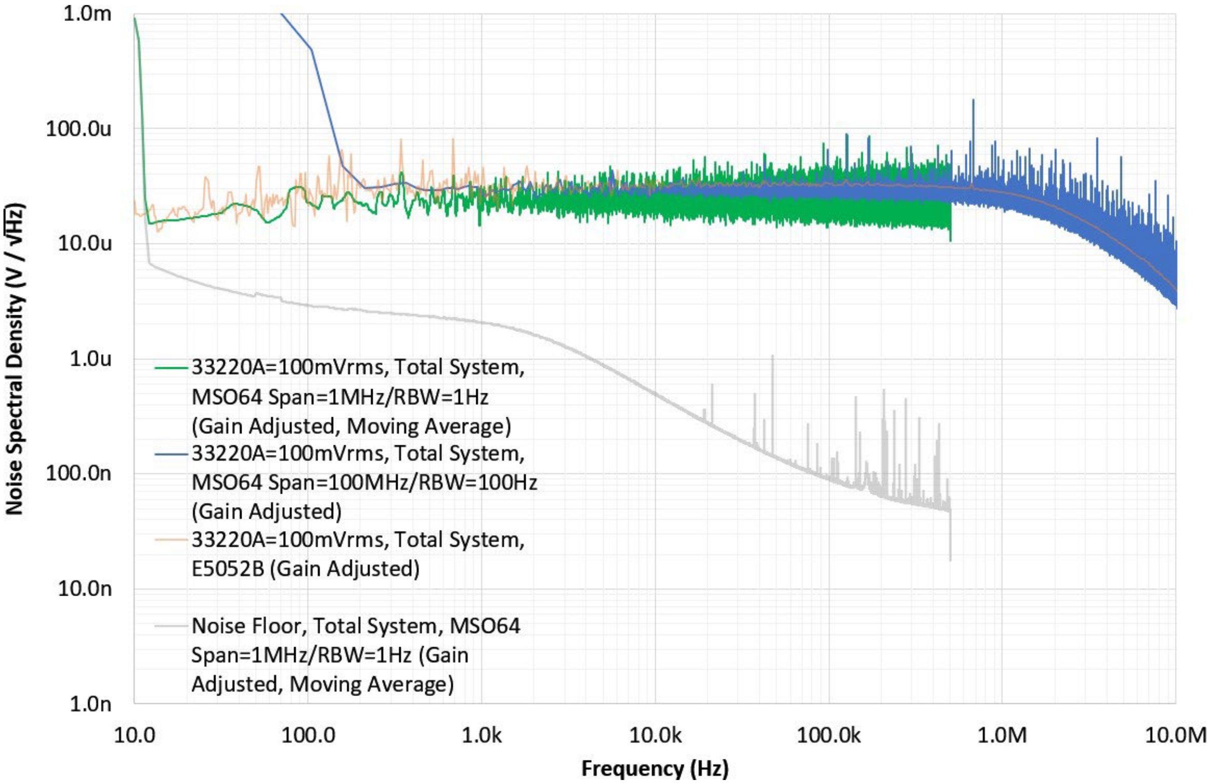


Figure 15: MSO64 data converted to noise density

Compared with the E5052B analyzer, the oscilloscope spectrum view noise is correct beginning at 200Hz with the 100Hz RBW setting and correct beginning at 20Hz with the 1Hz RBW. Note that once again, using the J2180A-20 also introduces a 20Hz low frequency cutoff, while the J2180A low frequency cutoff would be at 0.1Hz.

Summary and Conclusions

Starting from a known noise signal, and repeating cross-comparison steps, it is demonstrated that we can accurately measure 50VDC output voltage regulator noise with the setup of P2106A + J2180A + E5052B.

We see from the broadband noise measurements, shown in the Figure **8**, that this setup is good for RMS noise measurement up to approximately 2MHz. The major limitations of the bandwidth are the probe resistance and the cable capacitance.

The proposed P2106A + J2180A solution yields the lowest noise floor and the most accurate measurement. Our attempts with other non-DC-blocked amplifiers all resulted in higher noise than the proposed solution, we highlighted in the Figure **12** that the P2106A + J2180A + E5052B proposal provides the lowest measurement noise floor.

We also confirmed that P2106A + J2180A + Tektronix MSO64 Oscilloscope works well for measuring low level spectral noise using its ‘Spectrum View’ function.

Appendix A Agilent 33220A Output Setting and Signal Amplitude

By toggling output setting of the Agilent 33220A, the unit automatically changes its output signal amplitude.

33220A Output Setting to Hi-Z

33220A Noise Output Amplitude Display, 100mVRMS

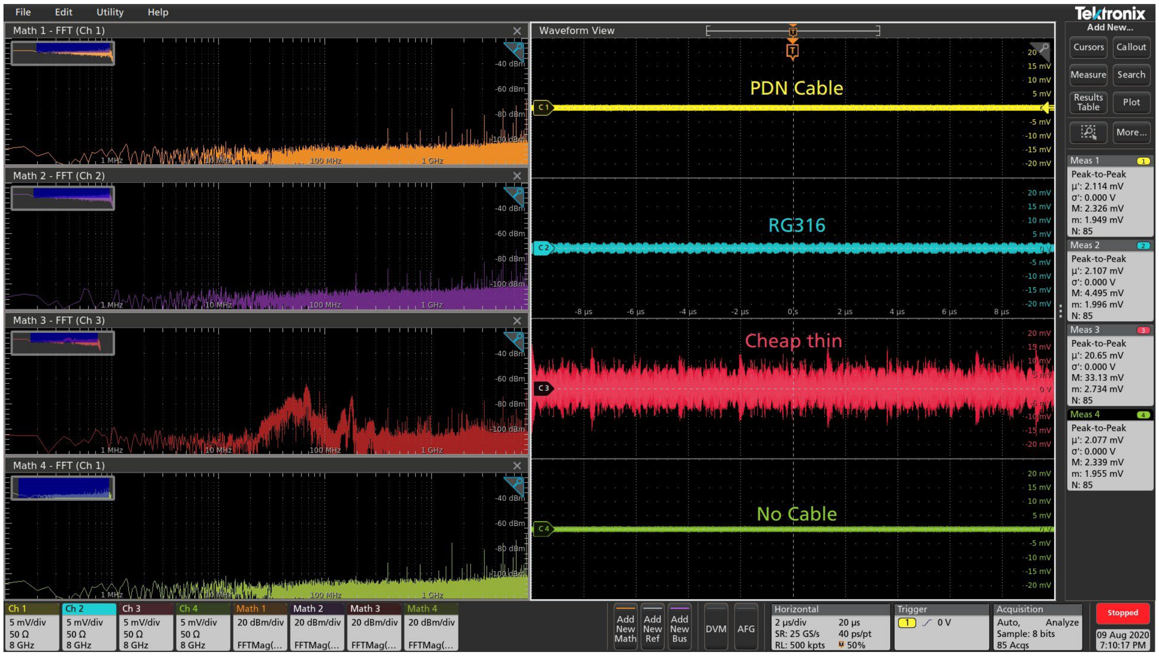
33220A Output Setting to 50Ω

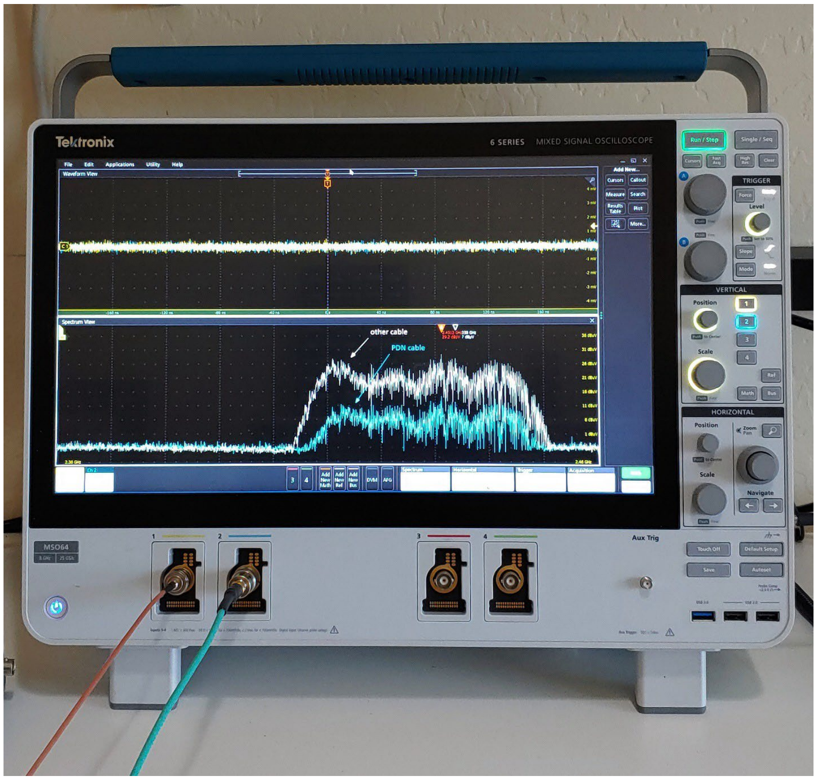
33220A Noise Output Amplitude Display, 50mVRMS

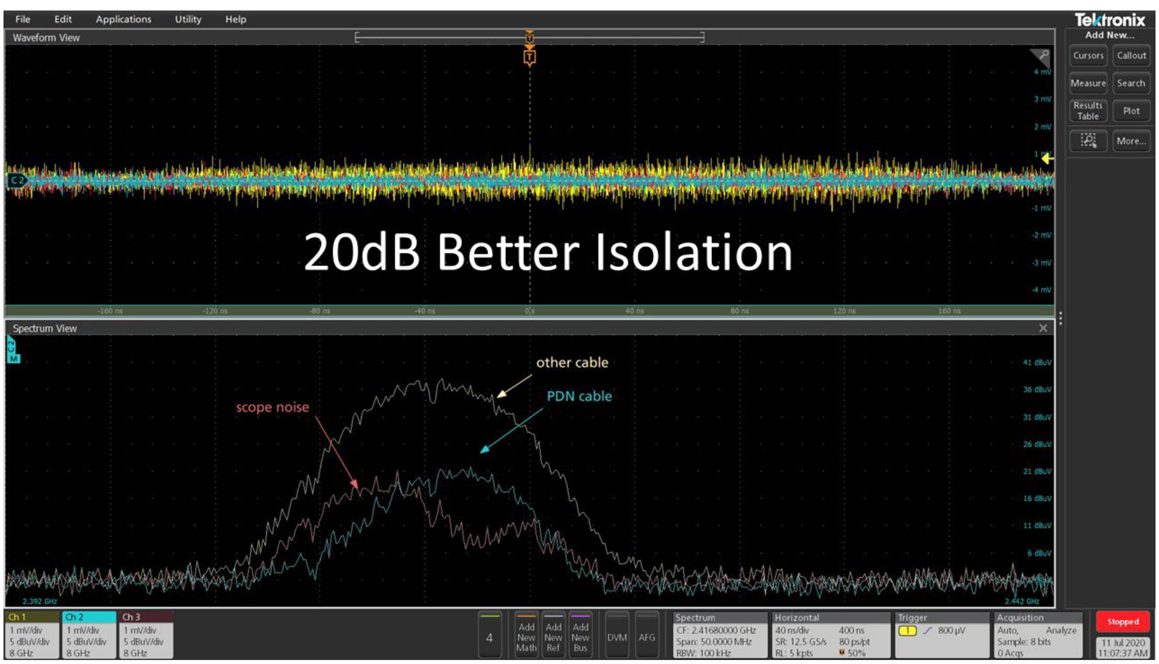
Appendix B

The benefit of the Picotest Power Distribution Network (PDN) cable is seen measuring unterminated cables. Airborne signals, including broadcast radio transmission, Wi-Fi, Bluetooth^{TM}, cellphone and even from instruments and lighting are always present and the quality of the cable shield determines how much gets into the measurement (refer to a course at https://www.picotestonline.com).

Figure 16 to Figure 18 show comparisons between the Picotest PDN cable and alternatives.




Tektronix
6 SERIES MIXED SIGNAL OSCILLOSCOPE
other cable
PDN cable
MSO64


Tektronix
Waveform View
20dB Better Isolation
Spectrum View
other cable
PDN cable
scope noise
Cursors
Callout
Measure
Search
Results Table
Plot
More...
Stopped

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