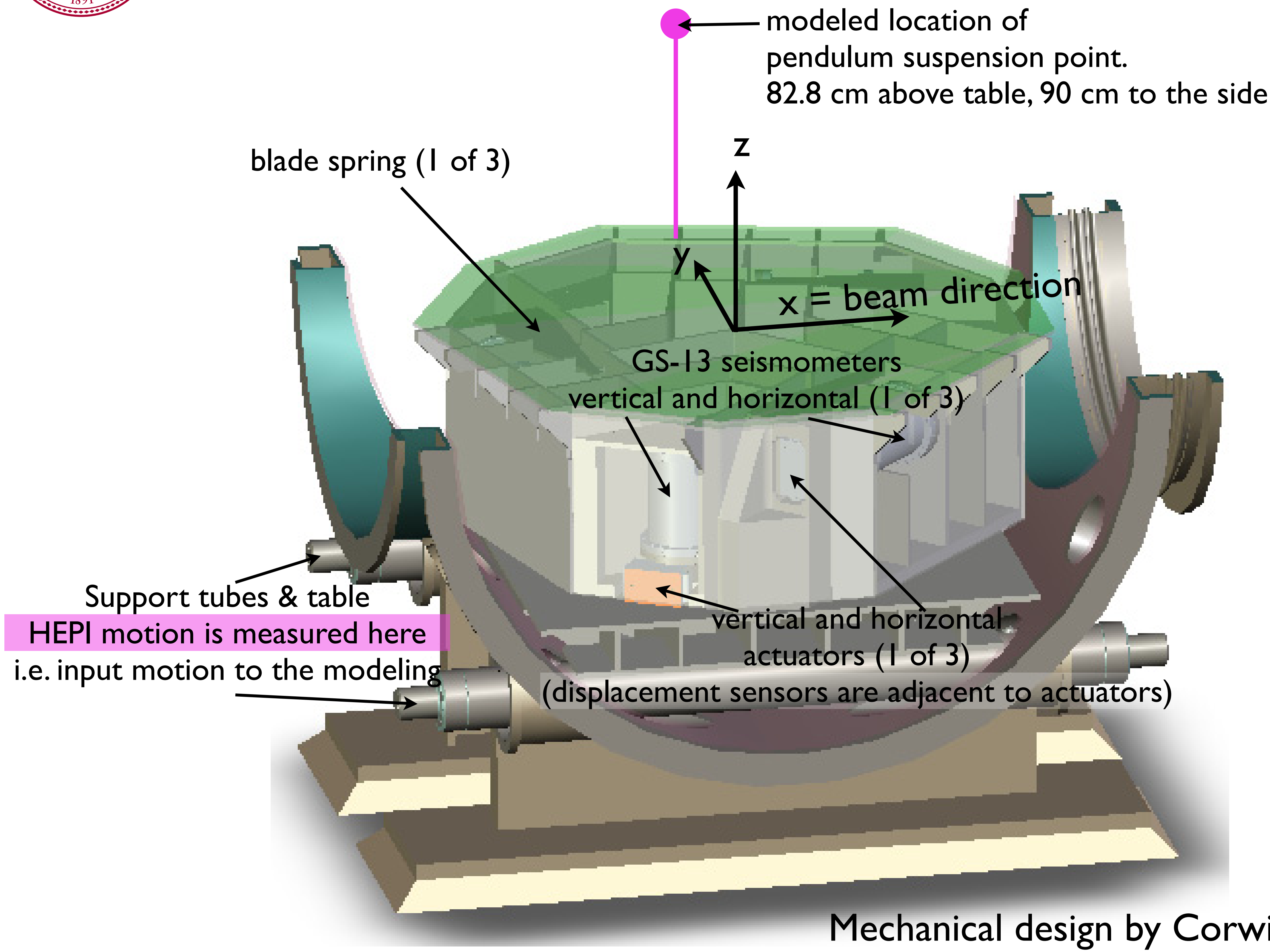
Materials for the Single Stage HAM review: Performance Modeling Info

Brian Lantz, March 31, 2006

Drawing of Single Stage HAM



Mechanical design by Corwin Hardham

Outline

Input motion

- Assume the system is supported by an external HEPI system
- Create a simple fit (fat green curve) to various performance data , shown on the next 4 pages. Fits are based on:
    - Measured motion of BSC HEPI
    - Measured motion of HAM HEPI
    - HAM HEPI still needs to incorporate feedback inertial sensors, so current performance above a few Hz is not as good as we expect for Advanced LIGO (or even initial LIGO), this is especially clear in Z.
    - HAM HEPI rX and rY are now different, I picked the best one.
    - HAM X is not good at 0.1 Hz, yet the optics table for HAM X is very good. HAM sensors are probably contaminated by tilt. I've picked BSC performance around the microseism, which has better instrumentation.
    - Based on the 90th percentile of motion for 3-10 Hz band horizontal.
    - HAM data and floor data by Shyang Wen, presented at LSC meeting, LIGO-G060125-00-L.

HEPI motion estimate: X&Y

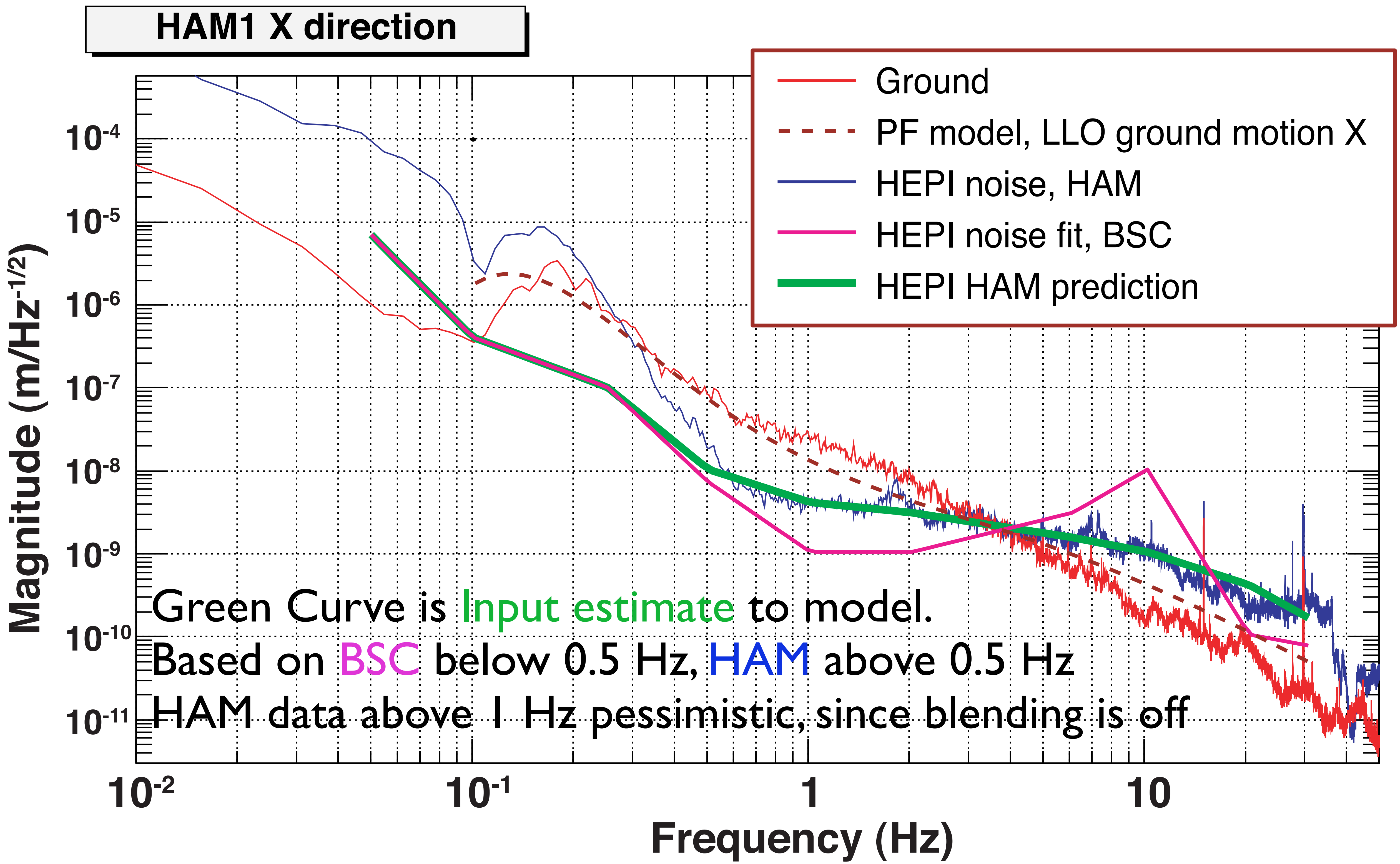


figure adapted from Shyang Wen, HAM1.pdf, SEI log #604

HEPI motion estimate: Z

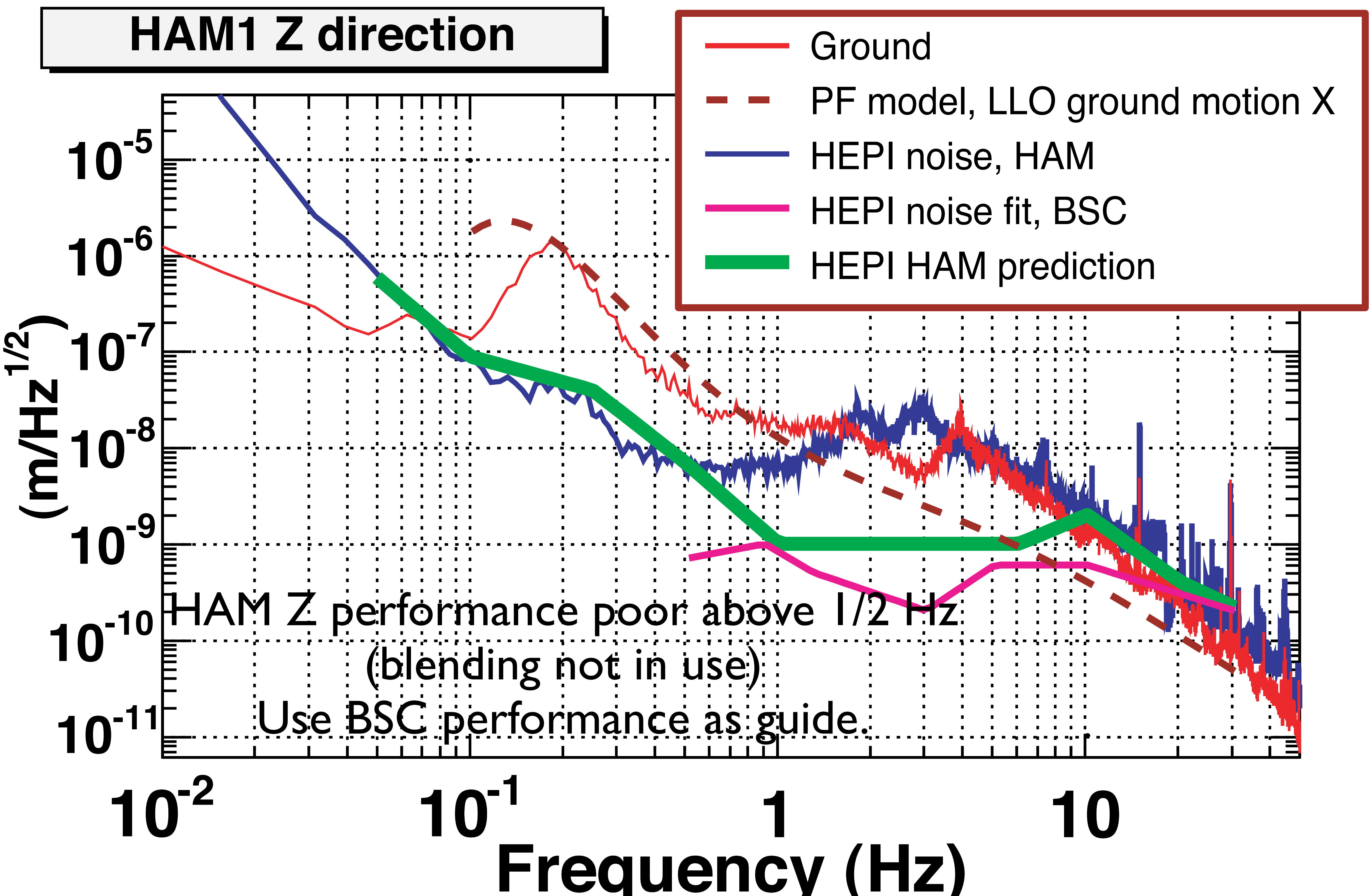


figure adapted from S. Wen LIGO-G060125

HEPI motion estimate: rX & rY

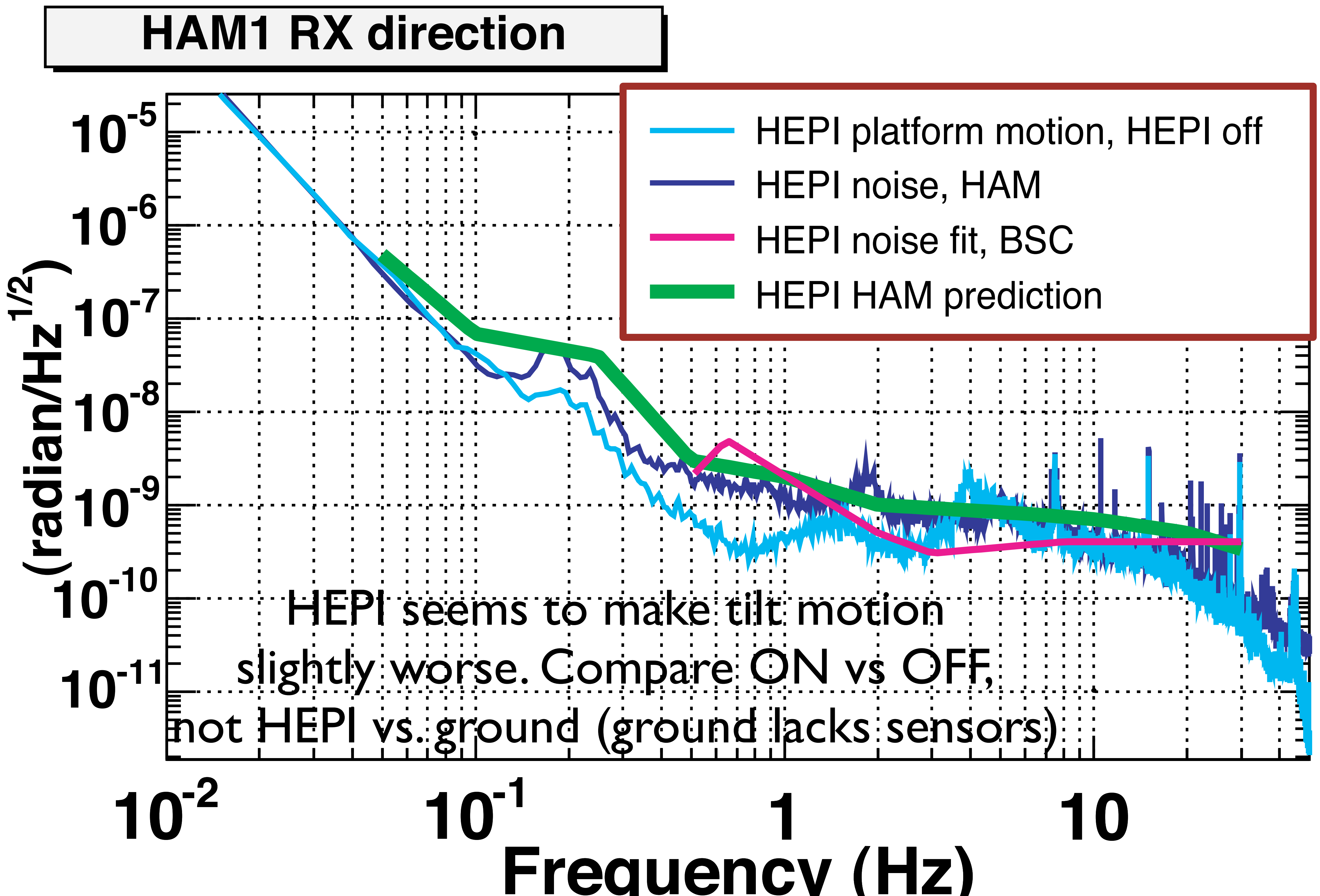


figure adapted from S. Wen LIGO-G060125

HEPI motion estimate: rZ

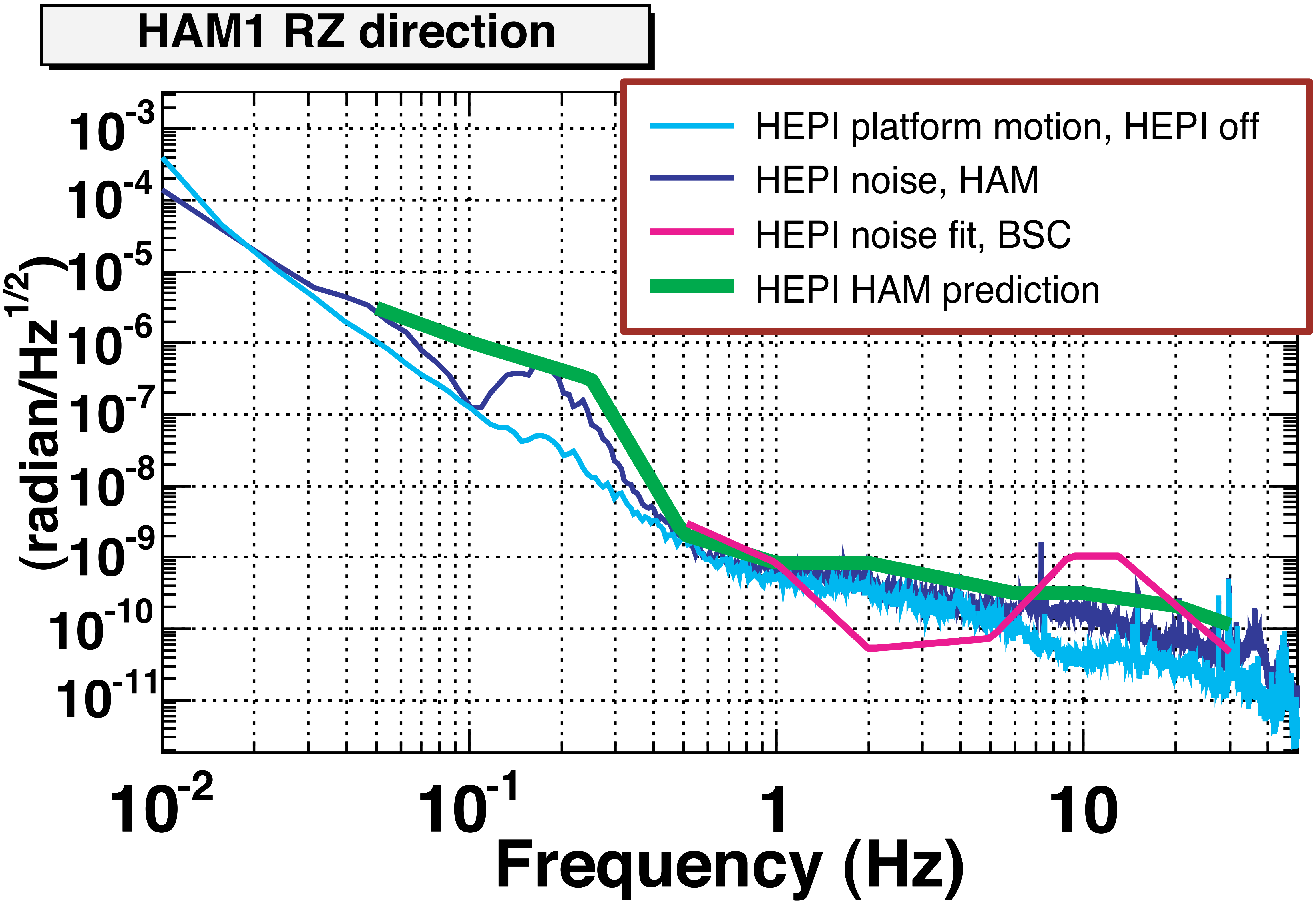


figure adapted from S. Wen LIGO-G060125

Percentiles of Motion

When this HAM data was taken, the band limited RMS velocity of the floor was

STATION,DIRECTION	0.1-0.3Hz		0.3-1Hz		1-3Hz		3-10Hz	
CORNER, X	7.81e-007	(75%)	2.59e-007	(70%)	2.06e-007	(80%)	1.21e-007	(90%)
CORNER, Y	7.5e-007		2.22e-007		1.85e-007	(75%)	1.13e-007	
CORNER, Z	4.09e-007	(80%)	1.21e-007	(50%)	3.52e-007	(80%)	5.18e-007	(95%)

data in rms meters/sec, in the band. Percentiles based on LLO data from E. Daw et. al 'Long Term Study of the Environment at LIGO'.

velocities at the 95th percentile for LLO & LHO are: (and the 95% is larger than our data by):

LLO Corner X	1.7 e-6	(*2.2)	6.3e-7	(*2.4)	4.0e-7	(*2.0)	1.6e-7	(*1.3)
LLO Corner Y	1.7 e-6	(*2.3)	6.3e-7	(*2.9)	3.8e-7	(*2.1)	2.0e-7	(*1.8)
LLO Corner Z	0.91e-6	(*2.2)	5.6e-7	(*4.6)	7.5e-6	(*2.1)	6.1e-7	(*1.2)
LHO Corner X	0.60e-6	(*0.7)	1.3e-7	(*0.5)	1.2e-7	(*0.6)	2.1e-7	(*1.7)
LHO Corner Y	0.58e-6	(*0.8)	1.2e-7	(*0.5)	1.2e-7	(*0.7)	2.3e-7	(*2.1)
LHO Corner Z	0.78e-6	(*1.9)	0.9e-7	(*0.7)	1.0e-7	(*0.3)	4.0e-7	(*0.8)

data from Shyang Wen, SEI log entry #604

Plant Parameters

- Single stage system.
- Natural frequencies between 1 and 2 Hz.
- Uses capacitive displacement sensors and GS-13 inertial sensors.
- Details on next page
- LZMP is the Lower Zero-Moment Plane;
  horizontal actuation at this plane generates no tilt.

Various parameters used in the HAM model

parameters of the 1 stage HAM isolation system

mass of stage (kg, structure)	1400
mass from Corwin (for comparison)	1166
trim mass (kg)	100
payload total (kg)	510
payload fixed (kg)	435
payload suspended (kg)	75
total stage 1 fixed mass (kg)	1935
Ixx (kg-m^2) (for 1935 kg)	759
Rad Gyr X (m)	0.627
Iyy (kg-m^2)	797
Rad Gyr Y (m)	
Izz (kg-m^2)	770
Rad Gyr Z (m)	0.631
f0 - X (Hz)	1.22
f0 - Z (Hz)	1.83
f0 -rX (Hz)	1.04
f0 - rZ (Hz)	0.984
horizontal stiffness (N/m)	1.10E+05
vertical stiffness (N/m)	2.54E+05
rX stiffness (N-m/rad)	3.33E+04
rZ stiffness (N-m/rad)	2.93E+04
blade stiffness (N/m)	8.60E+04
blade length (m)	0.474
blade width (m)	0.237
blade thickness (m)	0.0107
tip radius (m)	0.512
effective rod length (m)	0.132
height of cg above LZMP (m)	0.048

(tip radius is the distance from center of table out to the flexures which are located at the tips of the blade springs - important for rotational stiffness)

Stiffness and Compliance

DC stiffness is similar to existing HAM platform

stiffness defined as F = K*X

compliance is X = C*F

Below is the DC compliance matrix for our model, and for the existing HAM stack.
for 6 DOF systems, compliance is what we are used to,
ie, push on the system, measure how far it moves.
(vs. put in a 6 DOF offset, and measure the resulting force)
F in N or N-m, X in m or radians

```
>> comp = 1e-12*(round(1e12*inv(-mvReaction)))
comp =
   9.0528e-06            0            0      7.73e-10   1.4465e-06            0
            0   9.0528e-06            0   -1.4465e-06     7.73e-10            0
            0            0   3.9346e-06             0            0     -7.71e-10
     7.73e-10  -1.4465e-06            0    2.9967e-05            0            0
   1.4465e-06     7.73e-10            0             0   2.9967e-05            0
            0            0    -7.71e-10             0            0   3.4109e-05
>> 1./diag(comp)
ans =
   1.1046e+05
   1.1046e+05
   2.5415e+05
        33371
        33371
        29318
```

'Stiffness' for x, y, z, rx, ry, rz
(N/m or N-m/rad)

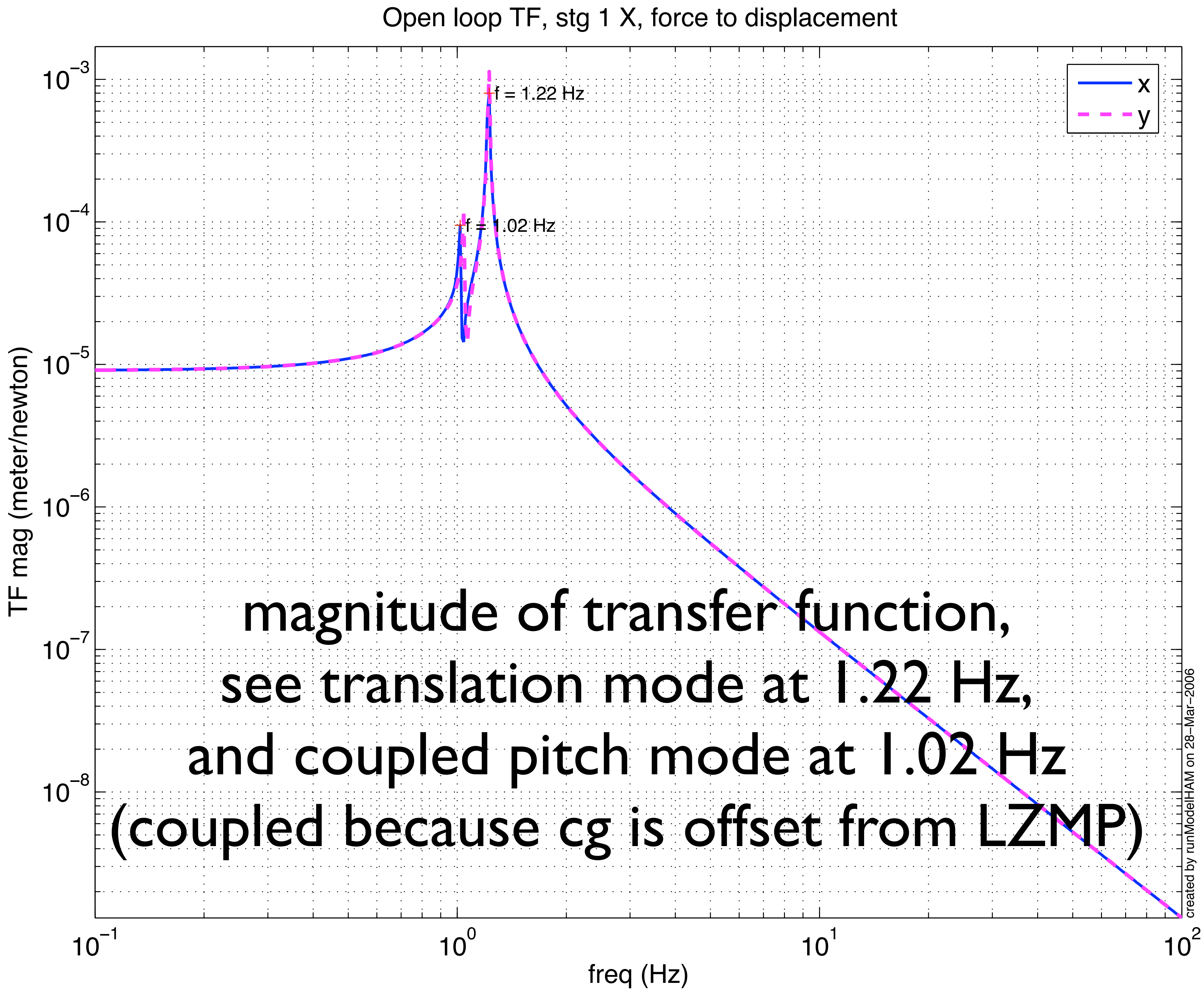
Proposed Single Stage HAM

```
HAM_stack_comp =
   1.0162e-05            0            0            0   9.9035e-06            0
            0   8.3301e-06            0  -4.2746e-06            0            0
            0            0    3.029e-06            0            0            0
            0  -4.2746e-06            0   1.3134e-05            0            0
   9.9035e-06            0            0            0    3.043e-05            0
            0            0            0            0            0   2.0404e-05
>> 1./diag(HAM_stack_comp)
ans =
        98406
   1.2005e+05
   3.3014e+05
        76138
        32862
        49010
```

Current HAM stack

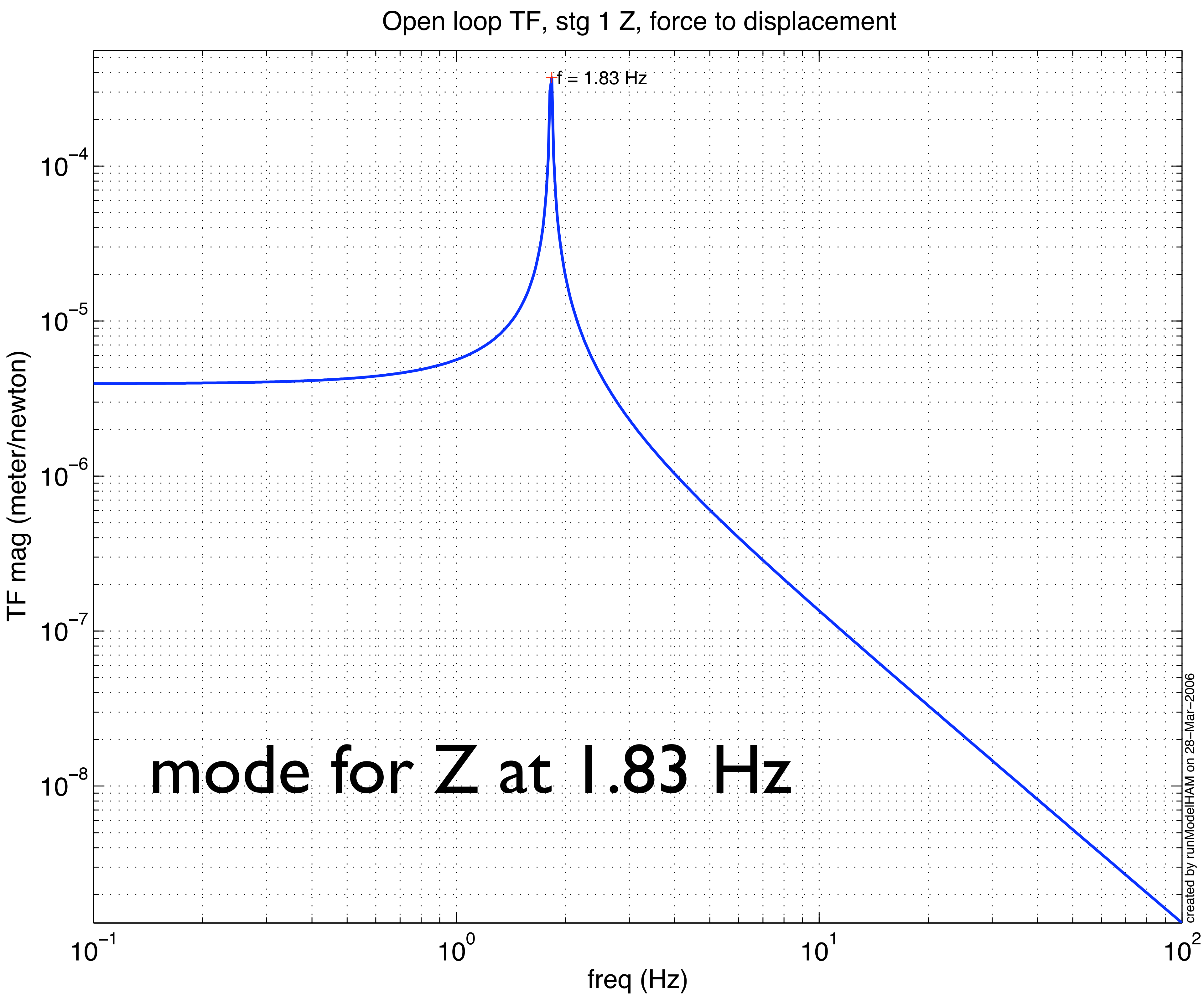
based on Hytec model

Open Loop plant plots X&Y

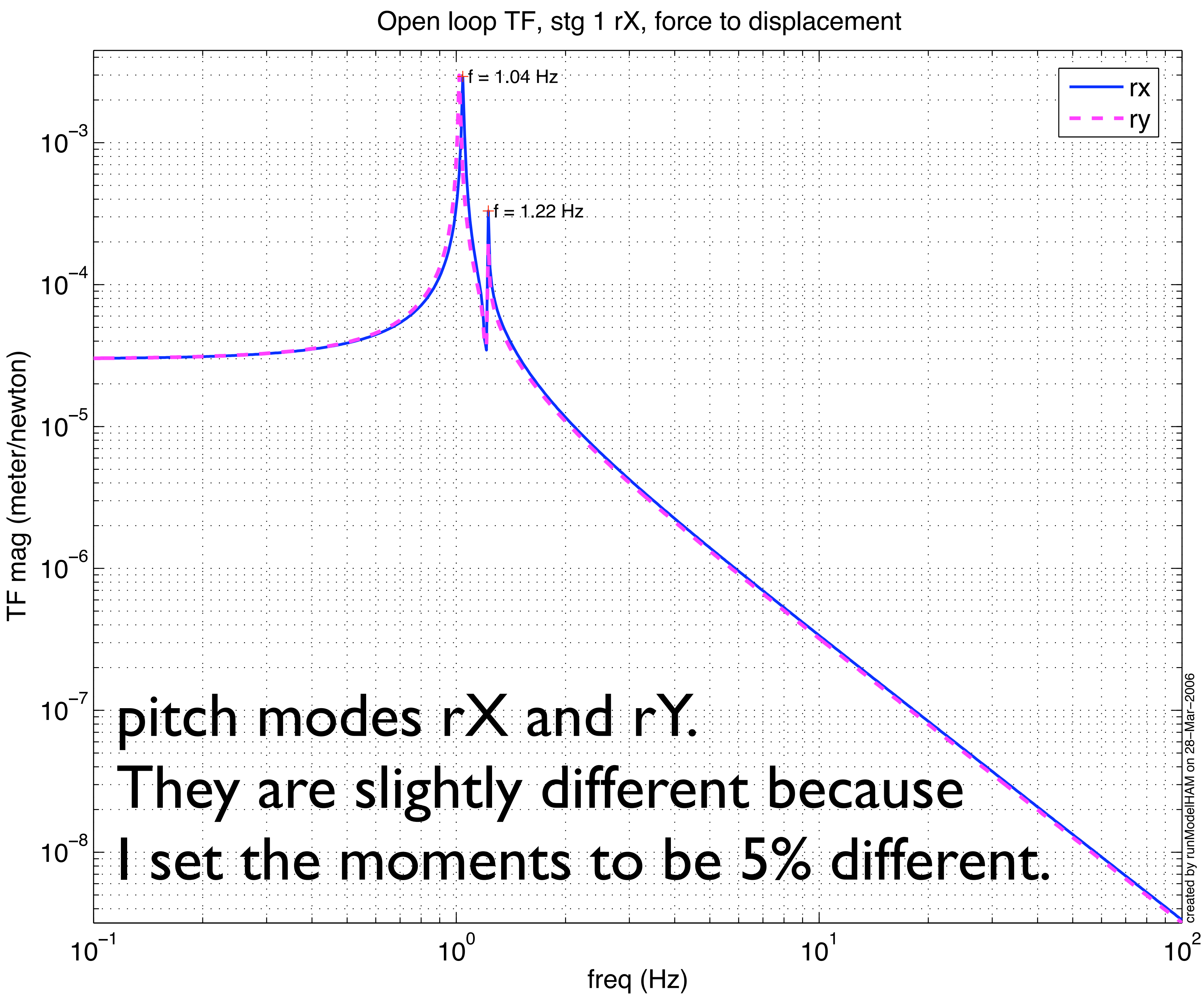


magnitude of transfer function,
see translation mode at 1.22 Hz,
and coupled pitch mode at 1.02 Hz
(coupled because cg is offset from LZMP)

Open Loop plant plots Z

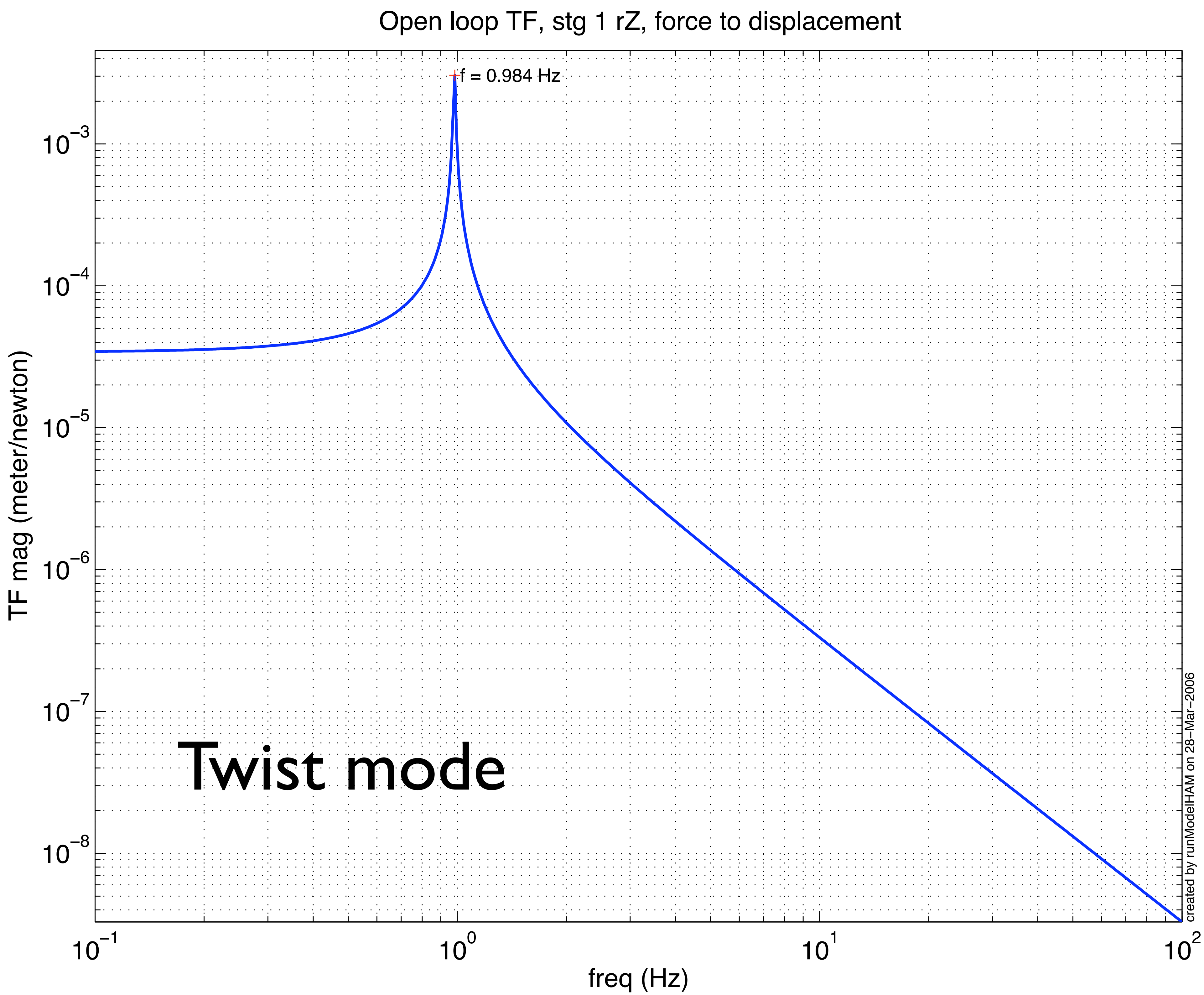


Open Loop plant plots rX & rY



pitch modes rX and rY.
They are slightly different because
I set the moments to be 5% different.

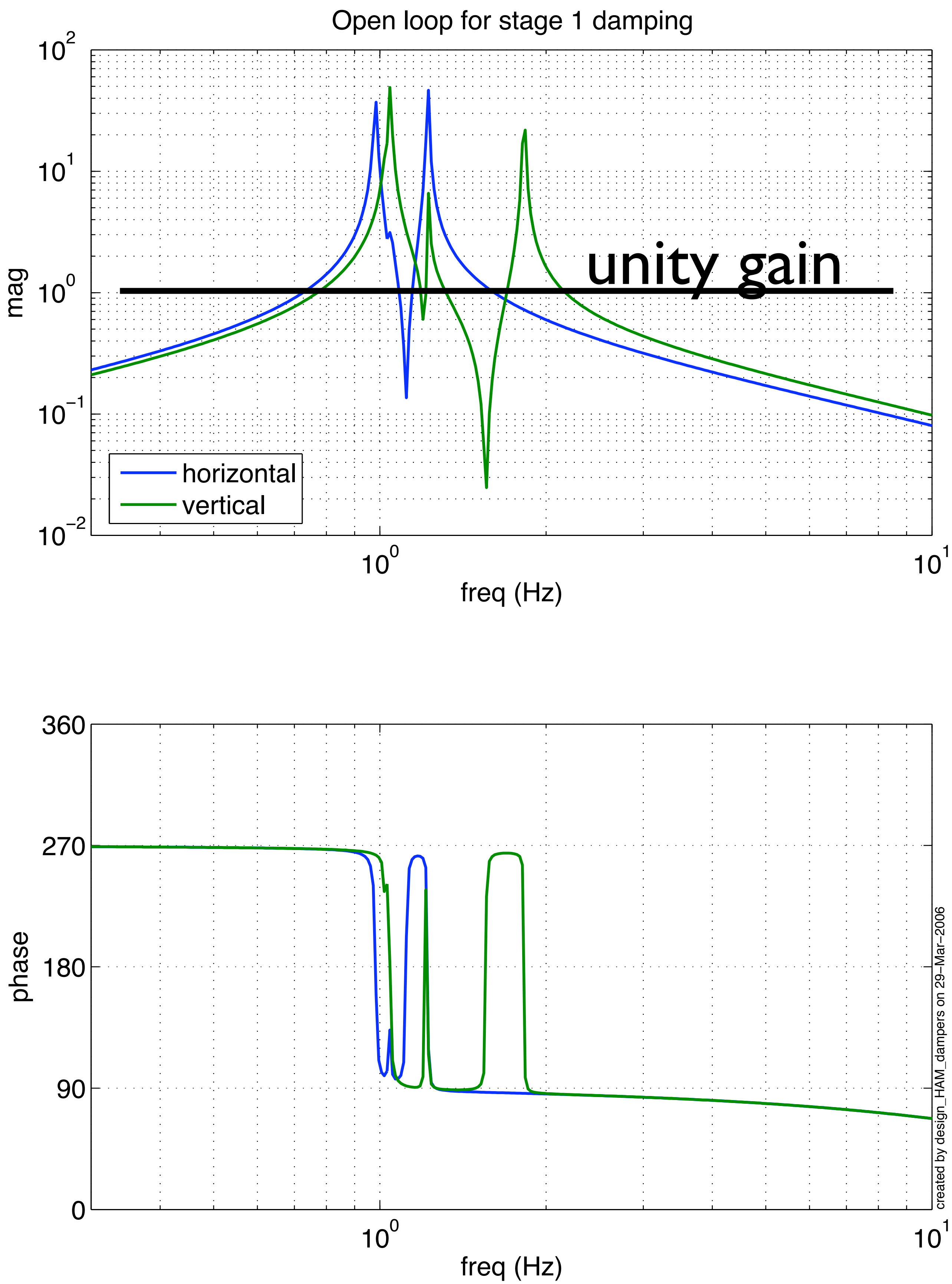
Open Loop plant plots rZ



Damping Loops

- 6 Simple SISO loops are used to damp the 6 body modes of the system.
- Run from local inertial sensor to the co-located actuator. 3 identical vertical loops, and 3 identical horizontal loops
- Damp to inertial space (really isolation, but just at peaks).
- Used to make the 6 co-ordinate plant directions better behaved, to simplify the isolation loops.
- Essentially identical to Stanford ETF system.

Damping loops



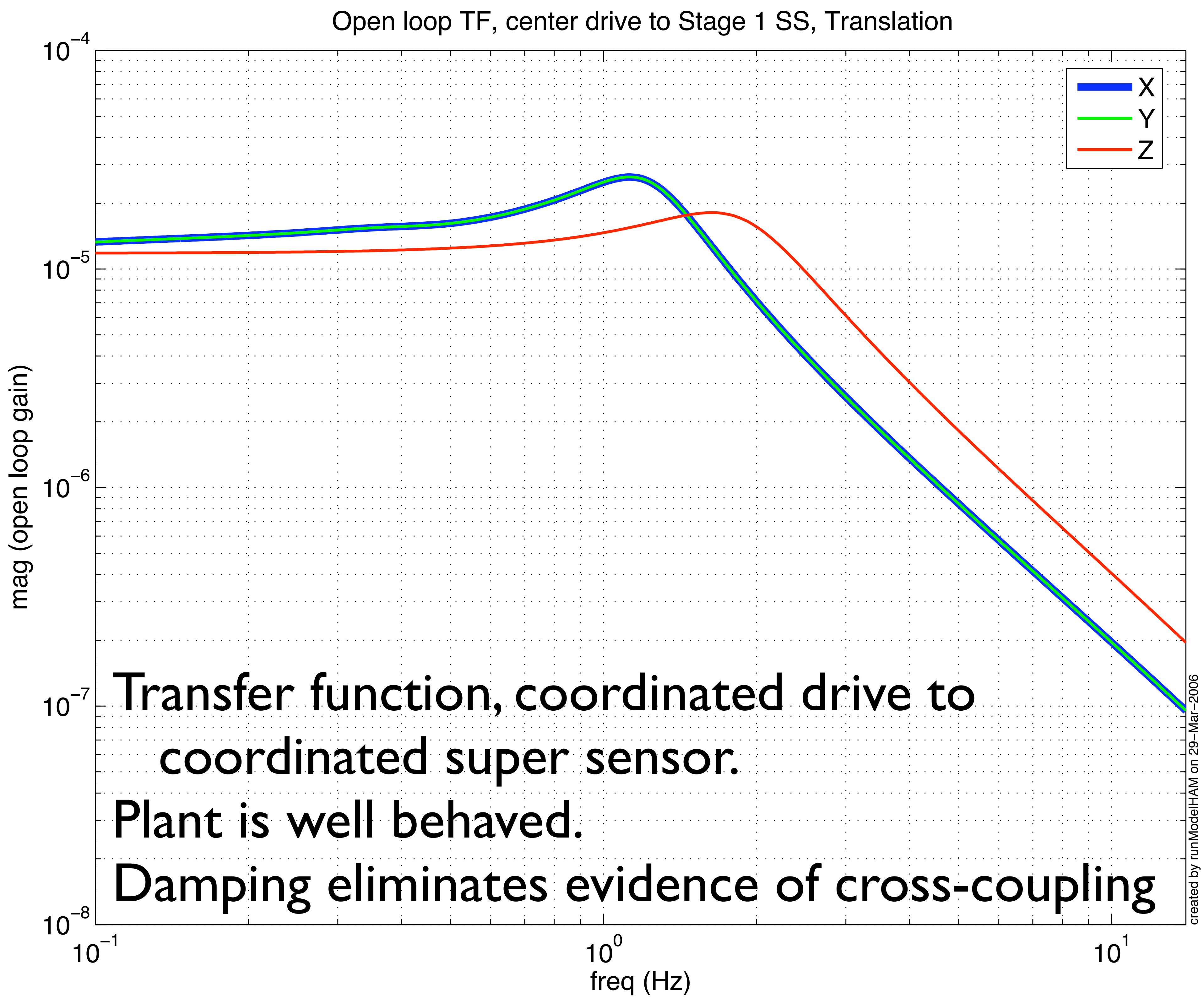
* open loop Bode plot for the damping loops.

* 3 vertical loops and 3 horizontal loops

* very simple damping loops

* loops closed with a plus sign, so phase needs to avoid 0, not -180 degrees.

Damped plant - translation

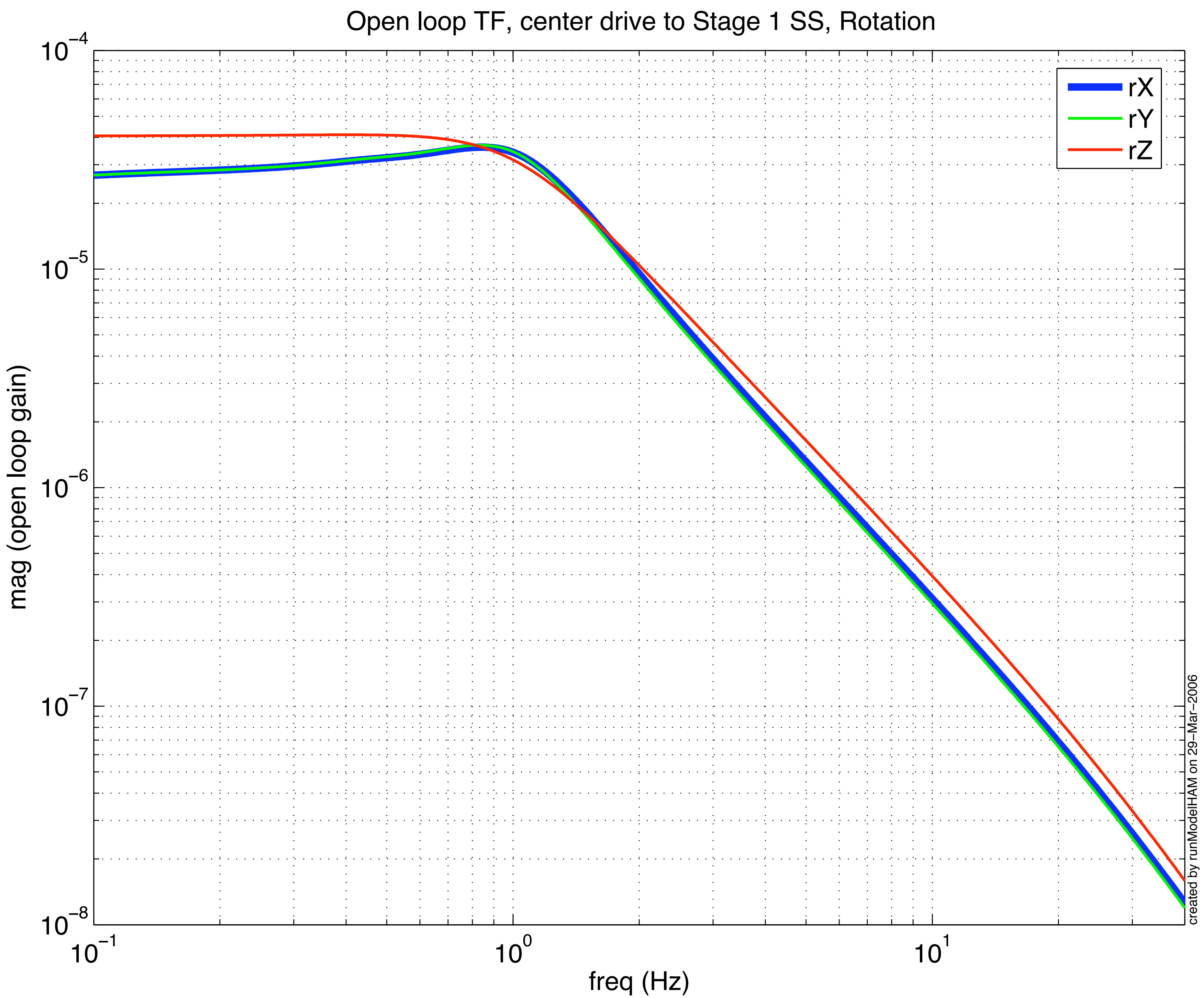


Transfer function, coordinated drive to coordinated super sensor.

Plant is well behaved.

Damping eliminates evidence of cross-coupling

Damped Plant - rotation



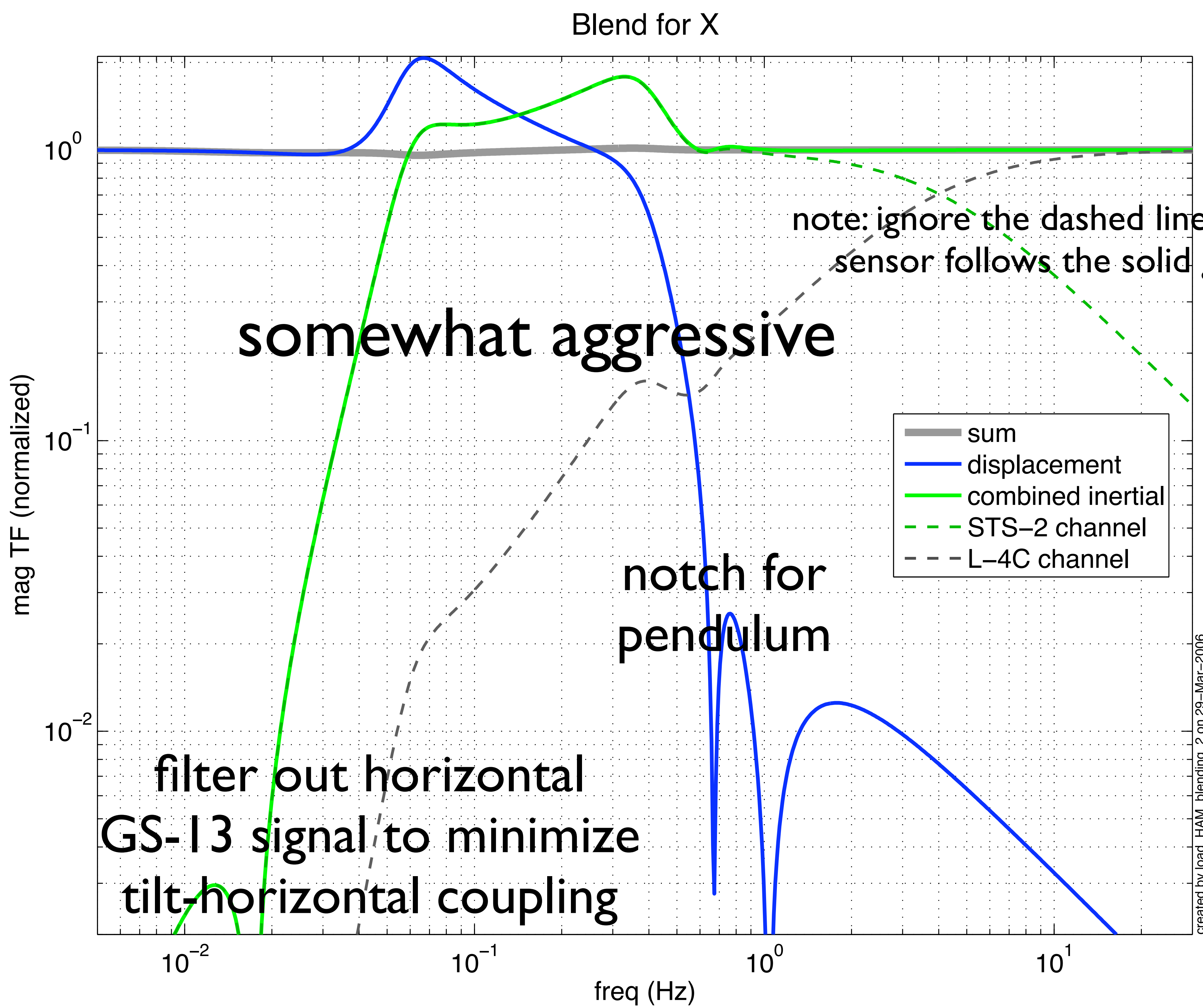
Blending loops

- Use displacement sensors at low frequency, GS-13 inertial sensors at high frequency.
- Each set of 6 sensors (displacement or inertial) is projected into a "coordinate system" basis (x, y, z, rx, ry, rz).
- center of system is at the center of the lower zero moment plane (not the cg). Choice isn't critical, ETF uses the center of the 3 STS-2 sensors.
- projected sensors are blended, i.e. supersensor X is composed of projected displacement sensor X and projected inertial sensor X.
- X and Y are the same, rX and rY are the same.
- All modeled loops are IIR, not the cool FIR 'Hua style' loops. This makes the modeling easier.
- These loops are good, but not optimal. I don't have a definition of optimal...

More on blending

- X, Y, rX and rY much more aggressive than Z and rZ.
  - to counter tilt (X and Y), and
  - vertical sensor noise generating tilt (rX and rY).
- Notches at 0.67 Hz to minimize rms from first pendulum mode.
- Grey sum line not exactly one because I've cancelled nearby poles and zeros to improve processing time.
- Dashed lines an artifact of model tool, which used to use 3 different sets of sensors for stage 1. Compare just the solid green and blue curves to see performance.
- Isolation from input motion occurs only when inertial sensor (green) dominates the response.

Blending for X & Y



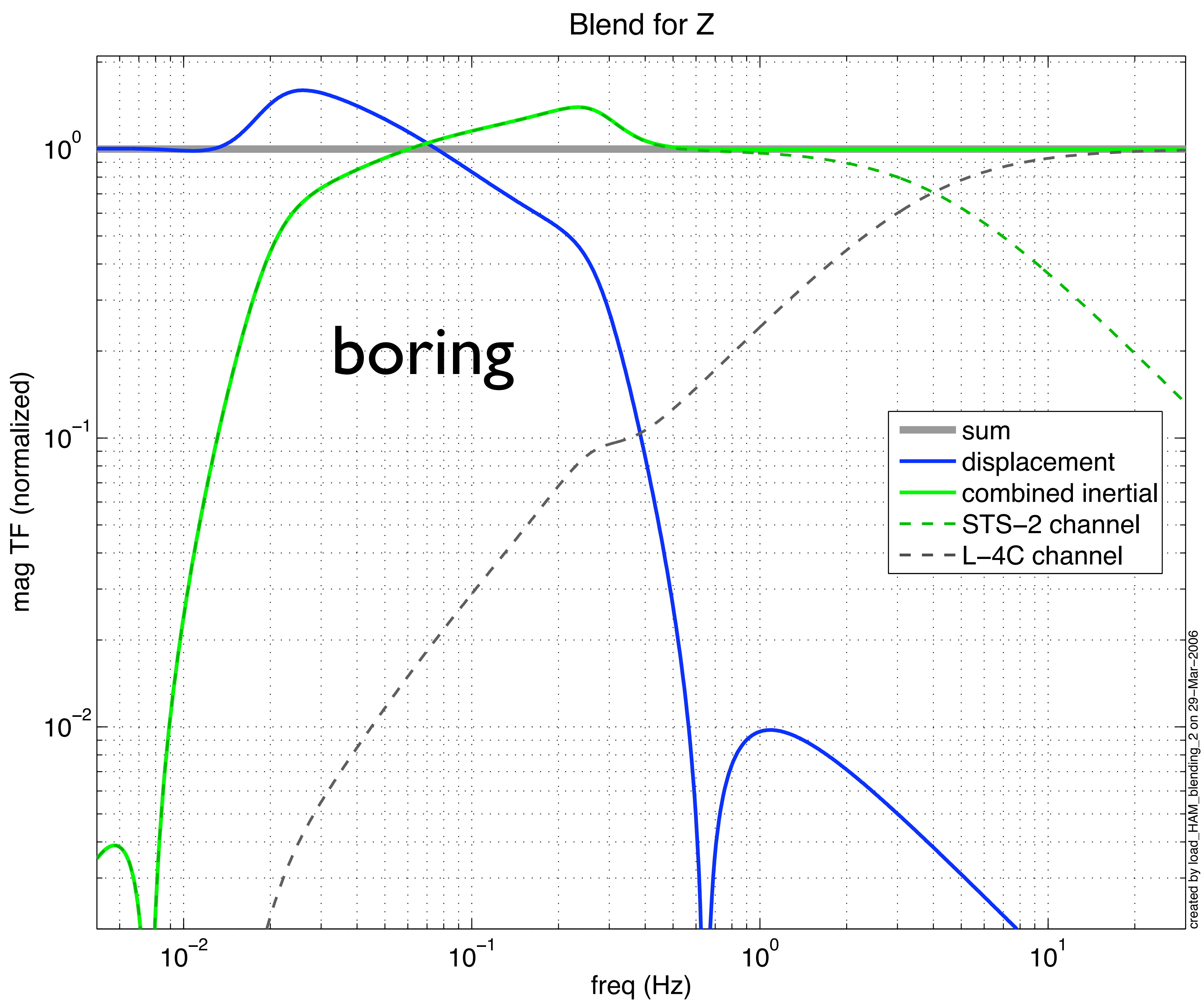
note: ignore the dashed lines, the inertial sensor follows the solid green line.

somewhat aggressive

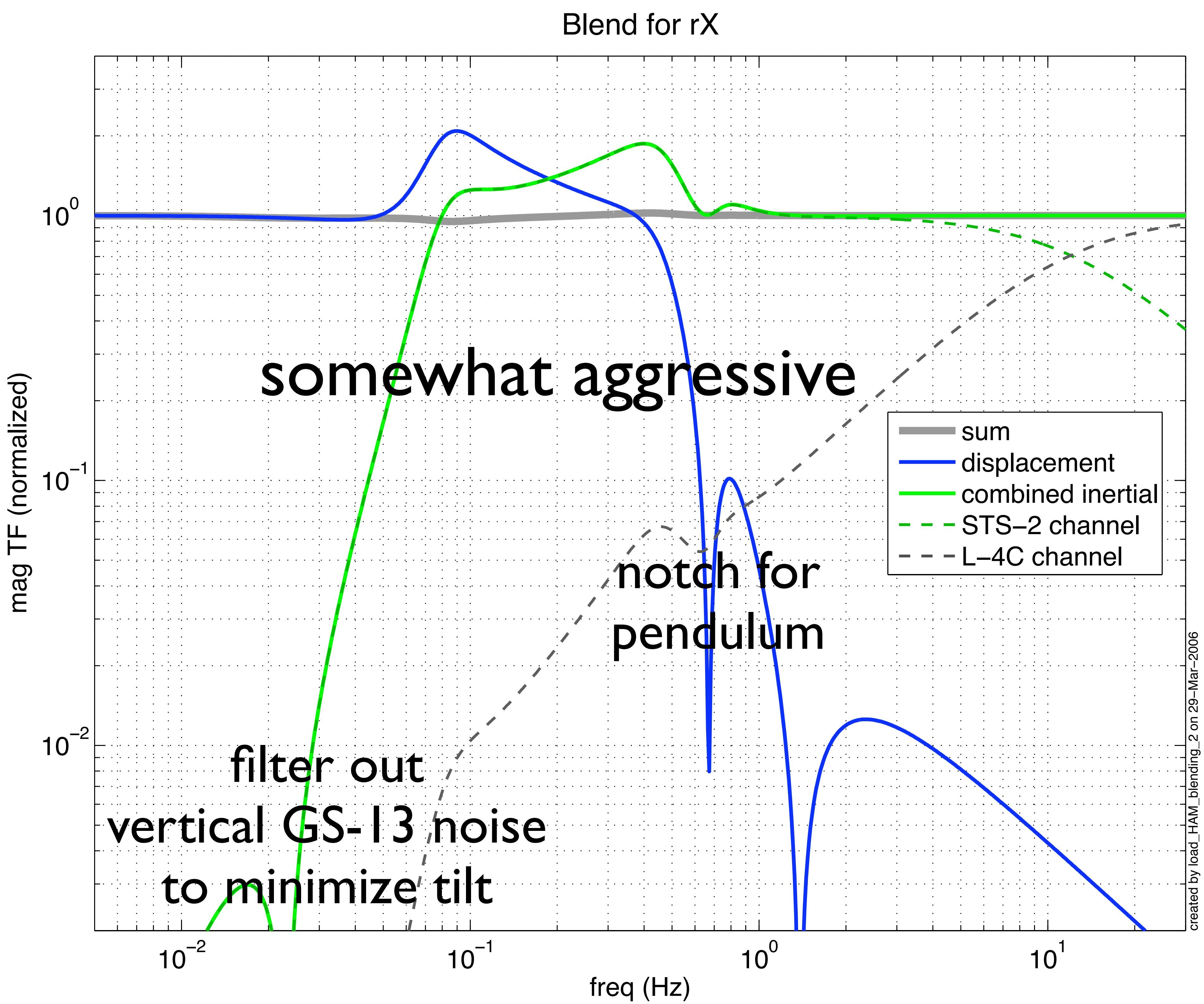
notch for pendulum

filter out horizontal GS-13 signal to minimize tilt-horizontal coupling

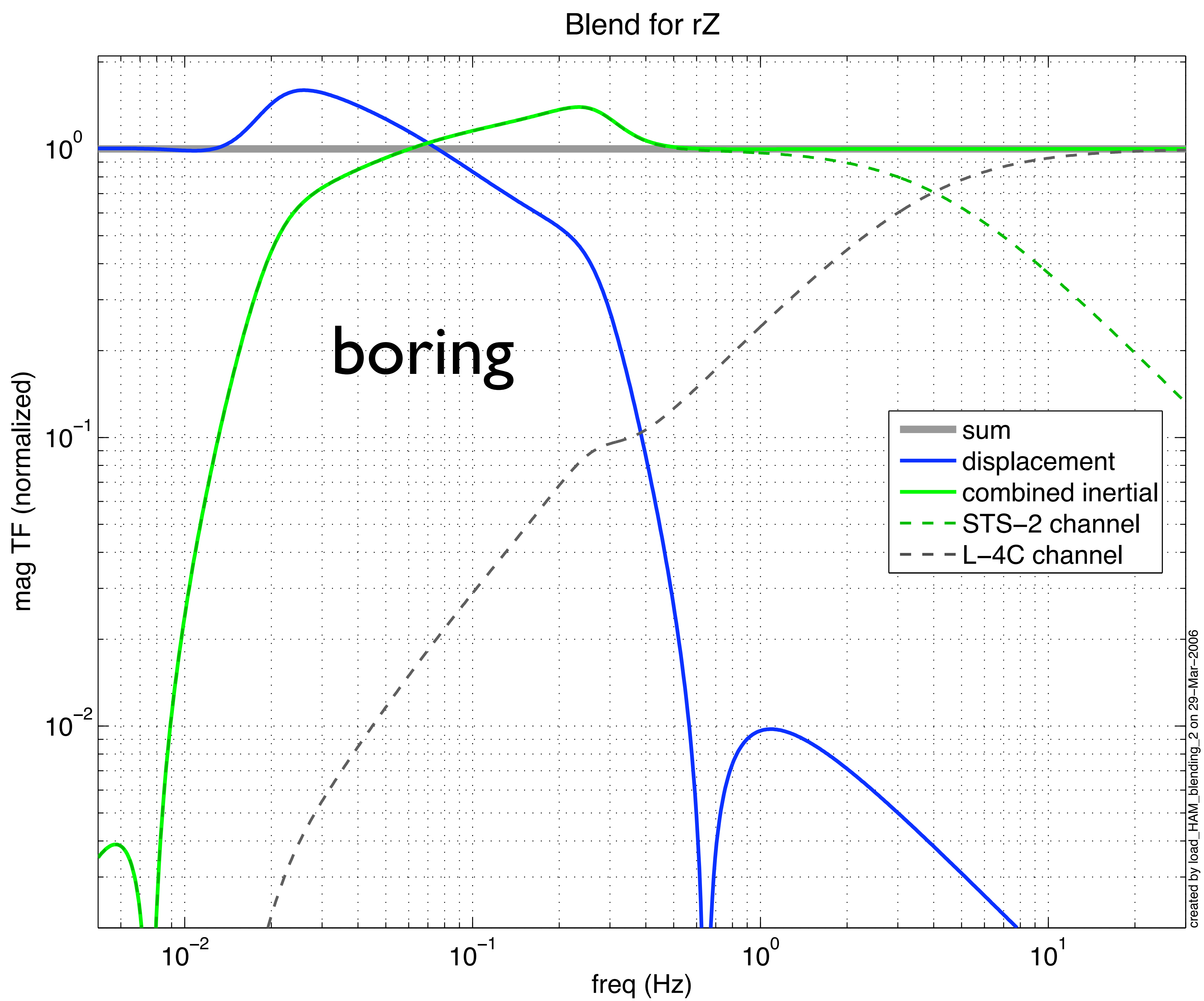
Blending for Z



Blending for rX & rY



Blending for rZ

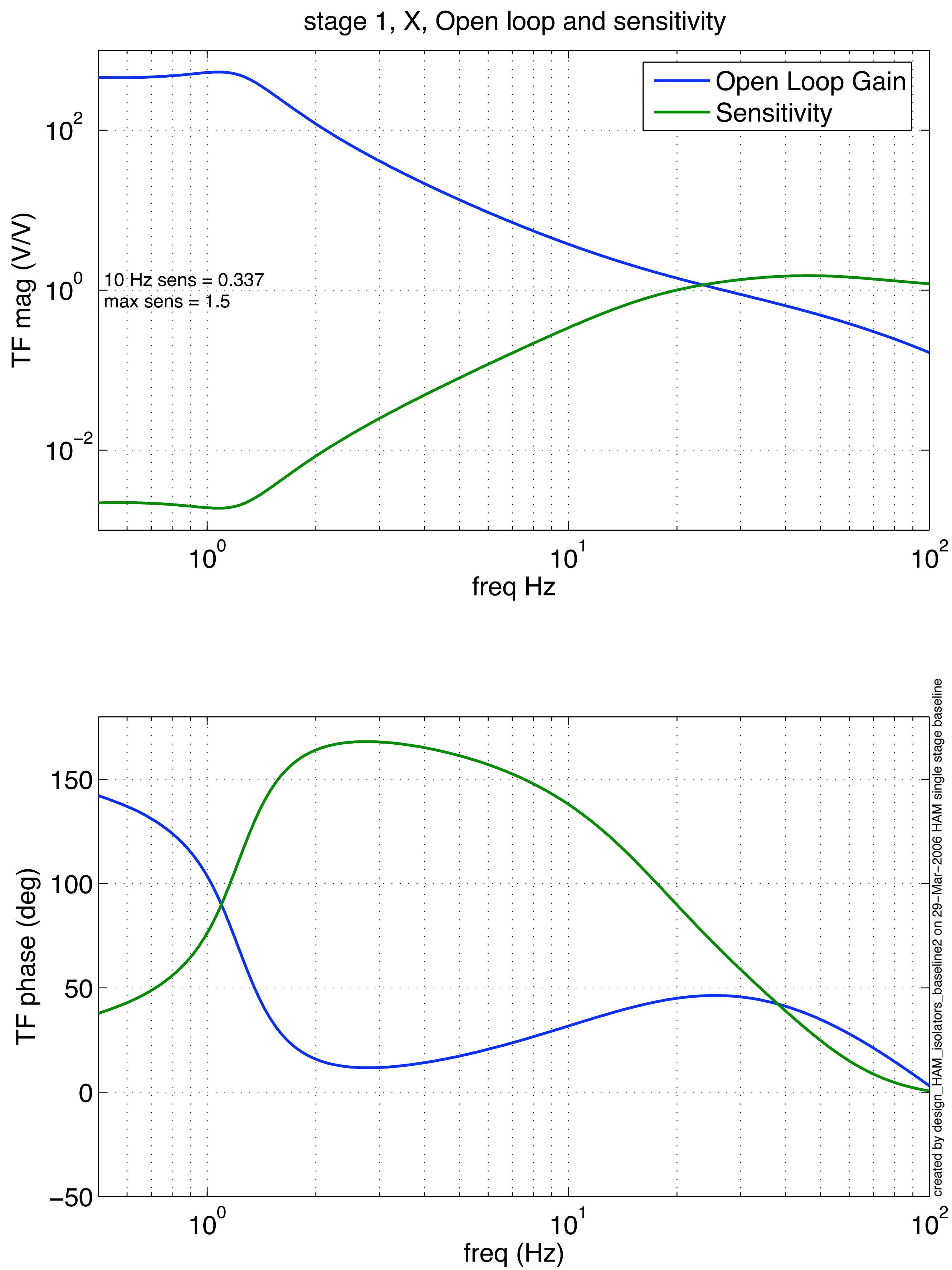


Isolation loops

- Set isolation loops to give isolation of 3.0 at 10 Hz.
- Upper unity gain frequencies are 27 Hz
- Max amplification is about 1.5 around 50 Hz.
- Controllers for all 6 DOF about the same
- Quite similar to ETF at Stanford

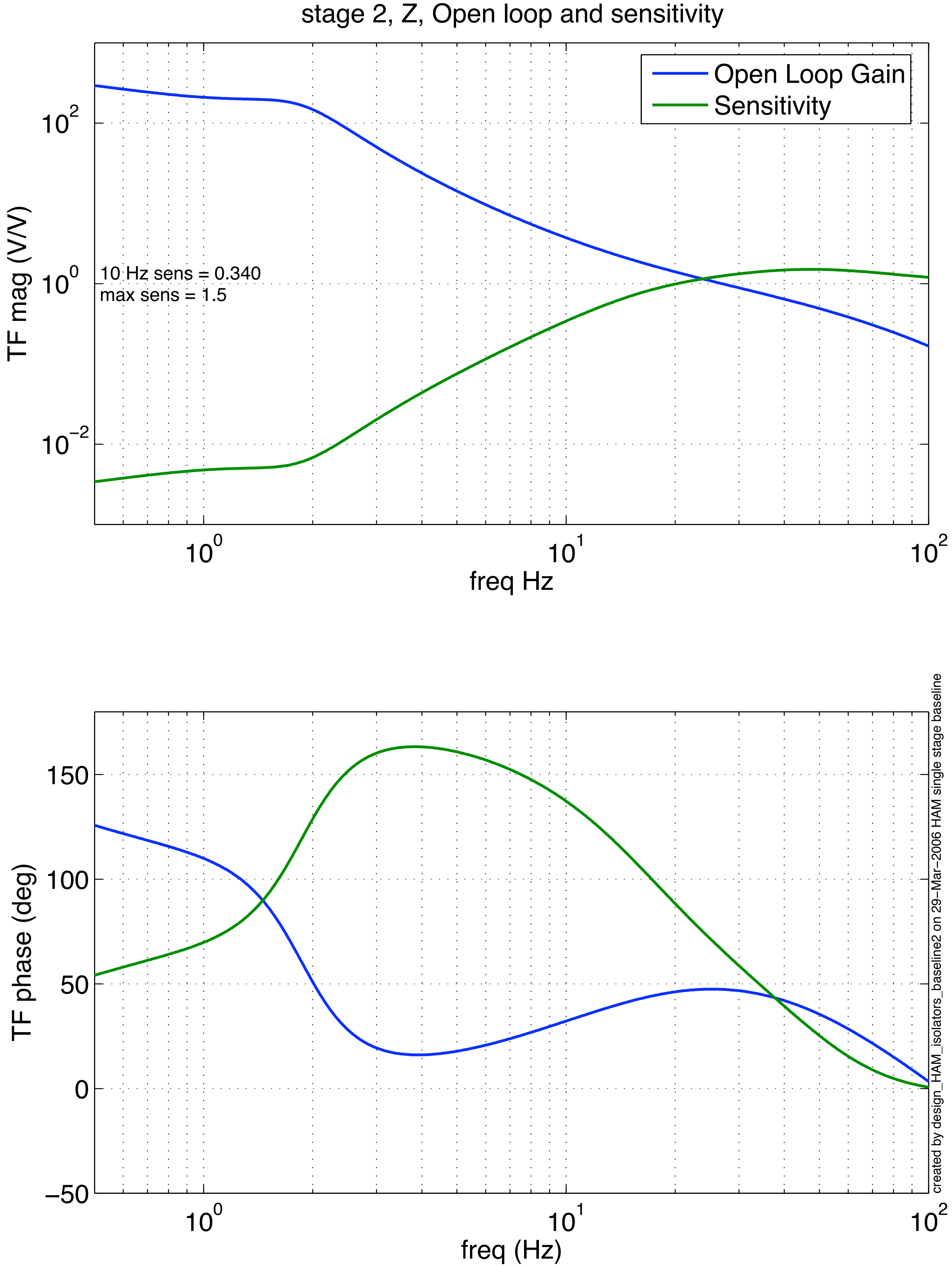
Isolation Loop, x & y

These are all boring



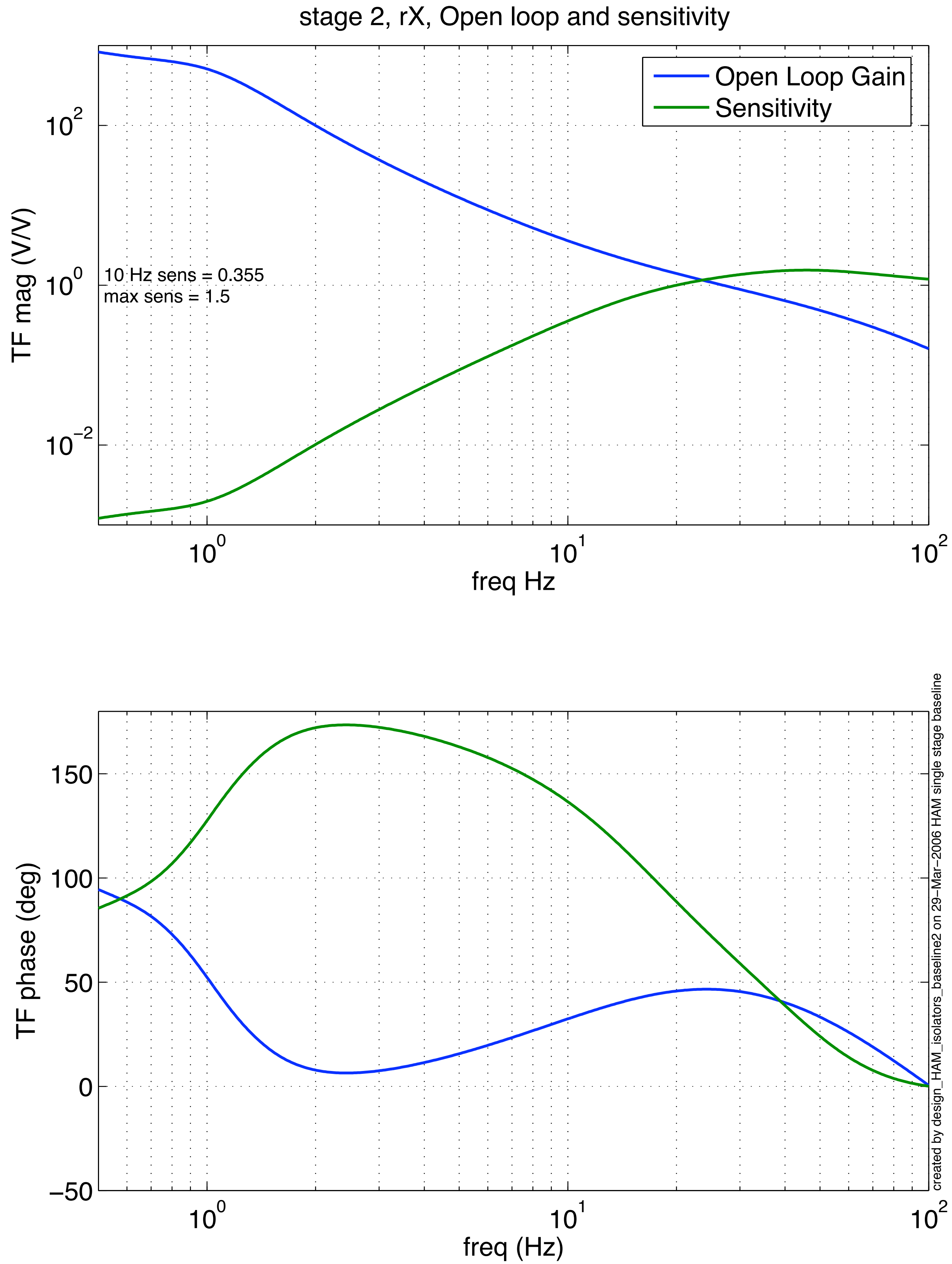
Isolation loop, z

boring



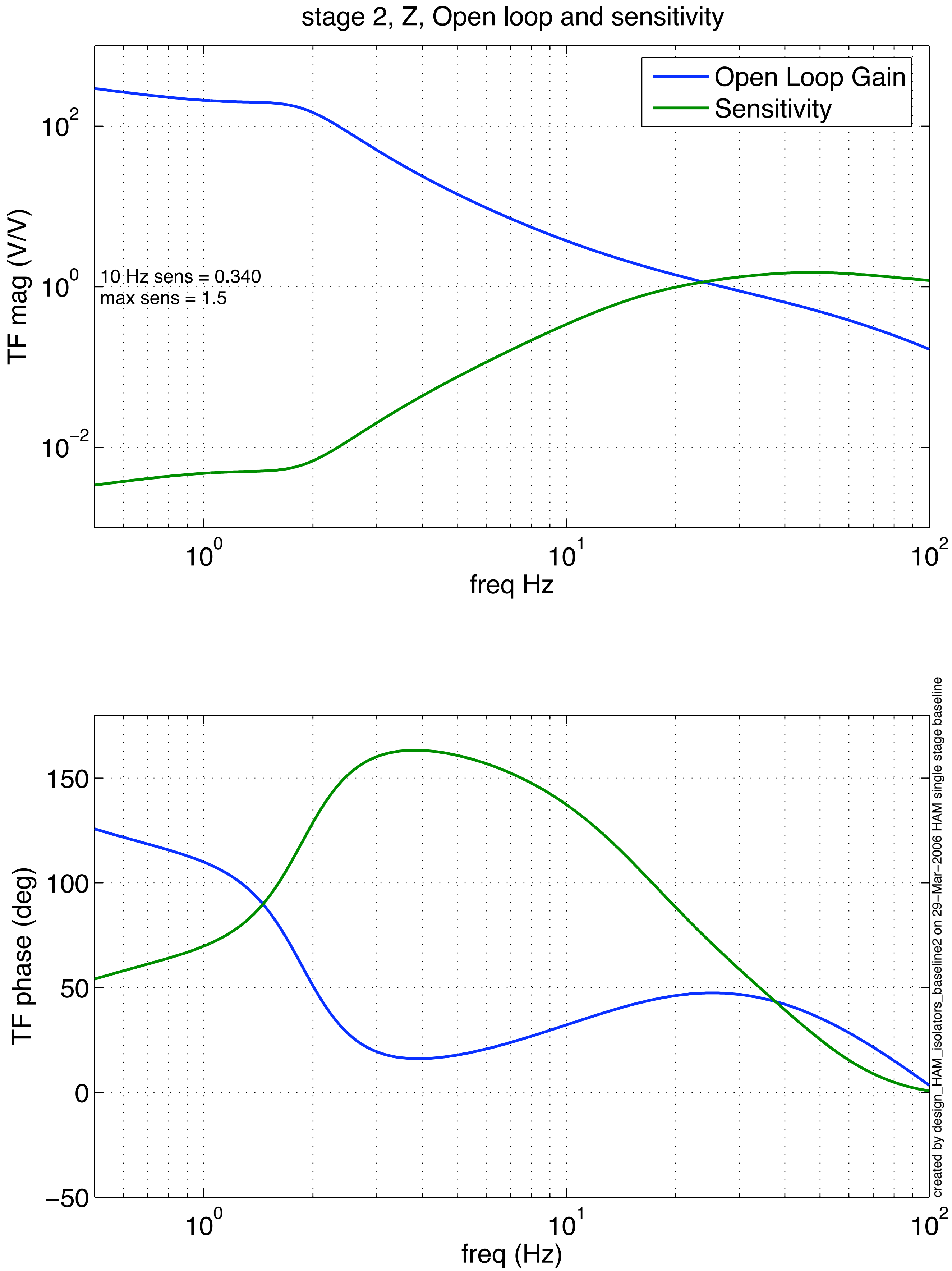
Isolation loop, rX & rY

boring



Isolation loop, rZ

boring

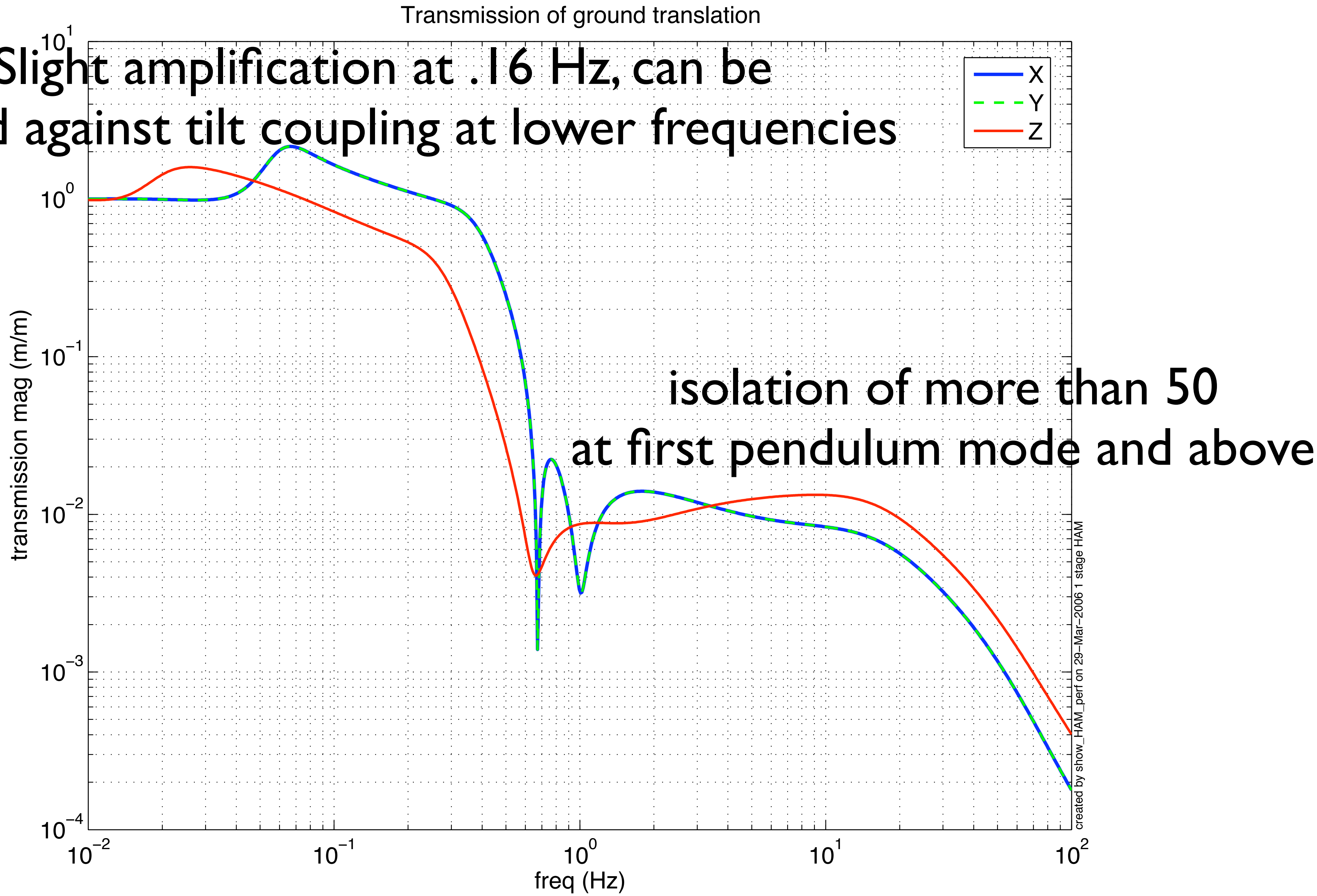


Performance of the system

- System dominated by transmitted HEPI motion.
  (note: although it is sometimes called 'ground motion' in the legends, it always means HEPI motion)
- 1 Hz isolation prediction for translation similar to measured performance at the Stanford ETF.
- We demand better rotational performance than seen at Stanford - this improvement is achieved passively (we expect).

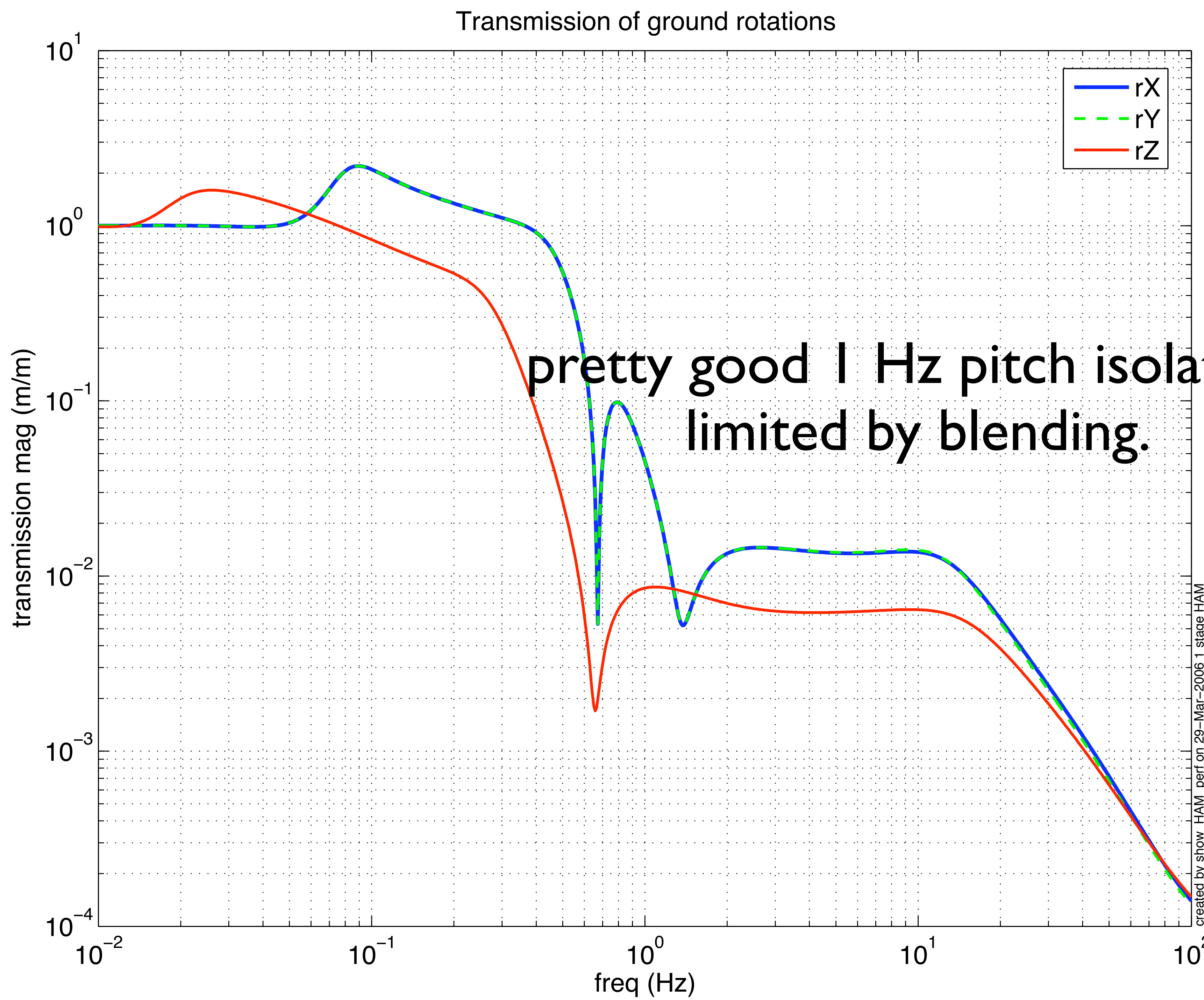
Coupling of HEPI motion

Transmission of translational input motion
HEPI motion -> table cg motion



Coupling of HEPI motion

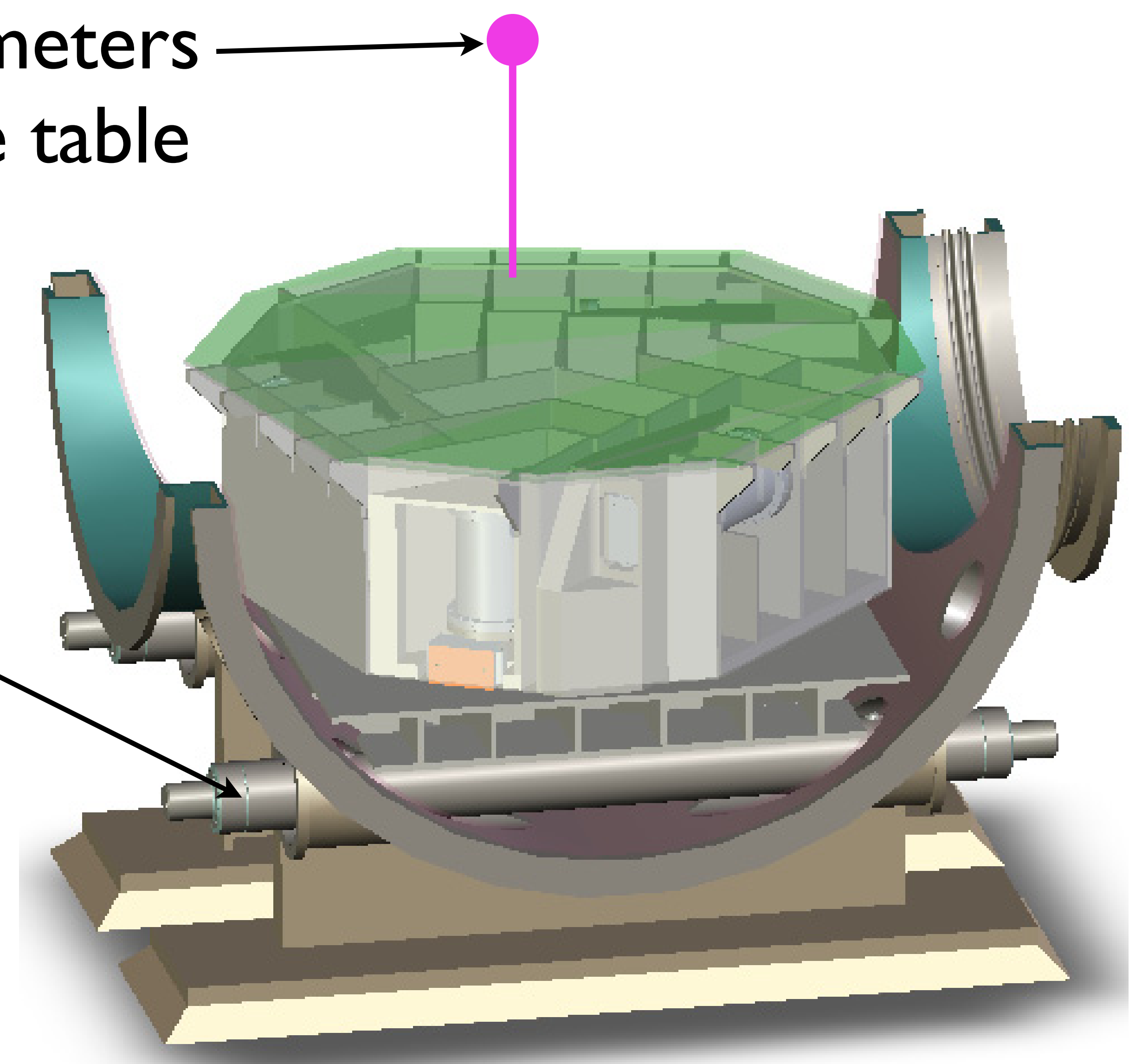
Transmission of rotational input motion
HEPI motion -> table cg motion



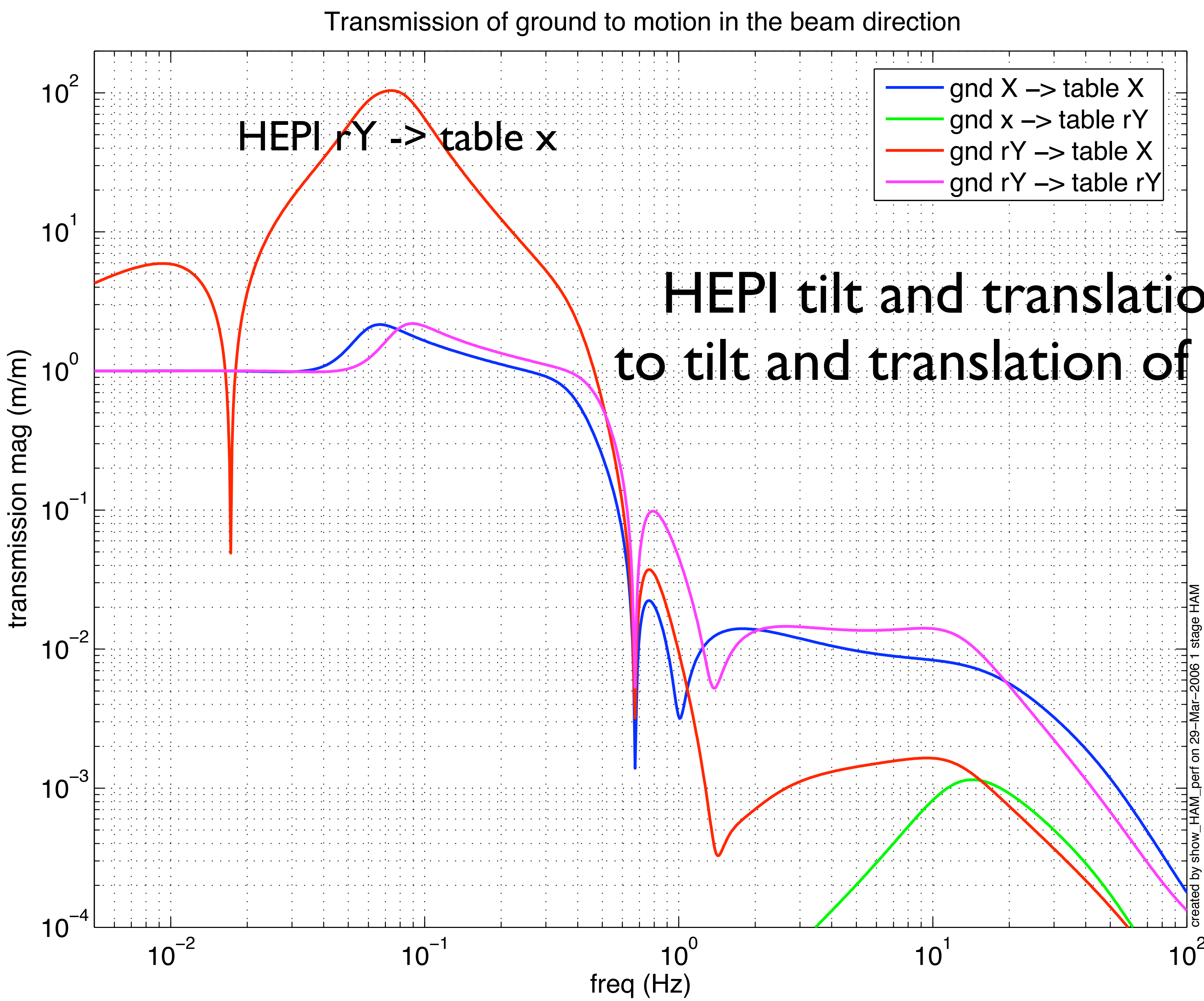
pretty good 1 Hz pitch isolation,
limited by blending.

Horizontal motion of the suspension point

- horizontal motion of the suspension point is defined as: X_table + 0.908 * rY_table + 0.9 * rZ_table.
- (puts cage all the way to one side of optics table)
- The suspension point is 0.828 meters above the table surface, and the table cg is assumed to be 0.08 m below the table surface.
- X and rY are both important.
- Input motion is from HEPI (not the ground)

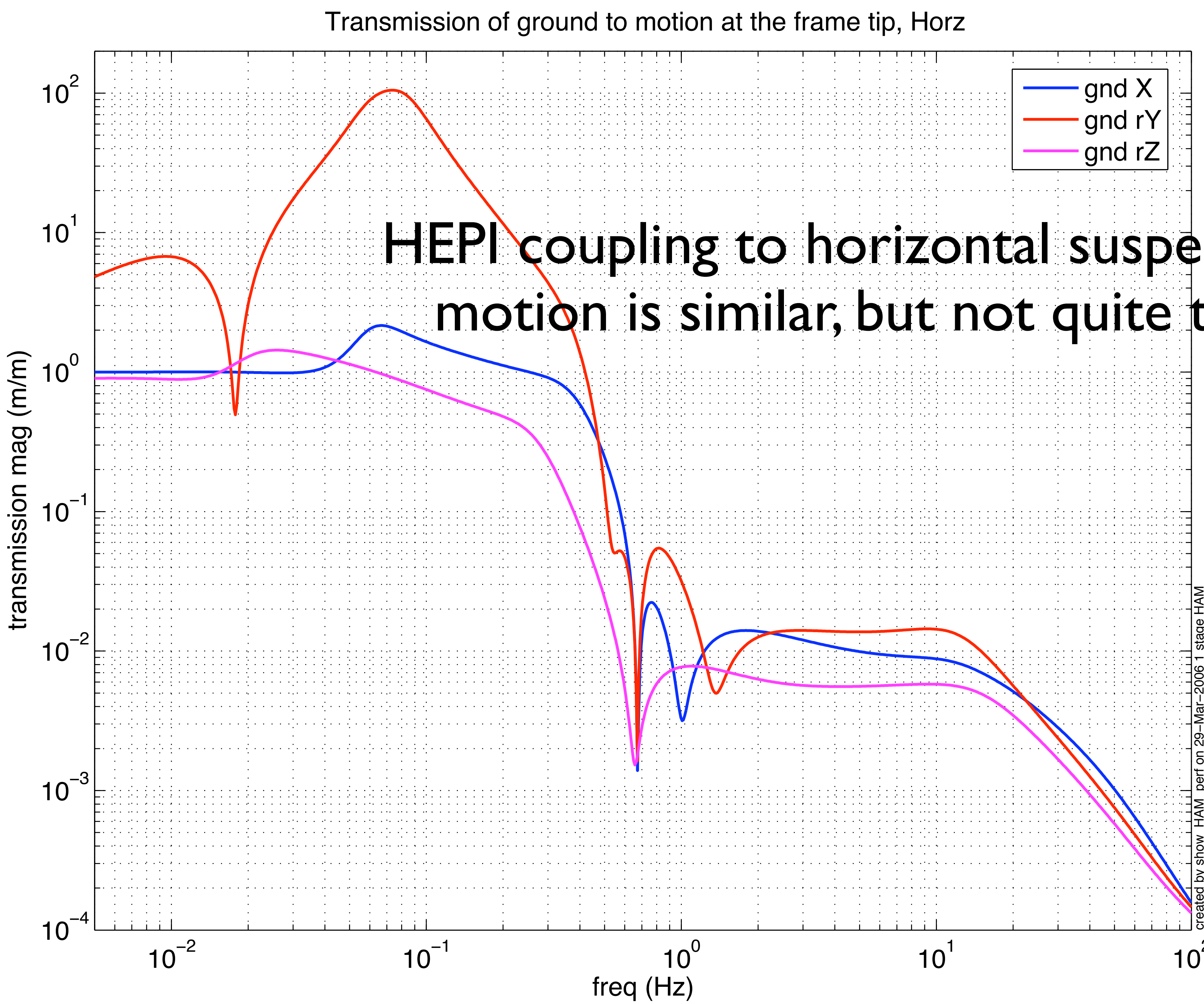


HEPI X and rY coupling to table cg



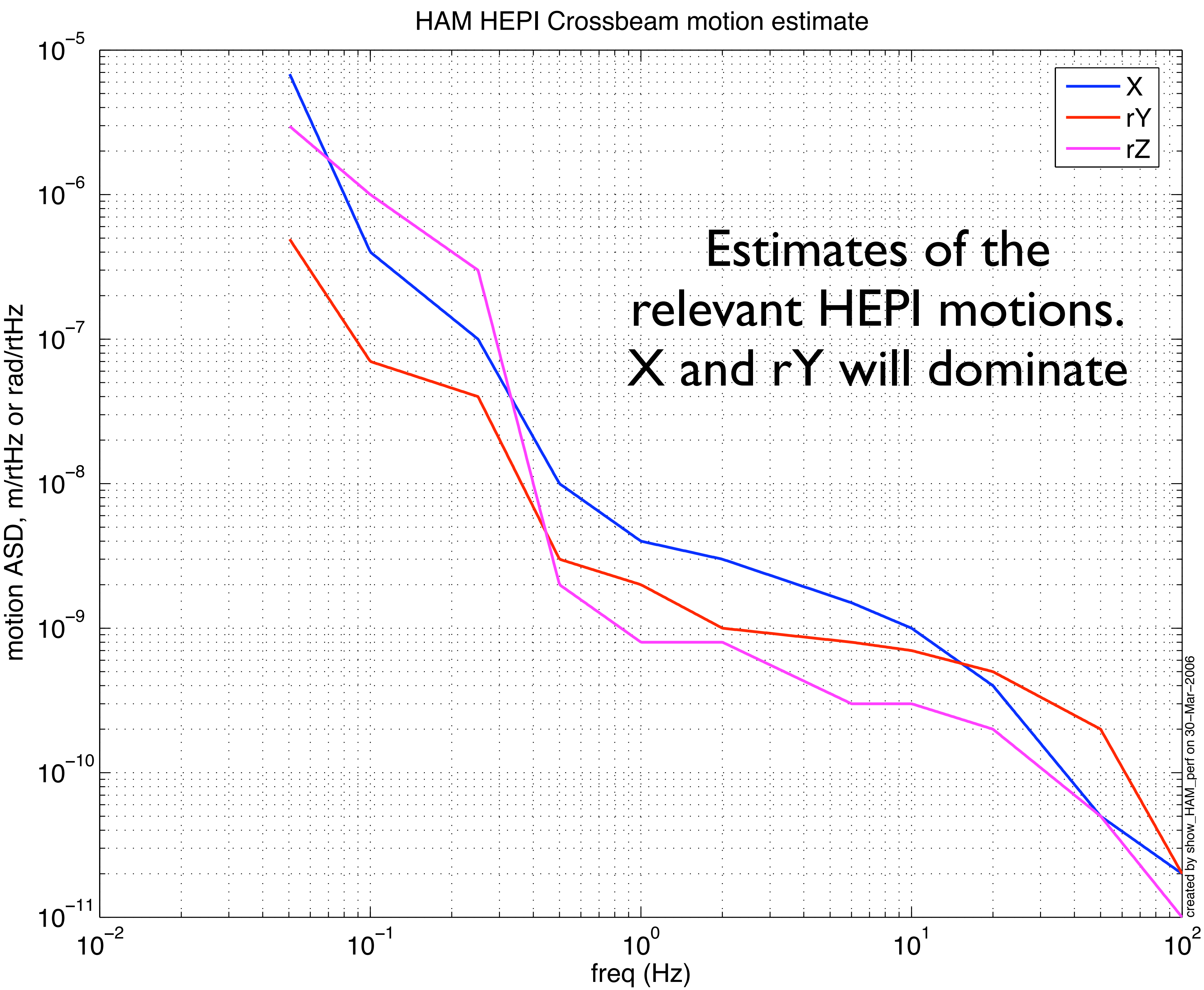
HEPI tilt and translation couples to tilt and translation of the table cg

HEPI X, rY, and rZ coupling to suspension point - horizontal

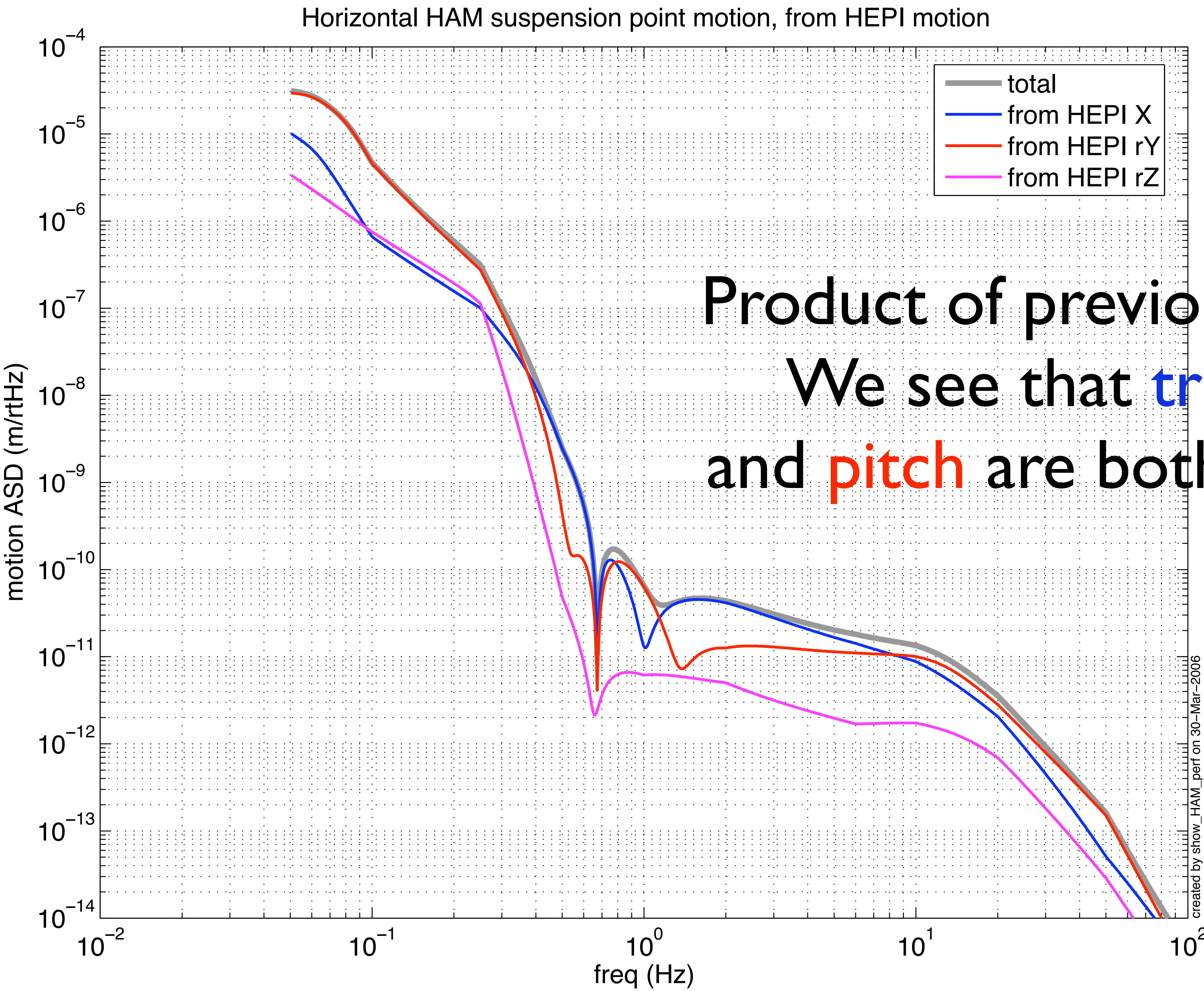


HEPI coupling to horizontal suspension point motion is similar, but not quite the same.

X, rY, and rZ motion of HEPI

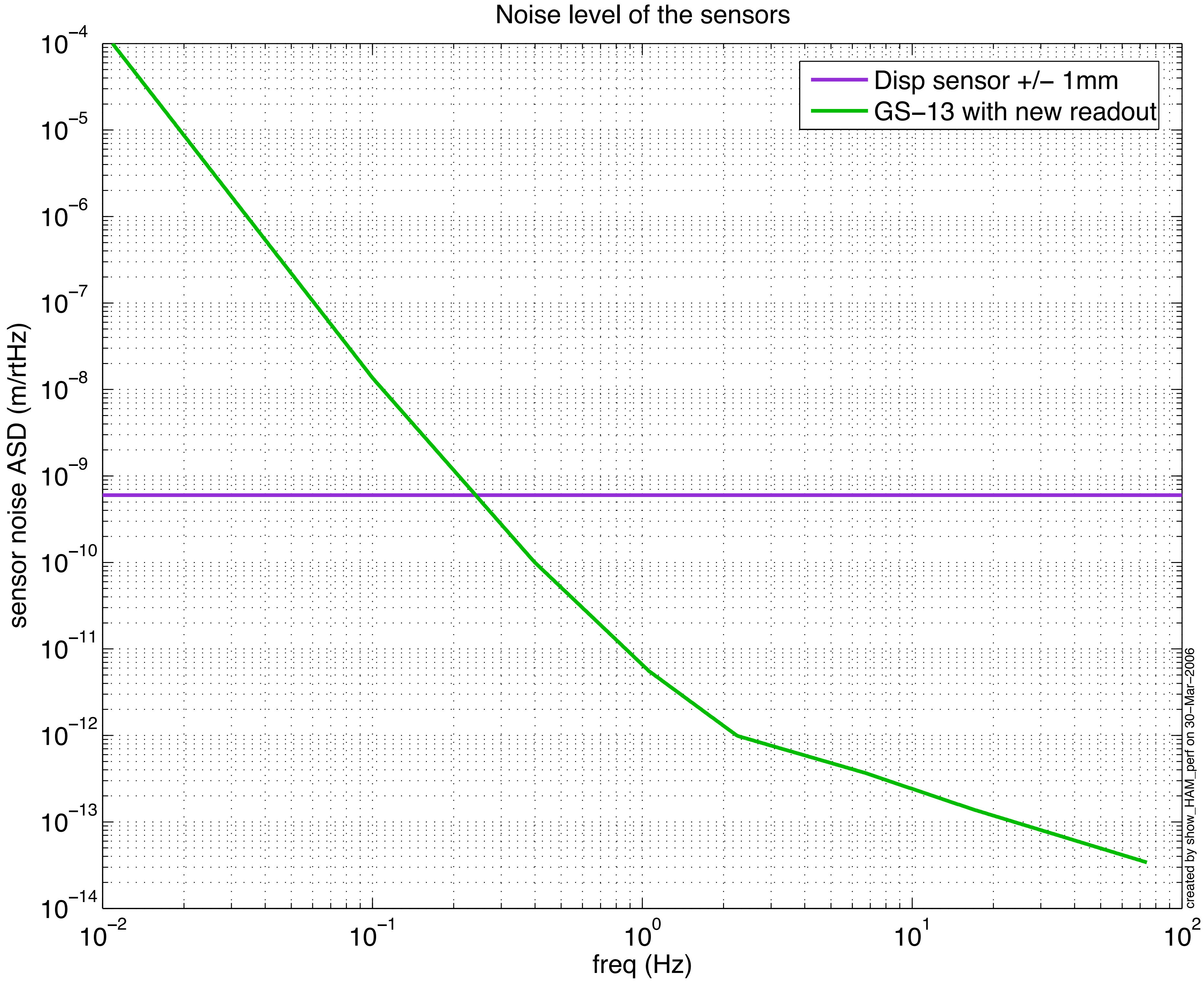


Horizontal Suspension point motion - from HEPI motion

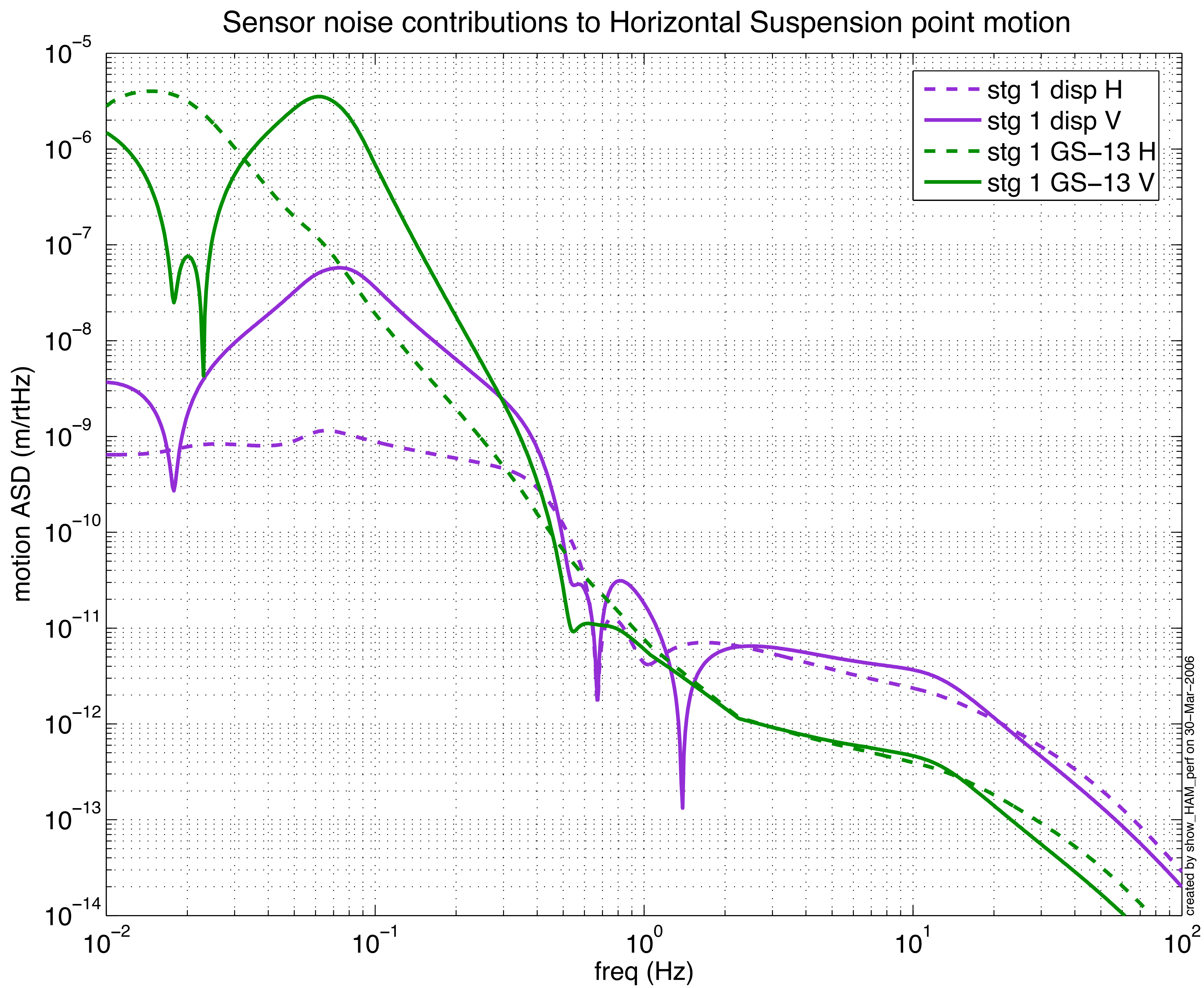


Product of previous 2 graphs.
We see that translation and pitch are both important

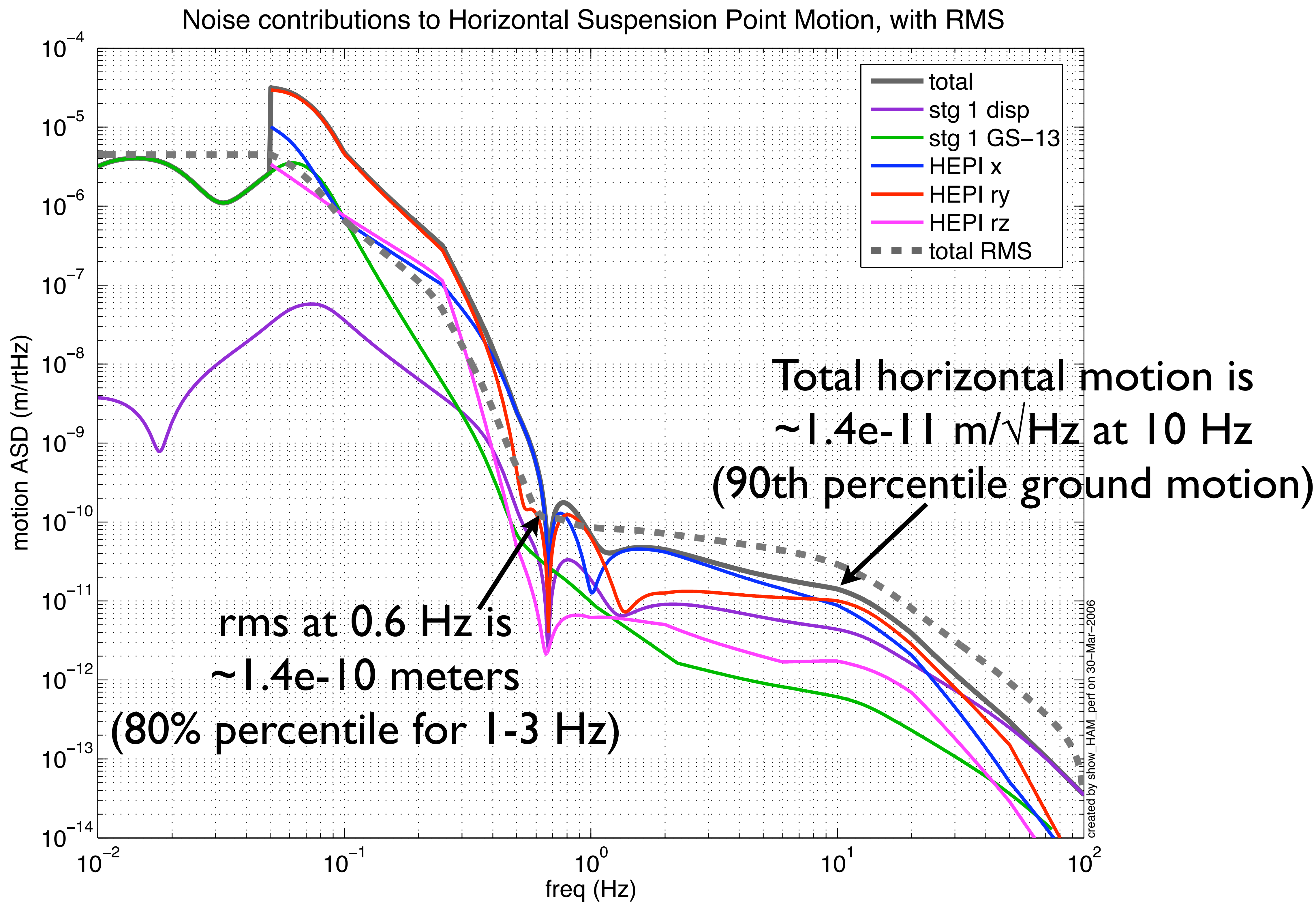
Noise of the sensors



Horizontal Suspension point motion from sensor noise



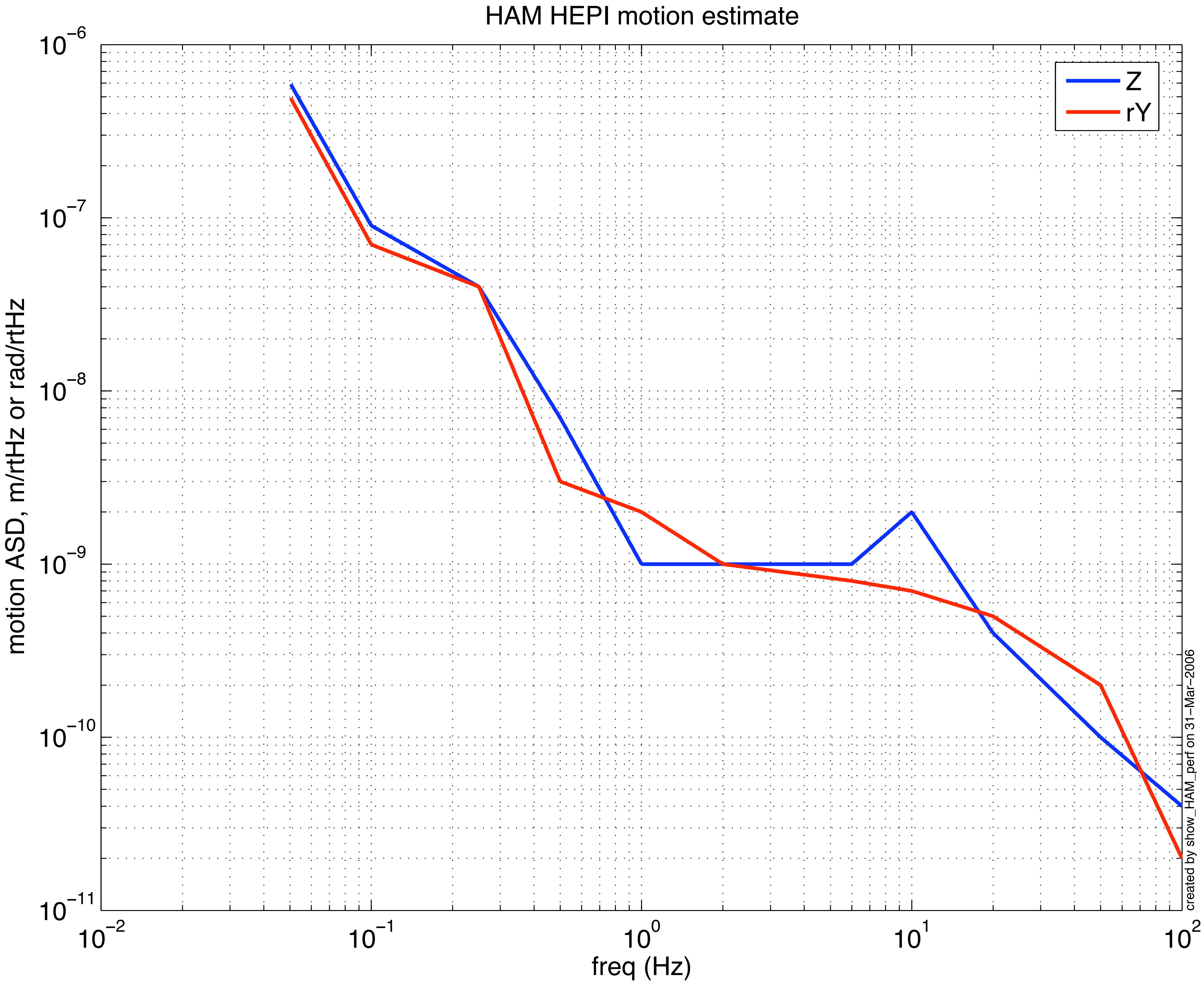
Final Horizontal Motion of the Suspension Point



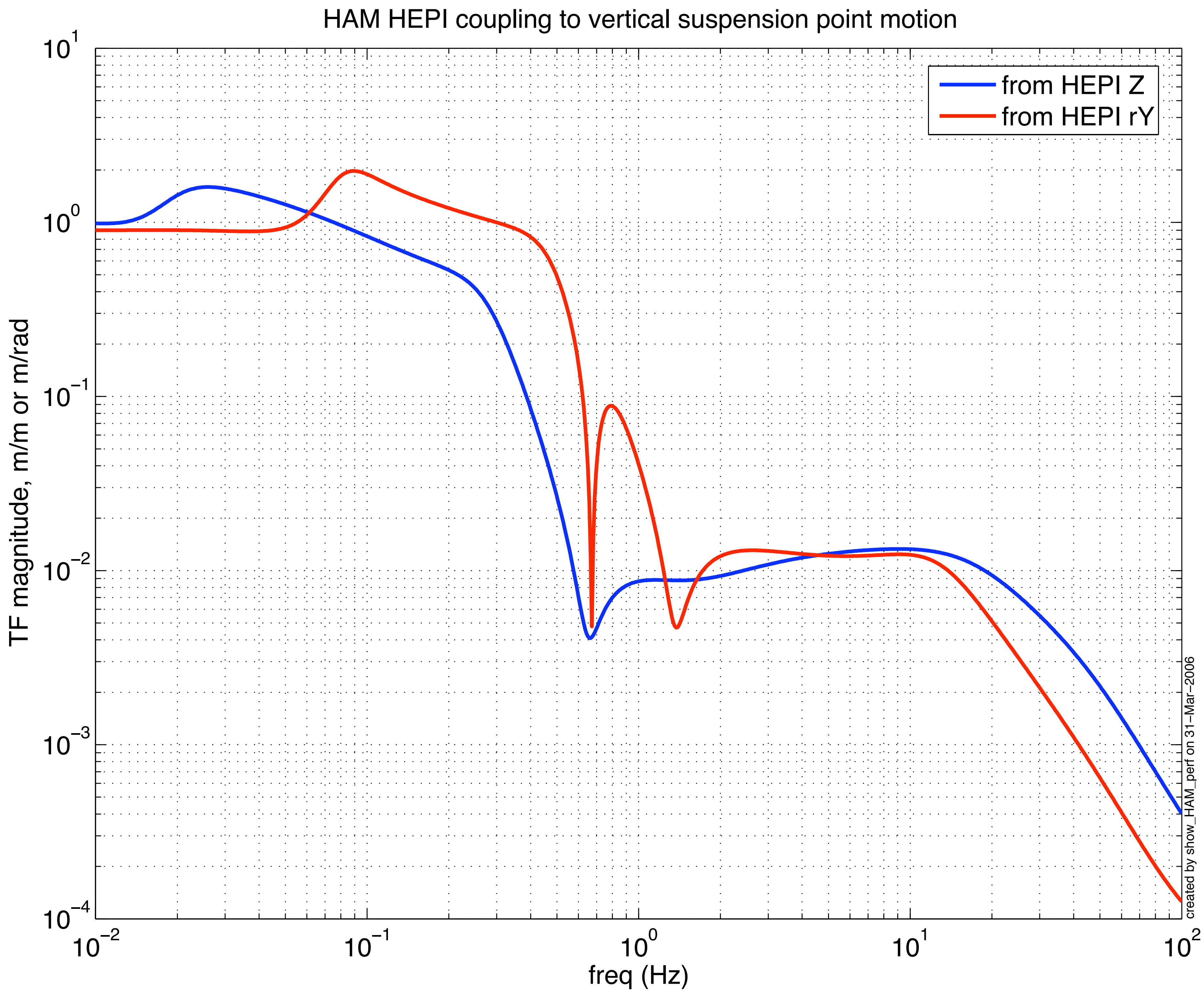
Vertical Motion of the Suspension point

- Both vertical and pitch contribute to vertical motion of the suspension point.
- We assume 1e-3 mechanical cross coupling from the pendulum.
- Vertical motion is not a significant factor.
- For vertical coupling, we assume the suspension point is at x = 0.9 meters to maximize the rY coupling. (For horizontal, it was at x = 0, y = 0.9 m).

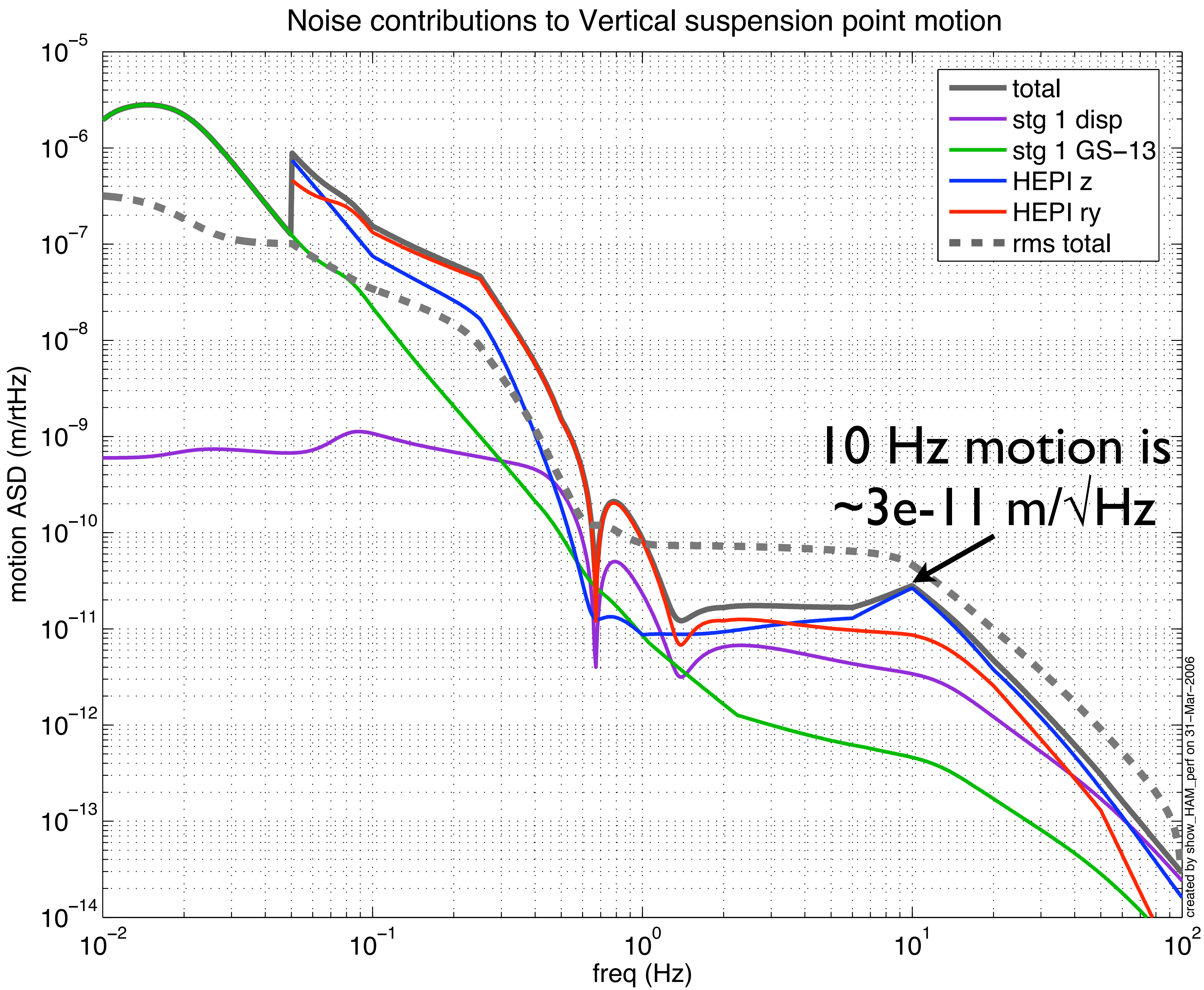
HEPI motion estimate for Vertical motion drivers



Coupling of HEPI motion to Vertical Suspension point

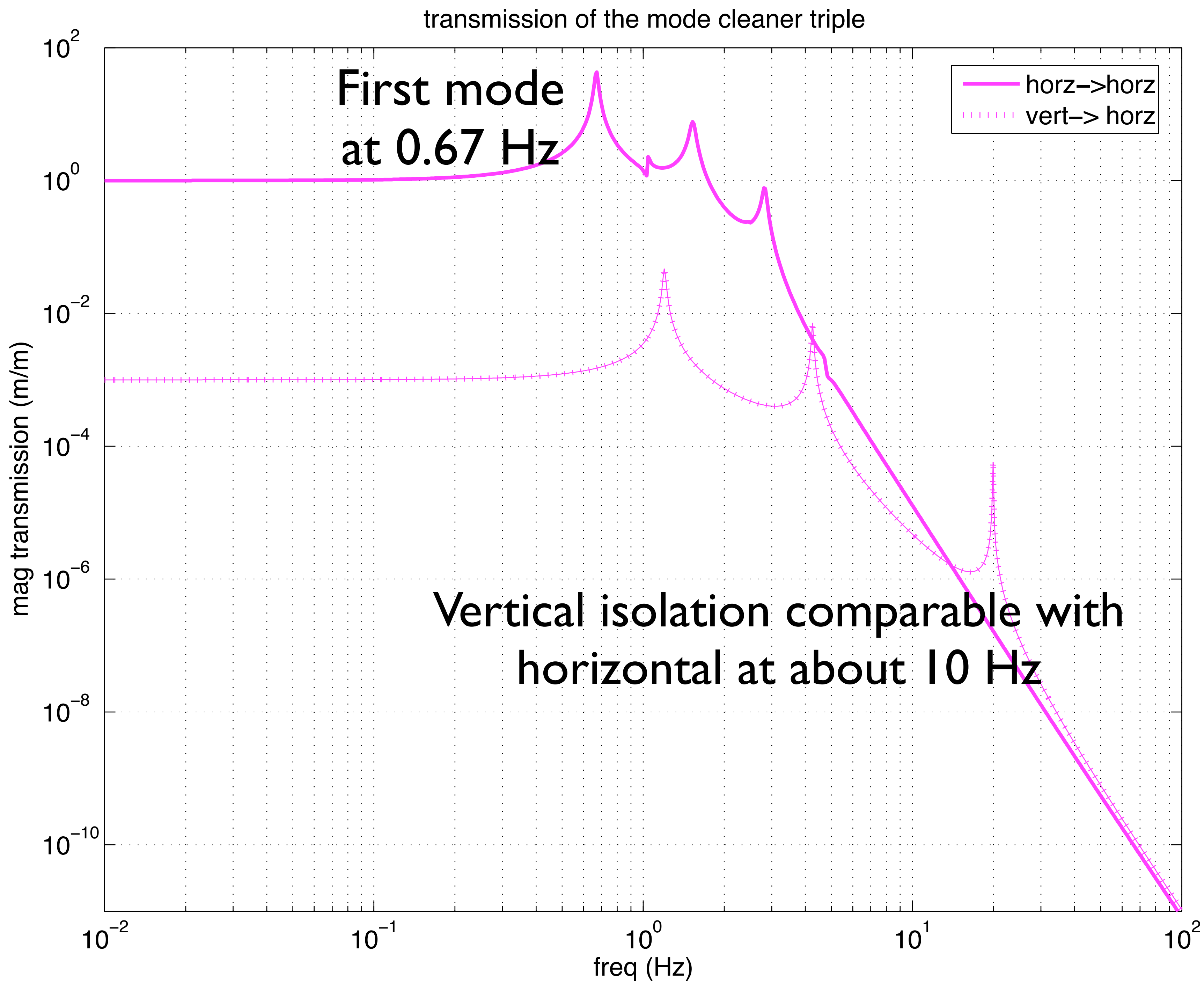


Vertical Motion of Suspension point



Pendulum Isolation

- Assume a triple pendulum, from Norna ~ June 2005.
- Use x_in -> x_out and z_in -> z_out/1000 = x_out
  (do not include x_in -> pitch_out, which may add a bump at about 5 Hz.)

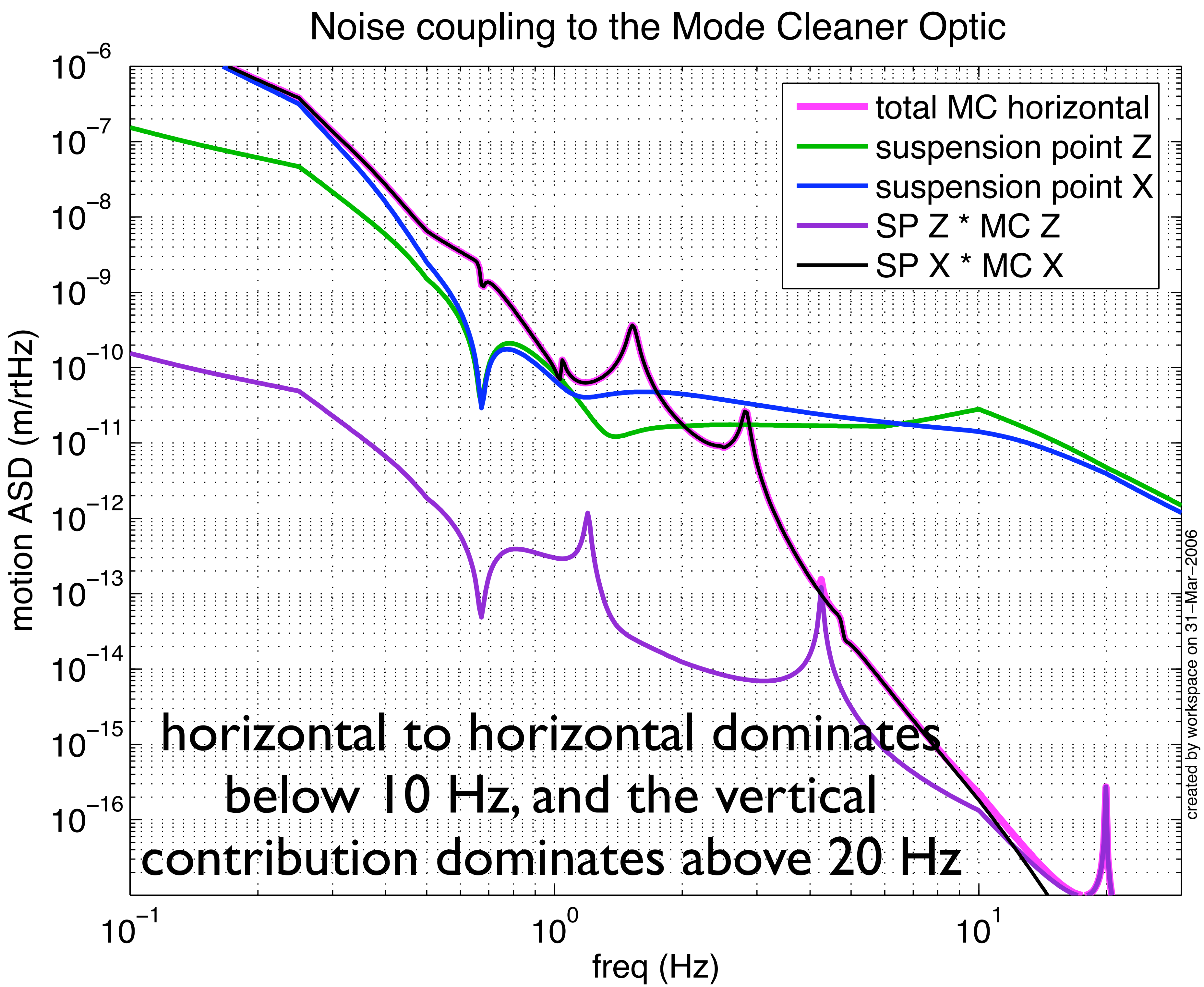


Pendulum motion

Calculate:

suspension point horizontal motion * pendulum horizontal isolation, and

suspension point vertical motion * pendulum vertical isolation (1e-3 to horizontal)



Pendulum motion with rms