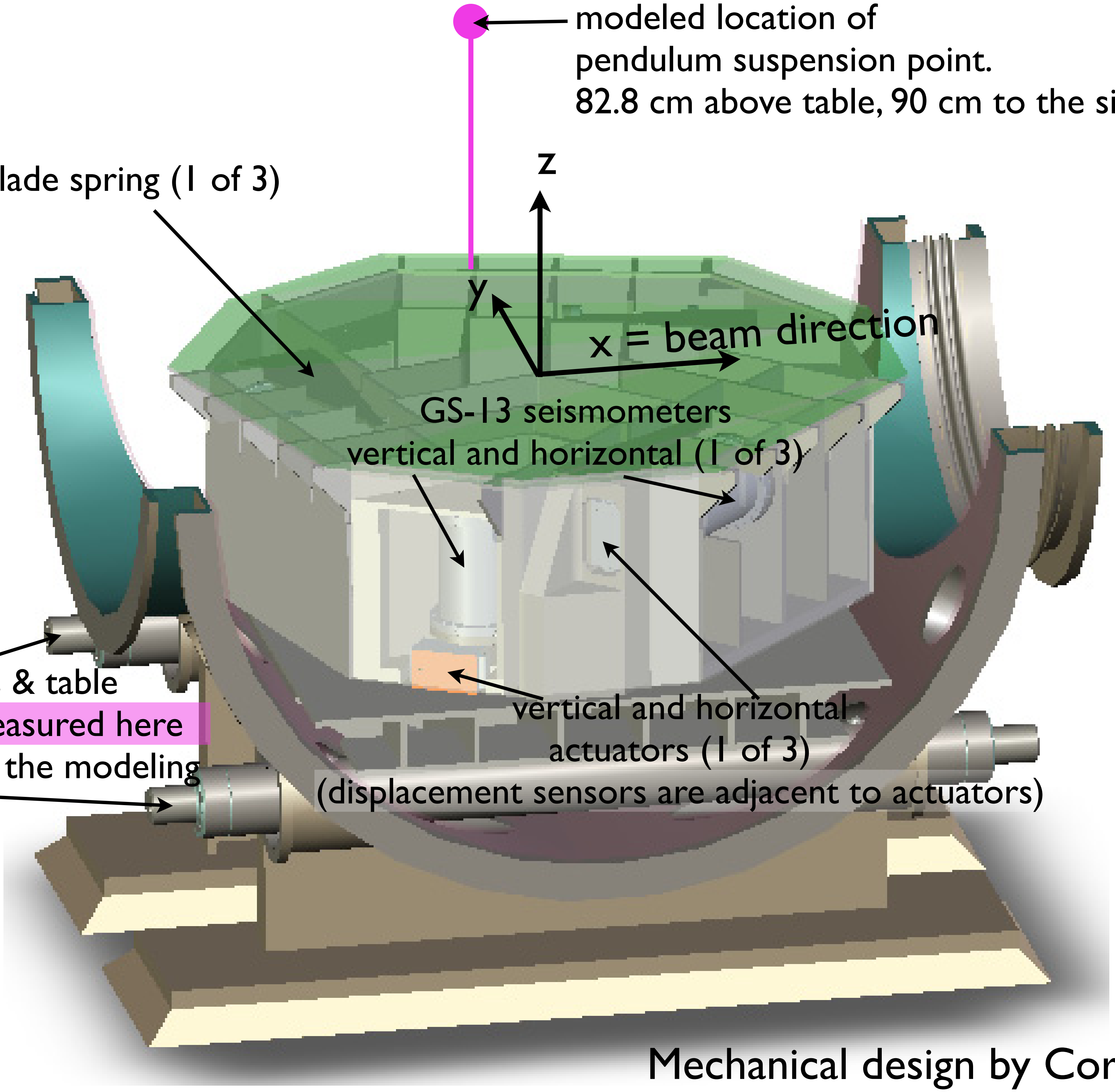
Single Stage HAM for Advanced LIGO: Performance Modeling

presented by Brian Lantz for the SEI team,
April 14, 2006

Outline

- Picture of the mechanical system (pg. 3)
- Review of requirements (pg. 4)
- Plot Horizontal HAM performance - what's important? (pg. 5)
- Ground motion estimates (pg. 6-12)
- Parameters of the mechanical plant (pg. 13-17)
- Blending and control (pg. 18-29)
- Isolation performance of pendulum support point (pg. 30-43)
- Pendulum models and motion of the optic (pg.44-48)

Drawing of Single Stage HAM



modeled location of
pendulum suspension point.
82.8 cm above table, 90 cm to the side

blade spring (1 of 3)

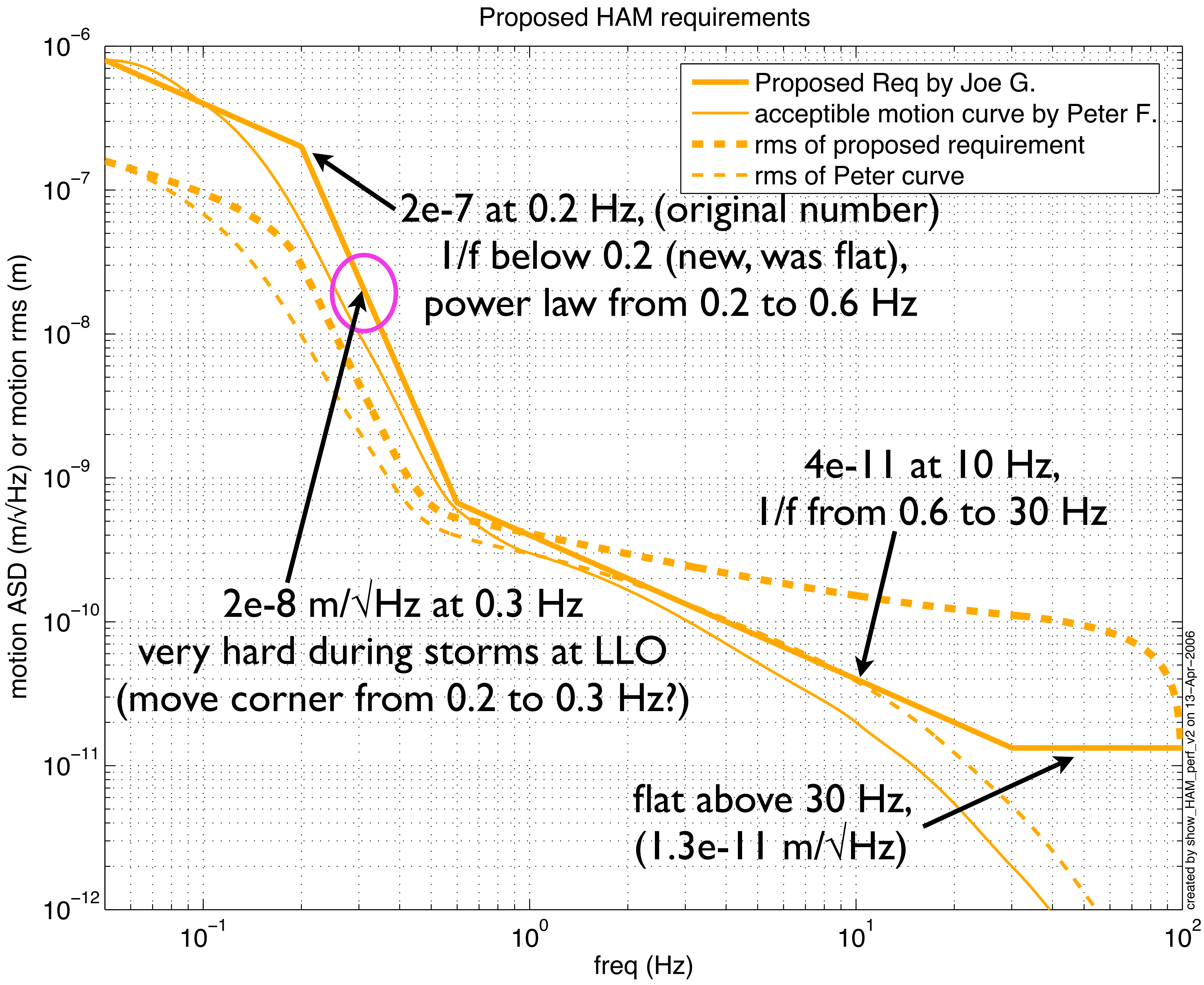
GS-13 seismometers
vertical and horizontal (1 of 3)

Support tubes & table
HEPI motion is measured here
i.e. input motion to the modeling

vertical and horizontal
actuators (1 of 3)
(displacement sensors are adjacent to actuators)

Mechanical design by Corwin Hardham

Requirements



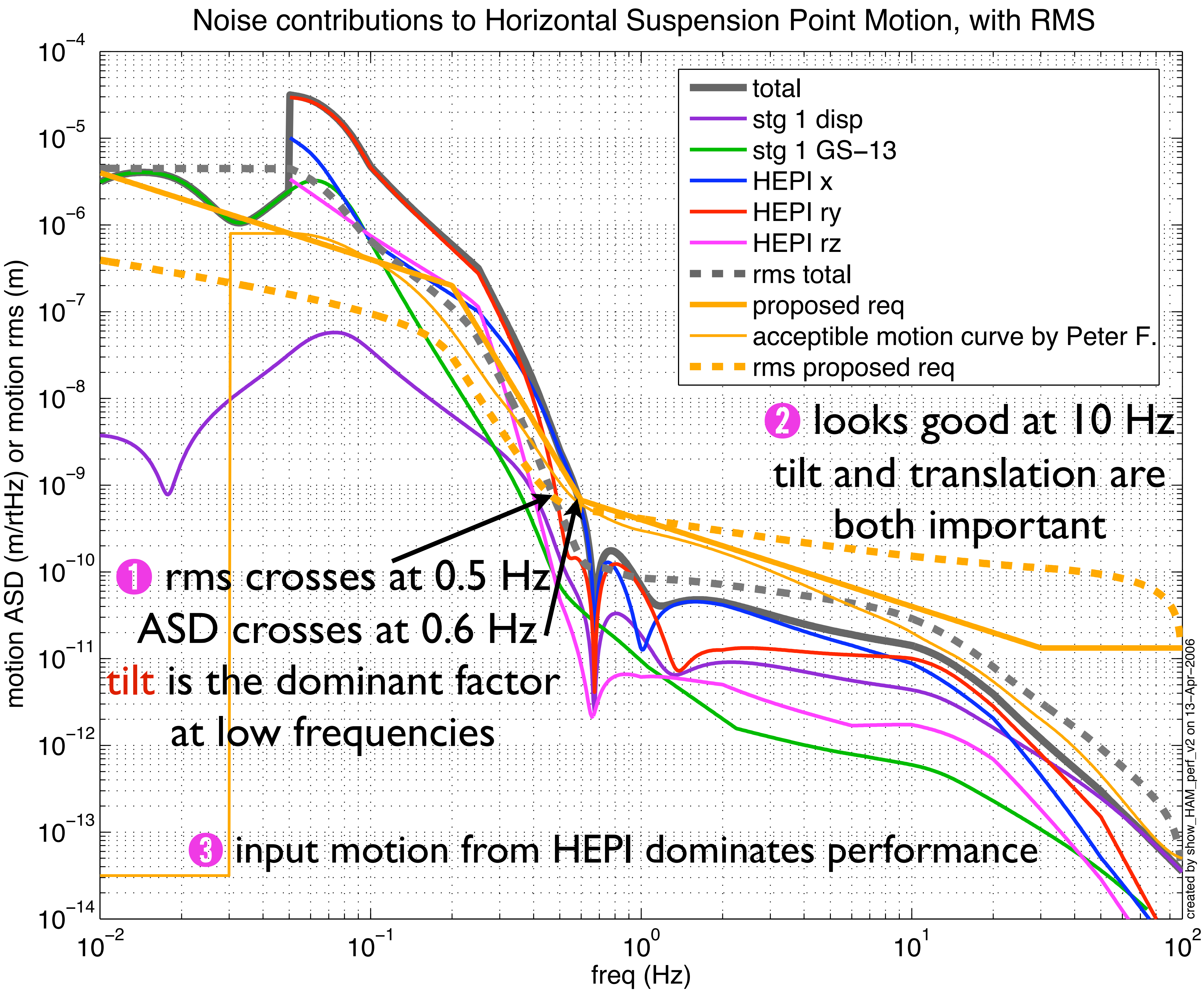
2e-7 at 0.2 Hz, (original number)
1/f below 0.2 (new, was flat),
power law from 0.2 to 0.6 Hz

2e-8 m/√Hz at 0.3 Hz
very hard during storms at LLO
(move corner from 0.2 to 0.3 Hz?)

4e-11 at 10 Hz,
1/f from 0.6 to 30 Hz

flat above 30 Hz,
(1.3e-11 m/√Hz)

HAM performance



② looks good at 10 Hz
tilt and translation are
both important

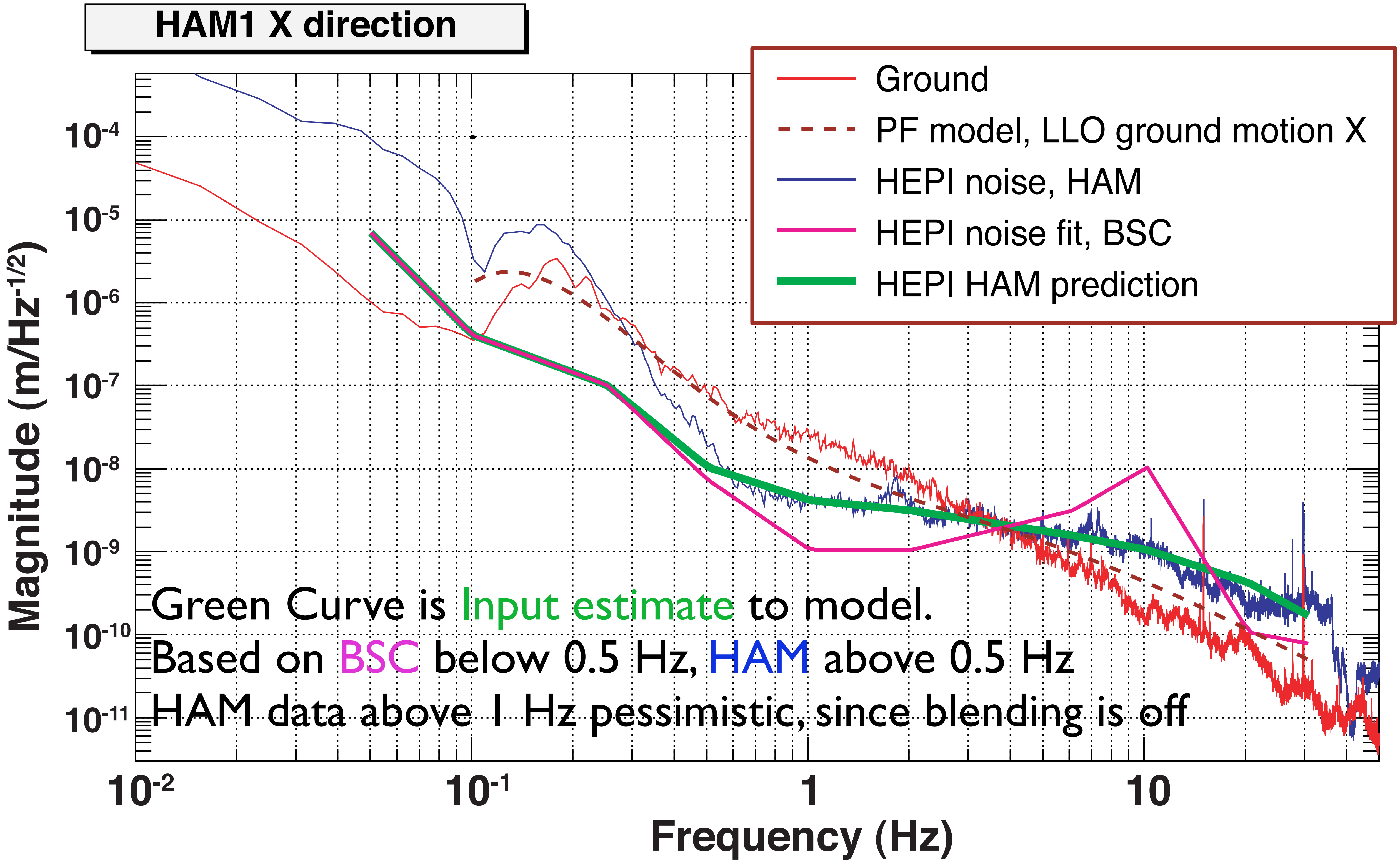
① rms crosses at 0.5 Hz
ASD crosses at 0.6 Hz
tilt is the dominant factor
at low frequencies

③ input motion from HEPI dominates performance

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

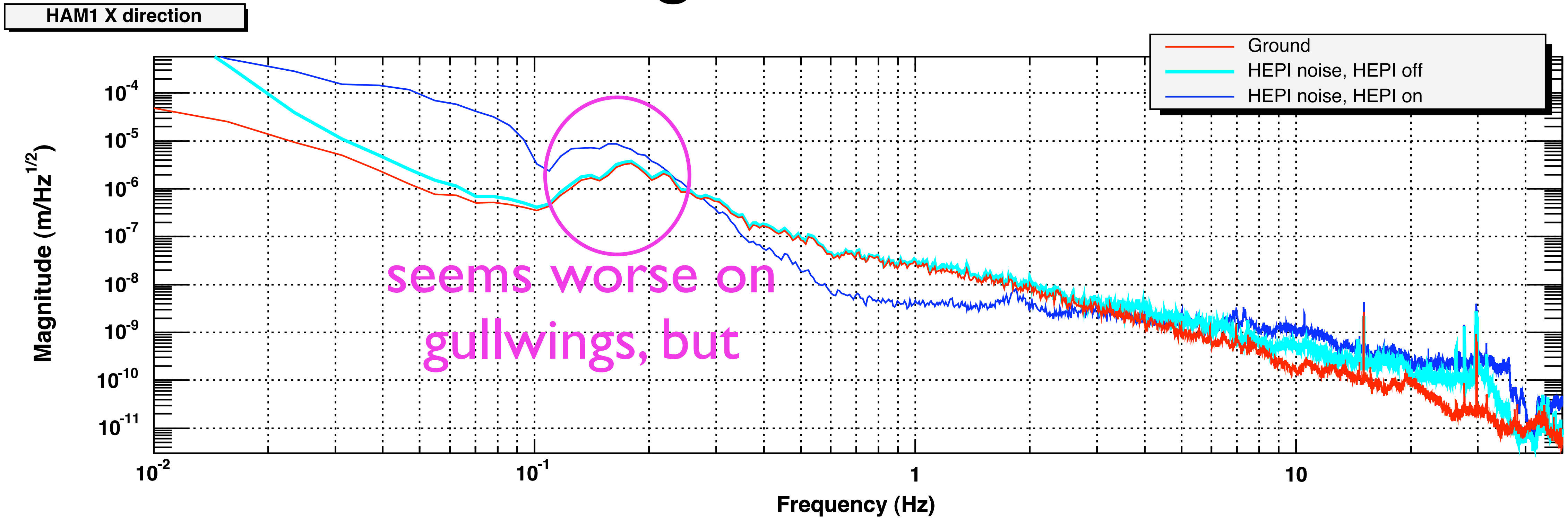


Green Curve is Input estimate to model.
Based on BSC below 0.5 Hz, HAM above 0.5 Hz
HAM data above 1 Hz pessimistic, since blending is off

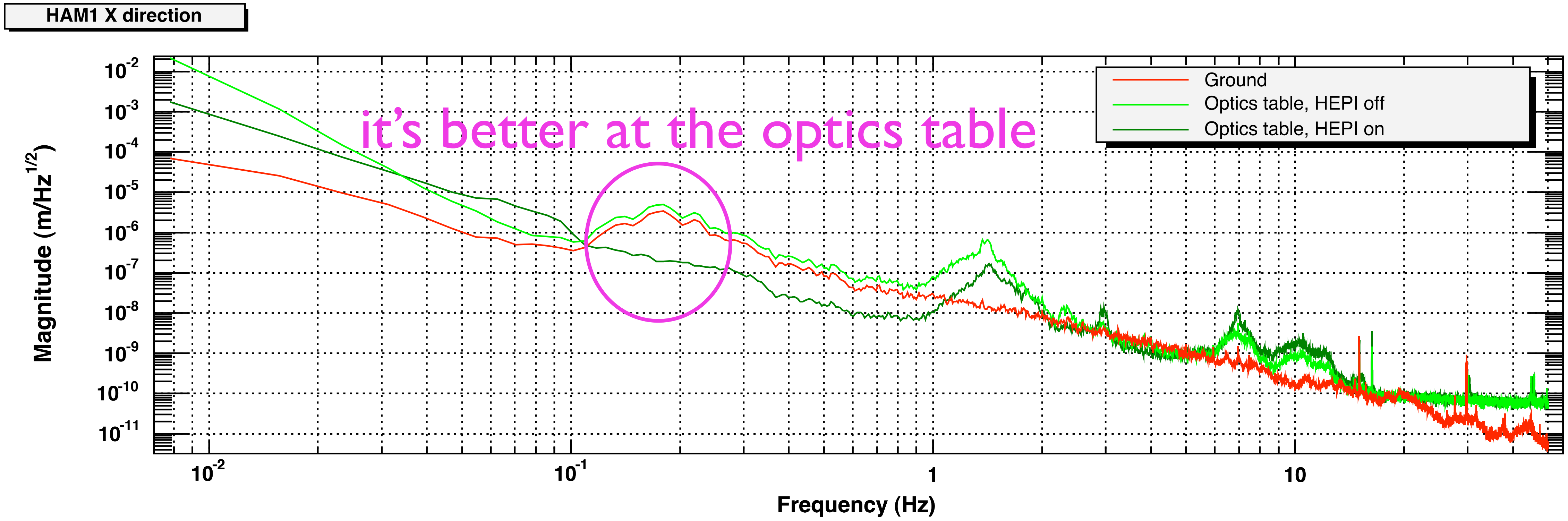
figure adapted from Shyang Wen, HAM1.pdf, SEI log #604

HAM1 X, at the Optics Table

HAM HEPI X is working, but the sensors are confused...

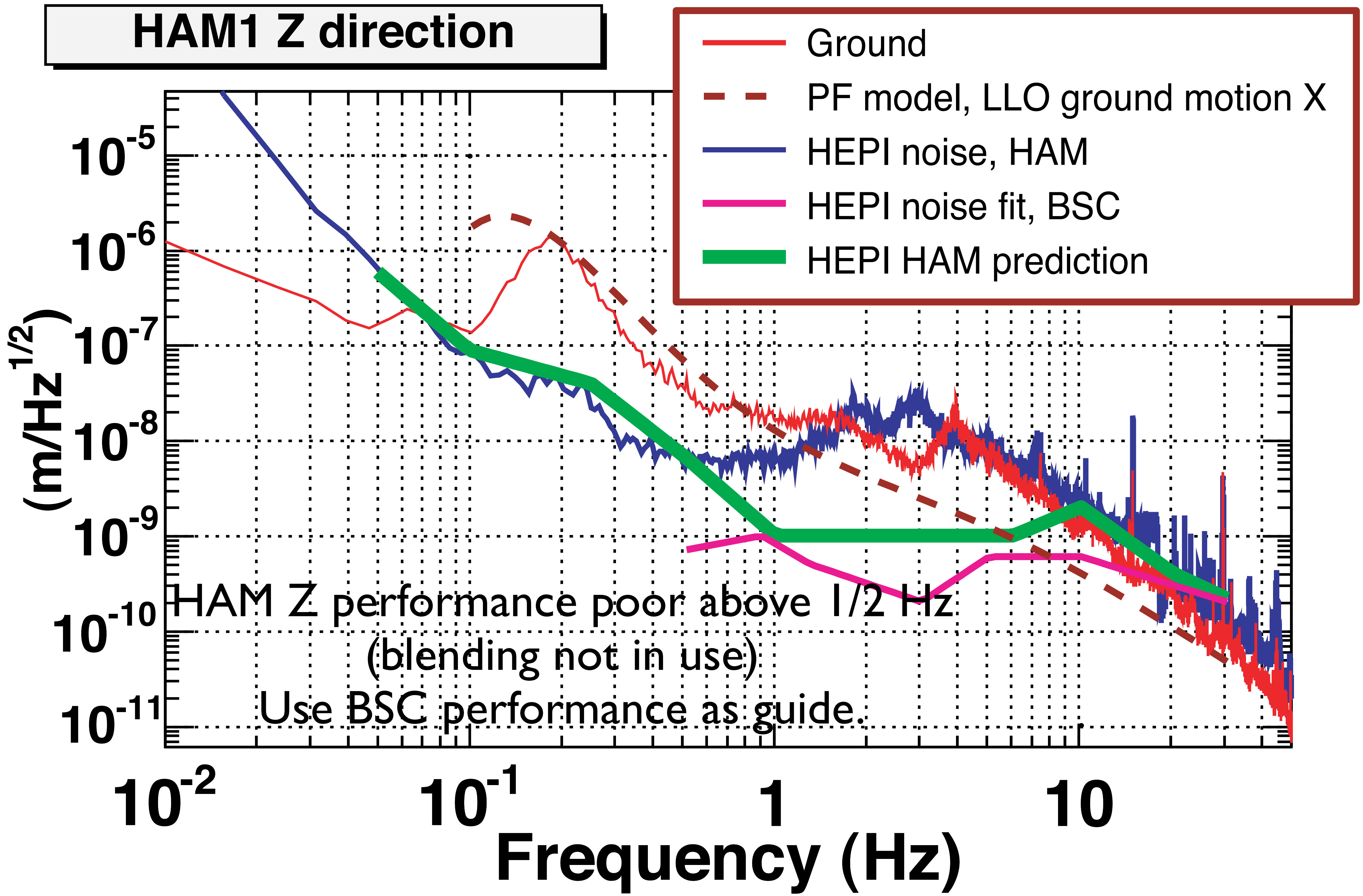


seems worse on gullwings, but



it's better at the optics table

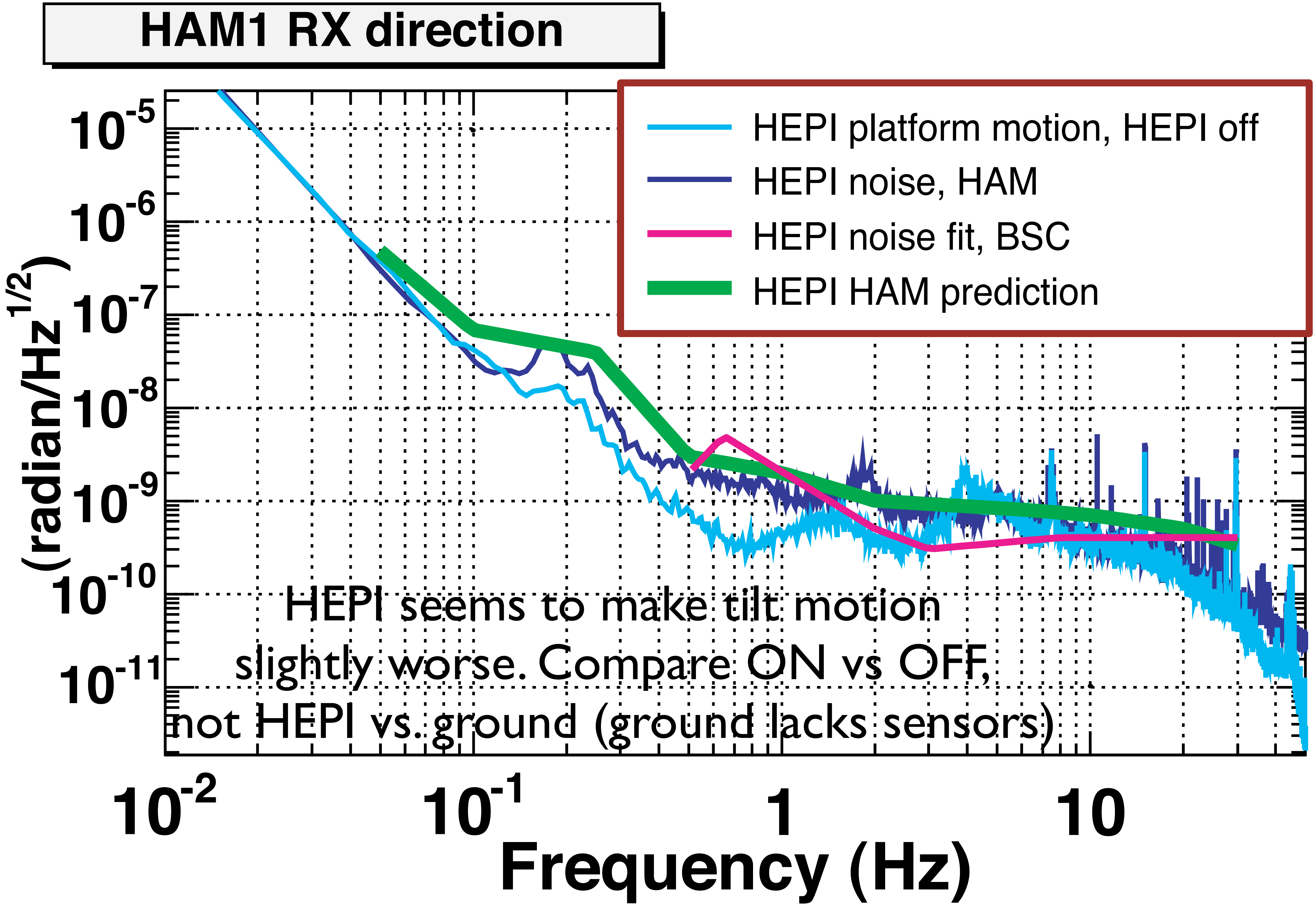
HEPI motion estimate: Z



HAM Z performance poor above 1/2 Hz
(blending not in use)
Use BSC performance as guide.

figure adapted from S. Wen LIGO-G060125

HEPI motion estimate: rX & rY



HEPI seems to make tilt motion slightly worse. Compare ON vs OFF, not HEPI vs. ground (ground lacks sensors)

figure adapted from S.Wen LIGO-G060125

HEPI motion estimate: rZ

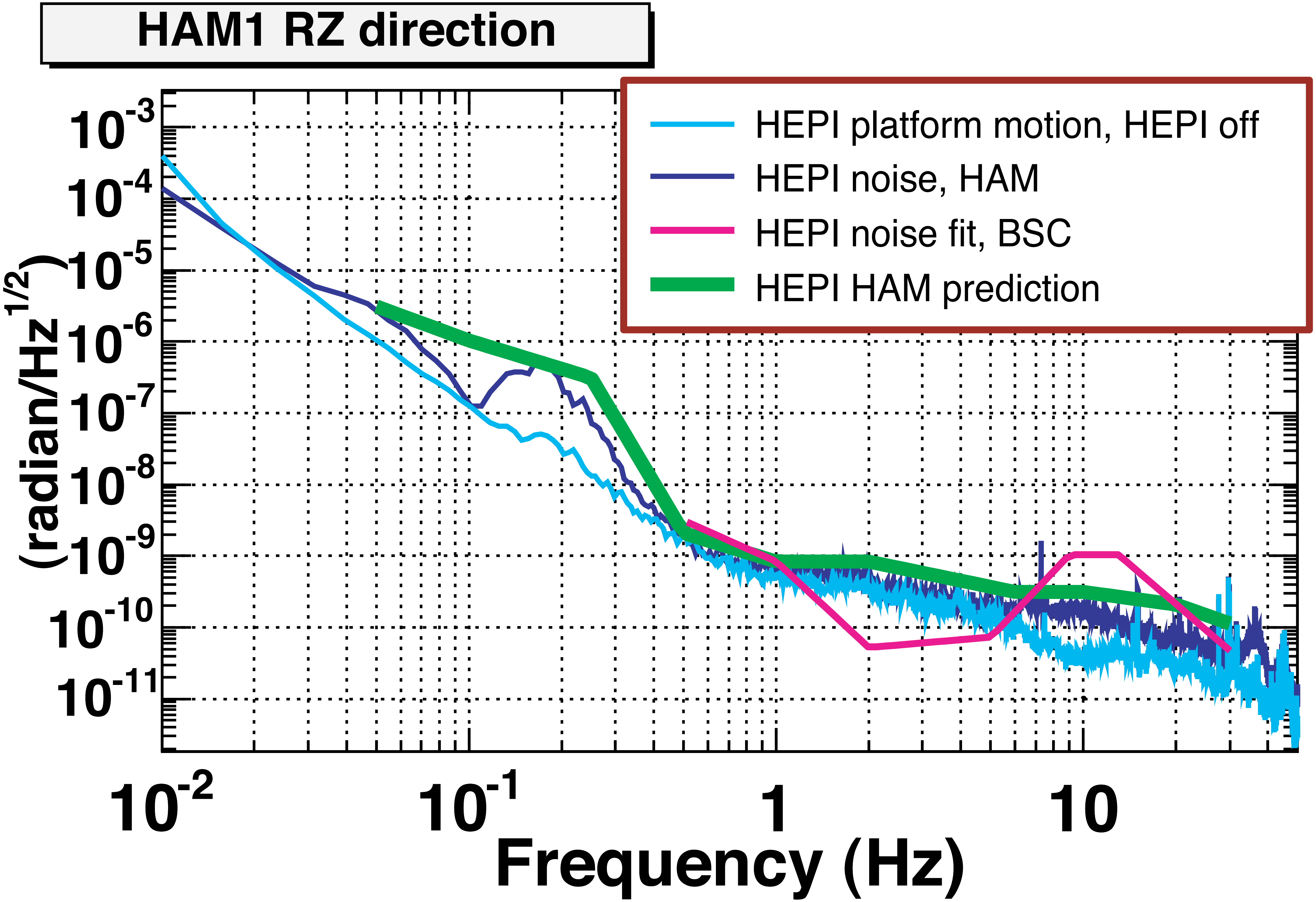


figure adapted from S. Wen LIGO-G060125

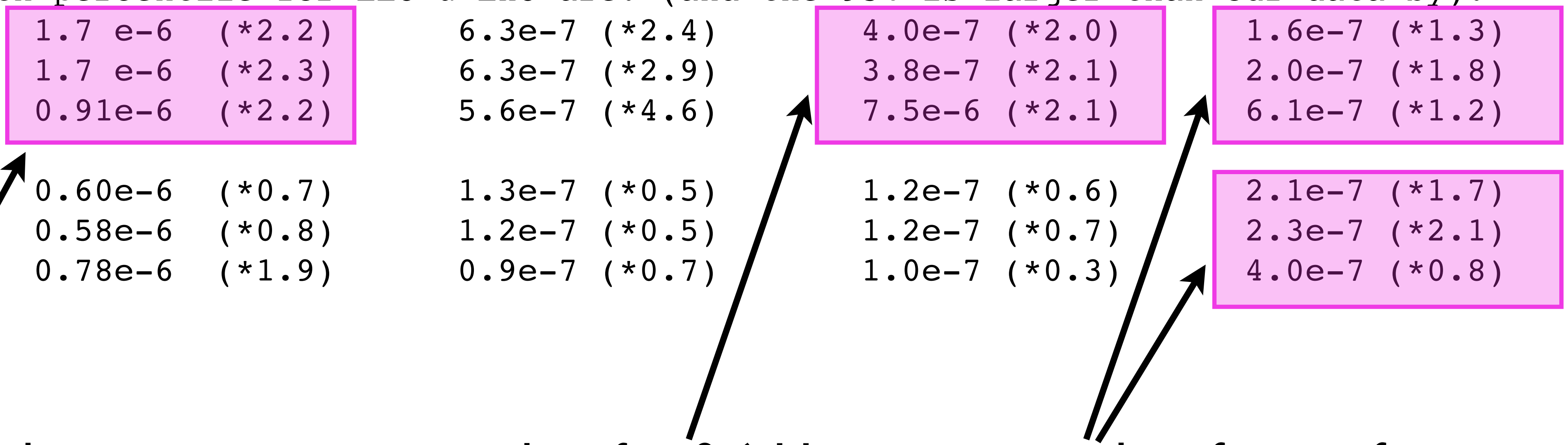
Percentiles of Motion

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)

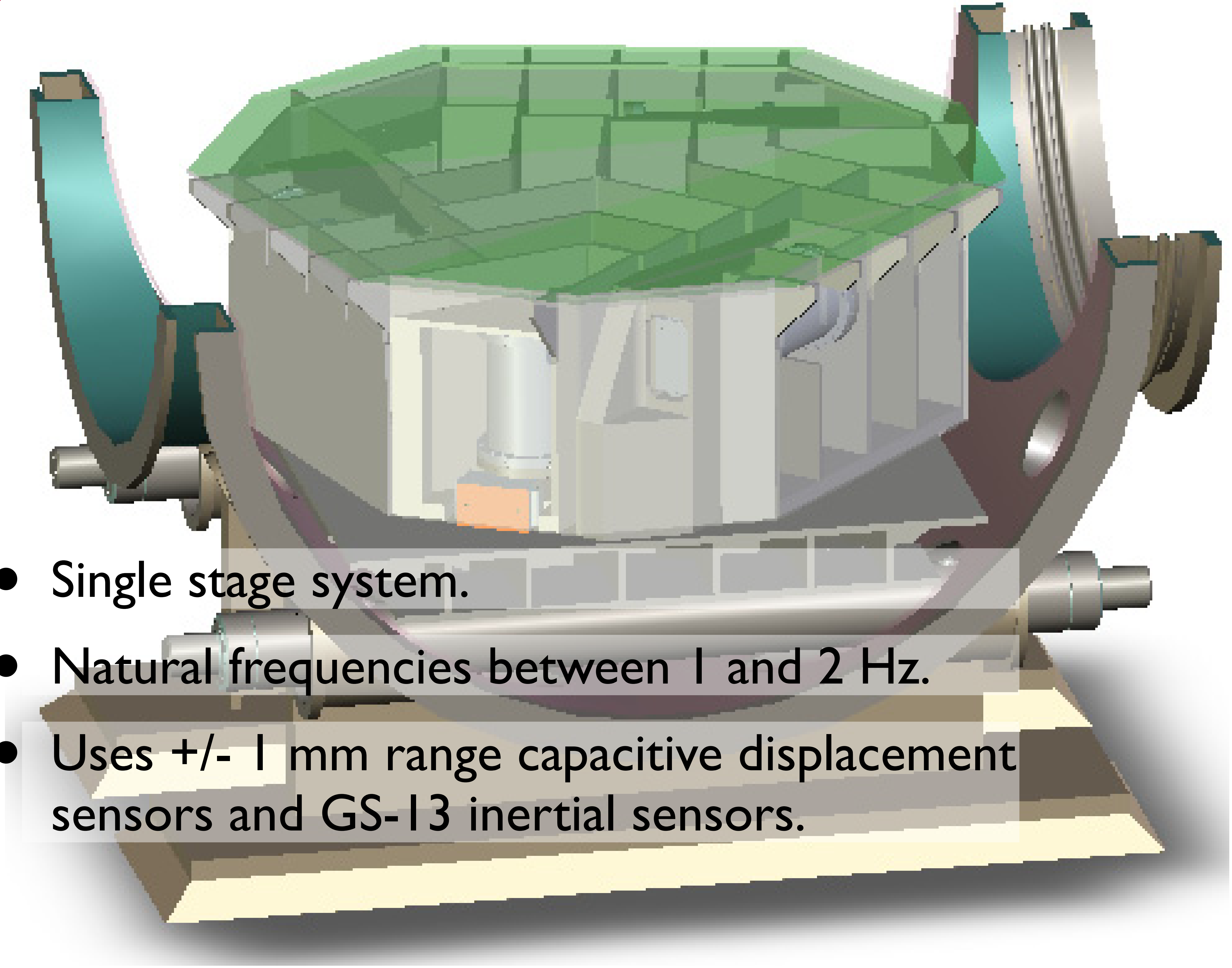
rms scaling for Lock acquisition

scaling for 0.6 Hz rms

scaling for performance

data from Shyang Wen, SEI log entry #604

Plant Parameters



- Single stage system.
- Natural frequencies between 1 and 2 Hz.
- Uses +/- 1 mm range capacitive displacement sensors and GS-13 inertial sensors.

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)

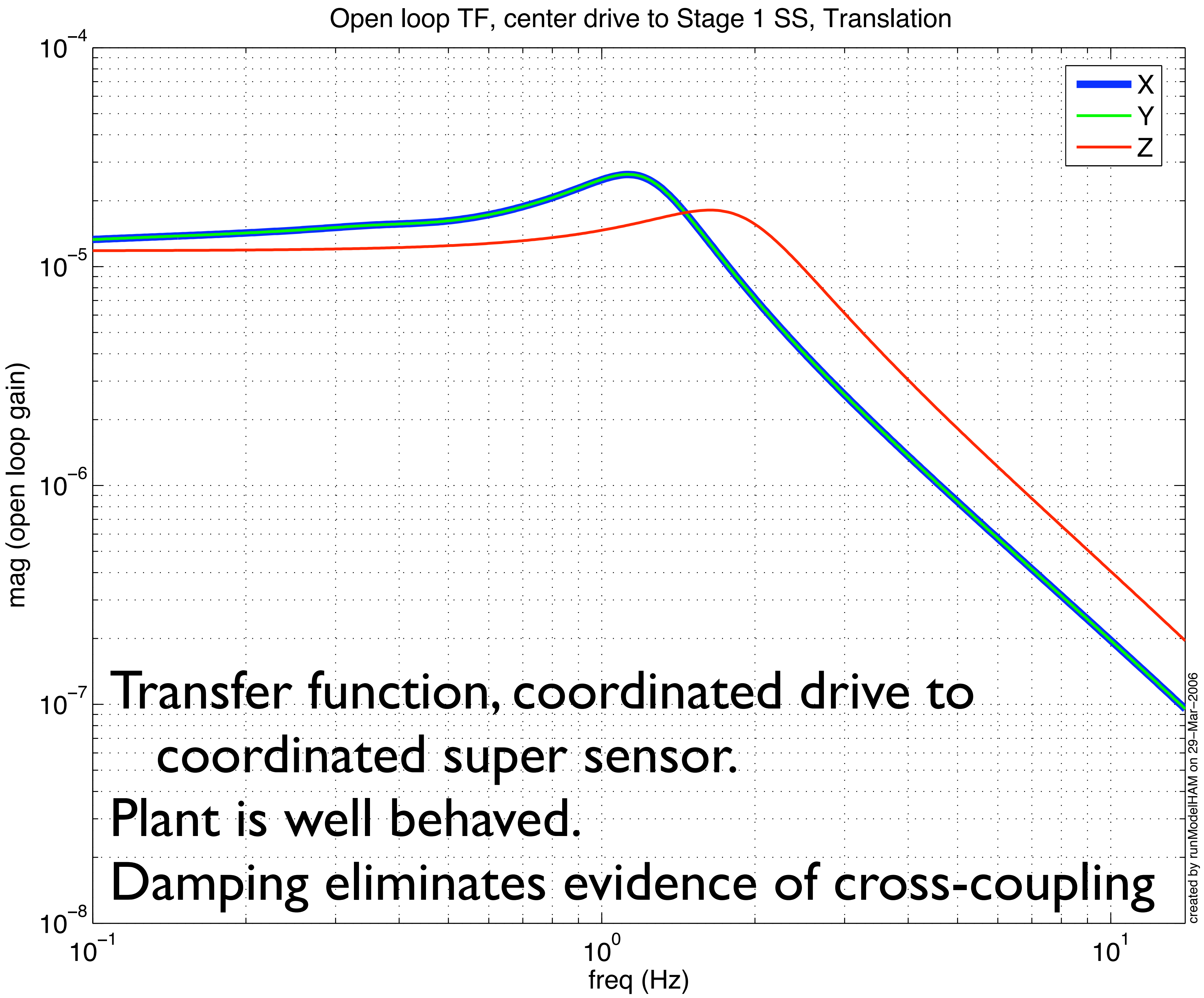
Proposed Single Stage HAM

```
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

Damped plant - translation



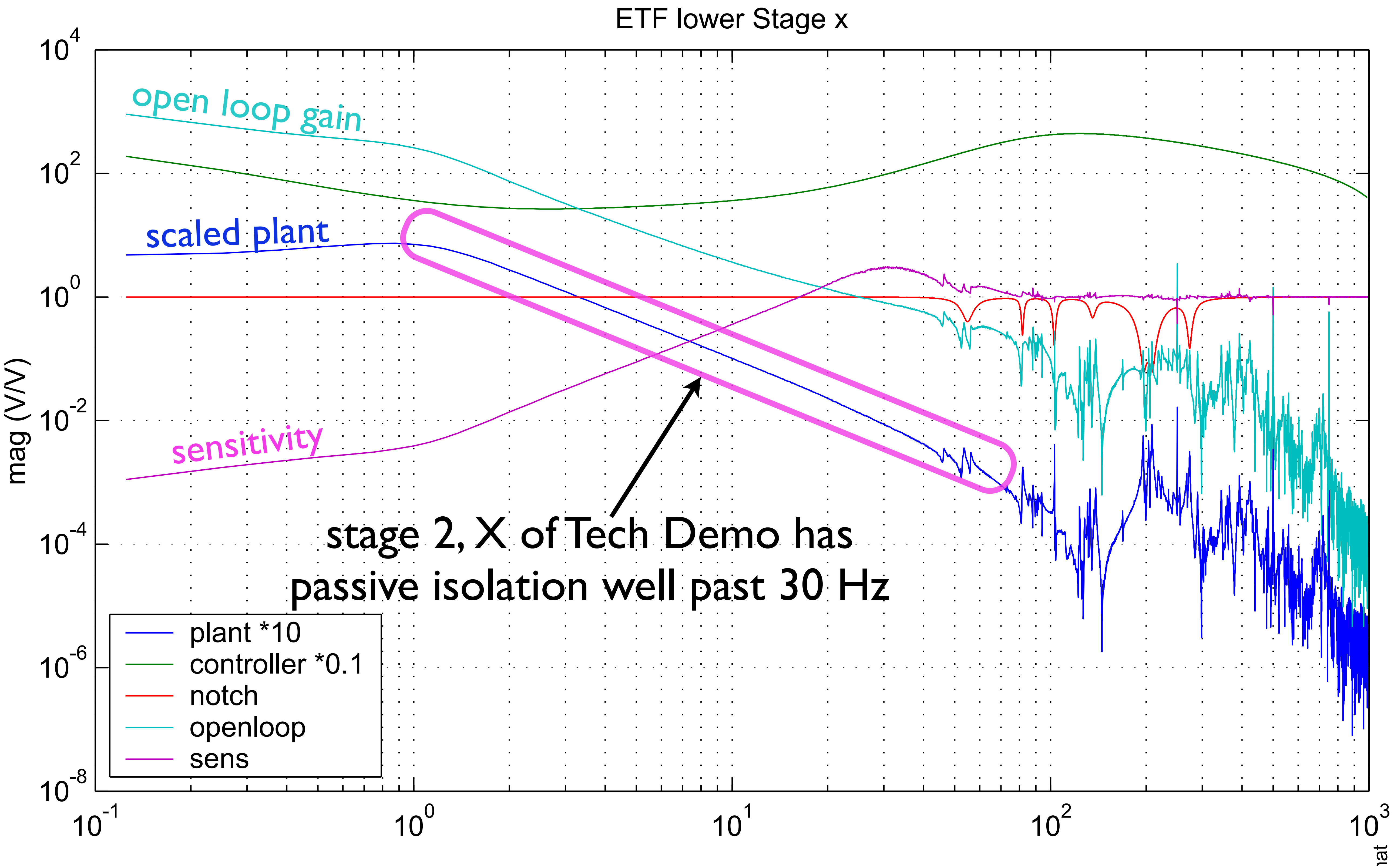
Transfer function, coordinated drive to coordinated super sensor.

Plant is well behaved.

Damping eliminates evidence of cross-coupling

Tech Demo experience

Passive Isolation



stage 2, X of Tech Demo has passive isolation well past 30 Hz

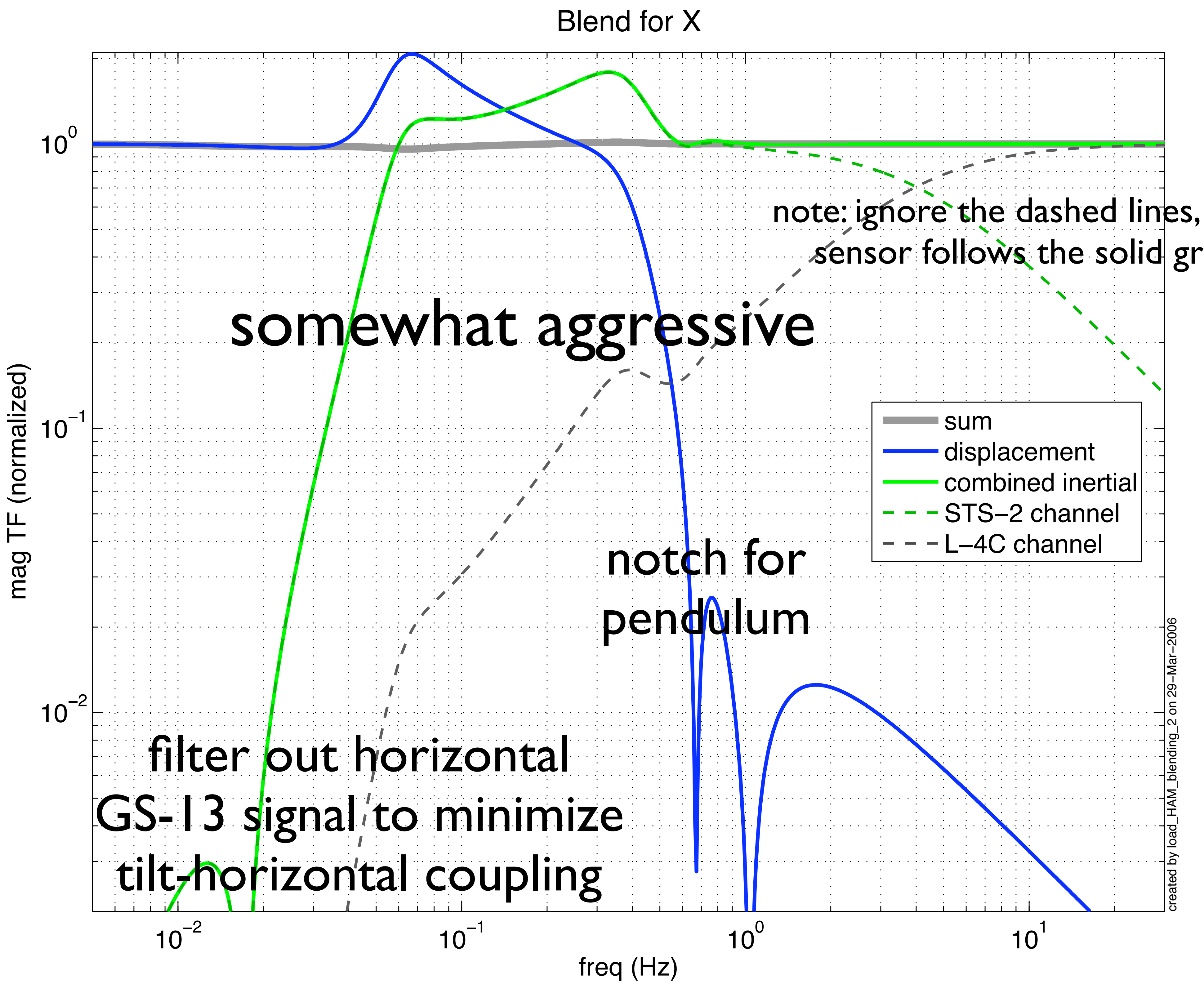
Blending loops

- 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.

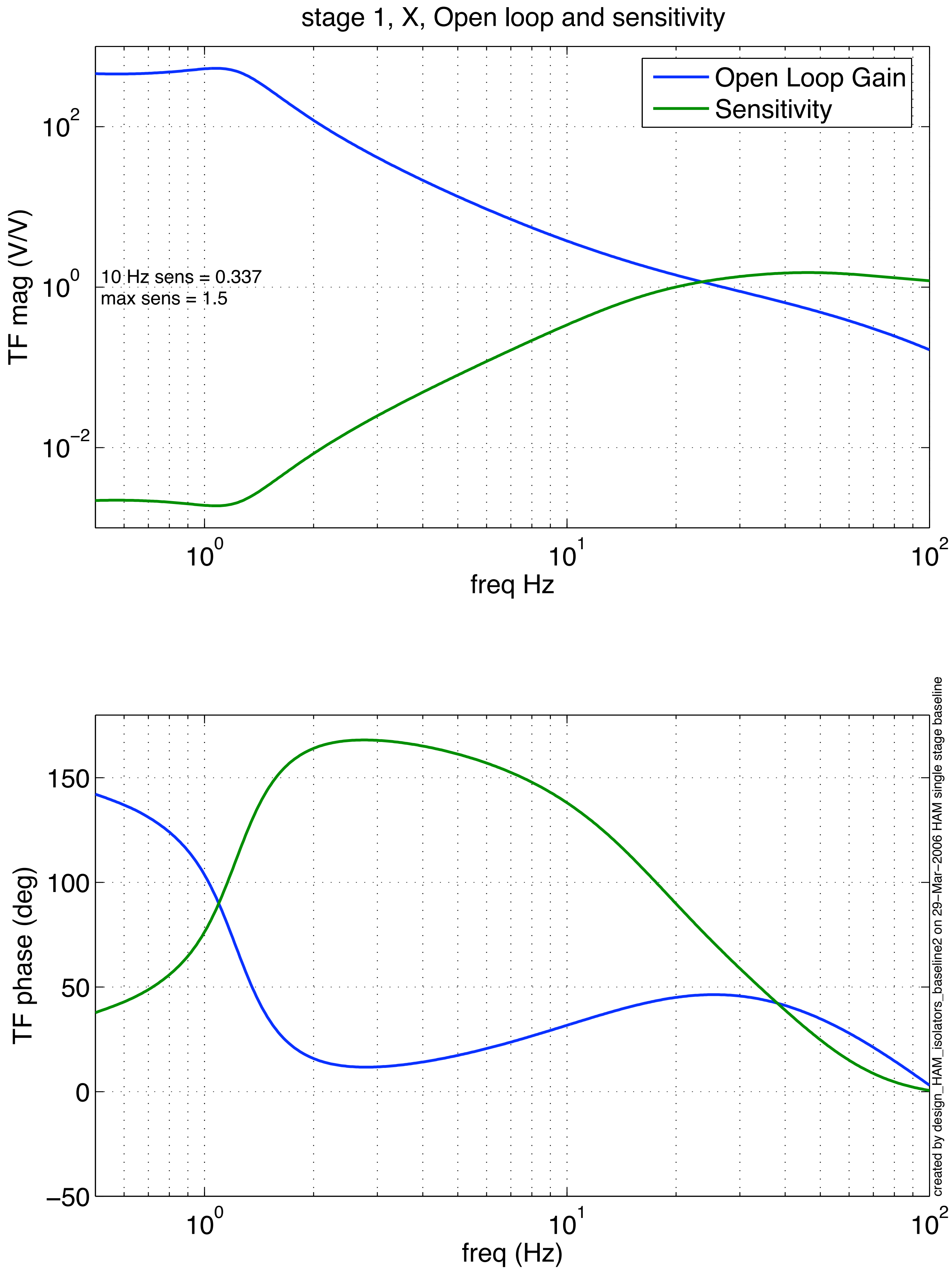
somewhat aggressive

notch for pendulum

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

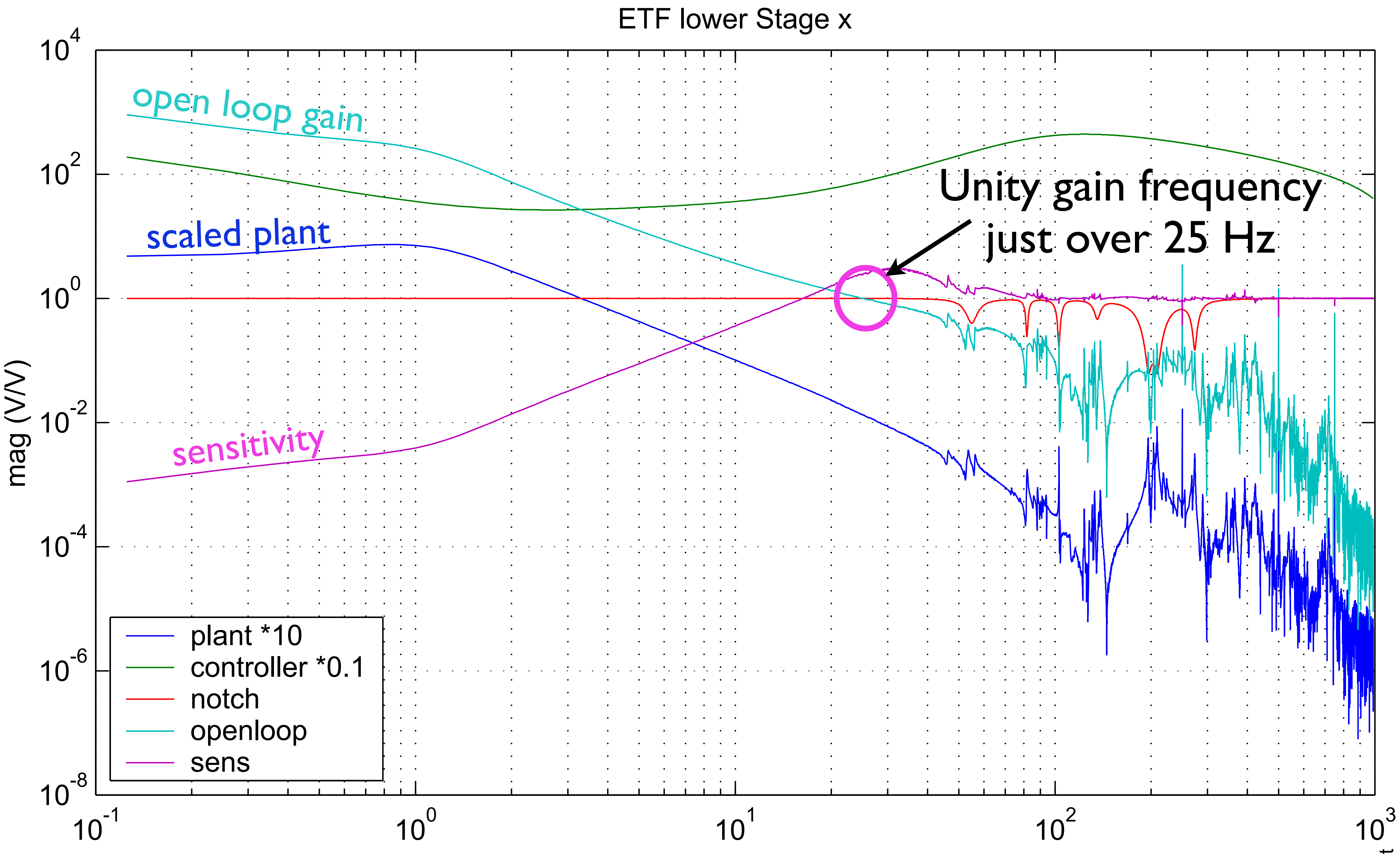
Isolation Loop, x & y

- Isolation factor of 3 at 10 Hz
- Unity gain at 27 Hz
- Like the Tech Demo
- All DOF are about the same.



Tech Demo experience

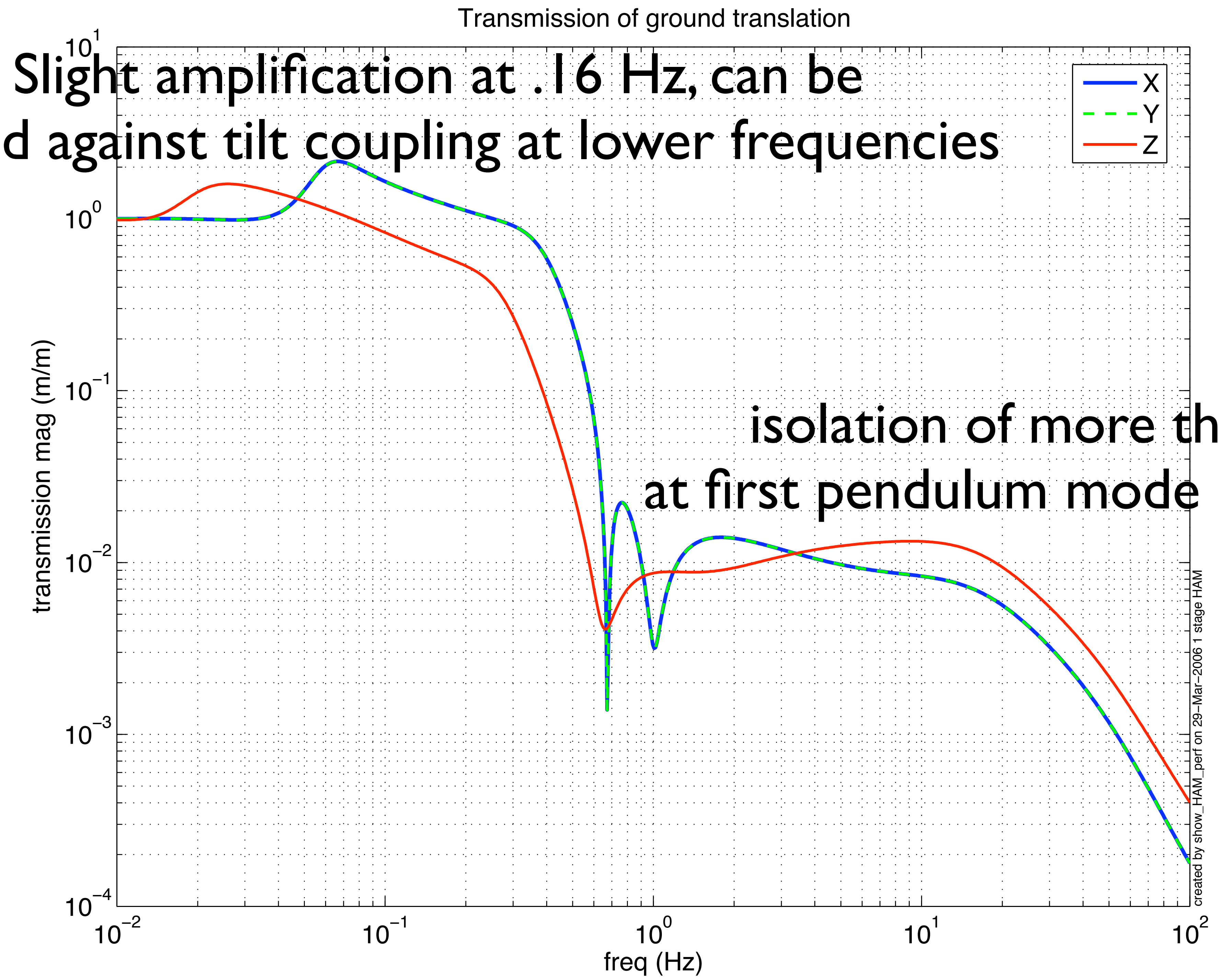
Active Isolation



Unity gain frequency just over 25 Hz

Coupling of HEPI motion

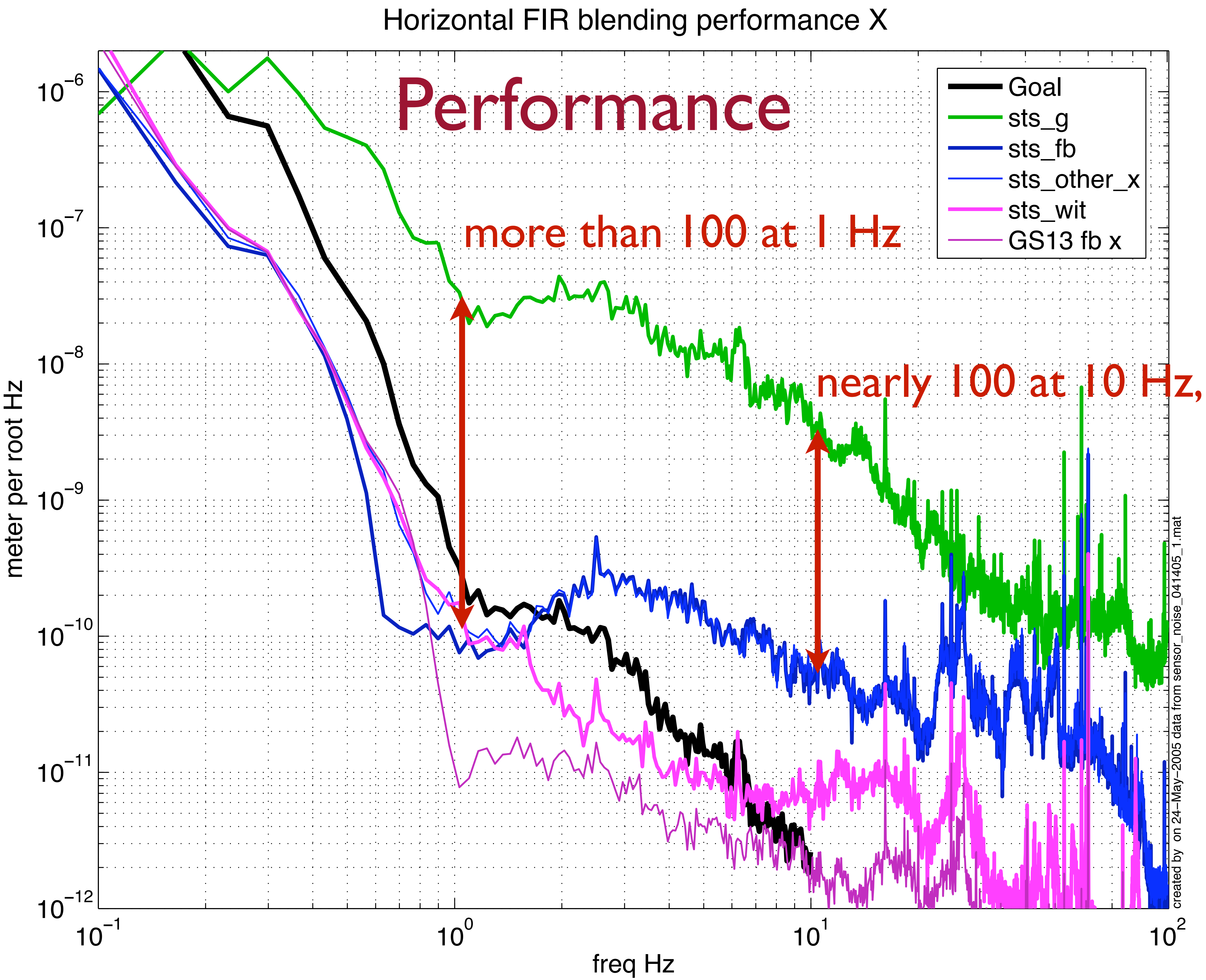
Transmission of translational input motion
HEPI motion -> table cg motion



Slight amplification at .16 Hz, can be
traded against tilt coupling at lower frequencies

isolation of more than 50
at first pendulum mode and above

Tech Demo experience



Performance

more than 100 at 1 Hz

nearly 100 at 10 Hz,

Pitch Difference

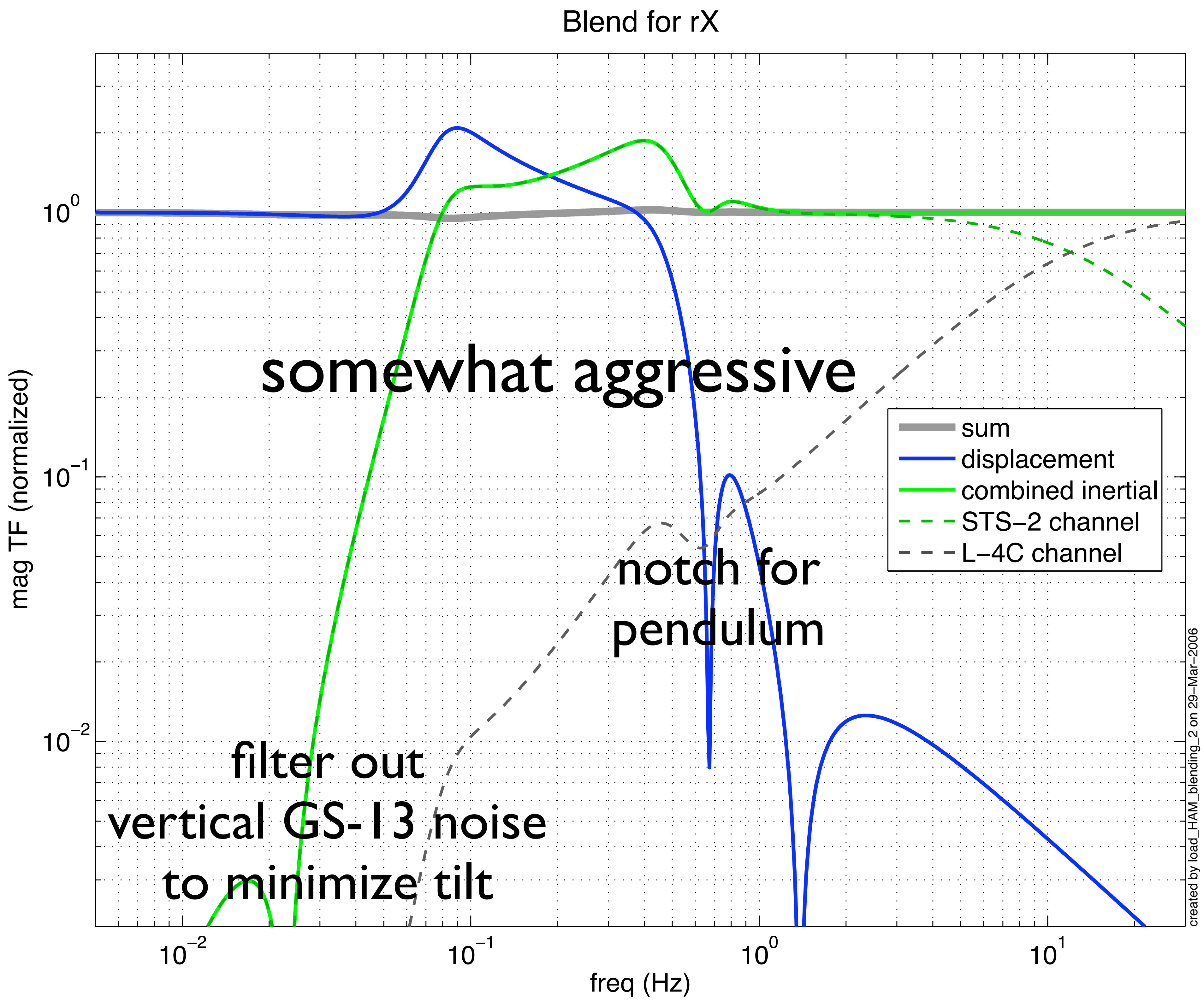
- Tech Demo pitch modes at about 2.2 and 12 Hz
- Single stage HAM pitch mode is about 1 Hz.

  No zero in single stage isolation to bring transmission back up.

  more than 5 times more pitch isolation.

  (I should do a real calculation)

Blending for rX & rY



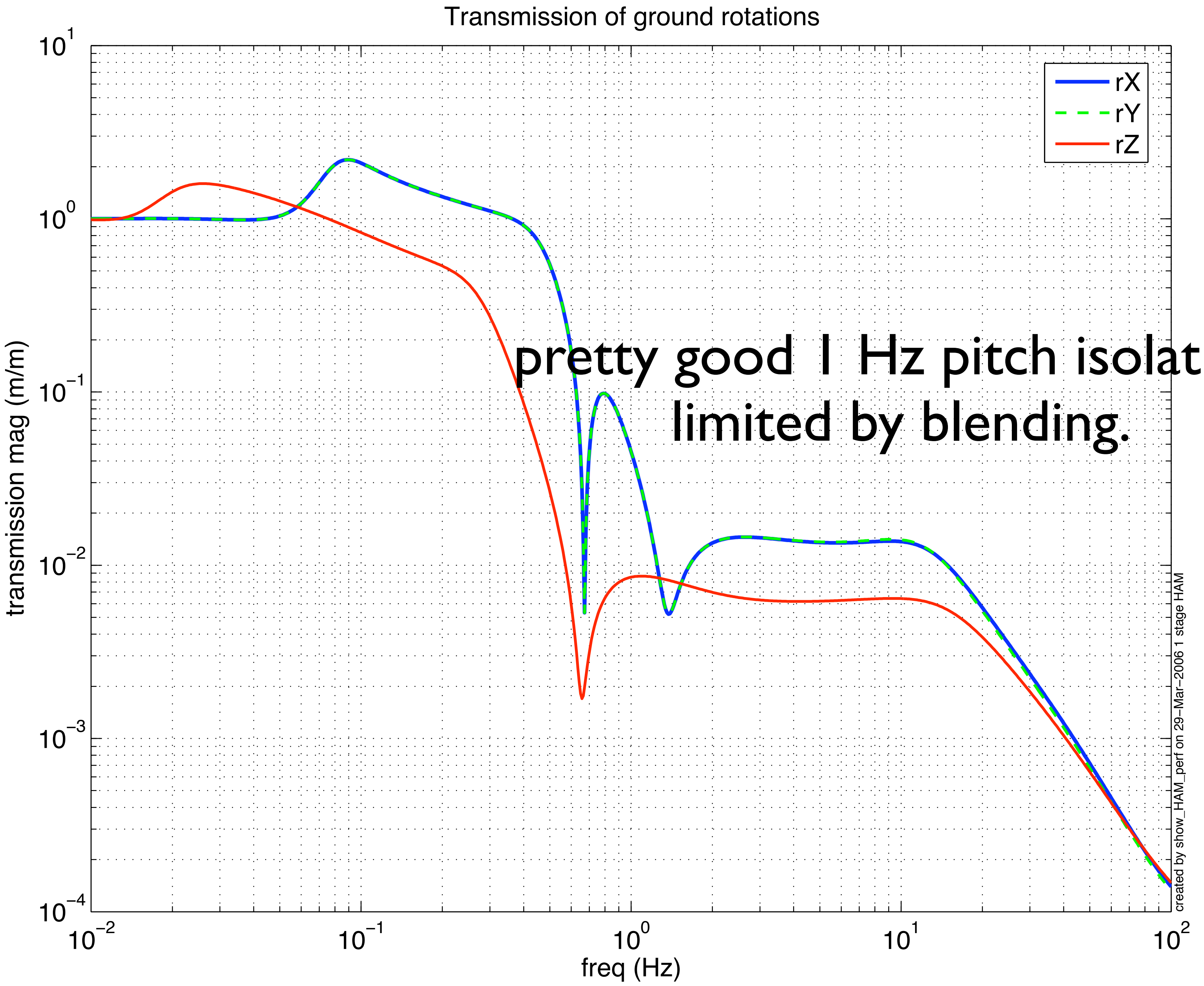
somewhat aggressive

notch for pendulum

filter out
vertical GS-13 noise
to minimize tilt

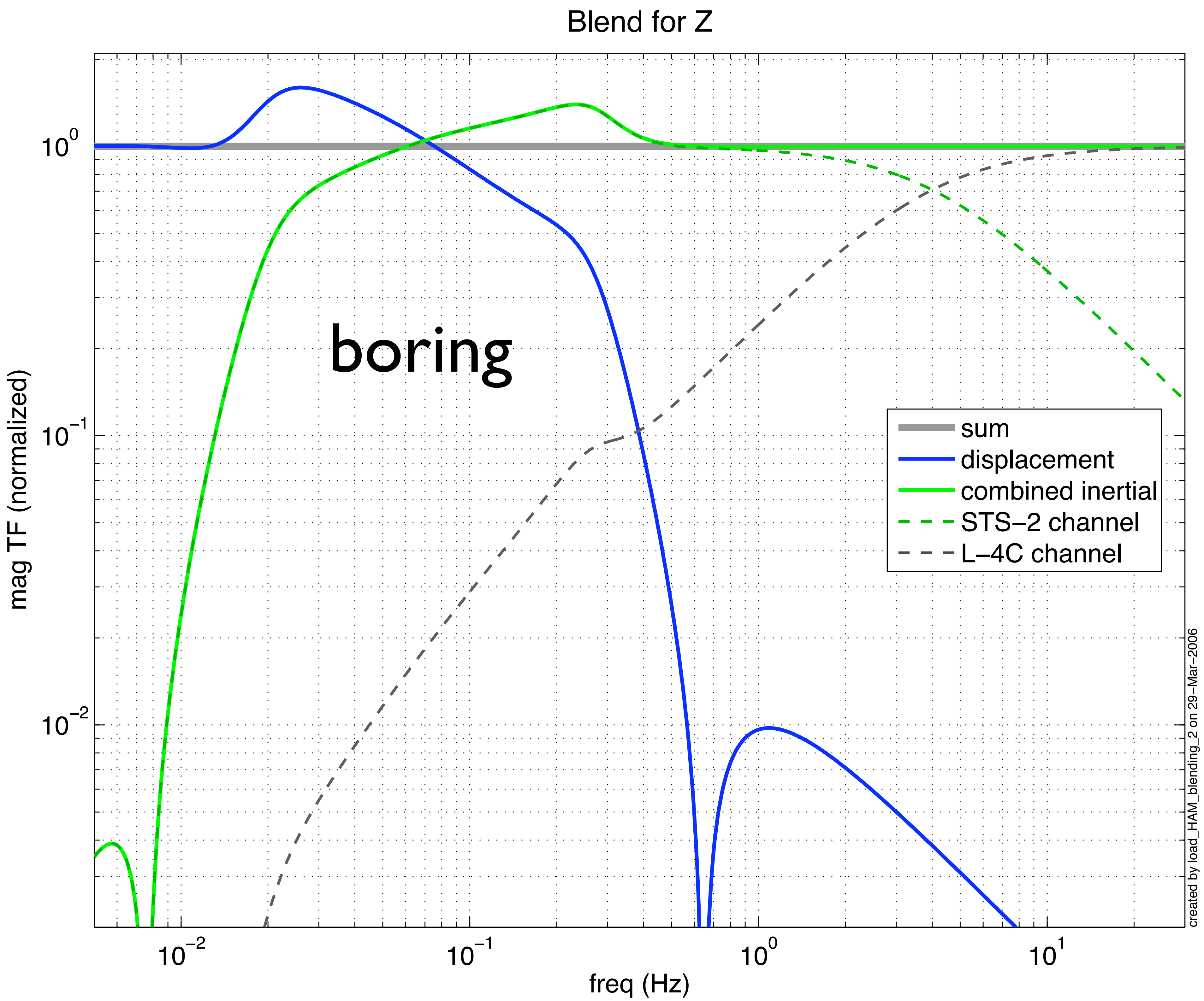
Coupling of HEPI motion

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

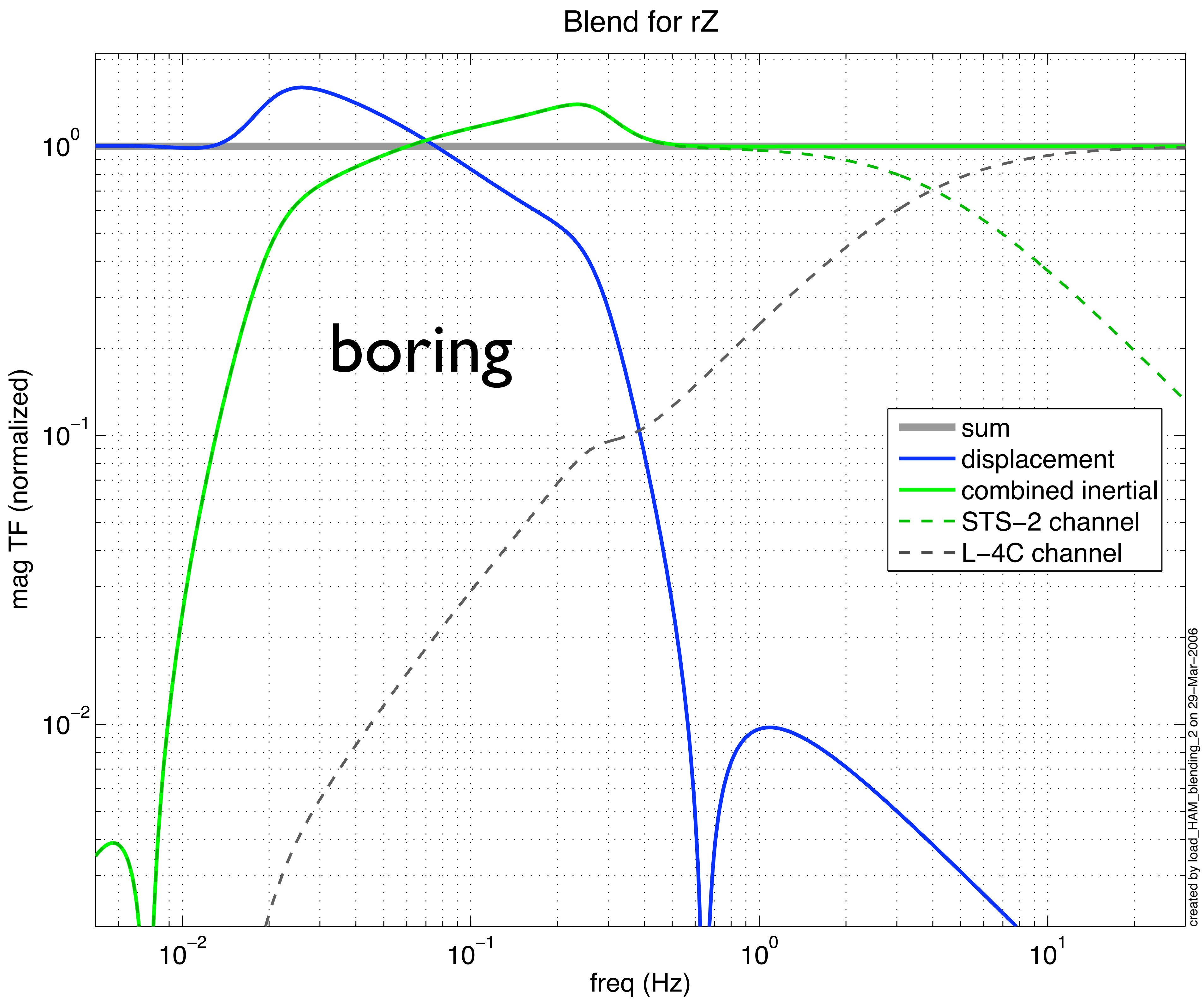


pretty good 1 Hz pitch isolation,
limited by blending.

Blending for Z



Blending for rZ



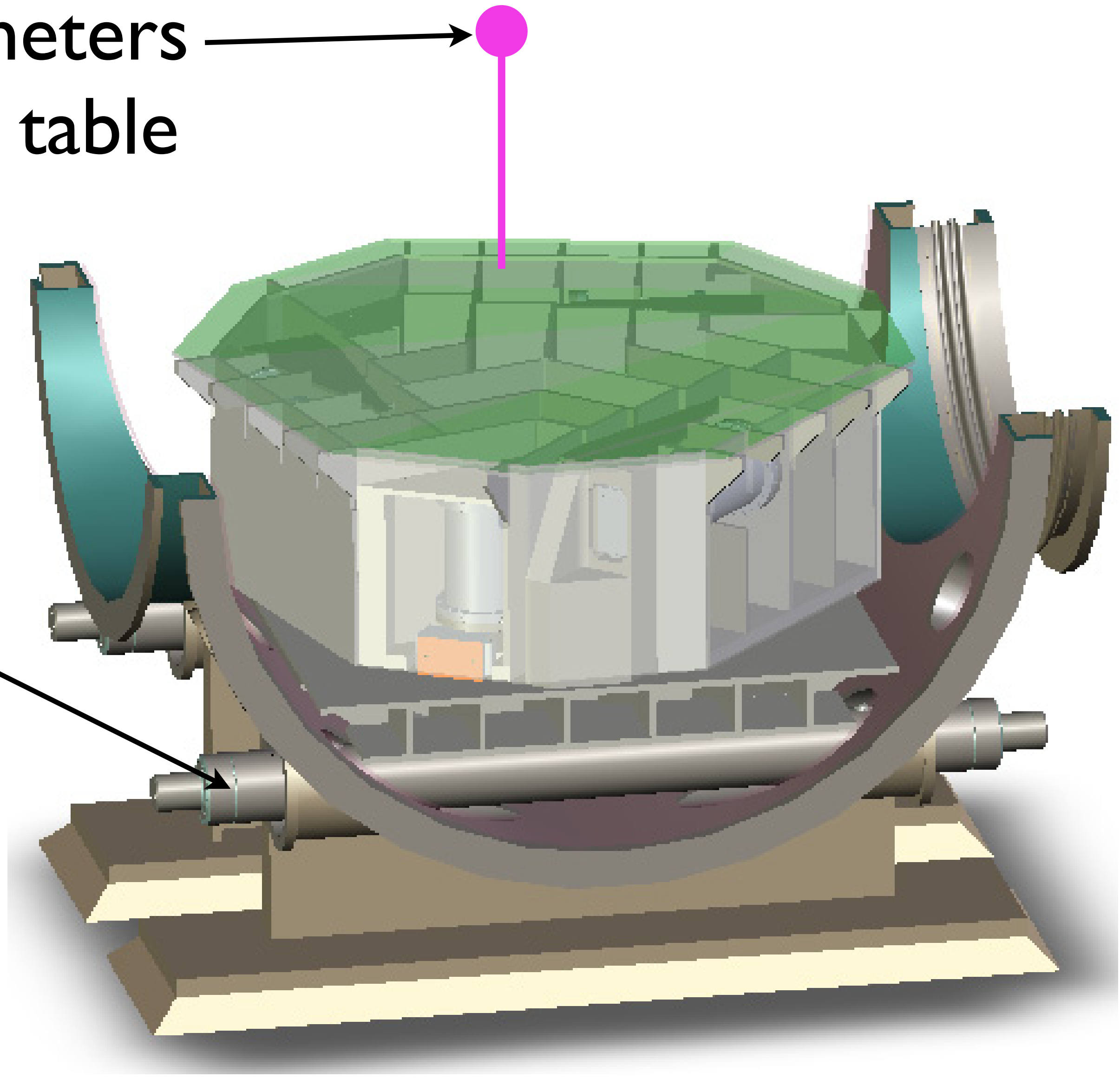
boring

Performance of the system

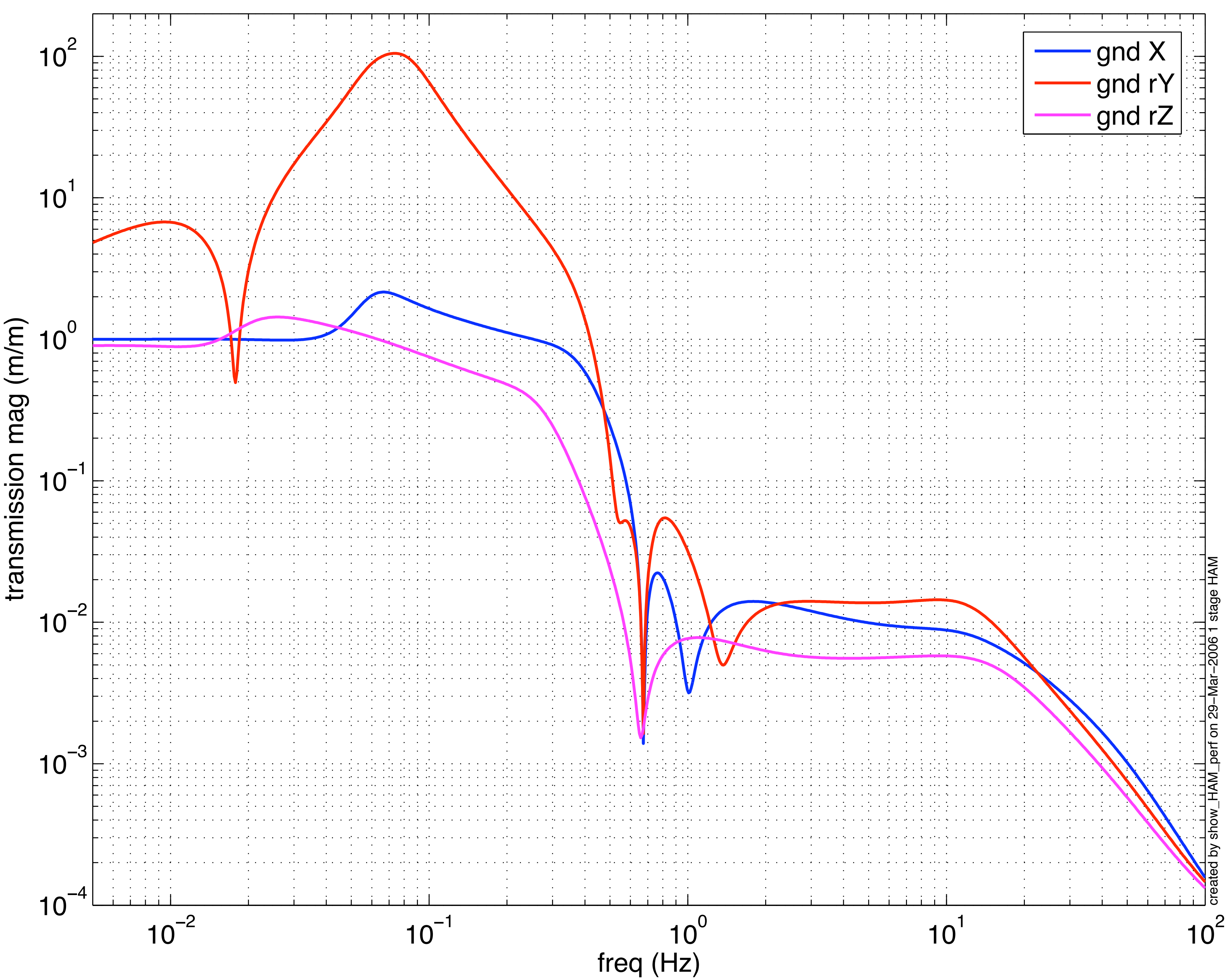
- System dominated by transmitted HEPI motion.
  (note: although it is sometimes called 'ground motion' in the legends, it always means HEPI motion)
- 1 Hz isolation prediction for translation similar to measured performance at the Stanford ETF.
- We demand better rotational performance than seen at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

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)

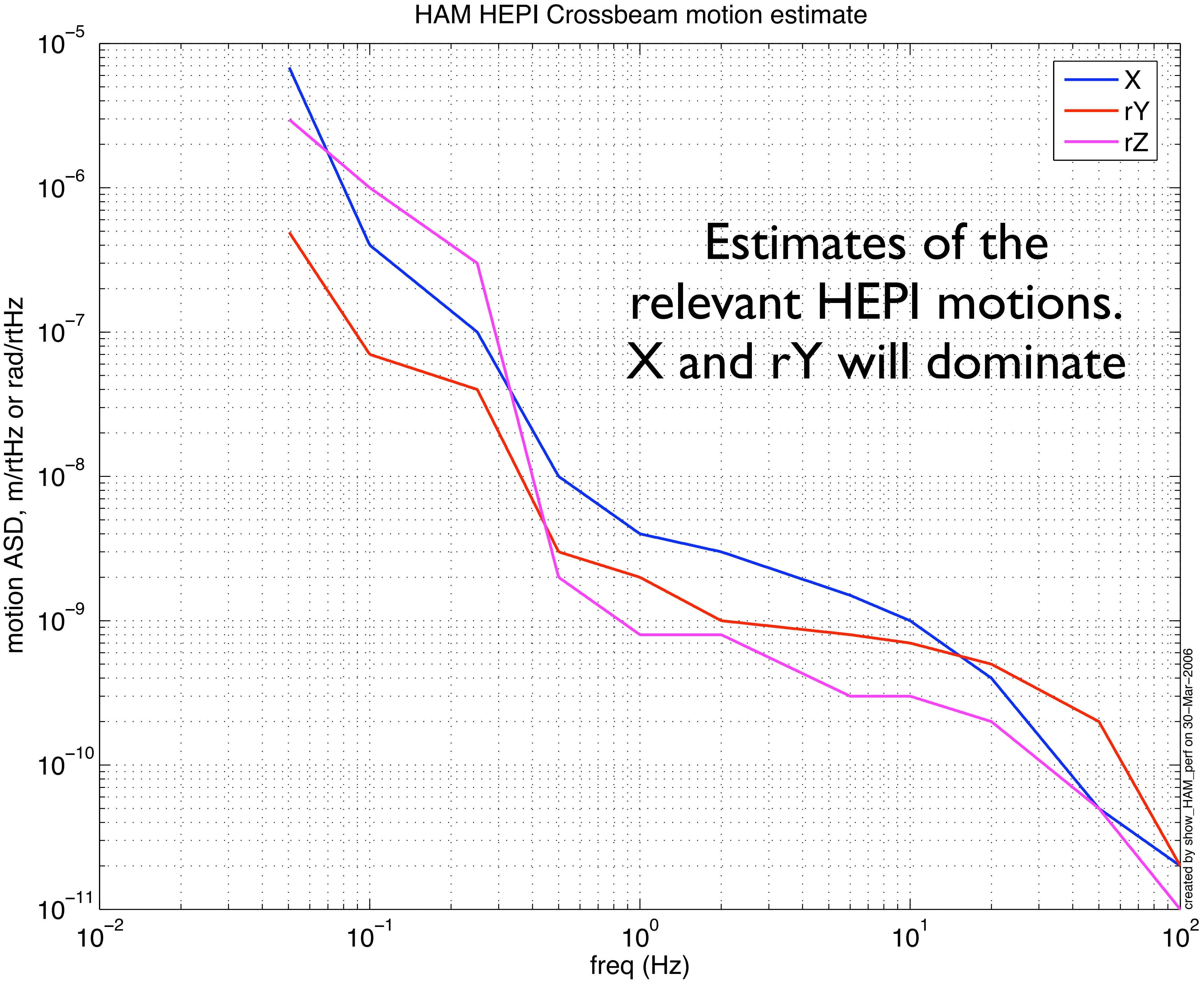


HEPI X, rY, and rZ coupling to suspension point - horizontal



Transmission of ground to motion at the frame tip, Horz

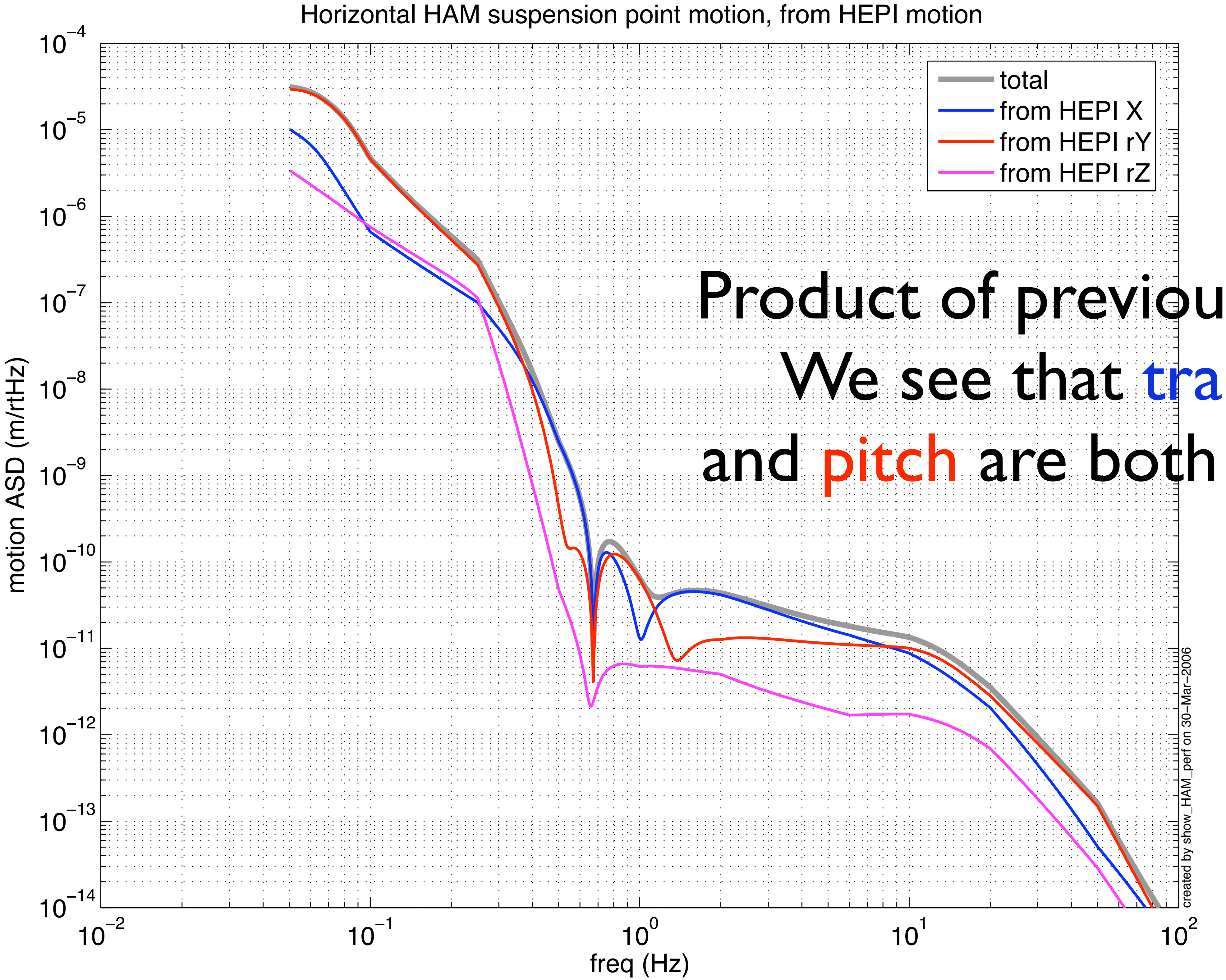
X, rY, and rZ motion of HEPI



Estimates of the relevant HEPI motions. X and rY will dominate

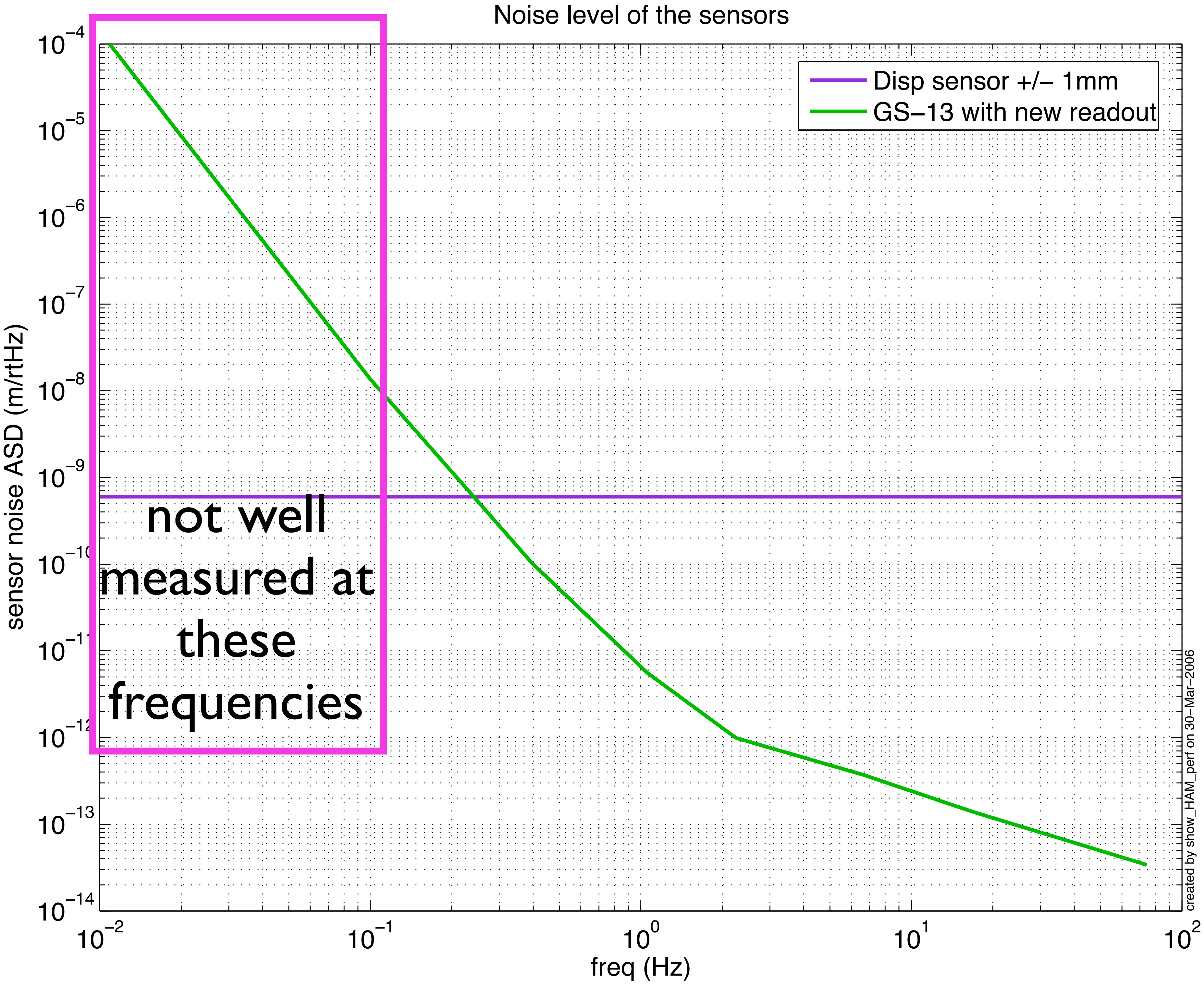
created by show_HAM_perf on 30–Mar–2006

Horizontal Suspension point motion - from HEPI motion



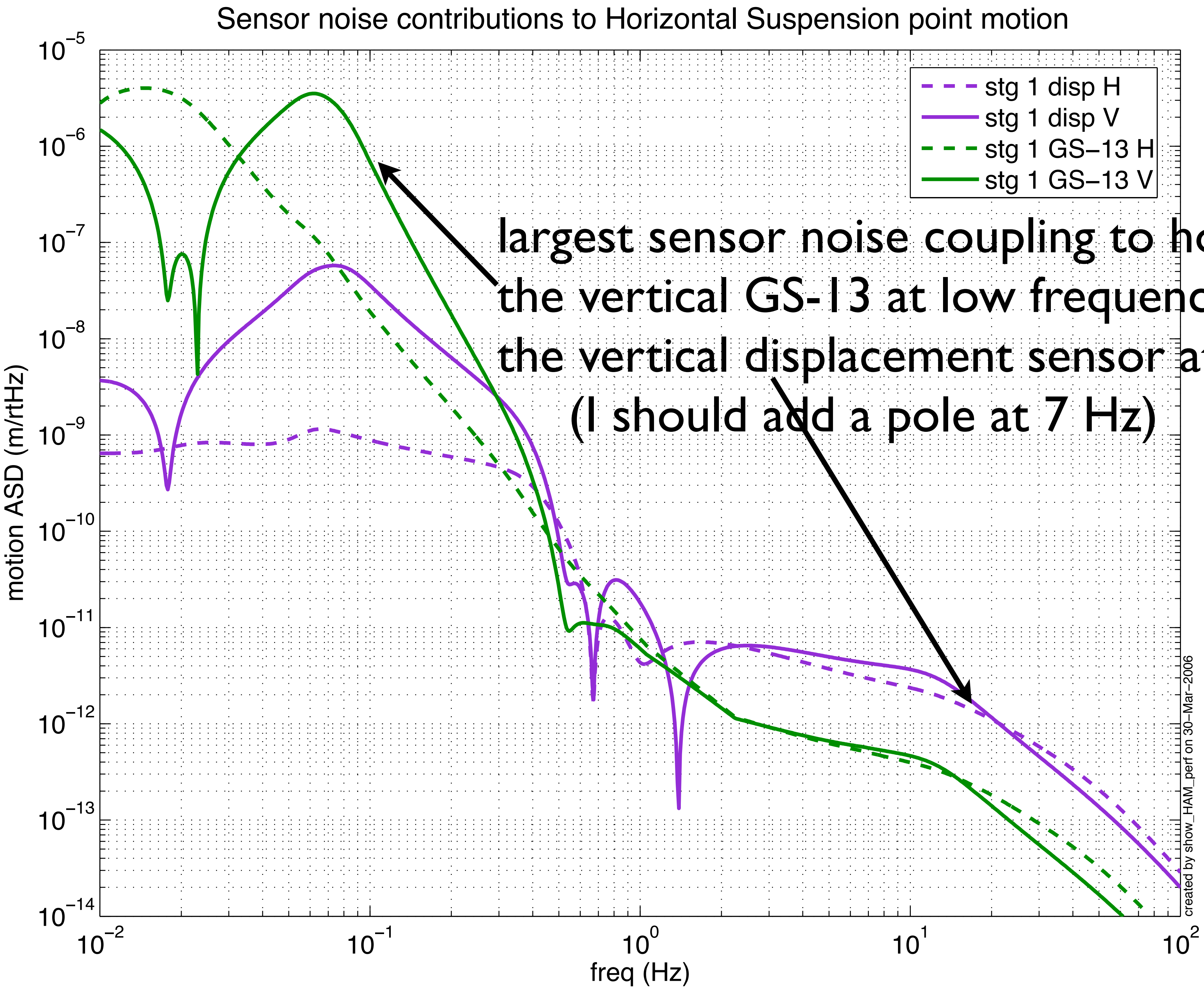
Product of previous 2 graphs.
We see that translation
and pitch are both important

Noise of the sensors



not well measured at these frequencies

Horizontal Suspension point motion from sensor noise

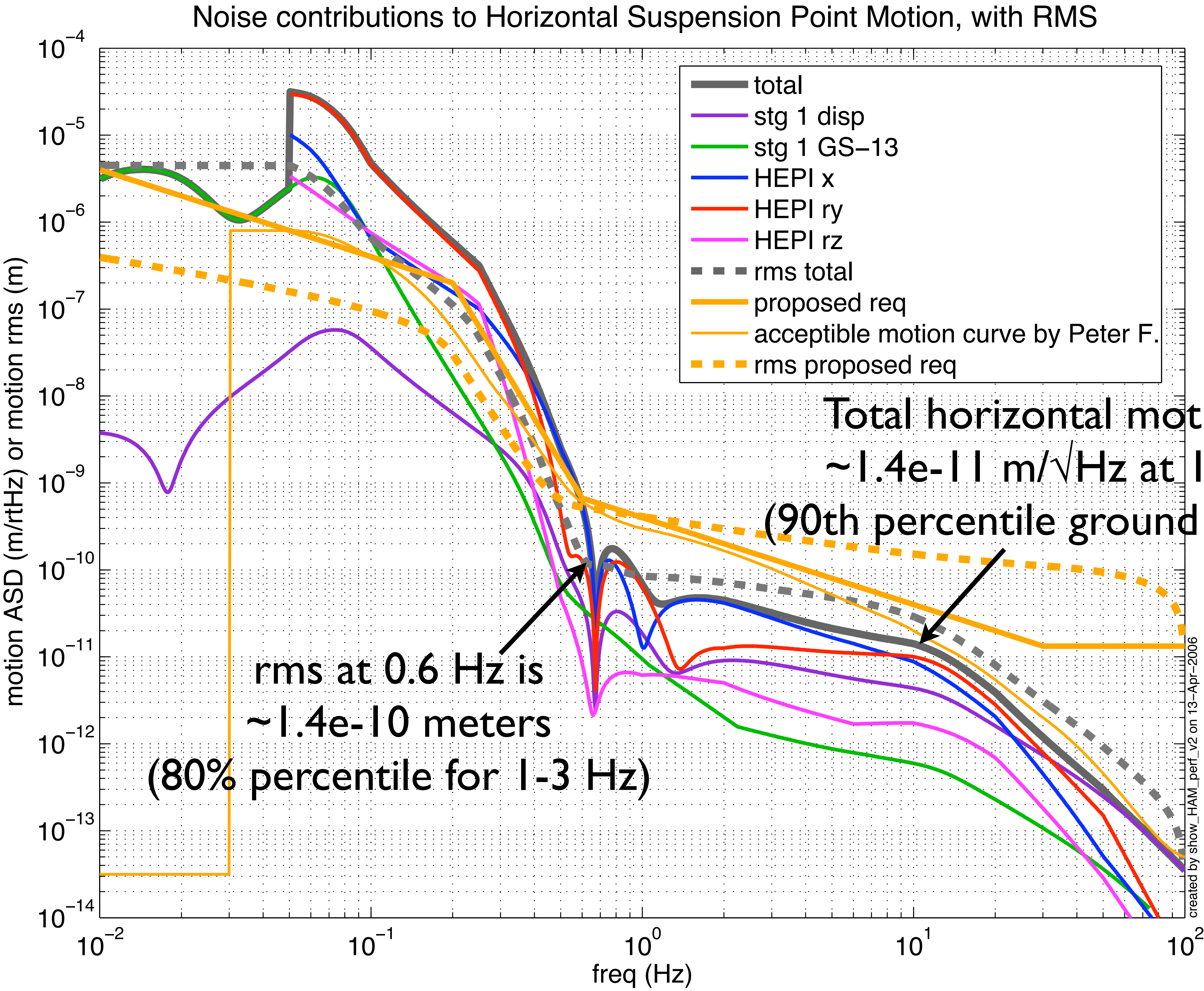


Sensor noise contributions to Horizontal Suspension point motion

largest sensor noise coupling to horizontal motion is the vertical GS-13 at low frequencies and the vertical displacement sensor at high frequencies

(I should add a pole at 7 Hz)

Horiz. Motion at Suspension Point



Noise contributions to Horizontal Suspension Point Motion, with RMS

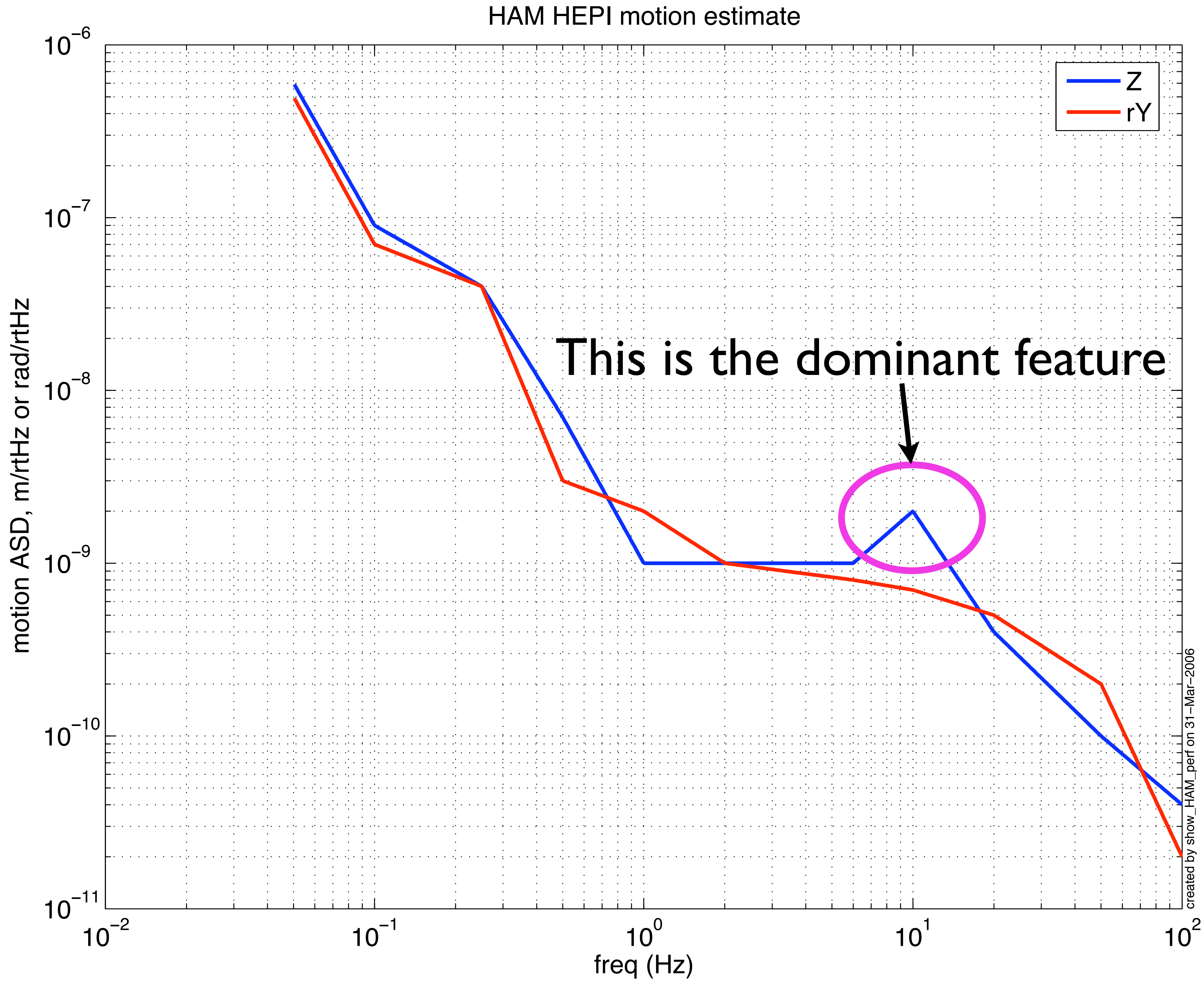
Total horizontal motion is
~1.4e-11 m/√Hz at 10 Hz
(90th percentile ground motion)

rms at 0.6 Hz is
~1.4e-10 meters
(80% percentile for 1-3 Hz)

Vertical Motion of the Suspension point

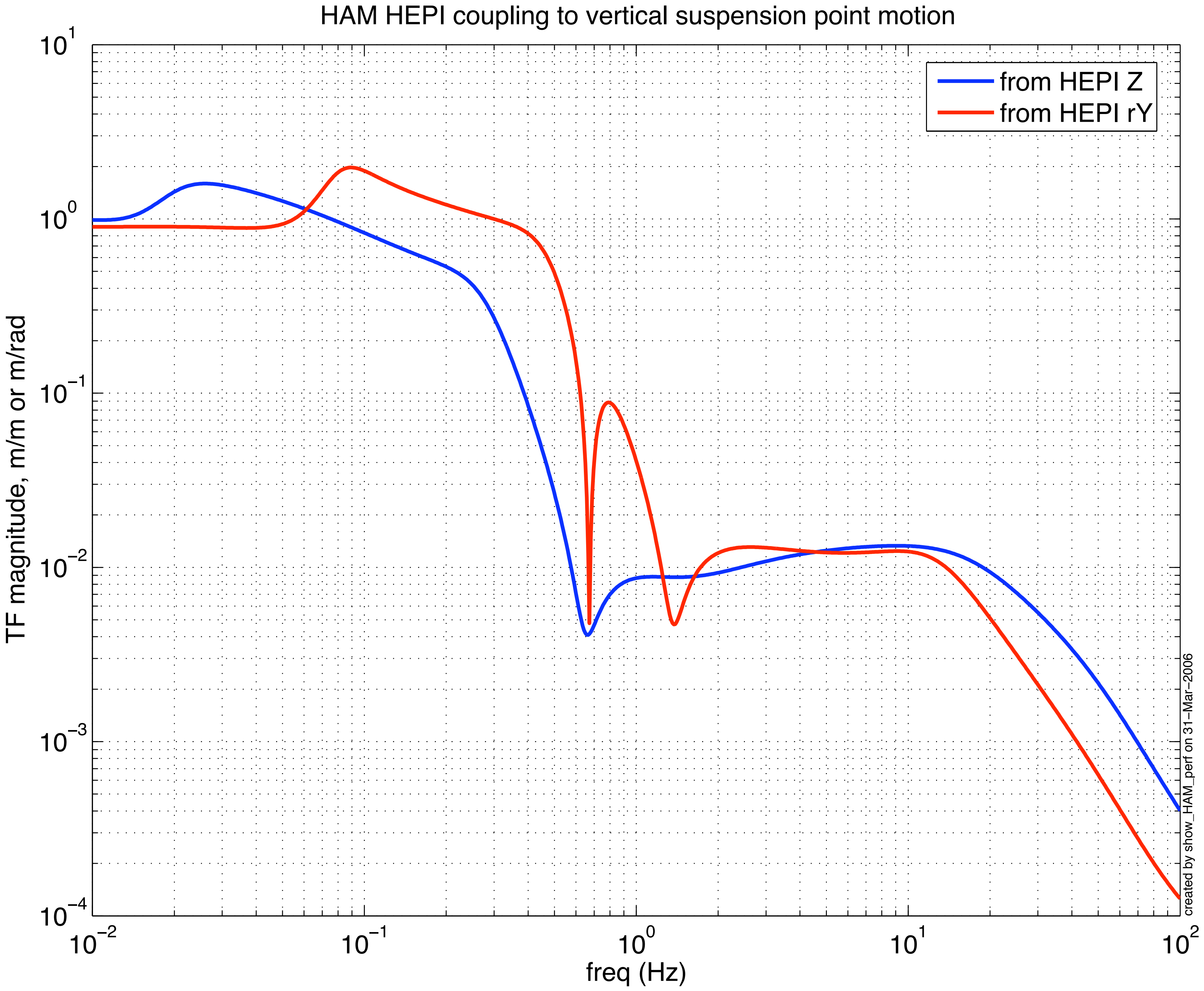
- Both vertical and pitch contribute to vertical motion of the suspension point.
- We assume 1e-3 mechanical cross coupling from the pendulum.
- For vertical coupling, we assume the suspension point is at x = 0.9 meters to maximize the rY coupling. (For horizontal, it was at x = 0, y = 0.9 m).

HEPI motion estimate for Vertical motion drivers

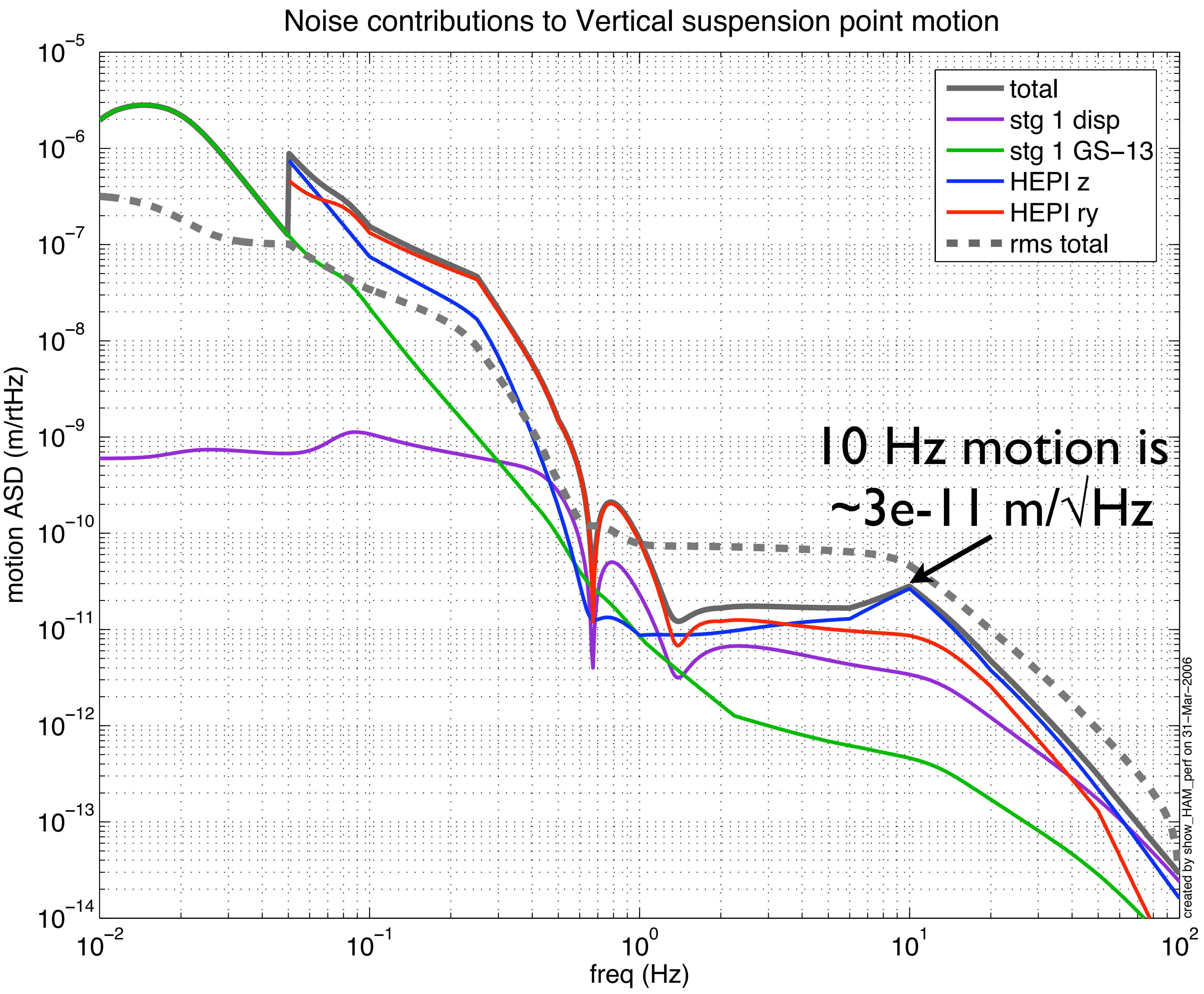


This is the dominant feature

Coupling of HEPI motion to Vertical Suspension point



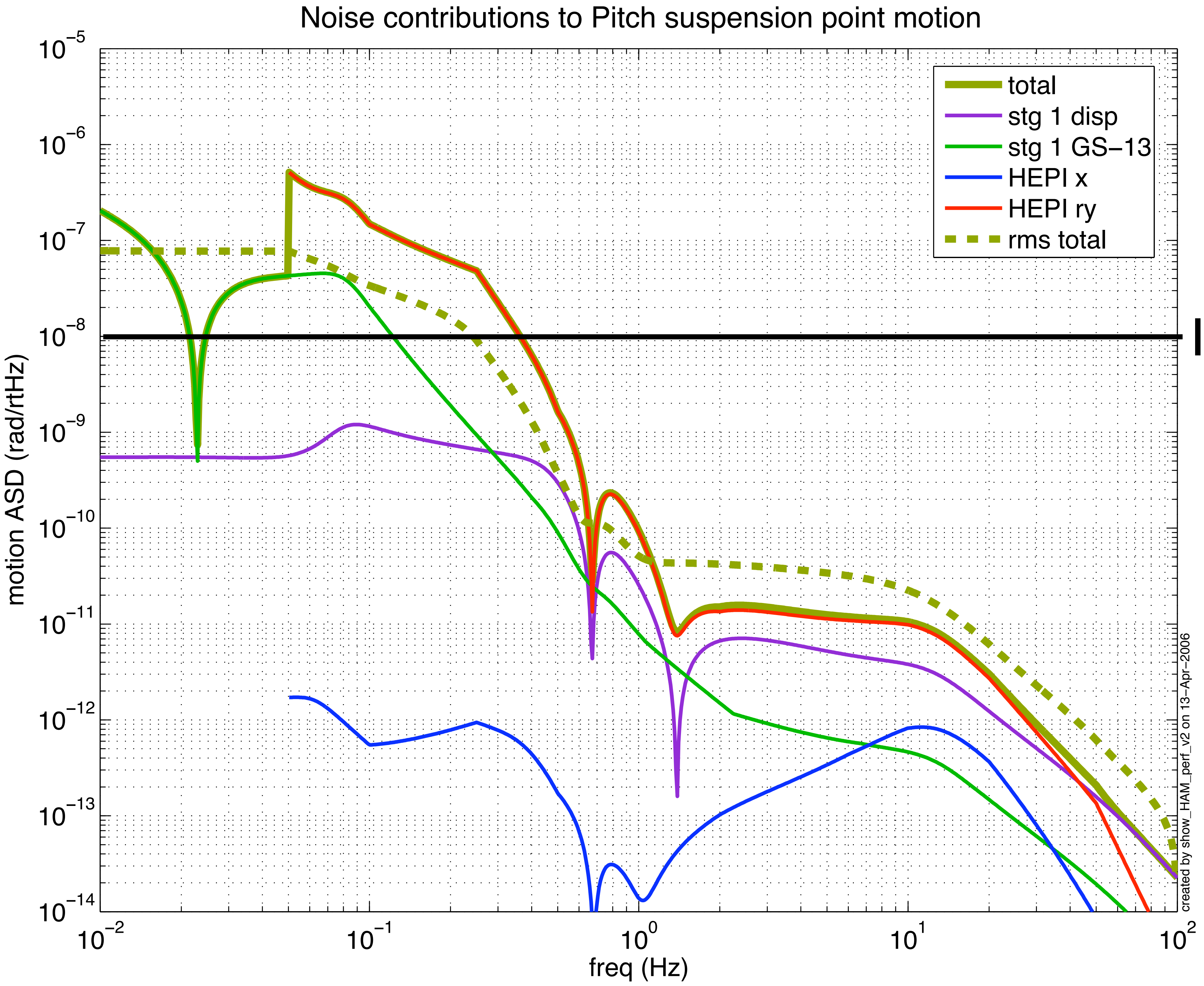
Vertical Motion of Suspension point



10 Hz motion is ~3e-11 m/√Hz

HAM table Pitch (rY)

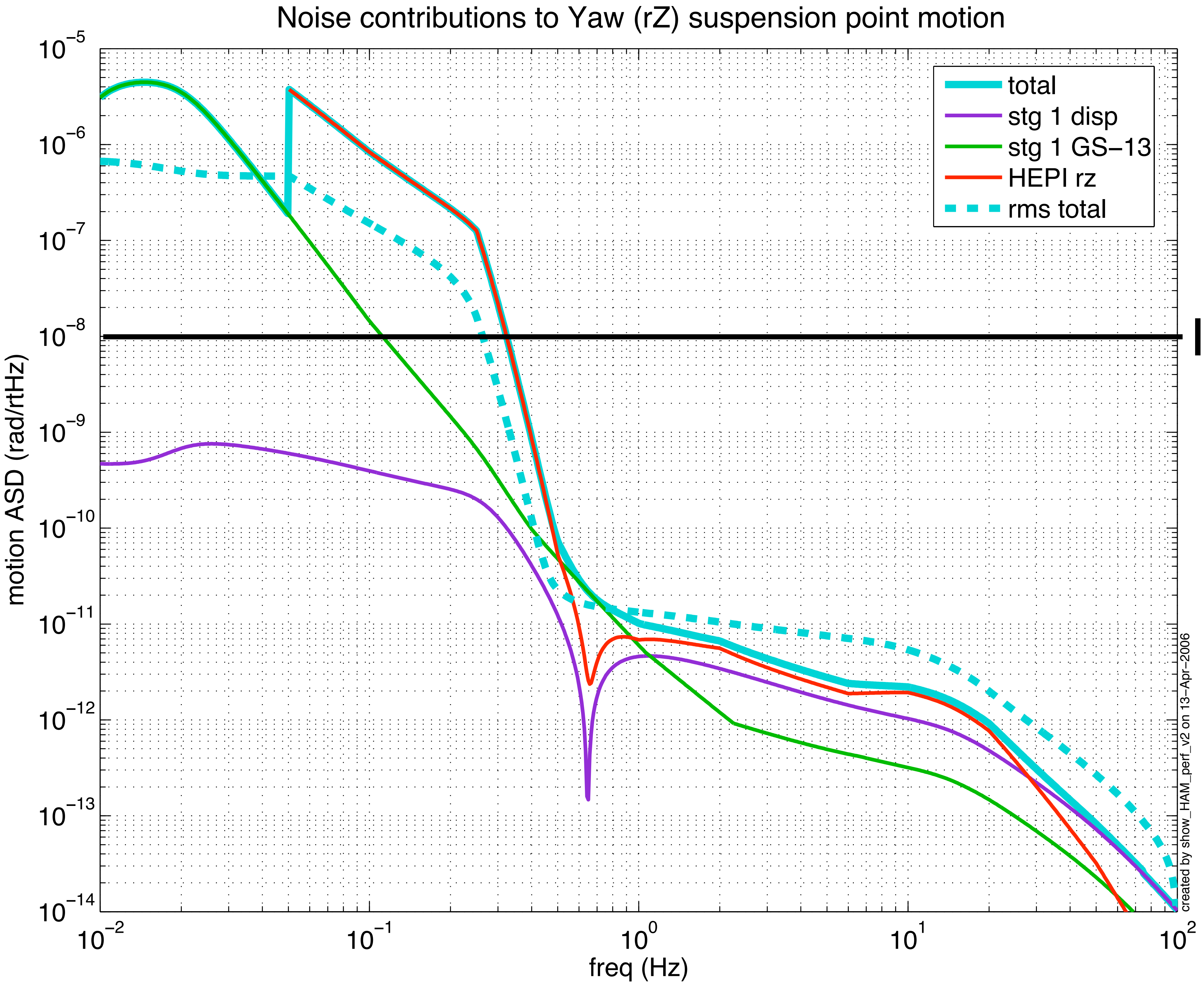
rms angle of table crosses 1e-8 radians at:
0.24 Hz for pitch (rY), and 0.26 Hz for yaw (rZ)



1e-8 radians

HAM table Yaw (rZ)

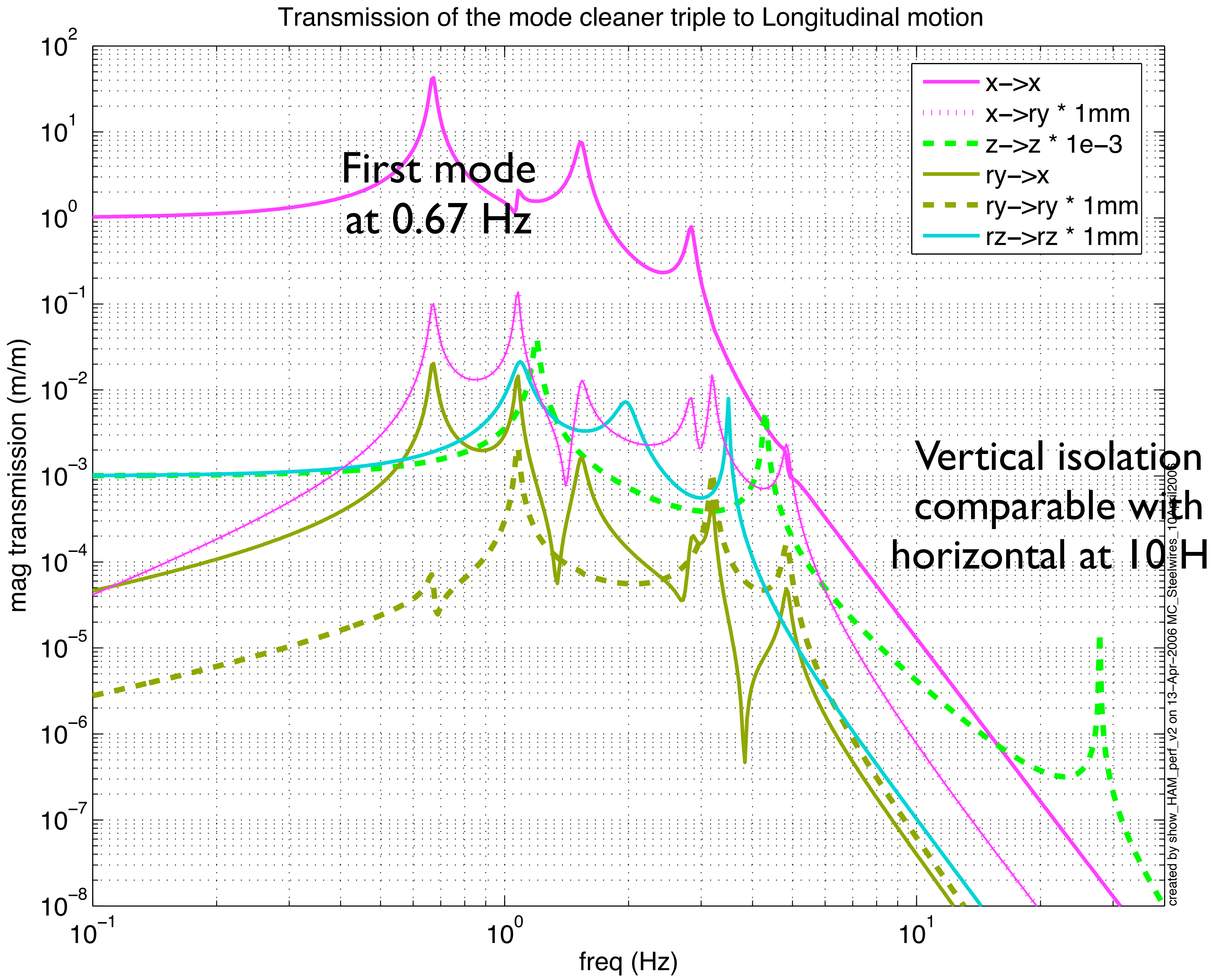
rms angle of table crosses 1e-8 radians at:
0.24 Hz for pitch (rY), and 0.26 Hz for yaw (rZ)



1e-8 radians

Pendulum Isolation, beam direction

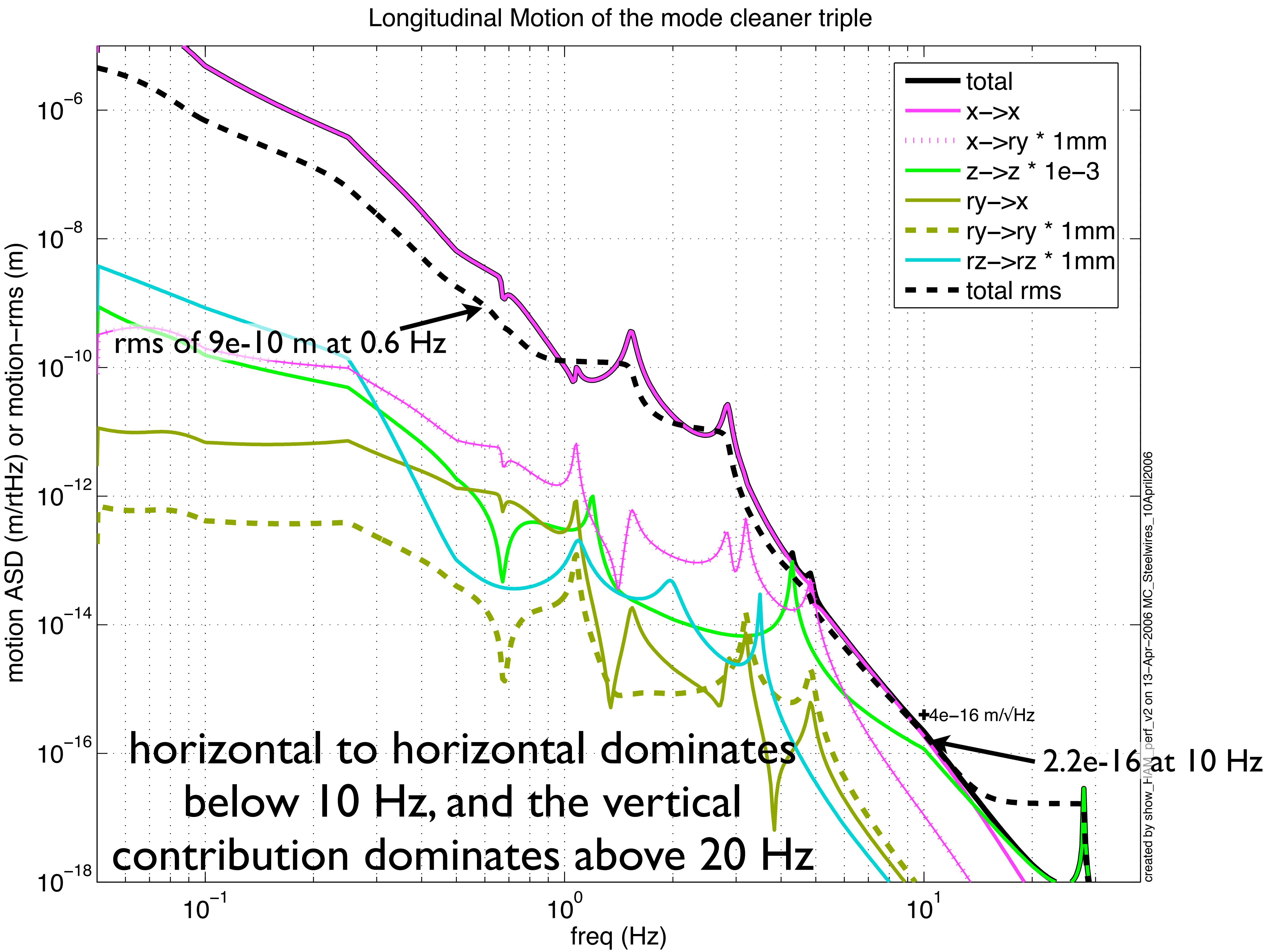
Assume a triple pendulum with steel wires, from Norna, April 2006


Transmission of the mode cleaner triple to Longitudinal motion

First mode
at 0.67 Hz

Vertical isolation
comparable with
horizontal at 10 Hz

Test mass motion, beam direction

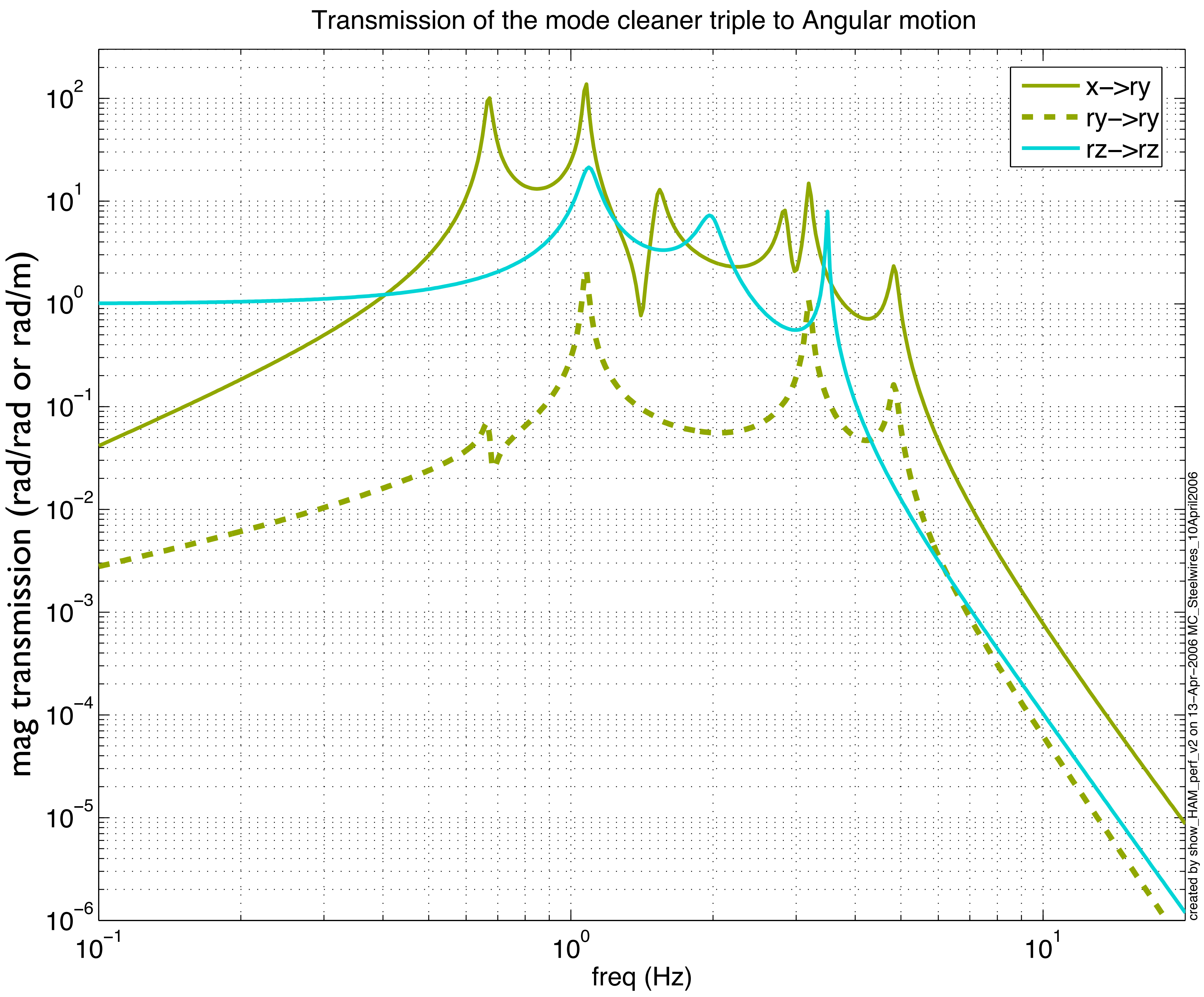


rms of 9e-10 m at 0.6 Hz

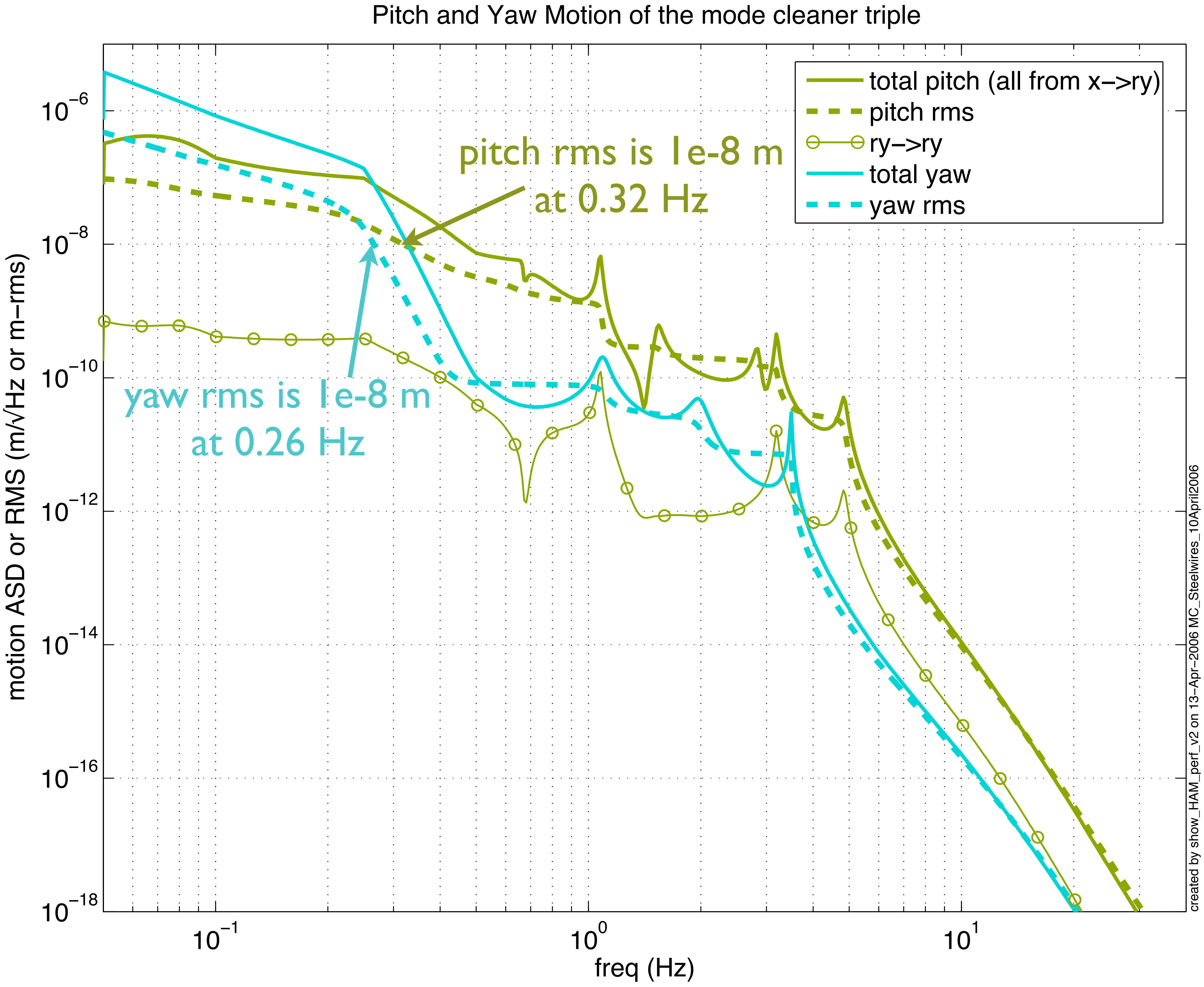
2.2e-16 at 10 Hz

horizontal to horizontal dominates below 10 Hz, and the vertical contribution dominates above 20 Hz

Pendulum Isolation, angles


Transmission of the mode cleaner triple to Angular motion

Test mass motion, angular



pitch rms is 1e-8 m at 0.32 Hz

yaw rms is 1e-8 m at 0.26 Hz

Conclusions

- Single stage HAM with these control laws provides good performance starting around 1/2 Hz.
- Most of the performance claims have been demonstrated with the Technology Demonstrator.
- 10 Hz ASD and 0.6 Hz rms meet new requirements.
- Requirements below 0.3 Hz (ASD and rms) need work, but double stage does not help meet those requirements. (try FIR filters, better HEPI tilt control, better tilt sensors)
- Single stage is easier to build, commission, and maintain.
- Seems like a good idea to change the baseline plan.