Seismic Isolation Discussions

Discussion of active seismic isolation for Advanced LIGO.
Emphasis on the Single stage HAM
July 2007
Brian Lantz

Outline

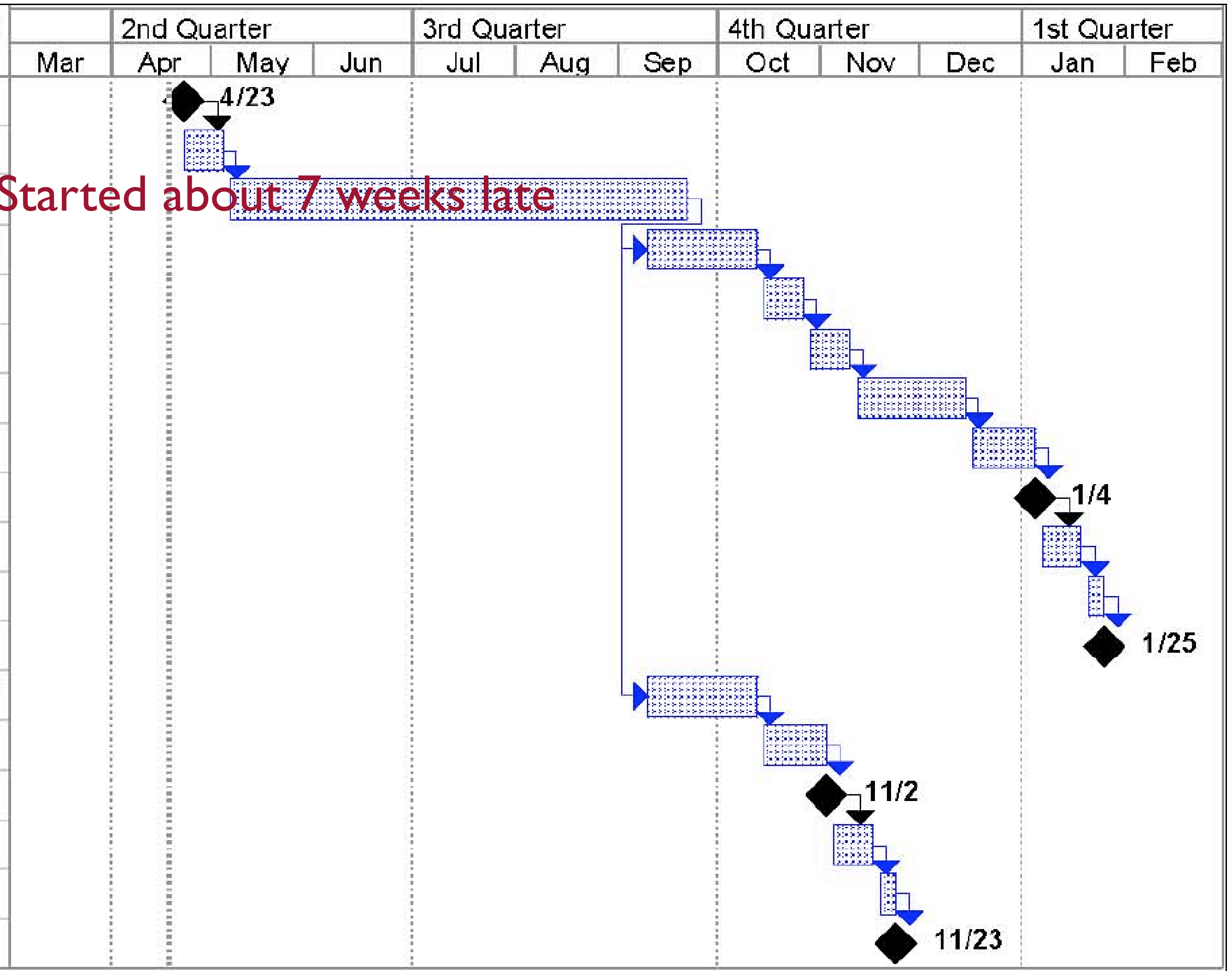
- Big Picture: platform geometry, req's, basic ideas.
- Big Problems: tilt-horz coupling, sensor noise.
- Mechanical design: make a system easy to control. minimize tilt, minimize cross-couplings, minimize annoying modes.
- Control system
    - Degrees of freedom
    - Correct the displacement sensors
    - Successive loop closure (damping, tilt, translation)
    - Sensor blending (disp sensors/ inertial sensors)
    - Sensor correction
    - Simple controllers
    - Notches

Big Picture - history

- History of the single stage HAM, new baseline for Advanced LIGO.
- Summer '05, Peter Fritschel held a meeting at Caltech to discuss new, relaxed requirements for HAM chamber optics - can we use a single stage?
- April '06 we presented a conceptual design to a review committee, and the single stage was adopted as the new baseline for the HAM.
- November '06 we awarded a design contract to HPD, with a construction option.
- Final Design Review in April '07
- Plan to build 2 for Enhanced LIGO plus 1 more for LASTI.

Big Picture - schedule

Task Name	Duration	Start	Finish	Predec
LIGO ISI/SAS Decision	0 days	Mon 4/23/07	Mon 4/23/07	
Initiate NSF and CIT approval	2 wks	Mon 4/23/07	Fri 5/4/07	1
Begin fabrication of 2 sets	20 wks	Mon 5/7/07	Fri 9/21/07	2
Dirty Assy of Unit #1	5 wks	Mon 9/10/07	Fri 10/12/07	3FS-2
Dynamic Testing of Unit #1	2 wks	Mon 10/15/07	Fri 10/26/07	4
Disassemble Unit #1	2 wks	Mon 10/29/07	Fri 11/9/07	5
Cleaning of Unit #1	5 wks	Mon 11/12/07	Fri 12/14/07	6
Re-assemble unit #1 at LHO	3 wks	Mon 12/17/07	Fri 1/4/08	7
Assembly of Unit 1 Complete	0 days	Fri 1/4/08	Fri 1/4/08	8
Install Unit #1 into WHAM6	2 wks	Mon 1/7/08	Fri 1/18/08	9
Final Testing of Unit #1 at LHO	1 wk	Mon 1/21/08	Fri 1/25/08	10
Installation of Unit #1 Complete	0 days	Fri 1/25/08	Fri 1/25/08	11
UHV Cleaning of Unit #2	5 wks	Mon 9/10/07	Fri 10/12/07	3FS-2
Assemble Unit #2 with Mods	3 wks	Mon 10/15/07	Fri 11/2/07	13
Assembly of Unit #2 Complete	0 days	Fri 11/2/07	Fri 11/2/07	14
Install Unit #2 at LLO	2 wks	Mon 11/5/07	Fri 11/16/07	15
Final Testing of Unit #2 at LLO	1 wk	Mon 11/19/07	Fri 11/23/07	16
Installation of Unit #2 Complete	0 days	Fri 11/23/07	Fri 11/23/07	17



Big Picture - Tech Demo

Technology Demonstrator is a nearly-full scale prototype with 2 active stages. Designed & built by HPD. Now in use at Stanford's Engineering Test Facility.

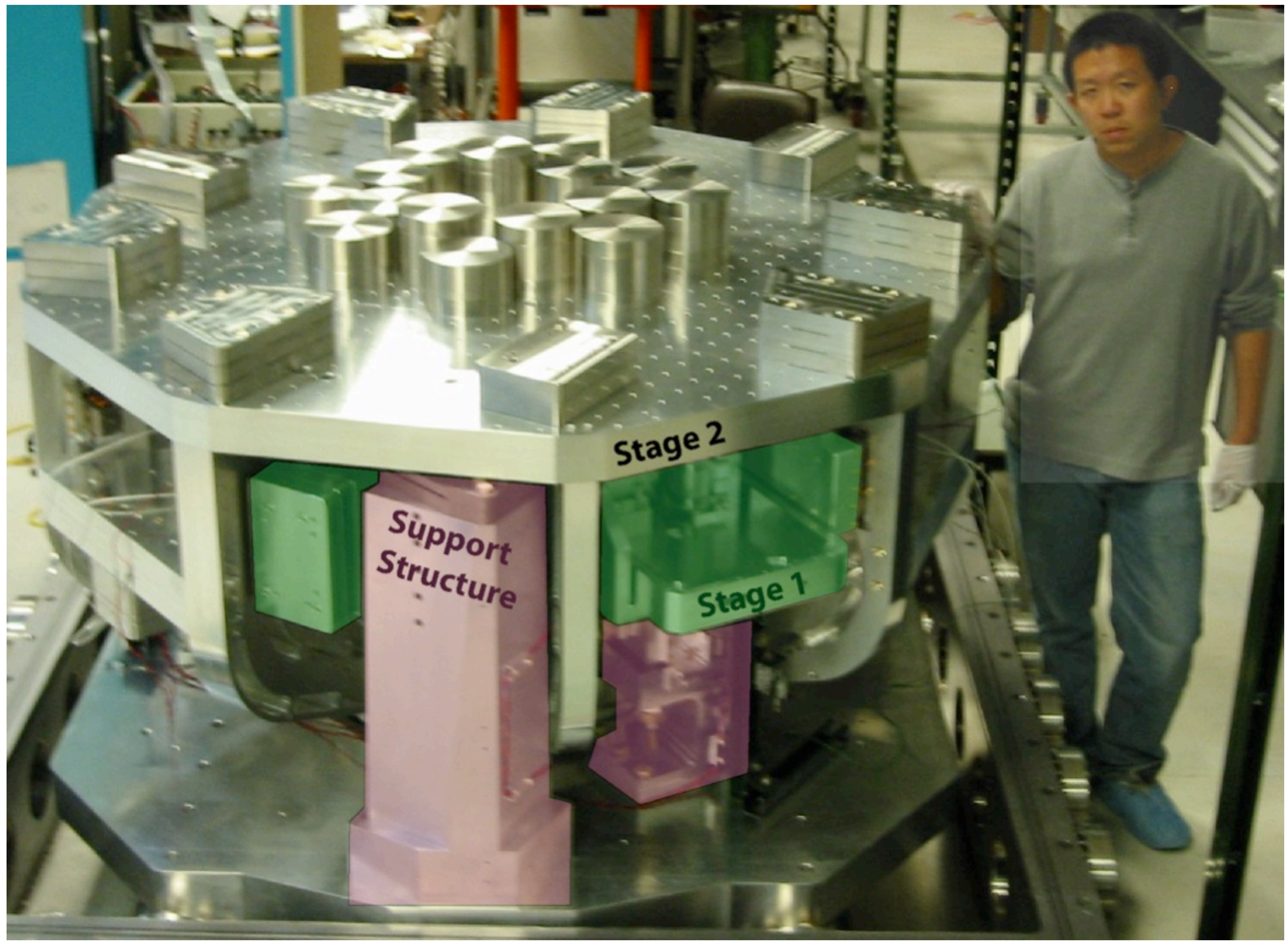
2 stage isolation and alignment system.

Each stage aligned and isolated in 6 DOF.

Passive isolation at
1 Hz horz, 3 Hz vert
Tilt modes at 12 Hz.

Active isolation below 30 Hz

Feedforward added by Matt DeGree.



Big Picture

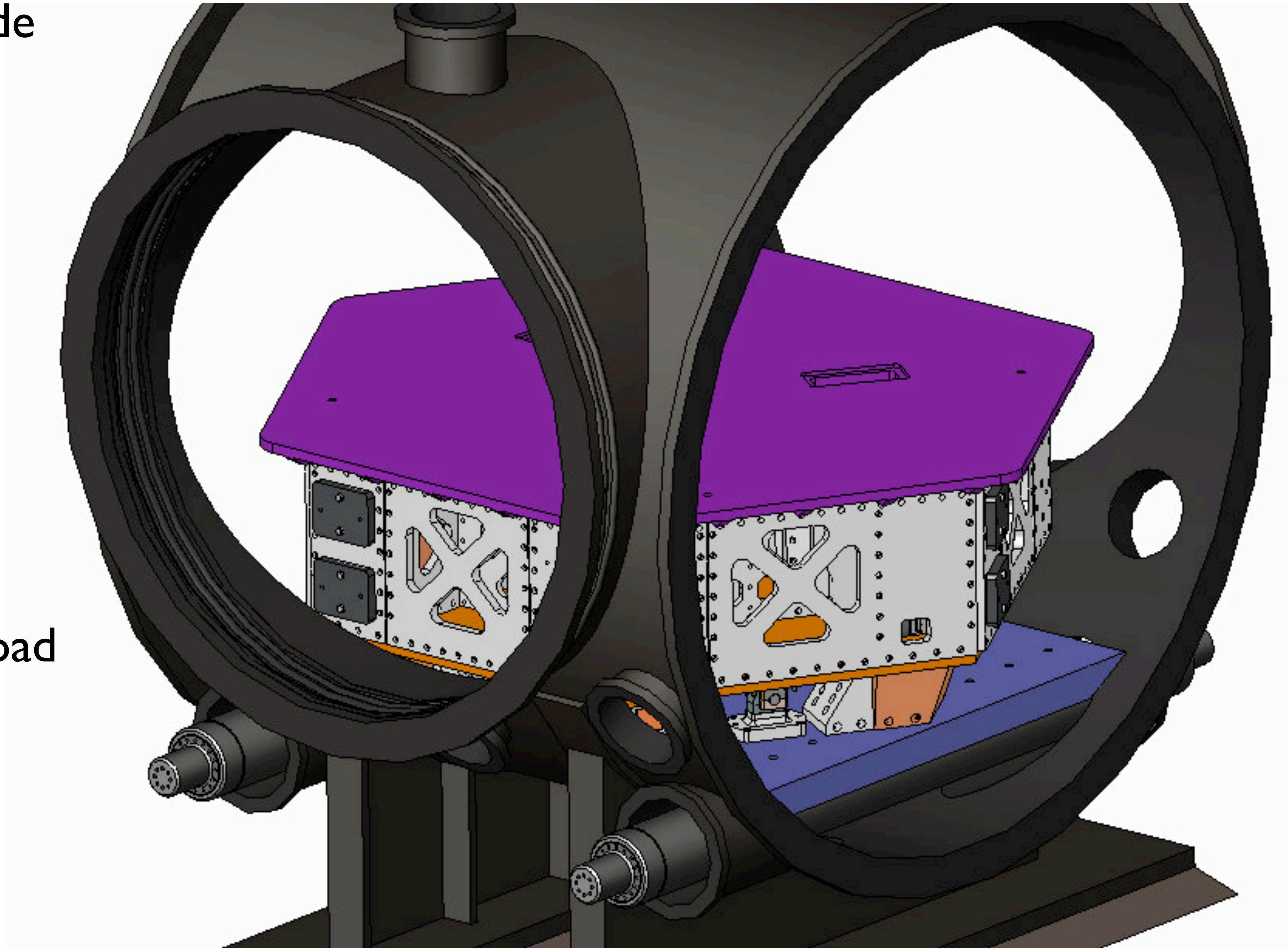
- Bolted aluminum structure
- Suspended by 3 blade springs & "wires"

- Natural freq's
  x & y: 1.35 Hz
  z: 1.8 Hz
  tip/tilt: 1.07 Hz
  yaw: 0.9 Hz

- mass:
  stage 1 ~ 1500 kg
  plus 510 kg of payload

- first bending mode:
  > 250 Hz

- assume servos with unity gain of 27 Hz



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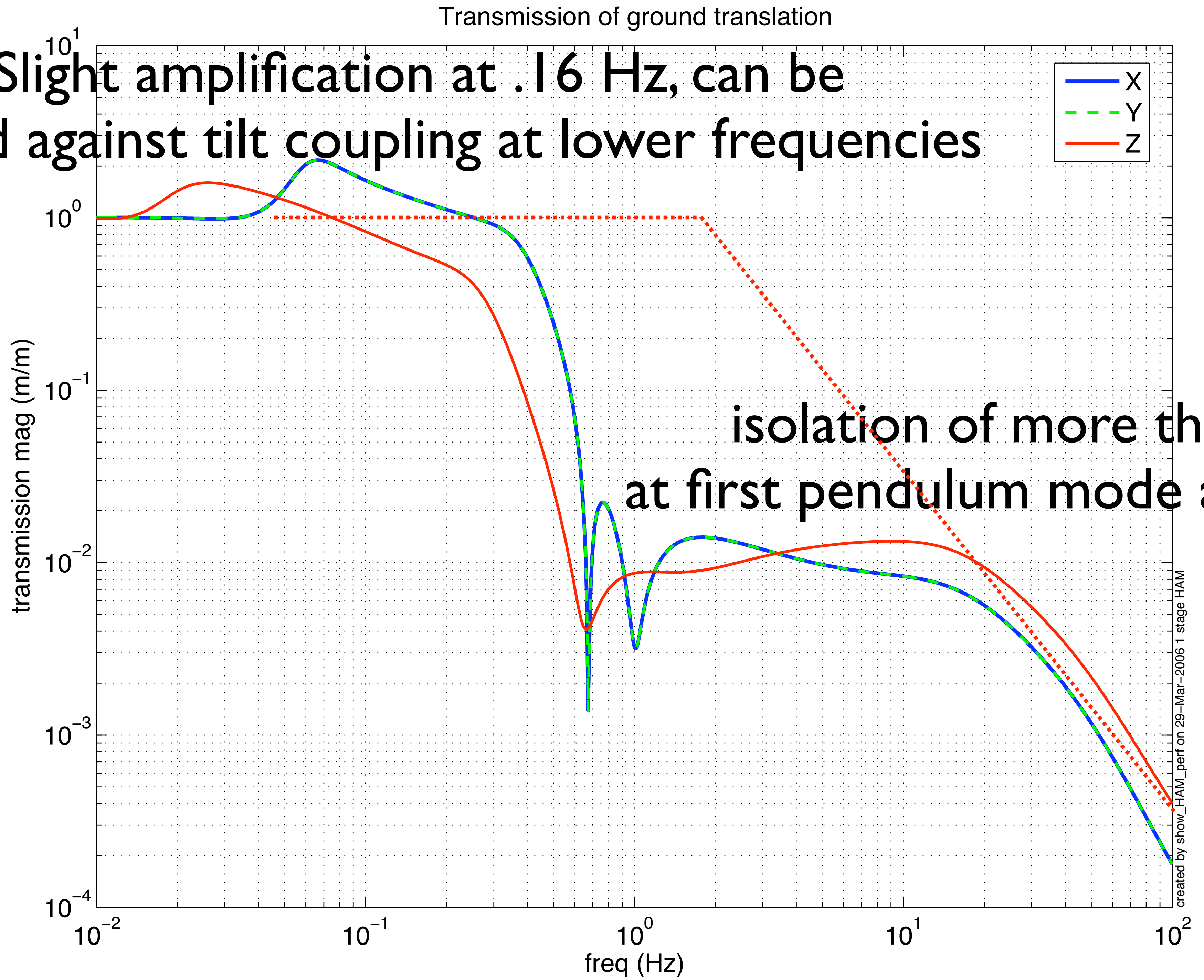
Modeled HAM Isolation

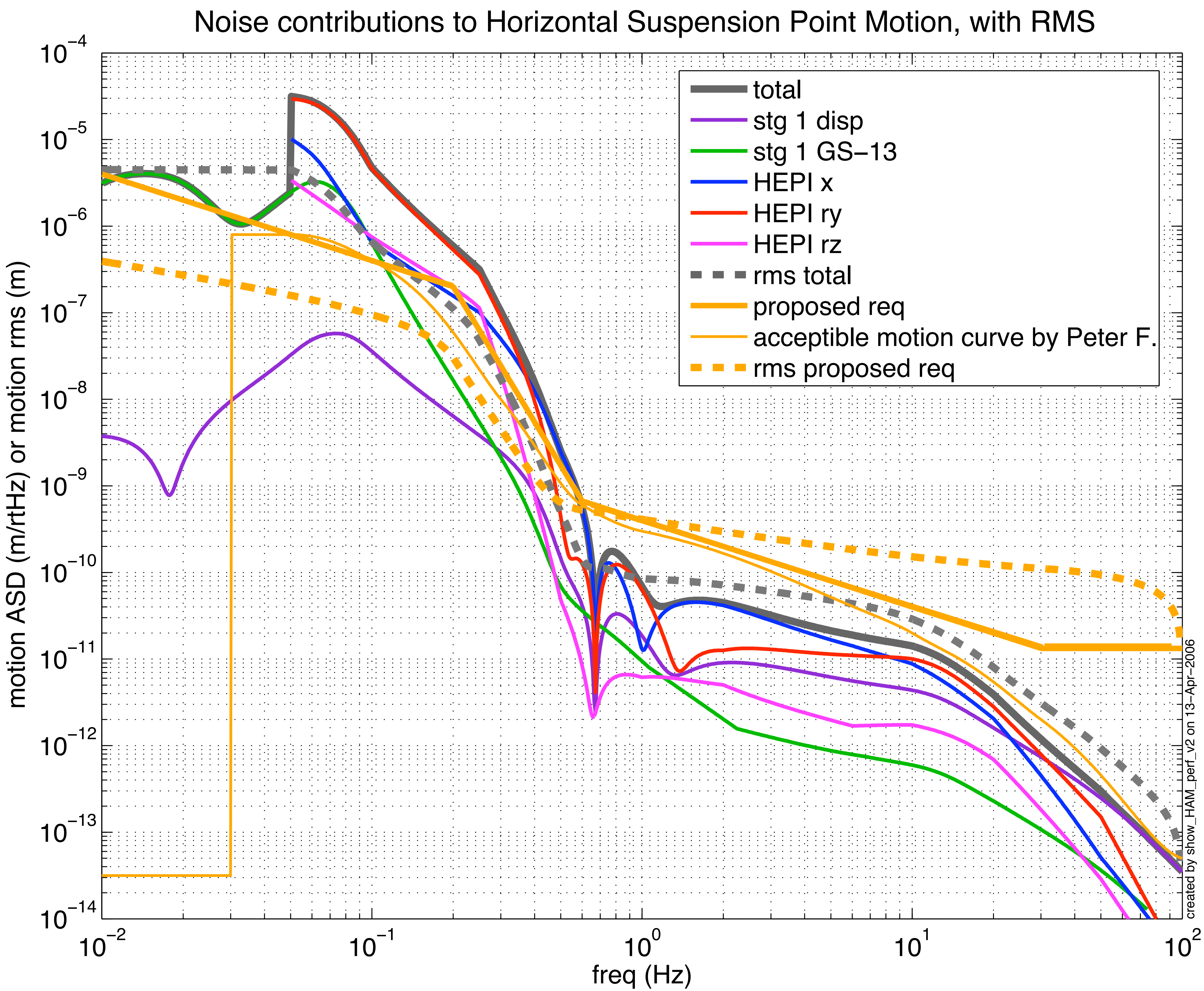
Transmission of translational input motion
HEPI motion -> table cg motion

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

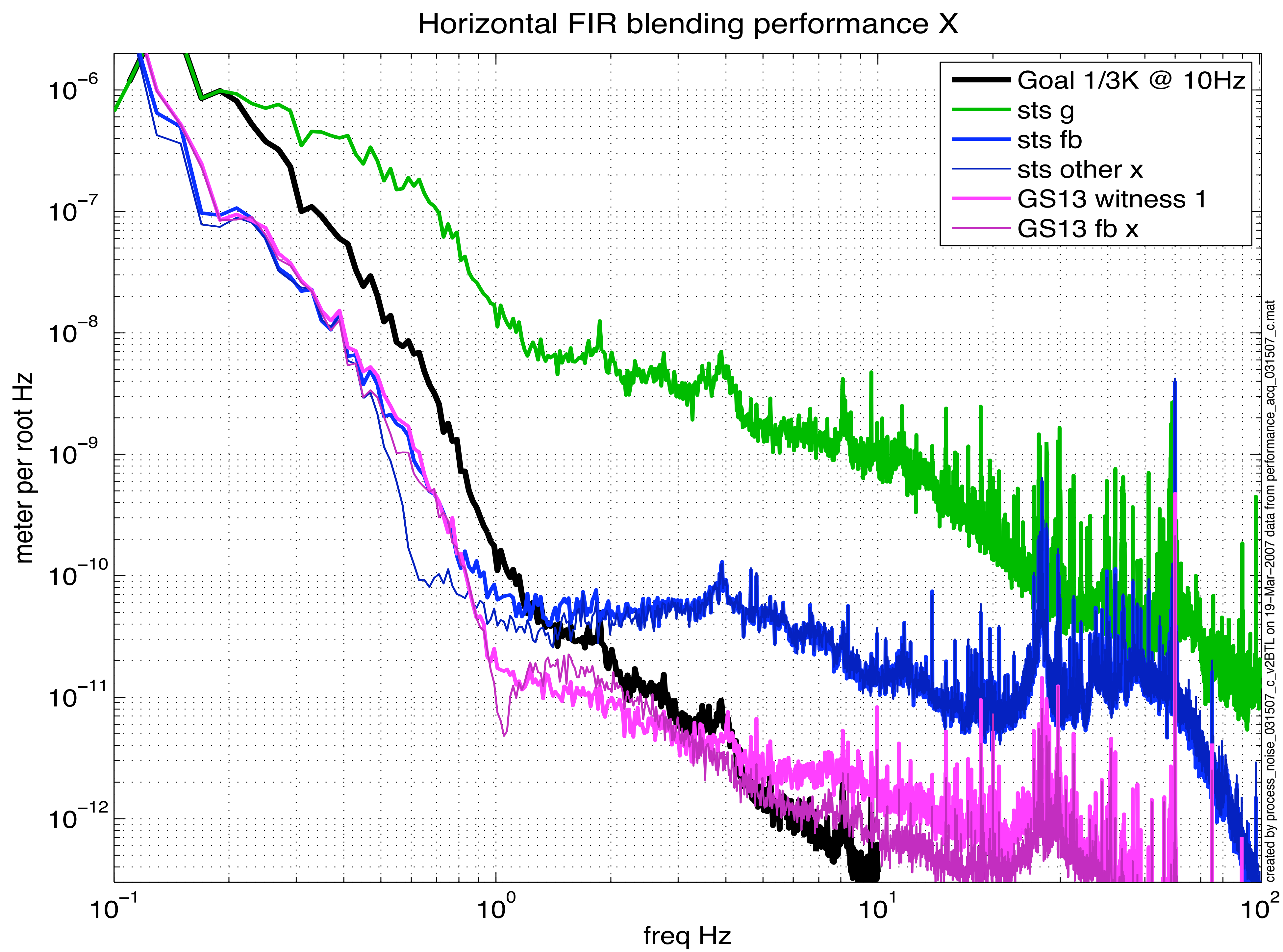


isolation of more than 50 at first pendulum mode and above

Performance predictions



Compare HAM to stg 1



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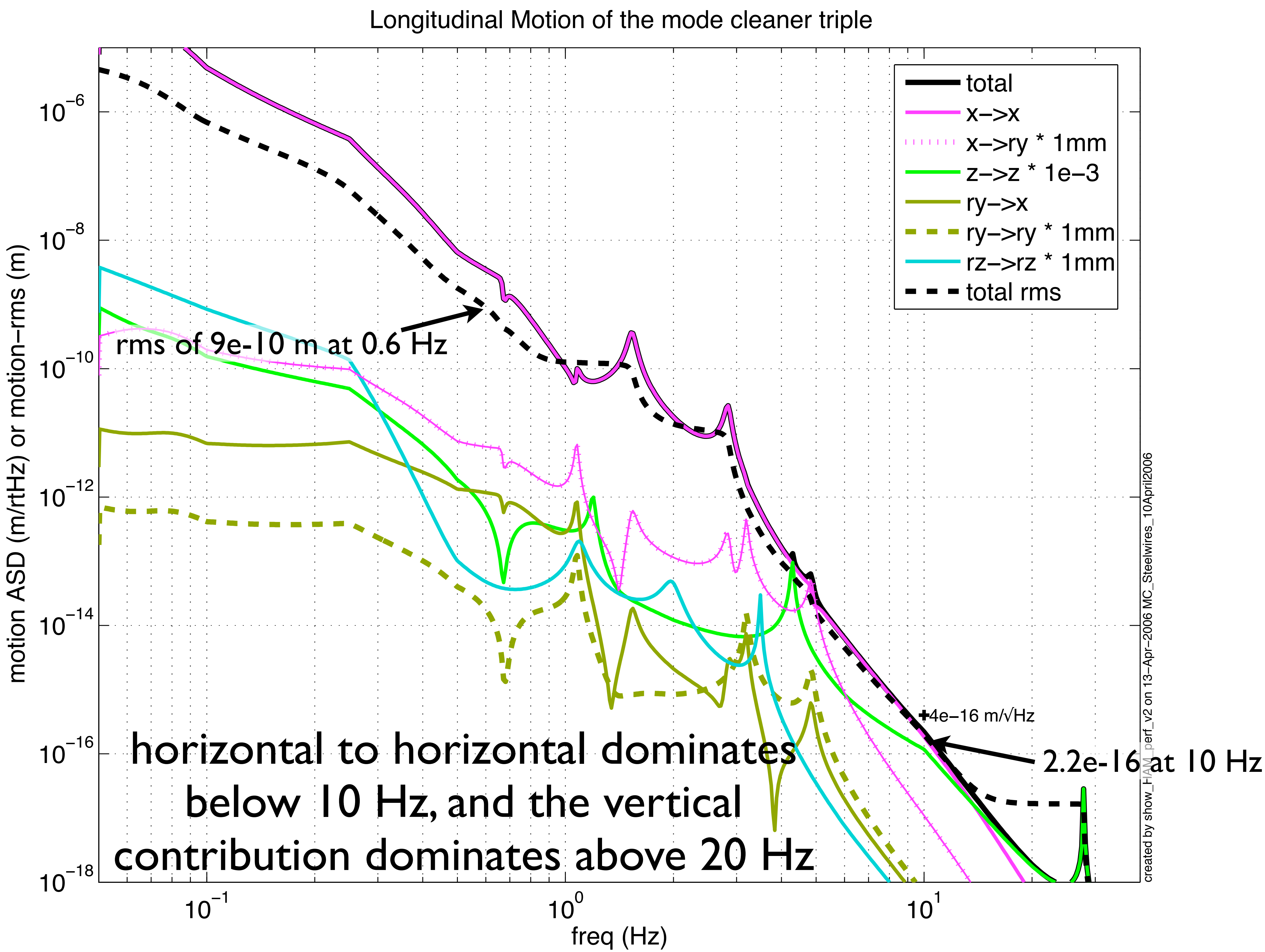
Performance Predictions



Big Picture - some ideas

- Use passive and active isolation
  - natural freq's a compromise between: good passive isolation, low stress on springs (35% of yield), CTE of material and temp. co. of Young's modulus have similar effects, Simple spring/ flexure design, good alignment between CG and LZMP (horz actuator plane).
  - Active isolation has upper unity gain frequency around 30 Hz, gives factor of 3-5 isolation at 10 Hz. Limited by modes of table and payload.
- Must control all 6 DOF per stage.
  - Platforms better than HEPI in that differential vertical readings are meaningful, because the stages are very stiff.
- Displacement sensing gives control all the way to DC.
- Translation is not the biggest problem. Biggest problem is tilt.
- Controlling low frequency motion with sensors gives motions which are linear, temp. stable, controllable, and known.

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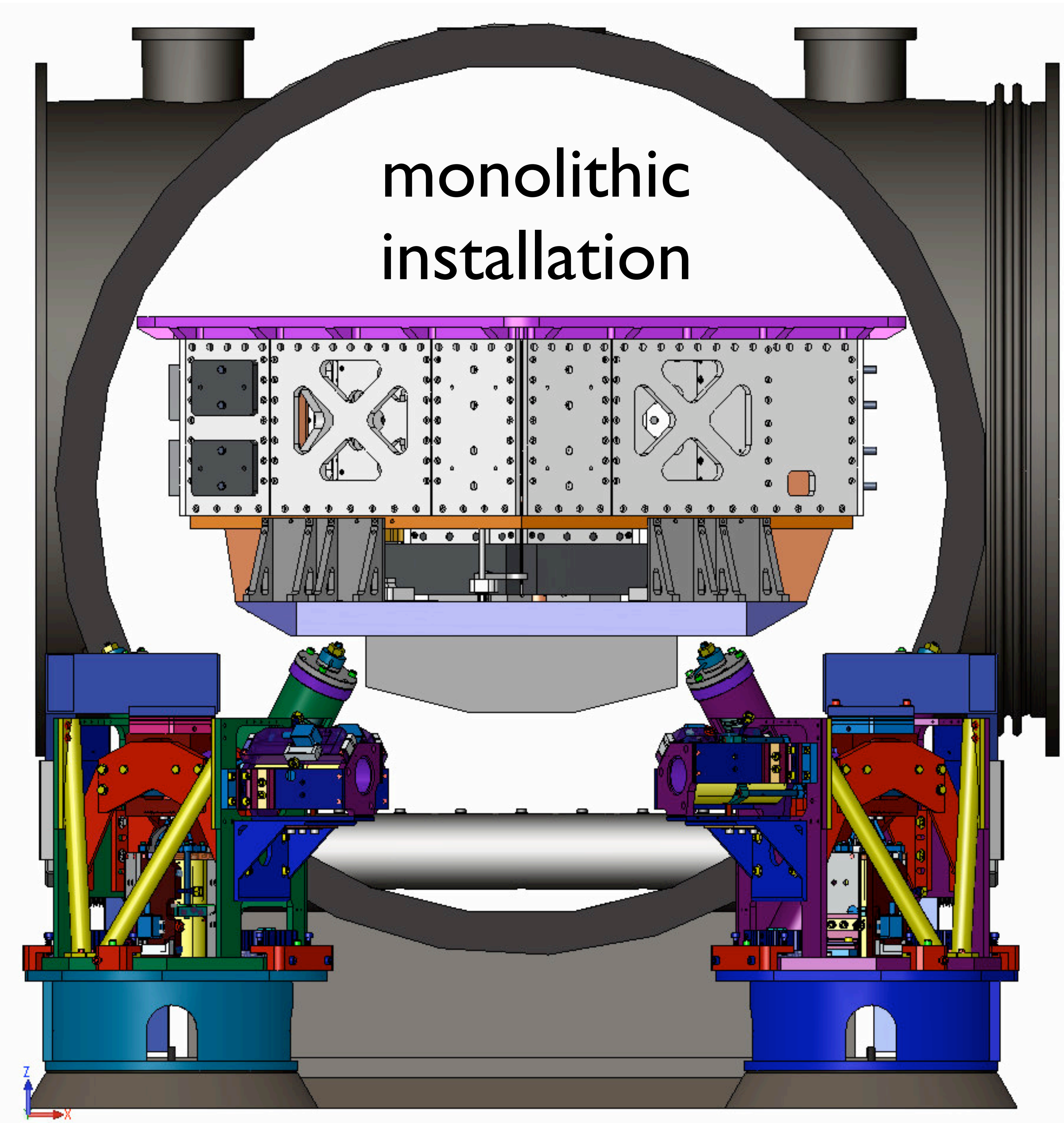
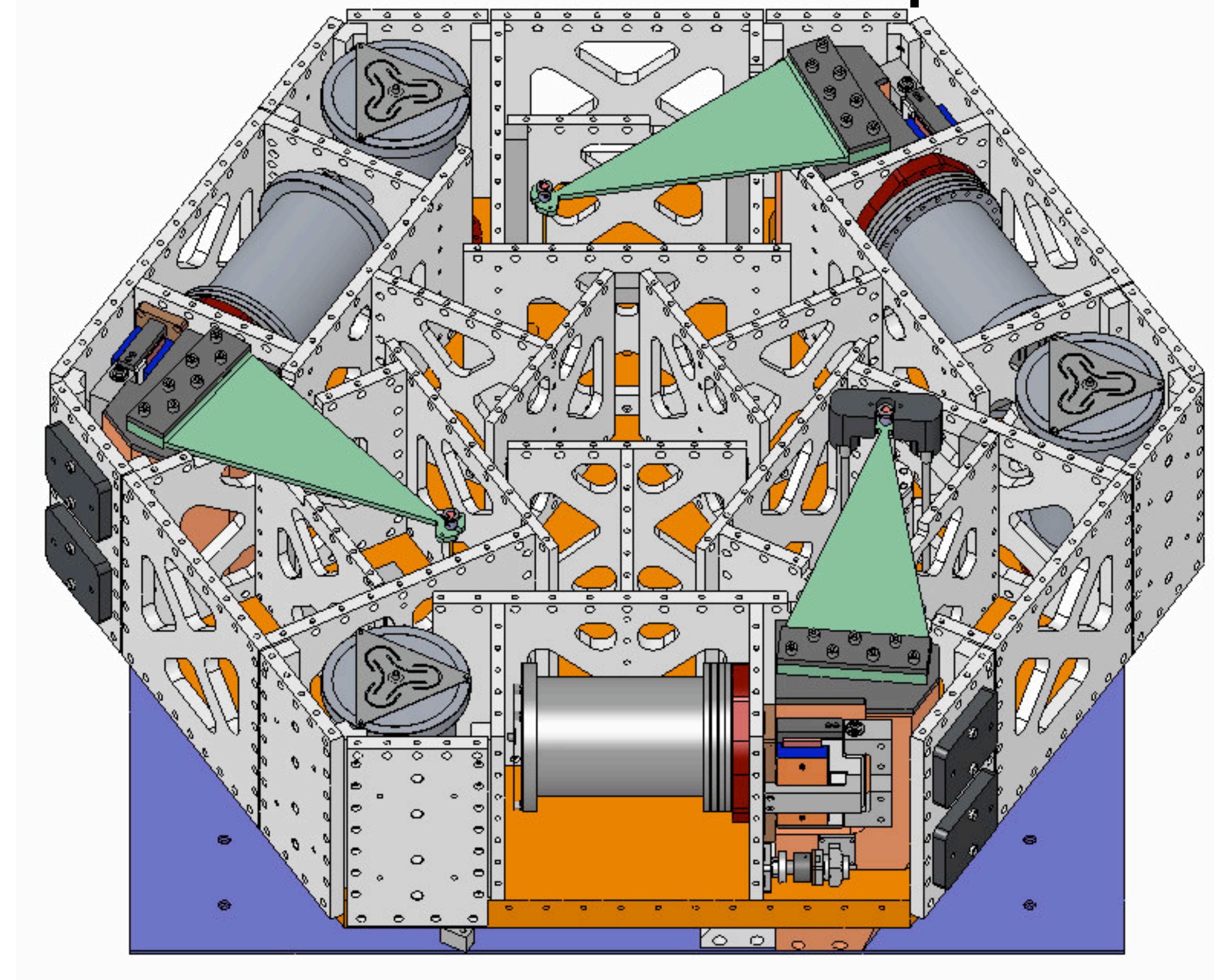
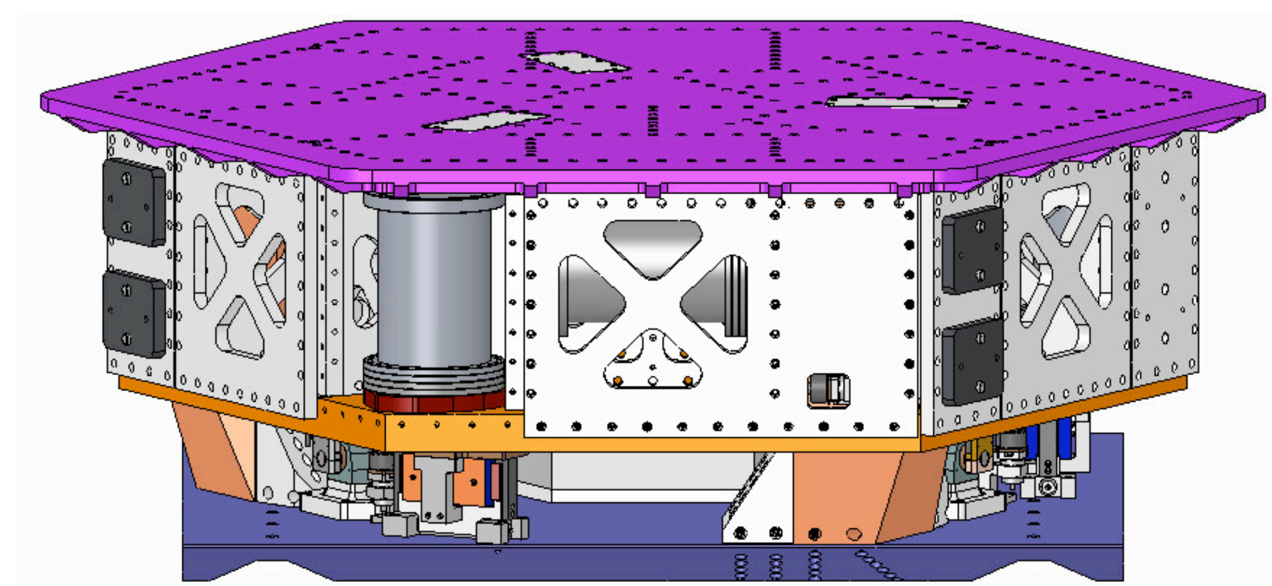
Views of HAM



springs and sensors under the table top



access to a vertical sensor



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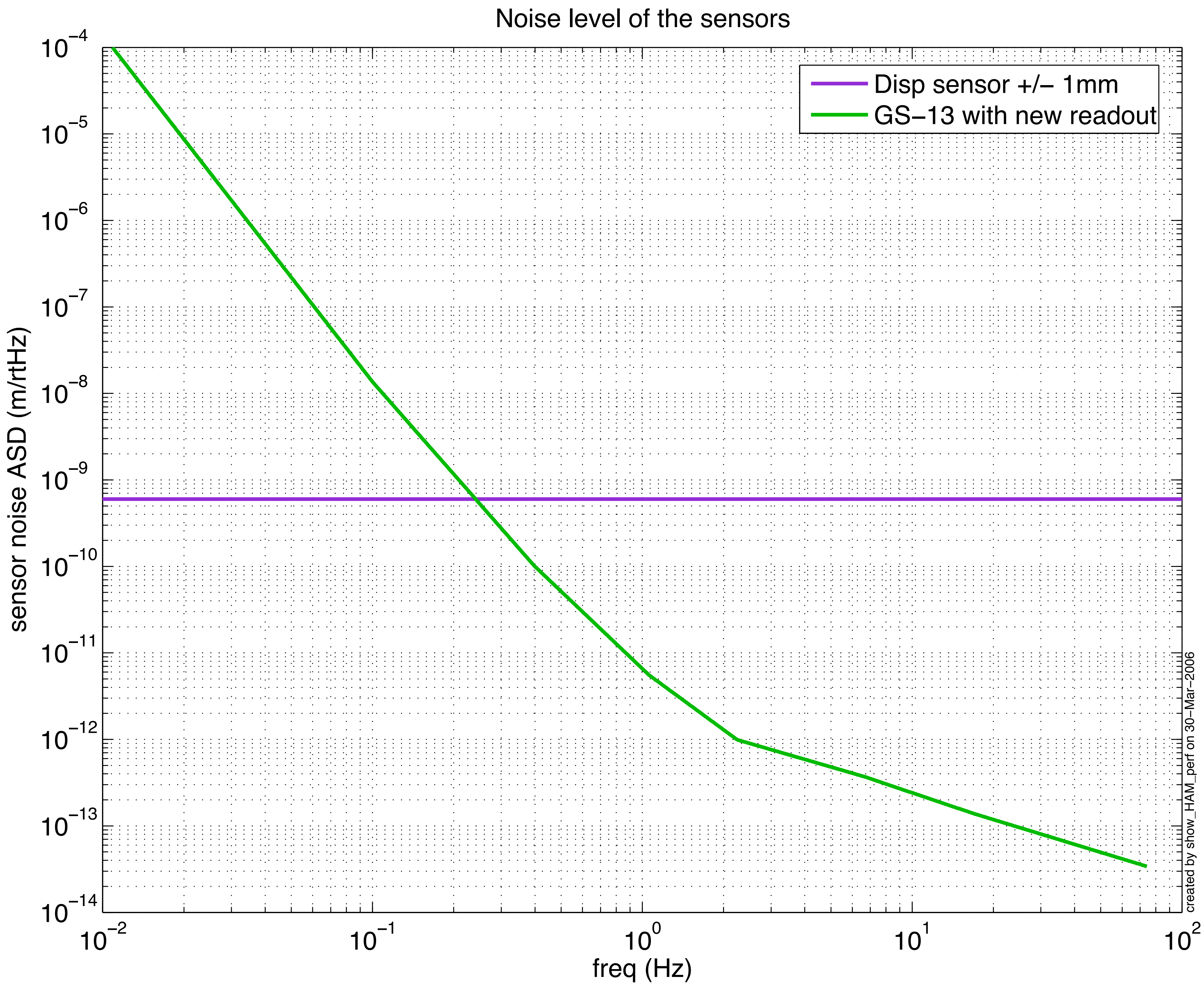
Big Problems

- Tilt - horizontal coupling - Low Frequency
  - at low frequencies, horizontal sensors can't distinguish horz acceleration and tilt into gravity
  - ratio of
    (resp/horz displacement (m)) / (resp/ tilt (rad))
    = g/w^2 (1 at about 0.5 Hz).
  - can cause large, unwanted excursions, (feedforward/ sensor correction from ground sensors).
  - can cause loop instabilities (feedback sensors)
- Tilt-horizontal coupling - High Frequency
  - rotation at table cg * radius = translation motion.
  - Mechanical structures generate twist.
  - Dominates x motion of Tech Demo at 1 Hz and 10 Hz.
    Dominates BSC at 10 Hz.
    Tied with translation in HAM at 1 Hz and 10 Hz.

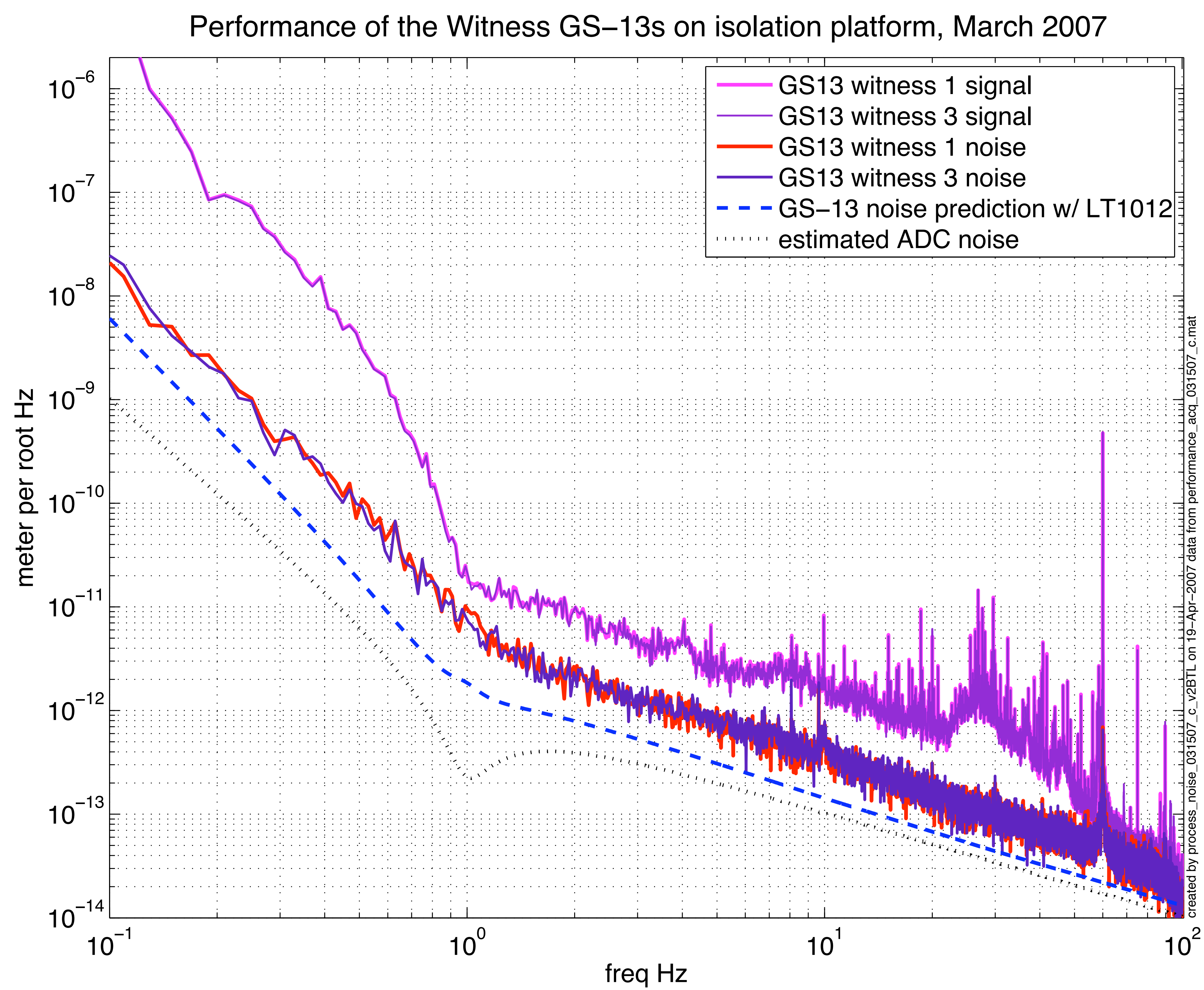
Big Problems - what we do

- Low Freq tilt-horz coupling
  - Put lowest frequency translation sensors on the ground and feed info forward (sensor correction).
    - Ground tilts less than platforms do.
    - Feedforward doesn't cause loop instabilities (but...)
  - Hold tilt of platform fixed with servos.
    - Displacement sensors hold stage parallel to support
    - Inertial sensors hold stage without tilt.
  - Combo of these was used by Hua to get best 3 DOF microseismic isolation ever.
  - A gyro would be good, but I don't know of any which are good enough and less than $1M/ DOF.
  - SPI would be great.

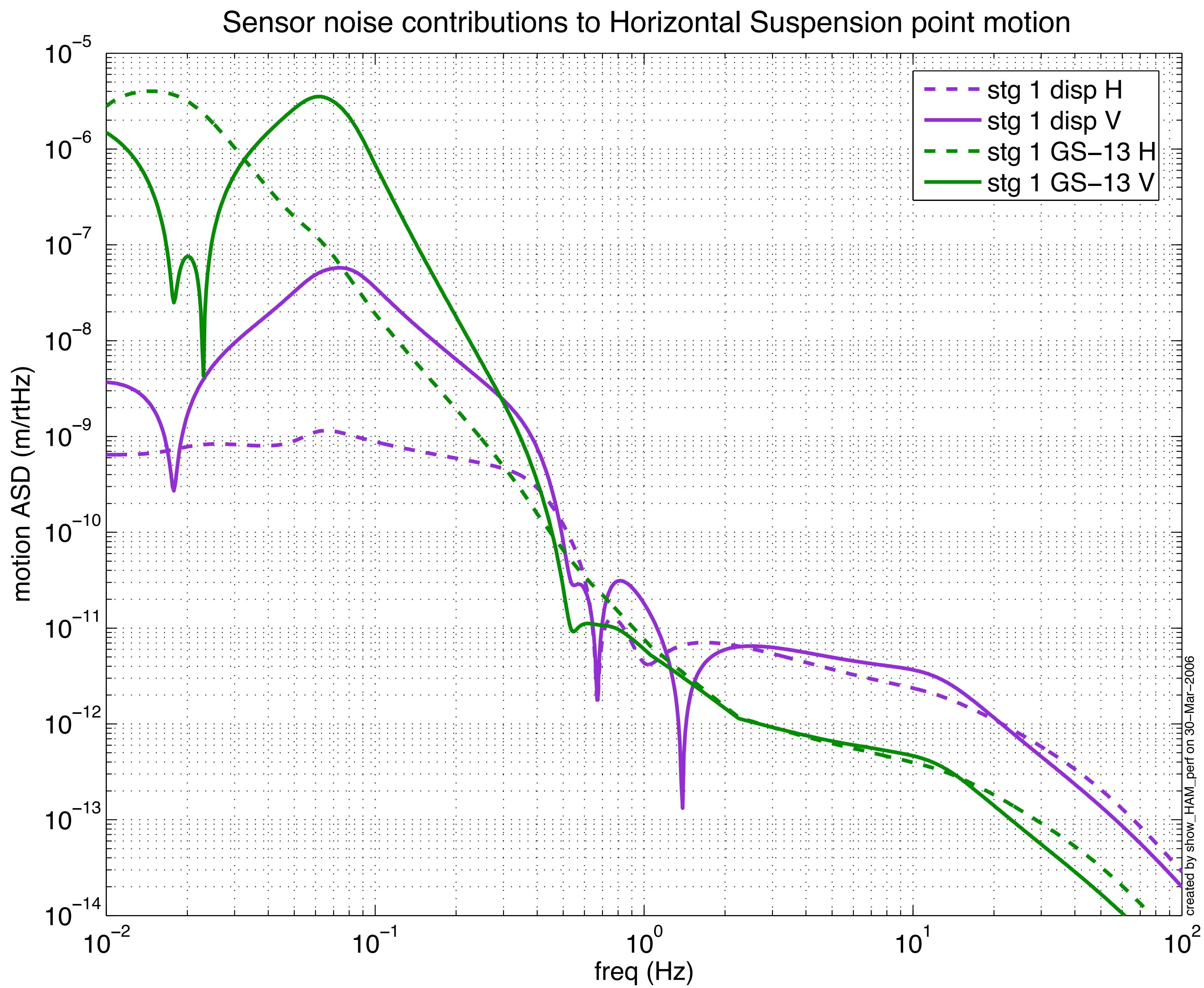
Noise of the sensors



Seismometers



Horizontal Suspension point motion from sensor noise



Mechanical Design for Control

- Make a system easy to control.
  - minimize tilt
    - Design spring/ flexures to not move vertically (to first order) when pushed horizontally.
    - Put CG close to actuator plane.
    - Put system under sensor control (discuss later)
  - minimize cross-couplings,
  - minimize annoying modes.

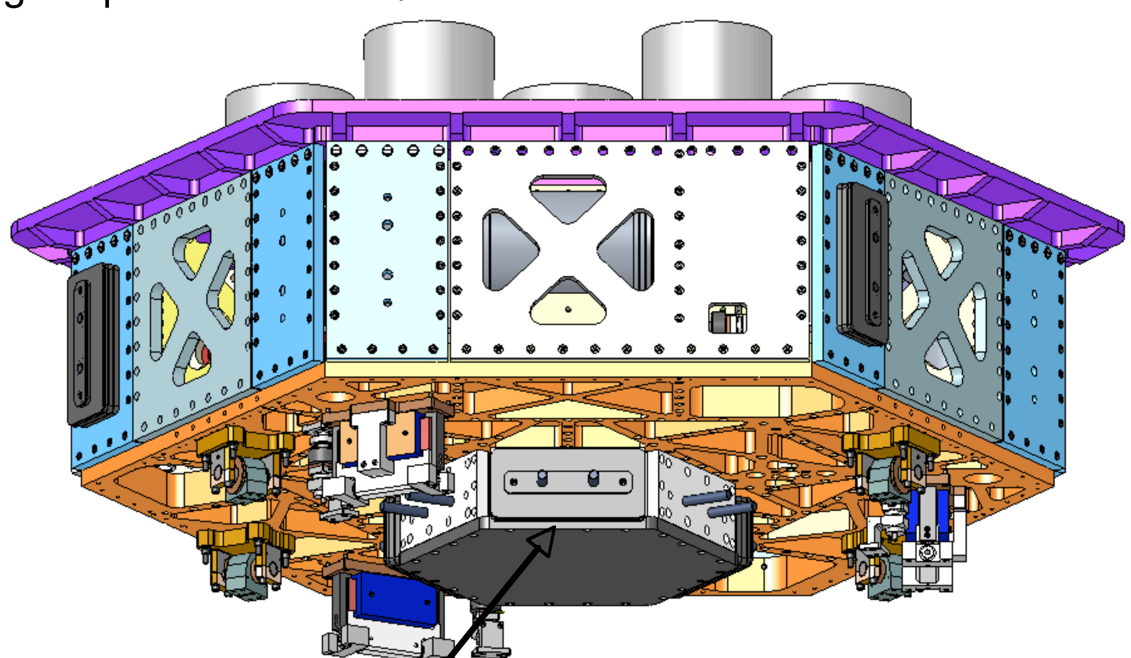
Spring Flexure Design

- Flexures have zero-moment-points at their upper and lower ends (UZMP and LZMP).
- Blade springs soft in Z, and soft in curl about tip transverse to orientation direction. Stiff in other 4 DOFs.
- Put flexure UZMP at neutral axis of blade.
- Put flexure LZMP at center of horizontal actuator.
- Detour by Jonas slides from FDR, to see:
  - alignment of spring/ flexure and flexure/ actuator
  - alignment of flexure/ actuator with CG

CG adjustment

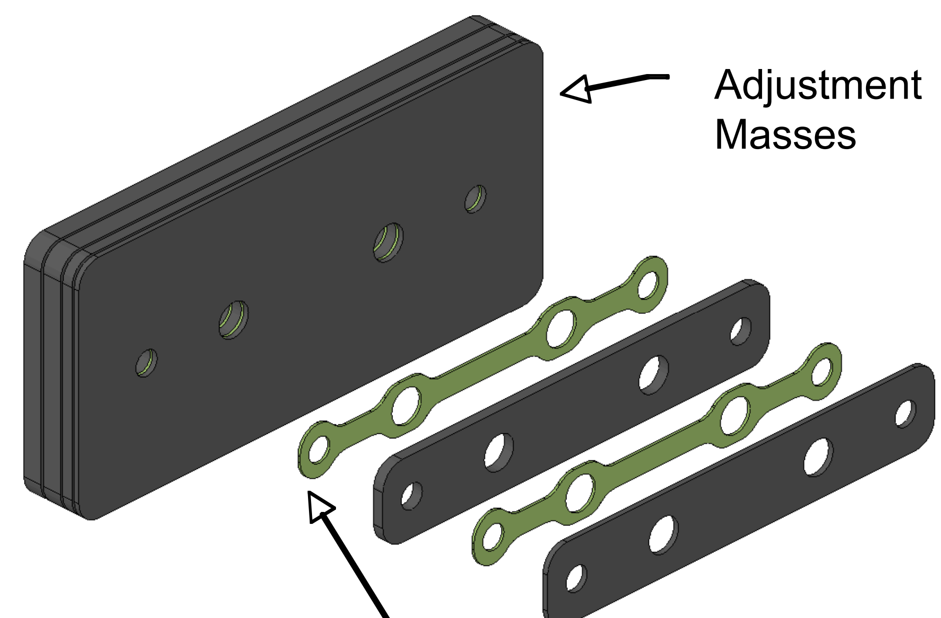
- Payload is 510 kg total. Some is science payload, rest is dead weight to hold springs flat and balance the table. Design allows up to 150 kg of the dead weight to be put on the stub keel.
- Payload 1 = 75 kg suspended + 435 kg load with moment of 112 kg-m above the table surface (ie 435 kg at 25.7 cm up). System CG is 2.72 cm above LZMP.
- Payload 2 = 75 kg suspended + 285 kg load at 25.7 cm above table +150 kg on 'stub keel'. System CG is 3.19 cm below the LZMP.

Payload Masses
• 285 – 435 Kg
• + 75 Kg suspended



Ballast Masses
• Adjust table height
• Up to 150 Kg of payload goes here

Adjustment Masses



Mass Spacers for venting

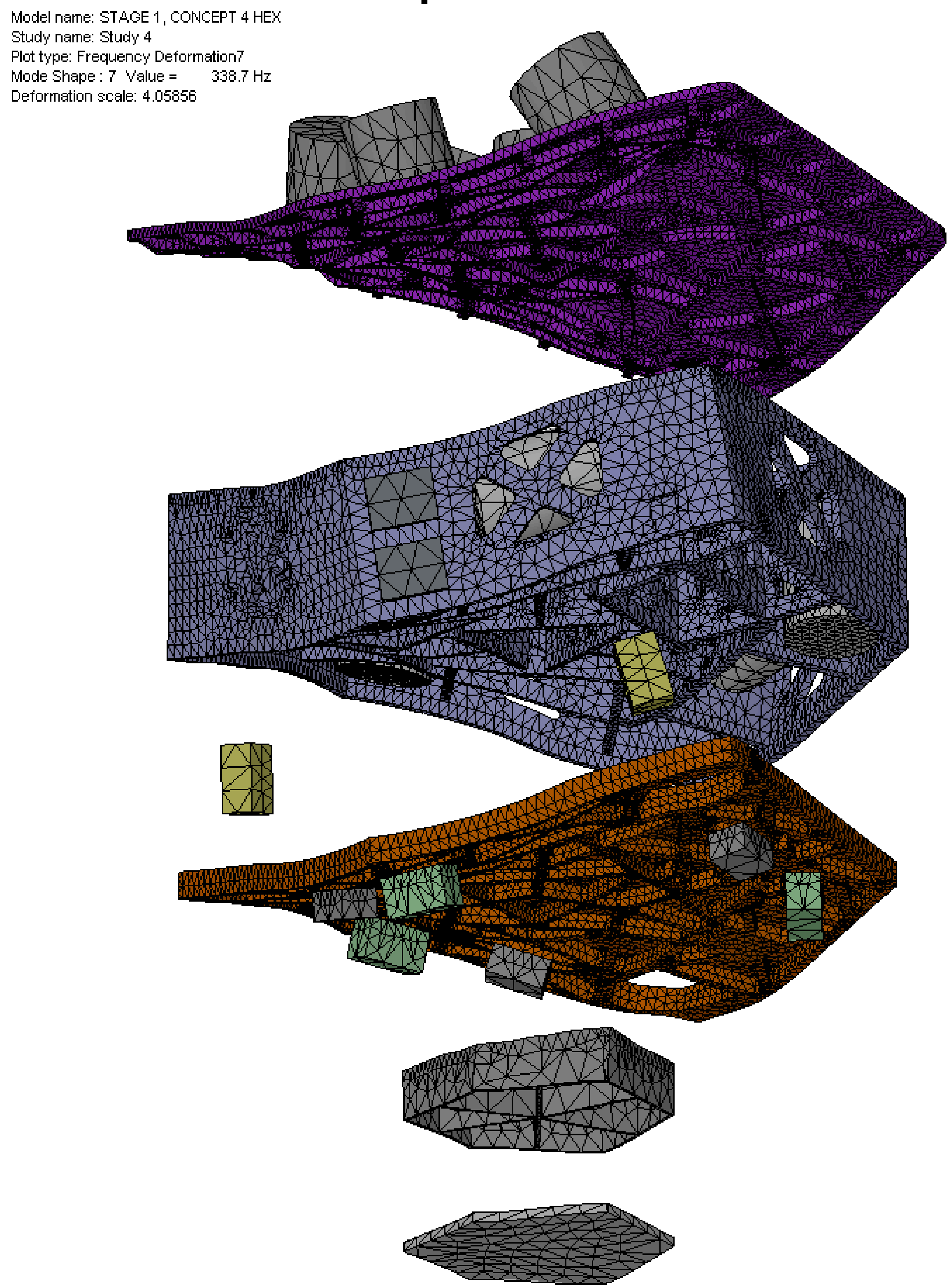
Adjustment Mass Requirements - for U_Kzz = 3.2%		
	Total (nominal)	Min. Increment
Trim Mass	35.1	0.32
Ballast Mass	38.4	2.12

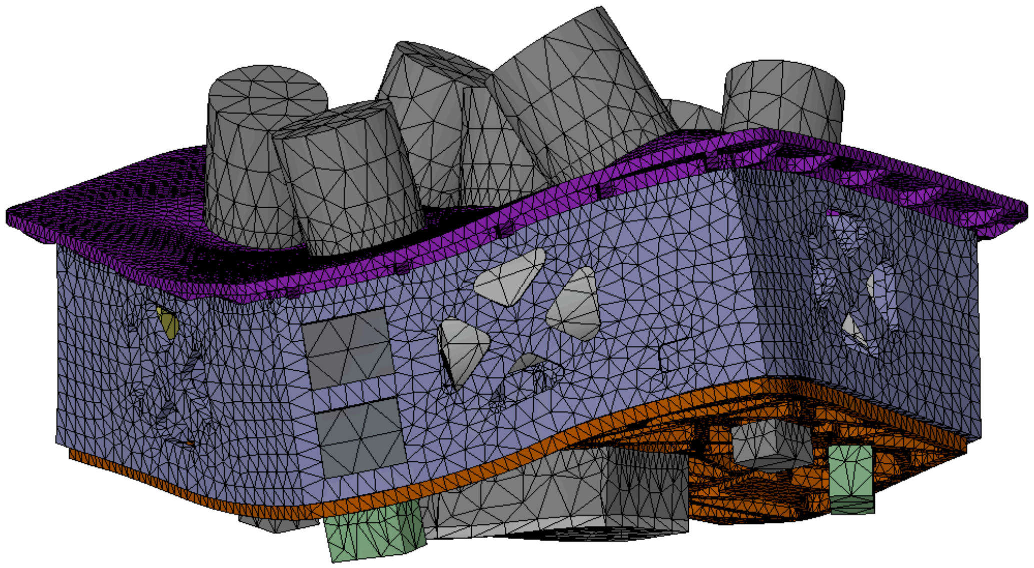
Minimize cross-couplings

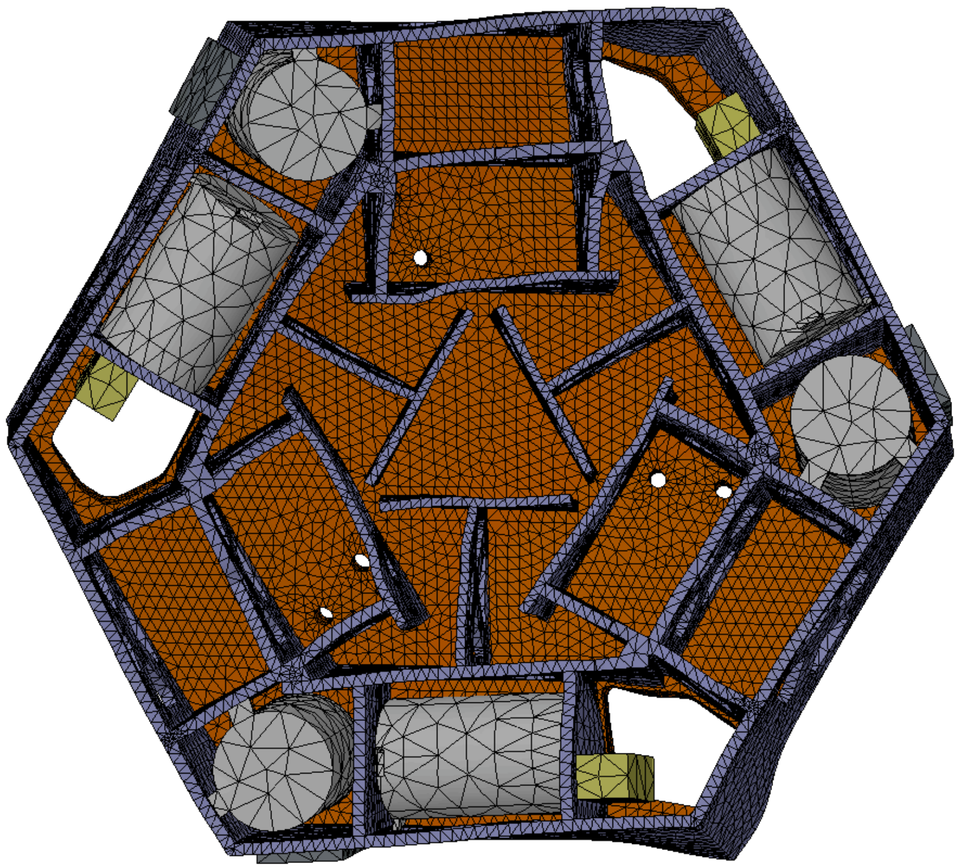
- Make system x-y symmetric. Thus, it moves in the direction you push it. (The eigenmode directions are the coordiate control directions.)
- Minimize translation - torque coupling from springs & flexures.
- Use square coil to minimized torque coupling in the actuators.
- Make sensors each really 1 DOF, so they don't pick up other DOFs (cap sensors see flat target, inertial sensors have good flexure design). Tilt/ horz coupling of geophones violates this rule.
- Run light damping on 6 body modes. The eigenmode directions on resonance are probably not aligned with the coordinate directions, but this is not a problem if the modal Qs are small.
- Bending modes are notched out in controllers. These are inherently high-cross coupling and can be problematic if not treated aggressively.

Minimize annoying modes

First bending mode of stage 1 should be above 250 Hz.
Simplified, bonded FEA gives 339 Hz.







Control System

- Degrees of freedom
- Steps to isolation.
- Damping
- Sensor blending (disp sensors/ inertial sensors)
- Tilt correction of the displacement sensors.
- Successive loop closure (damping, tilt, translation)
- Sensor correction
- Simple controllers
- Notches

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Degrees of Freedom

- Each stage has 6 actuators and sets of 6 sensors, 3 tangential and 3 vertical, in equilateral triangles.
- Each sensor set has a 'sensor basis': H1, H2, H3, V1, V2, V3
  Each actuator set has an 'actuator basis': H1, H2, ...V3.
  These are all different, since the parts have a physical size.
- These are all projected to a 'coordinate system' basis: x, y, z, rx, ry, rz. x&y are horizontal, z is vertical, rx is the rotation about the x axis, etc.
- x = 0, y = 0 at the center of the table.
  z = 0 at the horizontal actuator center (ie the LZMP)
  this is somewhat arbitrary, but is convenient.
- Projections all created from the drawings. Successful so far.
- Results in 6 projected displacement sensors, 6 (or 12 for Stg 1 BSC) projected inertial sensors, and 6 projected actuators per stage: x, y, z, etc.

Projections

```
%%%%   code segment from mkGeoMat2_stg2only_070708.m   %%%
clear;
coords;

%for sensors
GS13CToS=[...
    geoSensModel([H_GS13.X  H_GS13.Y  H_GS13.Z - H2_Actuator.Z]', [0 1 0]); ...
    geoSensModel([V_GS13.X  V_GS13.Y  V_GS13.Z - H2_Actuator.Z]', [0 0 1])];

PSStg2CToS=[...
    geoSensModel([H2_PS.X  H2_PS.Y  H2_PS.Z - H2_Actuator.Z]', [0 1 0]); ...
    geoSensModel([V2_PS.X  V2_PS.Y  V2_PS.Z - H2_Actuator.Z]', [0 0 1])];

%for acts
ActStg2AToC=[...
    geoActModel([H2_Actuator.X  H2_Actuator.Y              0]',                [0 1 0]), ...
    geoActModel([V2_Actuator.X  V2_Actuator.Y  V2_Actuator.Z-H2_Actuator.Z]', [0 0 1])];

projection_note = ['projection matricies for stage 2 of Tech Demo, created by ',mfilename,' on ',date]
%save ETFprojMat_v2 projection_note  GS13CToS PSStg2CToS ActStg2ATo
```

GeoSensModel:
If the stage moves (coord. basis, 6 DOF), what will a sensor at location L pointed in direction D see? Does 3 sensors, at 120 degrees.

GS13CtoS is the projector from Coord. motion to 6 sensor signals.
Desired Projection matrix is inv(GS13CtoS).

ActStg2AtoC is the projection from the force from each Actuator to force in the Coord Basis. Again, the desired projection matrix is inv(ActStg2AtoC).

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Code segments for projection

```
%%%%   code segment from coords.m  a few comments corrected  %%%%%%

%******************Coordinate system 2*************************
% This is coordinate system 1 rotated about z-axis by +40 degrees

% axis of GS13 on X-axis
H_GS13.Y = 0.00000000;
H_GS13.Z = -0.20510500;
H_GS13.X = 0.74946815;

V_GS13.Y = 0.07741314;
V_GS13.Z = -0.59213750;
V_GS13.X = 0.61534845;

V2_PS.Y = -0.00158750;
V2_PS.Z = -0.31137750;
V2_PS.X = 0.60801250;

H2_PS.Y = -0.02880250;
H2_PS.Z = -0.28416250;
H2_PS.X = 0.60801250;

V2_Actuator.Y = 0.07748916;
V2_Actuator.Z = -0.27071955;
V2_Actuator.X = 0.61207211;

% direction of force is on Y-axis
H2_Actuator.Y = -0.20488387;
H2_Actuator.Z = -0.21907500;
H2_Actuator.X = 0.74930000;


function sensMatCToS=geoSensModel(posi,sensDirc)
%calcualte geoMatCToS, center motion to Sensor output.
%posi is the posi of sensor at front.
%sensDirc is the sens dirction in a row vector.

rot=[0 120 240];
for n=1:3
    rMat     = rotMat(rot(n));
    horiSens = sensDirc*rMat';
    HRotMat  = crossTens(rMat*posi);
    sensMatCToS(n,:) = [horiSens zeros(1,3)]*[eye(3) -HRotMat;zeros(3) eye(3)];
end
```

crossTens, rotMat

```
function c=crossTens(a)
%crosstens is used to generate cross product operator.
% C=crossTens(a), a is a vector, C is a matrix
% to calculate a cross product, eg. F = A x B,
% use C = crosstens(A);  % so C is a 3x3 matrix
% F = C*B;
% the input, A, to crosstens can be either a row or column vector, but
% the input vector, B, and the output vector, F, must be column vectors
% z = x cross y,
% eg
% crosstens([1 0 0]') * [0 1 0]'
% ans =
%      0
%      0
%      1
% to be used to calculate a X (some thing else)
%
c=[    0     -a(3)    a(2)
     a(3)      0      -a(1)
   -a(2)     a(1)     0   ];


function mat=rotMat(ang)
% rotMat  generates a rotation matrix for rotations around the z axis
% mat=rotMat(ang)
% input is in degrees, output is a 3x3 matrix M designed for a state vector [x y z]'
% out = M * in
% out will be rotated CCW from in (viewed from above)
% eg,
% rotMat(45)*[1 0 0]'
% ans =
%       0.70711
%       0.70711
%             0

rat=ang/180*pi;
% mat=[cos(rat) cos(rat+pi/2) 0;
%    sin(rat) sin(rat+pi/2) 0;
%    0              0                1];

mat=[cos(rat), -sin(rat),       0;
   sin(rat),       cos(rat),    0;
   0,          0,               1];
```

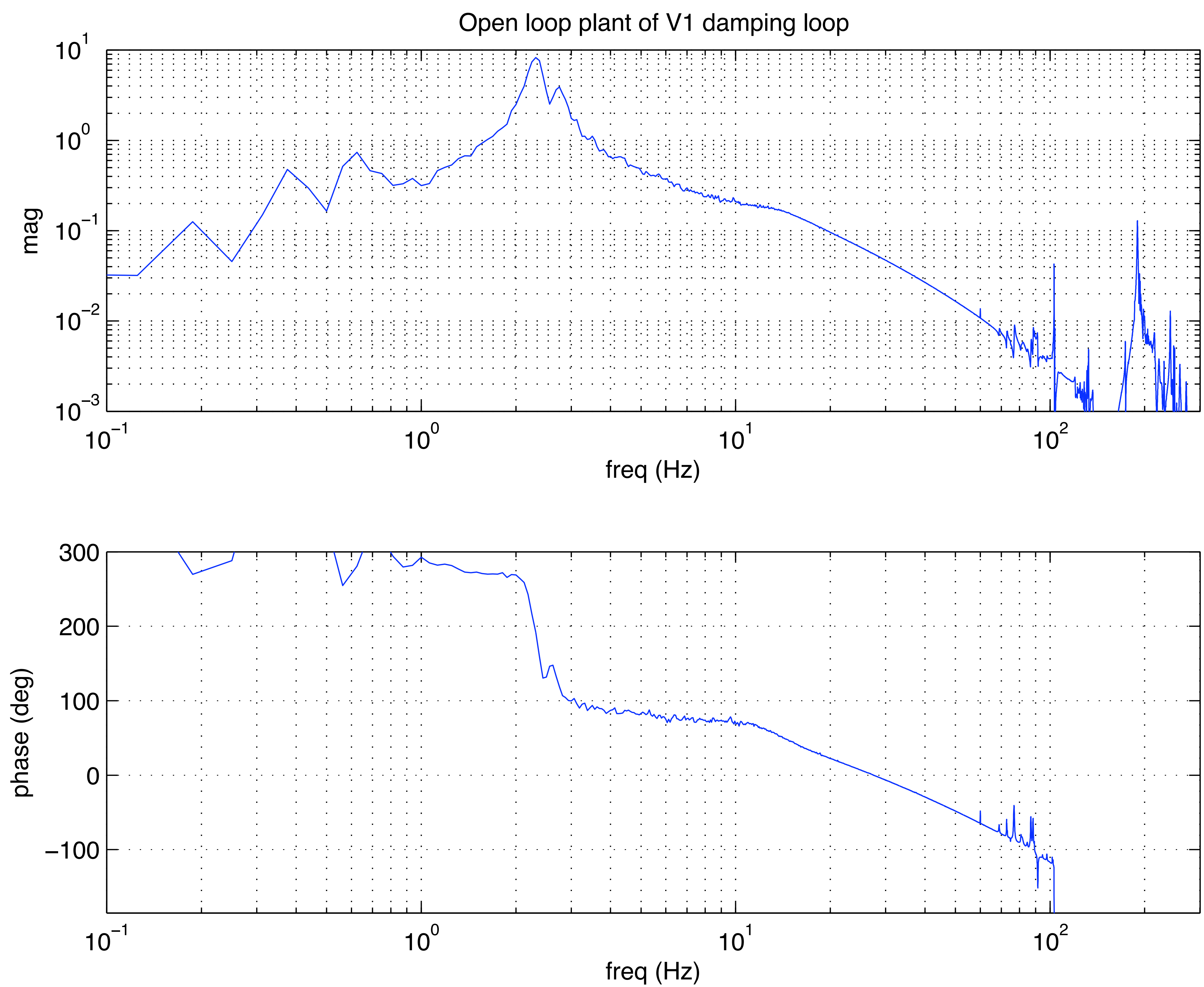
Steps to isolation

1. Damp the stage in 6 DOF.
2. Implement coordinate transforms to run system in 'coordinate' basis.
3. Sys-ID to make blending filters in 6 DOF.
4. Implement high-blend filters.
5. Sys-ID from coord drive to supersensor output rx and ry
6. Design and implement rx and ry controllers.
7. Sys-ID from coord drive to supersensor output in x, y, z, and rz
8. Design and implement x, y, z, rz controllers.
9. Generate tilt-correction matrix with high-blend filters.
10. Implement the tilt correction, lower the blend freq's.
11. Implement the sensor correction from ground STS-2.
12. Extra stuff: Add conditionally stable elements, offload commands, MIMO, feedforward from stage 0, etc.

Damping loops

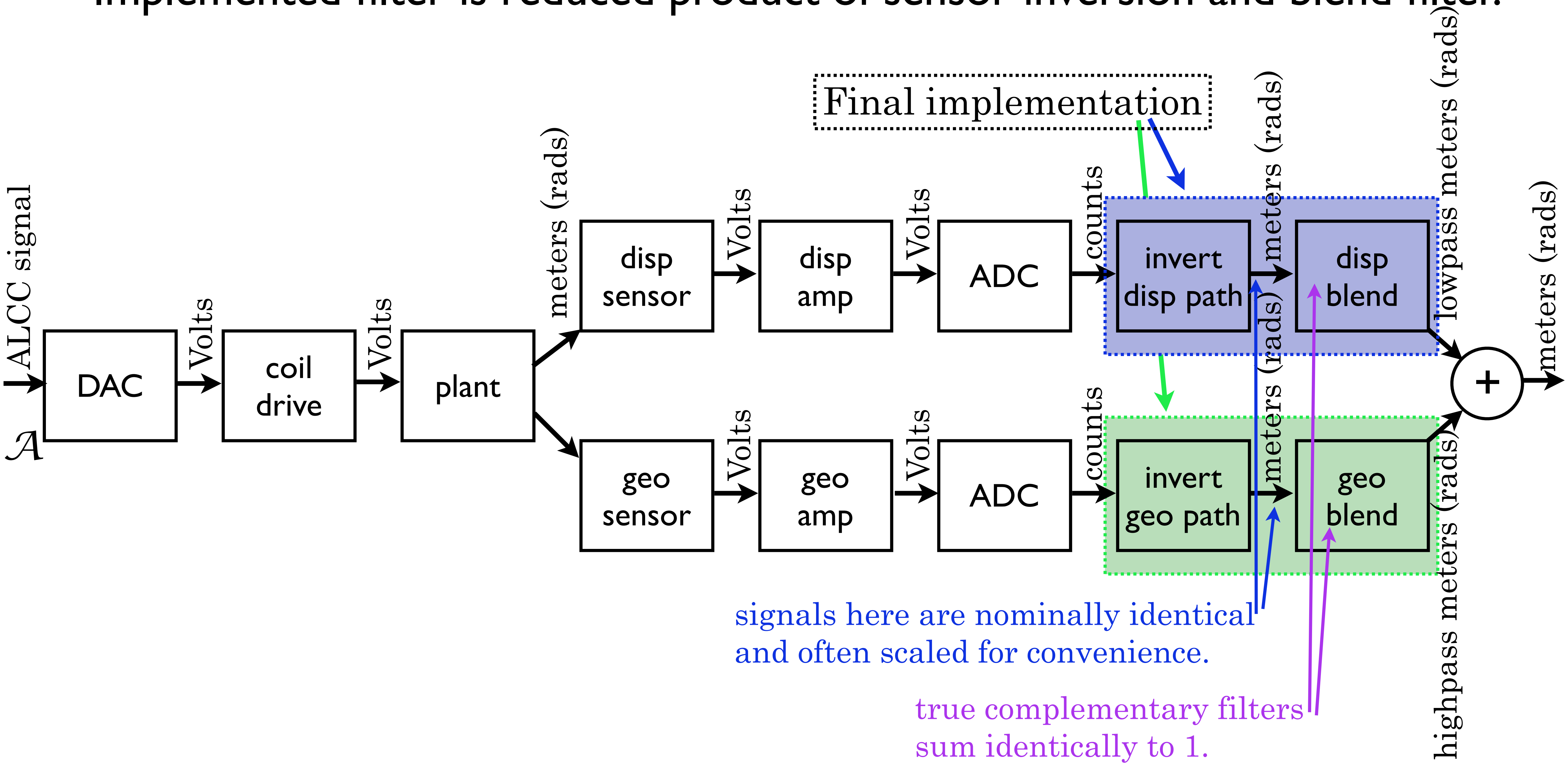
- simple velocity damping at peaks.
- collocated sensor-actuator pairs.
- 3 Horz loops identical, 3 vertical loops identical.
- Reduce Q to a few. Don't worry too much about what it is, but once you get a good value, don't ever change it.

Damping loop for V1

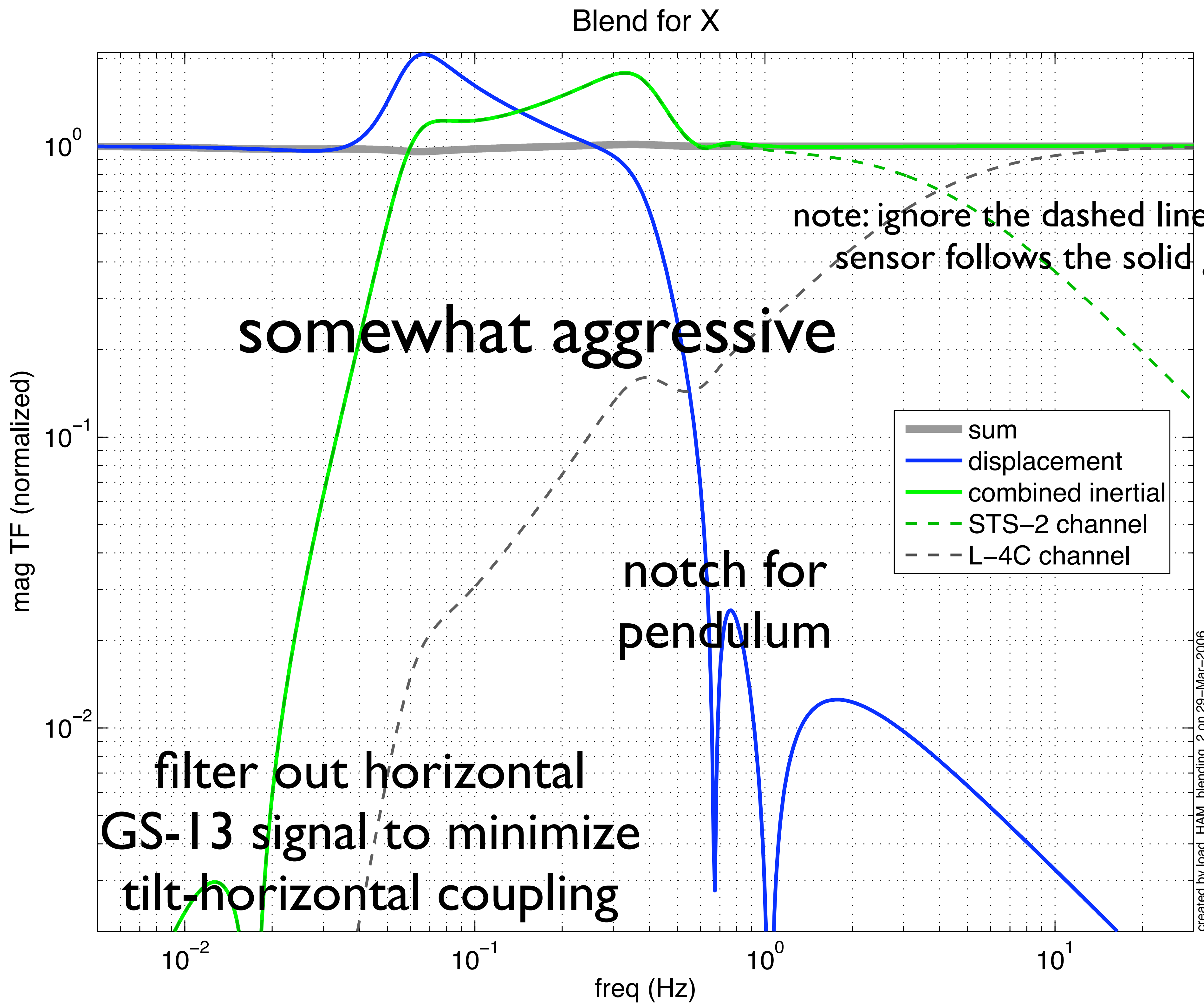


Sensor Blending

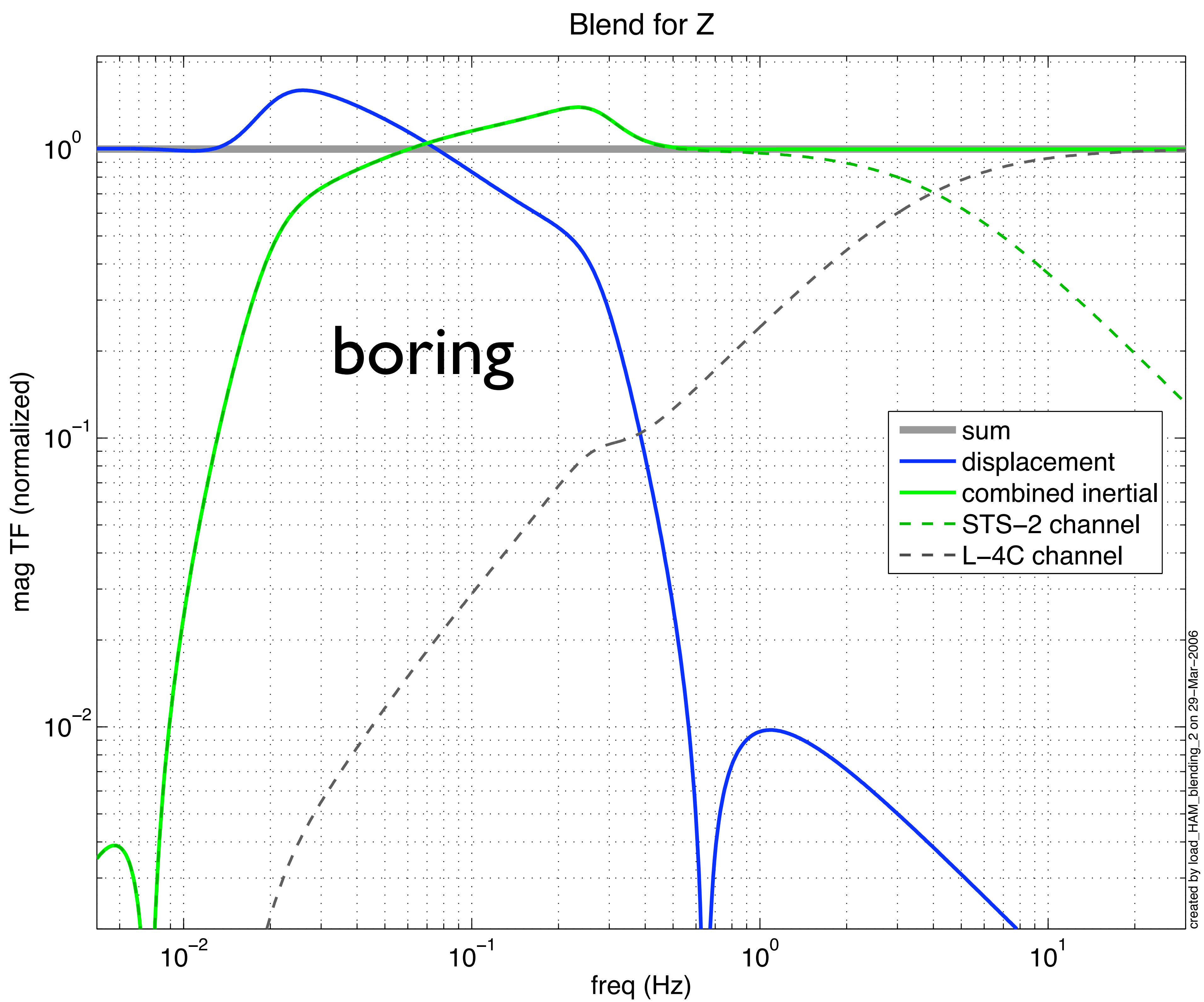
- Blend filters designed to be truly 'complementary', e.g. $1/(1+w)$ and $w/(1+w)$.
- Requires inversion of sensor dynamics and amp chain.
- Implemented filter is reduced product of sensor inversion and blend filter.



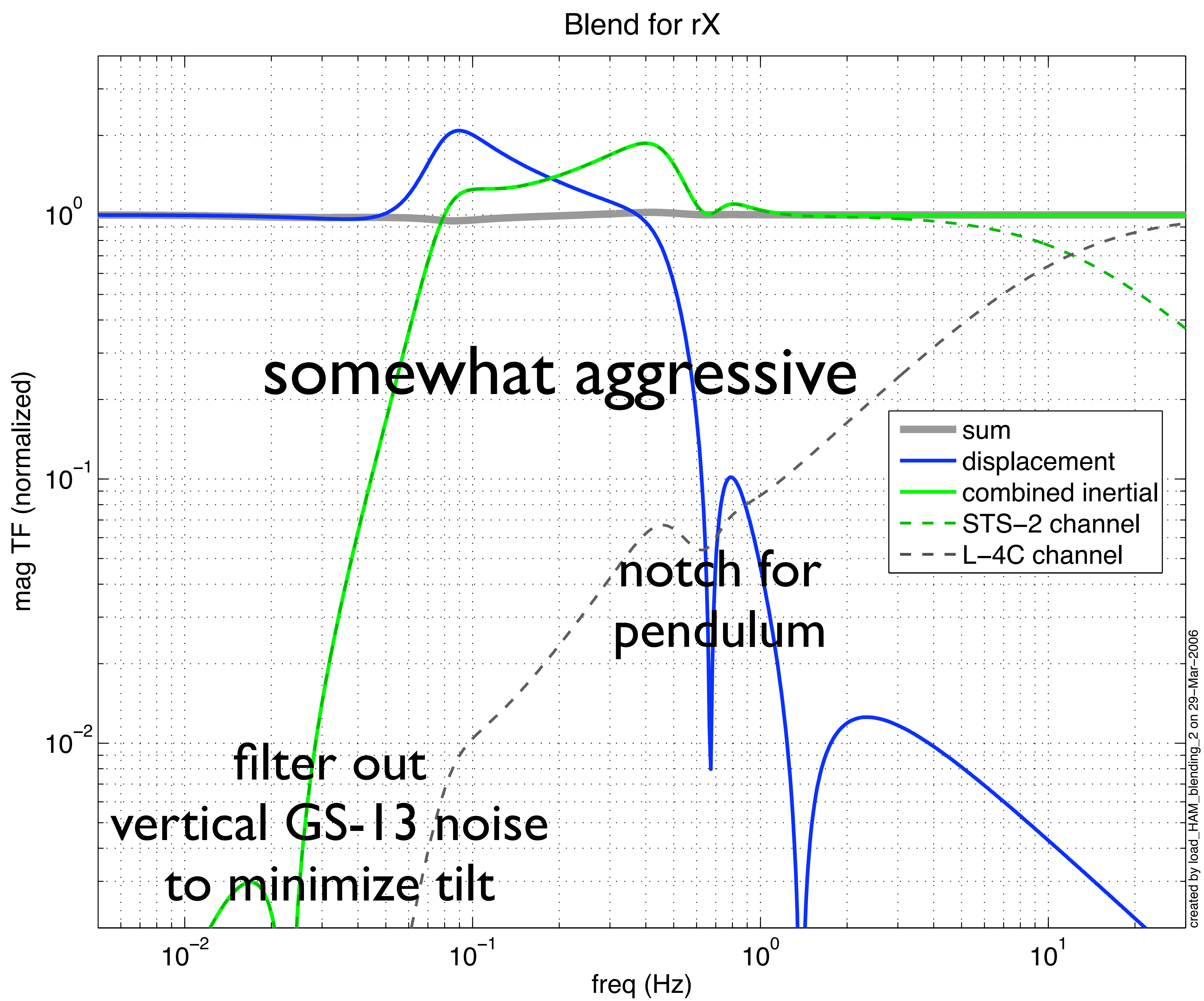
Blending for X & Y



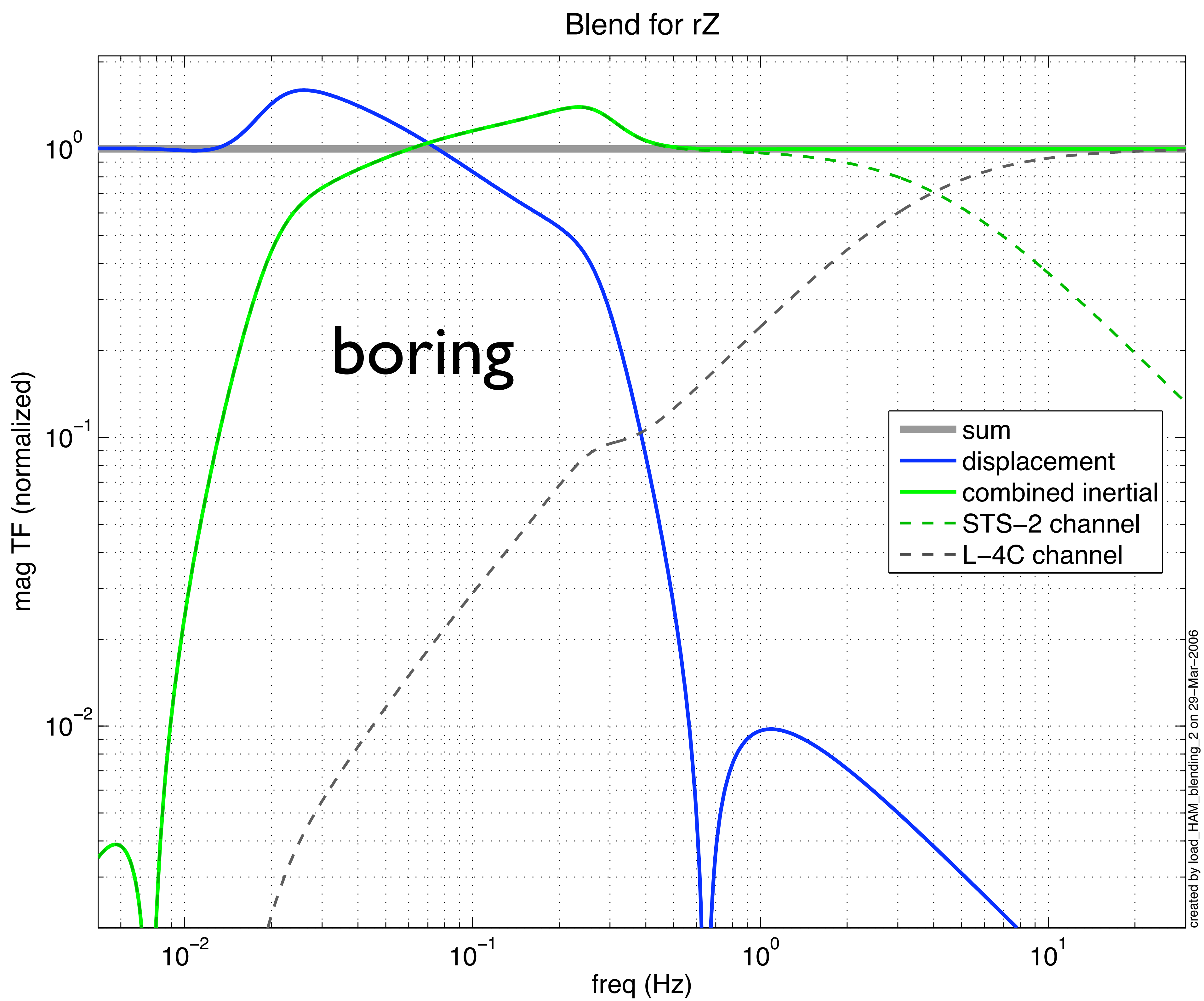
Blending for Z



Blending for rX & rY



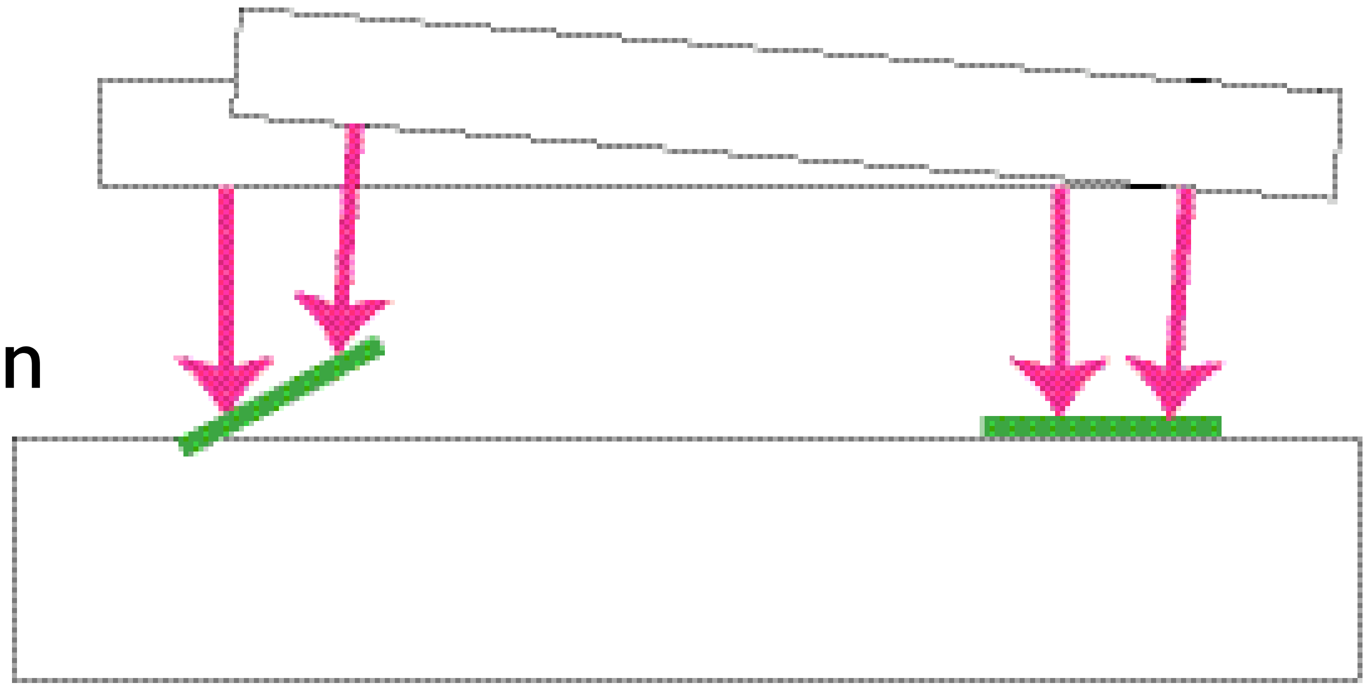
Blending for rZ



Correcting the displacement sensors

Problem: Tilt-horizontal coupling

Non-parallel reference surfaces can convert translation into tilt.



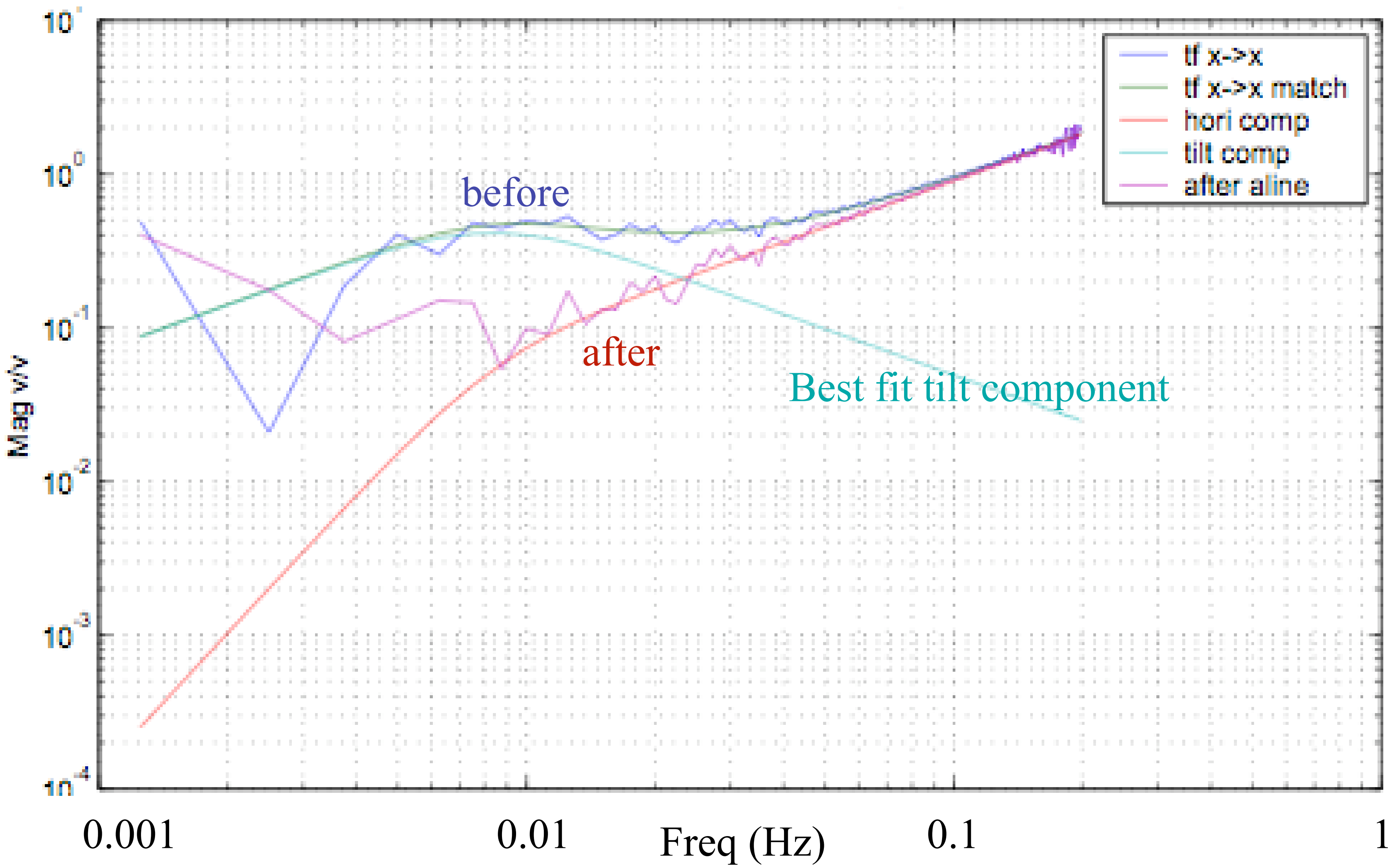
1) Set blend freq high (eg 3 Hz). Drive system in translation & Measure tilt with horizontal seismometer.

2) Calculate the ratio of translation-to-tilt coupling. ie Fit response as sum of translation and C*tilt.

3) Modify code: when you command a translation, also command an opposite tilt.

Benefit of tilt correction

Alignment Improvement for X to X coupling




```
alineMat =
```

$$
\begin{bmatrix} x \\ y \\ z \\ rx \\ ry \\ rz \end{bmatrix} = \begin{bmatrix} 1.0000 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.0000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.0000 & 0 & 0 & 0 \\ 0 & -0.0006 & -0.0116 & 1.0000 & 0 & 0 \\ 0.0022 & 0 & 0.0147 & 0 & 1.0000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.0000 \end{bmatrix} * \begin{bmatrix} x \\ y \\ z \\ rx \\ ry \\ rz \end{bmatrix}
$$

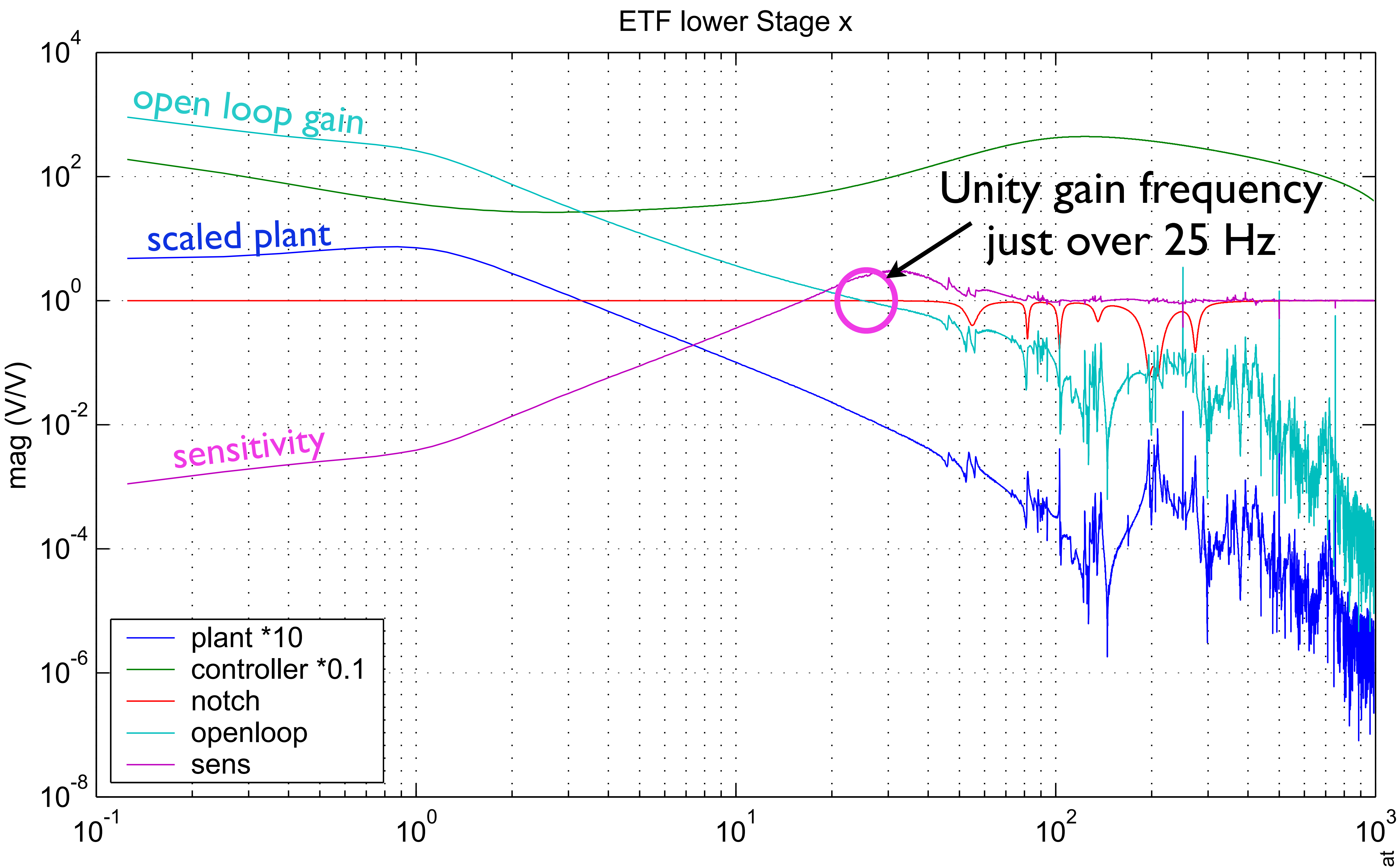
Successive loop closure

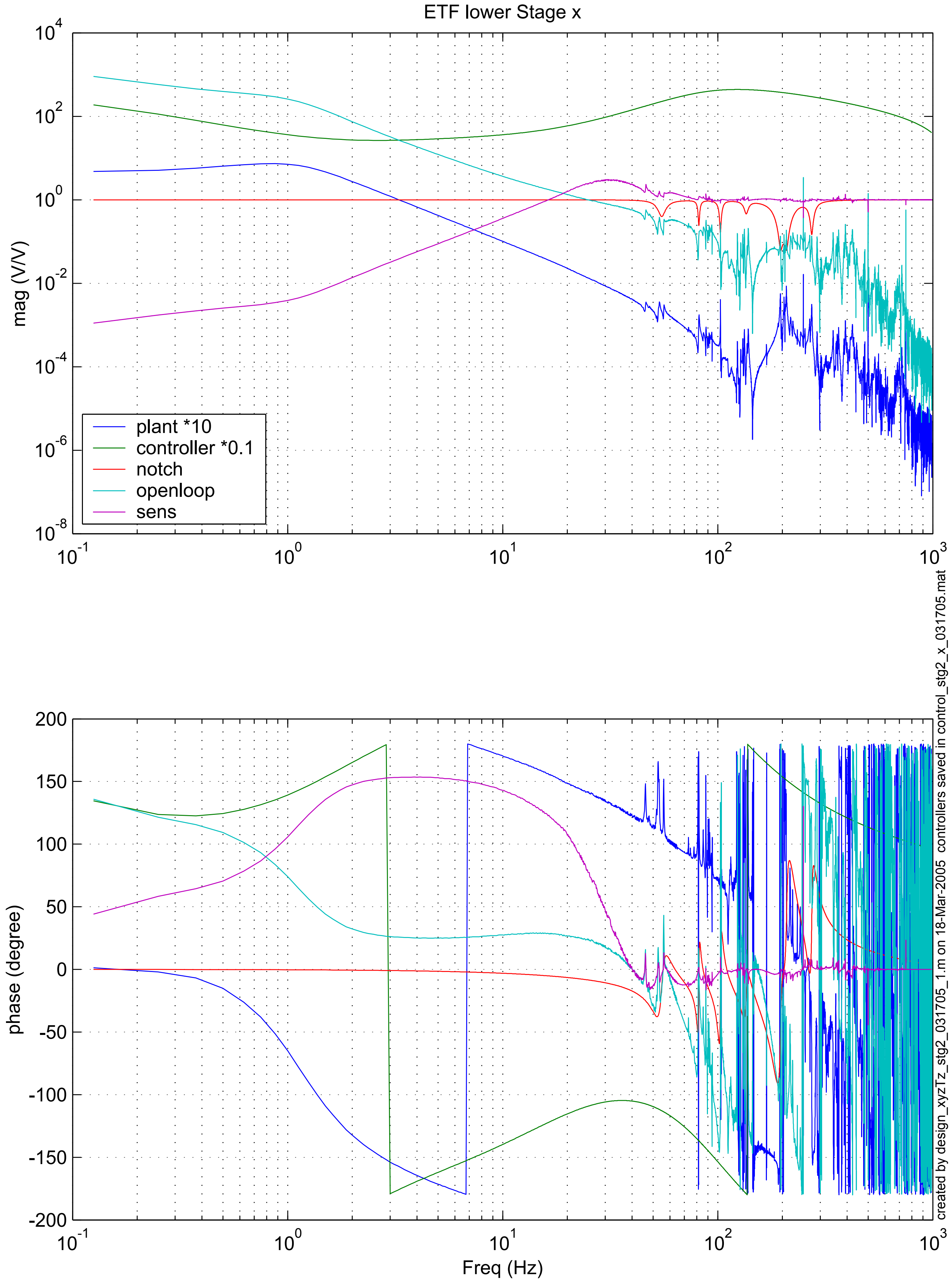
- First, close the 6 damping loops.
  makes plant quieter, and better behaved
  (reduces x-coupling of rigid body modes).
- Then, close rx and ry.
  Now translation loops will be well behaved.
- Close other 4 DOFs.

Simple loops with notches

- Brian likes:
  - No implied minus signs. Loops stable if phase above 0 deg, not -180.
  - Always plot the sensitivity, $S = 1/(1-L)$, L is the open loop gain. Use - because loops close with a +.
  - Loops are at nominal gain when the control gain knob = 1 (where ever that is).
  - Loops are unconditionally stable. ie. Can run at any gain between 0 and 1. Turn on bonus gain later (notches, extra low freq gain, etc.)

Example - Tech Demo stg2 X





ETF lower Stage x
mag (V/V)
plant *10
controller *0.1
notch
openloop
sens
phase (degree)
Freq (Hz)
created by design_xyzTz_stg2_031705_1.m on 18-Mar-2005 controllers saved in control_stg2_x_031705.mat

Sensor Correction

- Used to get microseismic performance
- Implement from the ground directly to stage 1, as was done by Hua on the rapid prototype.