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Methods and Practical Aspects of Measuring 1/f Noise in Zero-drift Operational Amplifiers

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Abstract: Operational amplifiers are an important ingredient of analogue electronic circuits, and their noise performance is an essential design parameter. However, at low frequencies, data provided by component manufacturers usually cover only a limited range (typically 0.1 Hz to 10 Hz). The frequencies below this range, critical for high-stability and precision circuits, such as signal conditioning stages, voltage references, or digitizing voltmeters, are rarely addressed. Therefore, it is often necessary to characterize the parts. The traditional noise measurement technique requires the amplifier to be configured for very high gain, which is seldom the way the amplifier is used. Different techniques for voltage noise density measurement are presented and compared in this paper, including two methods that allow for noise measurement with a unity gain configuration - a mode that has not been explored until now. Practical aspects required to obtain reliable results are highlighted. A side product of this work is an open-hardware design of an ultra low-noise amplifier, which can be used to measure the noise performance of operational amplifiers or resistors using regular measuring equipment readily available at universities or industrial laboratories.

Keywords: voltage noise density, zero-drift operational amplifier, cross spectral density, nanovoltmeter

1. Introduction

Operational amplifiers are an essential part of analogue electronic circuits. The typical input-referred noise density of an operational amplifier is constant over most of the operating frequency range (white noise), but at low frequencies the noise density rises by 3 dB/octave. The phenomenon is known as flicker noise or *1/f* noise. To minimize the effect of *1/f* noise, chopper-stabilized and auto-zero amplifiers were developed [1], [2], [3]. Both types are also known as zero-drift amplifiers. Their very low offset voltage, high temperature stability and low drift make such components an ideal building element for high-stability and precision circuits, such as signal conditioning stages, voltage references, and digitizing voltmeters.

The noise data provided by the component manufacturers usually cover only a limited subset of the frequency range of interest, typically 0.1 Hz to 10 Hz. The very low frequency data, which are important for high-stability applications, are rarely published. To obtain these data, it is necessary to characterize the amplifiers as part of the design effort. Measuring at levels of microvolts or below, at time scales exceeding minutes, is a non-trivial task, that normally requires special equipment and very good control of the environment [4], [5].

In this paper, the focus is on voltage noise measurements. However, at higher impedance levels, current noise plays a major role. The techniques described in this work are valid and can be adapted for current noise characterisation too.

2. Operational amplifier noise measurement methods

The most common method to measure operational amplifier voltage or current noise is in high-gain configuration. However, amplifiers are not always operating at high gain, especially in applications such as precision voltage sources or digitizers. Therefore, in addition to the traditional one, two methods that allow for noise characterization even at unity gain are also presented.

A low-pass filter is used at the output of the measured amplifier to define the noise measurement bandwidth, as illustrated in Fig. 1. The equivalent noise bandwidth depends on the filter order [6], [7], [8]. The equivalent noise bandwidth ENBW for a system with a gain of 1 can be calculated as:

$$ENBW = \int_0^\infty |H(j\omega)|^2 \, d\omega, \tag{1}$$

where $H(j\omega)$ is the transfer function of the used filter. ENBW

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is the bandwidth of a fictitious brick-wall filter, which will output the same noise power as the used low-pass filter (areas A1 and A2 will be equal). The relation between the cut-off frequency and ENBW for RC low-pass filters of different orders is listed in Table 1.

Table 1. Relation between cut-off frequency and ENBW for RC low-pass filters of different orders.

Filter order	Slope (dB/dec)	ENBW/$\omega_{-3\,\mathrm{dB}}$
1	20	1.57
2	40	1.22
3	60	1.15
4	80	1.13
5	100	1.11

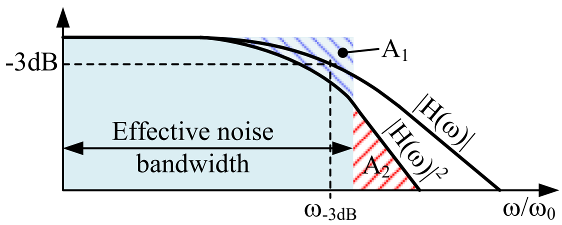


Fig. 1. Definition of effective noise bandwidth.

As all measurements are performed using a sampling digital voltmeter (DVM) with subsequent digital signal processing, the low-pass filter also serves as an anti-aliasing filter to prevent the folding of broadband noise into the first Nyquist zone and degradation of the measurement, as demonstrated in Fig. 13. In this work, 4^{th} order RC low-pass filters are used for all measurement configurations.

The quality of the passive components in the low-pass filters is also important for the overall result, so thin-film or metal foil resistors, together with foil or ceramic C0G/NP0 capacitors are recommended.

A. *Cross-correlation spectral density technique*

The spectral density of noise is commonly estimated using digital signal processing techniques, such as Discrete Fourier Transform (DFT), along with windowing and averaging multiple DFTs to decrease the variance by statistical means. The cross-spectral density technique uses two independent measurements of the same quantity to obtain the common correlated component, while suppressing the non-correlated noise of the two measurement channels [9], [10]. Thus, it provides a way to resolve signals below the noise floor of an instrument. The technique is commonly implemented using digital signal processing; it requires two nominally equal digitizing measurement channels with the capability for synchronized sampling. The digitizers produce two data streams $v_1[t]$ and $v_2[t]$:

$$v_1[t] = s[t] + n_1[t], \\ v_2[t] = s[t] + n_2[t], \tag{2}$$

where s[t] is the measured correlated component (e.g. signal from device under test) and $n_1[t]$, $n_2[t]$ are the uncorrelated components (e.g. noise of each digitizer). Both signals are Fourier transformed:

$$V_1[k] = \mathscr{F}(v_1[n]), \\ V_2[k] = \mathscr{F}(v_2[n]), \tag{3}$$

and the cross-correlation spectrum is calculated as

$$S_{12} = \frac{1}{N}\Re(V_1 V_2^*). \tag{4}$$

Fig. 2 shows the cross-correlation technique applied to data acquired by two Keysight 34420A nanovoltmeters. The instruments were measuring the voltage of a low thermal electromotive force (EMF) short, sampling at 5 Sa/s, input range 1 mV, NPLC 2, with both the digital and analogue internal filters in the instruments disabled. The individual instrument noise floors are estimated at $8\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ to $9\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$. However signals as low as $1\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ to $2\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ can be resolved, opening the possibilities for measuring techniques presented later in this paper.

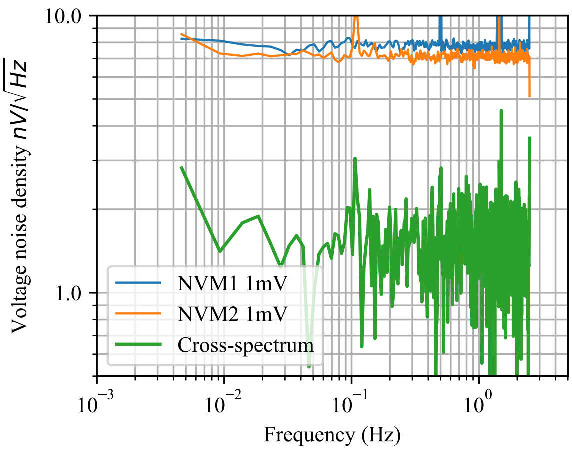


Fig. 2. Measurement noise floor obtained by measuring a short circuit with two simultaneously sampling nanovoltmeters (NVM1, NVM2).

B. *Direct measurement in high gain configuration*

The high-gain method is the most popular, as it does not require any special instrumentation [11]. The amplifier is configured for high gain (typ. 100 to 10 000) and its non-inverting input is grounded (Fig. 3). The output voltage is acquired either by an oscilloscope or a sampling DVM. The measured noise spectrum is shaped by the frequency response of the amplifier, which must be obtained to calculate the input-referred noise.

For achieving reliable results, the feedback resistors R_1 and R_2 must be insensitive to environmental factors (temperature, vibrations, mechanical stress, etc.). Typically, thin-film or metal foil resistors are used. To avoid significant noise contribution from the feedback network, values must be kept low. Typically the value of R_1 is kept below 10 Ω, as the voltage noise of R_1 is multiplied by the amplifier gain and added to the measured output signal. It is also recommended to enclose the amplifier into a shielding box to prevent air currents.

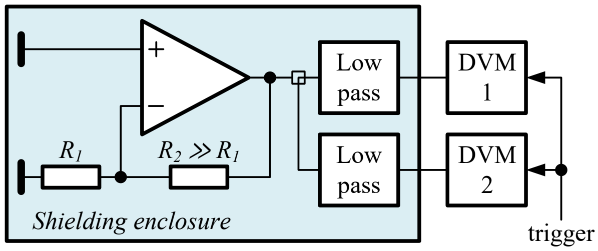


Fig. 3. Measurement in high gain using two simultaneously sampling digitizing voltmeters.

C. Direct measurement in low gain configuration

The noise floor of commercially available nanovoltmeters (NVM), such as Keysight 34420A or Keithley 2182A, is sufficiently low to measure the output voltage noise of auto-zero amplifiers directly, even in unity-gain configuration. The amplifier under test is installed in a metallic enclosure, which provides shielding against electromagnetic fields and air currents. Two nanovoltmeters with a common external trigger are used to simultaneously sample the output (Fig. 4). The voltage noise density of the tested device is calculated using the cross-correlation spectral density technique. Special precautions for very low signal levels are needed: avoidance of thermal gradients, low thermal EMF connectors, good shielding, twisted-pair cabling, etc. It is also recommended to perform the measurement in a globally electromagnetically shielded and well air-conditioned room. It was demonstrated that heat emitted by a person present in the room during the measurement can cause an observable drift of nanovoltmeter measured voltages, which translates into increased low-frequency noise.

The function of the low-pass filters is the same as in the previous section. For the direct measurement method, the series resistance of the RC filter must be kept low, since its thermal noise contributes directly to the measurement. As an example, a 1 kΩ resistor generates a noise voltage similar to the best low-noise zero-drift operational amplifiers (e.g. Analog Devices ADA4523). Hence, the construction of a low-pass filter is not a trivial task, as this already low resistance value must be split into four sections (for 4^{th} order), requiring the use of a very high value capacitors to obtain a cut-off frequency in the range of ≈ Hz. For measurements presented in this paper, the "low noise, low pass" filter was realized with four 200 Ω thin-film resistors (total 800 Ω, contributing $3.6\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$) and four foil capacitors with capacitance in the range of 10 µF to 50 µF.

Despite the high cost, complex operation and maintenance of nanovoltmeters, the method is important and useful for long-duration measurement campaigns covering the very low frequency range, where record lengths of hours or even days are necessary.

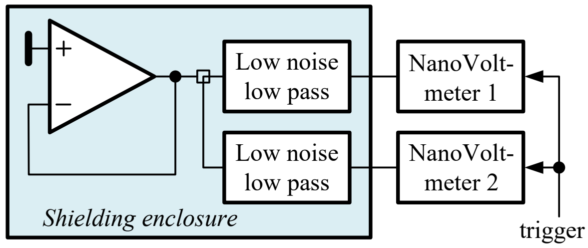


Fig. 4. Noise measurement in G=1 using two simultaneously sampling nanovoltmeters.

D. Low-gain measurement using a low-noise amplifier

In this approach, the amplifier under test is configured for low gain and its output signal is amplified by an external ultra-low-noise amplifier (LNA), as shown in Fig. 5. The higher signal level allows for the use of a more standard instrument to record the noise signal - either a DVM or an oscilloscope [12]. Precautions should be taken when measuring with an oscilloscope due to loops that pick-up ambient magnetic fields. Leakage currents are minimized by using batteries to power the amplifier under test and the LNAs. The output signals, routed via coaxial cables, should be bundled together to minimize the area of the loops that pick up ambient magnetic fields. All shielding enclosures must be properly interconnected to provide good equipotentiality. For the first experiments, oscilloscope inputs were selected such to acquire LNA signals by different acquisition hybrids in the instrument (8-channel Rohde & Schwarz MXO58 has 4-acquisition chips). A number of nanocrystalline cores were used in an attempt to minimize leakage currents from the oscilloscope inputs towards the LNAs. This did not lead to significant improvements, so two neighboring input channels were finally used and a low impedance path, realized by a copper braid, was introduced to minimize the effect of leakage currents.

These measures, realized in a measurement setup, are shown in Fig. 6.

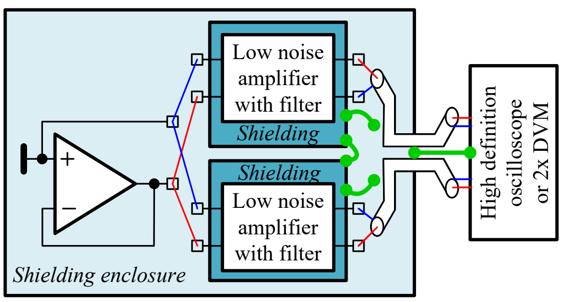
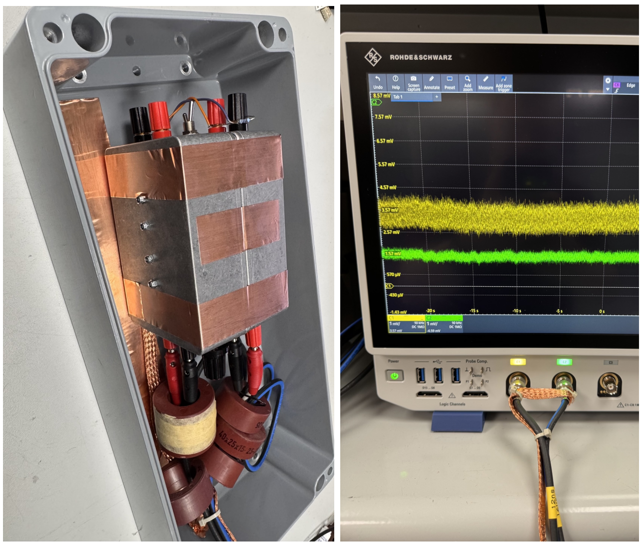


Fig. 5. Noise measurement in $G = 1$ using two ultra-low noise amplifiers and DVMs or an oscilloscope.



(a) (b)

Fig. 6. Providing robust equipotentiality and minimization of loop area to reduce magnetic field pick-up: (a) two LNAs interconnected in a shielding box; (b) detail of output coaxial cables routed to an oscilloscope.

3. Low-noise amplifier for measurements with standard instruments

A DC-coupled, ultra-low-noise amplifier with a noise floor $\approx$1.1 nV/$\sqrt{\text{Hz}}$, a low *1/f* corner frequency and a built-in selectable filter bank was developed to provide the means to measure low-level signals with standard laboratory instruments. The amplifier is available as a CERN Open Hardware project, and the design can be accessed via [13].

A. Amplifier design

For useful measurements, the noise contribution of the low-noise pre-amplifier must be significantly lower than the noise levels expected for the devices under test. One way to achieve this is to use a plurality of low-noise operational amplifiers operated in parallel and to benefit from the statistical properties of the amplified signals to reduce the overall noise floor of the LNA. If k-pieces of identical amplifiers are assumed, which inputs are connected in parallel and outputs are summed via low-value resistors, the output voltage for the correlated input signals e_s will be:

$$e_{signal} = \frac{1}{k}(e_{s0} + e_{s1} + ... + e_{sk}), \quad (5)$$

and the output voltage for the uncorrelated signals e_n :

$$e_{noise} = \frac{1}{k}\sqrt{e_{n0}^2 + e_{n1}^2 + ... + e_{nk}^2}. \quad (6)$$

As the correlated (useful signal) component is adding directly and the uncorrelated (additive amplifier noise) is adding by a square-root rule, a high gain composite amplifier with lower noise can be realized than a single amplifier can provide.

A conceptual diagram of the described LNA is shown in Fig. 7. The amplifier is based on standard, off-the-shelf, zero-drift operational amplifiers Analog Devices ADA4528. The first stage contains 32 paralleled amplifiers configured for a gain of 302, providing approximately 1 kHz bandwidth. Individual amplifier outputs are summed using 100 Ω thin-film current sharing resistors. A first-order low-pass filter (100 Ω + 470 pF) was added at the input of each block of four amplifiers to improve commutation noise leakage from the inputs of the zero-drift amplifiers. The noise of this filter, which defines the input AC impedance, is amplified by the LNA and contributes to the overall input-referred noise, therefore it needs to be minimized.

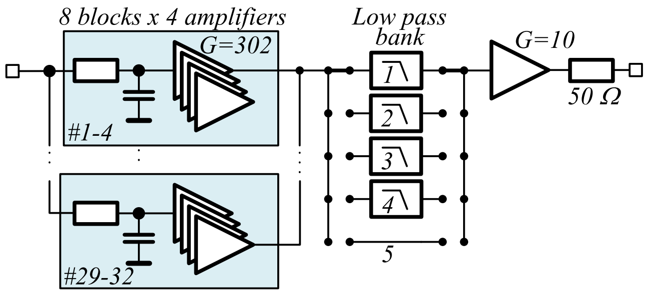


Fig. 7. Conceptual diagram of the low noise amplifier.

Following the gain stage is a switchable low-pass filter bank, which selects the desired measurement bandwidth. Five options were implemented: full bandwidth ($\approx$1 kHz), 100 Hz, 18 Hz and 2.5 Hz. In all cases, the filters are 4^{th} order and constructed using high-quality passive components as discussed in Section 2. Thanks to $\approx$ 3000$\times$ higher signal level, this filter does not need to be low-noise and can be constructed with the same thin-film resistors as the gain stage feedback. The rotary mechanical switch is a Grayhill series 50 type, with gold-plated common ring and contact terminals for reliability and low contact resistance. The LNA printed board is shown in Fig. 8. Note that almost half of the board's real estate is occupied by high stability C0G/NP0 capacitors.

To keep the output impedance of the LNA low, an output amplifier stage with a gain of 10 is inserted after the low-pass filter. The output is isolated by a 50 Ω resistor to allow for further paralleling of multiple LNA units.

The amplifier is battery-powered using four AA cells providing $\approx$30 h of operation. A symmetric bipolar $\pm$3 V supply is used. The LNA is housed in a die cast aluminium enclosure to provide electric field shielding and to prevent air currents. Low thermal EMF binding posts for input and output are used as well.

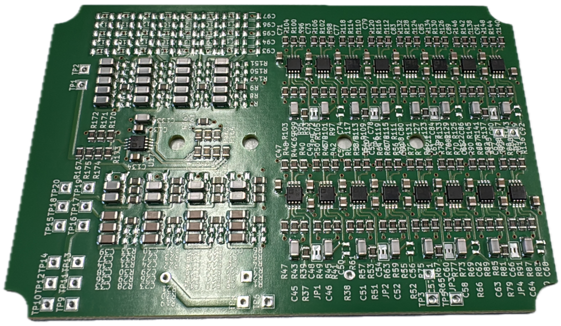


Fig. 8. Ultra low-noise amplifier. Low pass filters occupy the majority of the left half. High-stability C0G/NP0 capacitors provide only low capacity, so a large number must be connected in parallel.

B. LNA noise performance evaluation

The LNA's noise performance was measured with shorted input. The low-frequency segment was measured using two Keysight 34770 DVMs in the 100 mV range. High-frequency noise was measured with a Rohde & Schwarz MXO58 oscilloscope set to high-definition mode. The LNA output was always measured by two independent instruments or two oscilloscope channels to allow for cross-correlation spectral density analysis. Fig. 9 shows the measured LNA voltage noise density in five overlapping frequency bands. The obtained value, $\approx 1.1\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$, is in line with the expected noise floor of 32 paralleled zero-drift ADA4528 operational amplifiers. Using the cross-correlation spectral density technique with two LNAs, voltage noise density as low as $\approx 0.4\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ can be resolved, as illustrated in Fig. 10. A verification was performed by measuring the thermal noise of 0 Ω, 10 Ω, 36 Ω and 100 Ω resistors at room temperature. The LNA noise floor corresponds to a ≈10 Ω resistor, so the voltage noise spectral density of resistors with higher values can be reliably resolved.

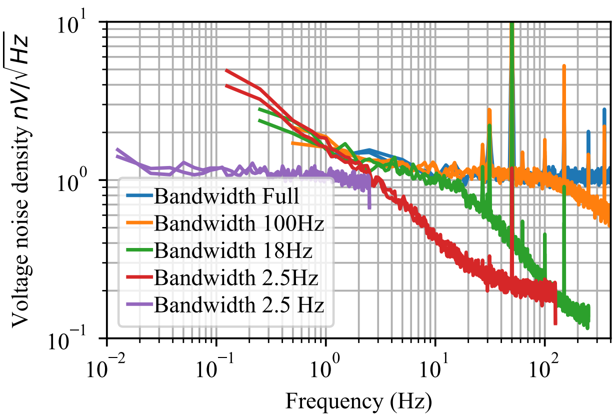


Fig. 9. Measured LNA input-referred voltage noise density. The violet curve is measured with a DVM; all others with an oscilloscope.

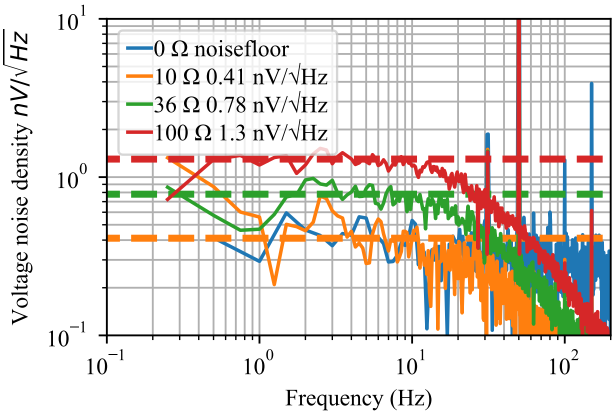


Fig. 10. LNA performance check by resistor thermal voltage noise. Dashed lines are the theoretical values; LNA bandwidth is 18 Hz.

4. Instrument noise floor

One of the goals of this work was to demonstrate the feasibility of measuring the noise of operational amplifiers with standard instruments available in a regular laboratory. The noise floors of the following instruments were evaluated. The instruments were used for measurements in accordance to Sections *2.B*, *2.C* and *2.D*. Both regular and high-end instruments were deliberately selected:

- Nanovoltmeter Agilent/Keysight 34420A
- Digital voltmeter Keysight 34470A
- Digital voltmeter RS-Pro RSDM3055
- Digital voltmeter Siglent SDM3065
- Oscilloscope Rohde&Schwarz MXO58
- Oscilloscope LeCroy HDO8108
- Oscilloscope Agilent DSOX3034A
- Oscilloscope Siglent SDS1104

The evaluation results are summarized in Fig. 11. The nanovoltmeter's noise floor in both ranges (1 mV and 10 mV, 2 NPLC) is suitable for direct measurement at low gain and for very long records. The memory in these instruments is nevertheless very limited, so for long measurements it is necessary to use the instrument's "talk only" mode and collect samples one by one via the serial link. Digital voltmeters at the lowest range of 100 mV (200 mV for some) exhibit about an order of magnitude higher noise floor, but are suitable for long-duration measurements with the LNA. On the other hand, the nanovoltmeters or digital voltmeters are not suitable for measurements with sampling frequency higher than ≈10 Sa/s, where high-performance digitizers or high-resolution oscilloscopes should be used instead.

Modern high-resolution oscilloscopes provide good sampling performance for noise measurements above ≈1 Hz. They are suitable for the high-gain or LNA methods.

An undocumented feature in the Siglent DVMs (SDM30xx, or all rebranded versions) was discovered:

the samples are apparently processed by a digital filter that cannot be disabled, rendering these instruments difficult to use for sampling applications (see the notches in the RSDM and SDM curves in Fig. 11).

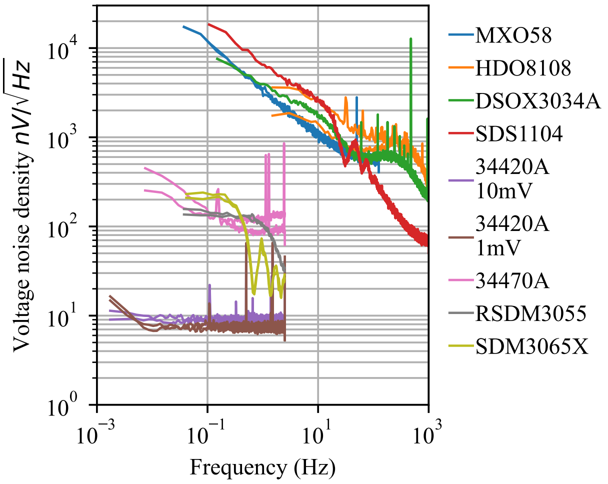


Fig. 11. Noise floor of evaluated instruments. Ranges are as follows: NVM 1 and 10 mV, DVM 100 (200) mV, oscilloscope 4 (5) mV/div.

5. RESULTS

To compare all presented methods, the same auto-zero operational amplifier, Analog Devices ADA4522-2, was characterized.

The cross-spectral density for all measurements presented in this paper was calculated using Welch's method with a Hann window and 50 % overlap. The segment length varies depending on the dataset origin and length. The nanovoltmeters and DVMs sampling at 5 Sa/s usually produce hundreds of thousands of measurement points, with typical segment lengths of 10 to 500. In contrast, oscilloscope measurements with a record length of 100 million points, or more, and a higher sampling frequency allow much longer segment lengths, typically 1000 to 10000.

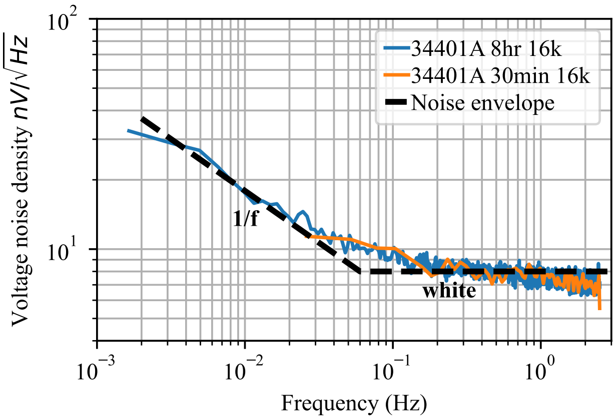


Fig. 12. Measurements in high gain as per Section *2.B*.

Measurements in high-gain configuration (Section *2.B*) are presented in Fig. 12. The direct measurement by nanovoltmeters (Section *2.C*) is presented in Fig. 13. Measurements using low-noise pre-amplifiers (Section *2.D*) with combined very low frequency data coming from a DVM and higher frequency data from an oscilloscope are presented in Fig. 14. All three methods provide consistent results - a noise floor of $8\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ to $9\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$, which is compatible with the manufacturer's datasheet [14] (page 26, Fig. 60 through Fig. 64). The *1/f* noise corner frequency is not specified in the datasheet; a value ≈0.05 Hz was found, consistent across all three methods.

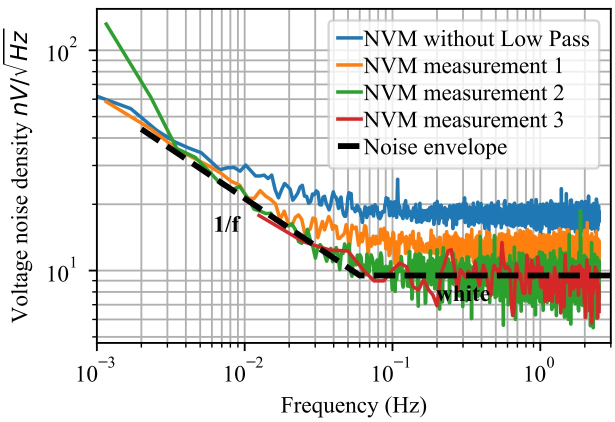


Fig. 13. Direct measurement by nanovoltmeters as per Section *2.C*. The contribution of the low-pass filter was subtracted.

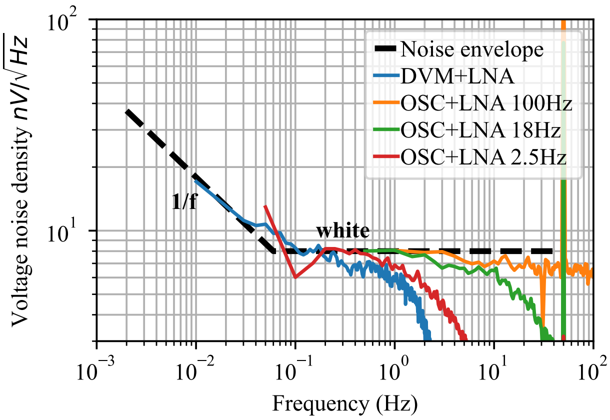


Fig. 14. Measurements using an LNA as per Section *2.D*.

6. CONCLUSION

Methods and practical aspects of measuring *1/f* noise in zero-drift operational amplifiers were presented. Knowledge of the very low frequency data is critical for the highest performance and stability electronics or metrology equipment, such as voltage references, signal conditioning stages or digitizing voltmeters. The popular high-gain method does not allow for the characterisation of amplifiers in their typical working configuration. Therefore, other possibilities to characterise the noise performance in more realistic operating conditions by alternative methods were investigated. A new method to measure the voltage noise density directly by simultaneous sampling with multiple nanovoltmeters and using digital signal processing techniques to extract correlated signals below the noise floor of the measuring instruments was proposed and successfully tested. Noise measurement of one of the lowest-noise operational amplifiers available from the industry was experimentally demonstrated. As nanovoltmeters are rather costly and challenging to operate, alternative noise measurement methods using low-noise preamplifiers and standard digitizing voltmeters were also investigated. For this purpose, an ultra low-noise amplifier was developed, which, together with the applied signal processing techniques is able to measure voltage noise density as low as $0.4\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ (corresponding to the thermal noise of a $10\,\Omega$ resistor at room temperature). The LNA design is available to the scientific community as a CERN open hardware project [13]. The importance of the cross-correlation spectral density technique and the use of regular sampling instruments was demonstrated. For each method, important practical aspects for experimenters who want to perform such measurements at universities, industry, or even home laboratory were highlighted.

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