Seismic Developments at LASTI

LIGO-G050184-00-Z

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OUTLI NE

1) Geophone tilt correction
    - HAM
    - BSC (non-linear bending??)

2) BSC Stack Characterization
    - Resonant Gain
    - Noise Study

3) Modal Control/Adaptive Filters

4) Estimators

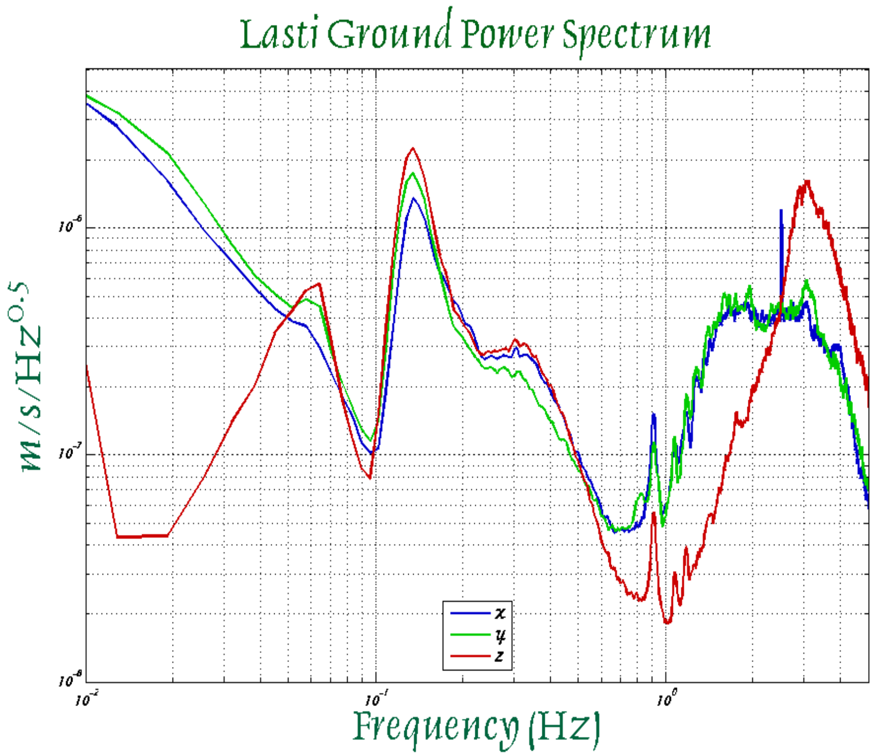
5) HAM Plant Modifications

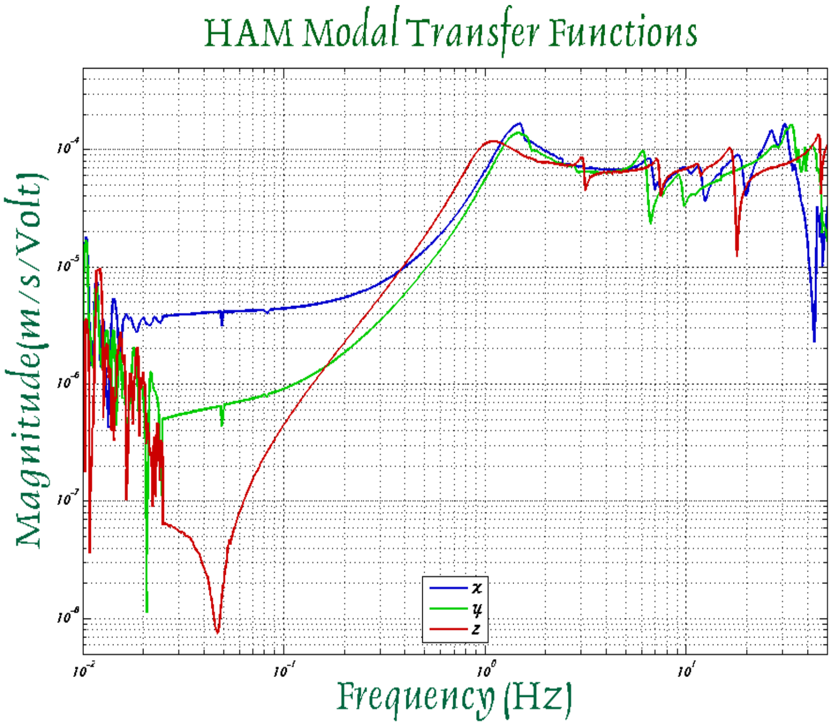
6) System identification noise subtraction
    - Triple
    - BSC Noise Measurements

7) Future Plans

Tilt Correction

The source of tilt can be divided into two categories, inherent and induced.





Geophone Tilt Subtraction

Tilt transfer function of an inertial sensor

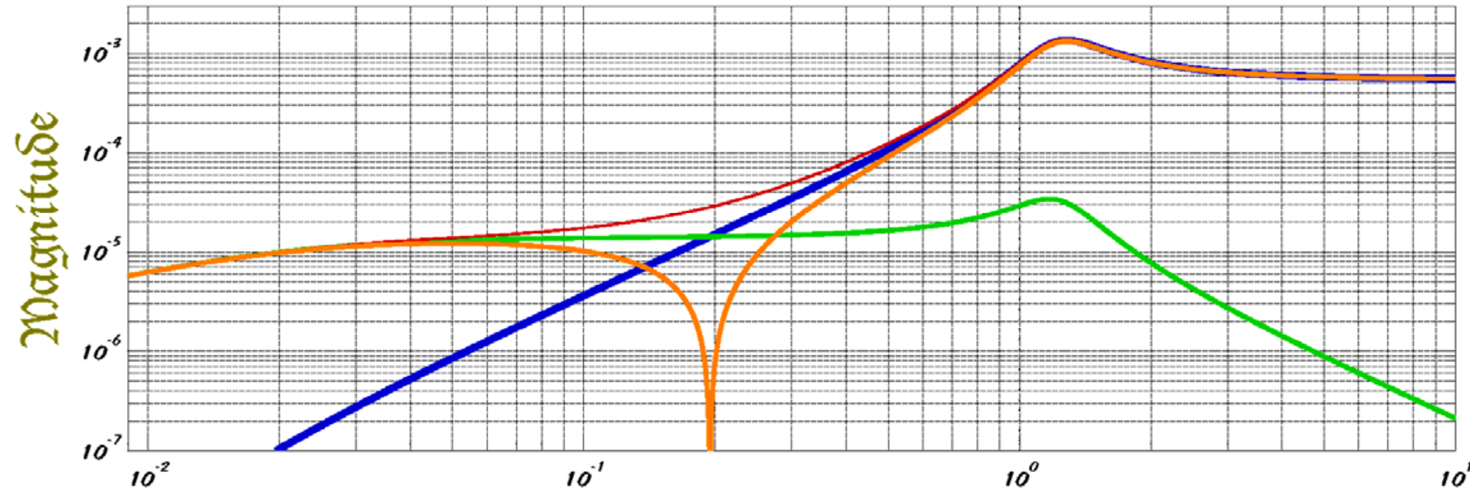
$$\frac{Output}{\theta} = \frac{Sensor\,\mathrm{Re}\,sponce}{f^2}$$

Assumptions

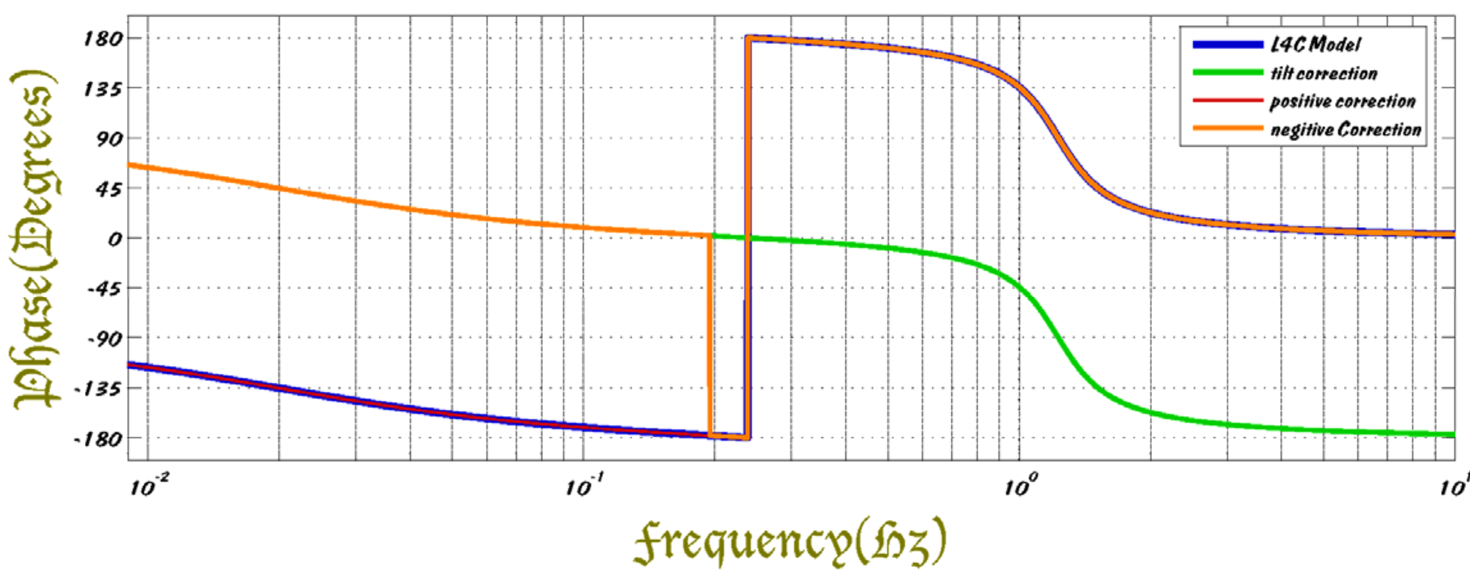
1) The plant is linear
2) The induced angle is proportional to the displacement

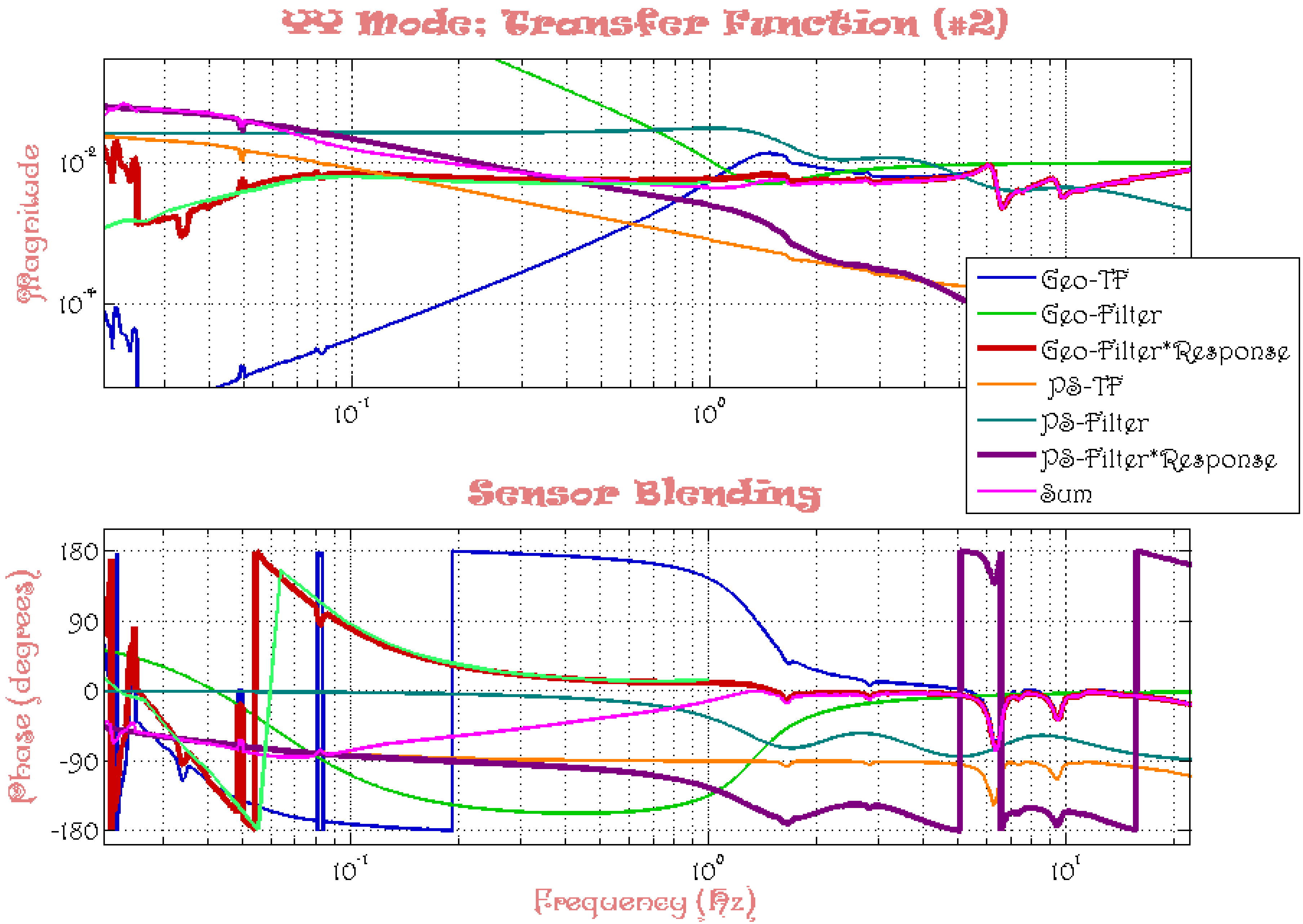
We can then predict the tilt-induced signal from the geophones

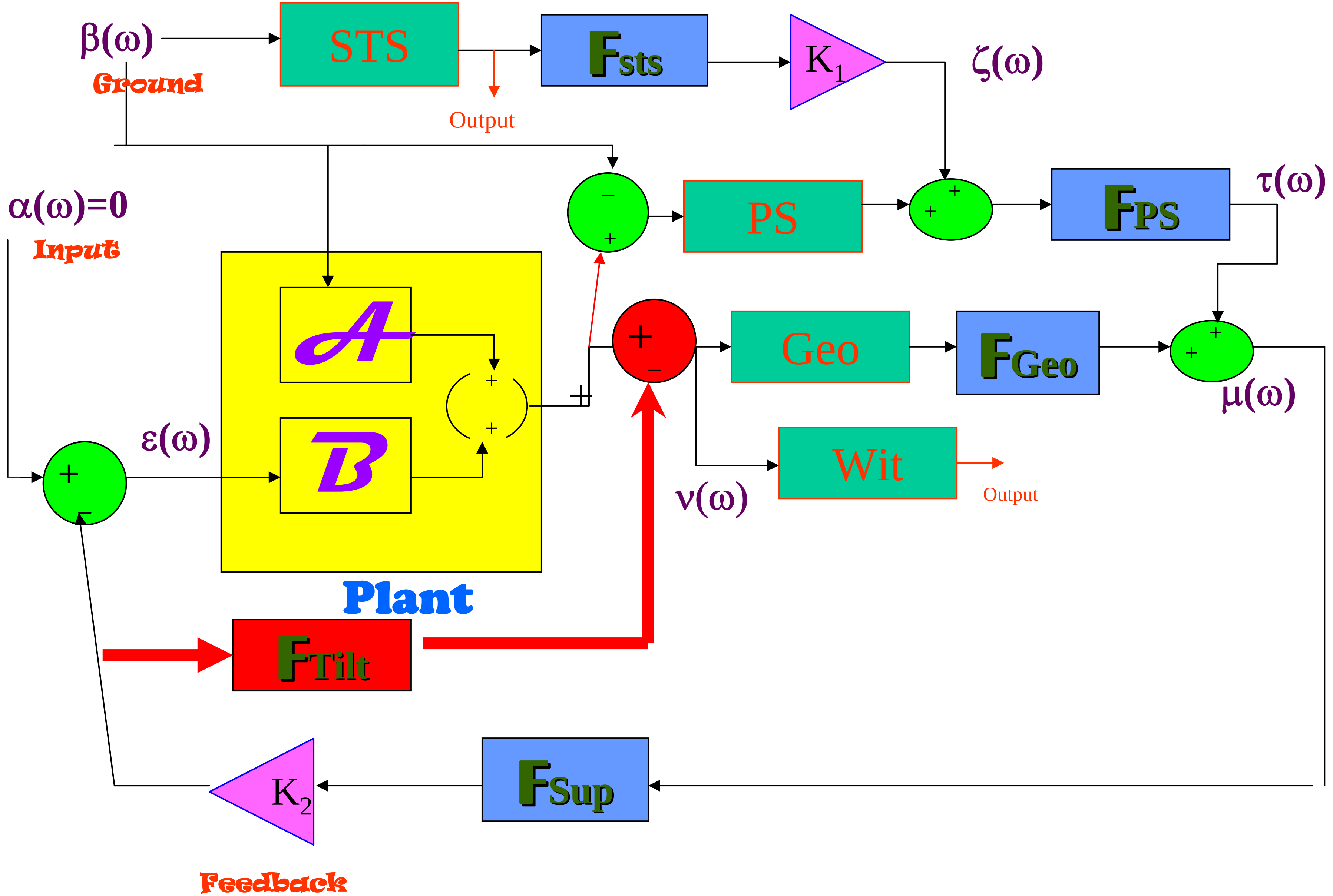
TILT MODEL



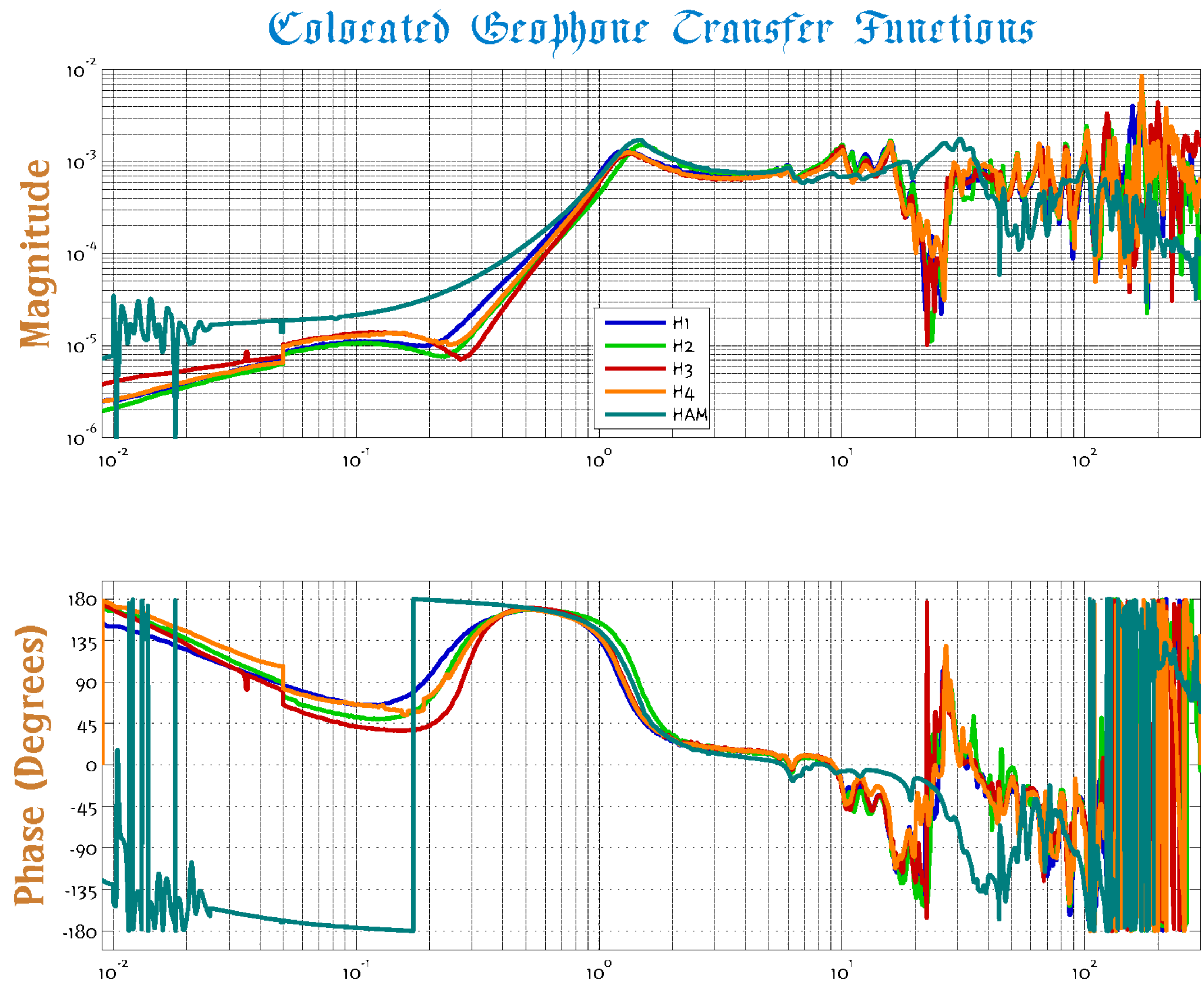
TILT ANGLE IS PROPORTIONAL TO THE DISPLACEMENT



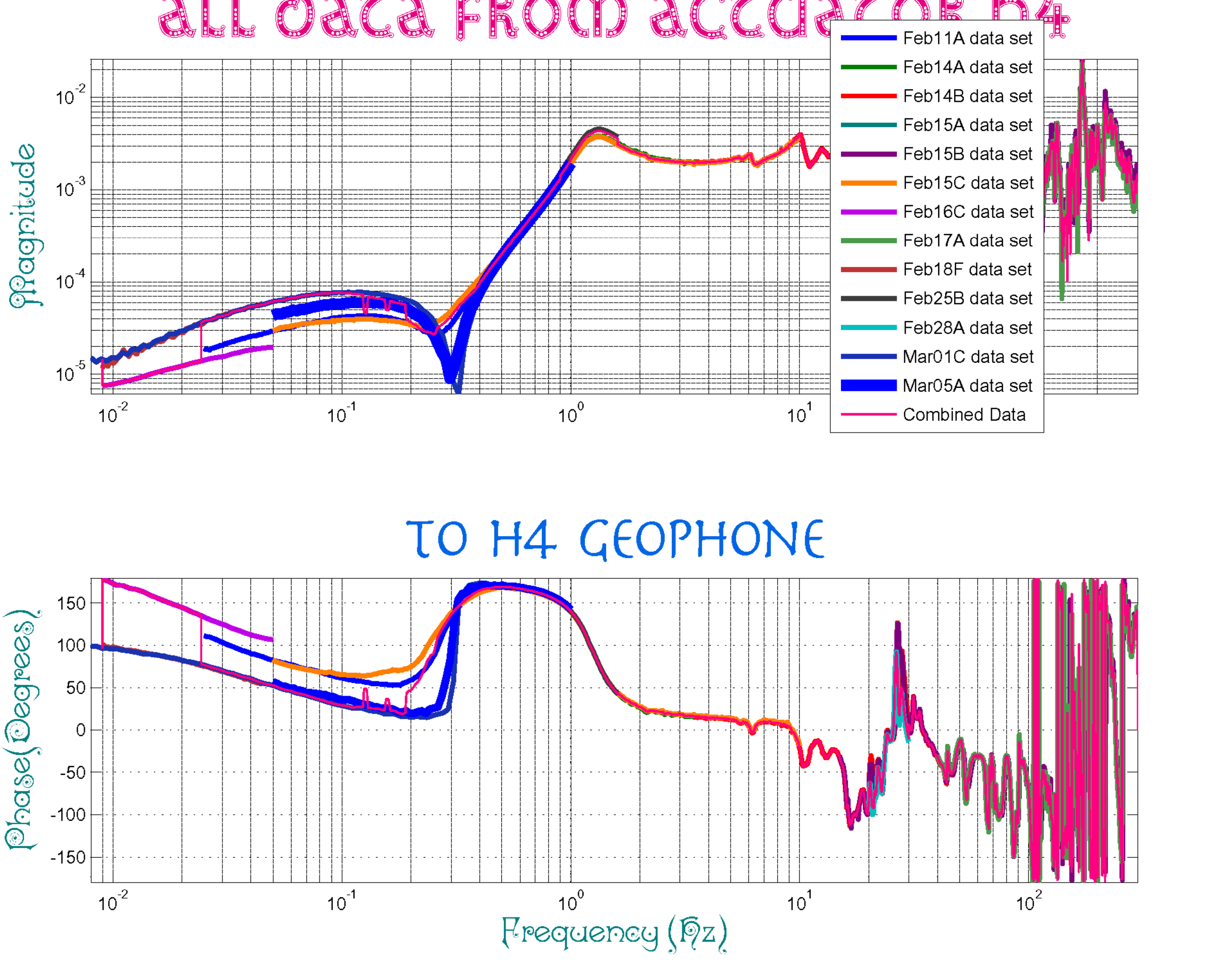

YY Mode: Transfer Function (#2)
Magnitude
10⁻²
10⁻⁴
10⁻¹
10⁰
Geo-TF
Geo-Filter
Geo-Filter*Response
PS-TF
PS-Filter
PS-Filter*Response
Sum
Sensor Blending
Phase (degrees)
180
90
0
-90
-180
10⁻¹
10⁰
10¹
Frequency (Hz)



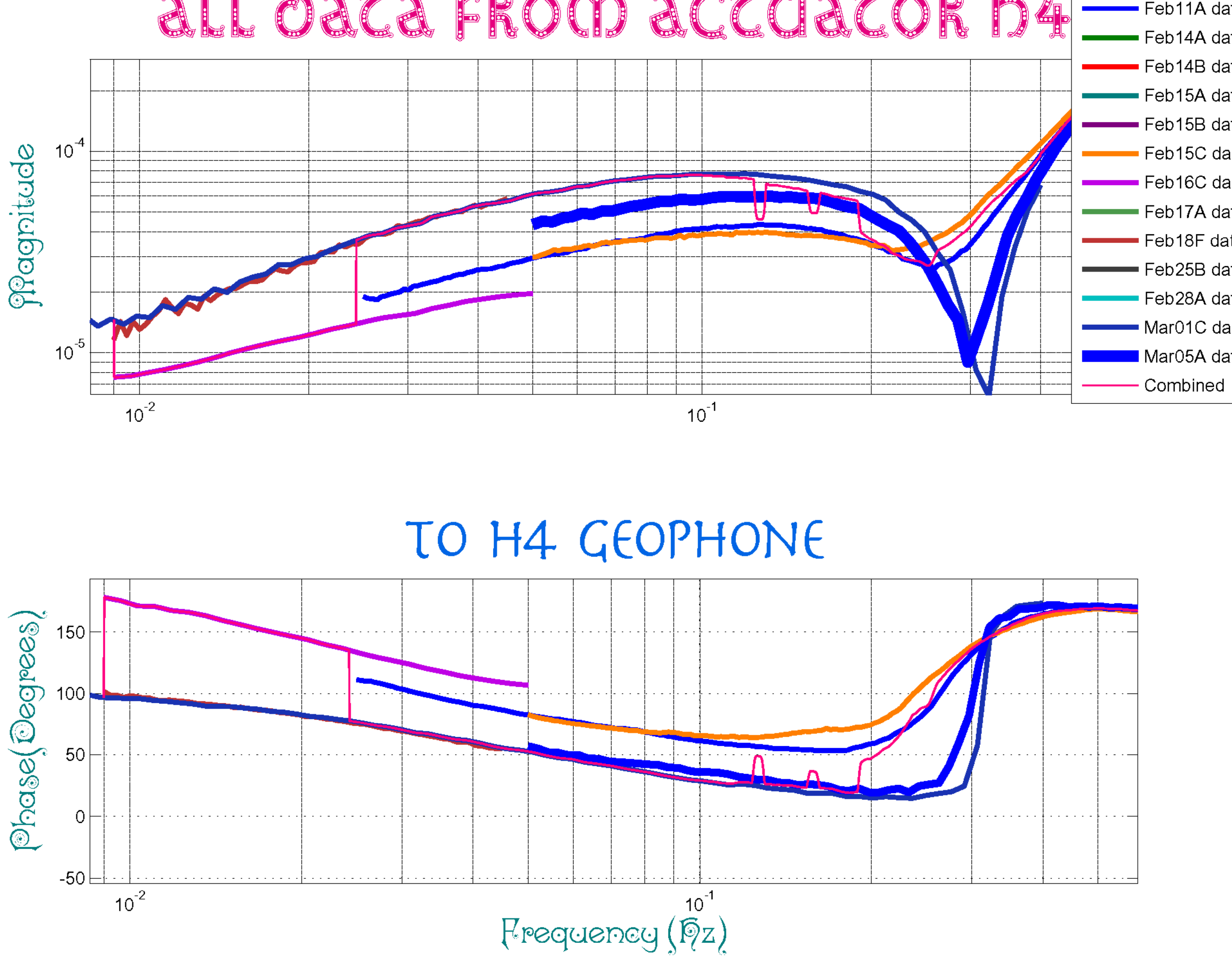
Control **Strategy**



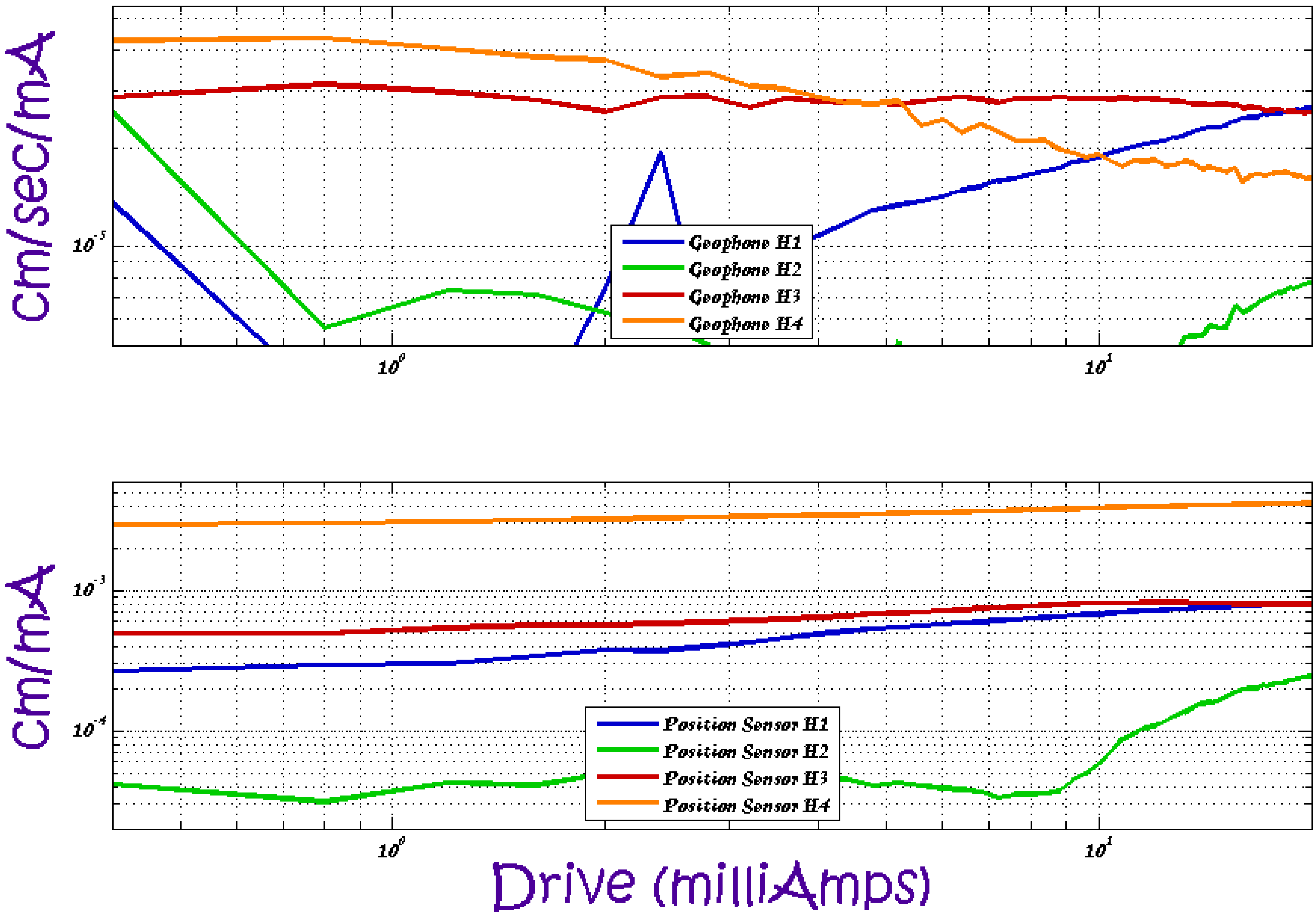
Colocated Geophone Transfer Functions
Magnitude
Phase (Degrees)
H1
H2
H3
H4
HAM
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
180
135
90
45
0
-45
-90
-135
-180
10^{-1}
10^{0}
10^{1}
10^{2}



all data from actuator H4
TO H4 GEOPHONE
Magnitude
Phase(Degrees)
Frequency (Hz)
Feb11A data set
Feb14A data set
Feb14B data set
Feb15A data set
Feb15B data set
Feb15C data set
Feb16C data set
Feb17A data set
Feb18F data set
Feb25B data set
Feb28A data set
Mar01C data set
Mar05A data set
Combined Data


all data from actuator h4
TO H4 GEOPHONE
Magnitude
10^{-4}
10^{-5}
10^{-2}
10^{-1}
Feb11A da
Feb14A da
Feb14B da
Feb15A da
Feb15B da
Feb15C da
Feb16C da
Feb17A da
Feb18F da
Feb25B da
Feb28A da
Mar01C da
Mar05A da
Combined
Phase(Degrees)
150
100
50
0
-50
Frequency (Hz)

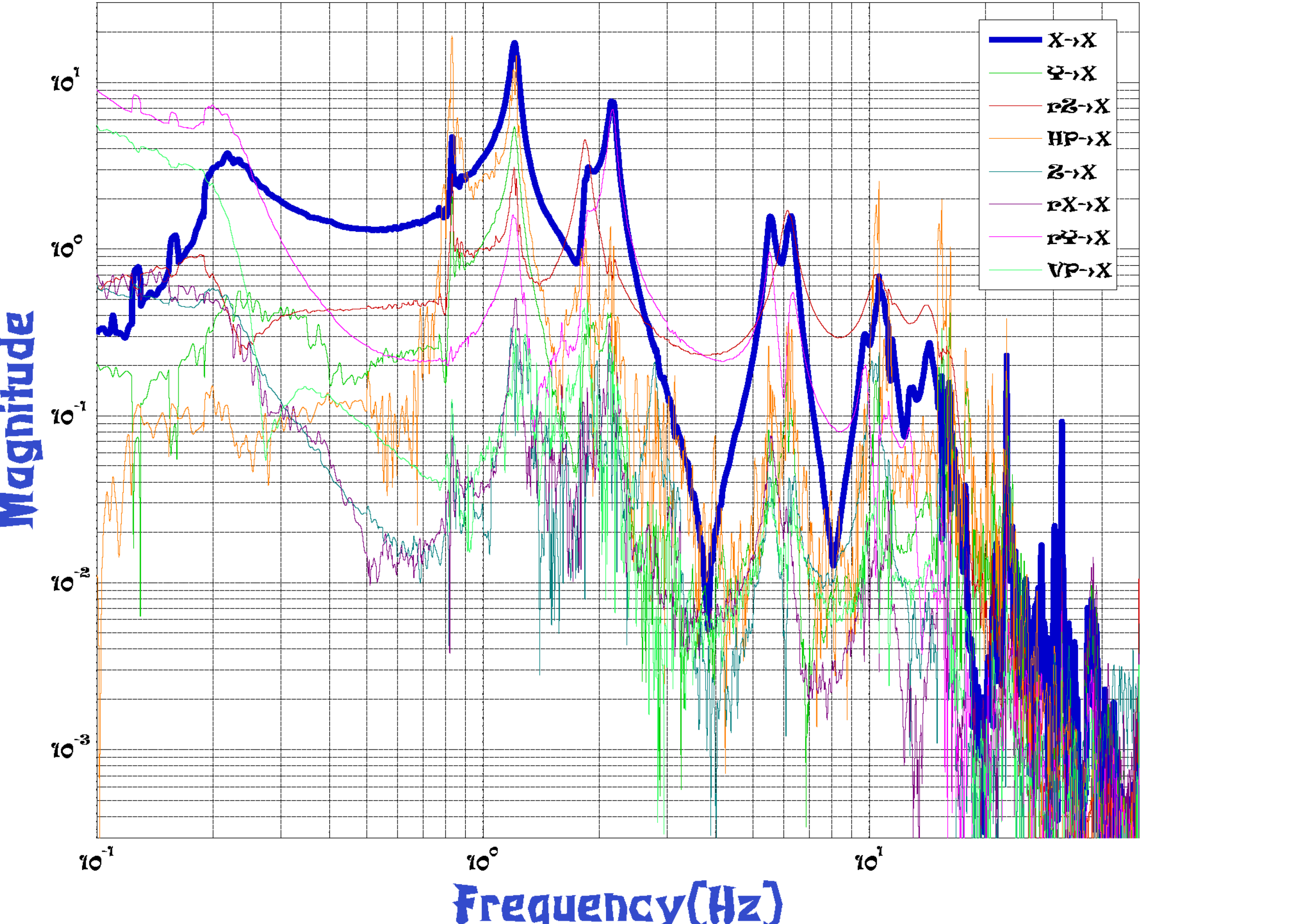
BSC Transfrer Functions from H4

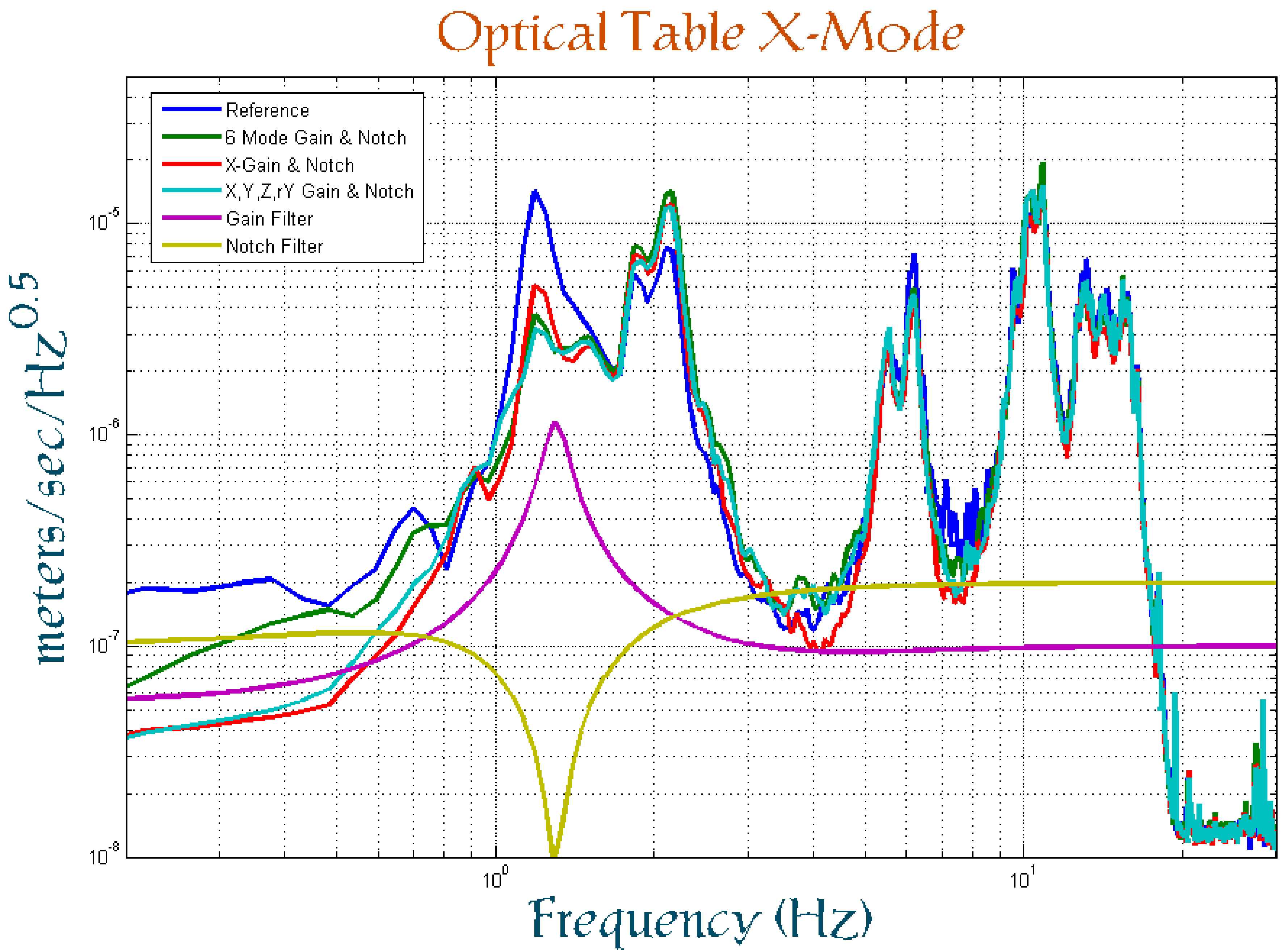


BSC Stack Transfer Functions

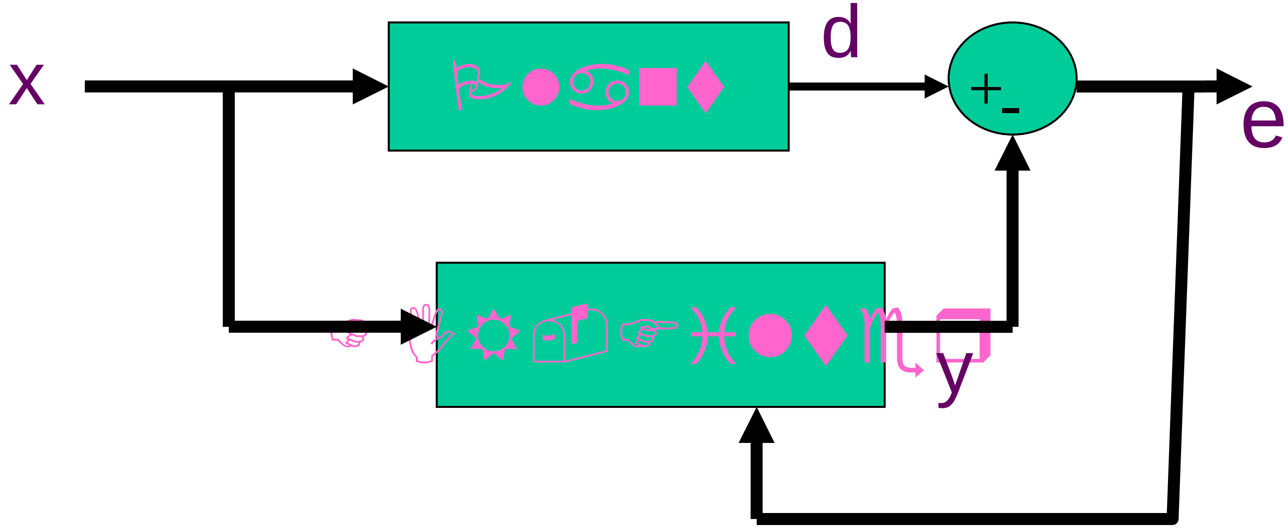
From the Support table to the Optics Table

Coupling to the X mode of the Optics table




Optical Table X-Mode
Reference
6 Mode Gain & Notch
X-Gain & Notch
X,Y,Z,rY Gain & Notch
Gain Filter
Notch Filter
10-5
10-6
10-7
10-8
100
101
meters/sec/Hz0.5
Frequency (Hz)

Adaptive Algorithm

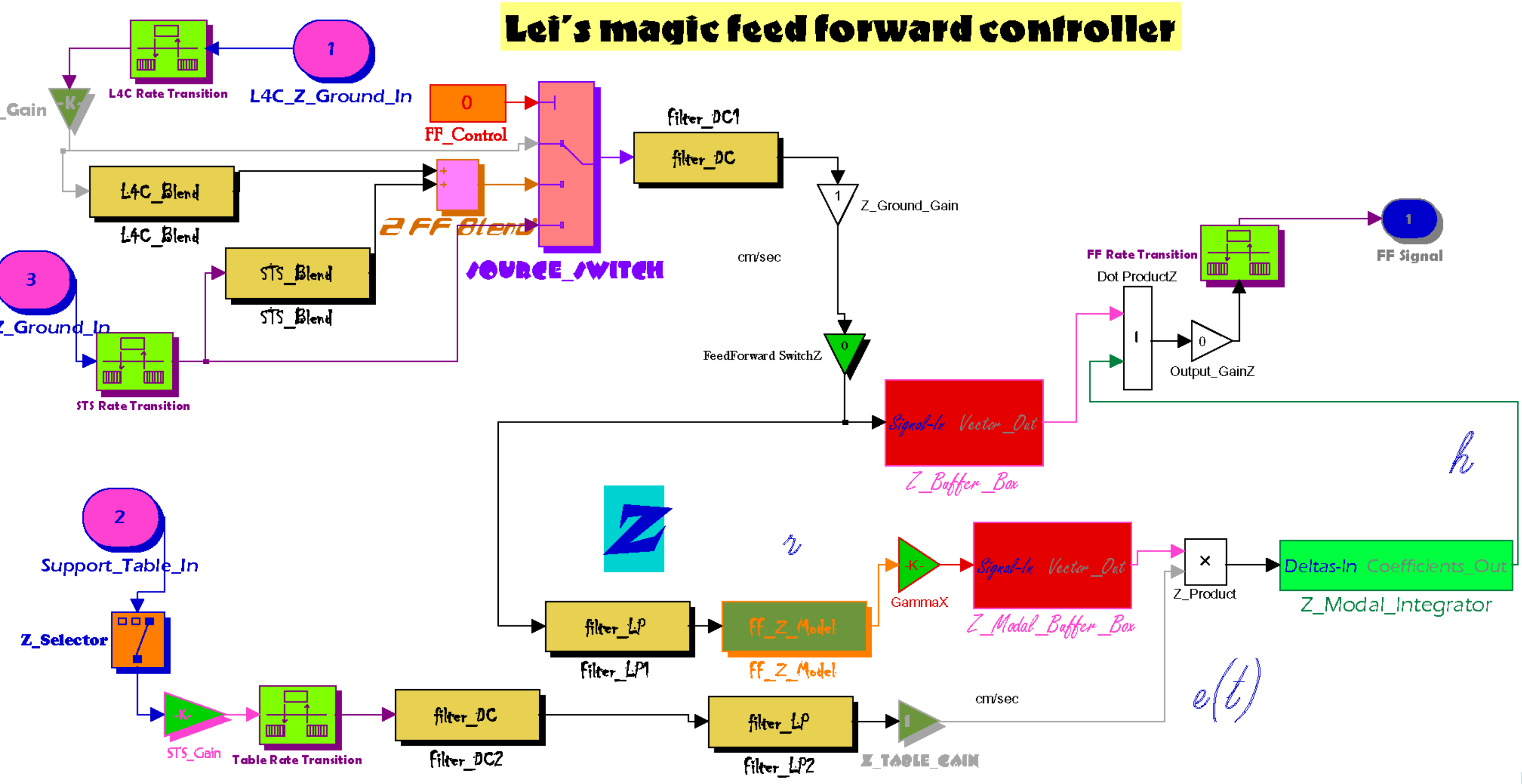


$$\text{Gradient} = \frac{\partial}{\partial h_i}|e|^2 = 2e\frac{\partial}{\partial h_i}[d-y] = 2e\frac{\partial}{\partial h_i}\left[d - \sum_{i=0}^{N-1}(h_i\, x_{N-i})\right]$$

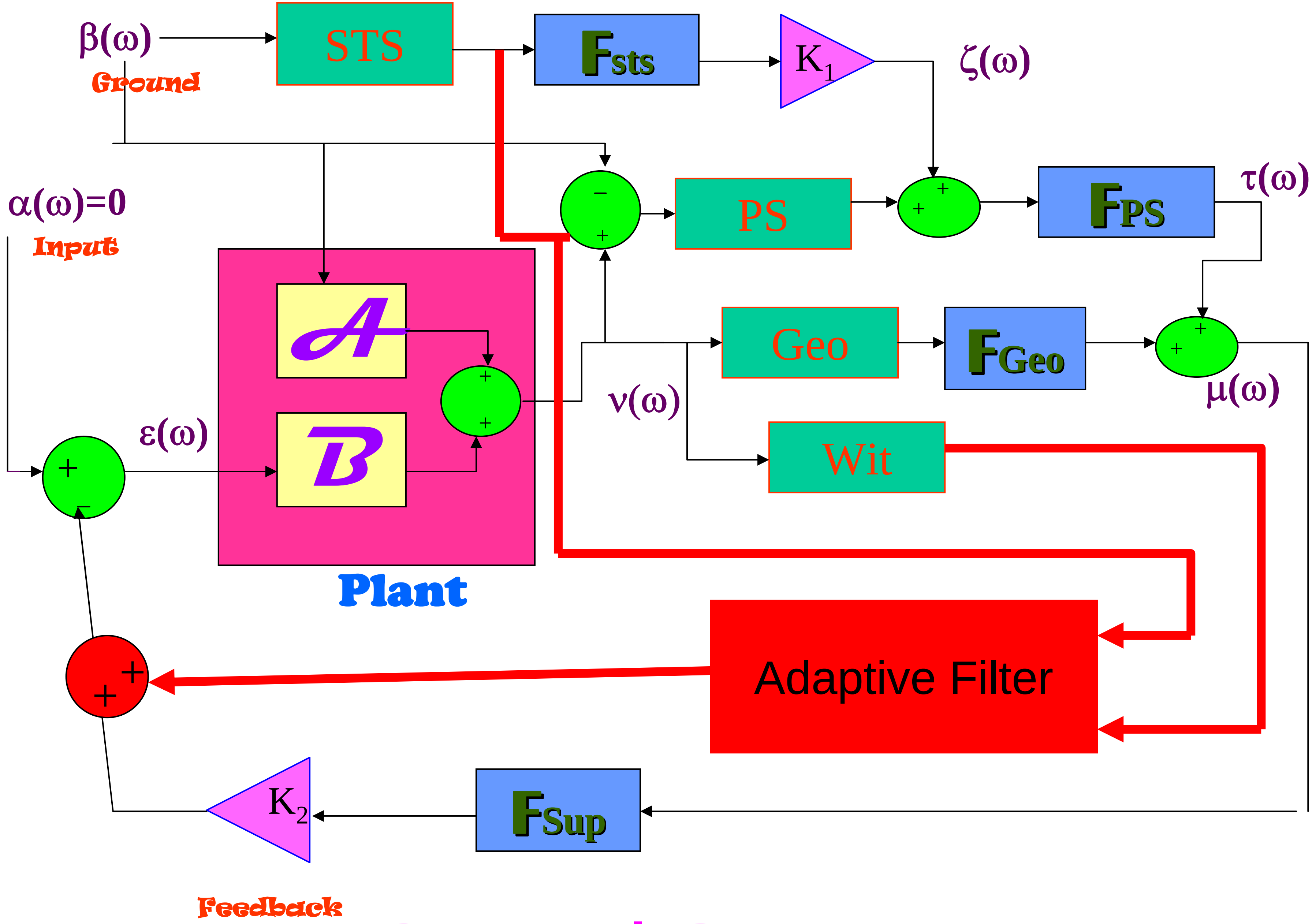
$$= 2e[-x_{N-i}]$$

FIR filter, of length N, has coefficients *h*

Simulink Diagram

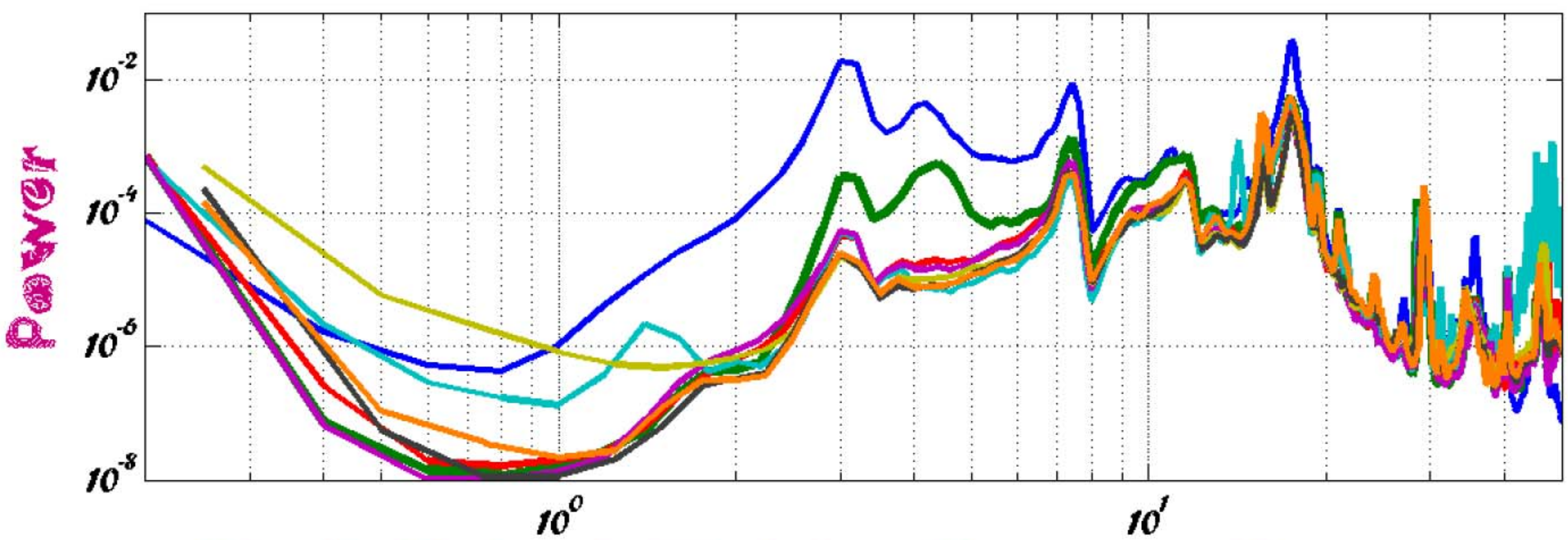


ff_z model is a fit of the actuator to witness transfer function

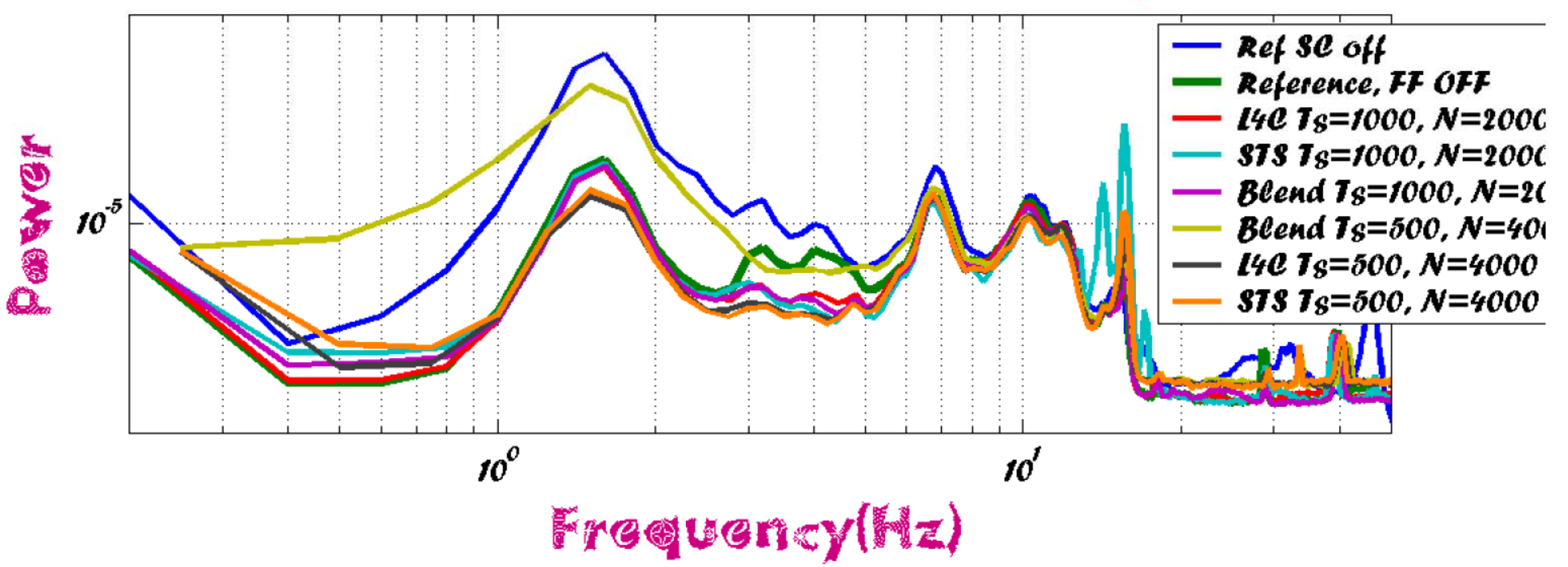


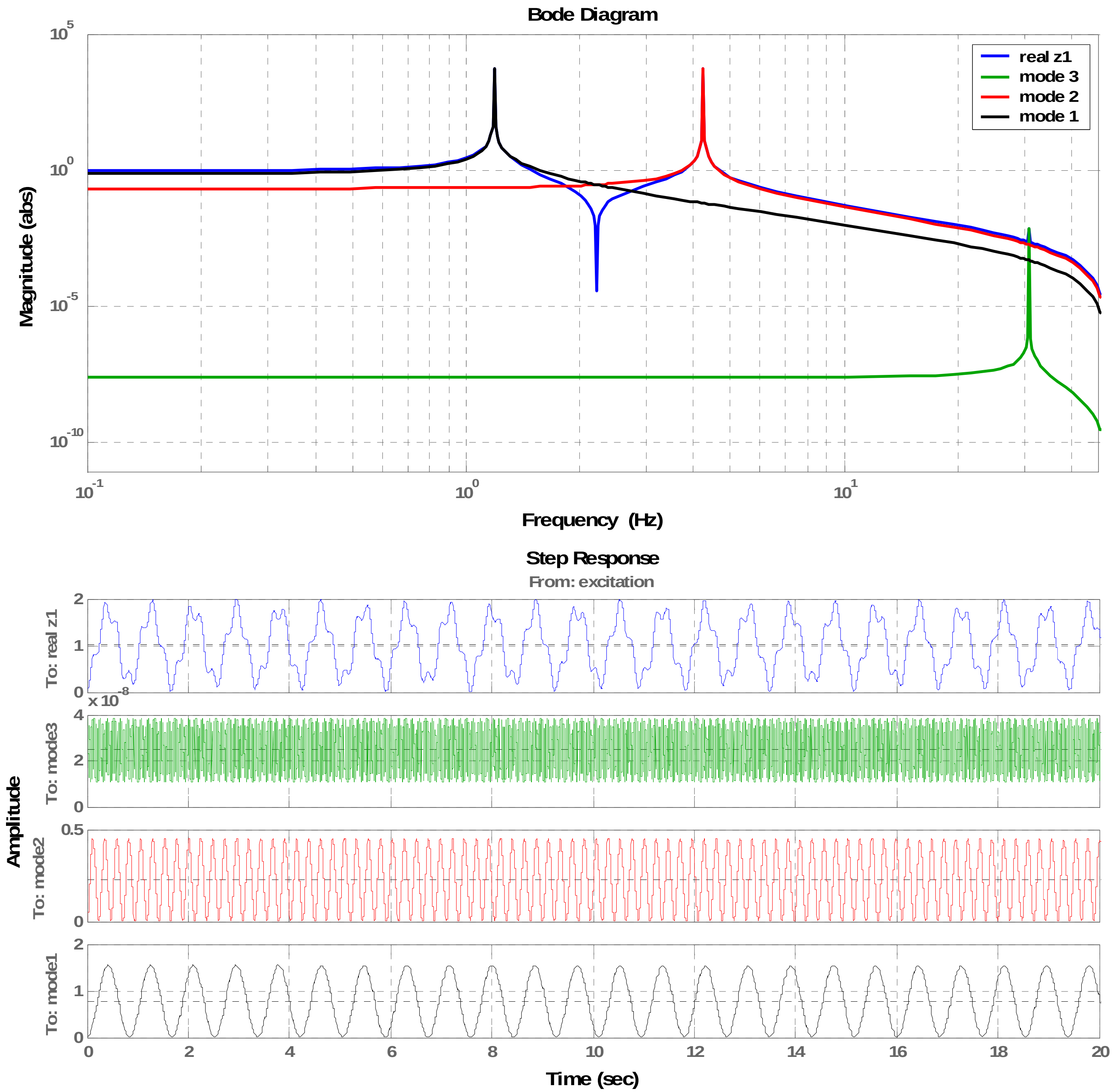
Control Strategy

Z-Gurlap Power Spectra

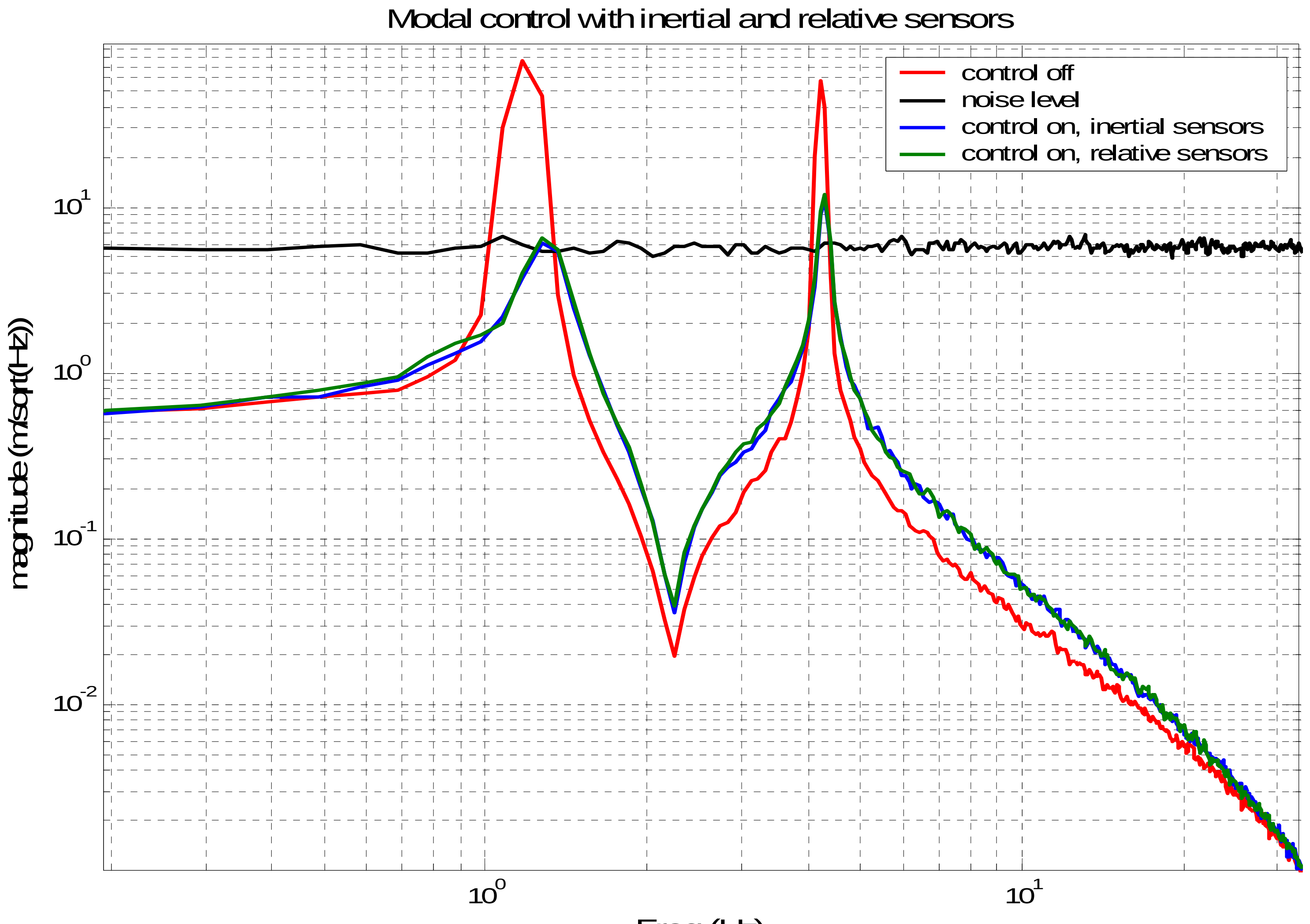


Z-Optical Table Power Spectra

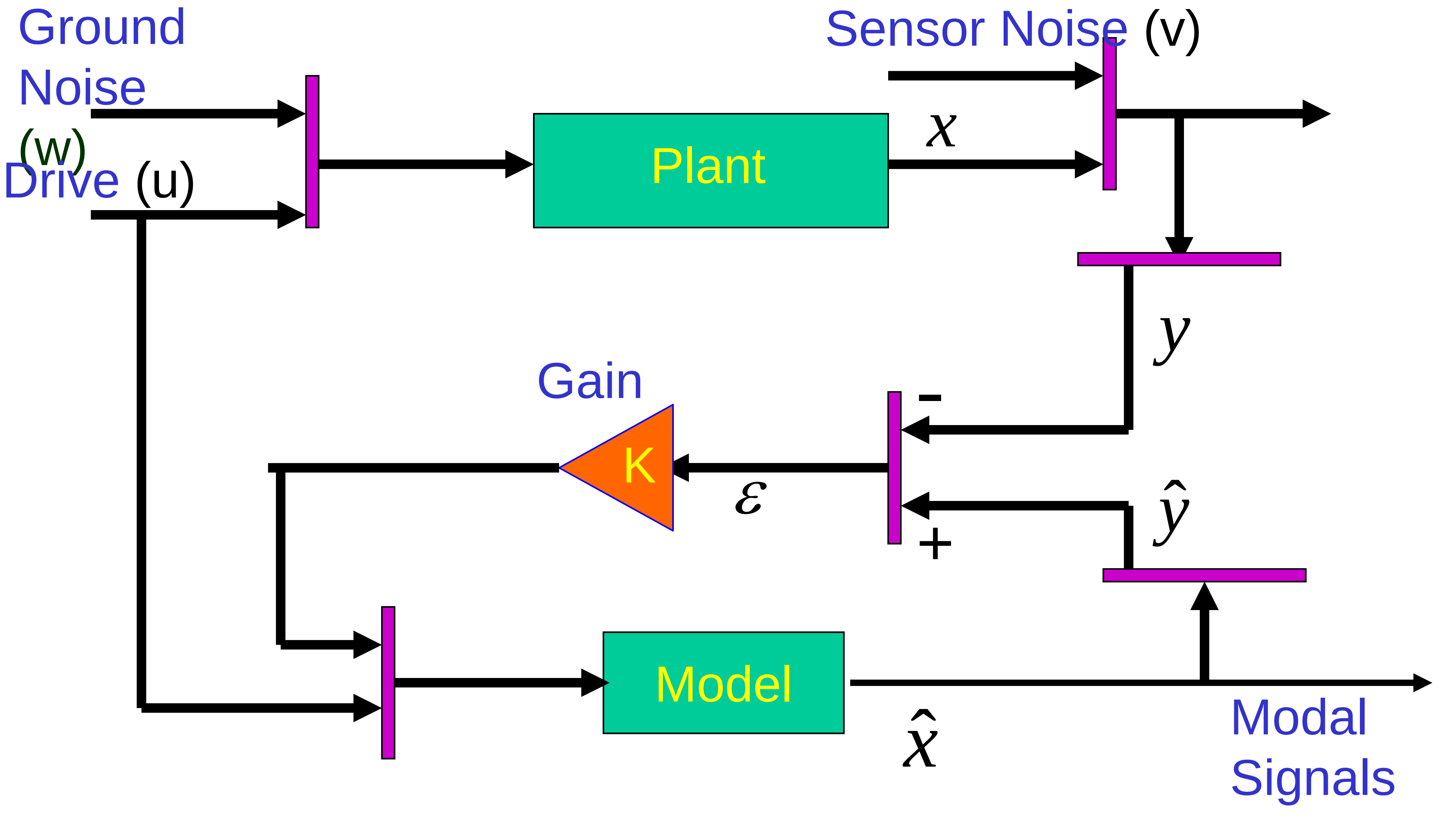



Bode Diagram
Magnitude (abs)
Frequency (Hz)
real z1
mode 3
mode 2
mode 1
Step Response
From: excitation
Amplitude
To: real z1
To: mode3
To: mode2
To: mode1
Time (sec)

Modal Control Results



Estimator Model



Estimator Math

$$\varepsilon = \hat{y} - y = [Ce]\hat{x} - [Ce]x - [Ce]v$$

Where C_e is a selector Matrix

$$\hat{x} = TF_m K \varepsilon$$

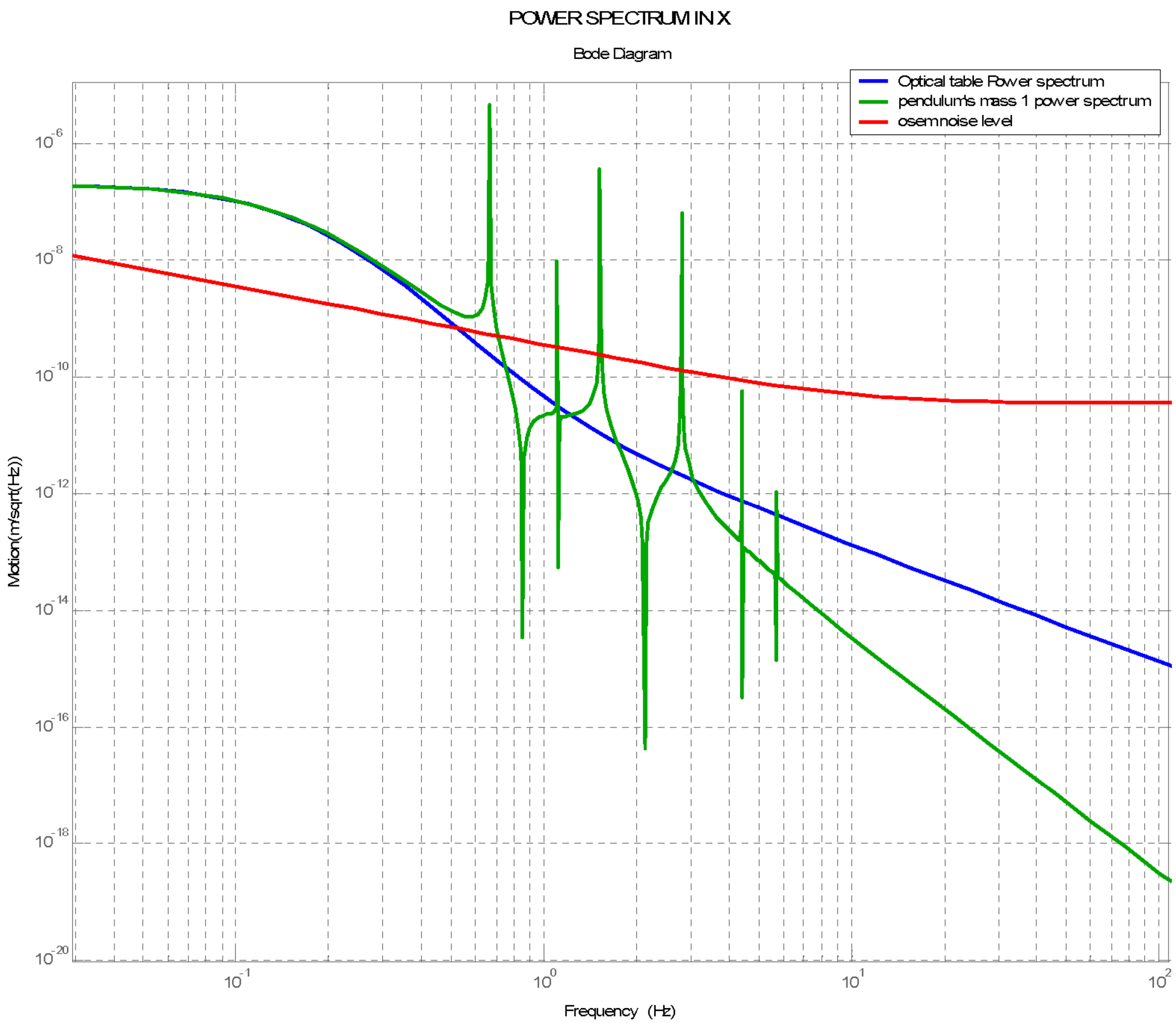
Where TF_m is the model transfer function

$$\hat{x} = \frac{x + v}{1 - \frac{1}{TF_m K C_e}}$$

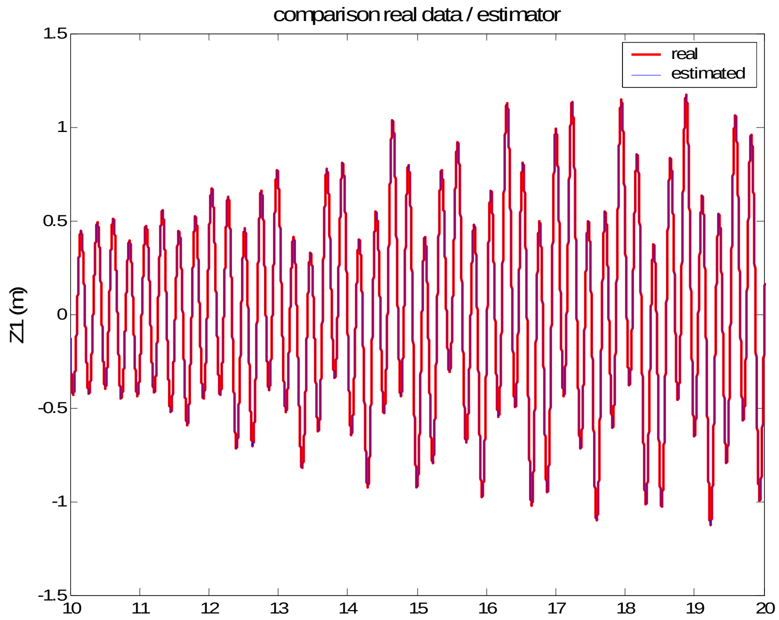
if $x >> v$ A large K will give $\hat{x} = x + v$

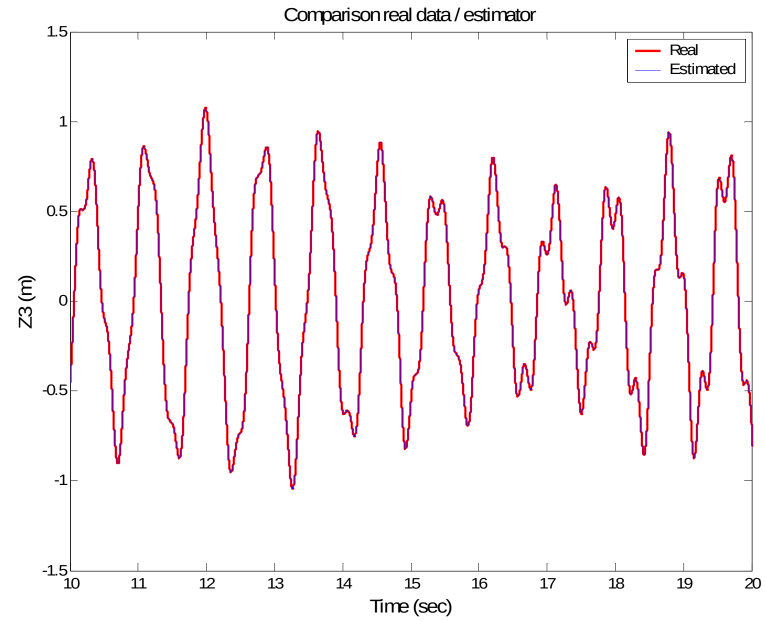
A small K will give

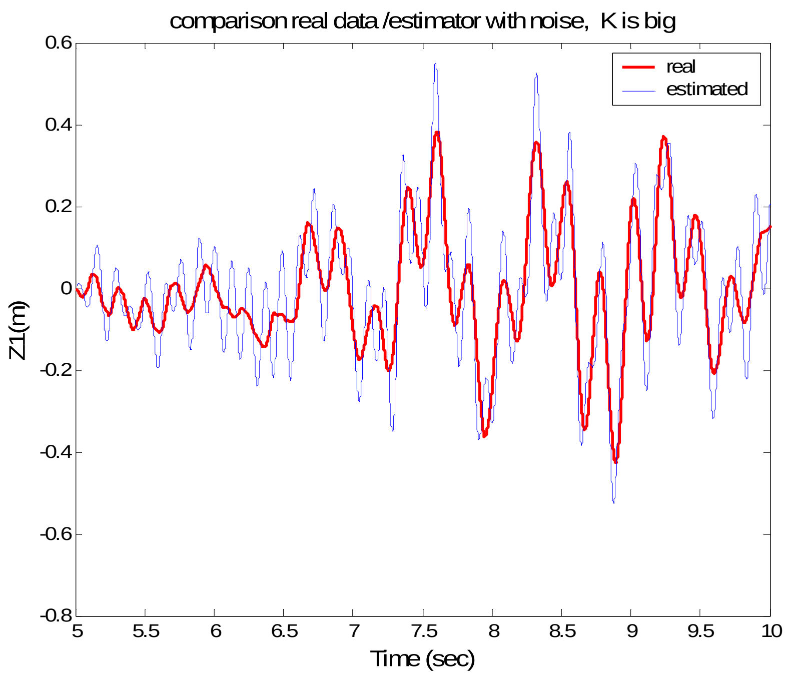
$$\hat{x} \approx 0$$

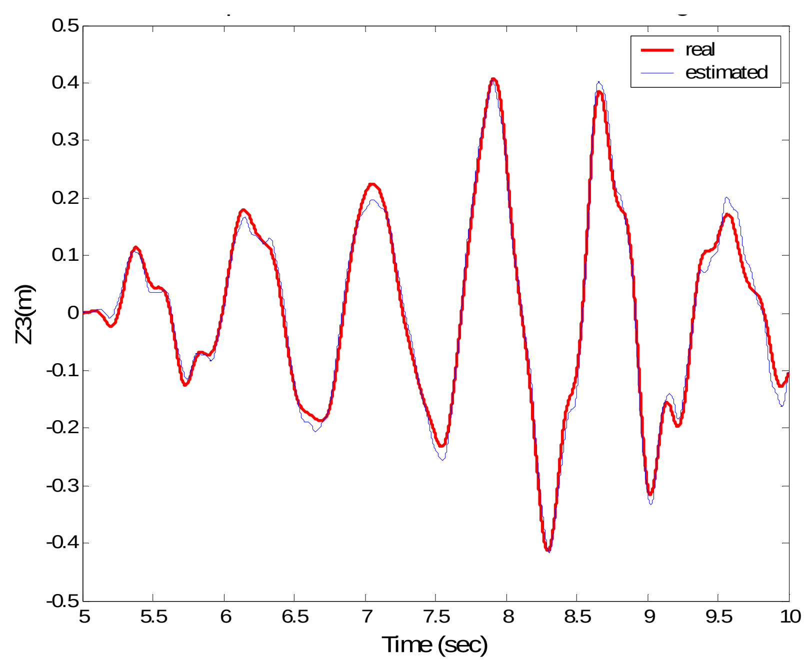

POWER SPECTRUM IN X
Bode Diagram
Optical table Power spectrum
pendulum's mass 1 power spectrum
osemnoise level
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
Motion(m/sqrt(Hz))
10^{-1}
10^{0}
10^{1}
10^{2}
Frequency (Hz)

Estimator Results

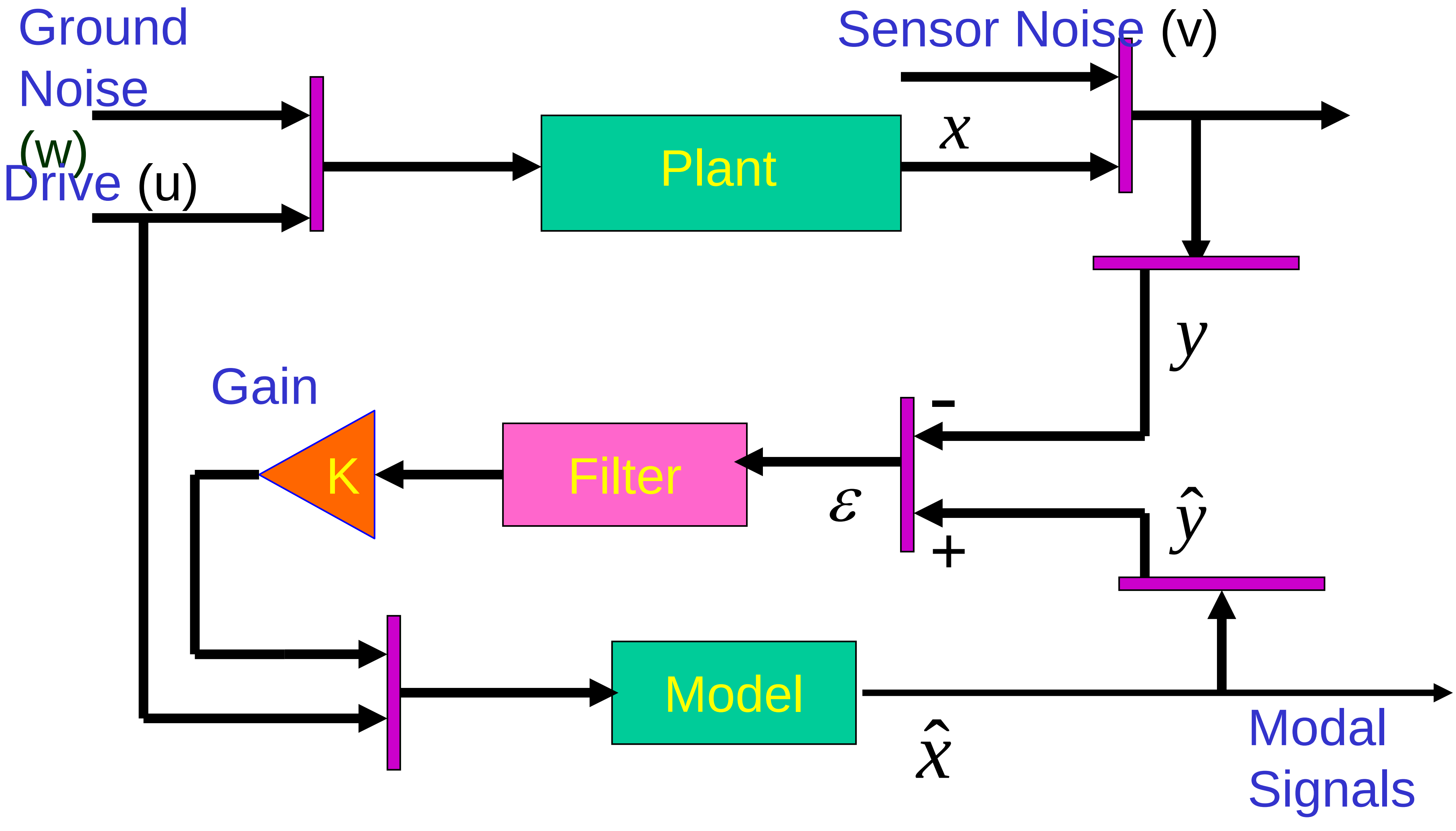


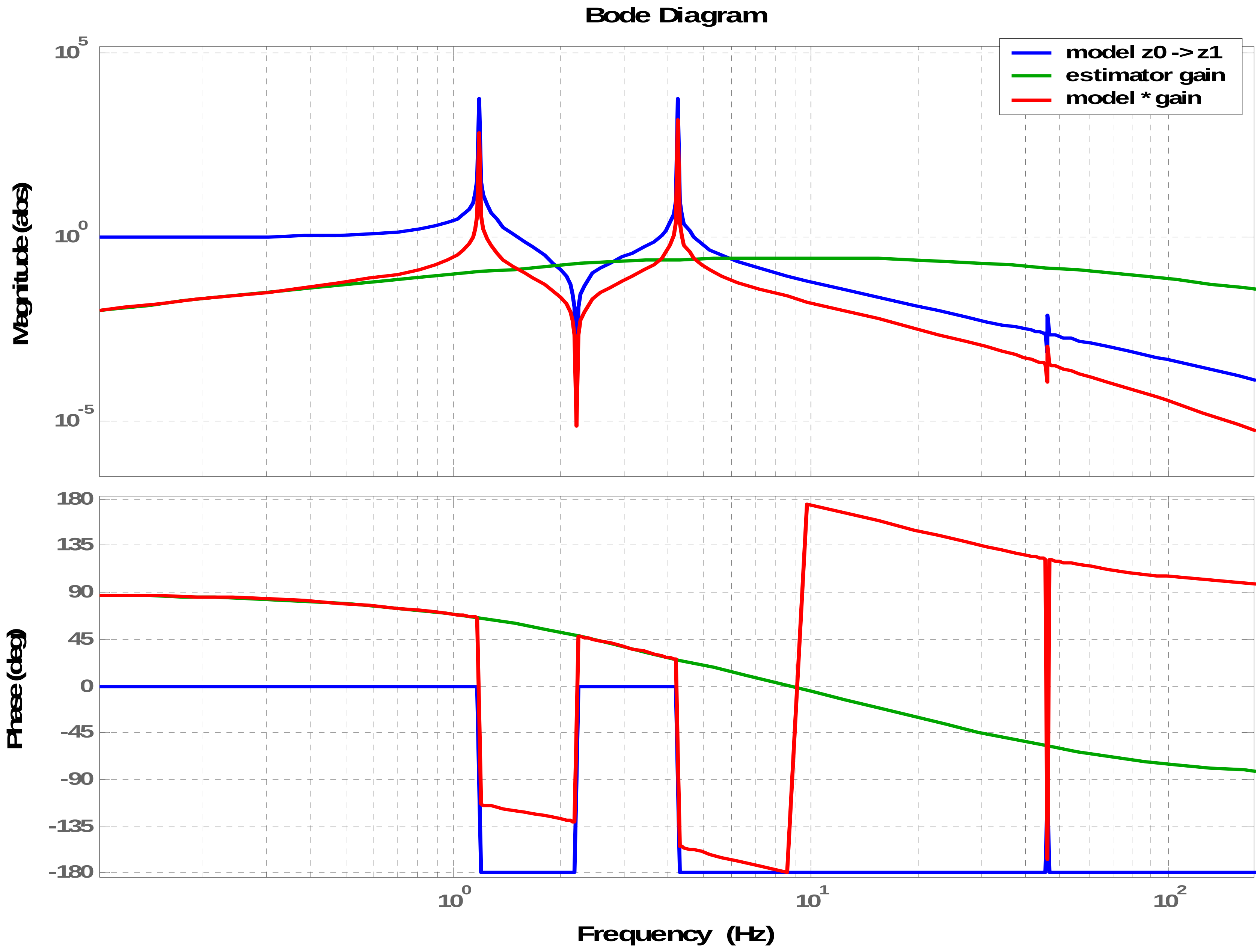






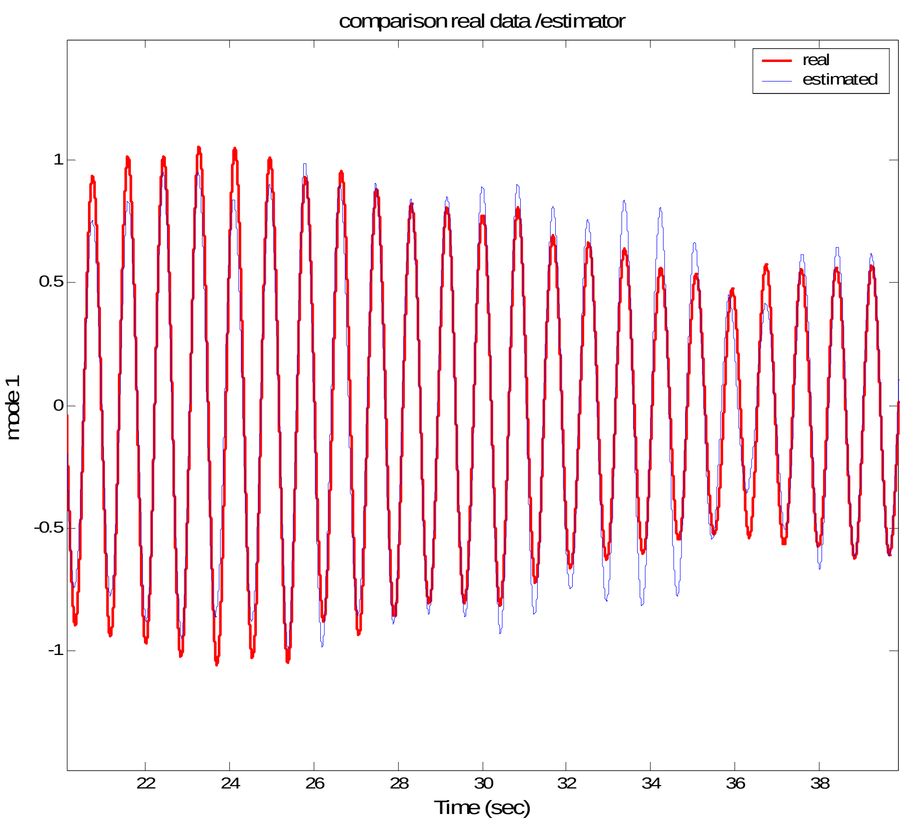
Estimator Model

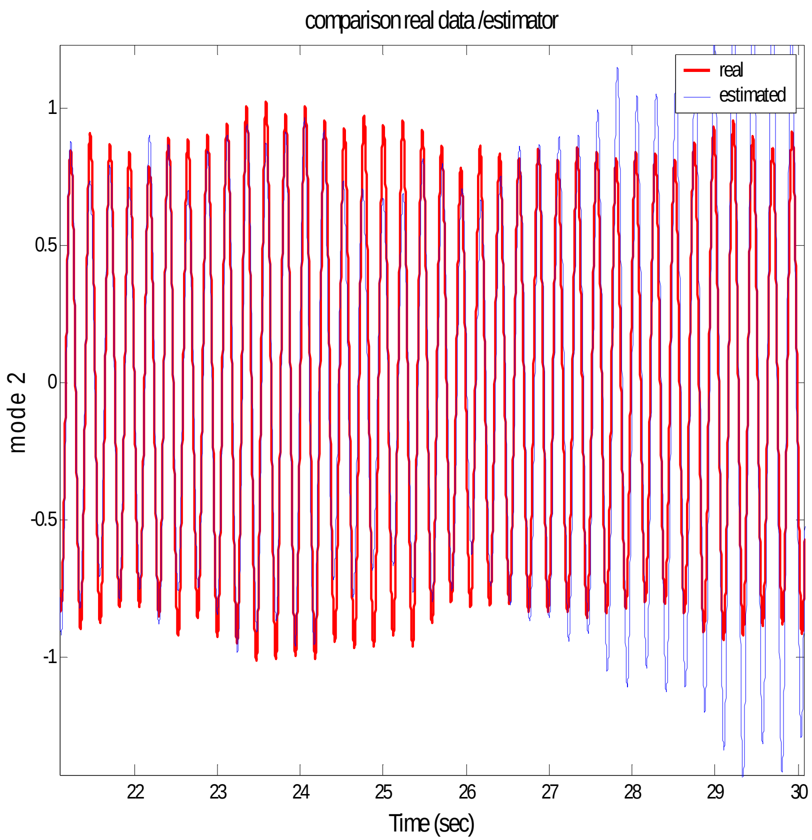




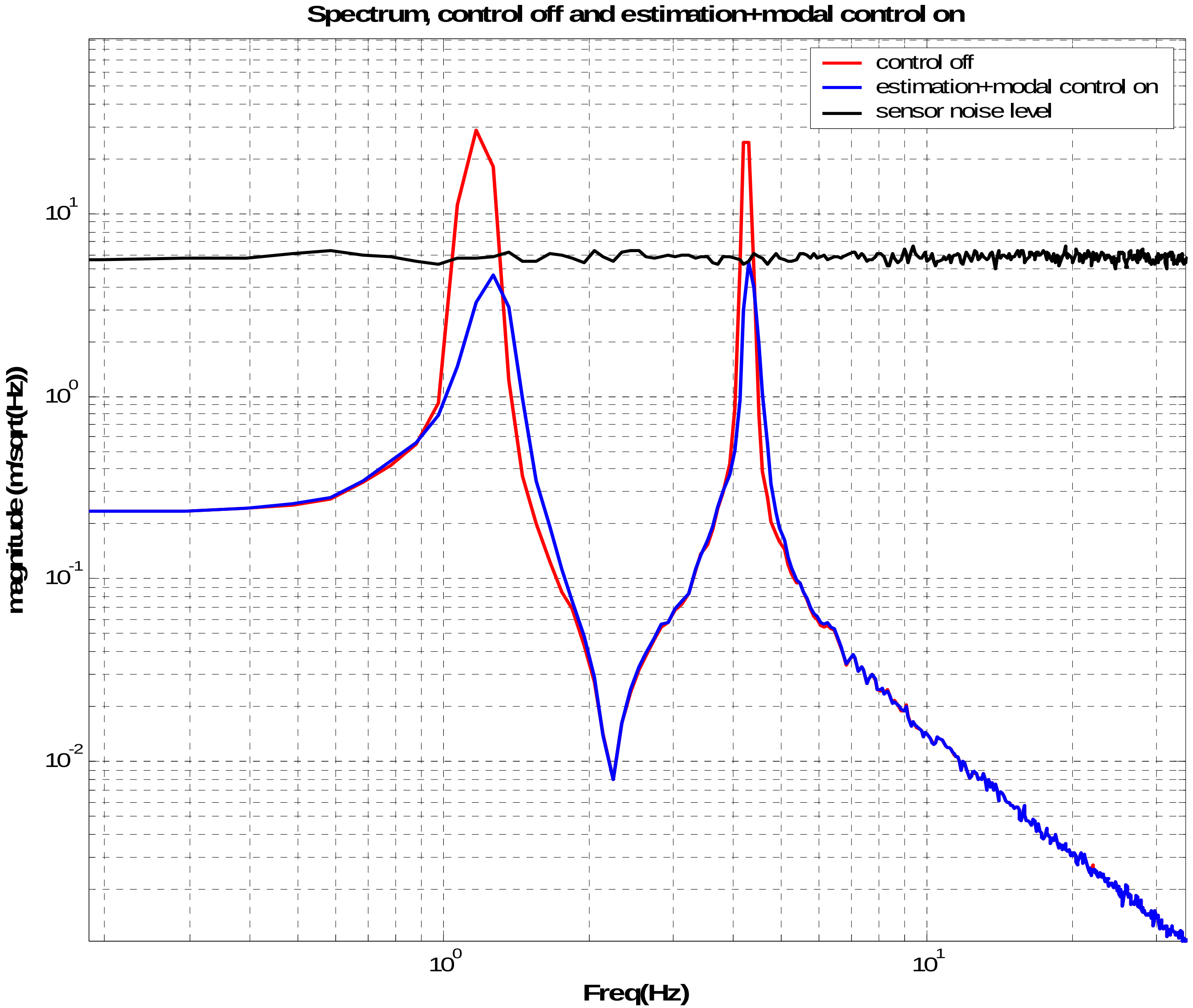
Bode Diagram
model z0 -> z1
estimator gain
model * gain
Magnitude (abs)
10^5
10^0
10^-5
Phase (deg)
180
135
90
45
0
-45
-90
-135
-180
10^0
10^1
10^2
Frequency (Hz)

Results


comparison real data /estimator
real
estimated
1
0.5
0
-0.5
-1
mode 1
22
24
26
28
30
32
34
36
38
Time (sec)


comparison real data /estimator
real
estimated
1
0.5
0
-0.5
-1
mode 2
22
23
24
25
26
27
28
29
30
Time (sec)

Spectrum



Spectrum, control off and estimation+modal control on
control off
estimation+modal control on
sensor noise level
magnitude (m/sqrt(Hz))
10^1
10^0
10^-1
10^-2
10^0
10^1
Freq(Hz)

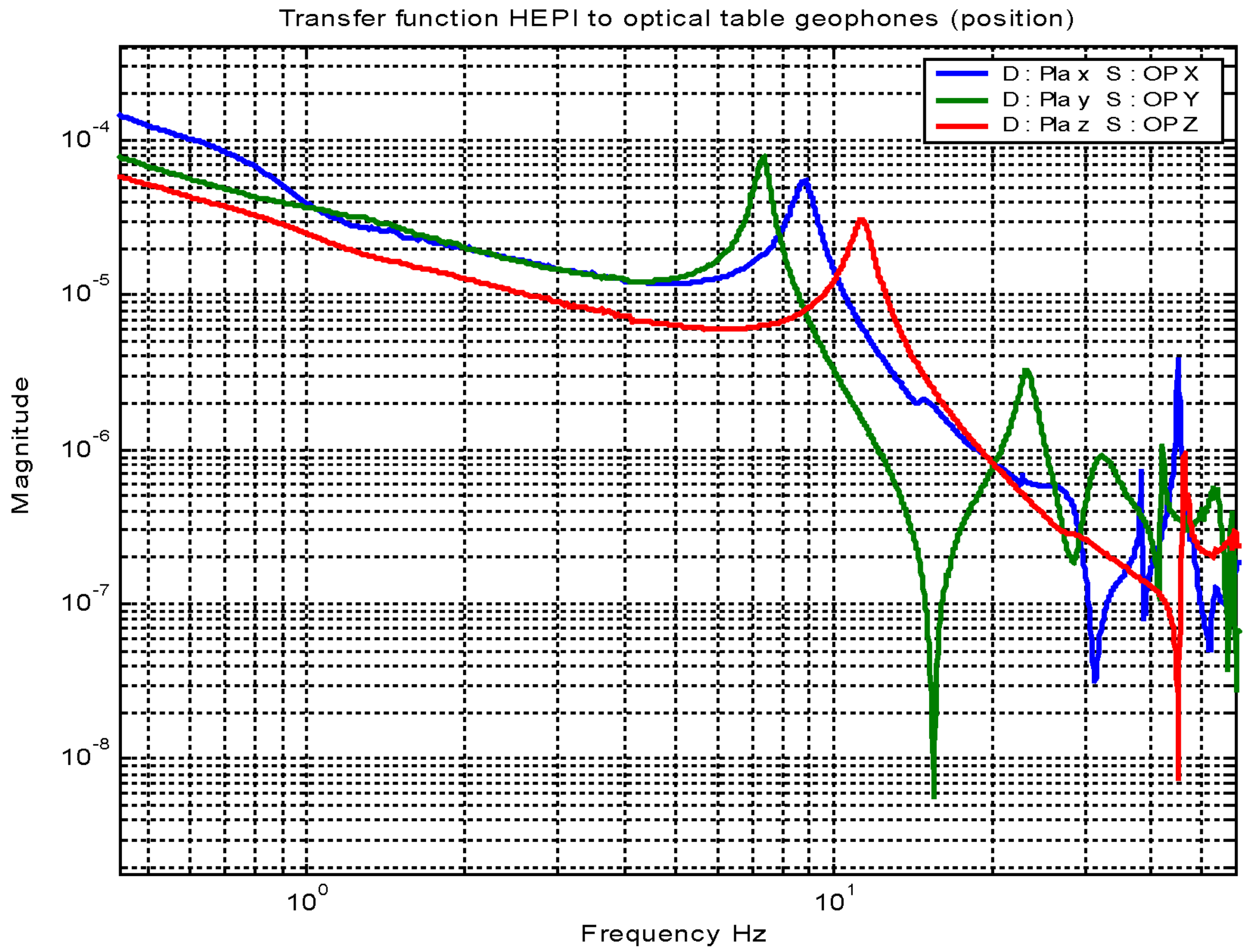
Future Estimator Work

How Good does the Model Need to Be?

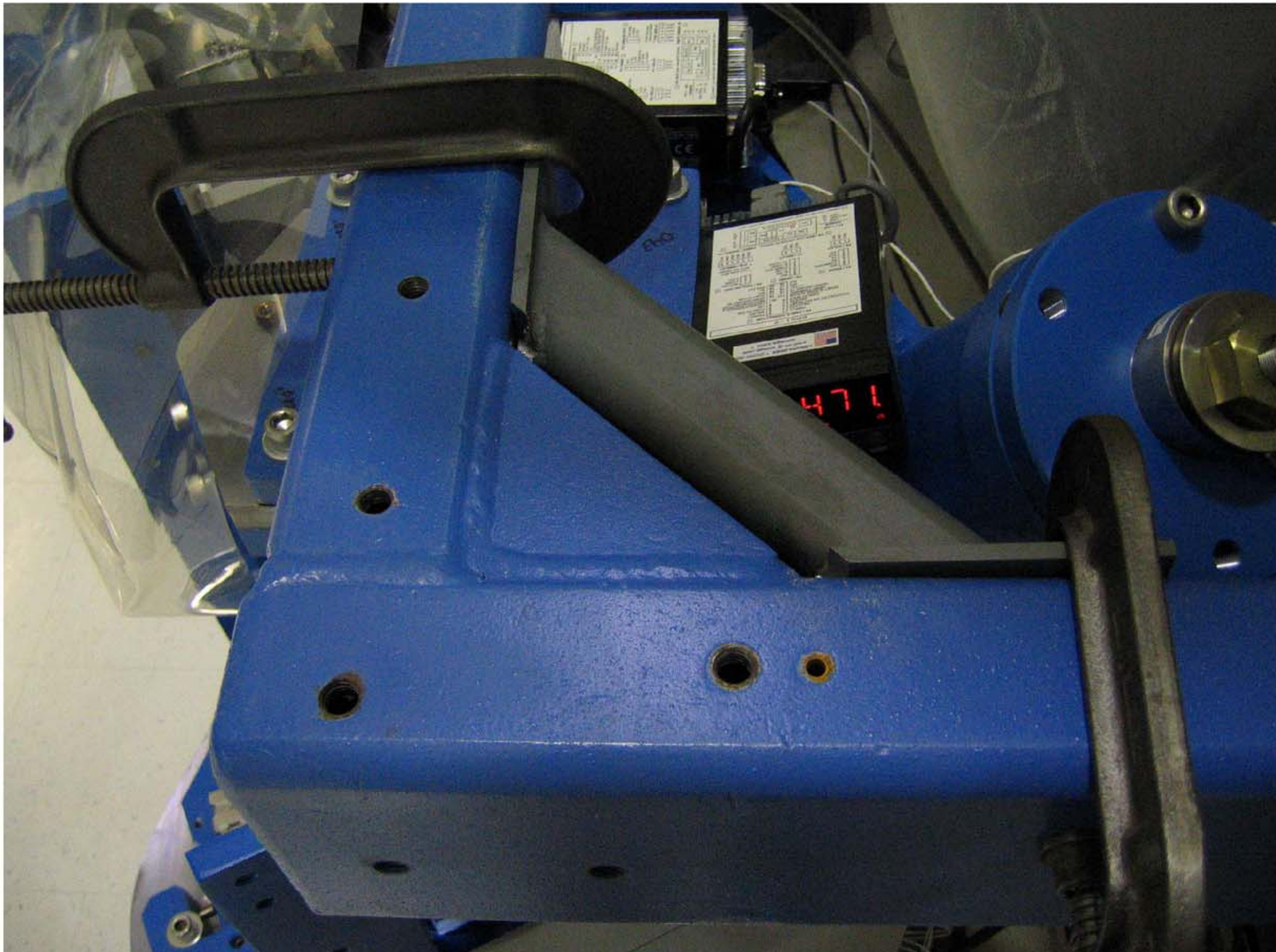
How do we optimize the Estimator Gain vs. the Control Gain?

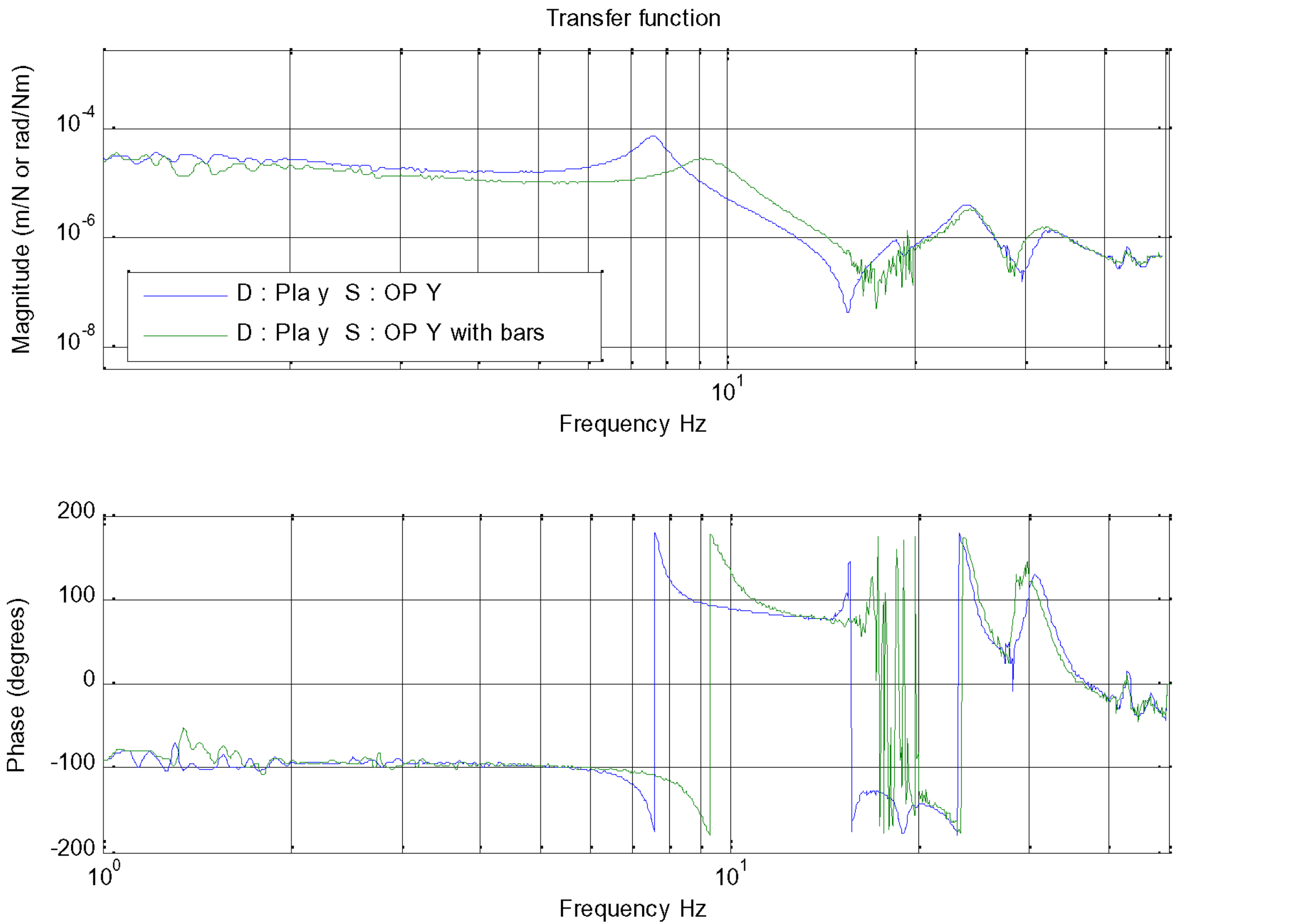
Try it on a piece of hardware; the triple pendulum control prototype.

Other Ideas?

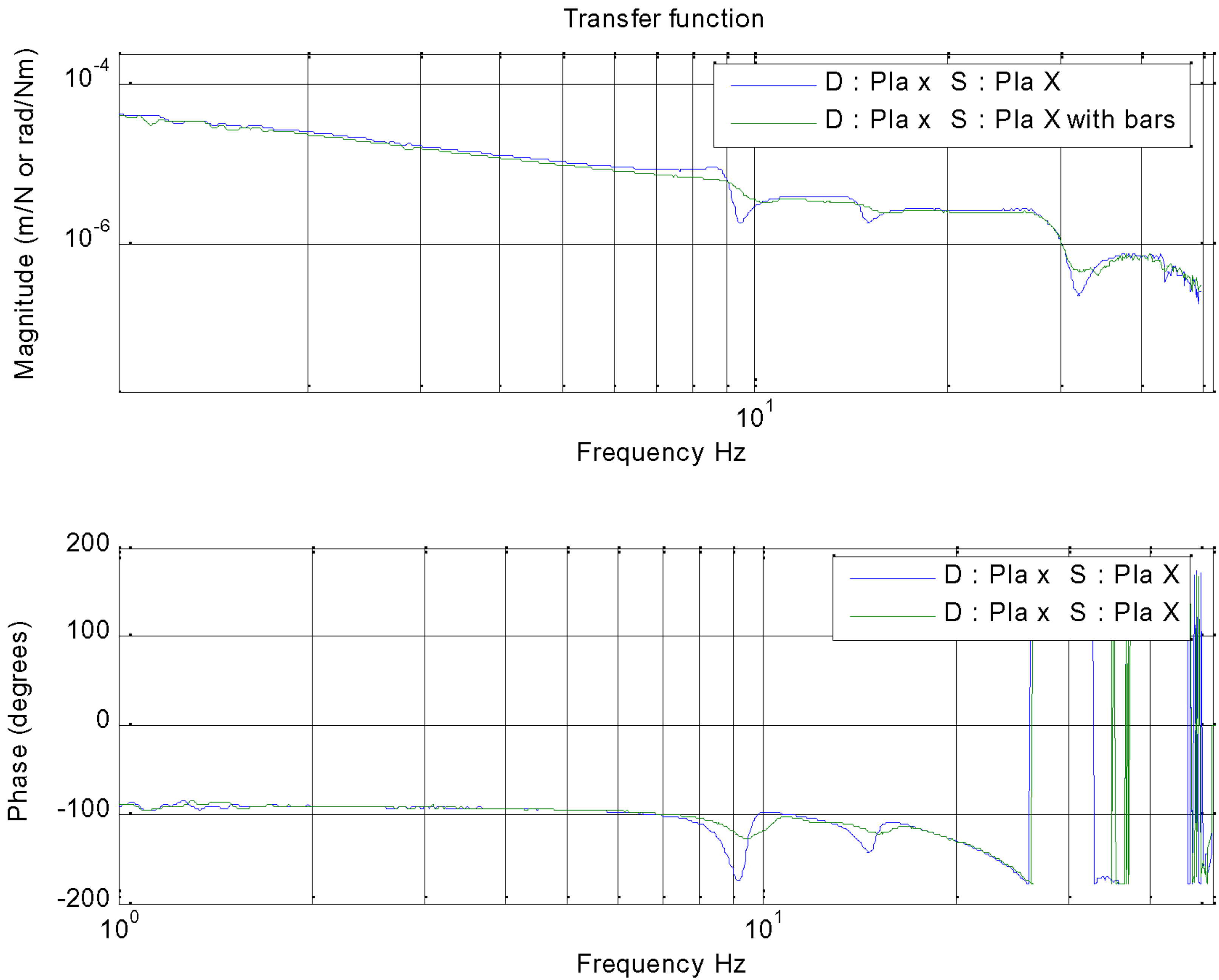


Transfer function HEPI to optical table geophones (position)
D : Pla x S : OP X
D : Pla y S : OP Y
D : Pla z S : OP Z
10^-4
10^-5
10^-6
10^-7
10^-8
Magnitude
10^0
10^1
Frequency Hz





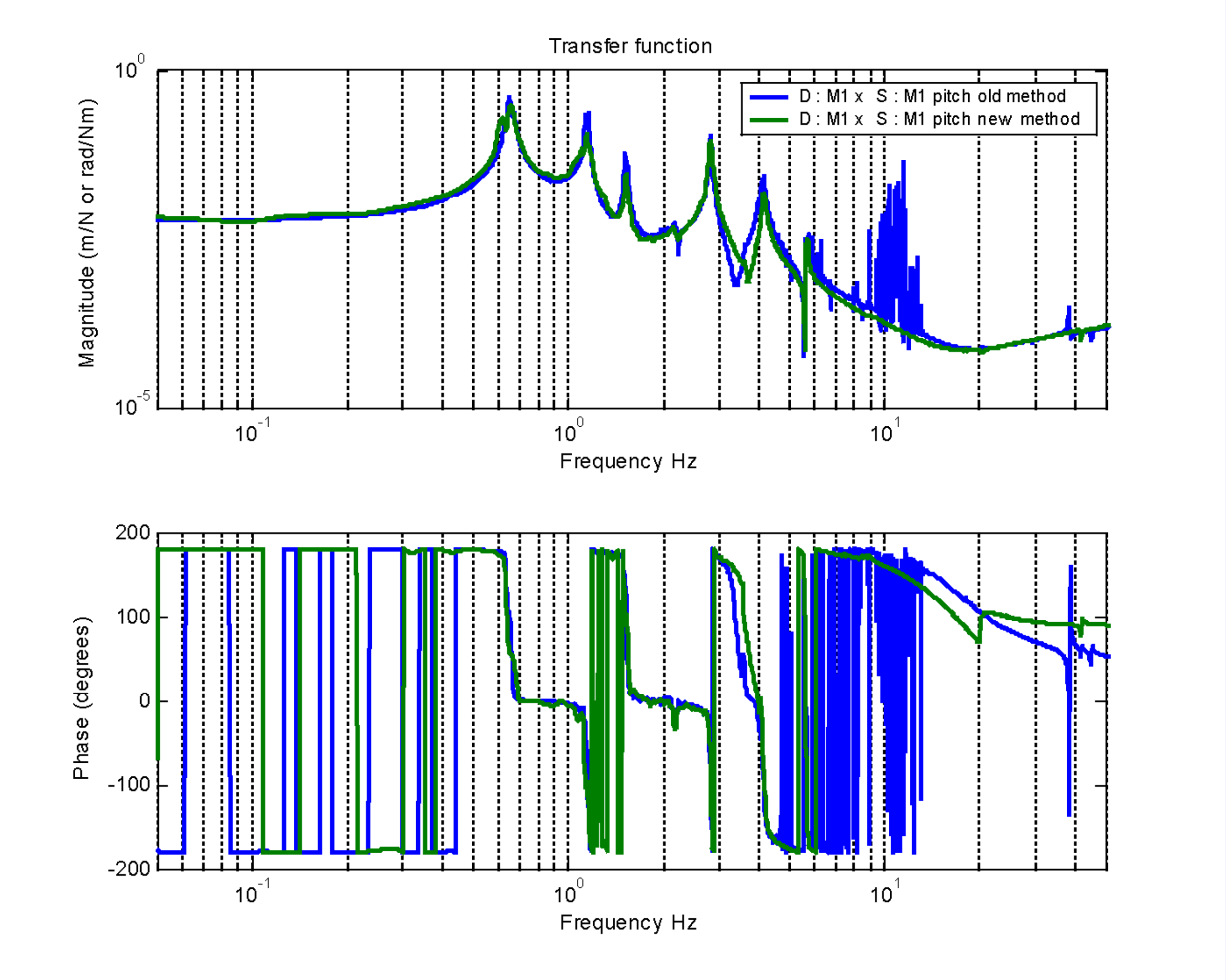
Transfer function
Magnitude (m/N or rad/Nm)
10^-4
10^-6
10^-8
D : Pla y S : OP Y
D : Pla y S : OP Y with bars
10^1
Frequency Hz
Phase (degrees)
200
100
0
-100
-200
10^0
10^1
Frequency Hz



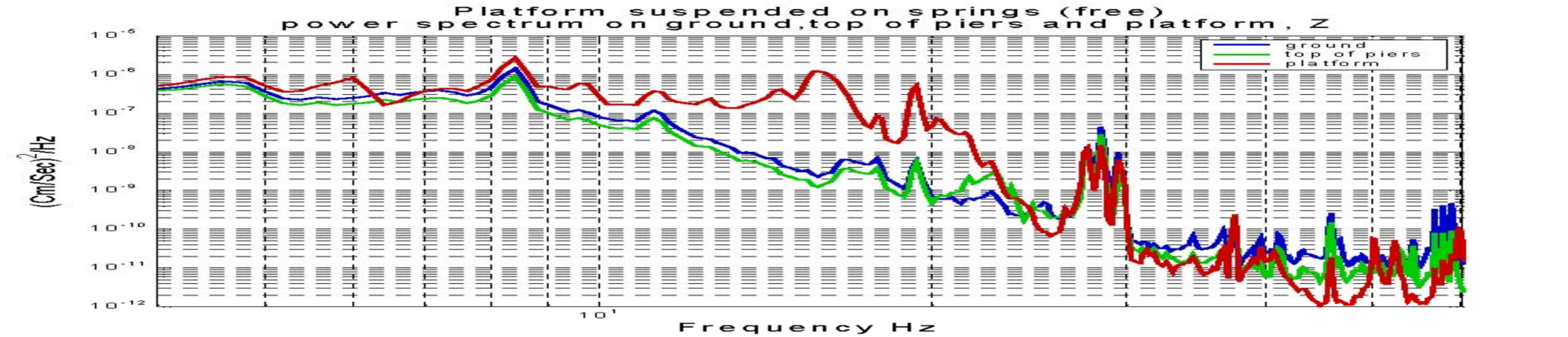
Transfer function
Magnitude (m/N or rad/Nm)
10^-4
10^-6
10^1
Frequency Hz
D : Pla x S : Pla X
D : Pla x S : Pla X with bars
Phase (degrees)
200
100
0
-100
-200
10^0
10^1
Frequency Hz
D : Pla x S : Pla X
D : Pla x S : Pla X

New acquisition method

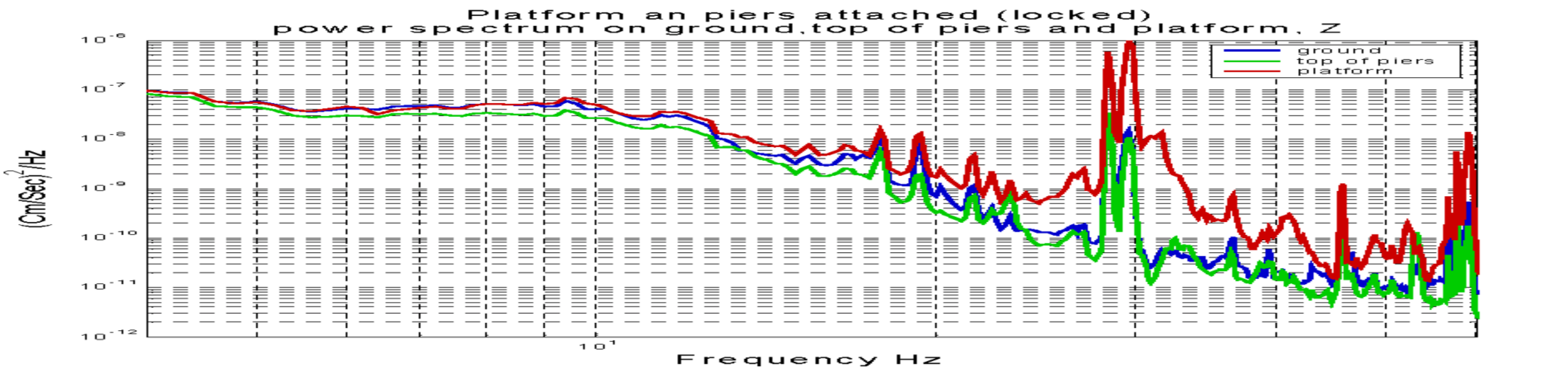
- Now use 3 sensors on the ground to clean the extra noise of the ground (amplified by the HEPI platform resonances (7,9,12 Hz))



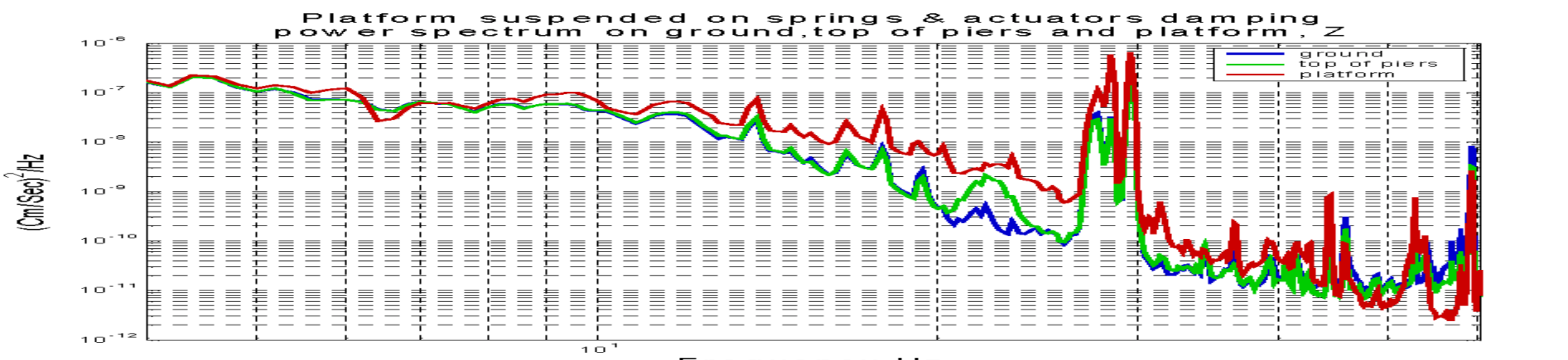
Z direction



Platform suspended on springs (free)
power spectrum on ground,top of piers and platform, Z
ground
top of piers
platform
(Cm/Sec)^2/Hz
Frequency Hz

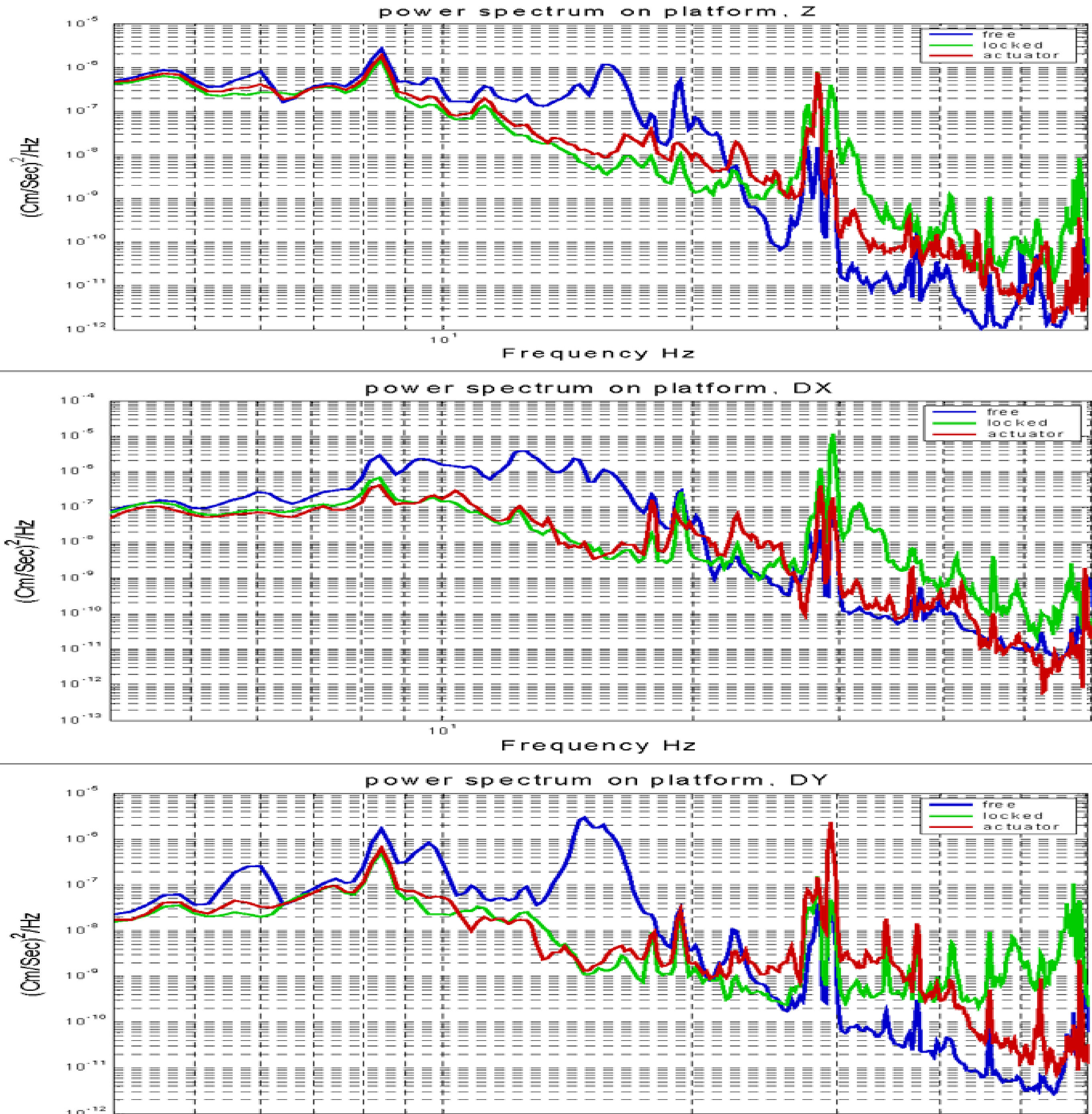


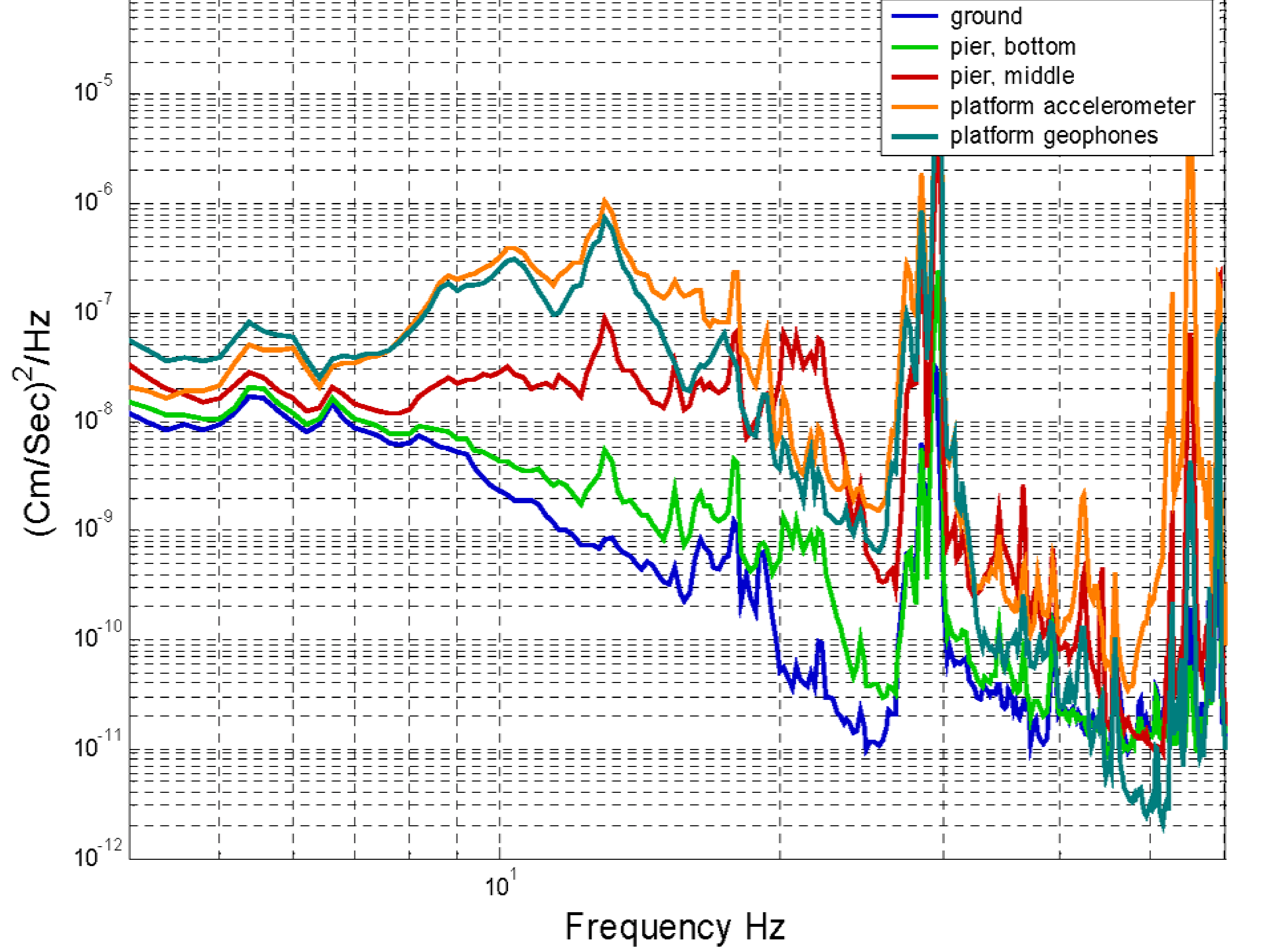
Platform an piers attached (locked)
power spectrum on ground,top of piers and platform, Z
ground
top of piers
platform
(Cm/Sec)^2/Hz
Frequency Hz



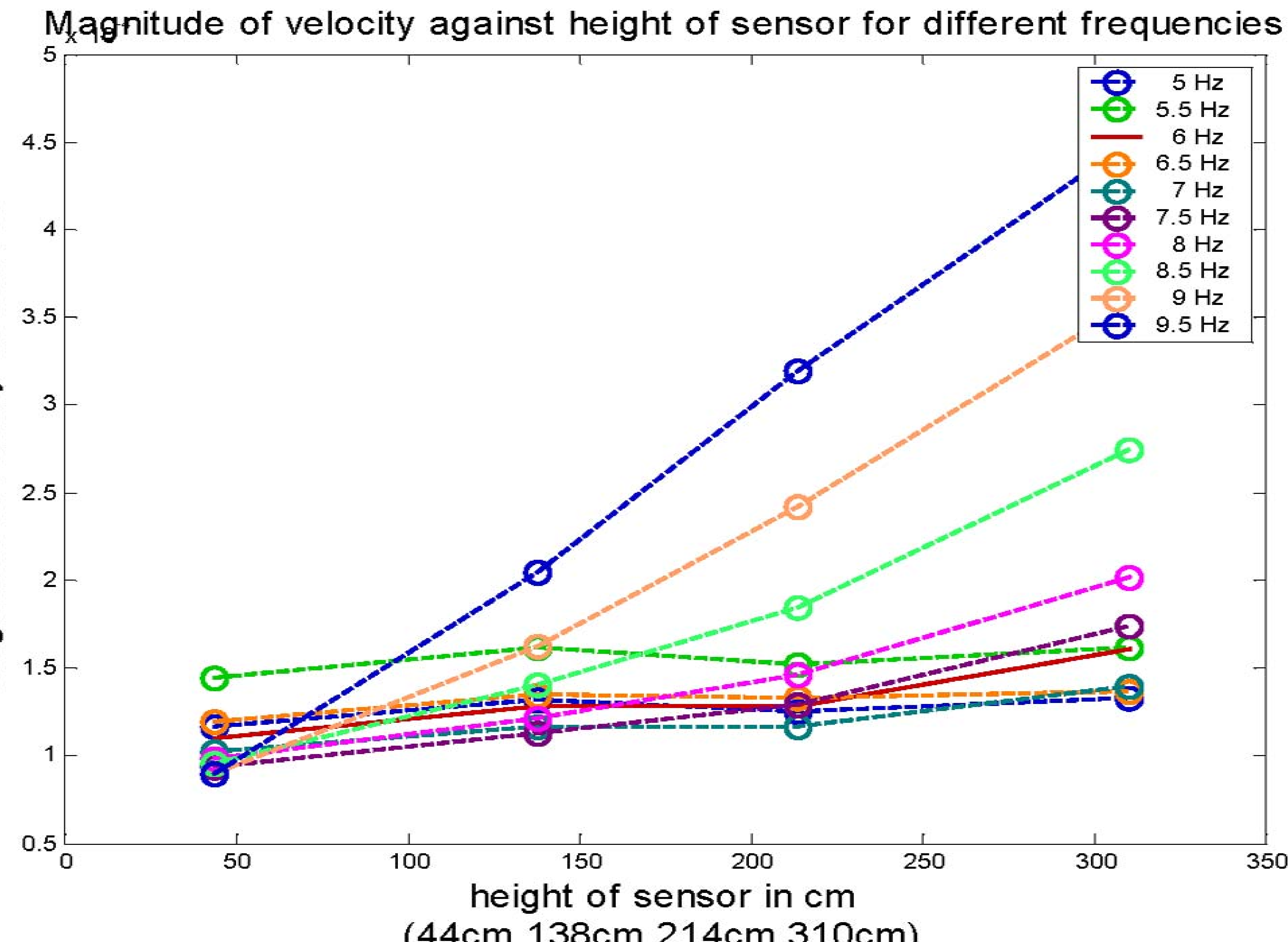
Platform suspended on springs & actuators damping
power spectrum on ground,top of piers and platform, Z
ground
top of piers
platform
(Cm/Sec)^2/Hz

Comparison

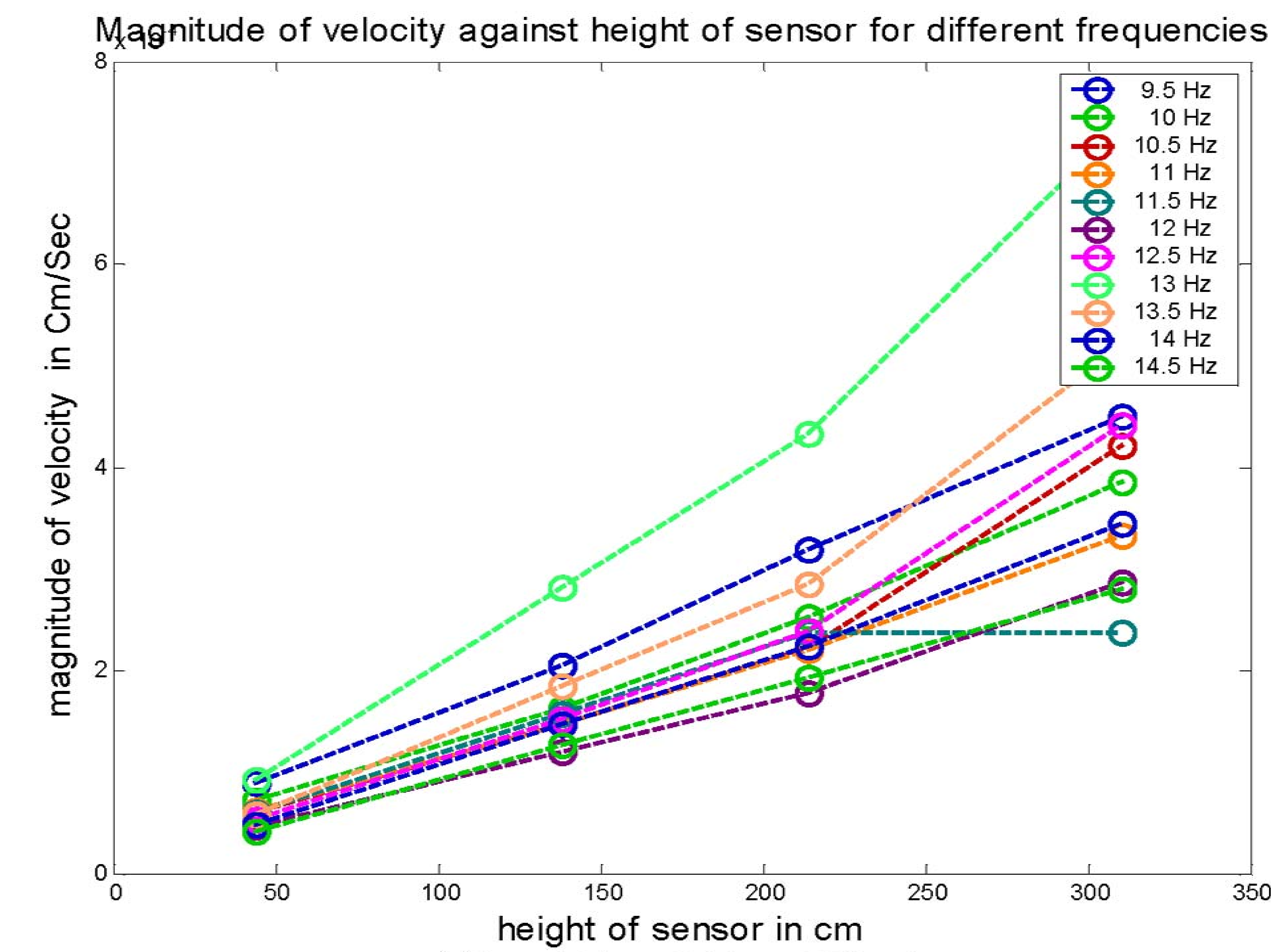

power spectrum on platform, Z
free
locked
actuator
(Cm/Sec)^2/Hz
Frequency Hz
power spectrum on platform, DX
free
locked
actuator
(Cm/Sec)^2/Hz
Frequency Hz
power spectrum on platform, DY
free
locked
actuator
(Cm/Sec)^2/Hz

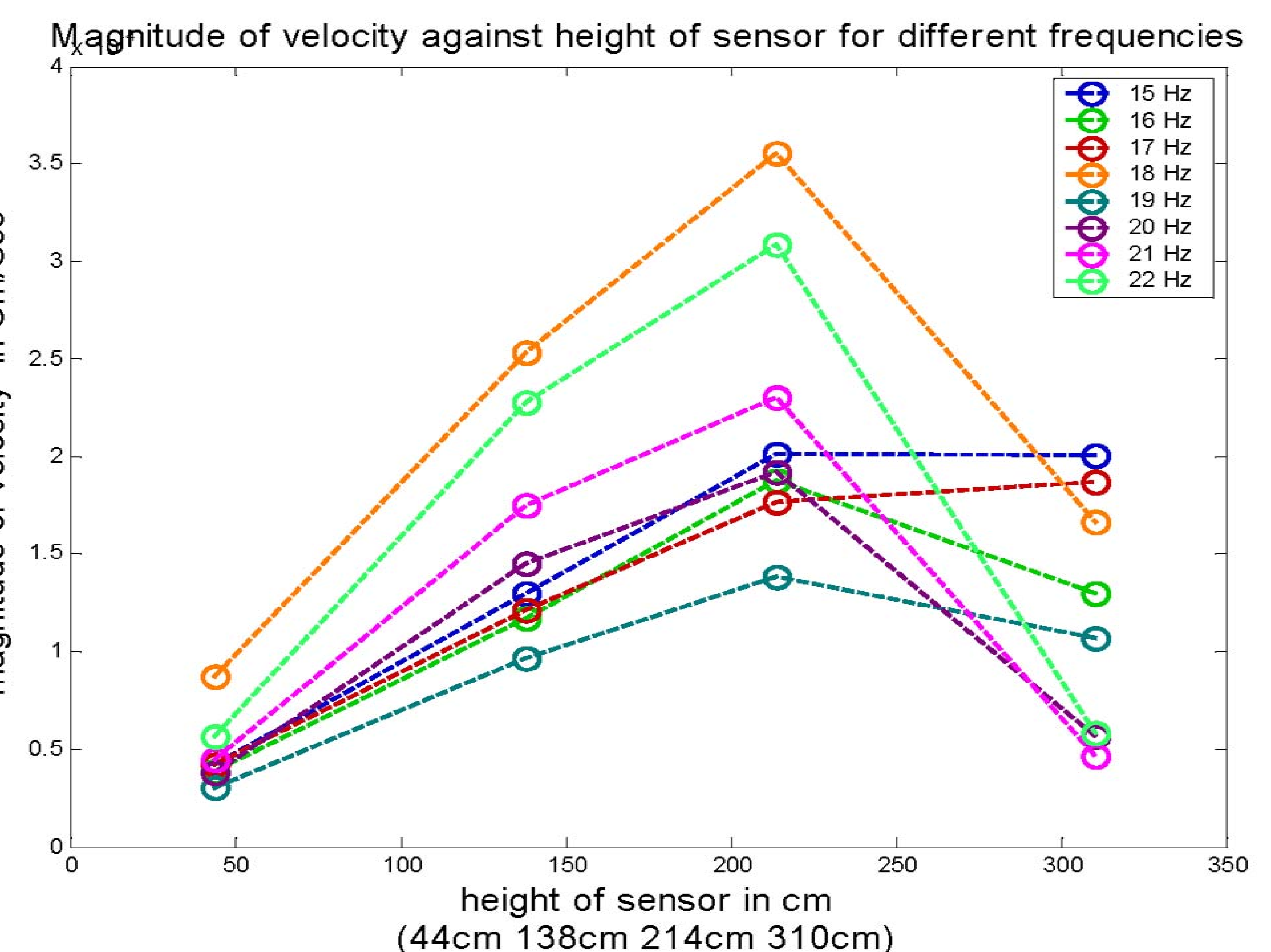


ground
pier, bottom
pier, middle
platform accelerometer
platform geophones
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$(Cm/Sec)^2/Hz$
10^{1}
Frequency Hz



Magnitude of velocity against height of sensor for different frequencies
x 10
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
50
100
150
200
250
300
350
5 Hz
5.5 Hz
6 Hz
6.5 Hz
7 Hz
7.5 Hz
8 Hz
8.5 Hz
9 Hz
9.5 Hz
height of sensor in cm
(44cm 138cm 214cm 310cm)


Magnitude of velocity against height of sensor for different frequencies
magnitude of velocity in Cm/Sec
height of sensor in cm
0
2
4
6
8
0
50
100
150
200
250
300
350
9.5 Hz
10 Hz
10.5 Hz
11 Hz
11.5 Hz
12 Hz
12.5 Hz
13 Hz
13.5 Hz
14 Hz
14.5 Hz



Magnitude of velocity against height of sensor for different frequencies
0
0.5
1
1.5
2
2.5
3
3.5
4
0
50
100
150
200
250
300
350
height of sensor in cm
(44cm 138cm 214cm 310cm)
15 Hz
16 Hz
17 Hz
18 Hz
19 Hz
20 Hz
21 Hz
22 Hz

$$\chi_{PS} = PS \times B$$

Transfer Function from dSpace to Position Sensors

$$\chi_{Geo} = Geo \times B$$

Transfer Function from dSpace to Support Table Geophones

$$\chi_{\sup} = F_{Geo}\chi_{Geo} + F_{PS}\chi_{PS}$$

Open Loop transfer function

$$\tilde{\chi}_W = A \times {Wit}/{STS}$$

Transfer Function from Ground STS to Witness Sensor

$$\chi_W = A \times Wit$$

Transfer Function from dSpace to Witness Sensor

$$\frac{\nu(\omega) \times Wit}{\beta(\omega) \times STS} = \frac{\tilde{\chi}_w - K_2 F_{\sup} F_{PS} \times \left[K_1 F_{STS} \chi_{Wit} - \chi_{PS} \left(\frac{Wit}{STS} \right) \right]}{1 + K_2 \chi_{\sup}}$$

Closed Loop Transfer Function from ground to witness sensor

THE

END