DT5: Design of whitening filters for DT5 part2

National Astronomical Observatory, TAMA project
Koji Arai

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1 Introduction

In the fifth Data Taking (DT5, from 2001/3/2∼8), two boxes of the WTF have used. They were 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 was applied. These whitening filters are hereafter called WTF#1 and WTF#2, respectively.

The design priciples and the performances of the prepared whitening filters have been described in the earlier document [1]. After that document was written, the circuits were modified just before the data taking in order to increase immunity of the circuit against nonstationary noise.

In this document, the circuit of the WTF, measured transfer functions, whitened output taken with the actual signal, and noise performance are described, concentrating on the modification from the previous version of the circuits.

2 Circuit

The WTF, depicted in Figure. 1, is formed by four stages of analog filters. Although the previous version of the filter worked fine, it was pointed out that the 2nd stage was about being saturated in the daytime operation. As a quick remedy, the second stage and the last stage was swapped.

3 Transfer function

After the modification of the filters, the gain matching at 625Hz were perfomed again. Also, the transfer funcitons of the filters were measured again.

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 spectrum analyzer are given by

$$|H_{\mathrm{WTF}\#2}(625\mathrm{Hz})/H_{\mathrm{WTF}\#1}(625\mathrm{Hz})| = -0.00066 \pm 0.001\,[\mathrm{dB}] \tag{1}$$

$$\mathrm{Arg}[H_{\mathrm{WTF}\#2}(625\mathrm{Hz})/H_{\mathrm{WTF}\#1}(625\mathrm{Hz})] = -4.0108 \pm 0.005\,[\mathrm{degree}]\ , \tag{2}$$

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.

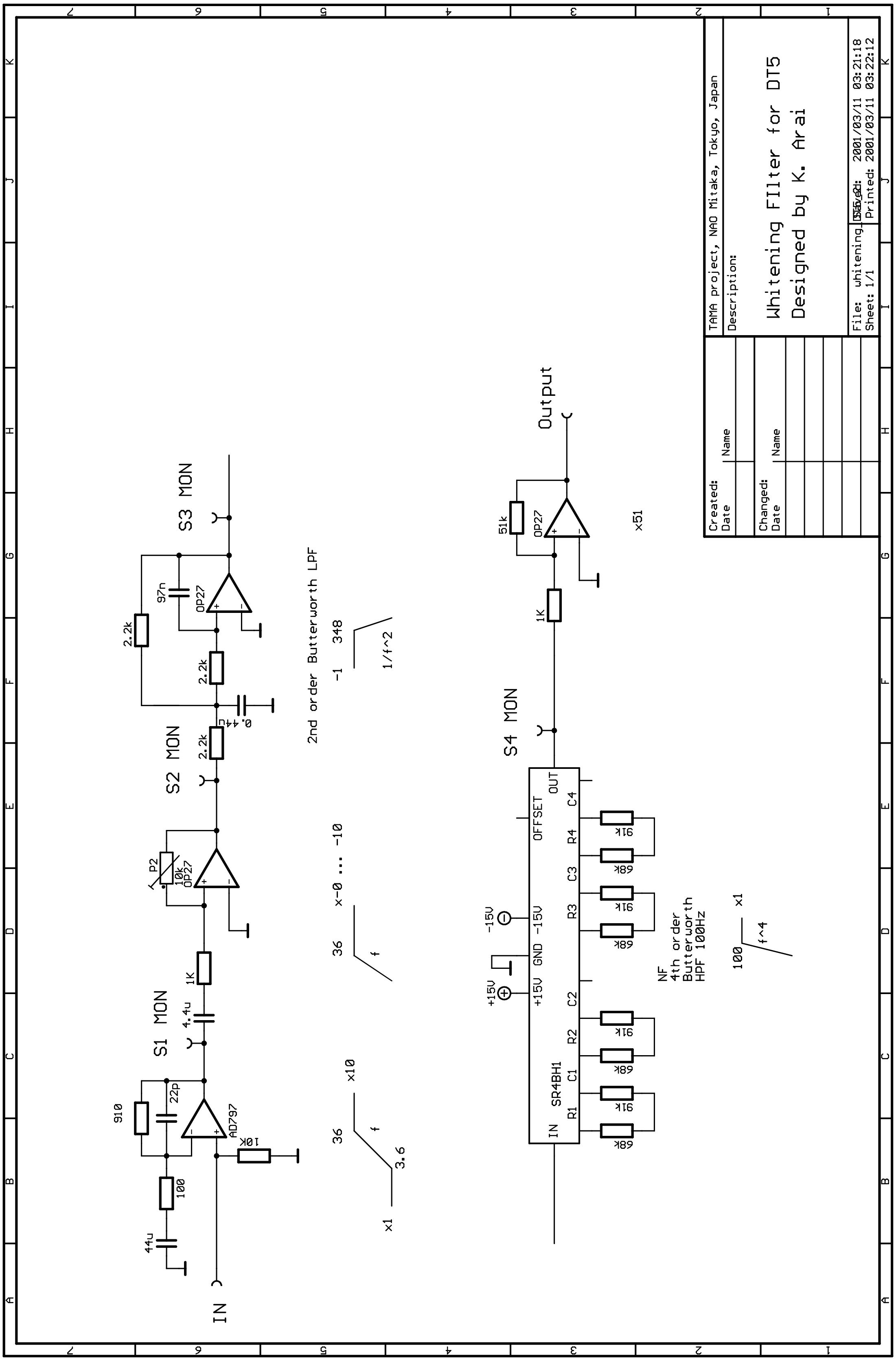

Figure 1: Circuit of the whitening filter actually used in DT5

In order to characterize the WTFs, the measured transfer functions were fitted using LISO [2]. This time, the polynomial functions were used to represent five zeros at the origin in the Laplace plane. The source code for the fitting are shown below.

```
a0 0
a1 0
a2 0
a3 0
a4 0
a5 1 # a0-a5 composes a polynomial which represents (s^5)
zero 3.5238299
pole 77.759692
pole 34.336386
pole 359.91245 697.81246m
pole 101.68389 1.276314
pole 99.681401 571.4866m
pole 71.110443k
factor -59.041861n
param zero0:f 1 10
param pole0:f 20 1500
param pole1:f 20 1500
param pole2:f 200 1000
param pole2:q 0.1 10
param pole3:f 10 200
param pole3:q 0.1 10
param pole4:f 10 200
param pole4:q 0.1 10
param pole5:f 1e3 1e6
param factor 1e-15 1e-6

fit llm_WTF1_tf.bod absdeg semi
rewrite samebetter
#gnuterm cps
tfoutput abs:deg
freq log 1 1e5 400
```

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

	WTF#1	WTF#2
A	$-59.041861n$	$-75.224937n$
f_0 (Hz)	3.5238299	1.8831484
f_1 (Hz)	34.336386	27.543661
f_2 (Hz)	77.759692	33.801999
f_3 (Hz)	359.91245	358.86281
q_3	0.69781246	0.69343594
f_4 (Hz)	101.68389	99.362801
q_4	1.276314	1.2476081
f_5 (Hz)	99681401	111.72927
q_5	0.5714866	0.62278847
f_6 (Hz)	71.110443k	221.2854k

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

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. 2 and 3 show the calculated and measured transfer functions of the whitening filters. Figure. 4 shows the errors in the fitting. The fitting has errors smaller than $\pm 1\%$ and ± 1 degree in magnitude and phase from 30Hz to 2kHz.

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 during the normal state of the interferometer.

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 $1.22 \times 10^{-4}\mathrm{V_{rms}}$. The peak amplitudes of $3.26310^{-1}\mathrm{V_{rms}}$ and $2.19110^{-1}\mathrm{V_{rms}}$ were observed at the outputs of WTF#1 and WTF#2. From the ratio of

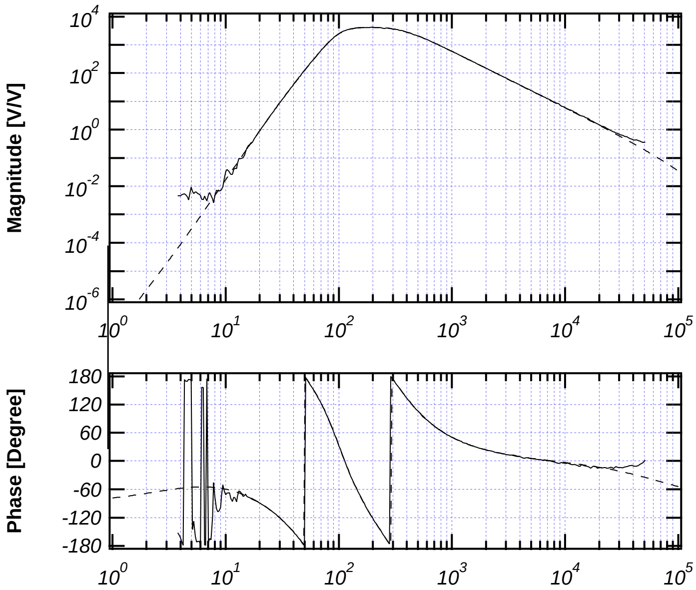

Figure 2: Measured (solid) and fitted (dashed) transfer functions of WTF#1. Values from 10Hz to 10kHz were used for the fitting.

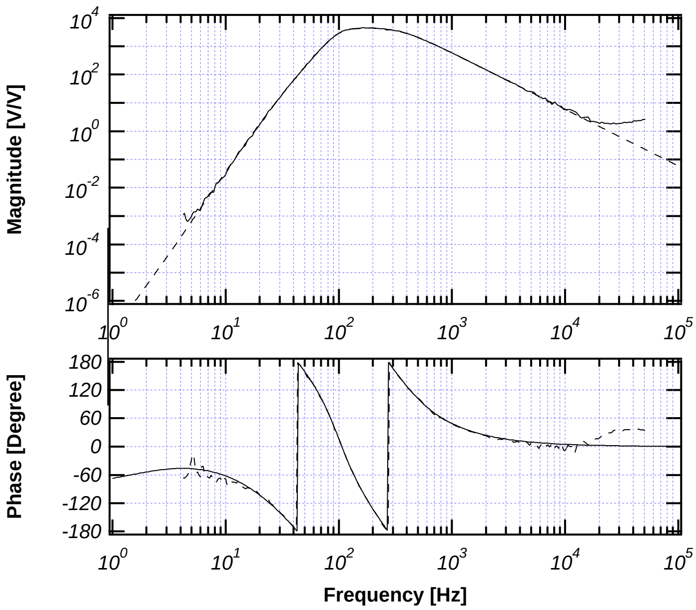

Figure 3: Measured (solid) and fitted (dashed) transfer functions of WTF#2. Values from 10Hz to 10kHz were used for the fitting.

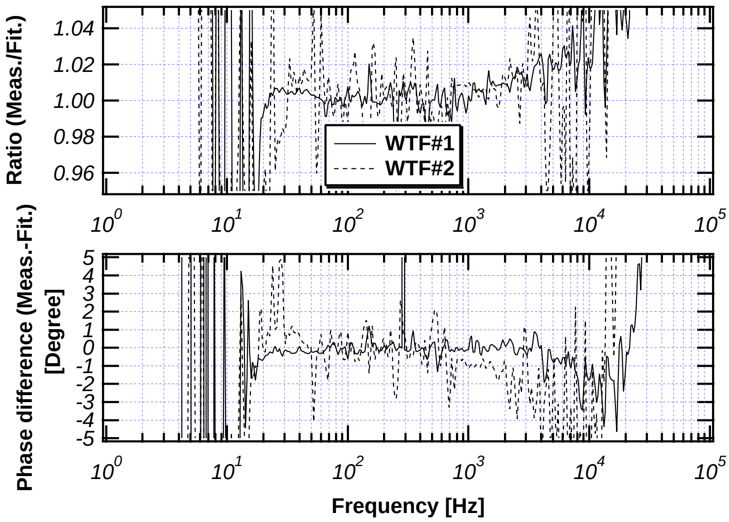

Figure 4: Comparison between the measured transfer functions and the fitted ones. Upper plots shows the magnitude ratio of the measured one and the calculated one. Lower plots show the difference of their phases.

OUTPUT	Observed Voltage
In	$< 4V_{\mathrm{pp}}$
S1 Mon	$< 4V_{\mathrm{pp}}$
S2 Mon	$< 3V_{\mathrm{pp}}$
S3 Mon	$< 1V_{\mathrm{pp}}$
S4 Mon	$< 300mV_{\mathrm{pp}}$
Out	$< 3V_{\mathrm{pp}}$

Table 2: Observed output at each output port.

these amplitudes the open-loop transfer function of 1.489 at 625Hz was deduced. This corresponds to the unity gain frequency of 942Hz.

The whitened output spectra are shown in Figs. 5 and 6. 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. 5 and 6 together with the whitened outputs. It was confirmed that the noise of the circuits does not disturb the target signal.

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.

References

[1] K. Arai, "DT5: Design of whitening filters for DT5", `http://tamago.mtk.nao.ac.jp/tama/recom/general_lib/circuits/010217_DT5_WTF/whitening.pdf`

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

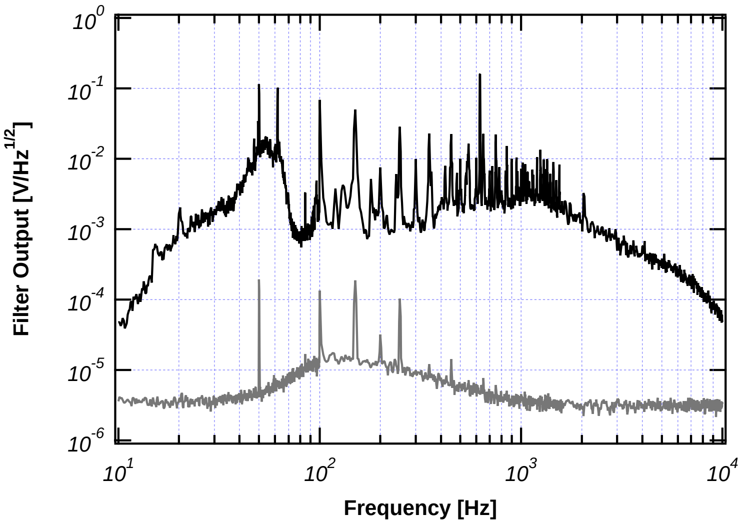

Figure 5: Whitened output of WTF#1 and the output noise level.

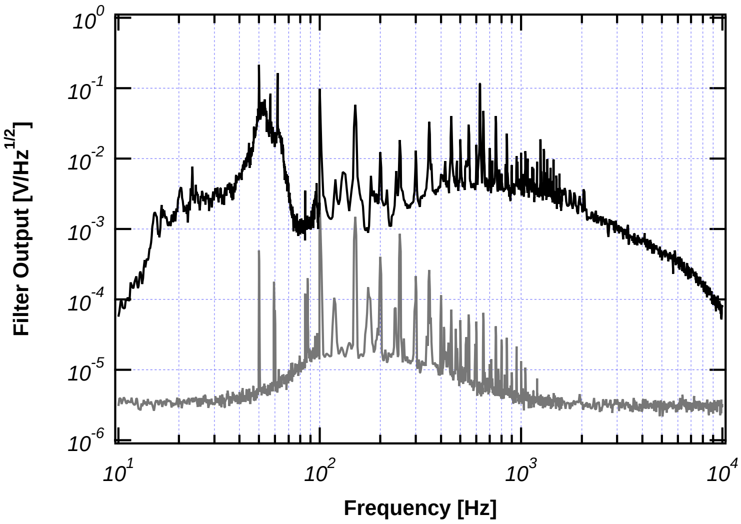

Figure 6: Whitened output of WTF#2 and the output noise level.

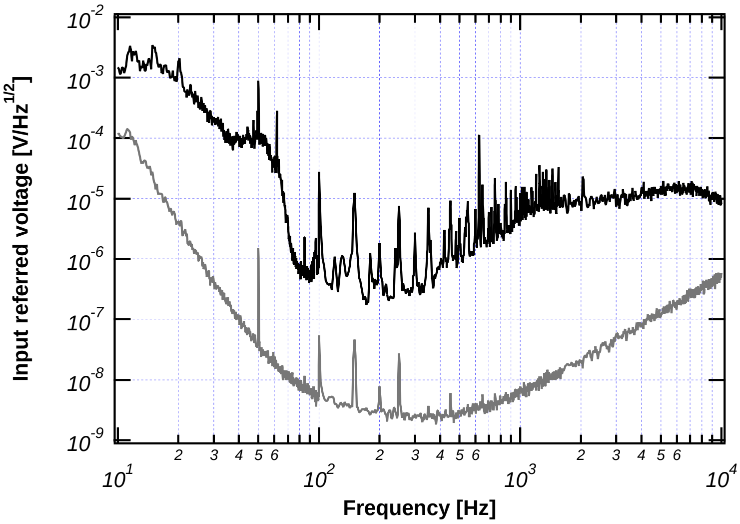

Figure 7: Input-referred noise of WTF#1 and reconstructed feedback signal for L_{-}.

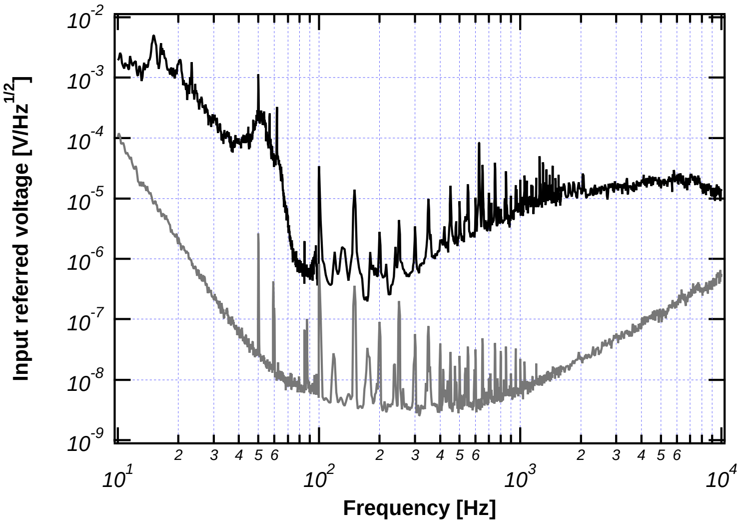

Figure 8: Input-referred noise of WTF#2 and reconstructed feedback signal for L_{-}.