AutoNaut - Wave Encounter Frequency Estimation

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August 30, 2019

Offline Matlab implementation based on [1].

Implementation

Algorithm Steps

- Log heave acceleration from IMU (ADIS 16485)
- Filter data to remove high-frequency noise.
- Estimate wave amplitude as:

$$\hat{A} = \sqrt{2\chi}$$

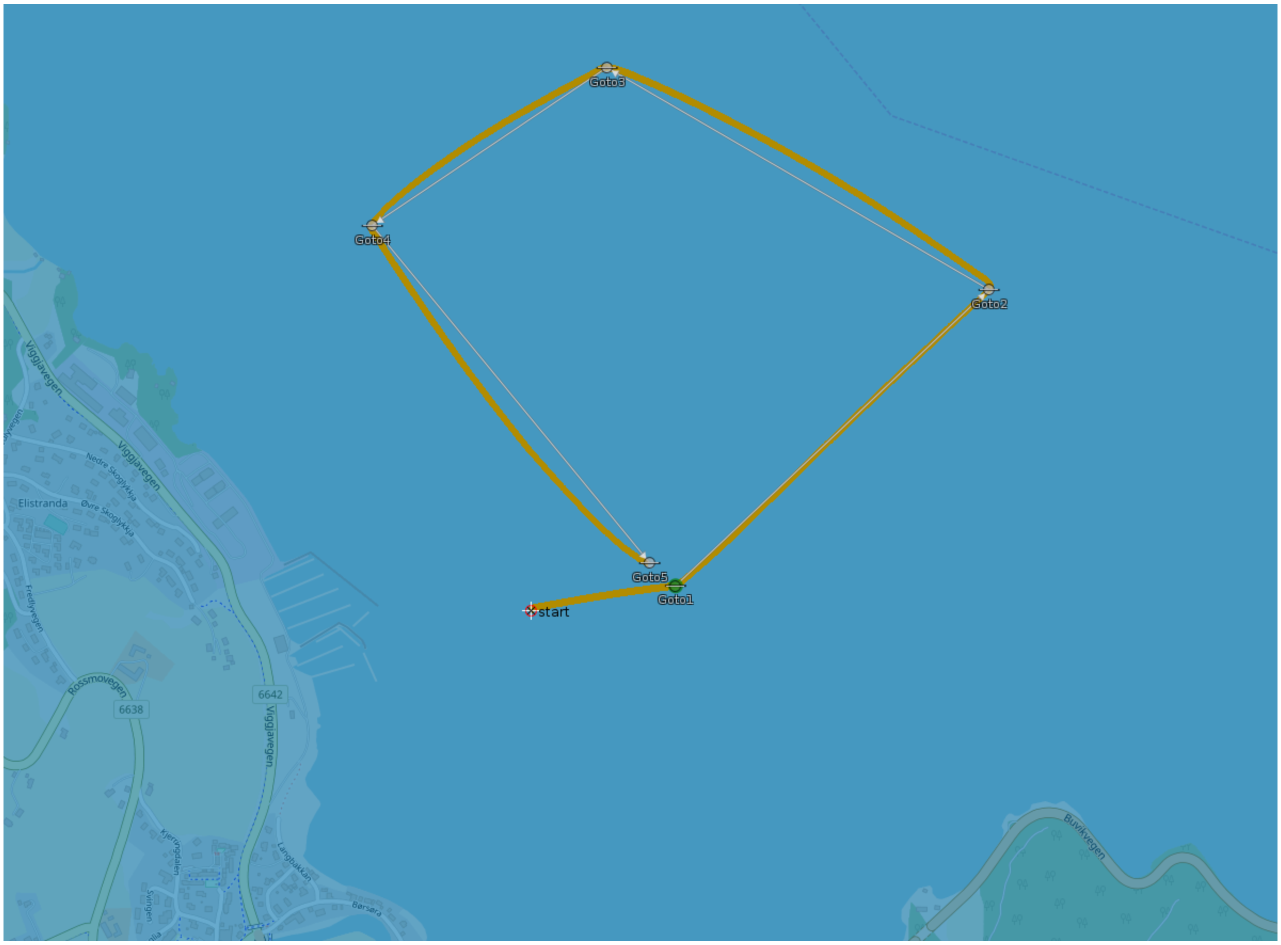
$$\text{where } \chi = \frac{1}{Ts+1} y^2$$

$$\text{and } y^2 = \frac{A^2}{2}(1 - cos(2\omega_e t + 2\epsilon))$$

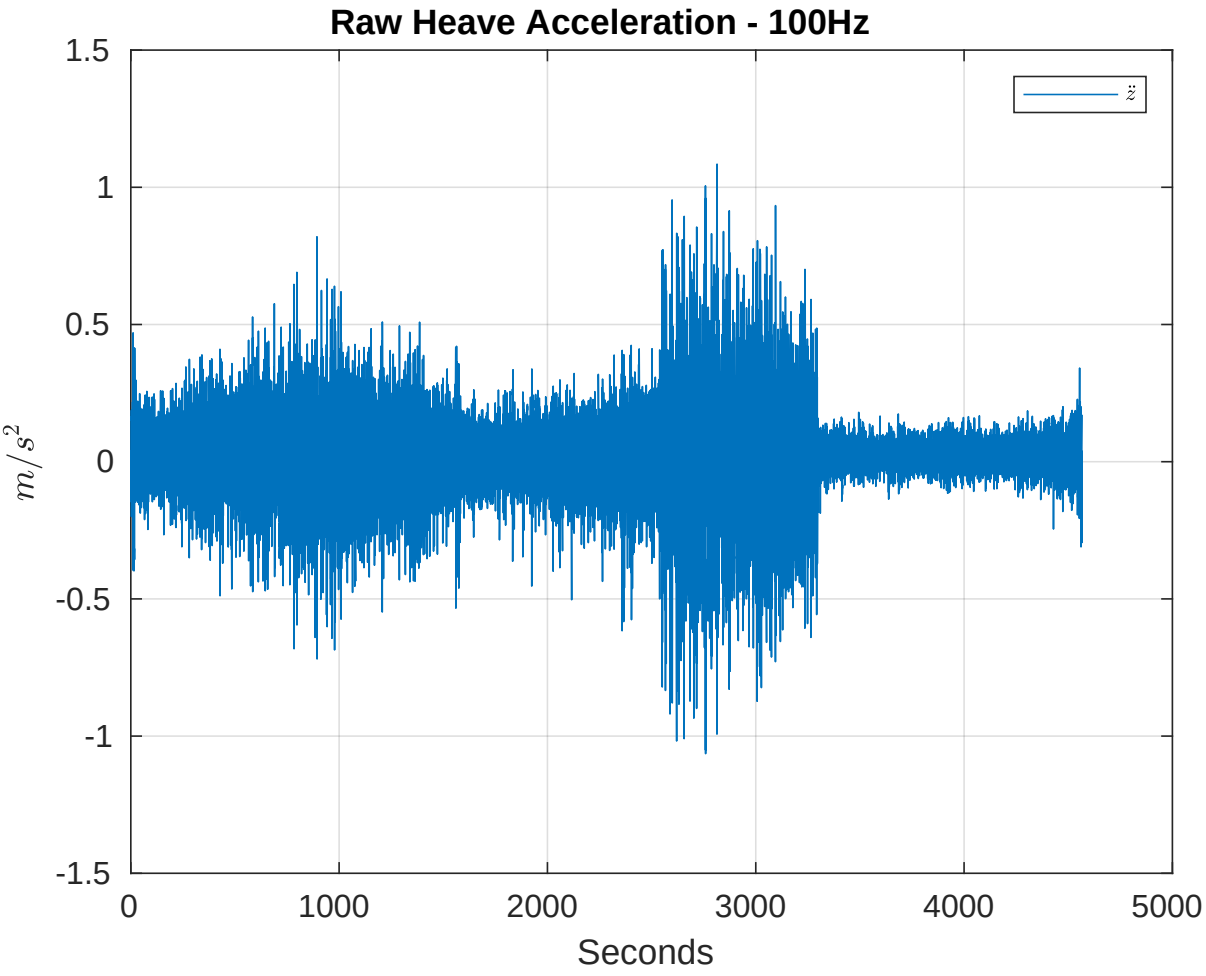
- Fixed-Gain Wave Encounter Frequency Estimator.
- Adaptive-Gain Wave Encounter Frequency Estimator.
- Comparison of both methods.
- Offline filtering of Rudder Servo commands with Notch Filter ($\omega_n = \hat{\omega}_e$) + Low-pass Filter ($\omega_{cut-off} = n\hat{\omega}_e$, with $n \geq 1$).

The encounter frequency is estimated for each waypoint transect. In the plots, red vertical dashed lines separate (in time) the 5 different phases of the mission. The encounter frequency is estimated for the whole mission. Then I compute the average estimated encounter frequency ($\hat{\omega}_{e-mean}$) for each GoTo and use that to filter the corresponding Servo Angles.

Mission

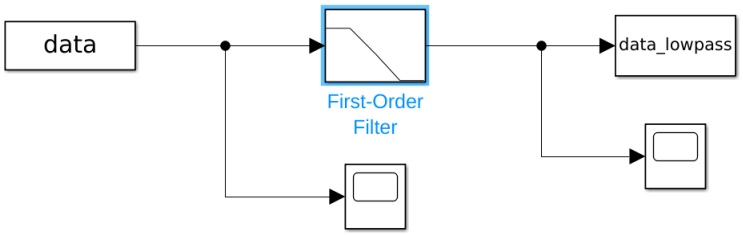

Goto3
Goto4
Goto2
Goto5
Goto1
start
Vigglavegen
Elistranda
Rossmovegen
6642
6638
Buvikvegen

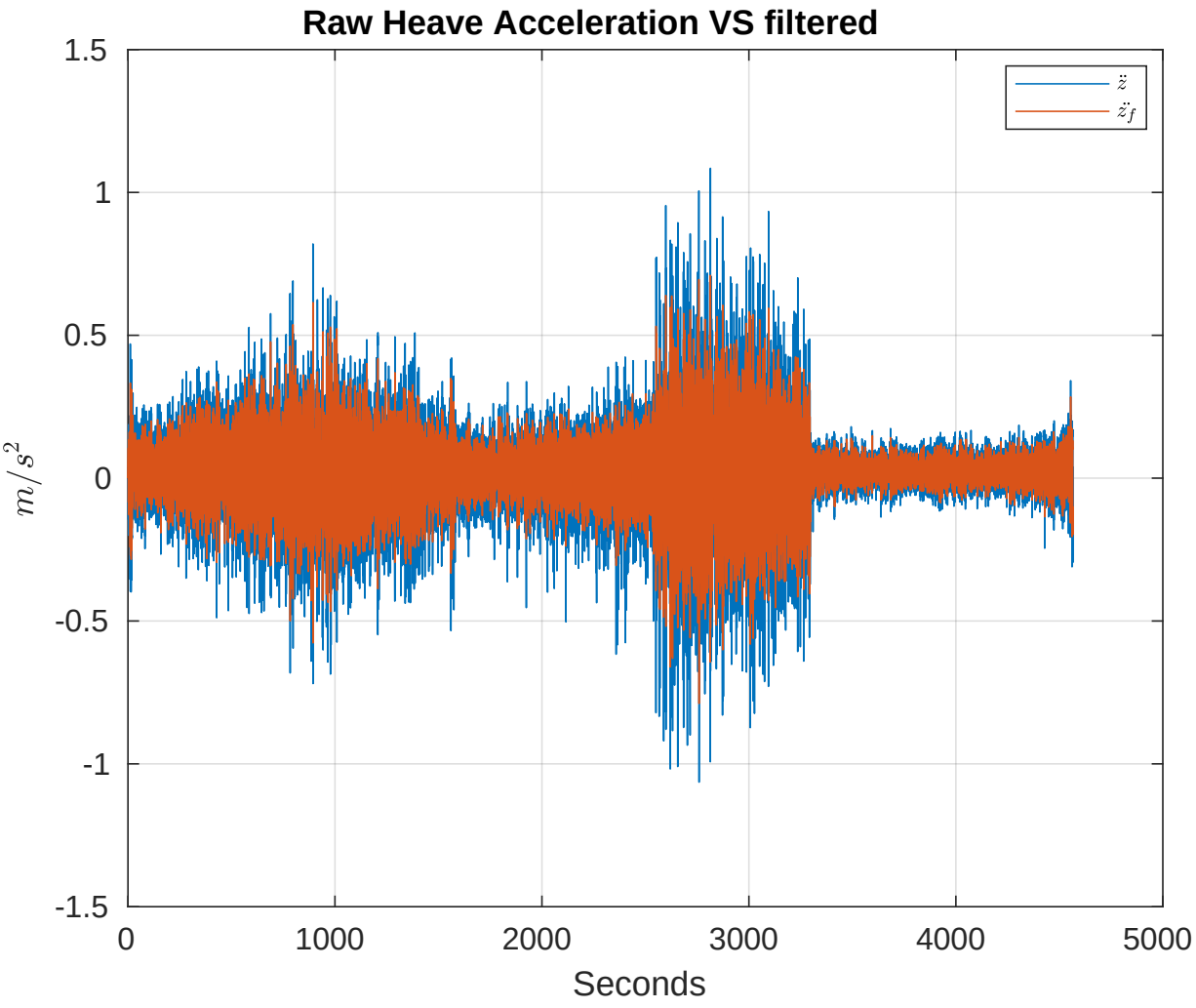
Log IMU heave acceleration

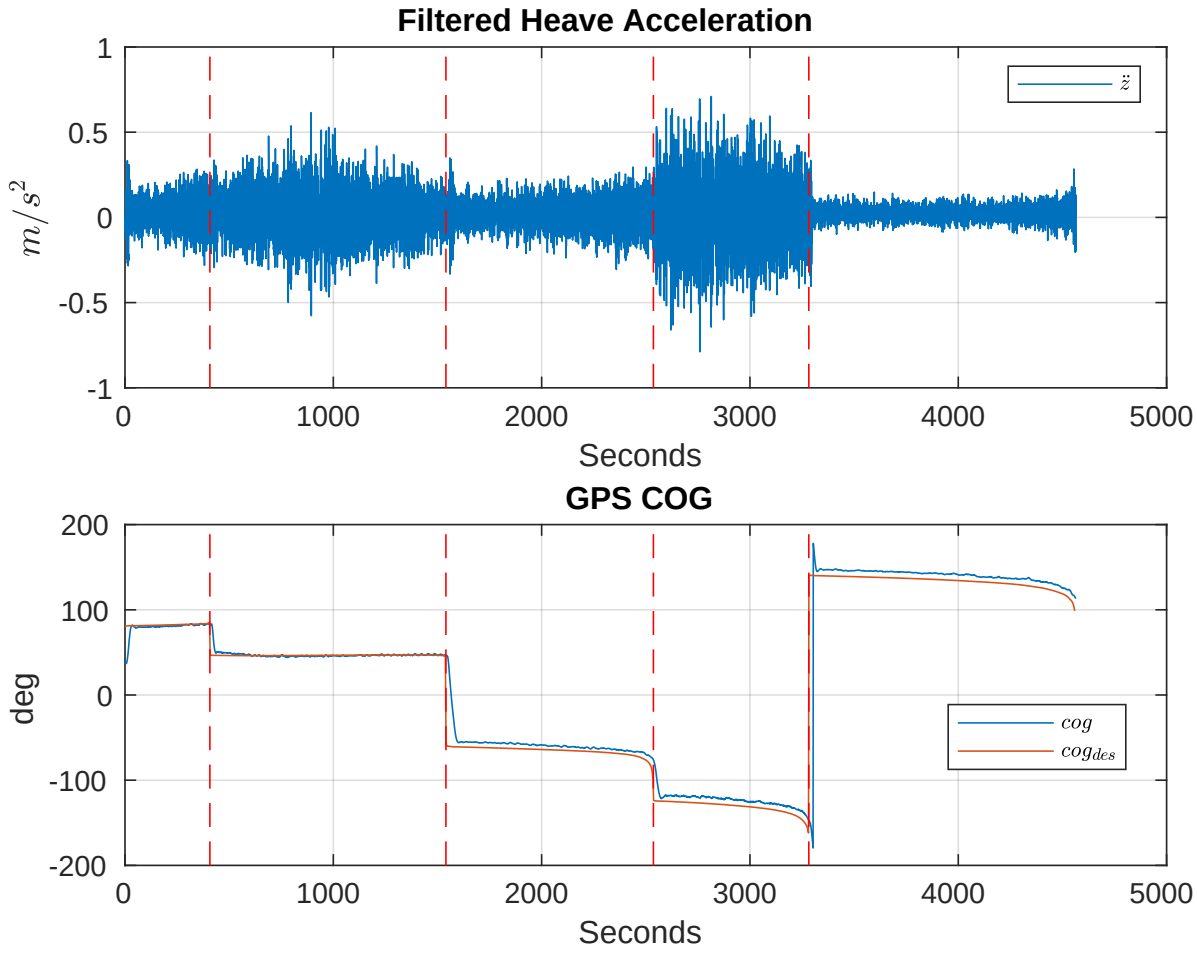


Filter data to remove high-frequency noise

Low-pass filter characteristics:
$T_s = 0.1$

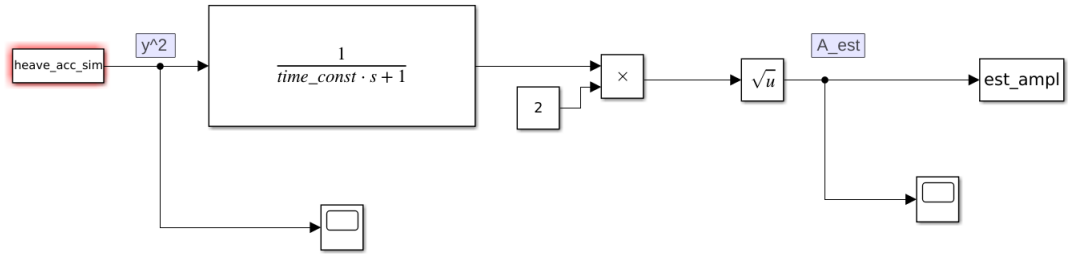


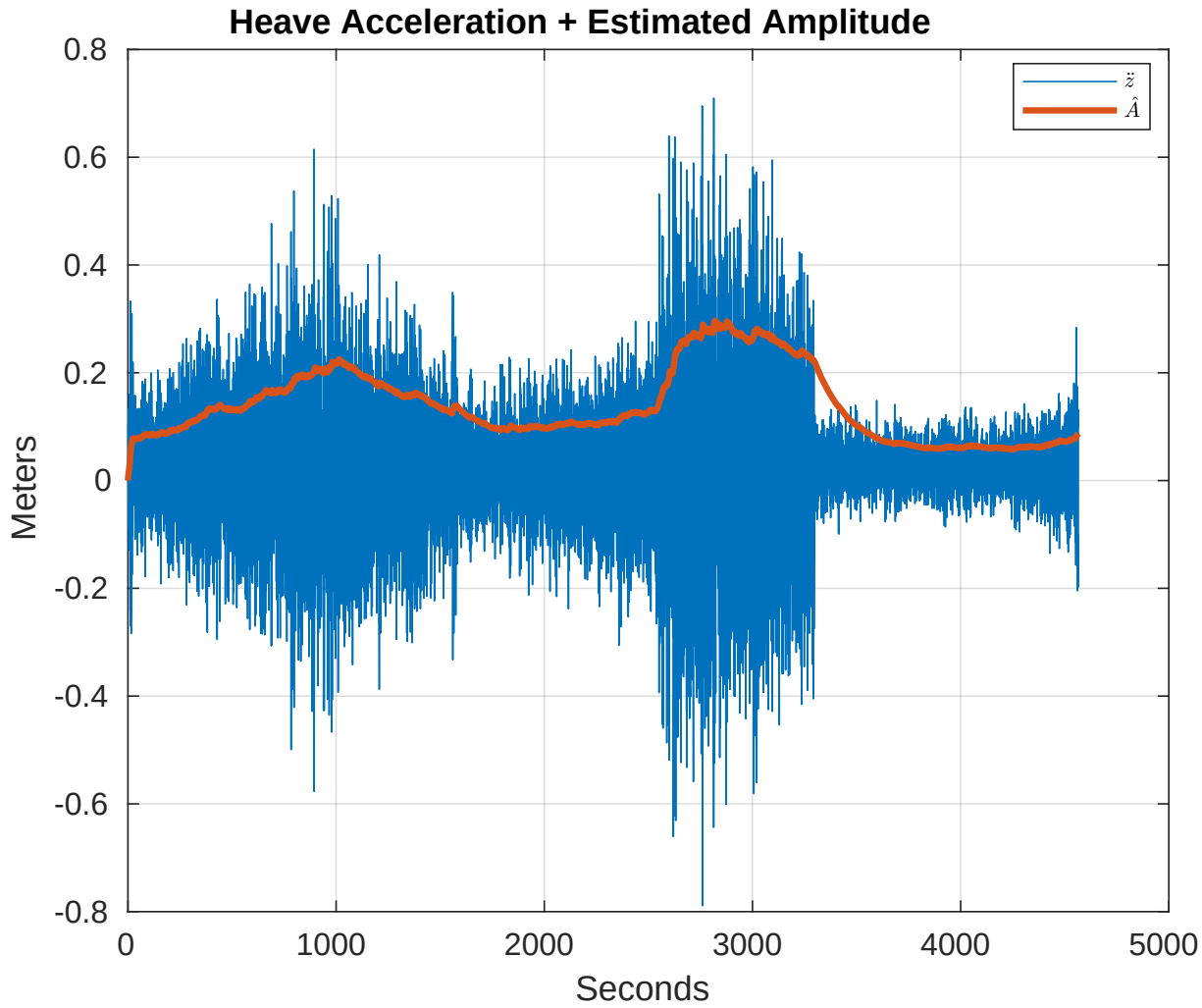



Filtered Heave Acceleration
m/s^2
1
0.5
0
-0.5
-1
0
1000
2000
3000
4000
5000
Seconds
$\ddot{z}$
GPS COG
deg
200
100
0
-100
-200
0
1000
2000
3000
4000
5000
Seconds
cog
cog_{des}

Wave Amplitude Estimation

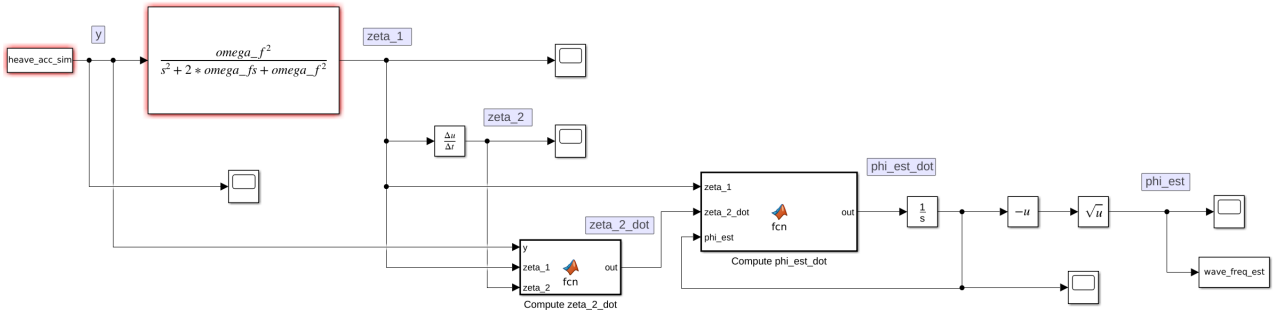
Low-pass filter characteristics for Amplitude Estimation:
$T_s = 10$ (*time_const* in block diagram).

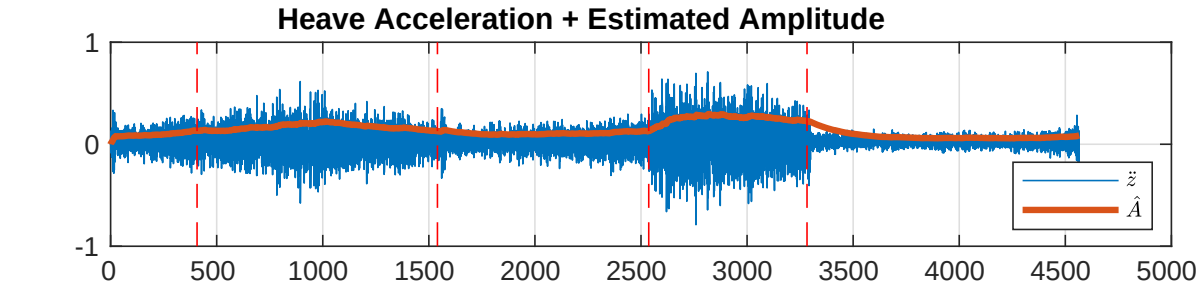


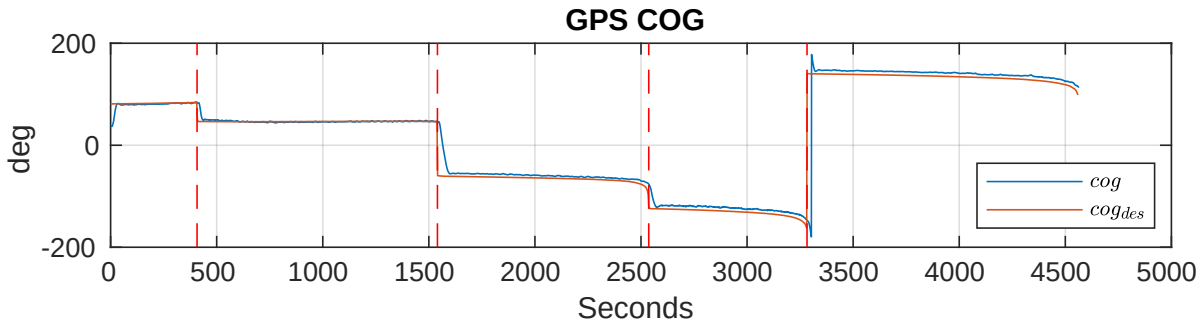


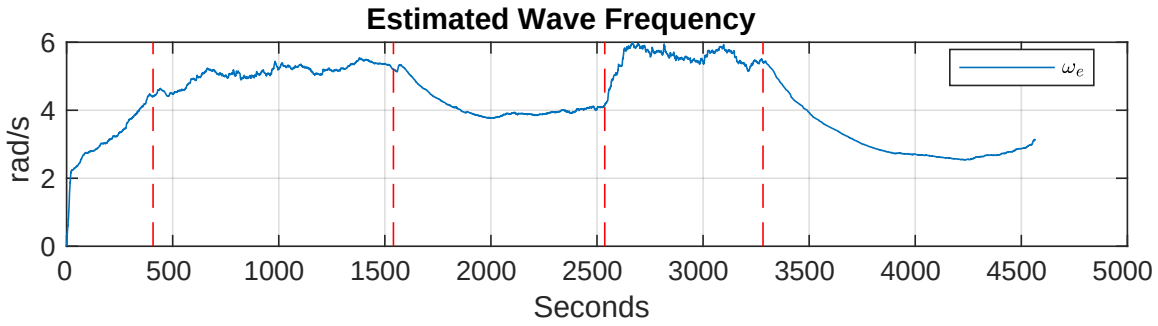
Fixed-Gain Wave Encounter Frequency Estimator

Estimator Parameters:
$\omega_f = 5$ ($omega\_f$ in block diagram)
$gain = 2.5$



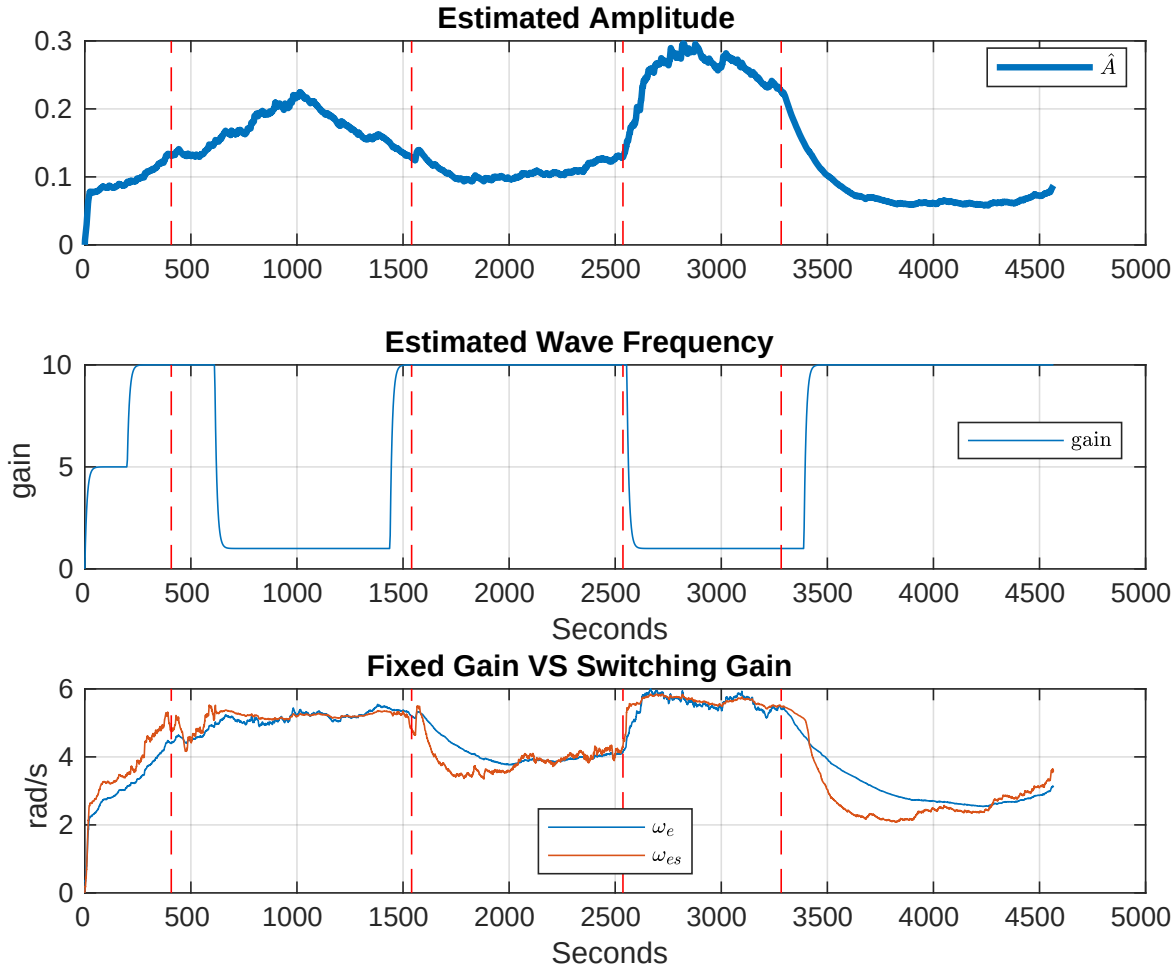


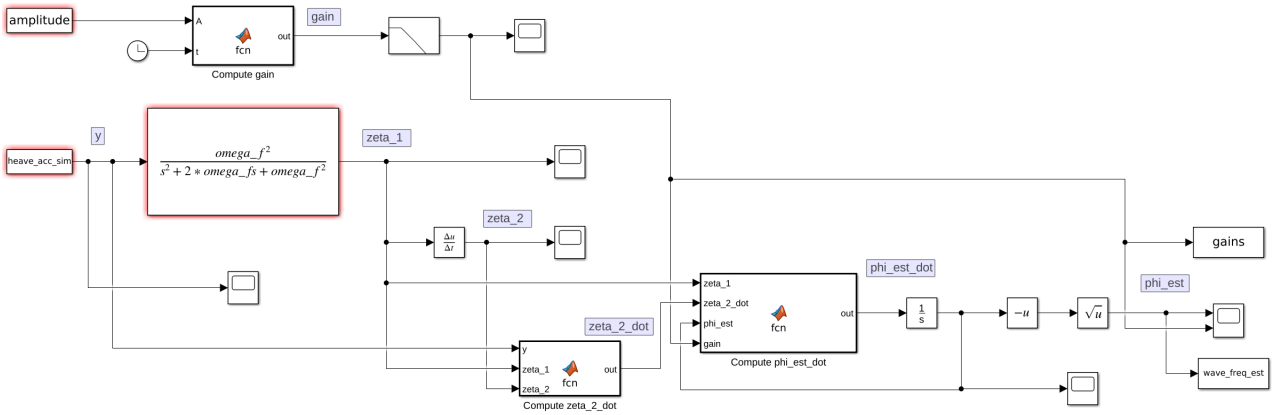




Adaptive-Gain Wave Encounter Frequency Estimator

Estimator Parameters:
$\omega_f = 5$ ($omega\_f$ in block diagram)
$T_f = 0.05$, switching time constant
$A_{switch} = 0.15$, switching heave amplitude (m)
$t_{init} = 200$, time period for initial gain ($gain_{init}$)
$gain_{init} = 5$
$gain_{min} = 1$
$gain_{max} = 10$



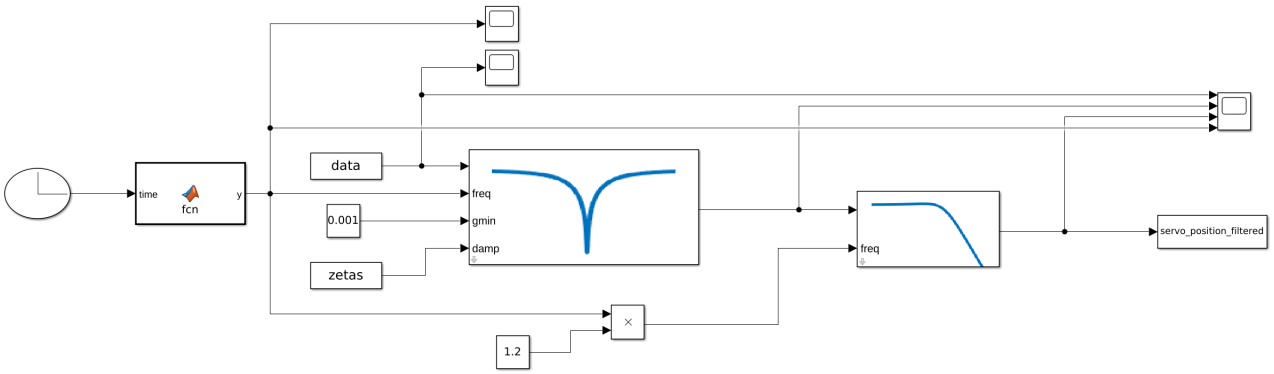


Filter Rudder Angle based on estimated wave encounter frequency

Notch Filter

$$N(s) = \frac{s^2+2G\zeta\omega_n s+\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \text{ with}$$

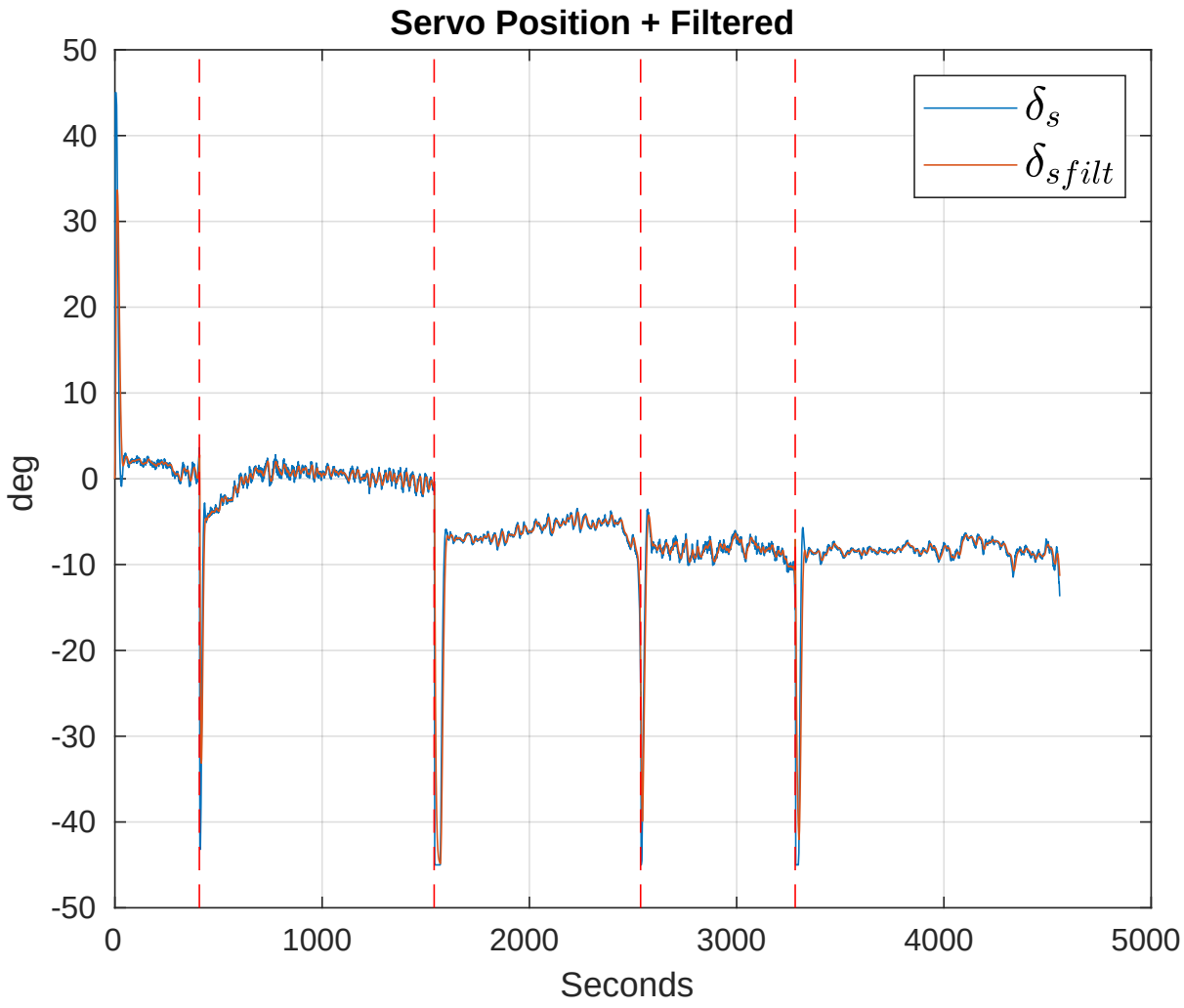
- $G = 0.001$, gain at notch frequency.
- $\zeta = 10$, damping ration of filter poles.
- $\omega_n = \hat{\omega}_e$, estimated encounter frequency.



1-st Order Low-pass Filter

$$LP(s) = \frac{\omega_{cut-off}}{s+\omega_{cut-off}} \text{ with}$$

$\omega_{cut-off} = 1.5\hat{\omega}_e$


Servo Position + Filtered
50
40
30
20
10
0
-10
-20
-30
-40
-50
deg
0
1000
2000
3000
4000
5000
Seconds
δ_s
δ_{sfilt}

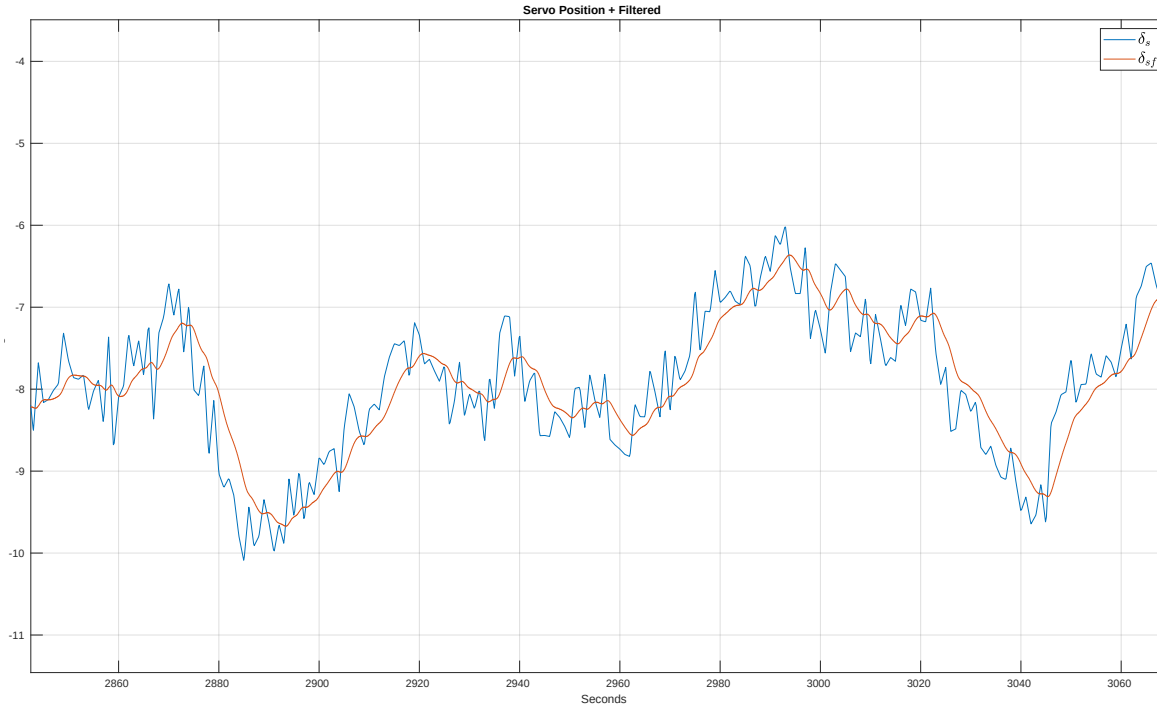


Figure 1: A zoom of the previous plot.

1 Response Analysis of LP and Notch filter

Here the response analysis of the filters used to smooth the rudder angle.

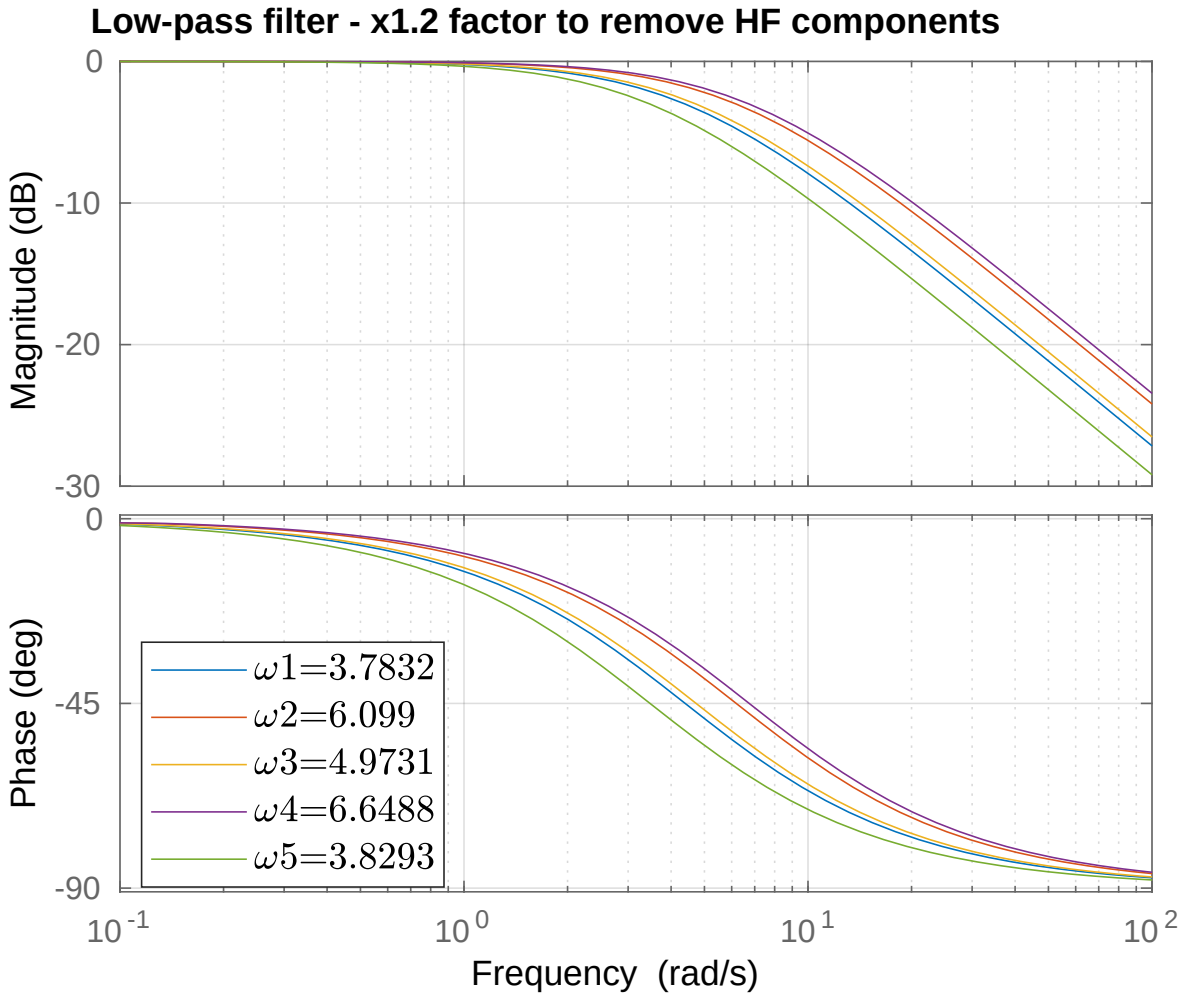


Figure 2:

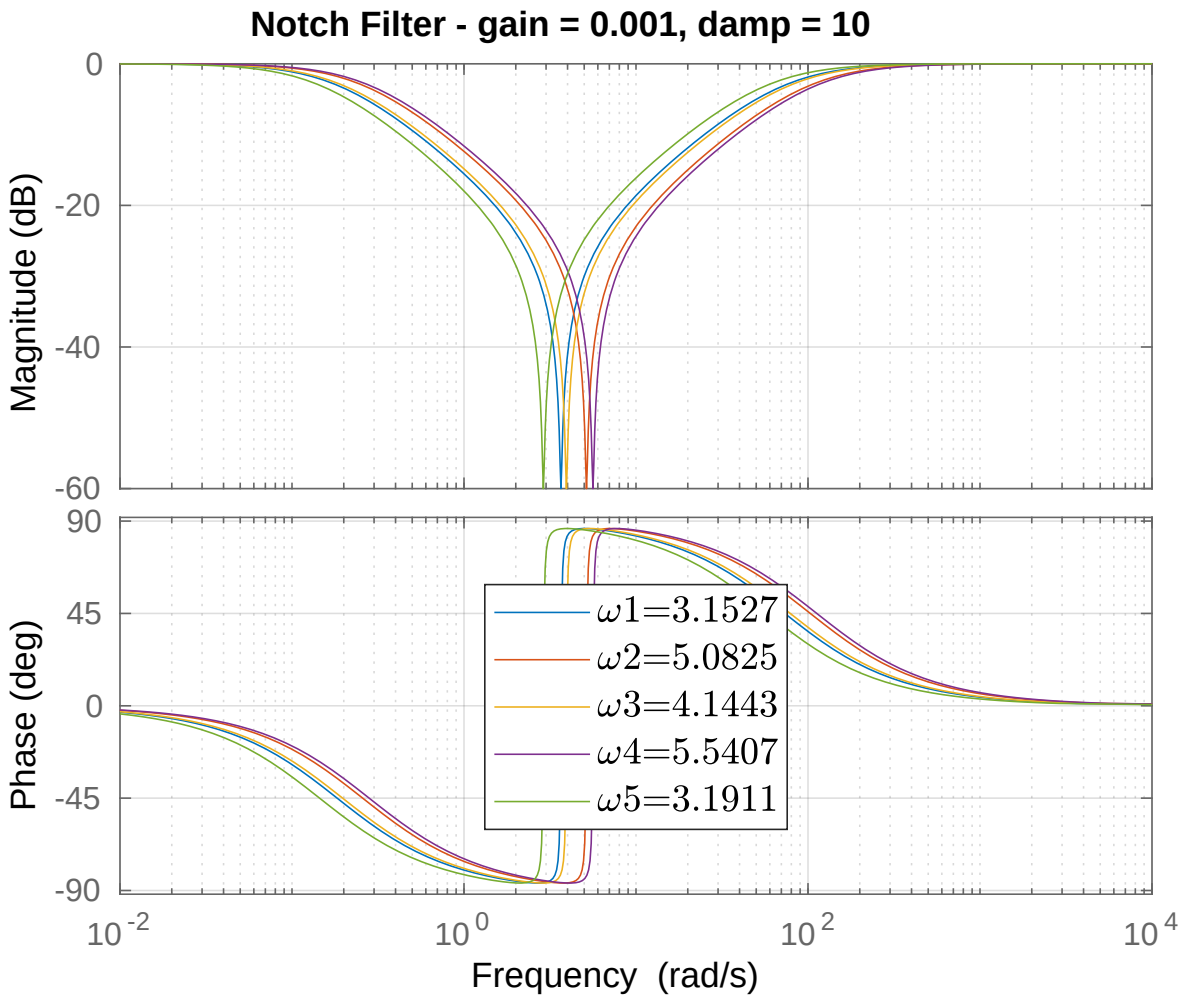

Notch Filter - gain = 0.001, damp = 10
Magnitude (dB)
0
-20
-40
-60
Phase (deg)
90
45
0
-45
-90
$\omega 1$=3.1527
$\omega 2$=5.0825
$\omega 3$=4.1443
$\omega 4$=5.5407
$\omega 5$=3.1911
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency (rad/s)

Figure 3:

FFT vs Estimator

For the same trajectories, FFT and the estimation are compared.

Trajectory 1

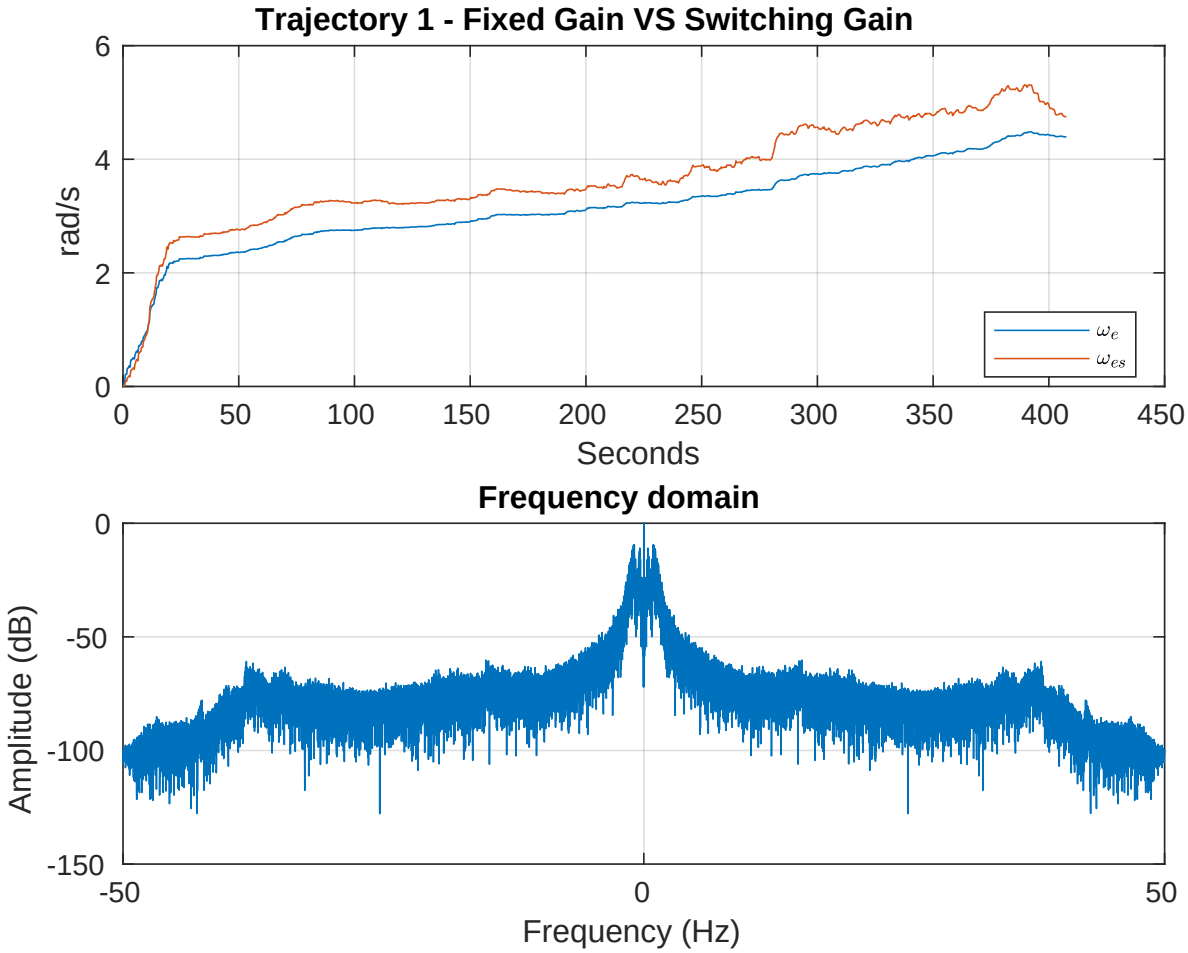


Figure 4: FFT peaks between: 0.5Hz = 2.51 rad/s and 0.9Hz = 5.6 rad/s

Trajectory 2

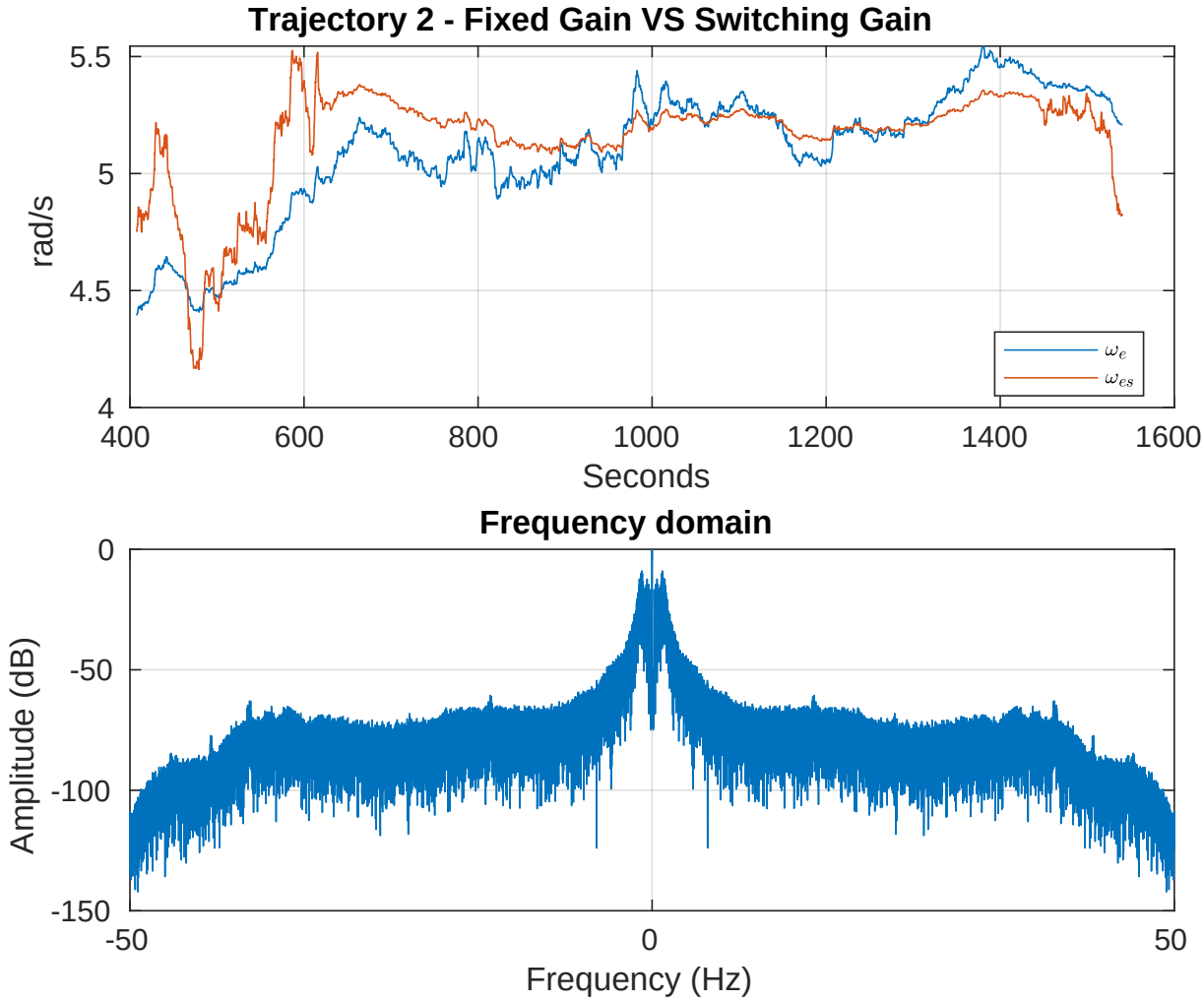


Figure 5: FFT peaks: around 1Hz = 2π

Trajectory 3

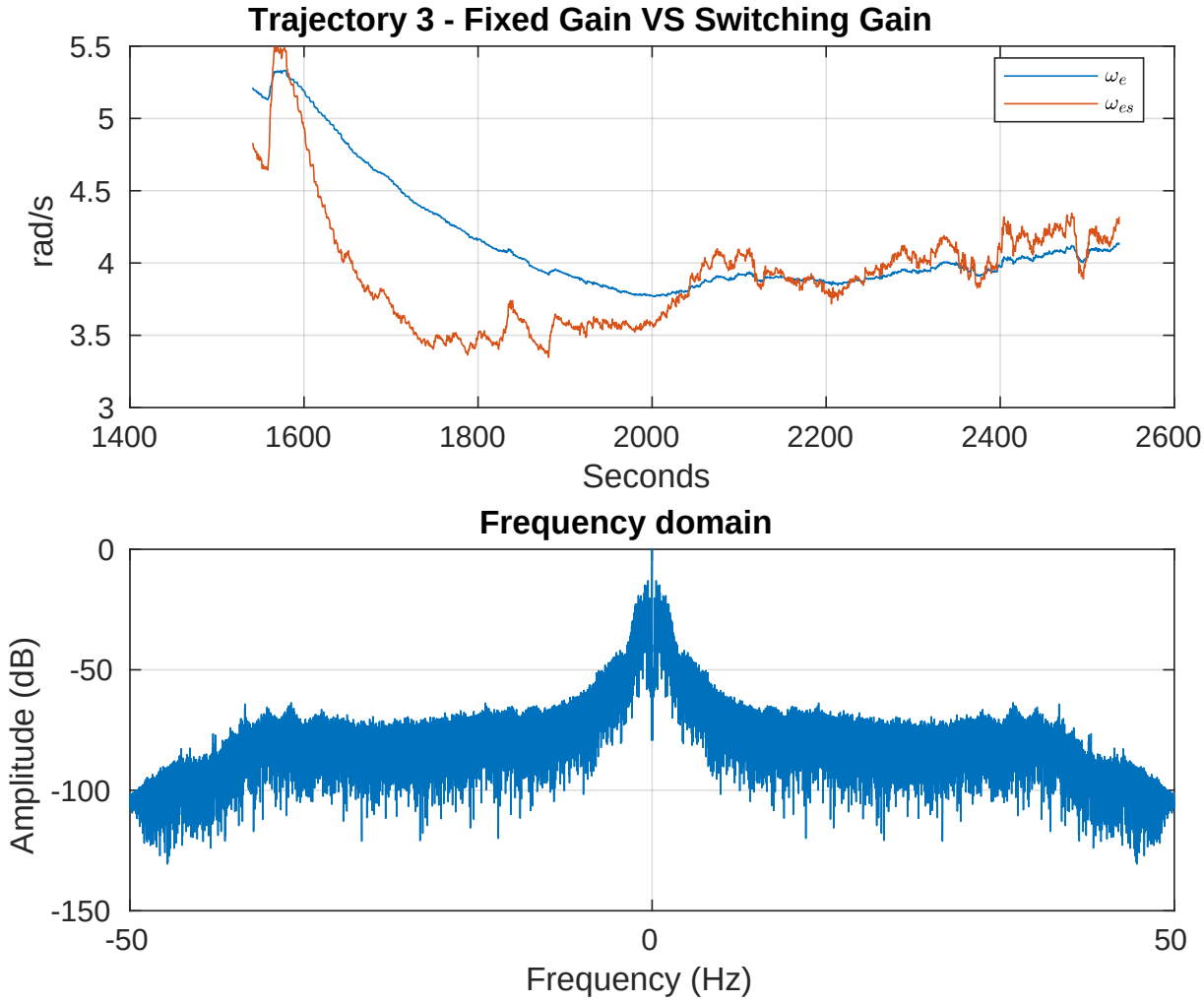


Figure 6: FFT peaks: around 0.39Hz = 2.45 rad/s

Trajectory 4

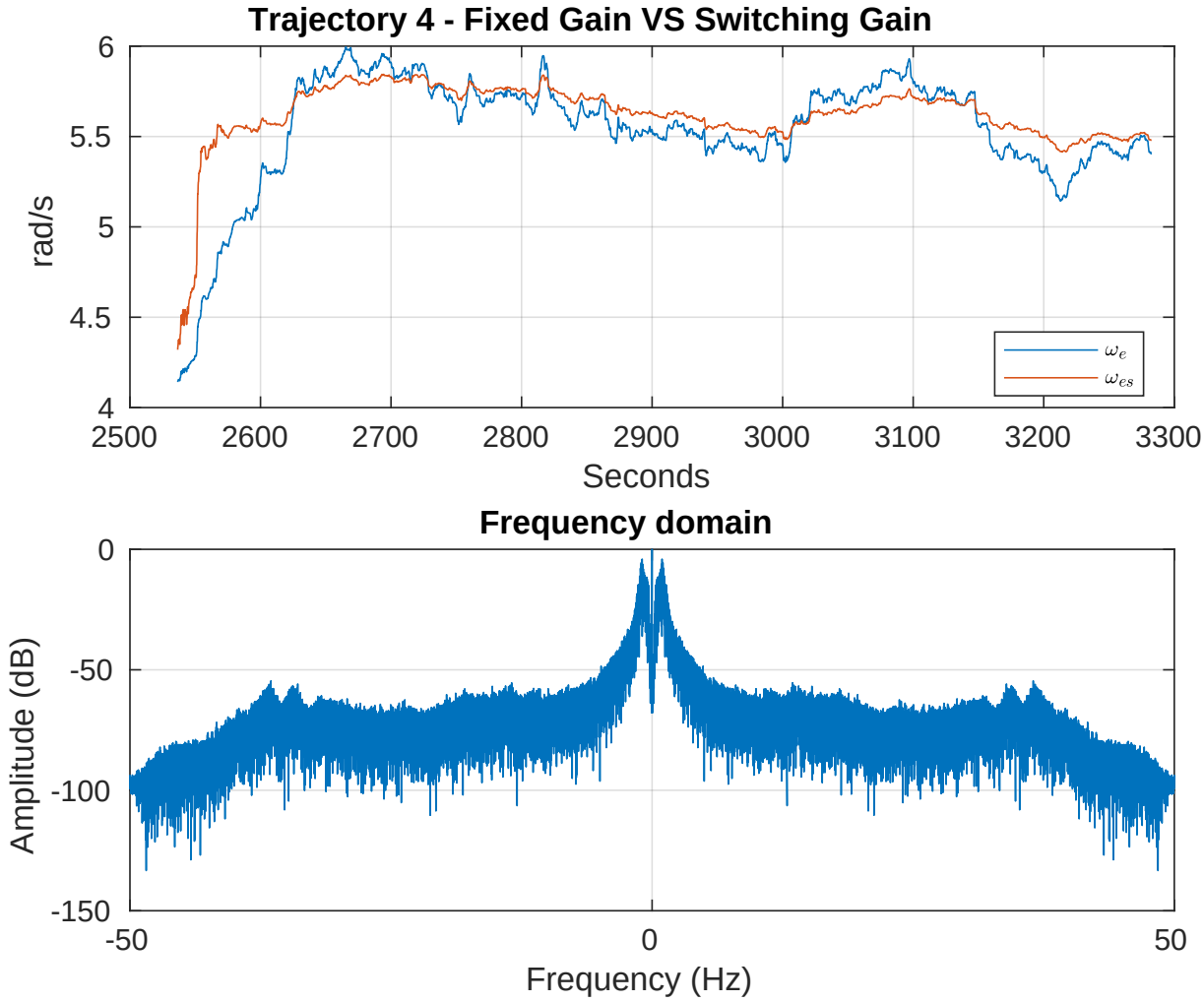


Figure 7: FFT peaks: around 0.95Hz = 5.96 rad/s

Trajectory 5

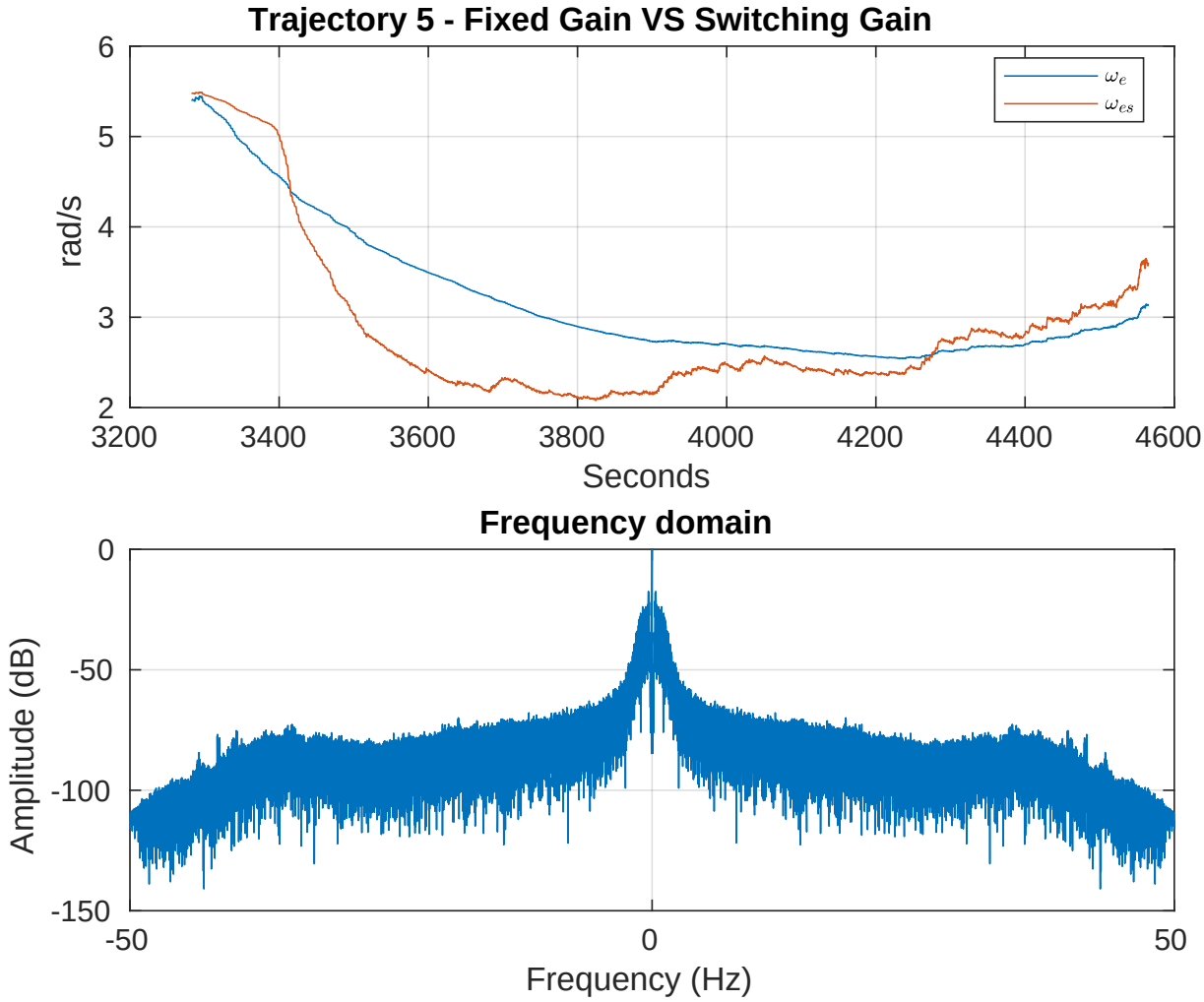


Figure 8: FFT peaks: around 0.355Hz = 2.23 rad/s

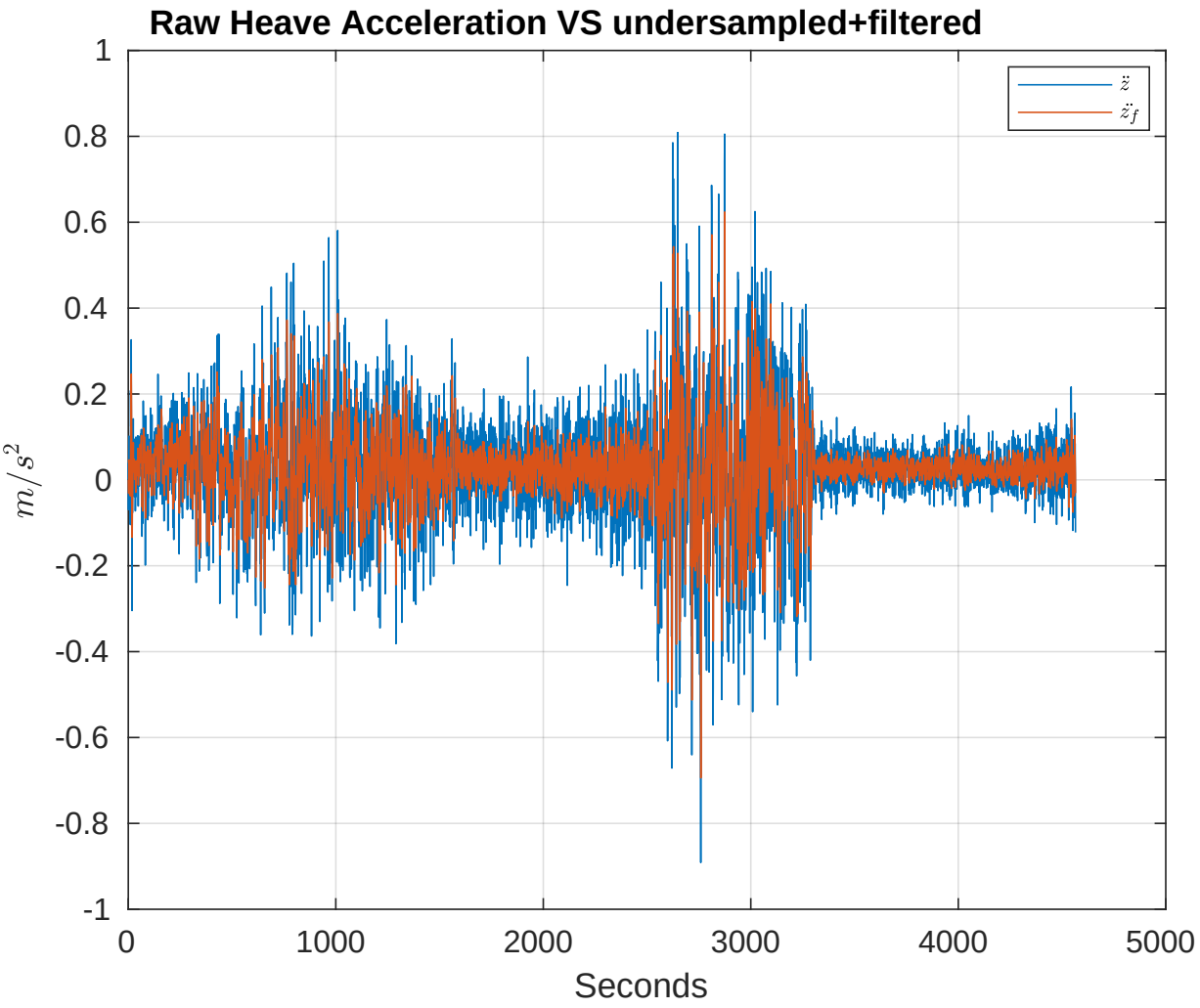
Variations

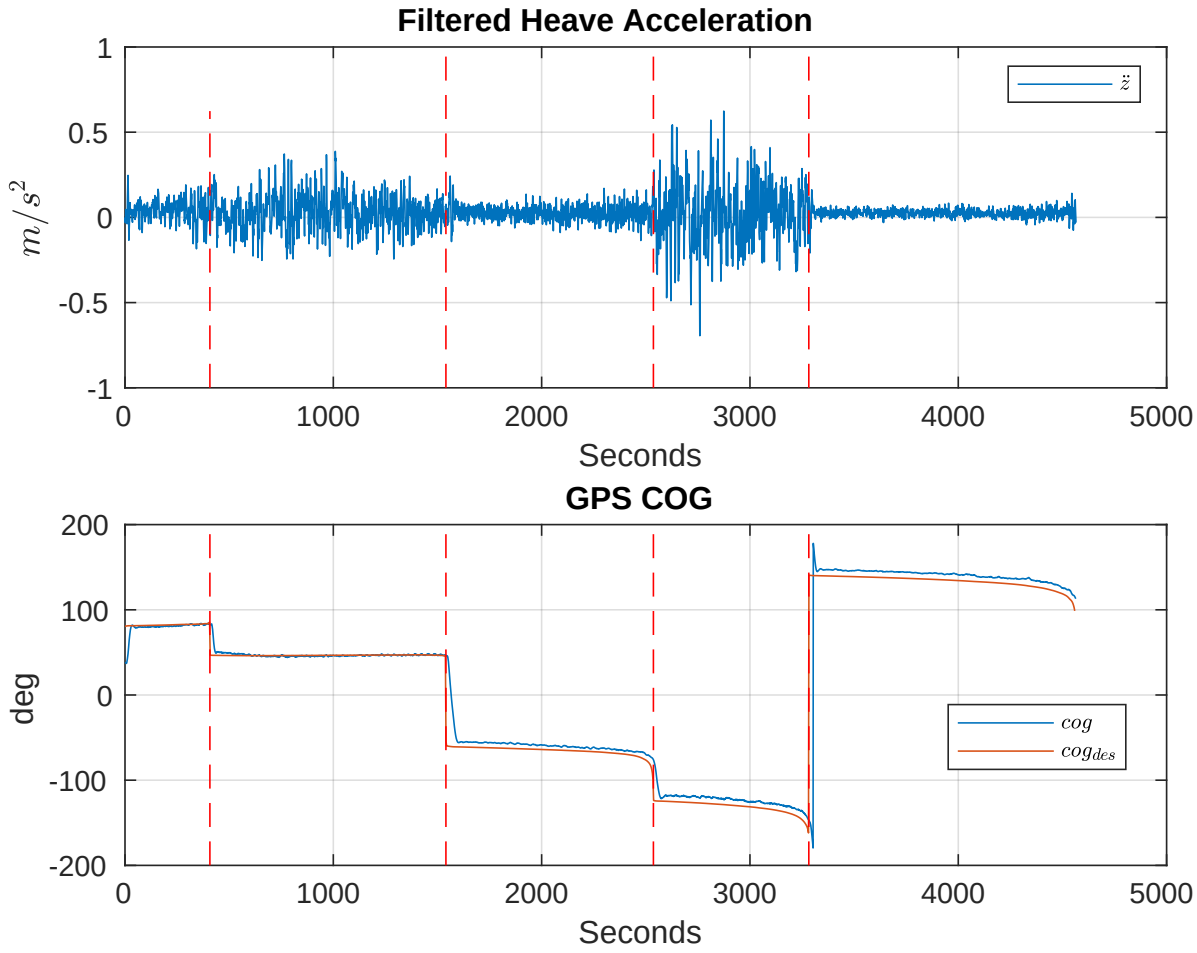
I have also tried to understand what happens if I had way less data. Say the IMU samples data at 1Hz/1s, how would the estimation be?

Then I re-sampled the original data at 1s.

Filter data to remove high-frequency noise

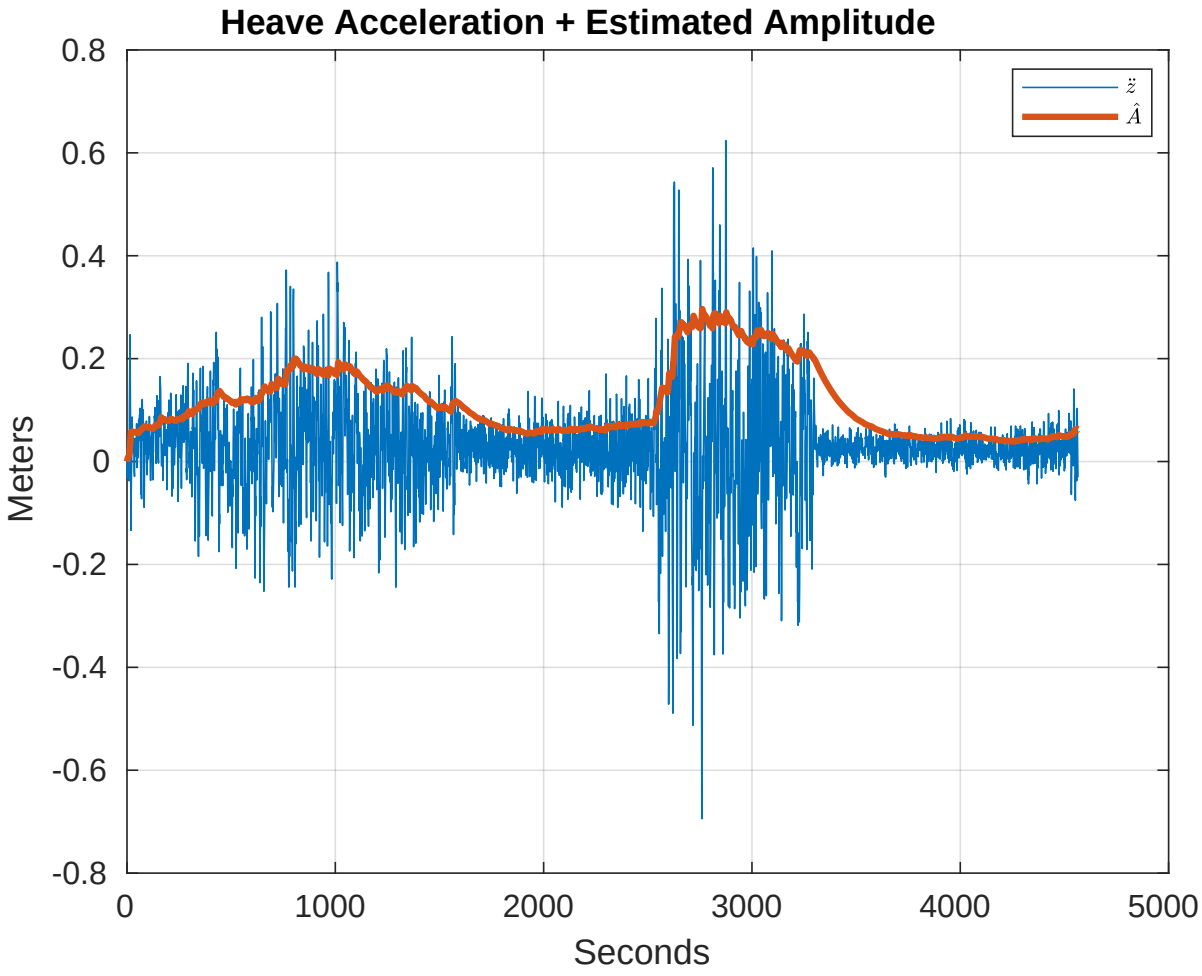
Low-pass filter characteristics:
$T_s = 1$




Filtered Heave Acceleration
m/s^2
$\ddot{z}$
Seconds
GPS COG
deg
cog
cog_{des}
Seconds

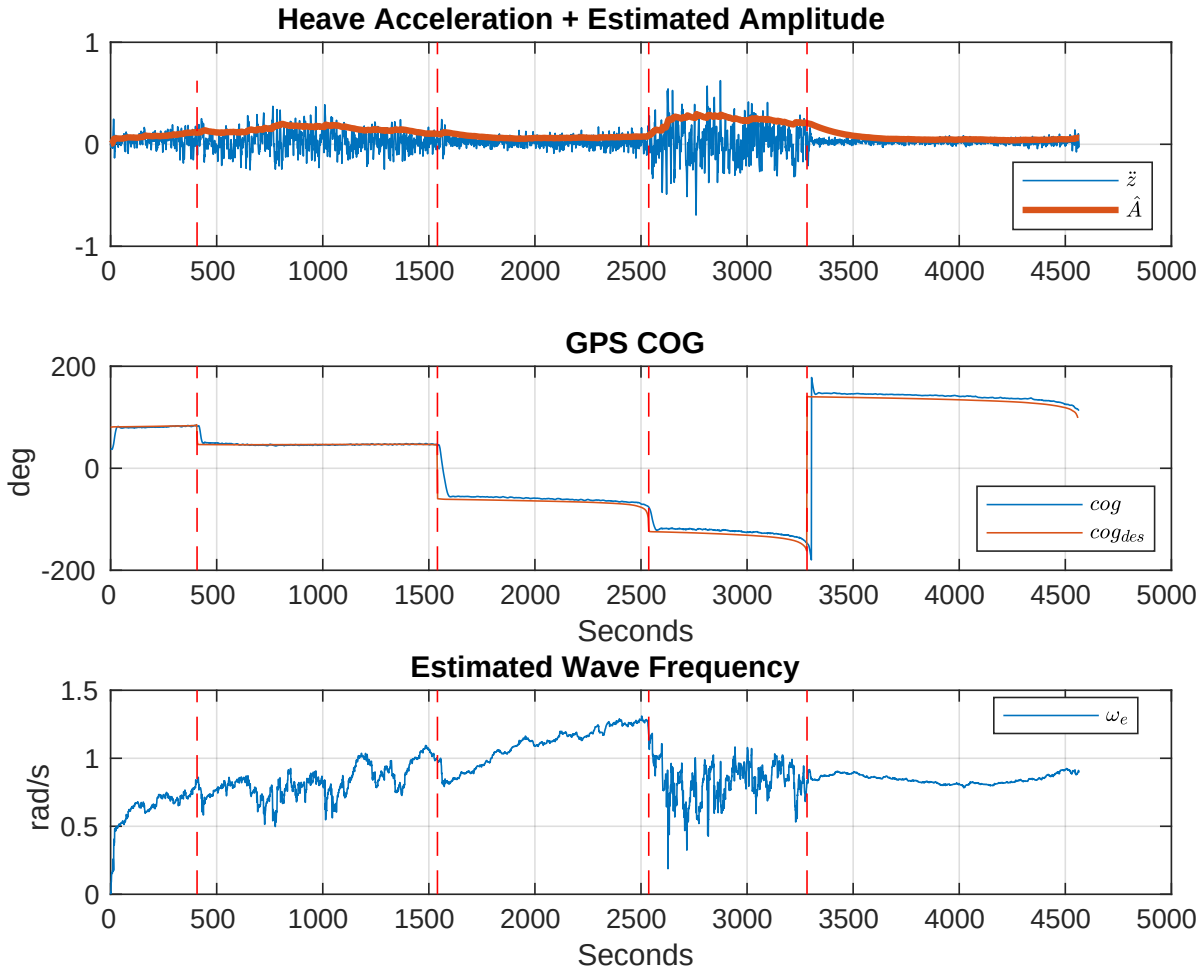
Wave Amplitude Estimation

Low-pass filter characteristics for Amplitude Estimation:
$T_s = 10$ (*time_const* in block diagram).



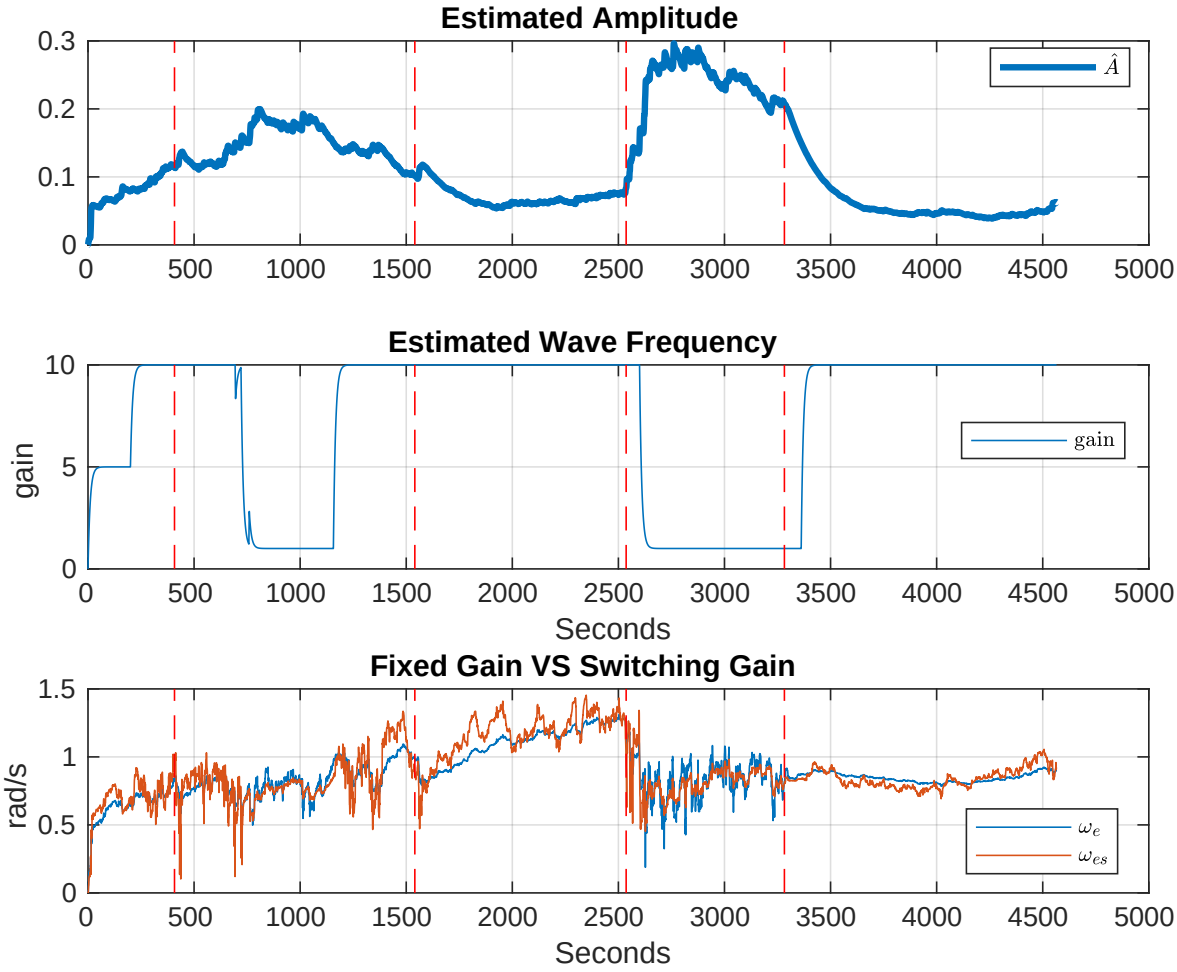
Fixed-Gain Wave Encounter Frequency Estimator

Estimator Parameters:
$\omega_f = 5$ ($omega\_f$ in block diagram)
$gain = 2.5$



Adaptive-Gain Wave Encounter Frequency Estimator

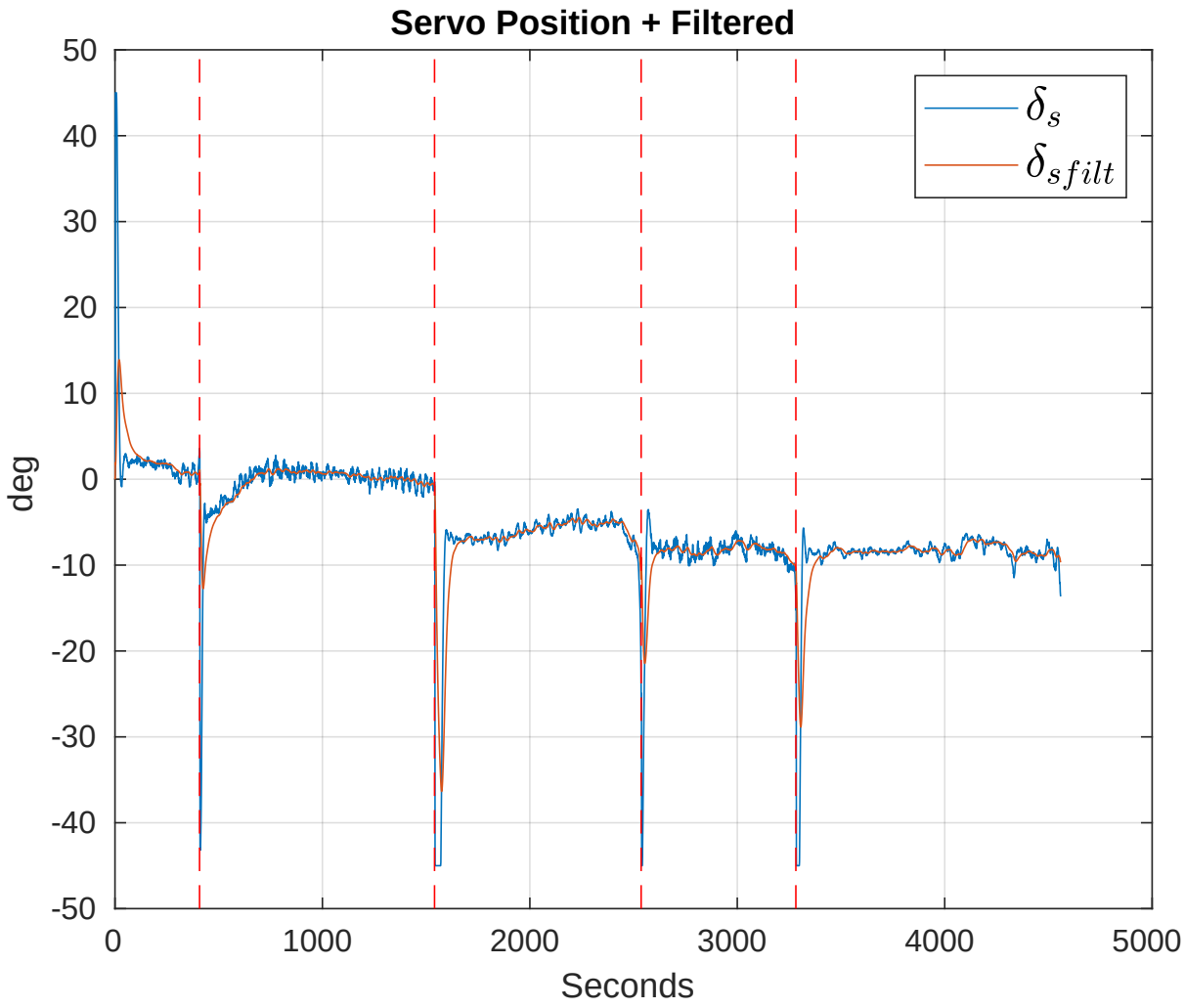
Estimator Parameters:
$\omega_f = 5$ ($omega\_f$ in block diagram)
$T_f = 0.05$, switching time constant
$A_{switch} = 0.15$, switching heave amplitude (m)
$t_{init} = 200$, time period for initial gain ($gain_{init}$)
$gain_{init} = 5$
$gain_{min} = 1$
$gain_{max} = 10$



Parameters need to be tuned.

Filter Rudder Angle based on estimated wave encounter frequency

Notch Filter and LP filter with same parameters as before.



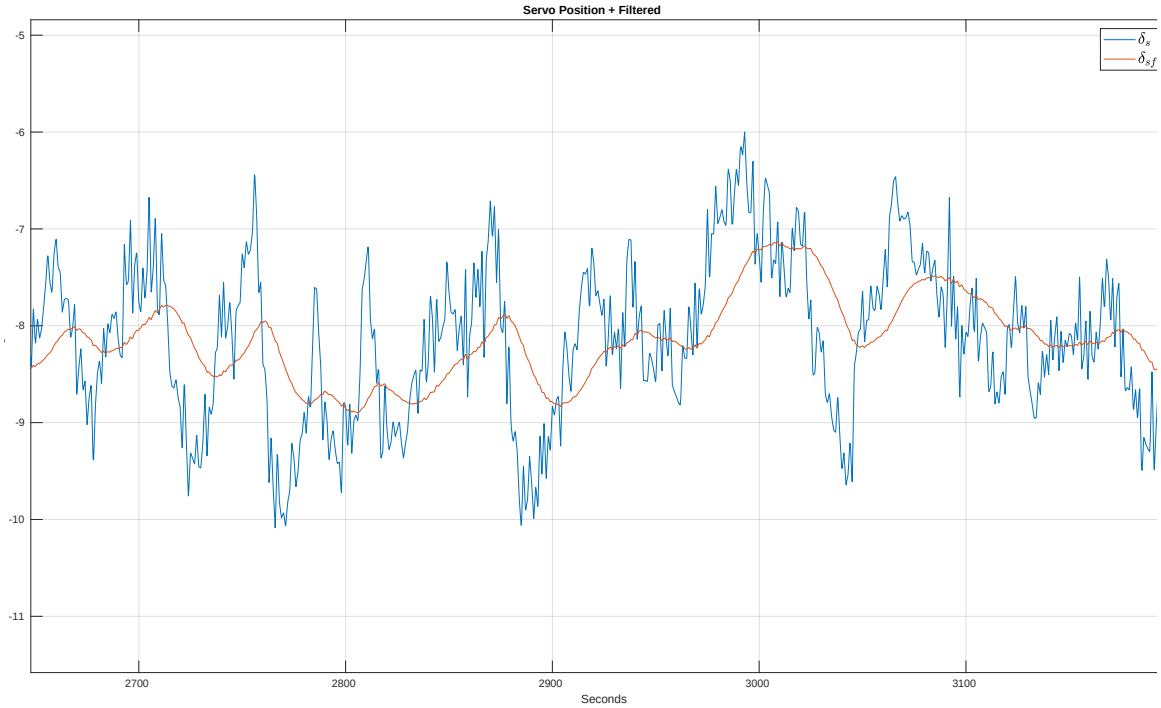


Figure 9: A zoom of the previous plot.

References

[1] Belleter, D. J., R. Galeazzi and T. I. Fossen., *Experimenal Verification of a Globally Exponentially Stable Nonlinear Wave Encounter Frequency Estimator*. Ocean Engineering Elsevier, Volume 97, 15 March 2015, pp. 4856. doi:10.1016/j.oceaneng.2014.12.030.