DT5: Design of whitening filters for DT5

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1 Introduction

Analog-to-digital converters (ADCs) are indispensable to measure and record analog signals on computers. Since ADCs have limited resolution and dynamic range, whitening filters (WTFs) are commonly used before sampling of the signals by ADCs. WTFs amplify the signals in order to exploit full resolution of the ADCs. In addition, to compensate the limited dynamic range of the ADCs, WTFs amplifies the signals especially in the frequency region where the power of the signals are small compared with the other frequency component. As a result, the output of the WTFs has an approximately flat spectrum.

The high-speed data acquisition system of TAMA300 (HDAQ) requires the following features for the WTF of the L_- feedback signal [1].

- The whitened output must be larger than half [1] of the noise level of the HDAQ system. Thus, the output must be $2.5 \times 10^{-6}\mathrm{V}/\sqrt{\mathrm{Hz}}$ from 50Hz to 5kHz.
- The input-referred noise of the WTF must be smaller than the spectrum of the L_- feedback signal from 50Hz to 5kHz (Fig. 2).
- The output of the WTF must be within ±5V [2]. Also, during the operation of the interferometer, any saturation in the WTF should be avoided as far as possible [3].

For the forthcoming fifth Data Taking (DT5, from 2001/3/2∼8), two boxes of the WTF are built. They are used to whiten the feedback signals of L_- before (HDAQ 0ch) and after (HDAQ 1ch) a summing point where a sinusoidal calibration peak at 625Hz is applied. They are hereafter called WTF#1 and WTF#2, respectively.

In this document, the circuit of the WTF, measured transfer functions, whitened output taken with the actual signal, and noise performance are described.

2 Circuit

The WTF, depicted in Figure. 1, is formed by four stages of analog filters.

[1] The differential driver used before HDAQ has a gain of 2 [1].
[2] HDAQ itself has a range of ±10V [1].
[3] Though, it is difficult to avoid saturation caused by sudden large disturbance to the interferometer.

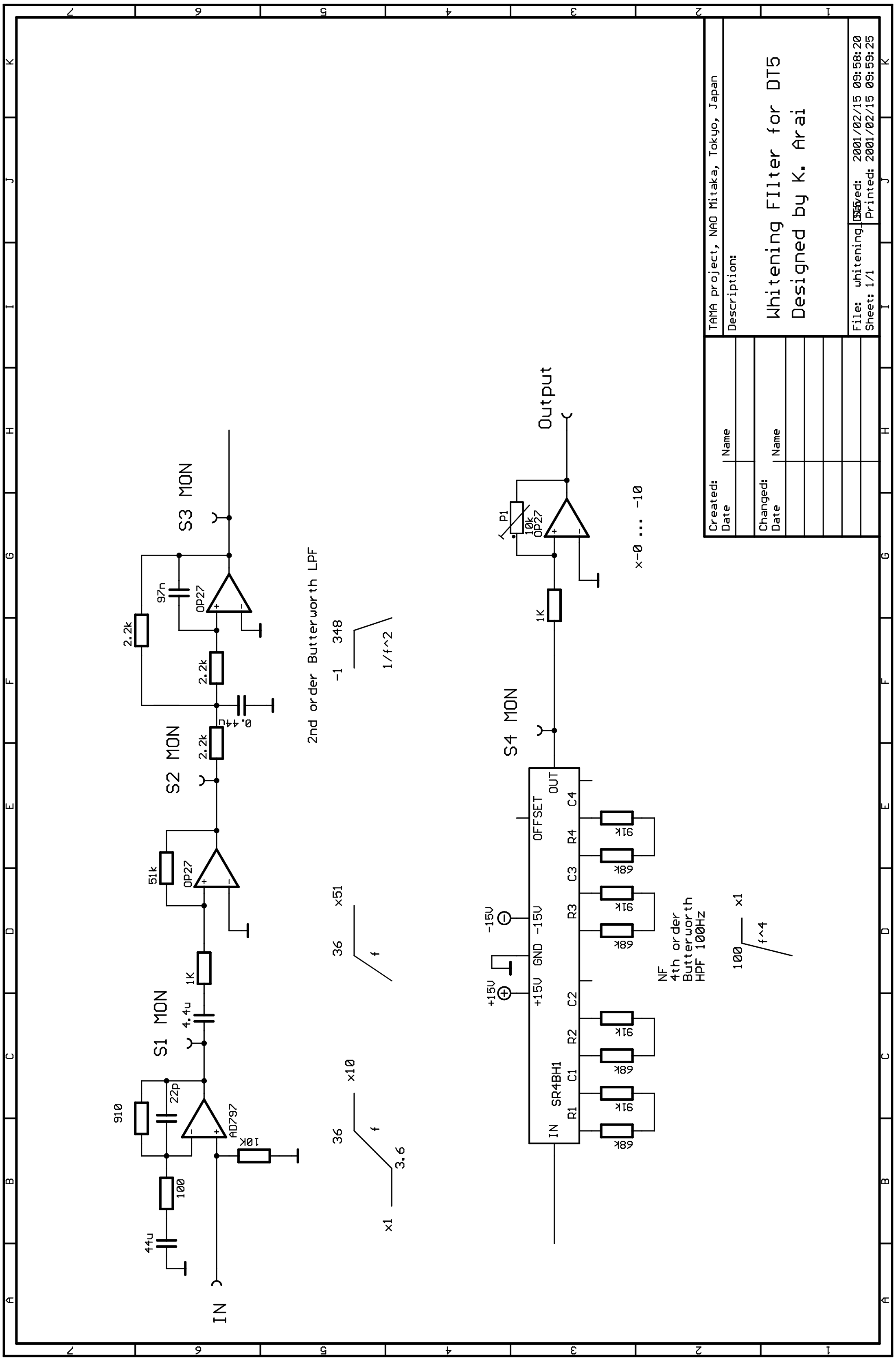

Figure 1: Circuit for the whitening filter for DT5

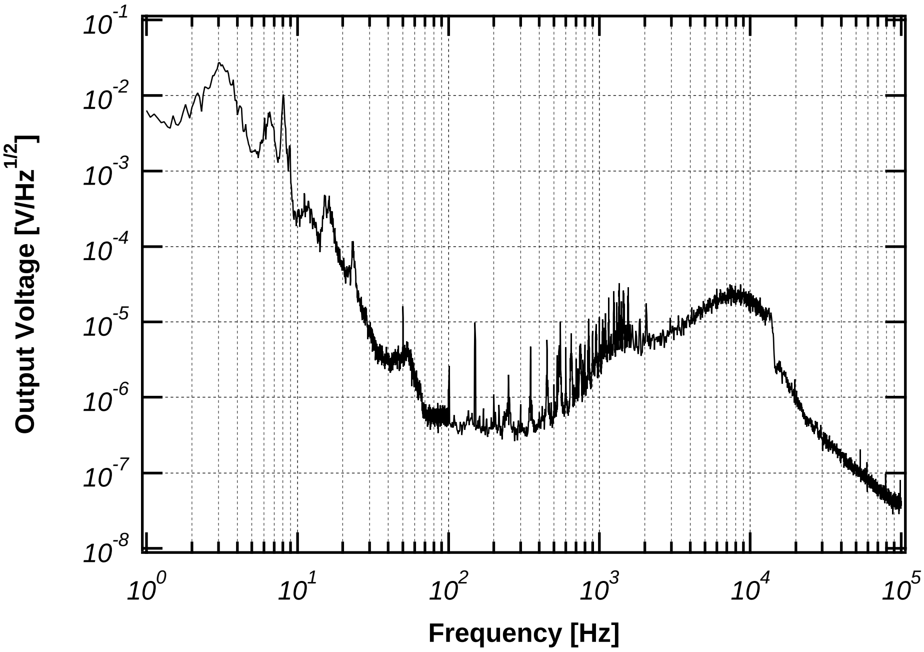

Figure 2: Feedback signal of TAMA300, taken on January 24th, 2001.

1st stage

This stage amplifies only above 36Hz by a factor of 10.

In order to increase the signal in the observation band above the noise level of the following stages, the input stage must have some amount of gain. The feedback signal of L_- has a large amplitude below 10Hz, as seen in Figure. 2. Therefore, low frequency components should not be amplified in order to avoid saturation.

The non-inverting amplifier with gain boost above 36Hz is used to satisfy the issue of having the gain without saturation. This stage does not amplify the low frequency signal, on the other hand the frequency components in the observation band are amplified. Note that a simple highpass filter was not applied as inverting amplifiers with low input noise inevitably involve the small value of a resistor in the input. It is safer to have a high input impedance (10kΩ) to preserve precision of the circuit.

The operational amplifier of AD797 [2] is used in this stage. The input-referred noise of the circuits are set to be dominated by the noise of this stage. The simulation by LISO [3] showed that the input-referred noise is to be $2\mathrm{nV}/\sqrt{\mathrm{Hz}}$ caused by the noise of the opamp and the feedback resistor of 910Ω.

A capacitance of 22pF was used in order to prevent from oscillation of the circuit.

2nd stage

The second stage is used to cut the low frequency component and to amplify the signal furthermore.

In order to have a sufficient gain without saturation, a highpass filer with an inverting amplifier using an OP-27 [4] is used. The gain in the transmission band is -51. Here, the input resistance of 1kΩ could safely be used because the signal was already amplified by the first stage.

3rd stage

The third stage is a 2nd-order butterworth lowpass filter with the cut-off frequency of about 350Hz. This stage is used to whiten the high frequency component which has an approximate slope of +12dB/Oct.

4th stage

The fourth stage is a 4th-order butterworth highpass filter with the cut-off frequency of 100Hz. This stage is used to further whiten the low frequency component.

A SR Resistor Tunable filter by NF circuit block design corporation is used for the filter. This filter allows us to make a 4th-order filter by just putting four equivalent resistors. On the other hand, this filter has an output noise of about $10^{-7}\mathrm{V}/\sqrt{\mathrm{Hz}}$. In spite of its poor noise performance, this output noise does not degrade the performance of our WTF due to the gain of the previous stages.

5th stage

The fifth stage is an inverting amplifier with gain of 0 to -10. This stage amplifies the signal so that the resulting output has sufficient amplitude for the ADC range of HDAQ.

Miscellaneous

The circuit has not only the connectors for the input and the output of the 5th stage, but also the connectors for monitoring the output of the other stages, labeled “S1 MON”, “S2 MON”, “S3 MON”, and “S4 MON”. They are used to confirm that each stage has no saturation.

3 Transfer function

In order to simplify the calibration process, the gains of the two whitening filters are adjusted to be same as far as possible. The difference of the transfer functions measured by an FFT

	WTF#1	WTF#2
A	$-6.3296461 \times 10^{-8}$	$-1.1138385 \times 10^{-7}$
f_0 (Hz)	3.8316963	3.0998213
f_1 (Hz)	38.236954	29.983979
f_2 (Hz)	67.846192	41.599029
f_3 (Hz)	348.34772	345.90772
q_3	0.68275571	0.68685034
f_4 (Hz)	101.02979	100.83677
q_4	1.308833	1.3192324
f_5 (Hz)	106.51815	104.45711
q_5	0.53343746	0.53522177
f_6 (Hz)	57.720477k	68.083472k

Table 1: Identified poles and zeros from the measurements of the transfer functions.

spectrum analyzer are given by

$$|H_{\mathrm{WTF\#2}}(625\mathrm{Hz})/H_{\mathrm{WTF\#1}}(625\mathrm{Hz})| = -0.0008 \pm 0.0005 \,[\mathrm{dB}] \tag{1}$$

$$\mathrm{Arg}[H_{\mathrm{WTF\#2}}(625\mathrm{Hz})/H_{\mathrm{WTF\#1}}(625\mathrm{Hz})] = -4.123 \pm 0.003 \,[\mathrm{degree}] \ , \tag{2}$$

where $H_{\mathrm{WTF\#}j}(f)$ is a transfer function of WTF#j. The difference of the phase was introduced by small deviation of cut-off frequencies from the designed values.

In order to characterize the WTFs, the measured transfer functions were fitted using LISO [4]. Overall transfer functions were parametrized as the following:

$$H(f) = A\frac{h(f,f_0)}{h(f,f_1)}\frac{\mathrm{i}f}{h(f,f_2)}\frac{1}{h(f,f_3,q_3)}\frac{(\mathrm{i}f)^2}{h(f,f_4,q_4)}\frac{(\mathrm{i}f)^2}{h(f,f_5,q_5)}\frac{1}{h(f,f_6)} \ , \tag{3}$$

where a single pole (or zero) on the imaginary axis and a double pole pair are respectively expressed by

$$h(f,f_0) = 1 + \mathrm{i}\frac{f}{f_0} \tag{4}$$

$$h(f,f_0,q_0) = 1 + \mathrm{i}\frac{f}{f_0 q_0} - \left(\frac{f}{f_0}\right)^2 \ . \tag{5}$$

Note that $1/h(f,f_6)$ was added so as to represent phase delay caused by the opamps.

The result of the fitting are shown in Table. 1. Figures. 3 and 4 show the calculated and measured transfer functions of the whitening filters. Figure. 5 shows the errors in the fitting. The fitting has errors smaller than ±1% and ±1 degree in magnitude and phase from 30Hz to 2kHz.

[4] In LISO, I could not find the directive to put zeros on the origin in the fourier plane. Therefore before the fittings have been performed, $(\mathrm{i}f)^5$ was multiplied to the transfer functions in advance

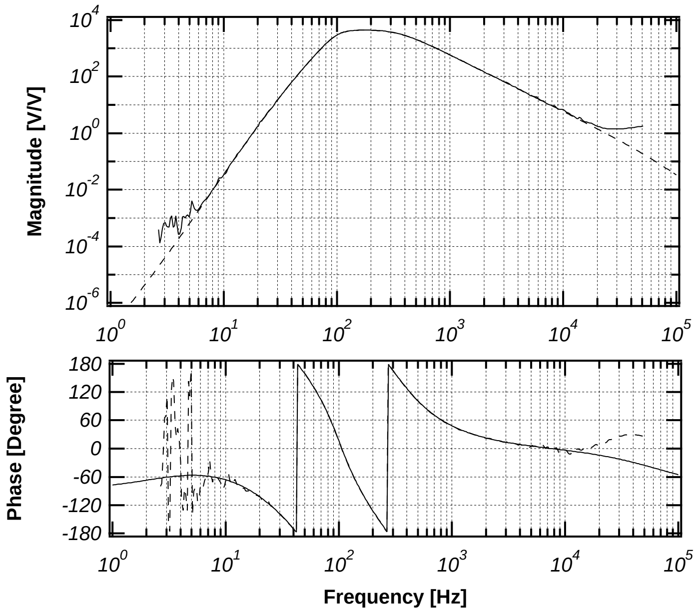

Figure 3: Measured (solid) and fitted (dashed) transfer functions of WTF#1. Values from 10Hz to 10kHz were used for the fitting.

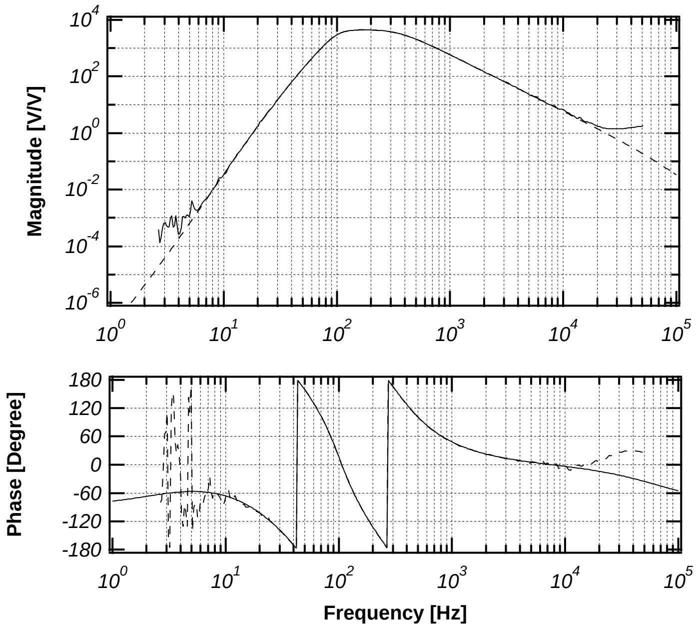

Figure 4: Measured (solid) and fitted (dashed) transfer functions of WTF#2. Values from 10Hz to 10kHz were used for the fitting.

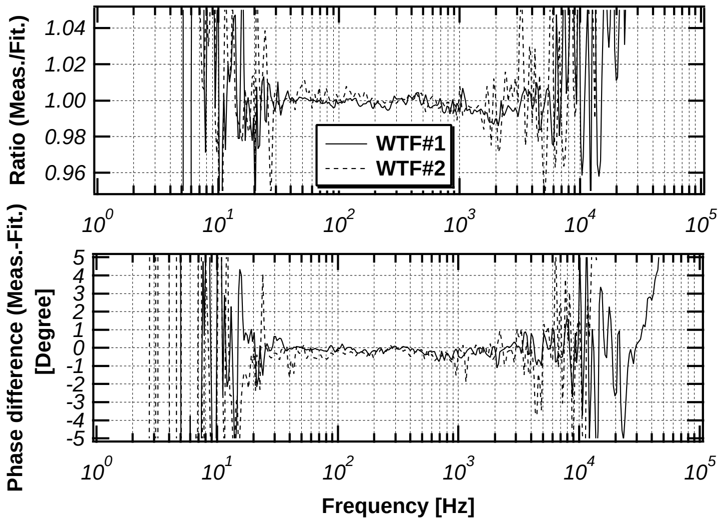

Figure 5: Comparison between the measured transfer functions and the fitted ones. Upper plots shows the magnitude ratio of the measured one and the calculated one. Lower plots show the difference of their phases.

4 Whitened output

The performance of the filters has been tested with the actual interferometer signals.

In order to confirm that saturation is not present in the circuits with the typical interferometer signal, the outputs of the circuits were observed with an oscilloscope. Table 2 shows the observed typical outputs. No saturation has been observed in the outputs and monitor points of the filters except for occasional large nonstationary burst.

Typical peak values for the calibration at 625Hz were measured. During the measurement the calibration peak at 625Hz has been added to the L_- loop. The amplitude of the injected signal was $1.2145 \times 10^{-4}\mathrm{V_{rms}}$. The peak amplitudes of $3.03110^{-1}\mathrm{V_{rms}}$ and

OUTPUT	Observed Voltage
In	$< 1V_{\mathrm{pp}}$
S1 Mon	$< 2V_{\mathrm{pp}}$
S2 Mon	$< 10V_{\mathrm{pp}}$
S3 Mon	$< 10V_{\mathrm{pp}}$
S4 Mon	$< 0.5V_{\mathrm{pp}}$
Out	$< 5V_{\mathrm{pp}}$

Table 2: Observed output at each output port.

$1.71610^{-1}V_{rms}$ were observed at the outputs of WTF#1 and WTF#2. From the ratio of these amplitudes the open-loop transfer function of 1.766 at 625Hz was deduced. This corresponds to the unity gain frequency of 1.11kHz.

The whitened output spectra are shown in Figs. 6 and 7. The obtained spectra were typically about $10^{-3}\mathrm{V}/\sqrt{\mathrm{Hz}}$, which is larger than the required value of $2.5 \times 10^{-5}\mathrm{V}/\sqrt{\mathrm{Hz}}$. During normal operations, the calibration peak at 625Hz is a dominant component in the whitening filter outputs, though excited violin modes of the suspension wires are dominant just after the lock acquisition. Even with the excited violin modes, it was confirmed the circuits have no saturation.

The output noise of the filters was also measured by grounding the circuit inputs. The noise level were plotted in Figs. 6 and 7 together with the whitened outputs. It was confirmed that the noise of the circuits does not disturb the target signal. The input-referred noise of the circuits are estimated by dividing the output noises by the transfer functions (Fig. 8 and Fig. 9). The input-referred noises of $2 \sim 3\mathrm{nV}/\sqrt{\mathrm{Hz}}$ were achieved.

5 Summary

The whitening filters for DT5 were built and tested. The circuit was designed and confirmed to have sufficient low noise for the L_- feedback signals. The filters have enough gain to record the output signals. Also, absence of saturation during normal operation was confirmed.

The transfer functions of the filters were measured and characterized by pole-zero models with accuracy of 1% in amplitude and 1 Degree in phase. These parameters will be used in reconstruction of the signals from the restored HDAQ signals.

References

[1] D. Tatsumi, private communications.

[2] Analog Devices Inc., "Ultralow Distortion, Ultralow Noise Op Amp AD797" `http://www.analog.com/pdf/ad797.pdf`

[3] G. Heinzel, "LISO - Program for Linear Simulation and Optimization of analog electronic citcuits".

[4] Analog Devices Inc., "Low Noise, Precision Operational Amplifier OP27" `http://www.analog.com/pdf/op27.pdf`

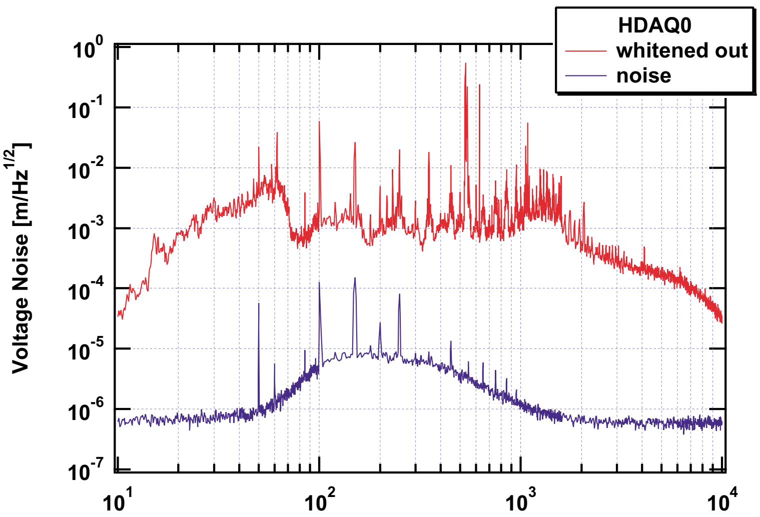

Figure 6: Whitened output of WTF#1 and the output noise level.

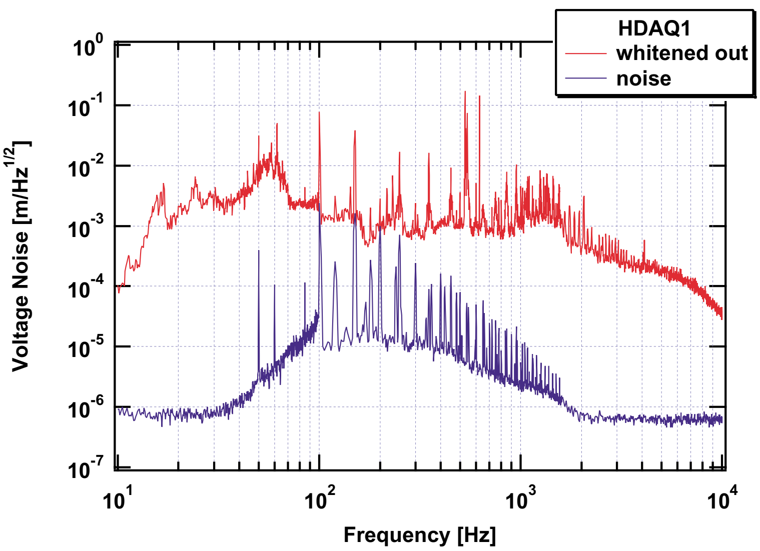

Figure 7: Whitened output of WTF#2 and the output noise level.

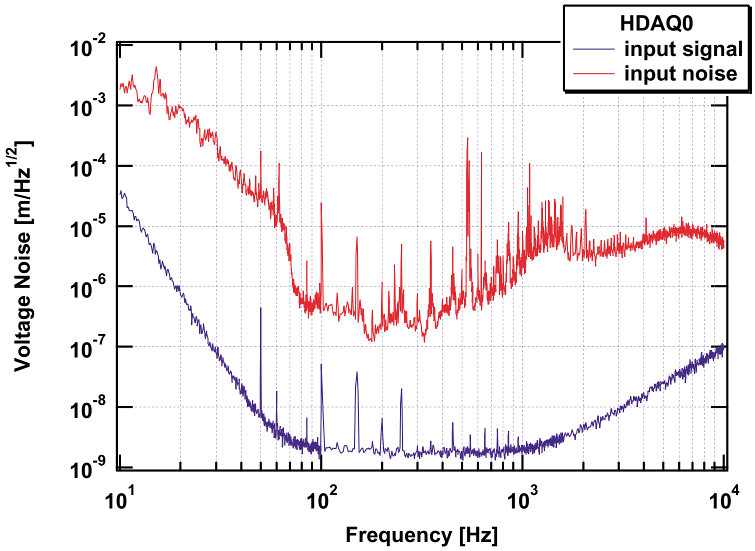

Figure 8: Input-referred noise of WTF#1 and reconstructed feedback signal for L_{-}.

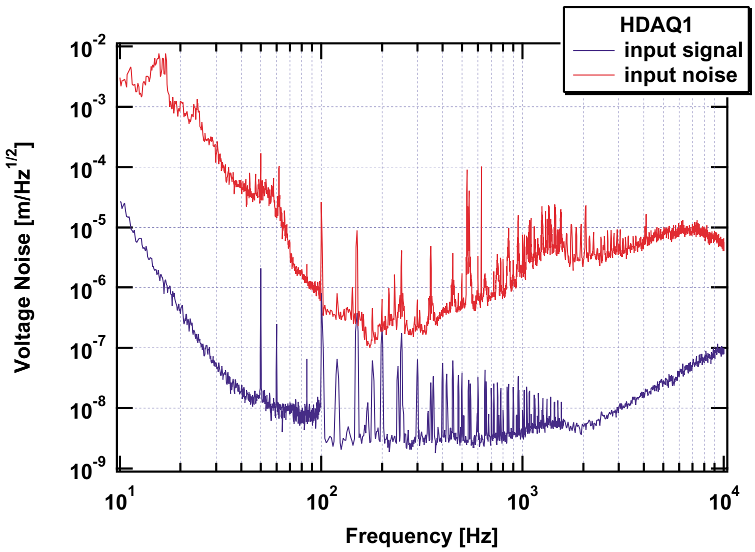

Figure 9: Input-referred noise of WTF#2 and reconstructed feedback signal for L_{-}.