Calibration of TAMA300 in Time Domain

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Contents

DAQ System of TAMA300

Optical Configuration

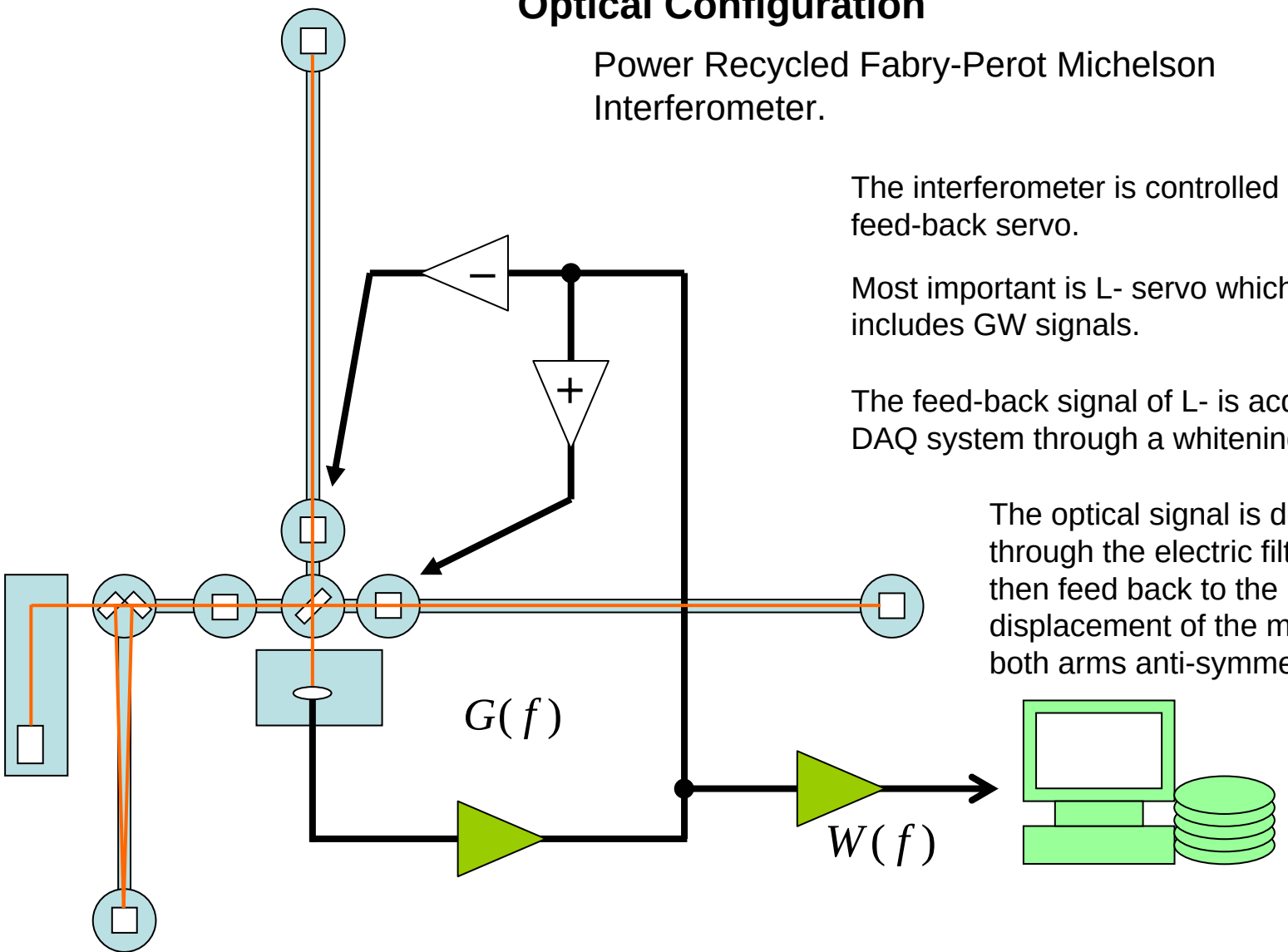
Power Recycled Fabry-Perot Michelson Interferometer.

The interferometer is controlled by feed-back servo.

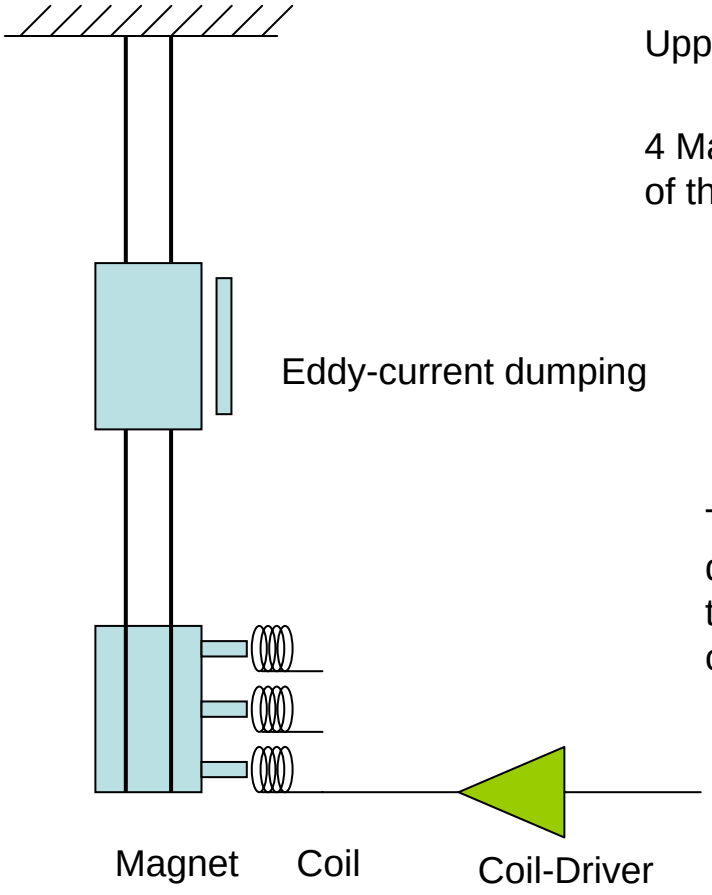
Most important is L- servo which includes GW signals.

The feed-back signal of L- is acquired by DAQ system through a whitening filter.

The optical signal is detected, through the electric filters and then feed back to the displacement of the mirrors of the both arms anti-symmetrically.



Coil-Magnet Actuator on Suspended Mirror



Each Mirror is suspended by double pendulum.

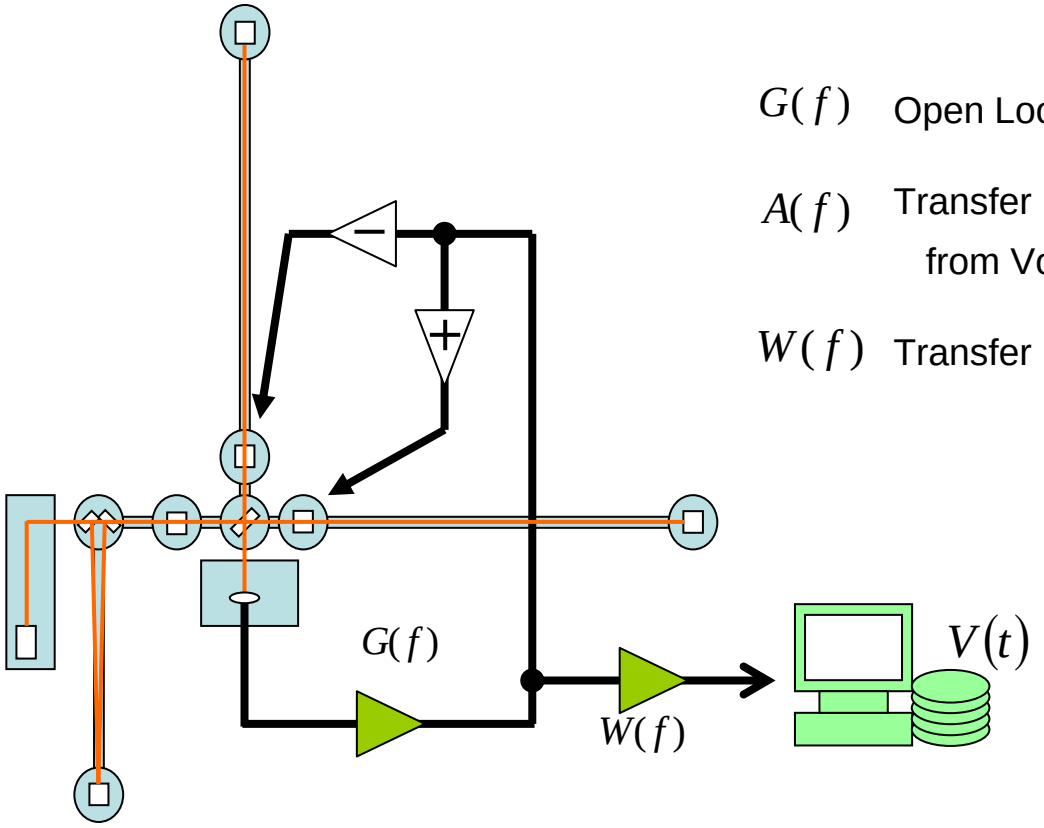
Upper Mass is dumped by Eddy-current dumping

4 Magnets on the Mirror and 4 Coils on the cage of the pendulum consist of Actuator.

The transfer function from input voltage of the coil driver to the displacement of the mirror is almost a transfer function of 2nd order low-pass filter with the cut off frequency of 1Hz and the Q-value of 3.

Reconstruct Data in Fourier Space

$$\tilde{h}(f) = \frac{1}{300\text{m}} \frac{1}{W(f)} A(f) \frac{1+G(f)}{G(f)} \tilde{V}(f)$$



$G(f)$ Open Loop Transfer Function of the Servo

$A(f)$ Transfer Function of Coil-Magnet Actuator from Voltage to Displacement

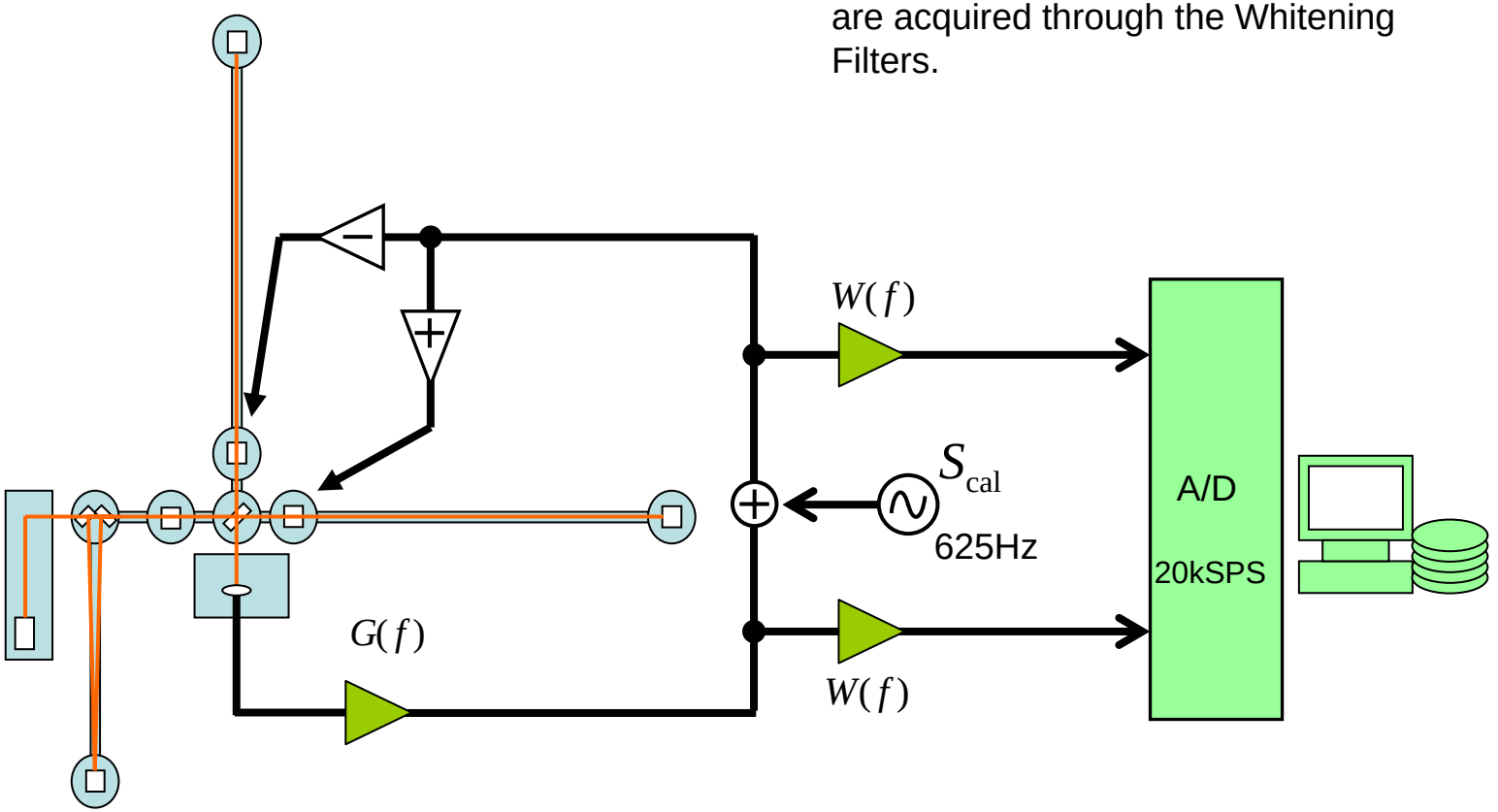
$W(f)$ Transfer Function of Whitening Filter

Calibration Signal

Calibration Signal is injected at just before the Coil-driver with Sum-amp..

The Calibration Signal is sinusodial wave of 625 Hz which is generated by dividing sampling frequency (20kHz) of ADC by 32.

Signals Before and After the Sum-amp are acquired through the Whitening Filters.



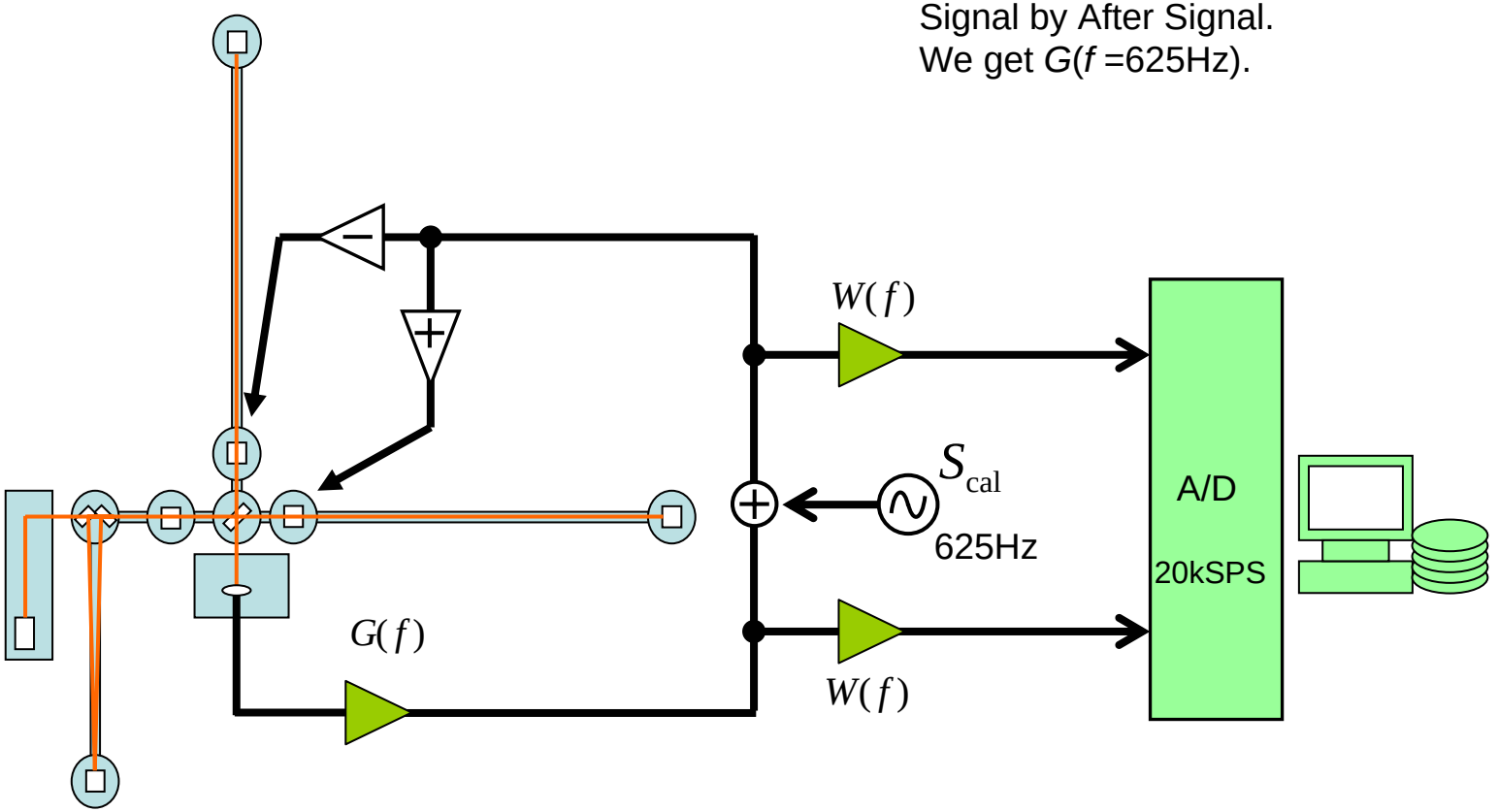
Calibration Signal

Before Sum-amp. $W(f)\dfrac{G(f=625\text{Hz})}{1+G(f=625\text{Hz})}S_{\text{cal}}$

After Sum-amp. $W(f)\dfrac{1}{1+G(f=625\text{Hz})}S_{\text{cal}}$

$\Rightarrow G(f=625\text{Hz})$

Extract 625 Hz components from both acquired signals and then divide Before Signal by After Signal.
We get $G(f=625\text{Hz})$.



Calibration Signal

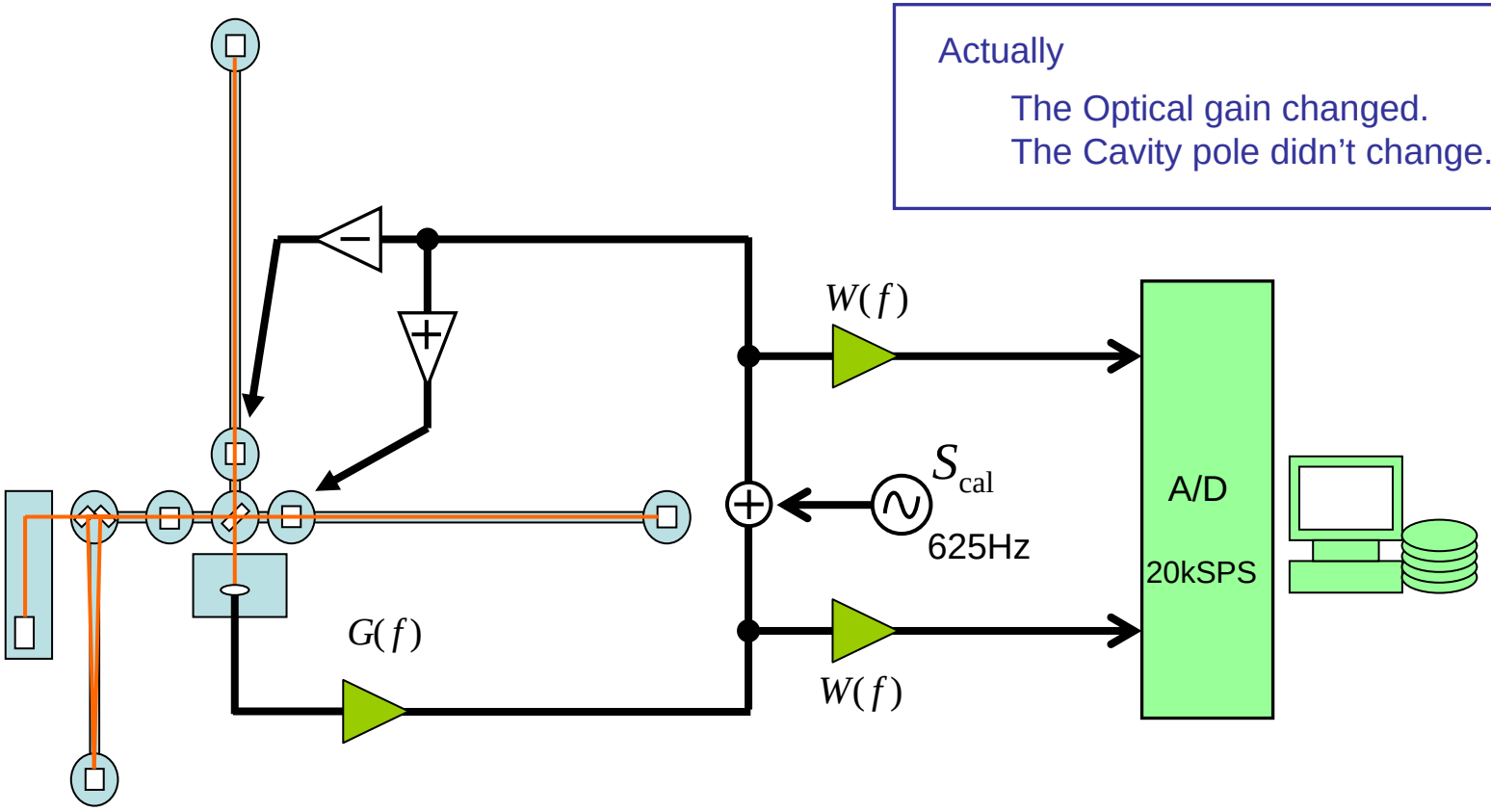
Changeable parameters are two.
One is the Optical gain.
- Flat characterization for frequency.

The other is Cavity pole of arm FP-cavity.
- 1st order low pass filter (fc=500Hz).

The Optical gain is obtained
from the amplitude of $G(f=625\text{Hz})$.
The Cavity pole is obtained
from the phase of $G(f=625\text{Hz})$.

Actually

The Optical gain changed.
The Cavity pole didn't change.



Reconstruct Data in Time domain

In order to analyze the observational data more generally, we need to produce the strain data *h*(*t*) in time domain.

$$V(t) \xrightarrow{\text{IIR}} h(t)$$

We use Infinite Impulse Response (IIR) filters to reconstruct data in time domain.

About IIR Filter

Notation of Infinite Inverse Response Filter

$$O_j = \sum_{k=0} c_k \, I_{j-k} + \sum_{k=1} d_k \, O_{j-k}$$

O_j jth Output data of IIR Filter.

I_j jth Input data.

With various set of $\{ c_k , d_k \}$, various filters can be constructed.

Ex.

1st order Low Pass Filter with cut off frequency of fc.

T : Sampling Time

f_c : Cut off freqency

$$c_0 = \frac{1}{1+\frac{2}{2\pi f_c T}}$$

$$c_1 = \frac{1}{1+\frac{2}{2\pi f_c T}} \qquad d_1 = -\frac{1-\frac{2}{2\pi f_c T}}{1+\frac{2}{2\pi f_c T}}$$

$$c_k = 0 \quad (k \geq 2) \qquad d_k = 0 \quad (k \geq 2)$$

Reconstruct Data in Time domain

General Characterization of IIR Filter

Stable or Unstable. Not all factor set { c_k, d_k } is stable.

IIR filters emulate analog filters not completely - There are differences in higher frequency. -

In practice, there are problems with overflow and precision in calculation of computer.

Specialties for our IIR

We made special IIR Filter Set, which is good agreement with analog filter in our observation range. But in higher frequency range (out of observation range), it is far from analog filter.

We produced Functions for calculation of closed loop.

TAMA300 in Fourier Space

$$\tilde{h}(f) = \frac{1}{300\mathrm{m}} \; \frac{1}{W(f)} \; A(f) \; \frac{1+G(f)}{G(f)} \; \tilde{V}(f)$$

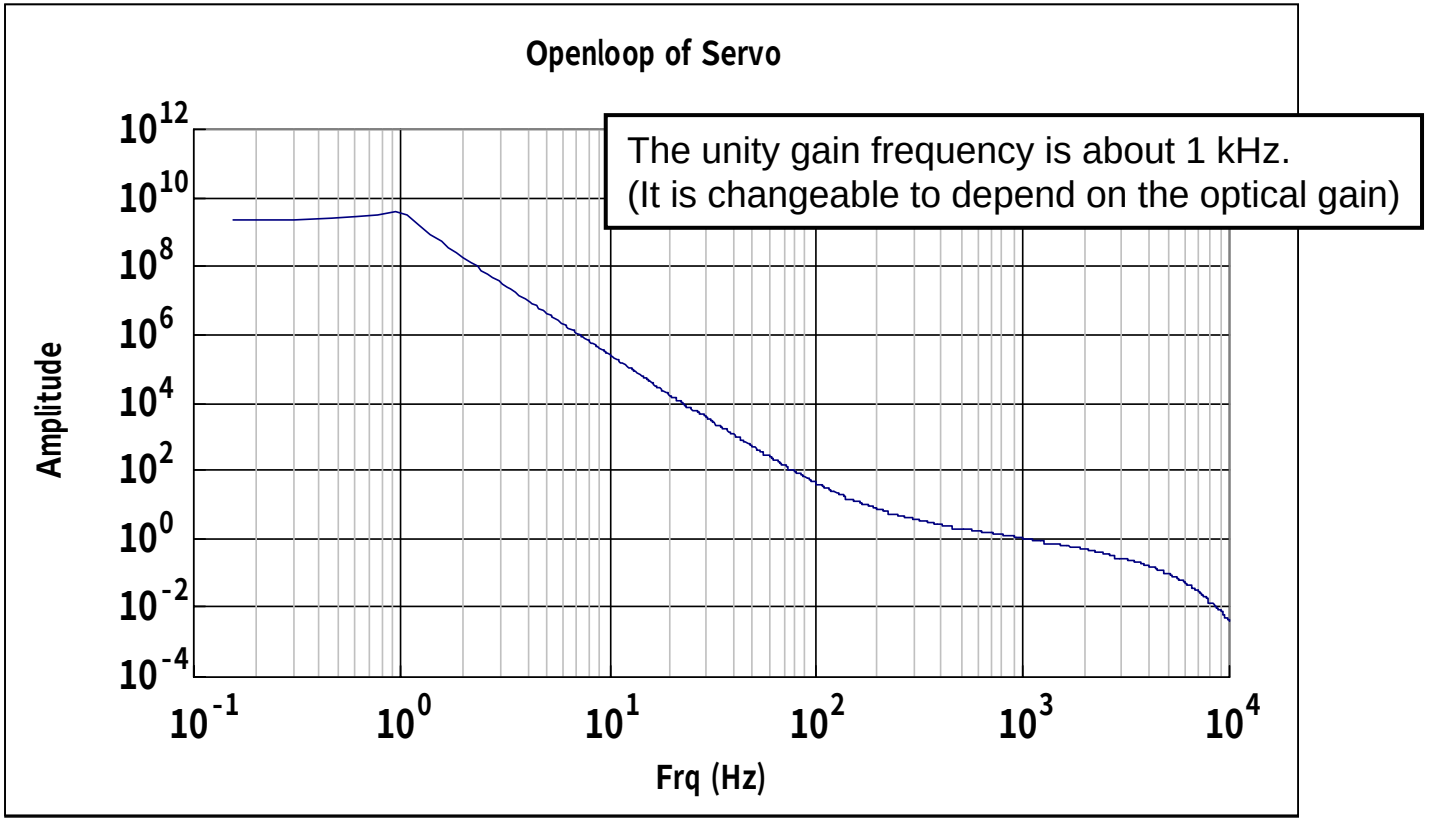
$G(f)$ Open Loop Transfer Function of the Servo

$A(f)$ Transfer Function of Coil-Magnet Actuator from Voltage to Displacement

$W(f)$ Transfer Function of Whitening Filter

Reconstruct Data in Time domain

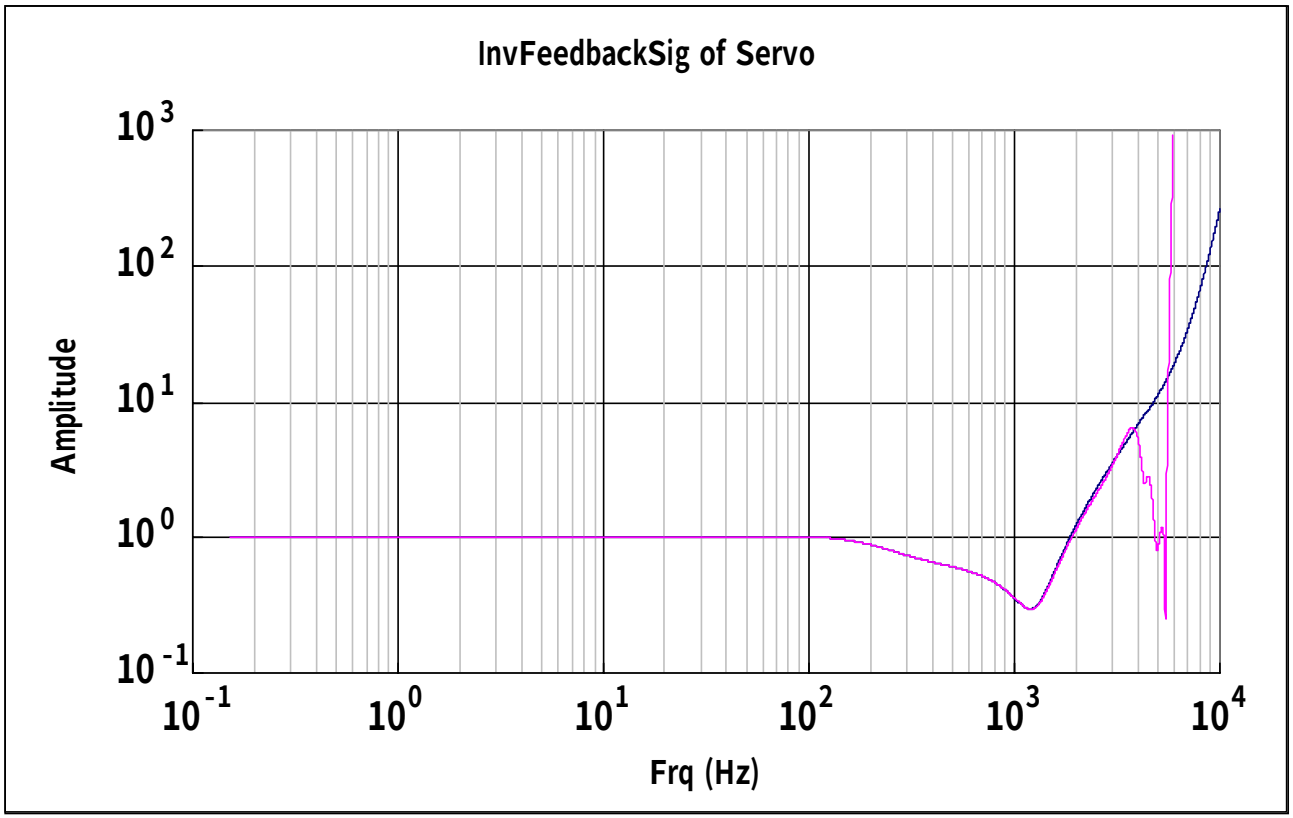
About $G(f)$ Open Loop Transfer Function of the Servo.



Reconstruct Data in Time domain

About $\frac{1+G(f)}{G(f)}$ Closed Loop Transfer Function of the Servo at Feed-back point.

Blue line is the transfer function of actual servo (Analog).
Pink line is the transfer function of IIR filter.

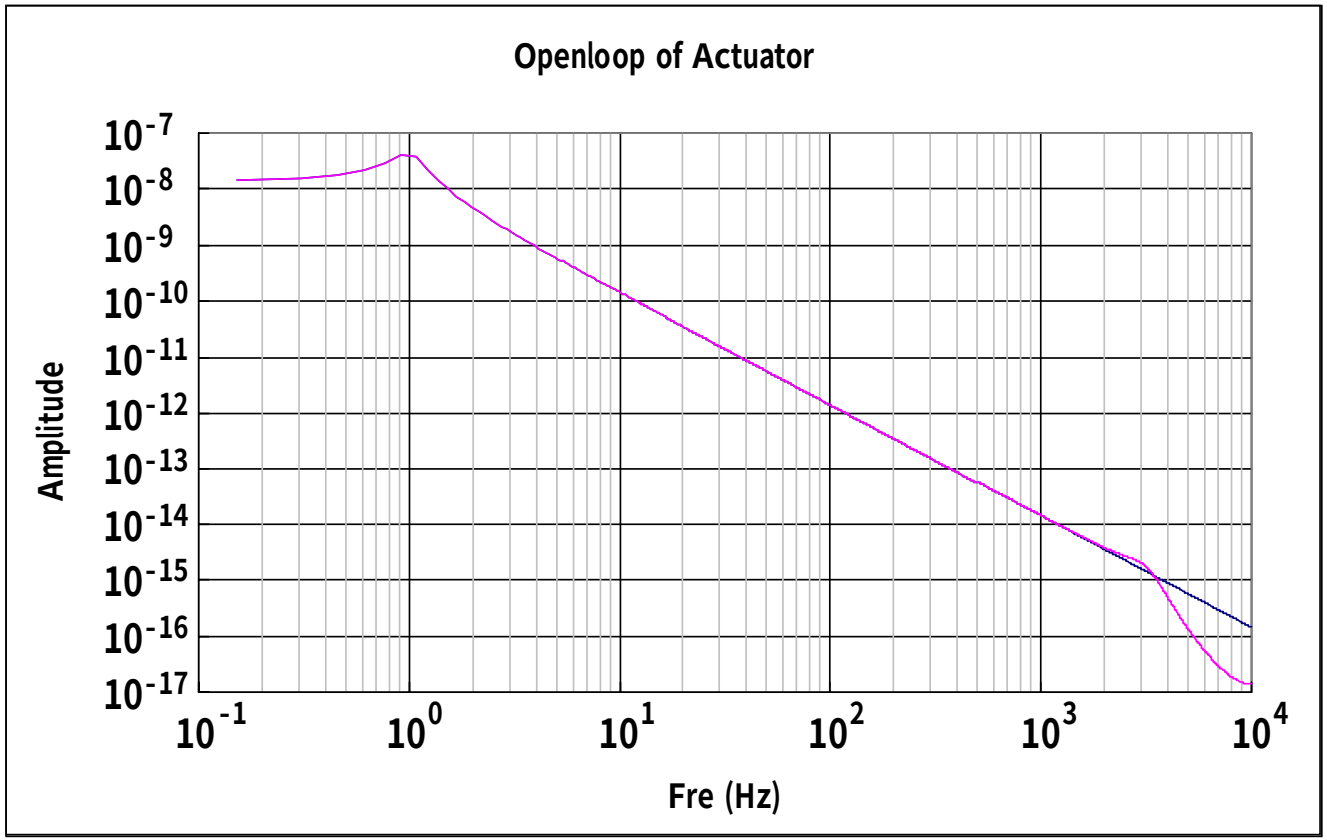


There are differences between Analog transfer function and Digital transfer function at the higher frequency (near Nyquist frequency).
It is characterization of IIR filter and impassible to emulate completely.

Reconstruct Data in Time domain

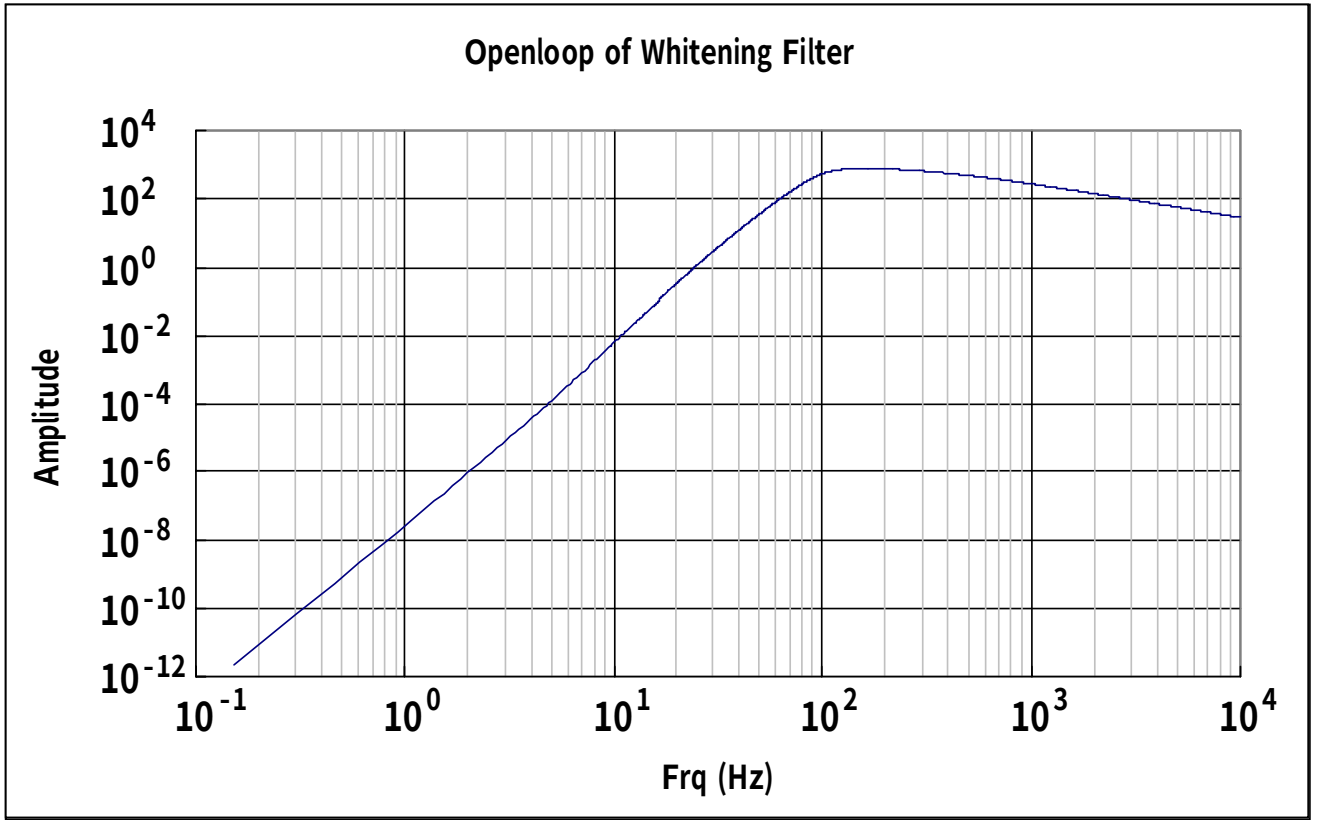
About $A(f)$ Transfer Function of Coil-Magnet actuator from input Voltage of coil driver to Mirror displacement.

It is 2nd order low pass filter whose cut off frequency is 1Hz and Q-value is 3.



Reconstruct Data in Time domain

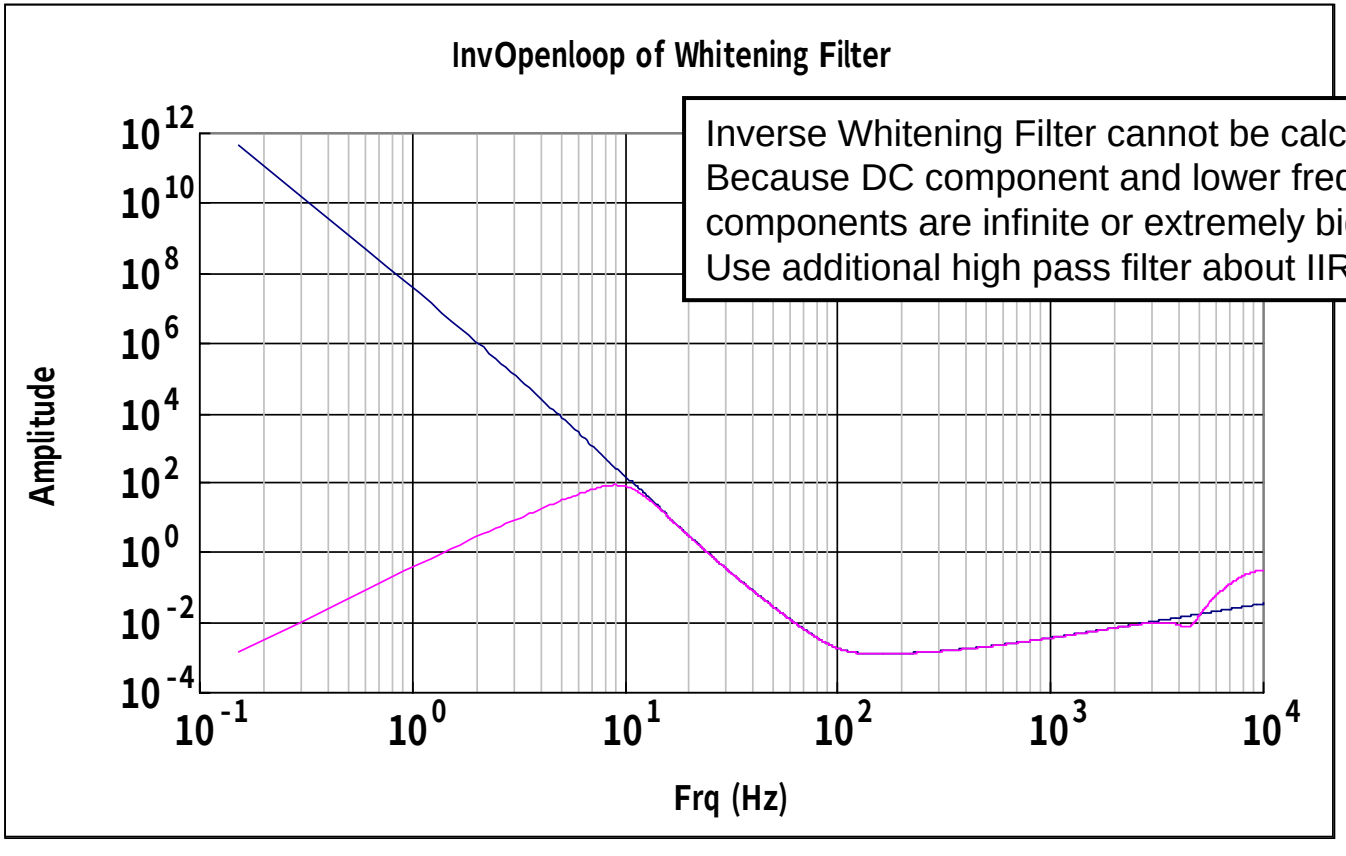
About $W(f)$ Transfer Function of the Whitening Filter.



Reconstruct Data in Time domain

About $\frac{1}{W(f)}$ Transfer Function of the Inverse Whitening Filter.

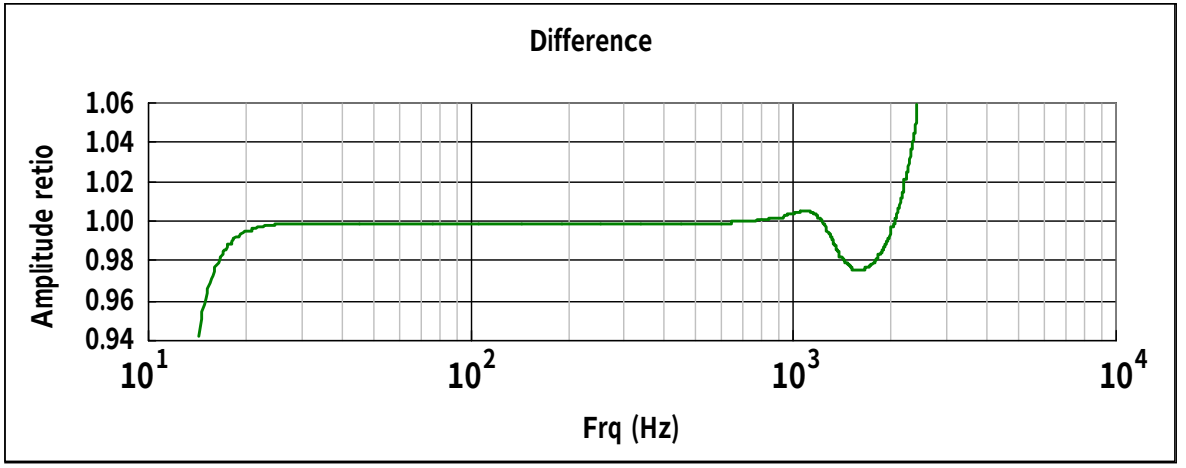
Blue line is the transfer function of Analog filter.
Pink line is the transfer function of IIR filter.

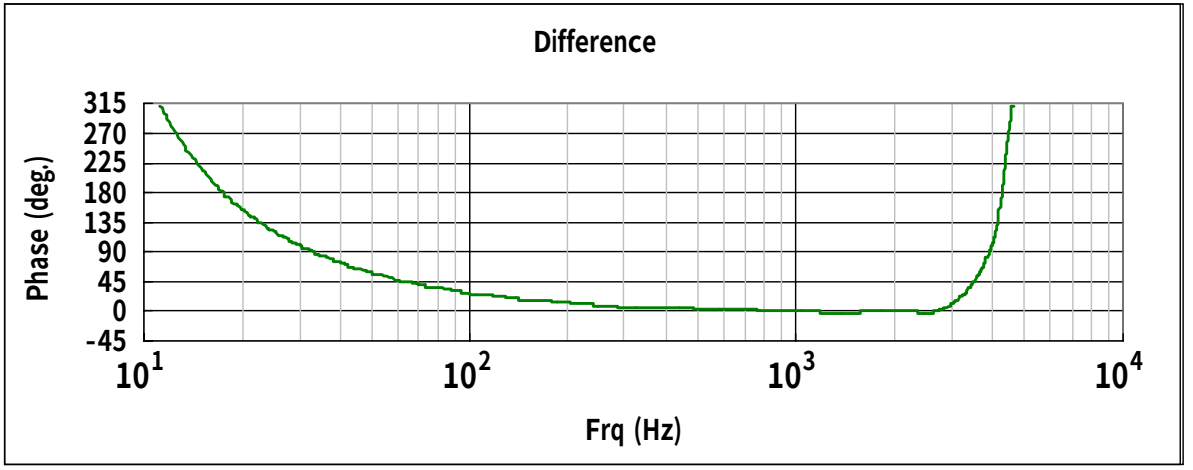


Inverse Whitening Filter cannot be calculated.
Because DC component and lower frequency components are infinite or extremely big.
Use additional high pass filter about IIR filter.

Reconstruct Data in Time domain

Total difference between frequency model and time domain model.

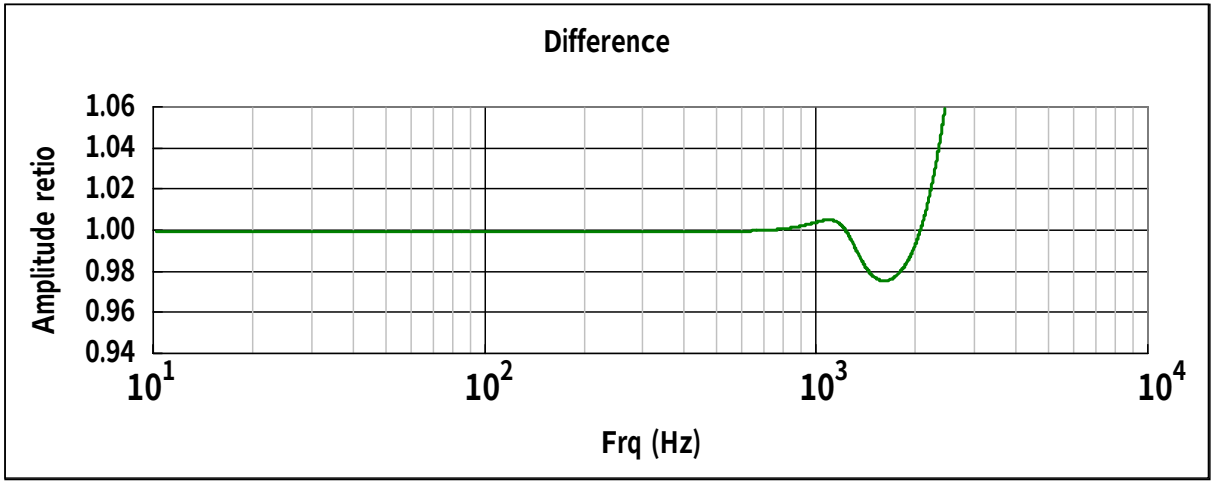


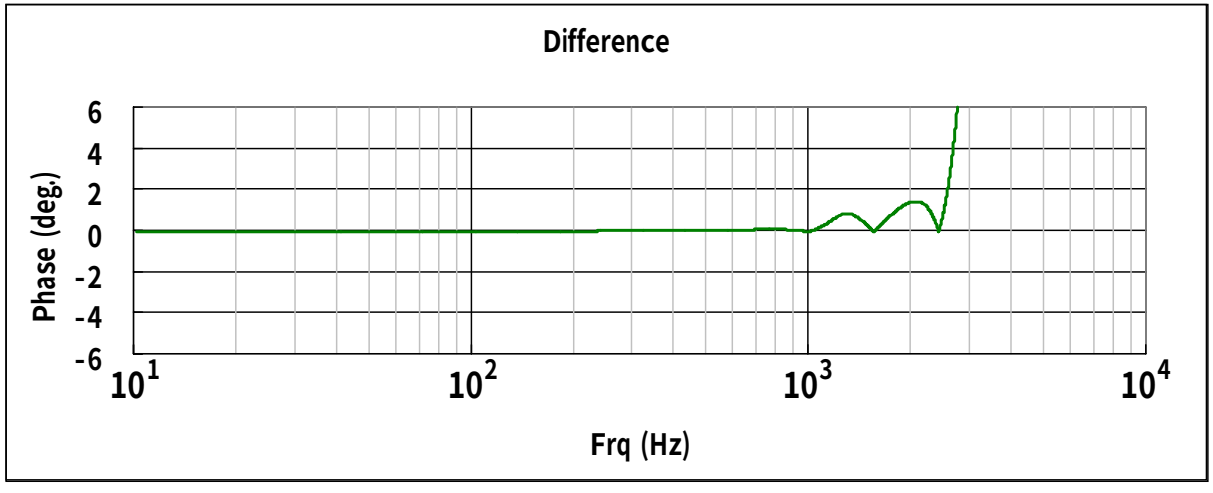


The difference at the lower frequencies caused by additional high pass filter in inverse whitening filter.

Reconstruct Data in Time domain

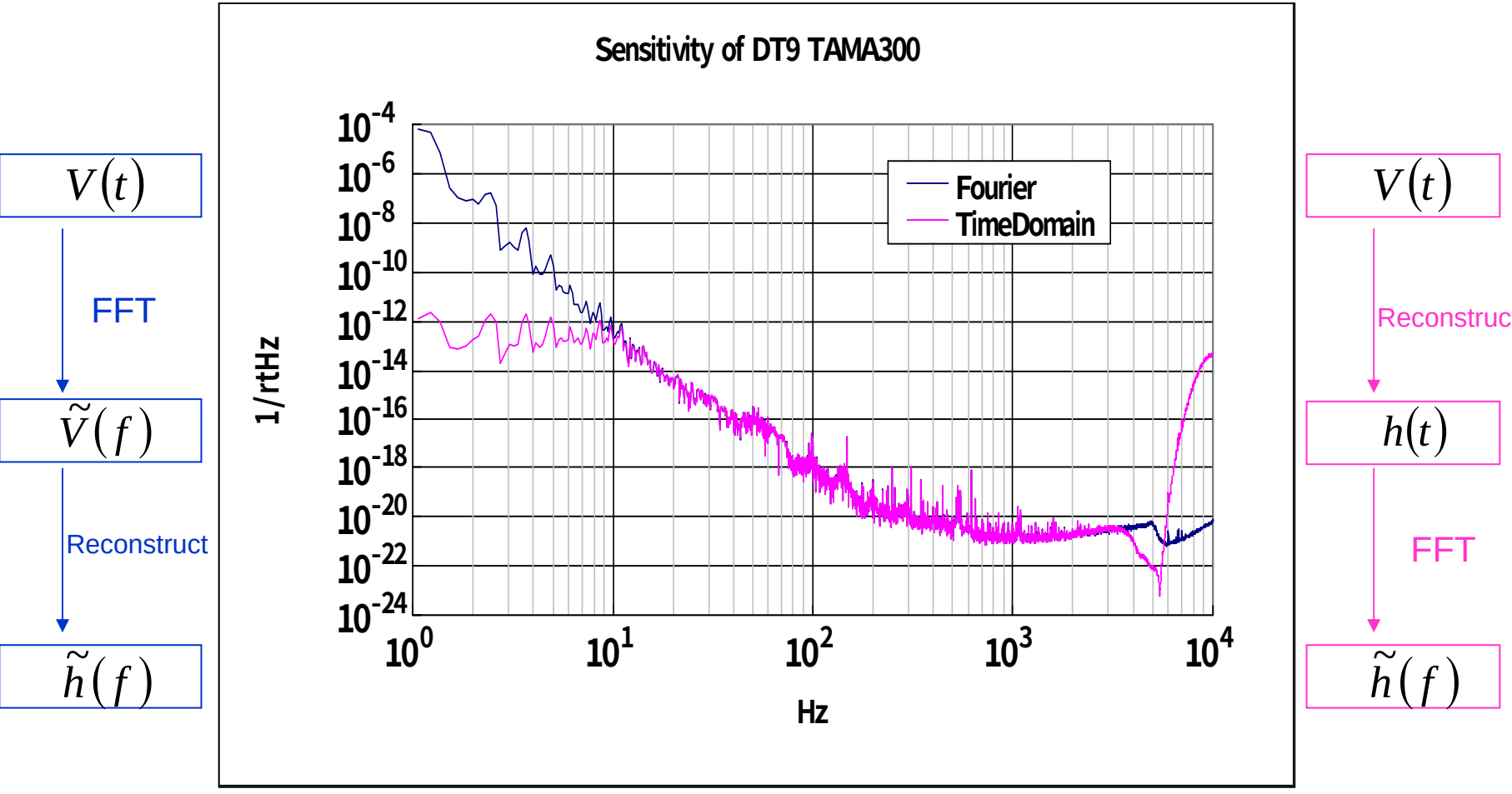
Total difference between Frequency model and Time domain model.





If without the additional high pass filter. But impossible to calculate !!

Reconstructed Data in Fourier Space & Time Domain



Time Domain Signals

We could produce

$$V(t) \rightarrow h(t)$$

We can also produce

$$h(t) \rightarrow V(t)$$

It is useful for some analysis !!

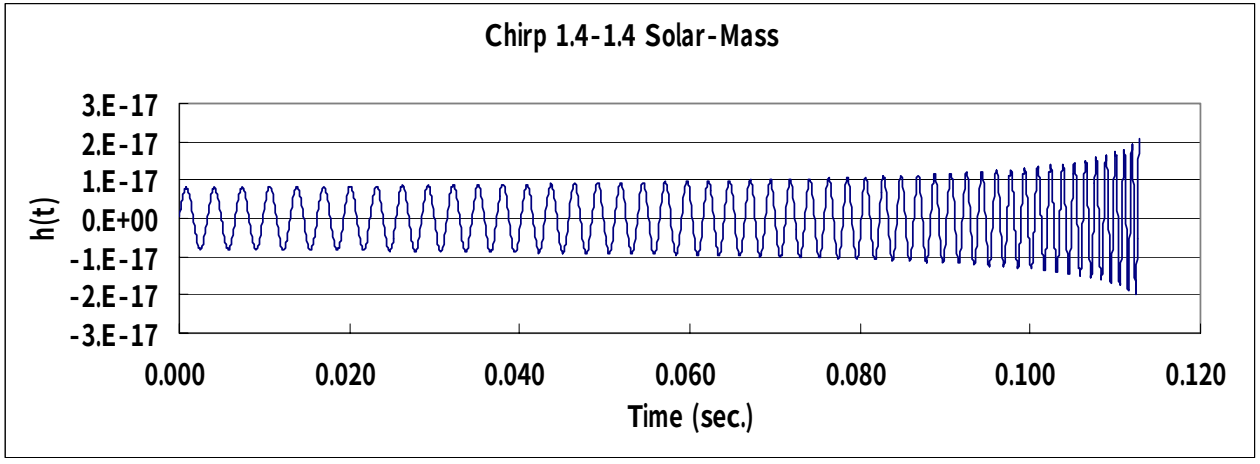
Ex.

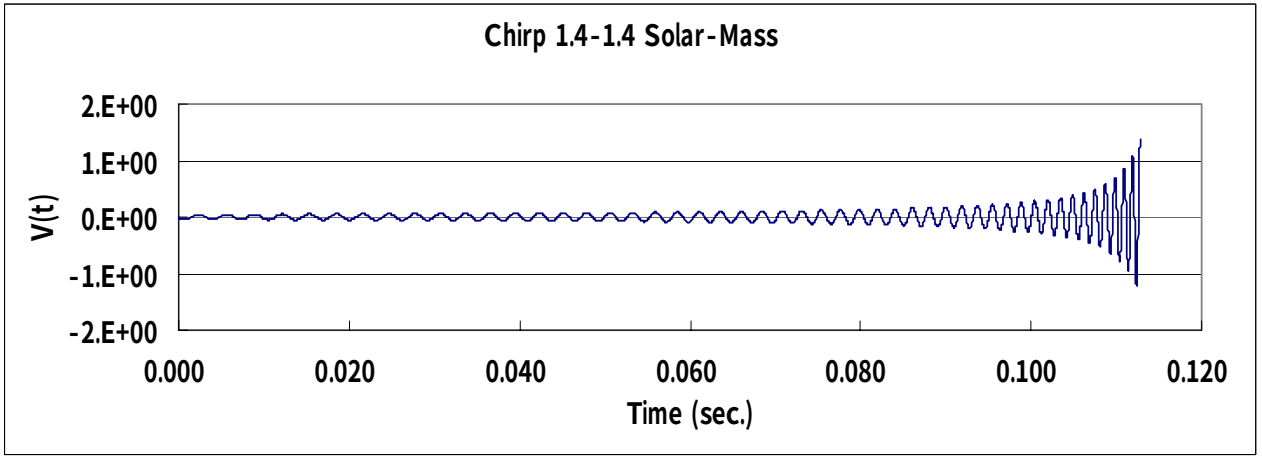
Simulation signals are injected to the observation data in Time domain.

Show some waves as $V(t)$.

Time Domain Signals

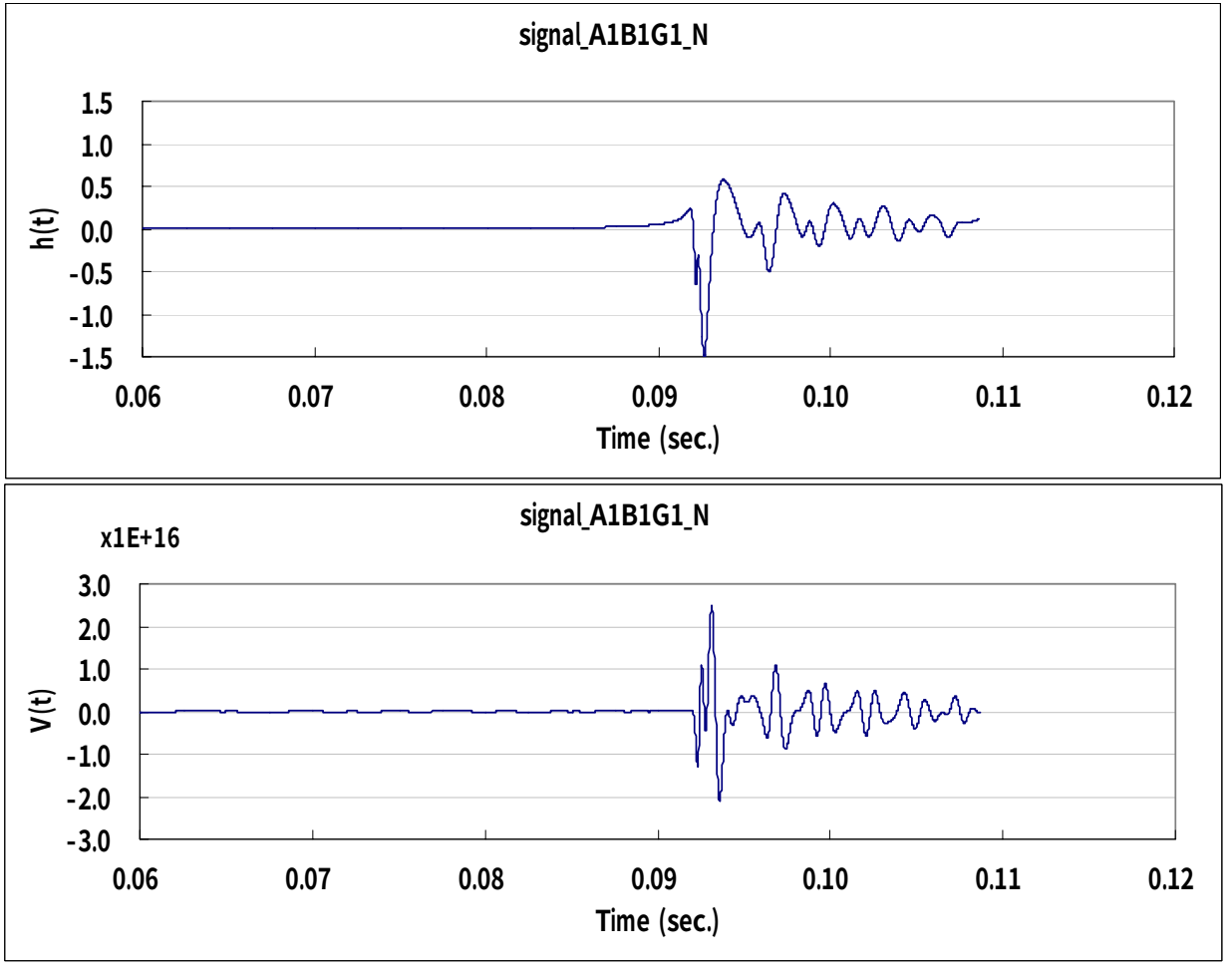
Chirp Signal of 1.4-1.4 Solar-Mass





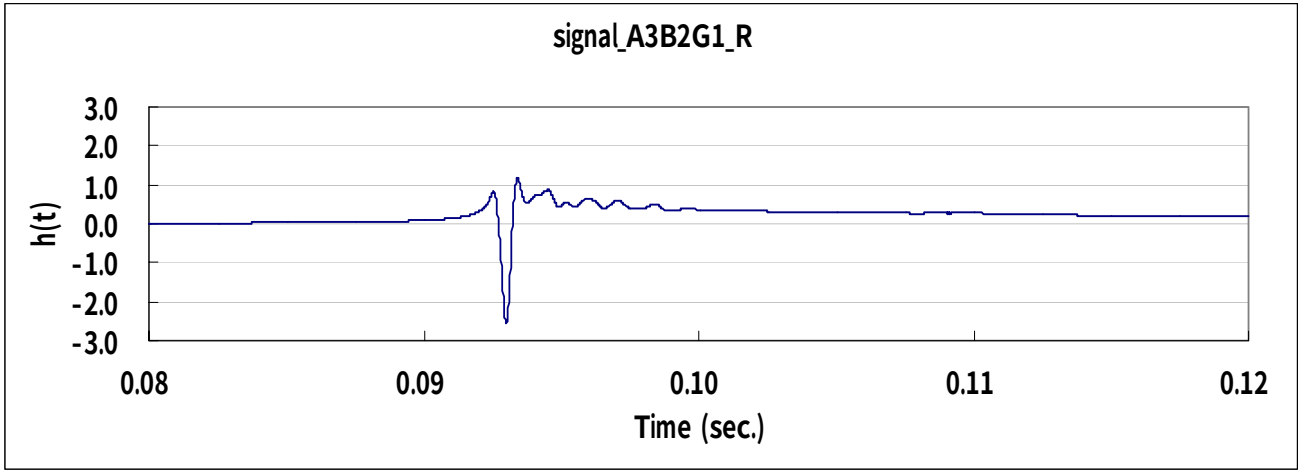
Time Domain Signals

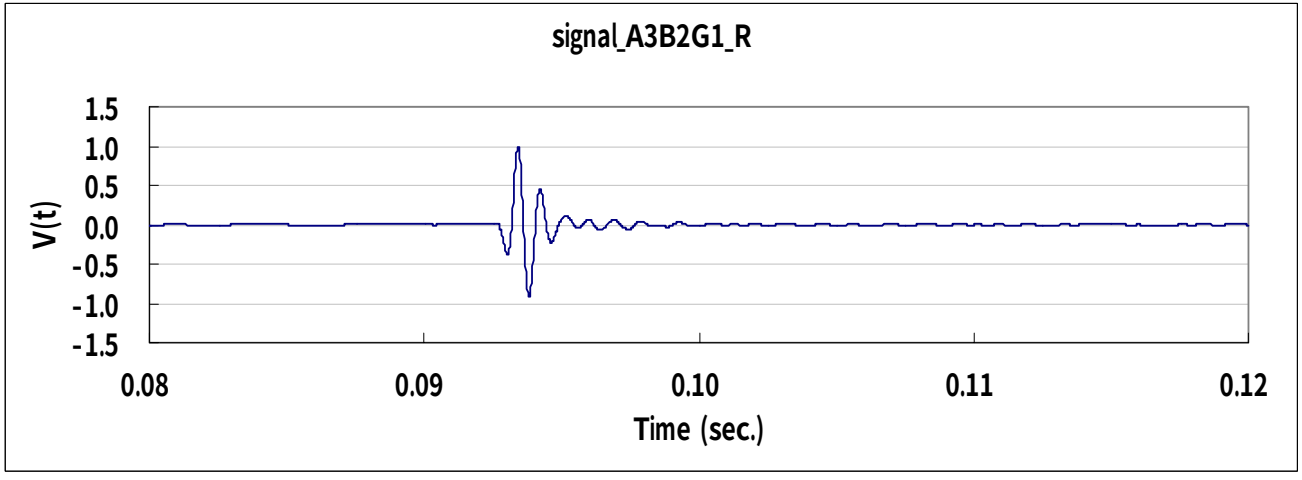
Dimmelmeier's Burst catalogue



Time Domain Signals

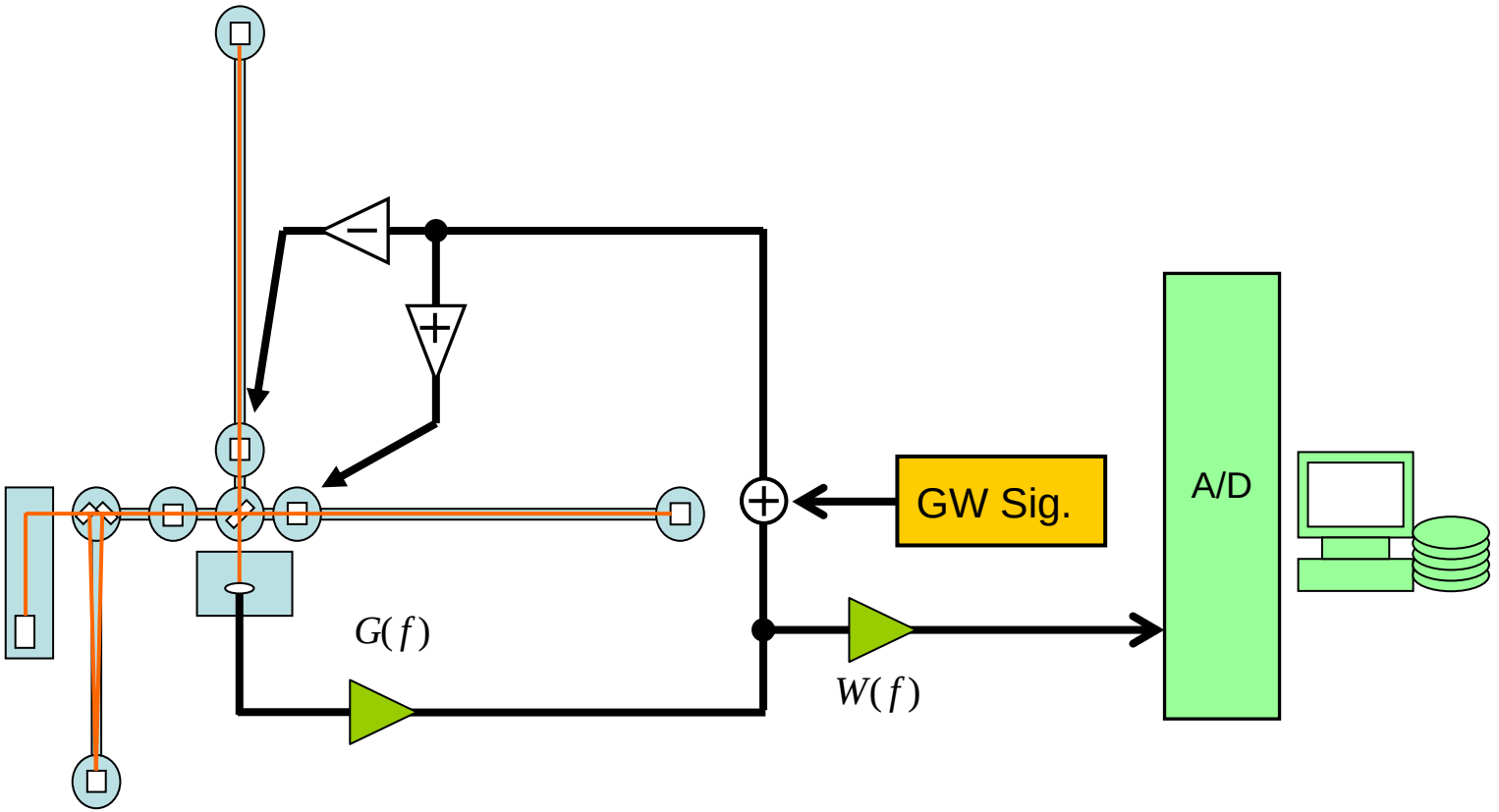
Dimmelmeier's Burst catalogue





Extract Hardware Signal Injection

In the Data Taking Run 8 (DT8), Some simulated GW signals were injected at just before the Coil driver with Sum-amp..



Extract Hardware Signal Injection

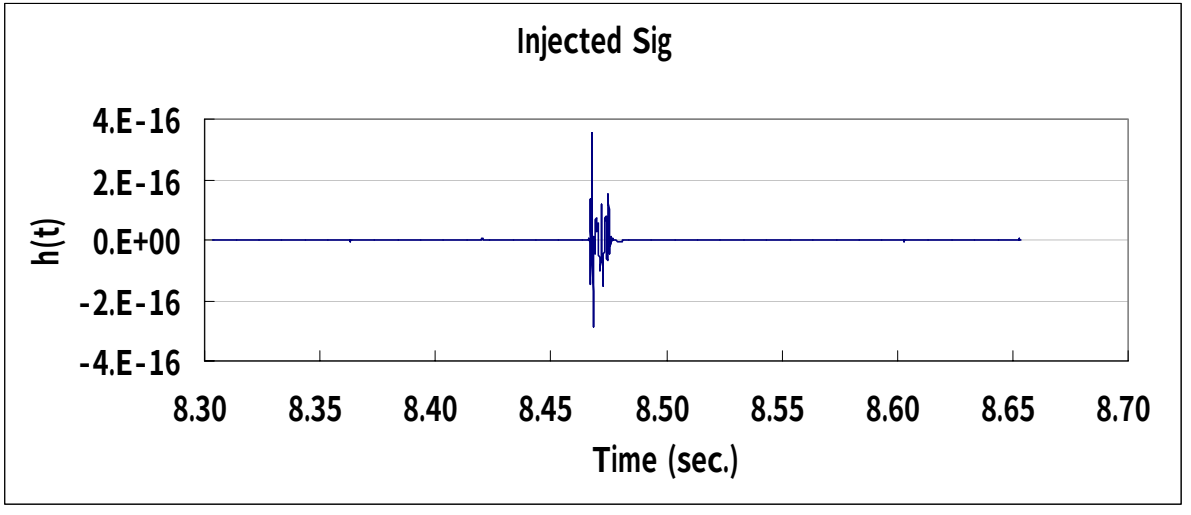
Upper graph is injected signal.
Lower graph is reconstructed data.

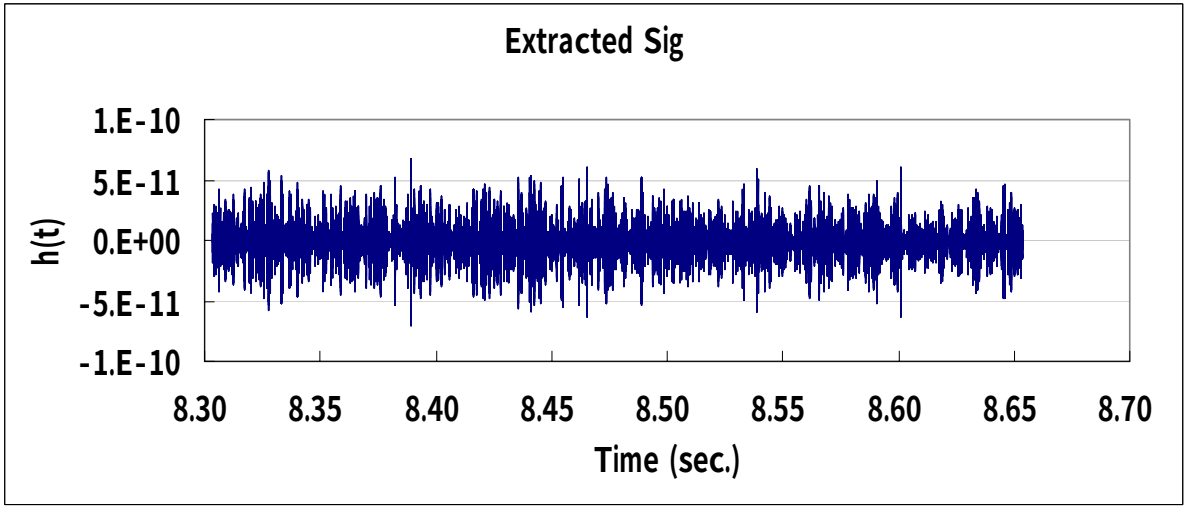
Reconstruct h(t)

Band Pass Filter

Zoom in

Curve Fit
&
Subtract the Curve





Extract Hardware Signal Injection

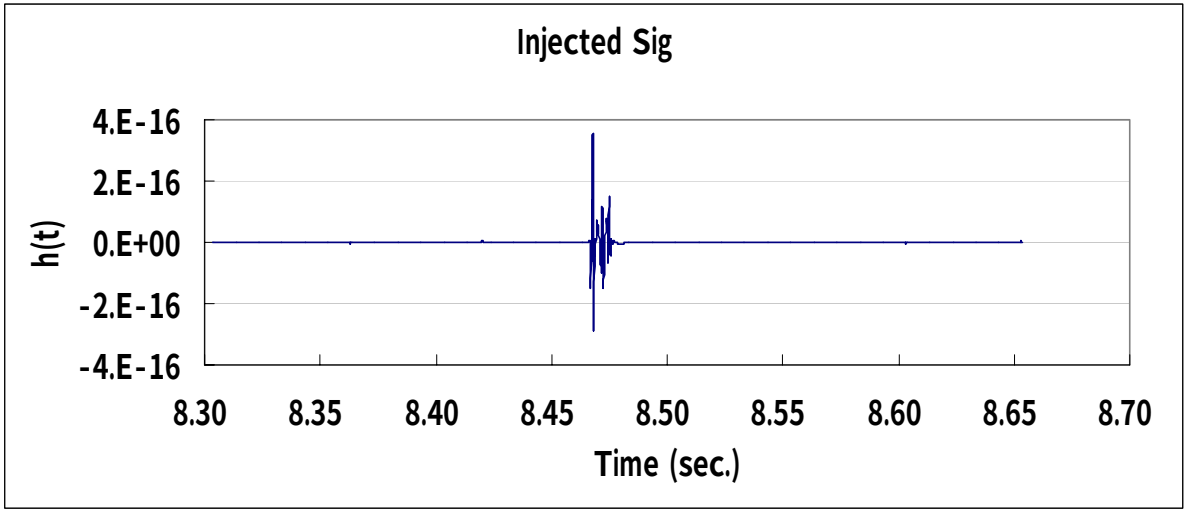
Upper graph is injected signal with band pass filter.
Lower graph is reconstructed data with band pass filter.

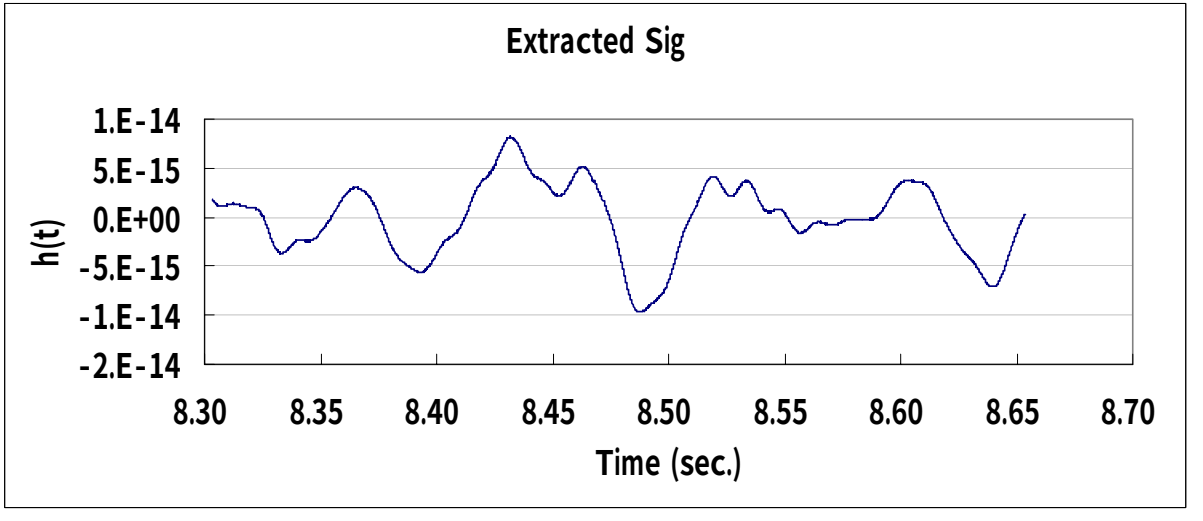
Reconstruct h(t)

Band Pass Filter

Zoom in

Curve Fit
&
Subtract the Curve





Extract Hardware Signal Injection

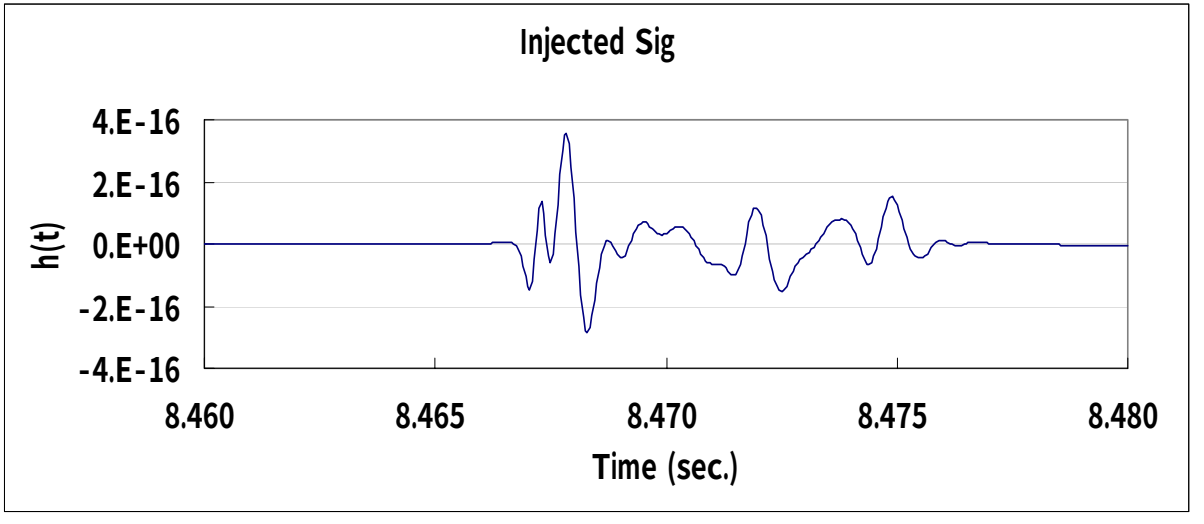
Zoom in time scale at the point of injection.
You can see small structure on the reconstructed curve.

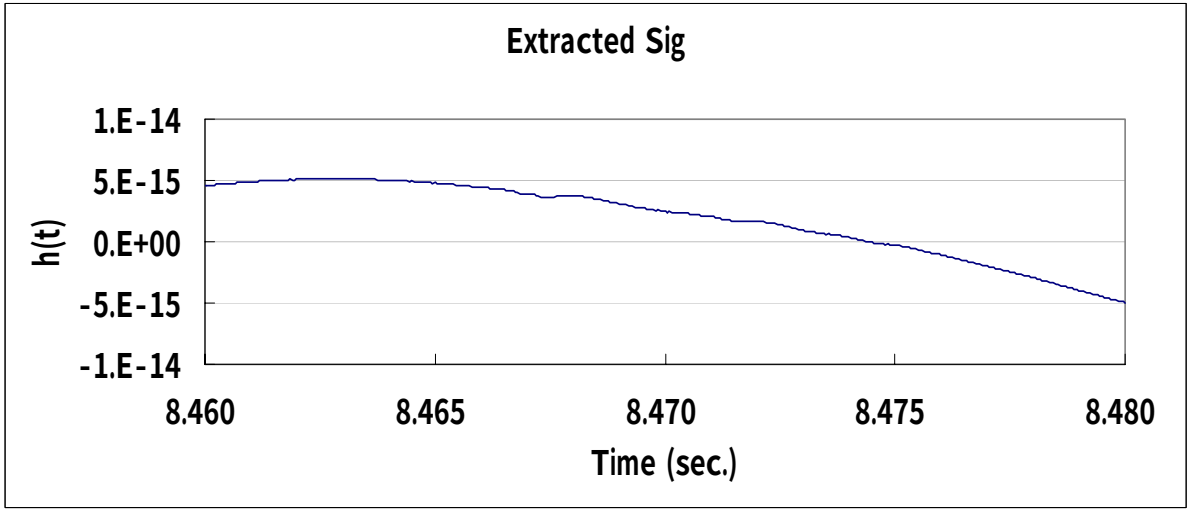
Reconstruct h(t)

Band Pass Filter

Zoom in

Curve Fit
&
Subtract the Curve





Extract Hardware Signal Injection

Remaining signal after subtracting the curve.

Reconstruct h(t)

↓

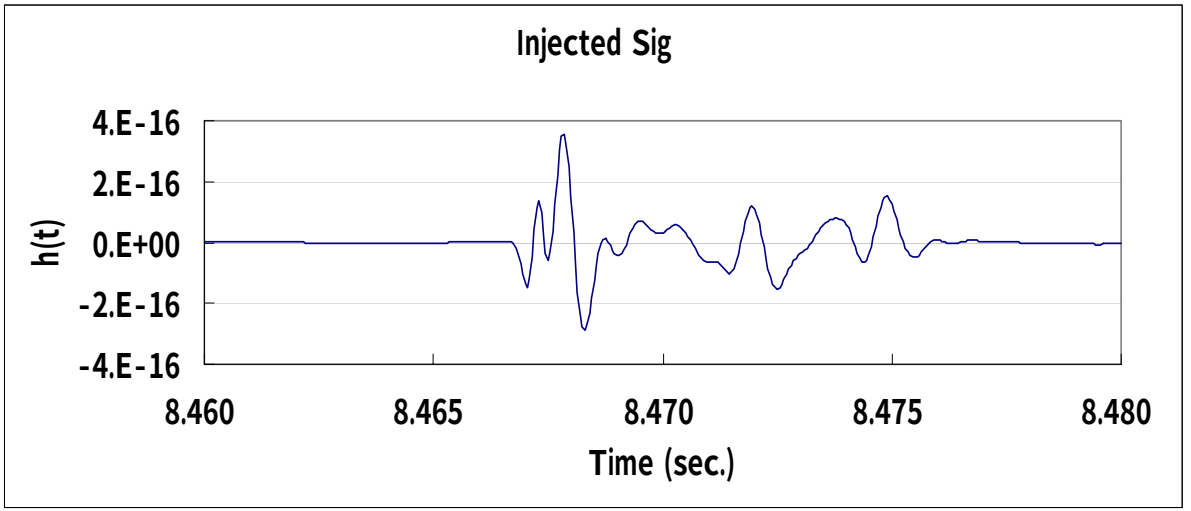
Band Pass Filter

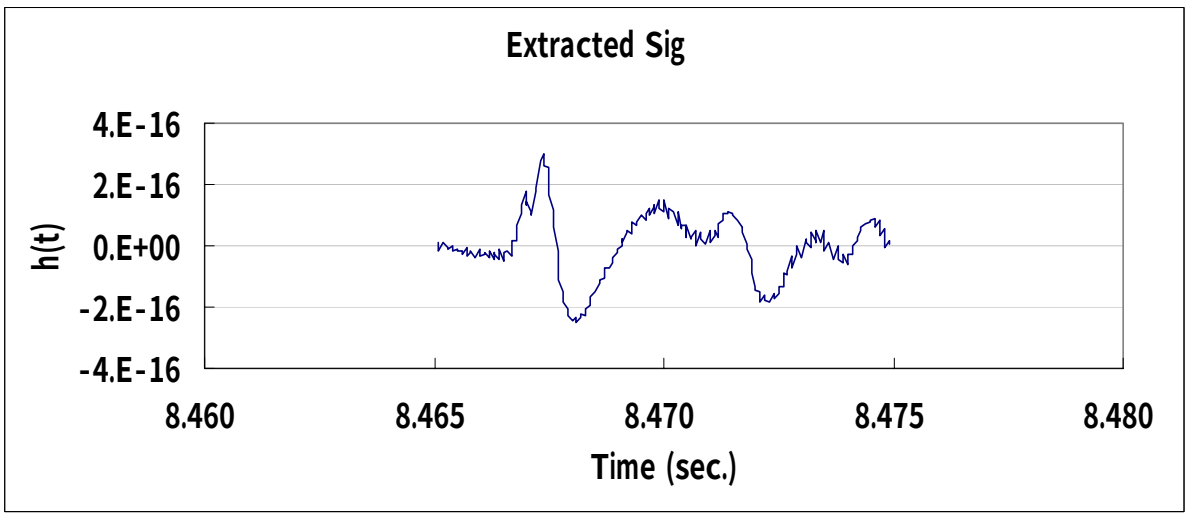
↓

Zoom in

↓

Curve Fit
&
Subtract the Curve





Similar or Not Similar !?

Summary

We could reconstruct from V(t) to h(t) by using IIR filter.

We could also produce from h(t) to V(t) by using IIR filter.

We could extract the hard ware injection signals.

Future

Do some analysis in Time Domain.