Advanced LIGO
Active Seismic Isolation

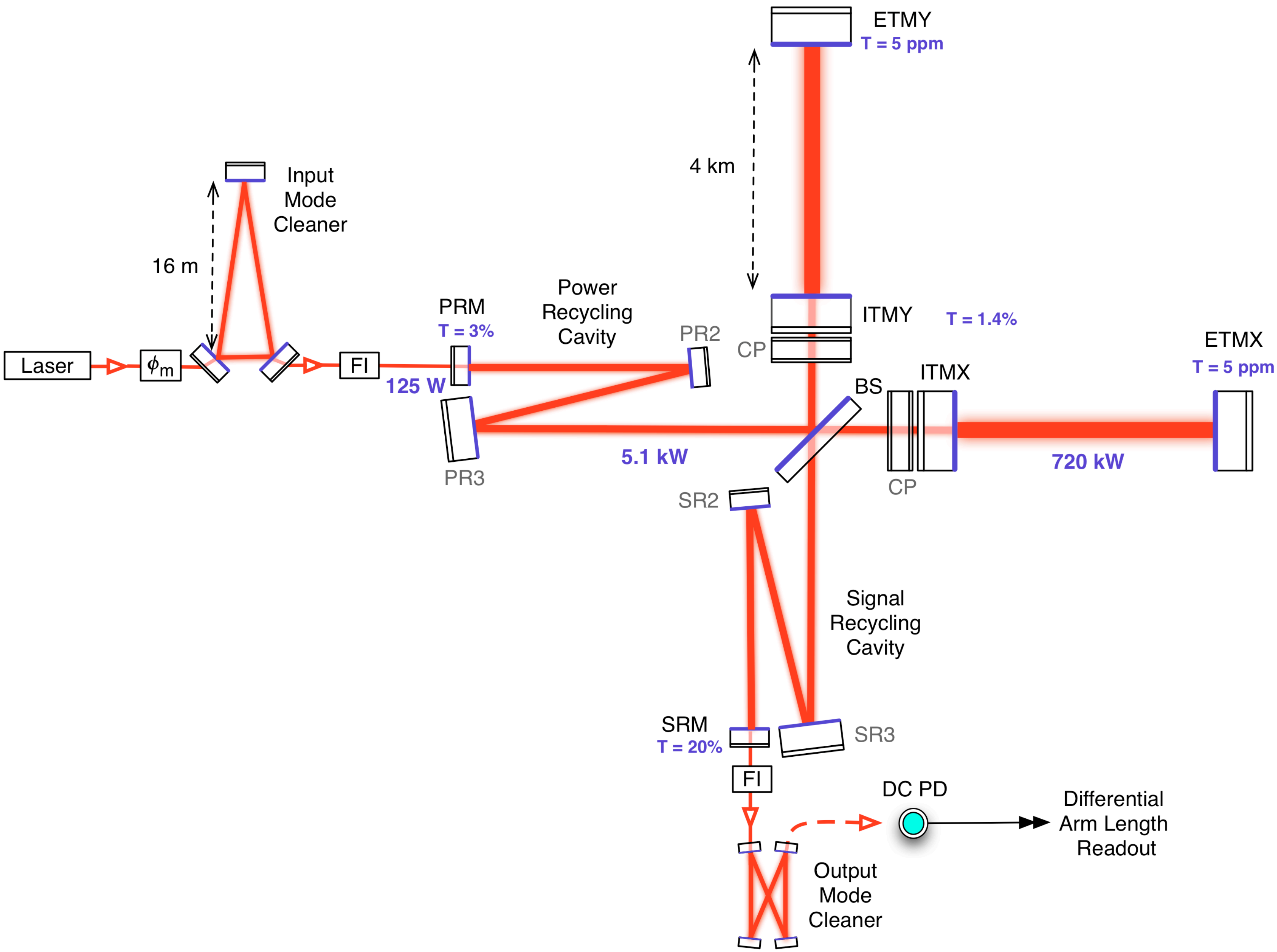
Jeff Kissel, for the Seismic Team

Det.Char. Telecon, April 7 2011
G1100431

What I'll squeeze into an hour

- A Bird's Eye View
- A Few Scary Pictures
- The Jargon
- The Requirements and Sensors
- HEPI
- HAM-ISI
- BSC-ISI
- The Philosphy of Control
- What you can do to help
- Who to bug when you're confused
- What channels matter to you

aLIGO (Simplified) Interferometer Layout



J. Kissel, Apr 7 2011

aLIGO Seismic Isolation

Core Optics
7 Stages

Active Isolation

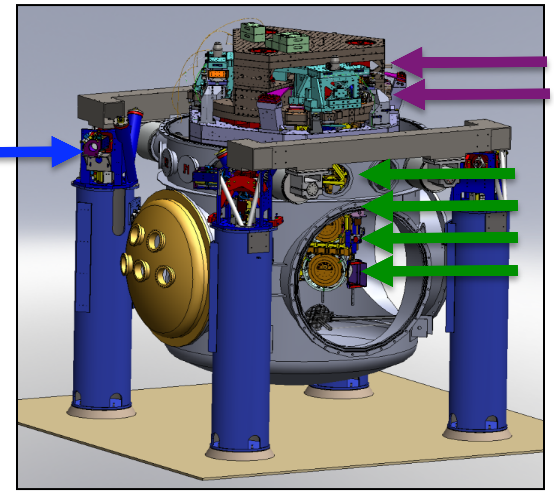
1 external stage (BSC HEPI)

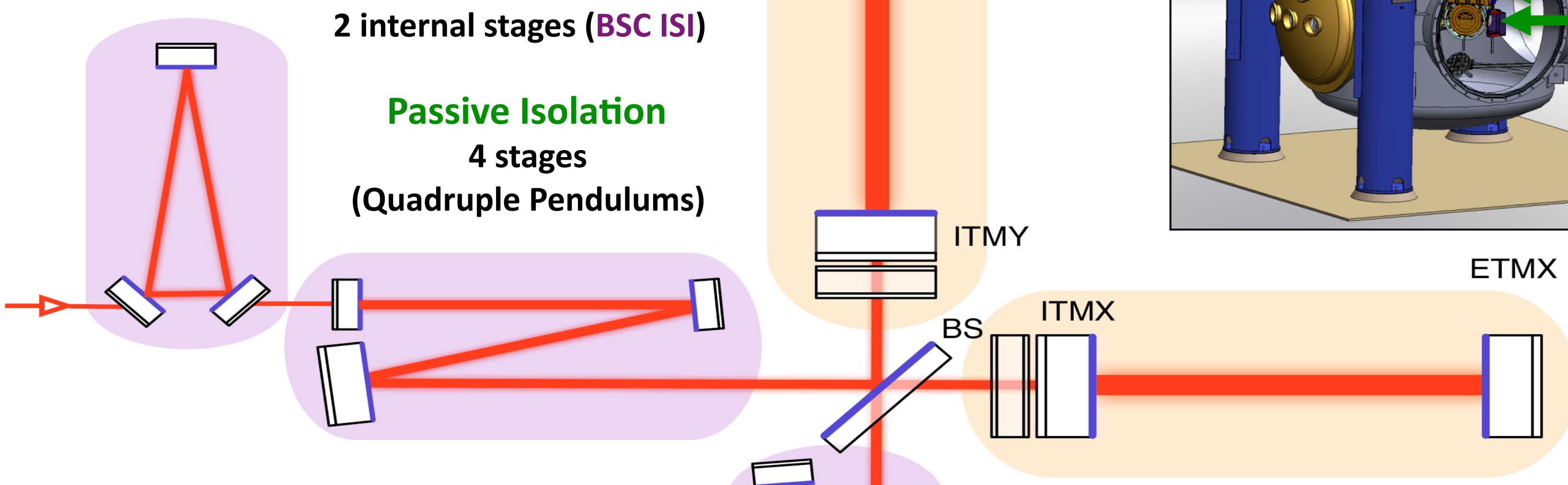
2 internal stages (BSC ISI)

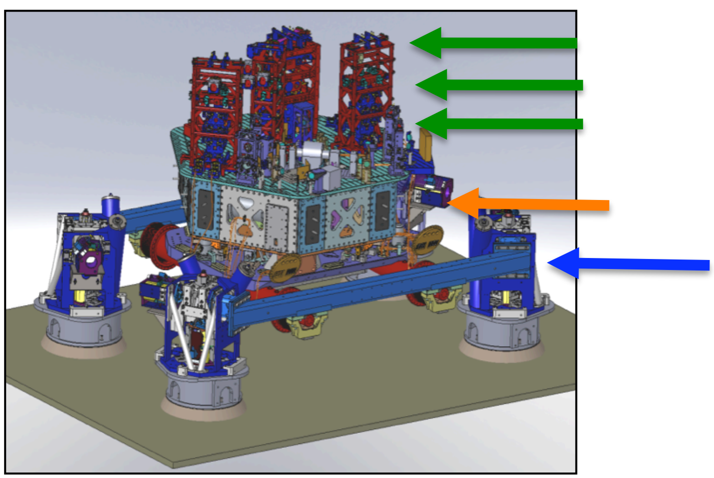
Passive Isolation

4 stages

(Quadruple Pendulums)







Auxiliary Optics
5 Stages

Active Isolation

1 external stage (HAM HEPI)

1 internal stage (HAM ISI)

Passive Isolation

3 stages

(Triple Pendulums)

What does it buy us?

Possible Intermediate Configuration:
- No Signal Recycling
- 25 W Input Power

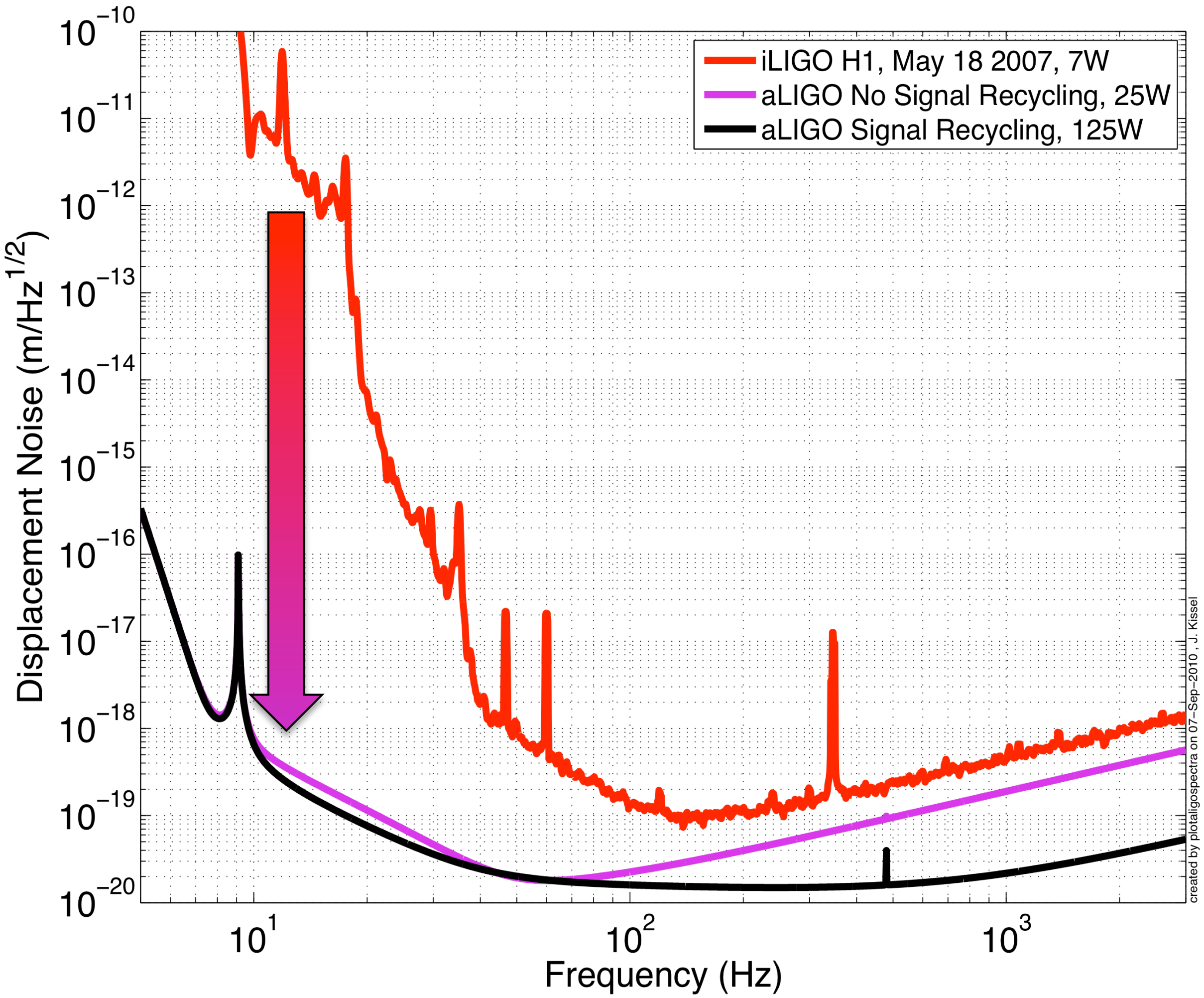
Demonstration of aLIGO suspensions and seismic isolation:

• 7 orders of magnitude less displacement at 10 Hz

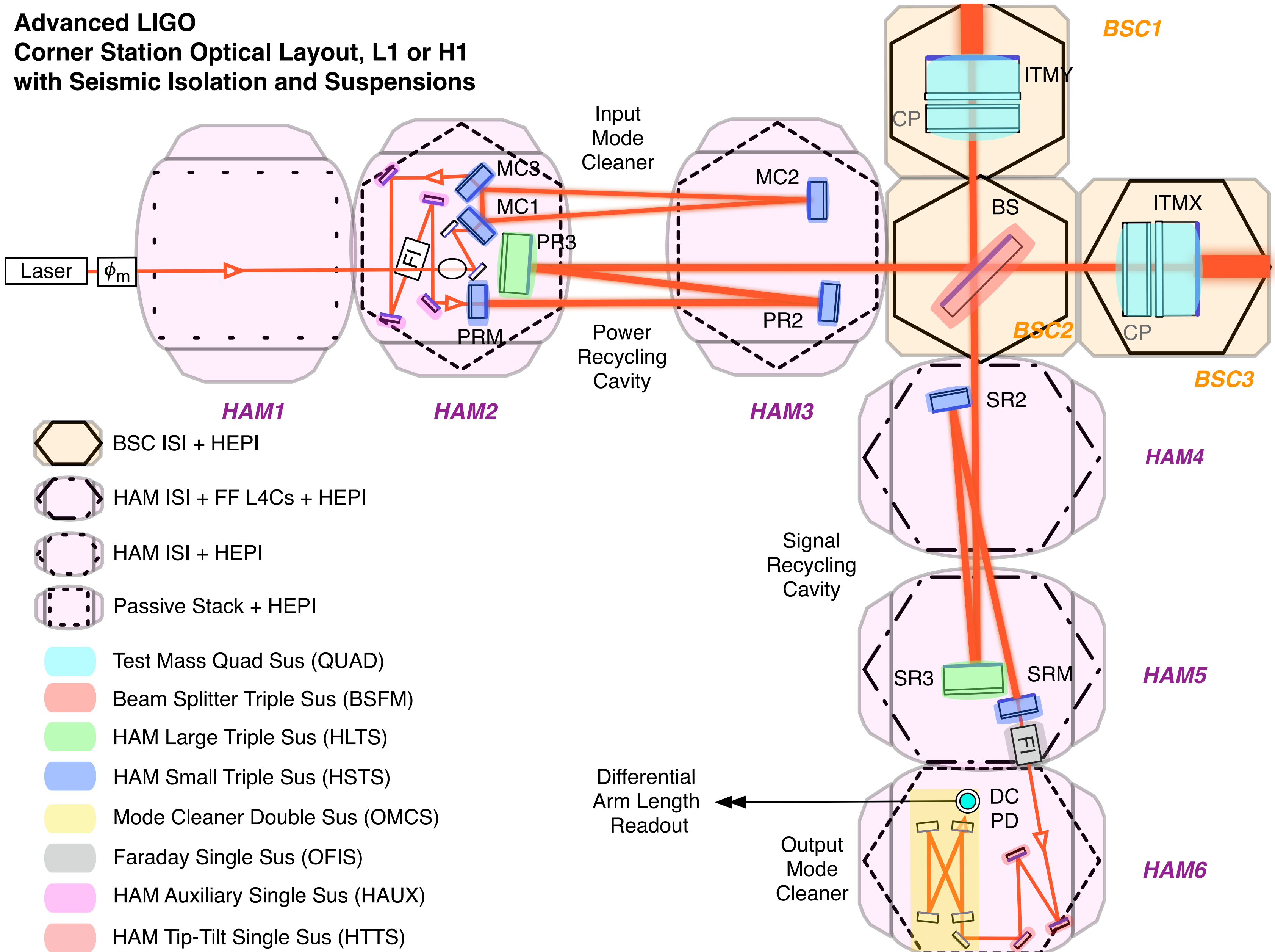
⇒ Predicted Binary Neutron Star Range: ~**145 Mpc**

⇒ Event Rate:

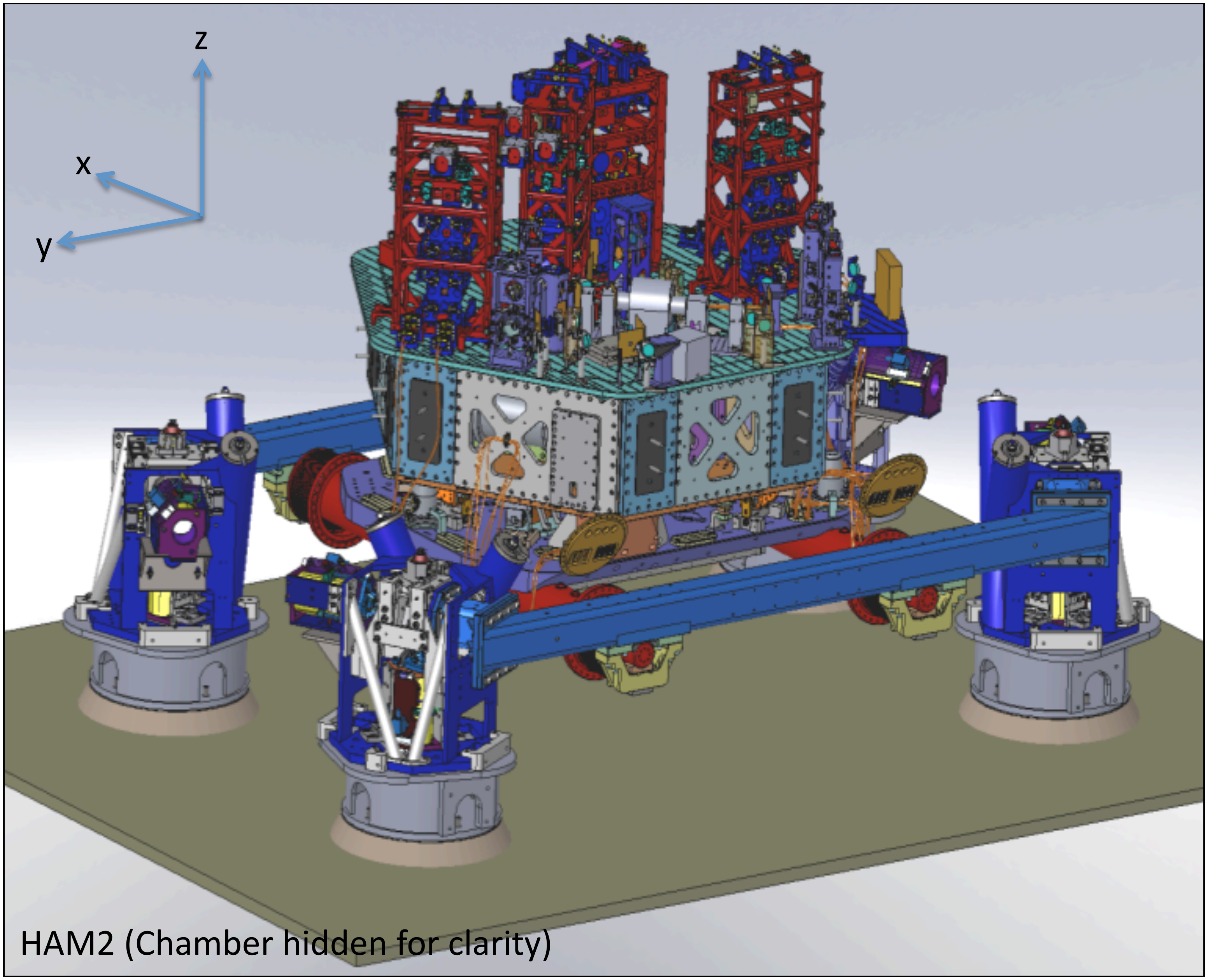
$$\dot{N}_{re}^{1.4-1.4} \approx 10 \ \ \mathrm{yr}^{-1}$$



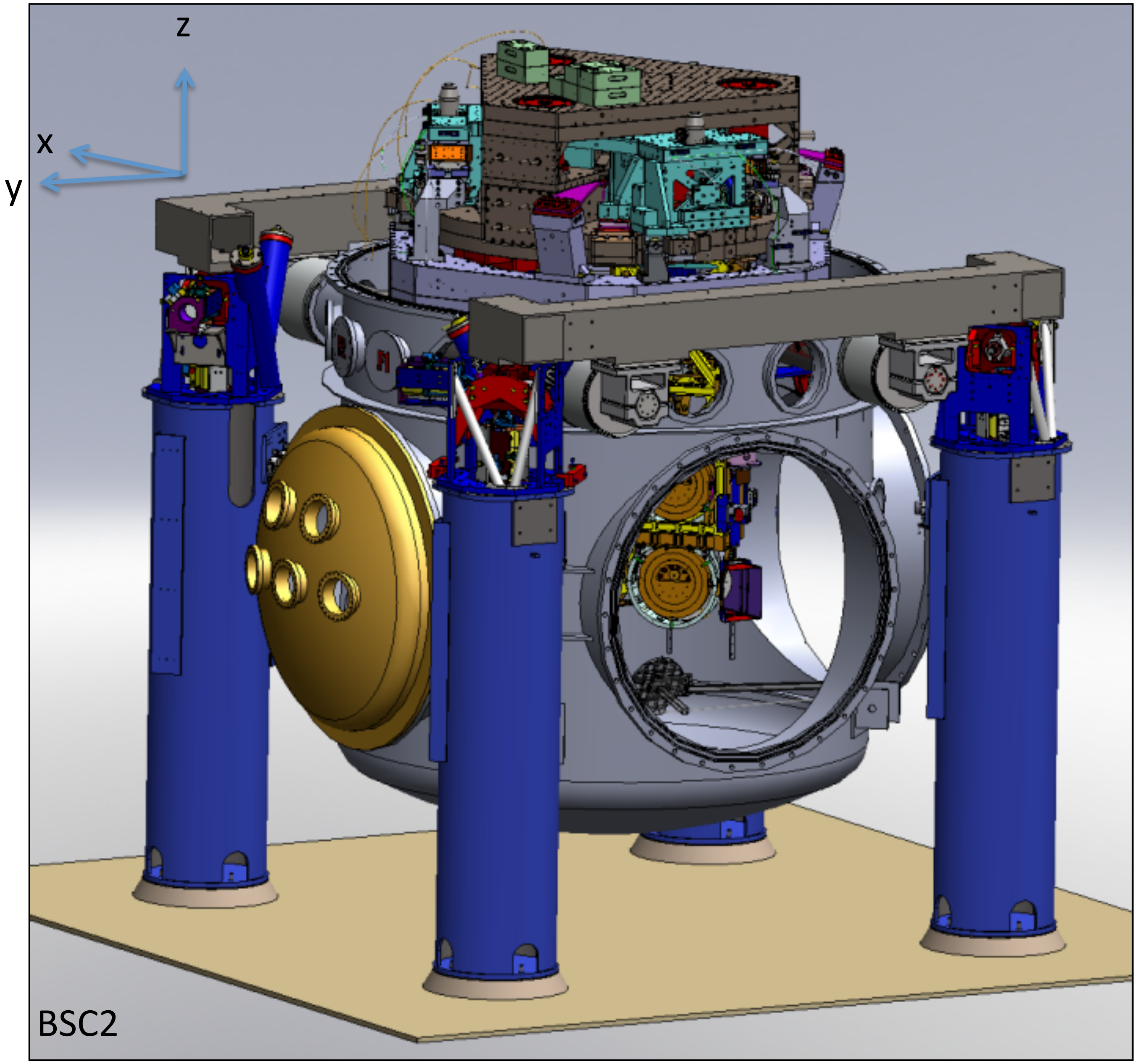
An aLIGO Corner Station



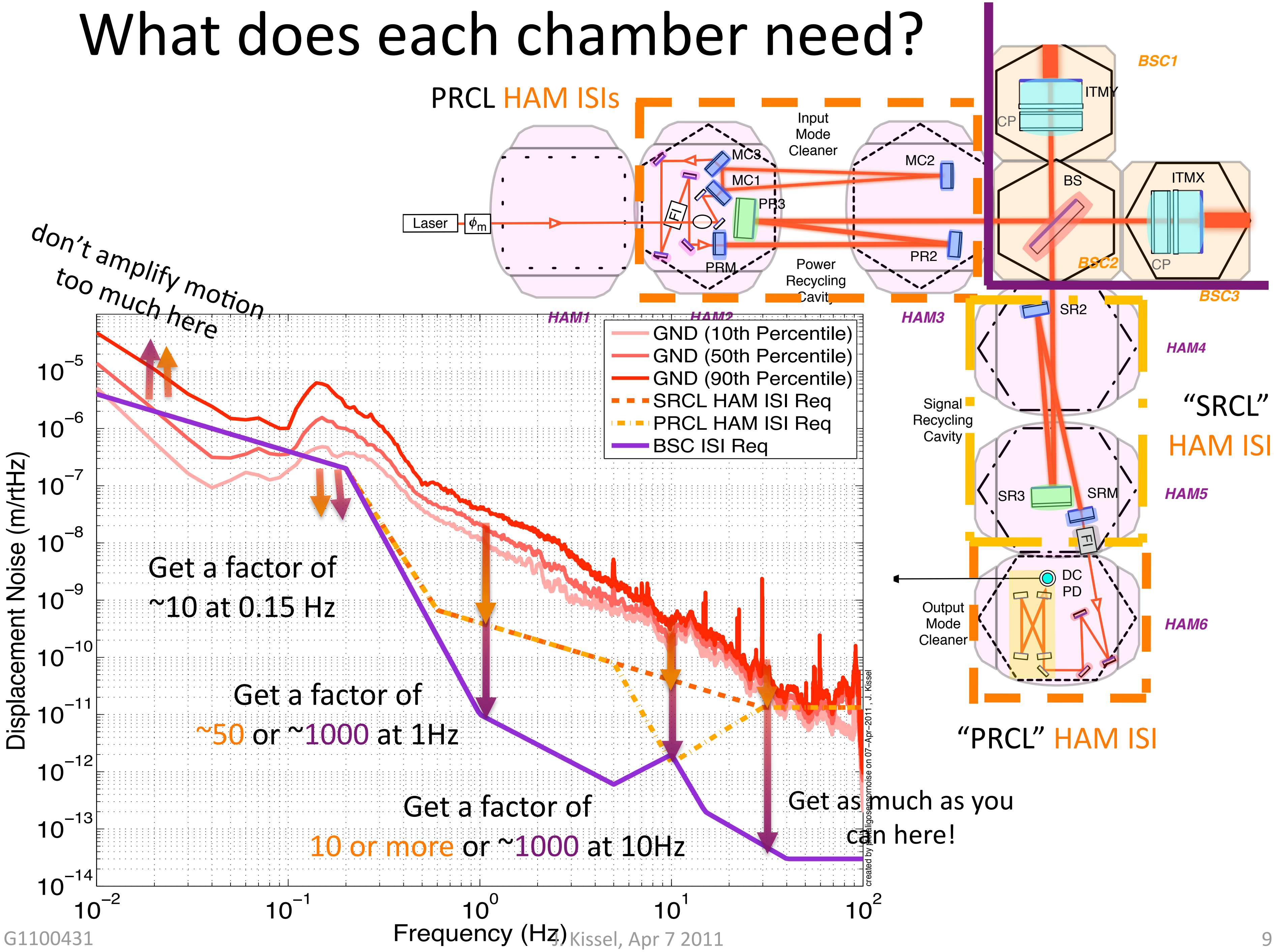
An aLIGO HAM Chamber



An aLIGO BSC Chamber



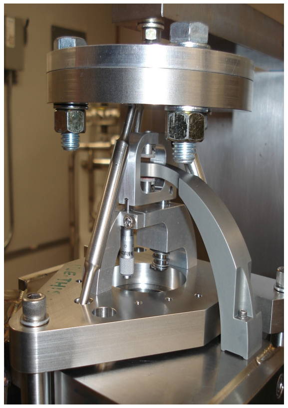
What does each chamber need?



SEI Sensors and Their Noise

"Low" Frequency

DC



IPS

Kaman's Inductive Position Sensors

Used On: HEPIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Reasonable Noise, Long Range

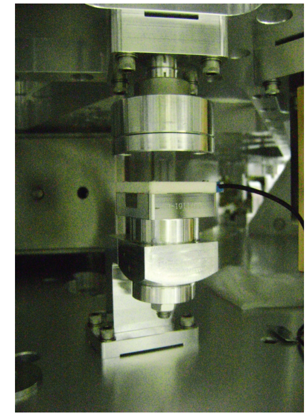
CPS

MicroSense's Capacitive Displacement Sensors

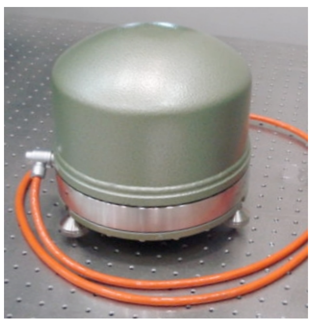
Used On: HAM-ISIs and BSC-ISIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Good Noise, UHV compatible



10 mHz



STS2

Strekheisen's STS-2

Used On: HEPIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Best in the 'Biz below 1 Hz, Triaxial

T240

Nanometric's Trillium 240

Used On: BSC-ISIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Like STS-2s, Triaxial, no locking mechasim -> podded

1 Hz

GS13

GeoTech's GS-13

Used On: HAM-ISIs and BSC-ISIs

Used For: ≥ 0.5 Hz Control

Used 'cause: awesome noise above 1Hz,

no locking mechanism -> podded

L4C

Sercel's L4-C

Used On: All Systems

Used For: ≥ 0.5 Hz Control

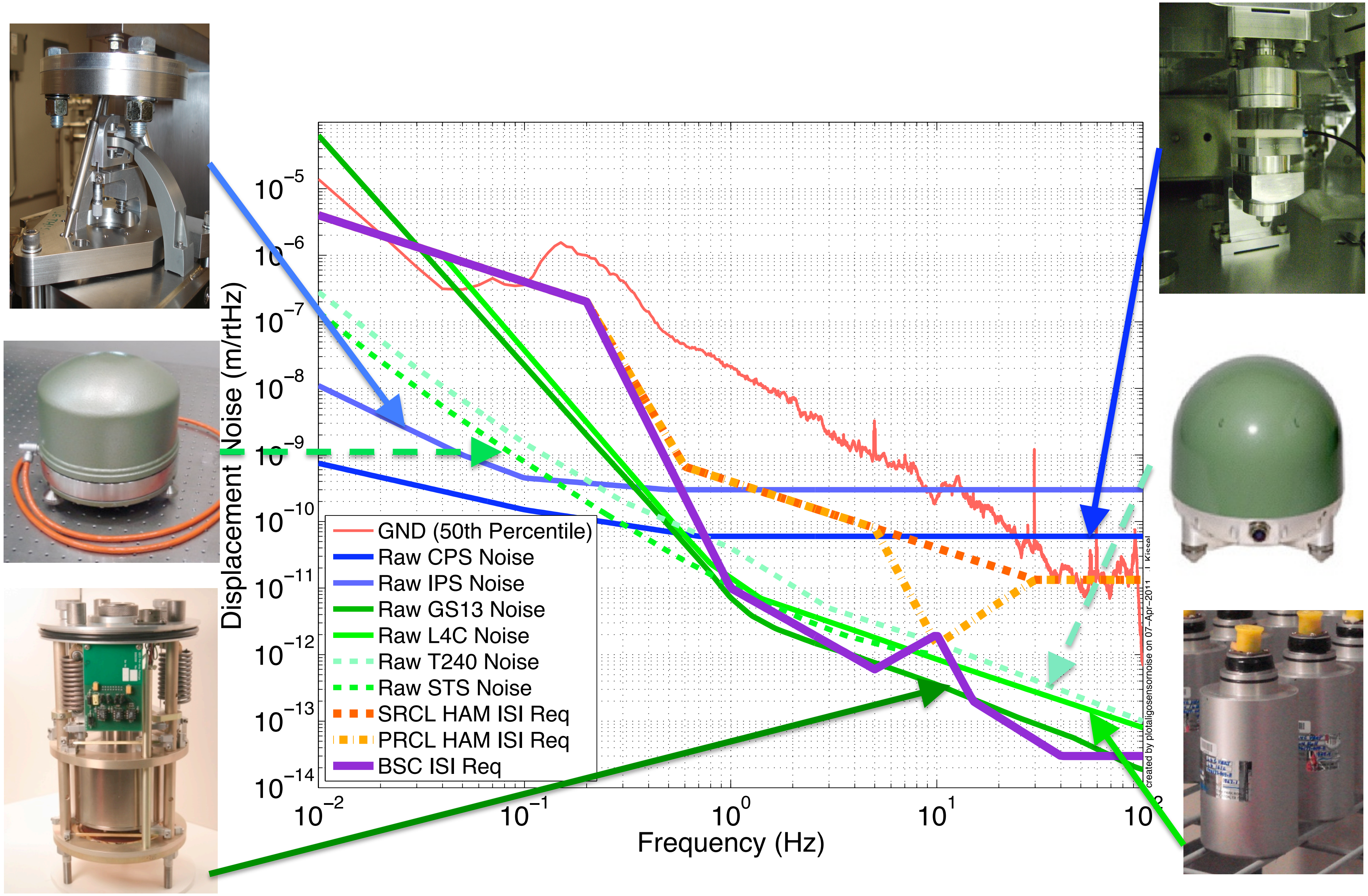
Used 'cause: Good Noise, Cheap,

no locking mechanism -> podded

800 Hz

"High" Frequency

SEI Sensors and Their Noise

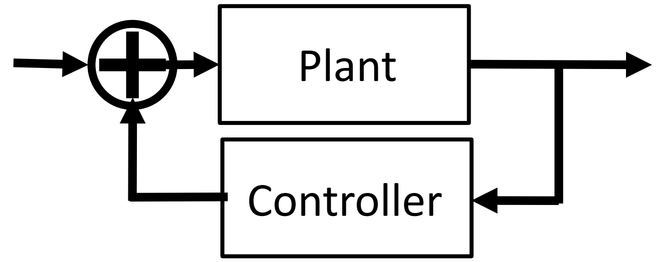


Some Jargon

- Plant, Controller, Open Loop Gain
  - **Plant** – Platforms response to ground motion as a function of frequency (as measured displacement and inertial sensors when driven by actuators) – looks like a simple pendulum!

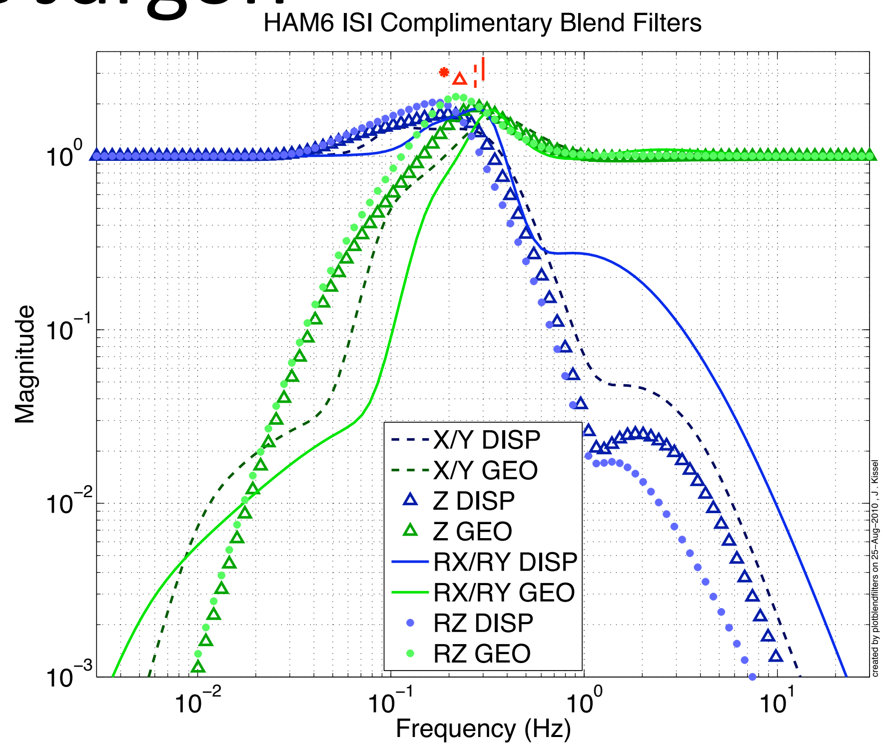
  - **Controller** – digial filters used to shape sensor displacement singals into actuaction force signals

  - **Open Loop Transfer Function** – the product of the plant times the controller, used as a measure of control loop stability



- Position ~ Displacement
  - You'll here the seismic crew use these interchangably; "The position sensors" the "displacement sensors" – are subtly different, but realize they serve the same function in aLIGO SEI
- Inertial sensor = Geophone = Seismometer
  - Again, used interchangibly, all "the same thing" with subtle differences, but all serve the same function in aLIGO SEI

Some More Jargon

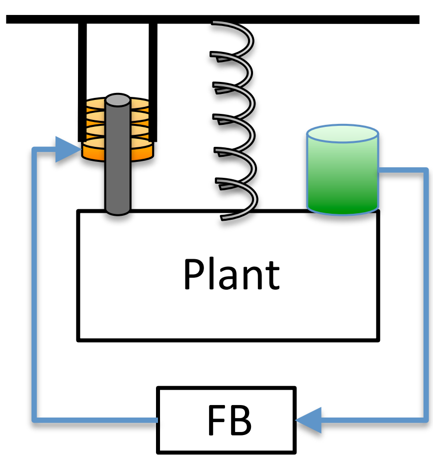


- **Super Sensor** – The combined inertial and displacement signals of all sensors on one stage of isolation, serves as error signal for isolation loops
- **Blend Filters "Blends"** – The set of digital filters on the inertial sensor (high pass) and displacement sensor (low pass)
- **Blend Frequency** – The frequency at which high pass and low pass blends cross over (important for performance)
- **Damping loops**
  - Inertial Sensors only
  - Only reduces Q of blade-spring/wire-flexure pendulum resonances
  - Small bandwidth around resonances
  - Unconditionally stable
- **Isolation loops**
  - Uses Super Sensor
  - Bandwidth from ~25 Hz down to DC
  - High performance, unconditionally stable

Some More Jargon

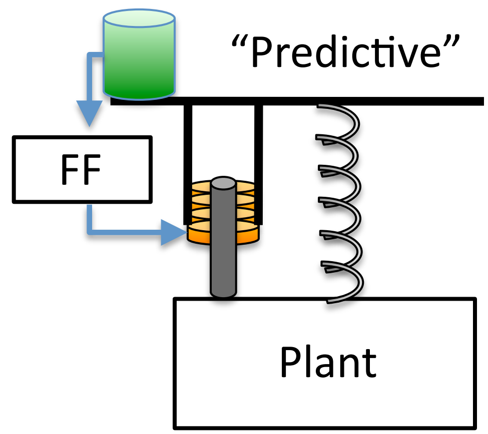
Feedback

"Reactive"



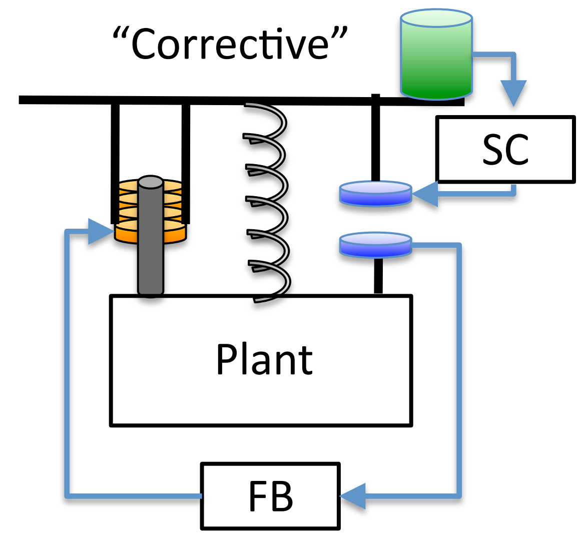
Feedforward

"Predictive"



Sensor Correction

"Corrective"

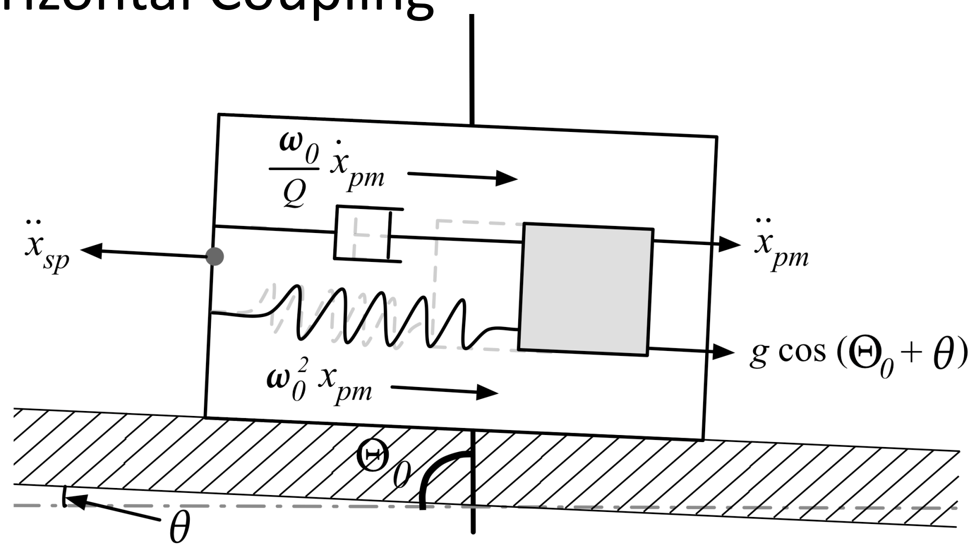


Tilt – Horizontal Coupling

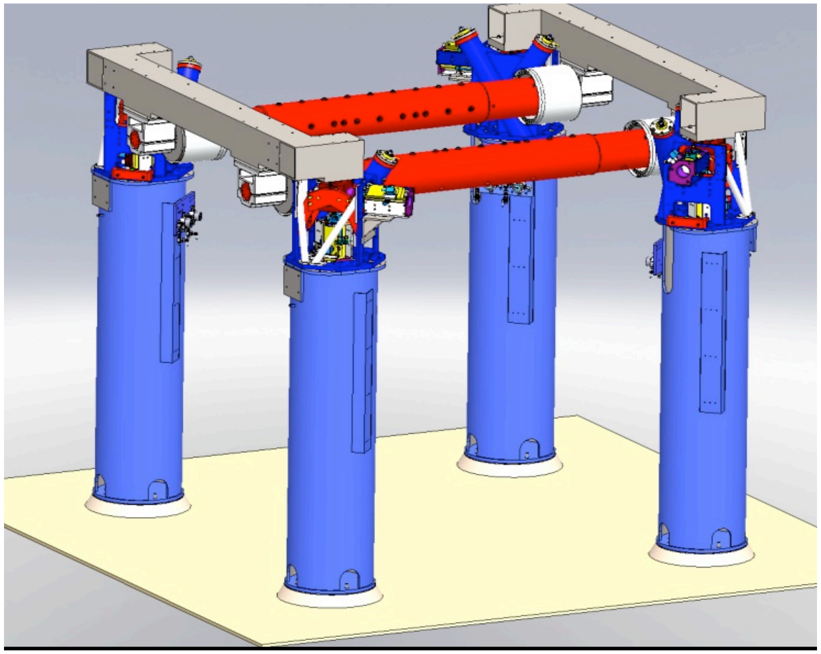
- Fundamental property of a horizontal inertial sensor

$$x_{pm}^{(h)} \propto \left(x_{sp}^{(h)} - \frac{g}{\omega^2}\theta \right)$$

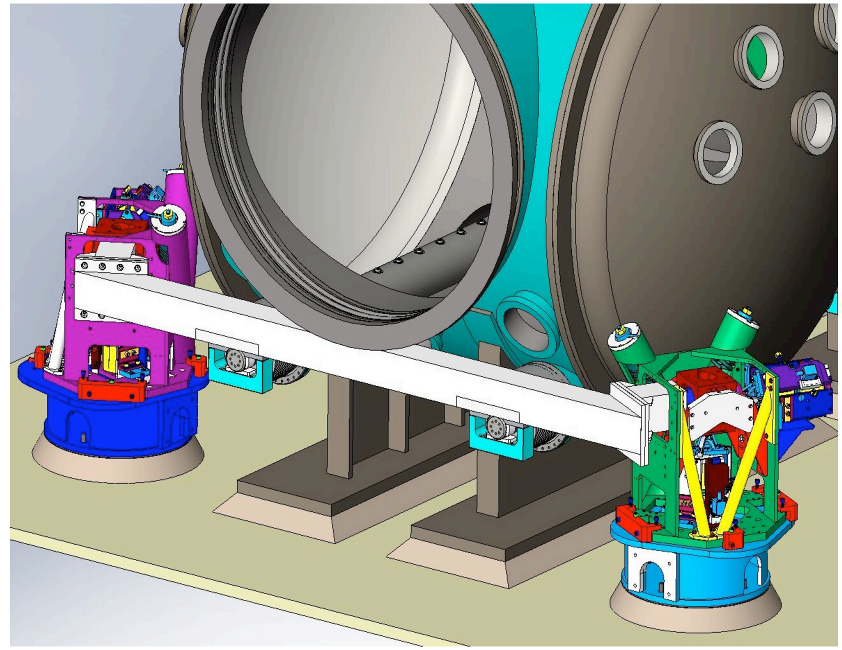
- Effect dominant at low frequency (< 0.5 Hz)



The External Pre-Isolators (HEPI)



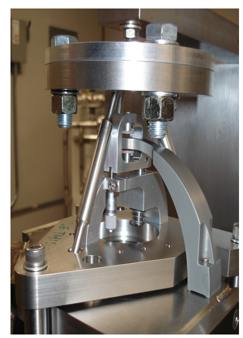
BSC HEPI (Core Optics)



HAM HEPI (IOO Optics)

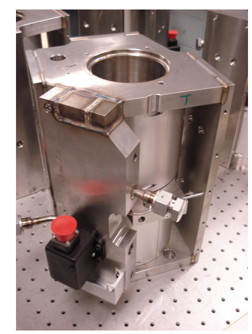
- Single stage systems
- 8 DOF motion per stage
- Over-damped coil springs in compression
- **Active isolation** 8

and 8 on-board Position and Inertial Sensors, with 8 hydraulic actuators



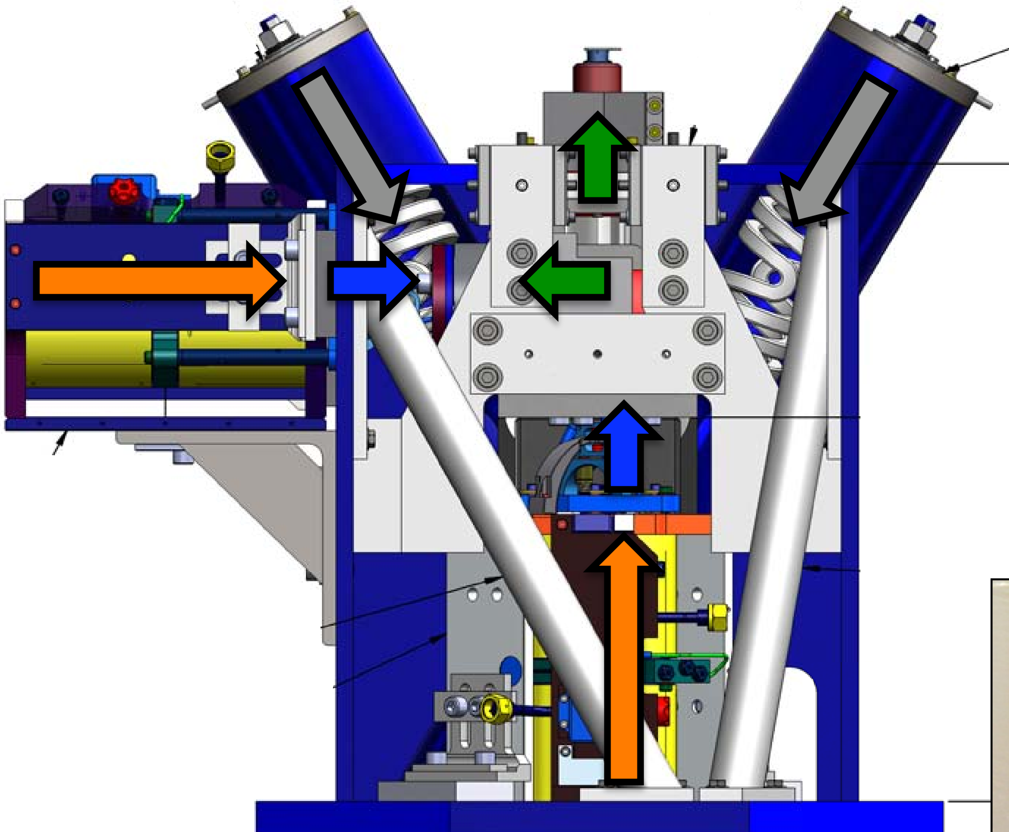
IPS
Position Sensor

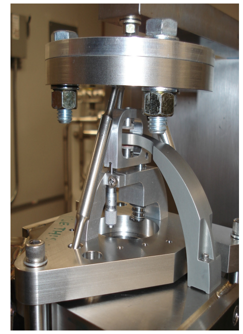
L4C
f = ~1 Hz
Inertial Sensor



Hydraulic Actuators

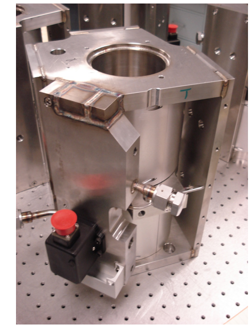
Where stuff is on HEPI



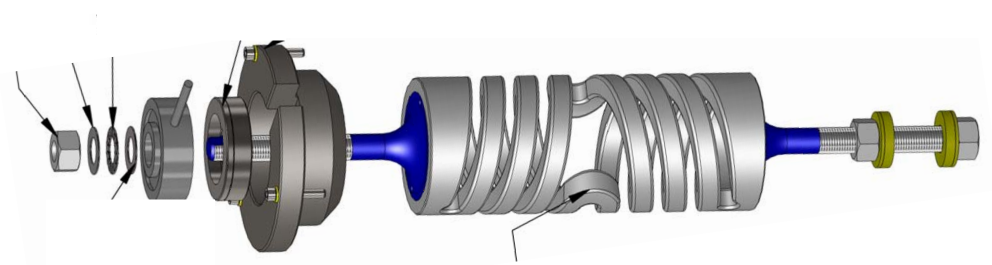


IPS
Position
Sensor

L4C
f = ~1 Hz
Inertial
Sensor



ACT
Hydraulic
Actuators



Euler Springs

The In-vacuum Seismic Isolators (ISI)

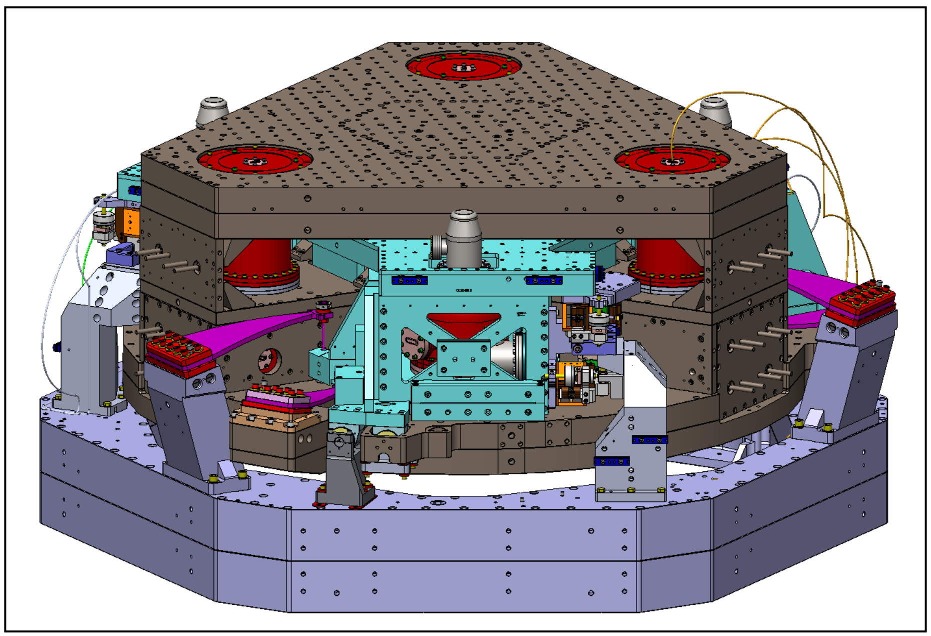
BSC ISI (Core Optics)

- Two-stage system
- 6 DOF motion per stage
- **Passive isolation**

2 x 3 Blade springs + wire flexure systems
Fundamental modes ~ 1Hz

- **Active isolation**

12 and 15 on-board Displacement and Inertial Sensors, with 12 EM Coil actuators



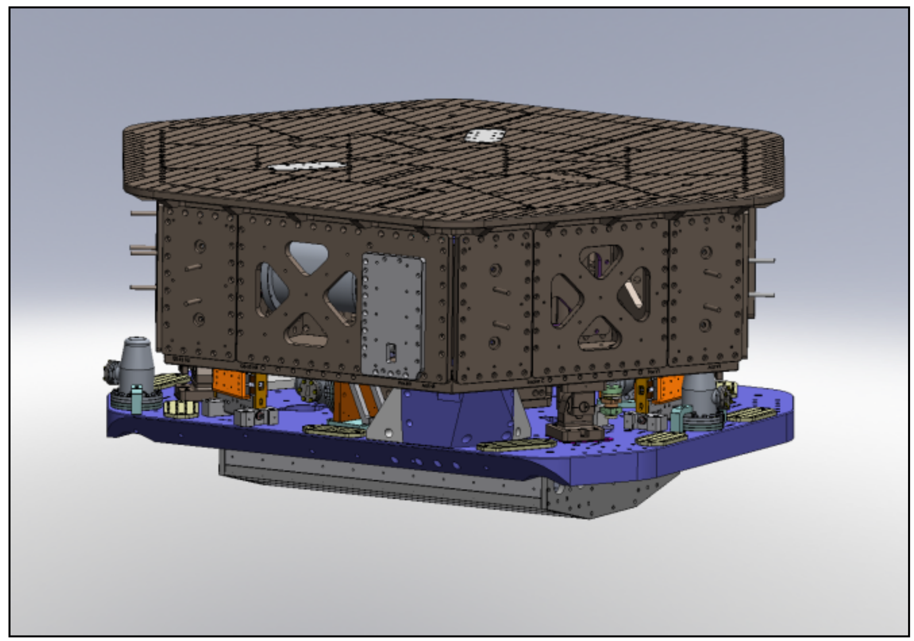
HAM ISI (IOO Optics)

- Single-stage System
- 6 DOF motion single stage system
- **Passive isolation**

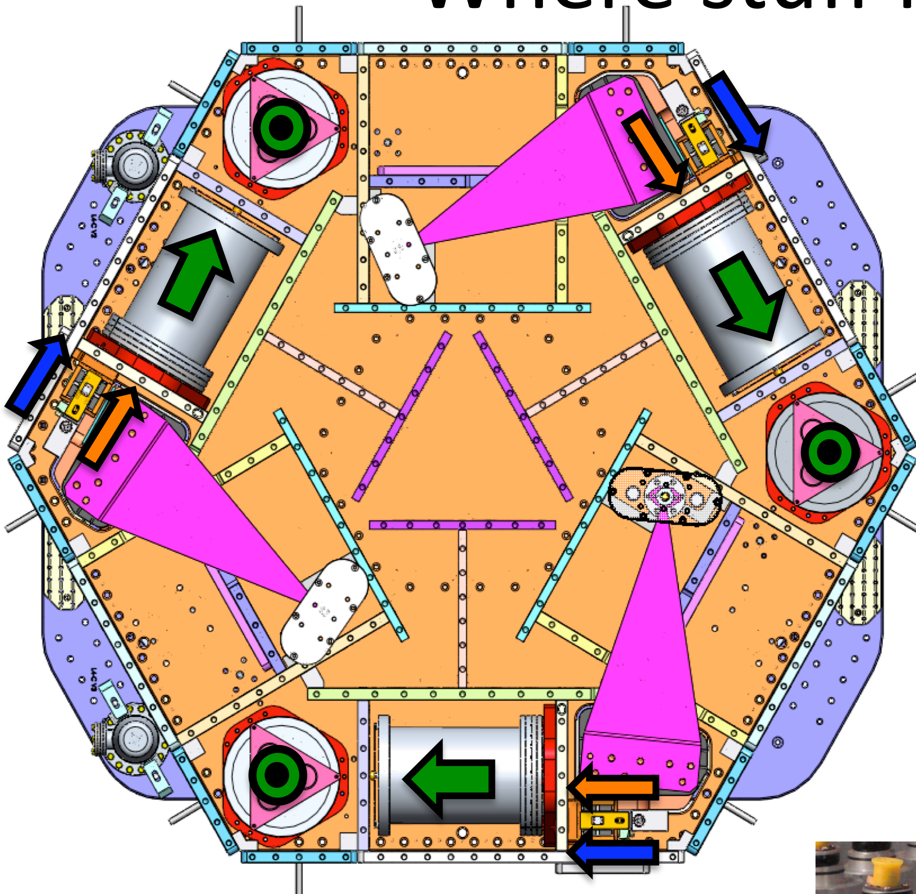
3 Blade springs + wire flexure systems
Fundamental modes ~ 1Hz

- **Active isolation**

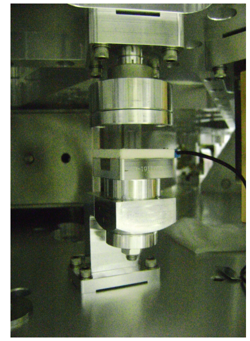
6 and 6 on-board Displacement and Inertial Sensors, with 6 EM Coil actuators



Where stuff is on a HAM-ISI



STAGE 1 (ST1)

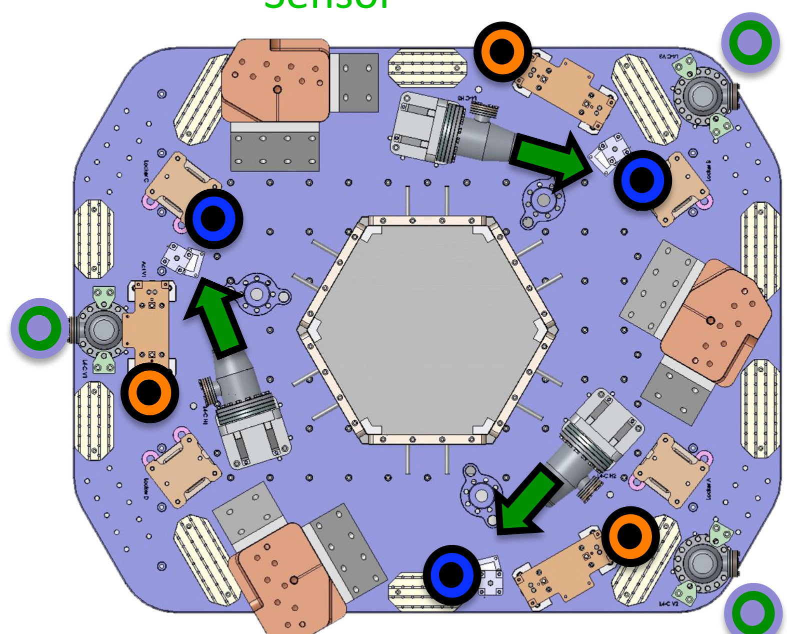


CPS
Displacement Sensor

GS13
f = ~1 Hz
Inertial Sensor

SRCL HAM-ISIs will have "extra" L4Cs on the support stage (ST0) for feed-forward use around 10 Hz

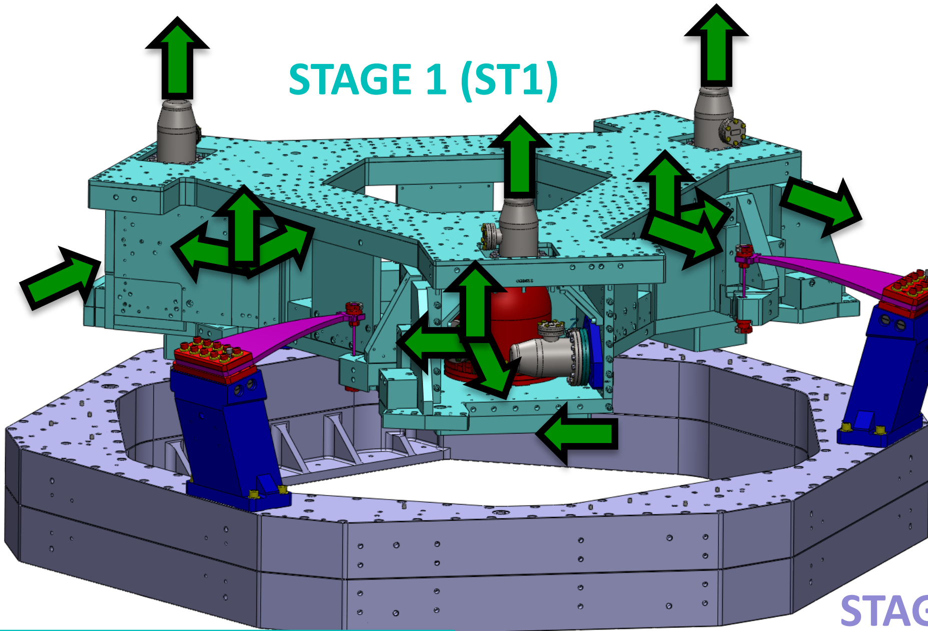
L4C
f = ~1 Hz



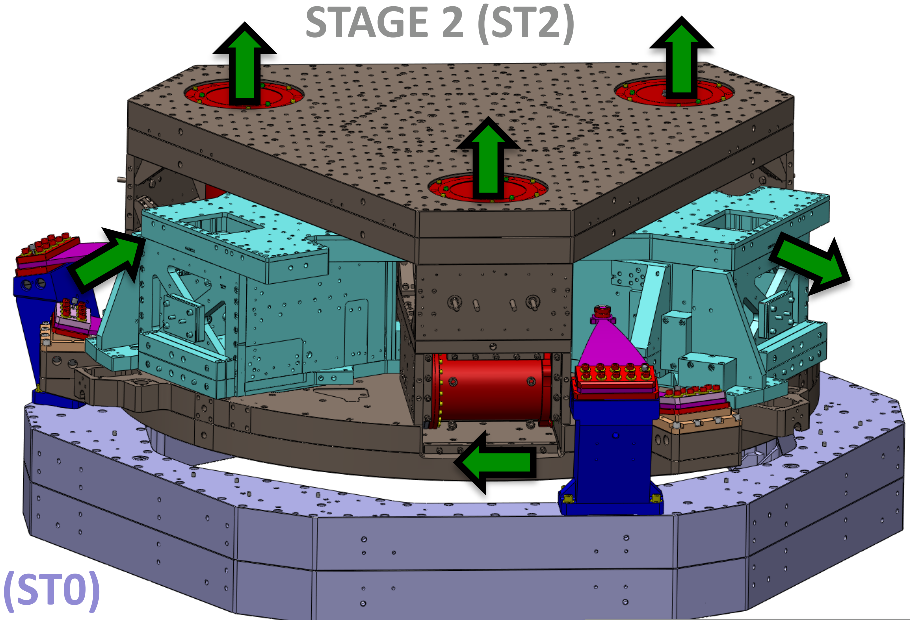
STAGE 0 (ST0)

Where stuff is on a BSC-ISI

STAGE 1 (ST1)



STAGE 2 (ST2)

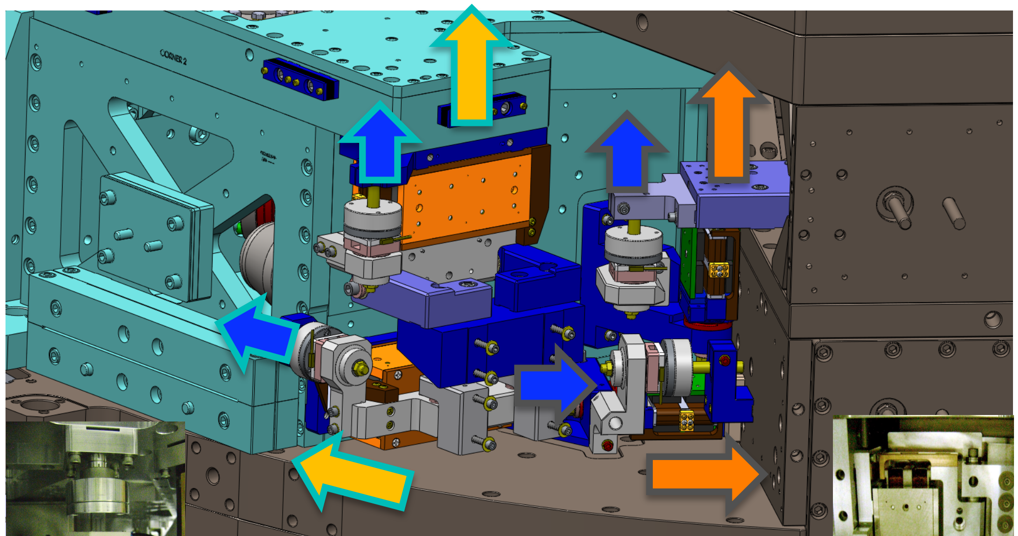


STAGE 0 (ST0)

L4C
f = ~1 Hz

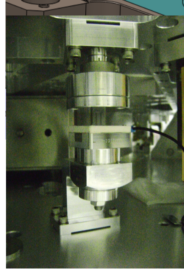
T240
f = ~5 mHz

Inertial Sensors

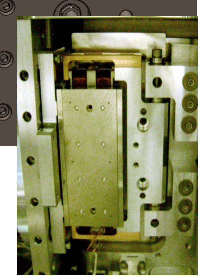


GS13
f = ~1 Hz
Inertial Sensor

CPS
Displacement Sensor

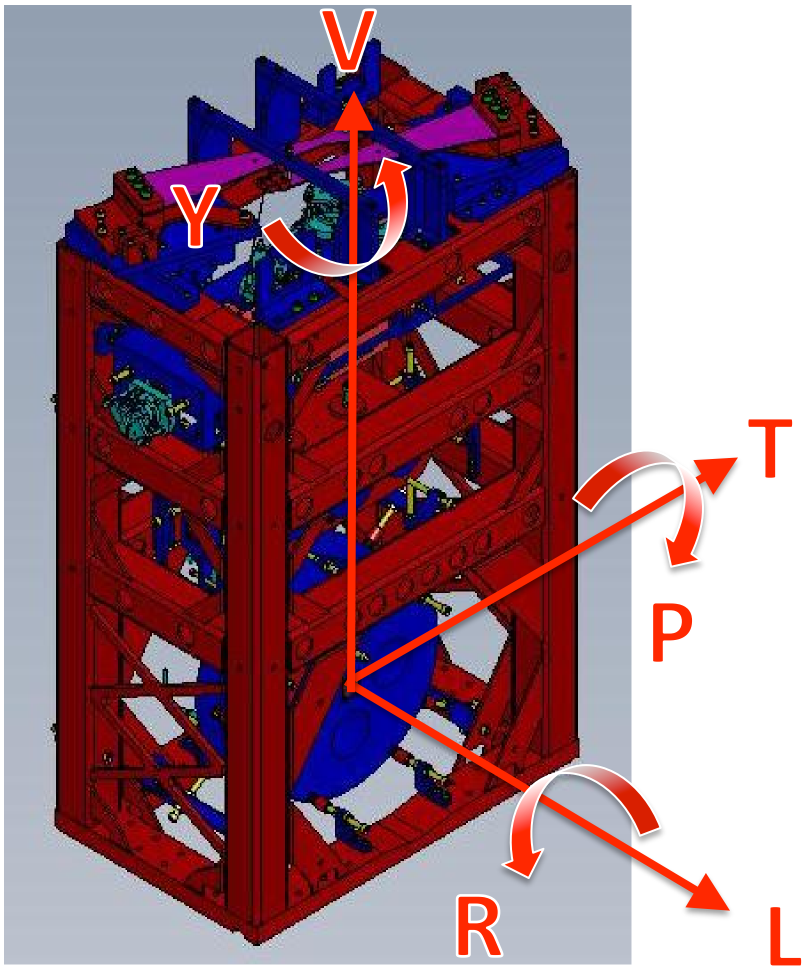


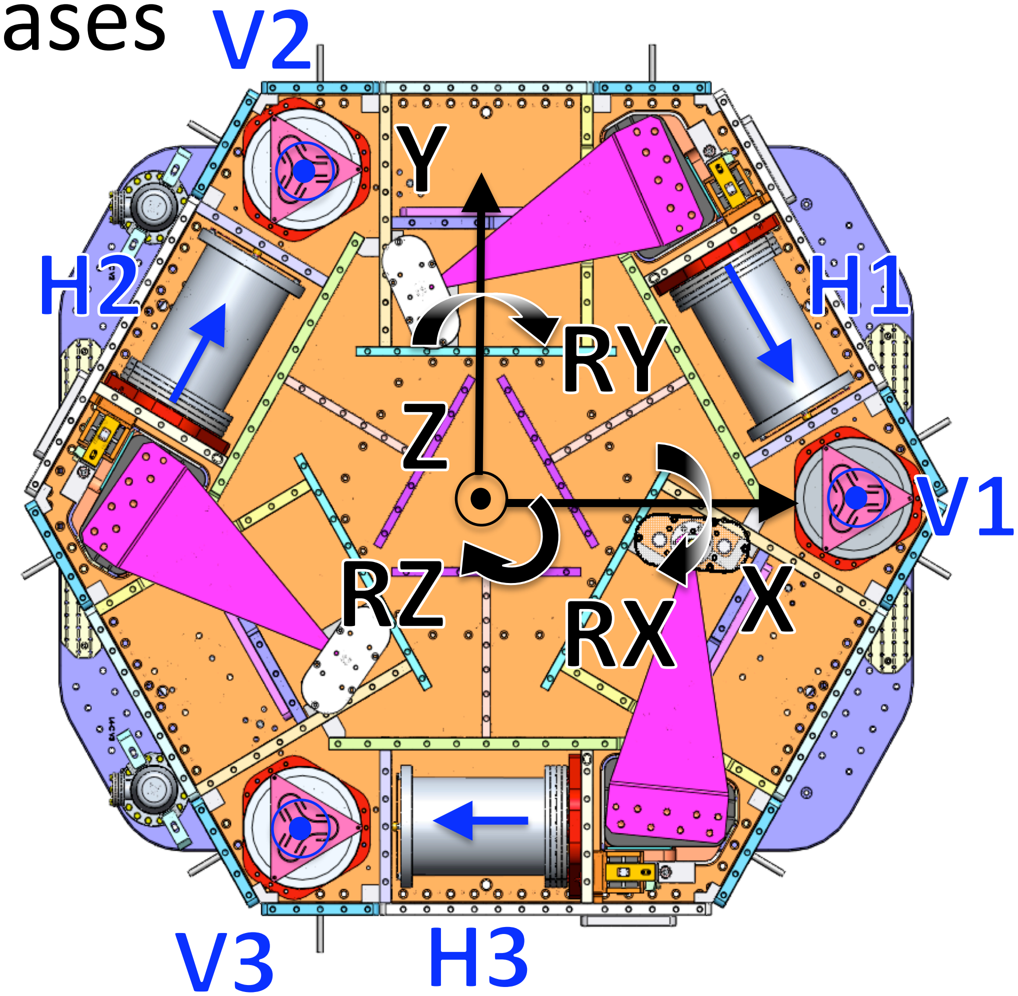
One corner's ST0-1 and ST1-2 position sensors and actuators



ACT
Electromagnetic Actuators

Colocated vs. Euler vs. Cartesian Bases

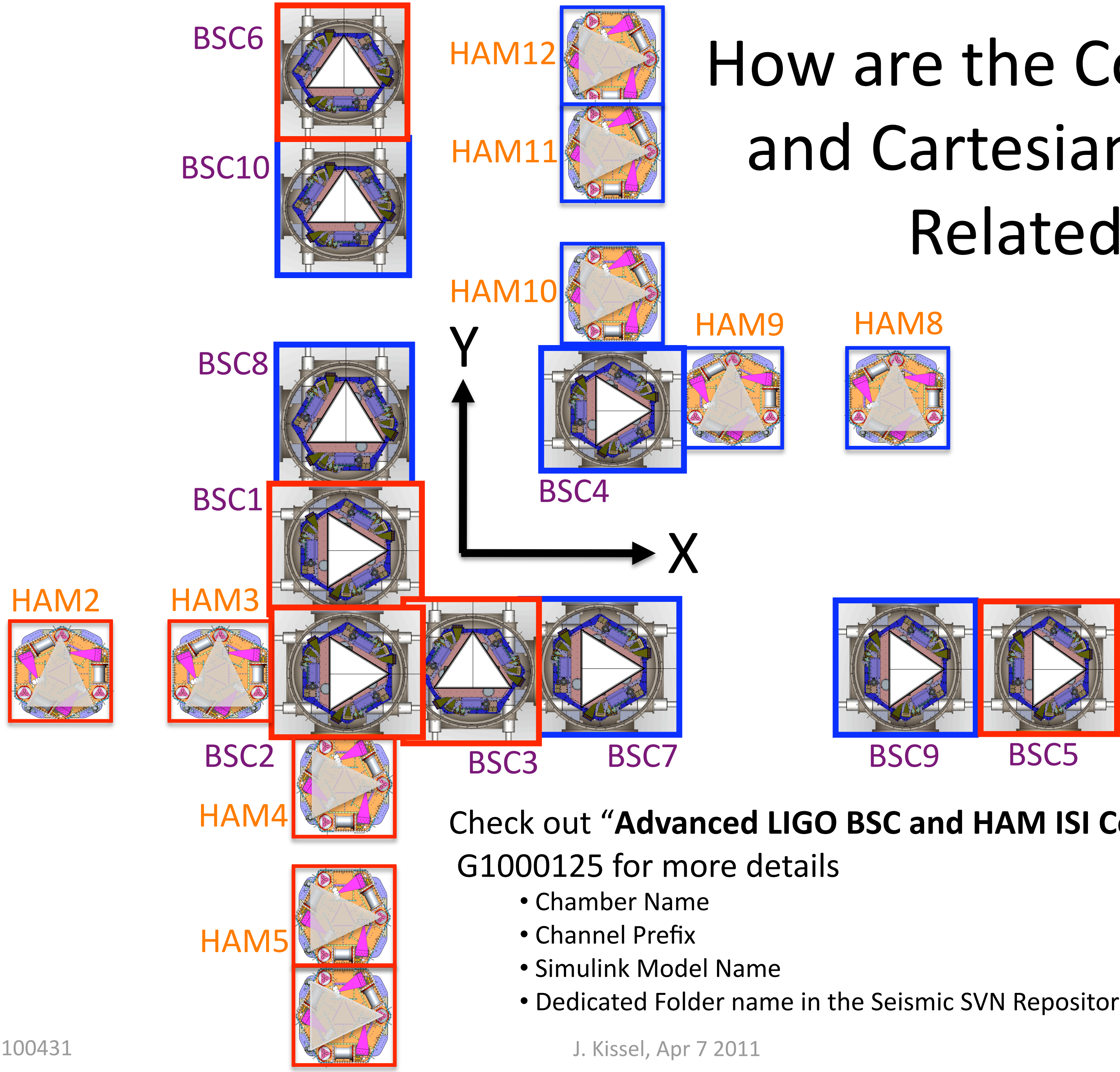




Aligned with the Sensors
Aligned with the Beam
Aligned with the IFO arms

H1, H2, H3, V1, V2, V3
Longitudinal, **T**ransverse, **V**ertical,**R**oll, **P**itch, **Y**aw
X, Y, RZ, RX, RY, Z

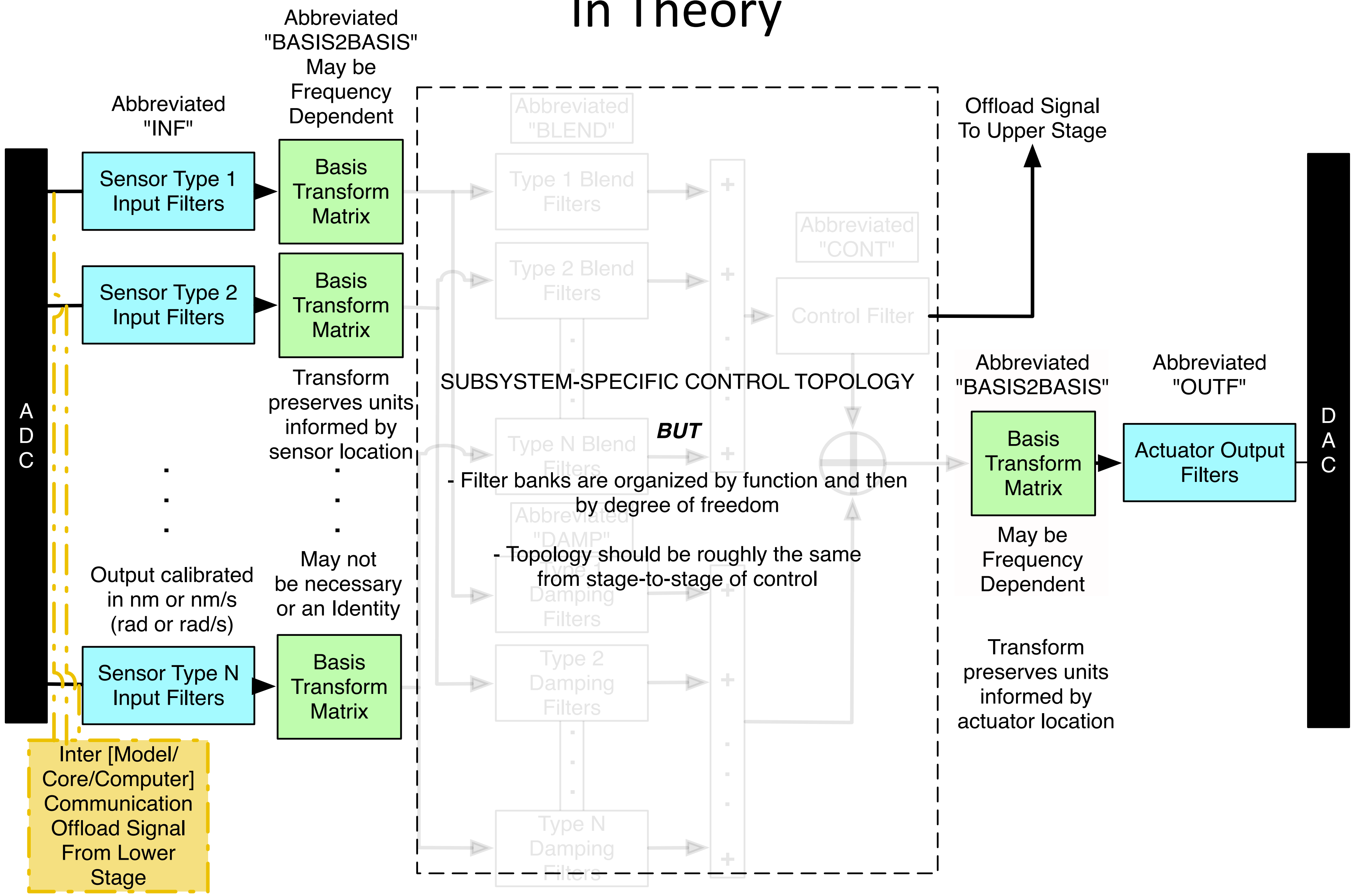
How are the Colocated and Cartesian Bases Related?



Check out "**Advanced LIGO BSC and HAM ISI Conventions**" G1000125 for more details

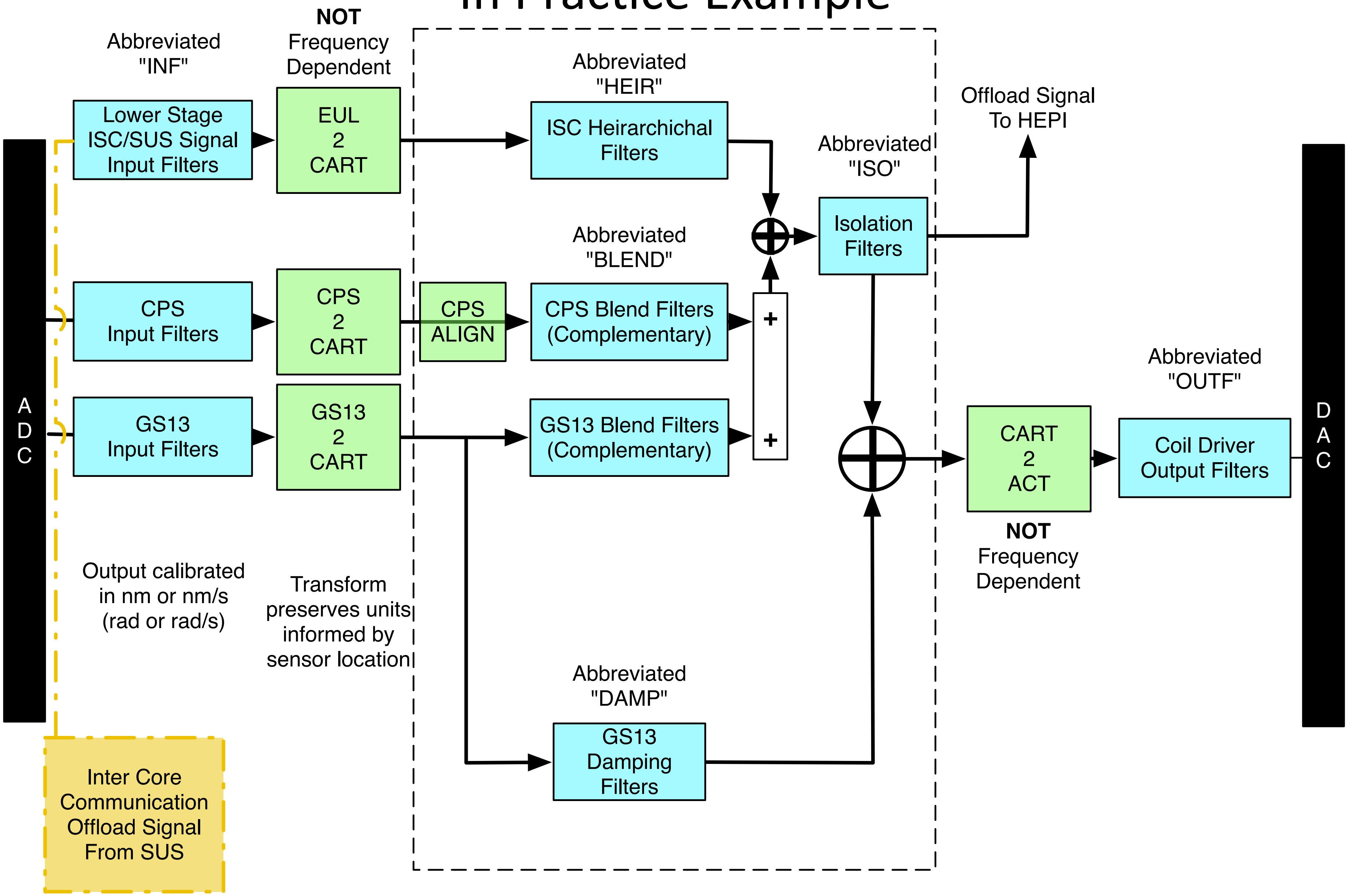
- Chamber Name
- Channel Prefix
- Simulink Model Name
- Dedicated Folder name in the Seismic SVN Repository

Each Stage of Isolation
In Theory

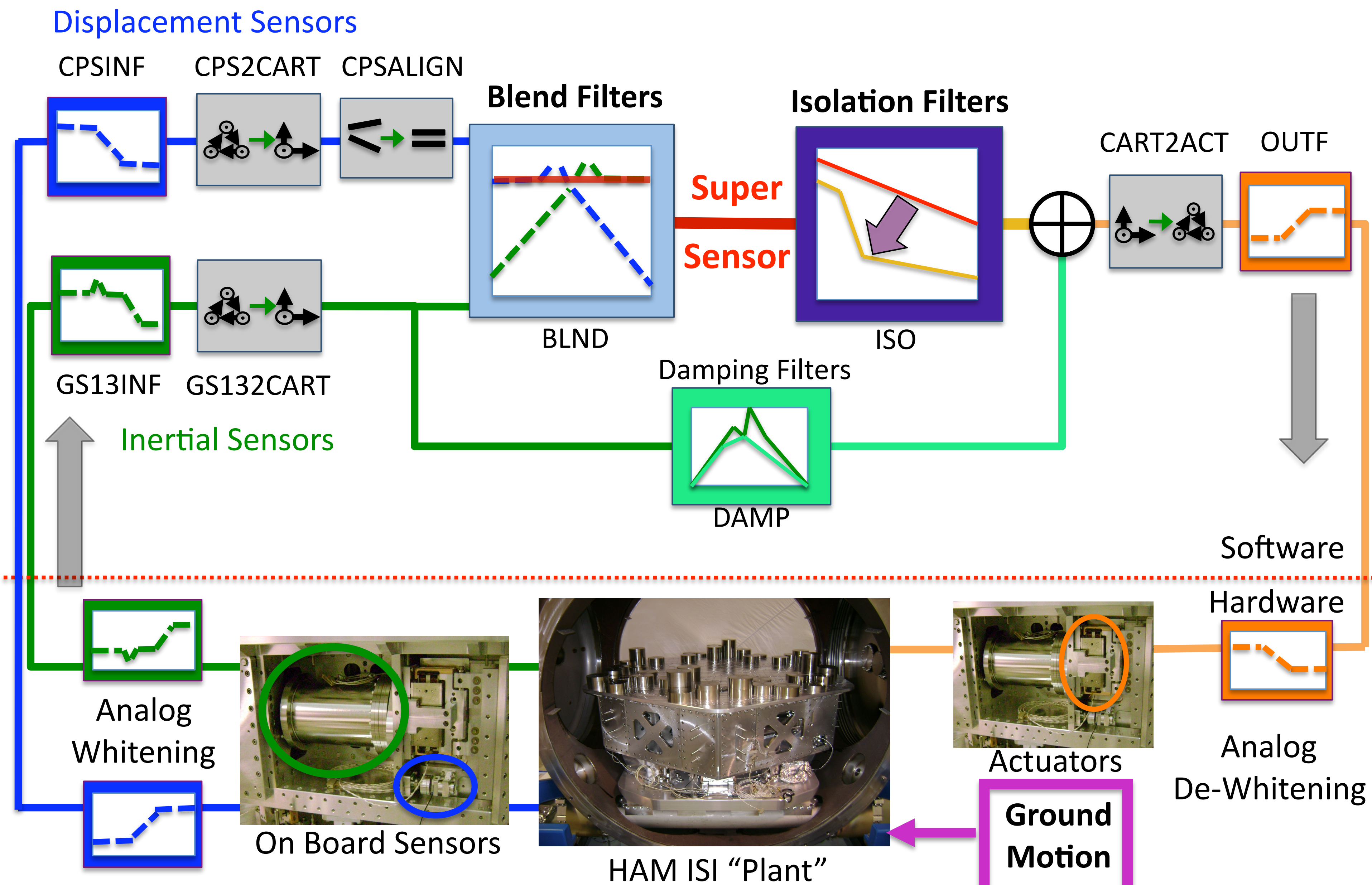


Each Stage of Isolation

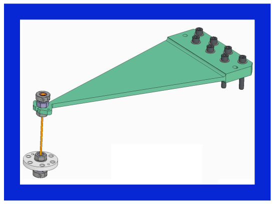
In Practice Example

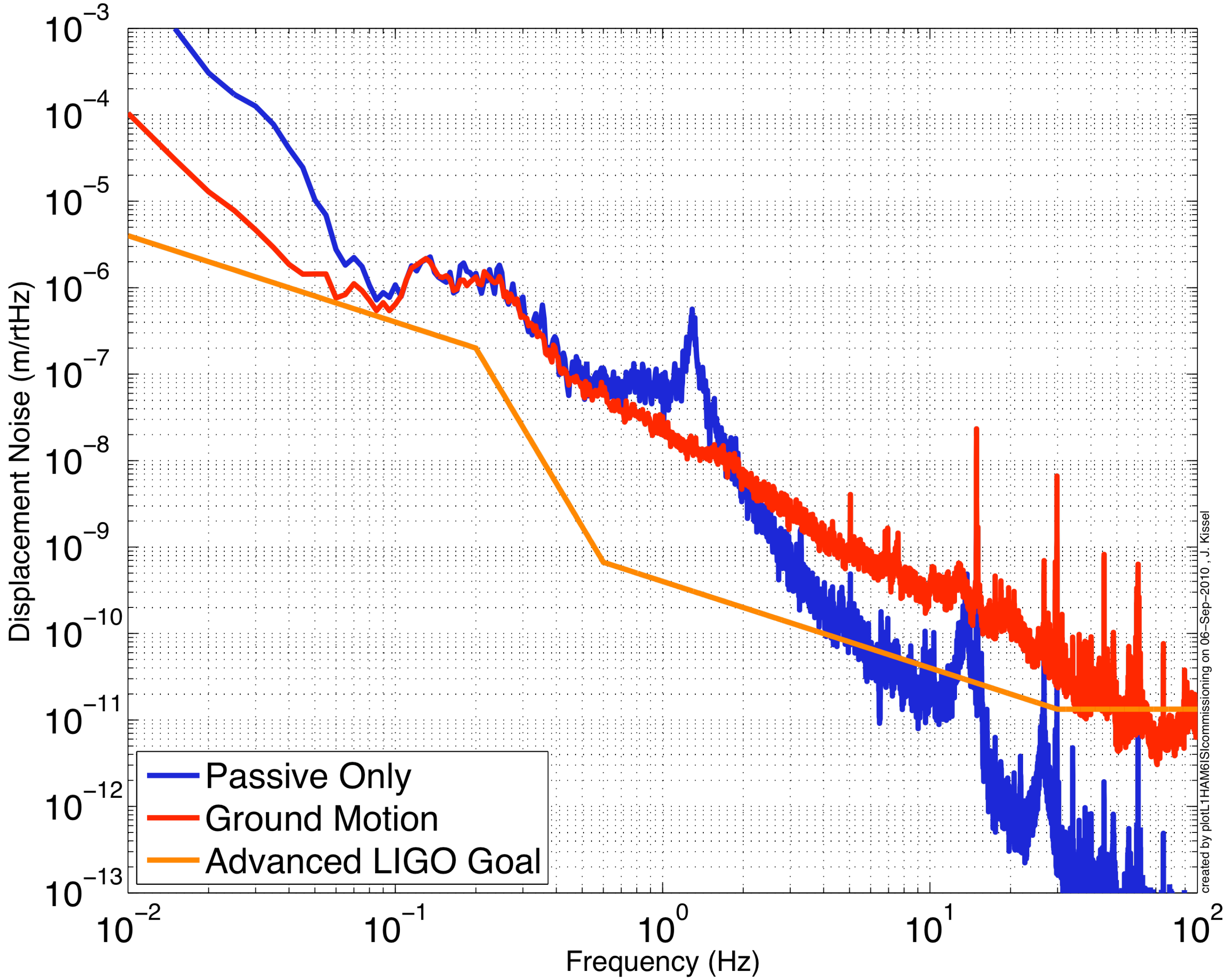


Active Isolation – The Basic Control Loop

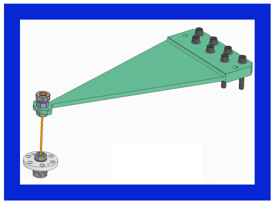


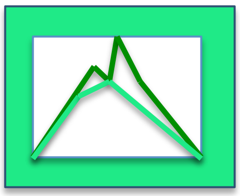
Active Isolation – Successive Loop Closure

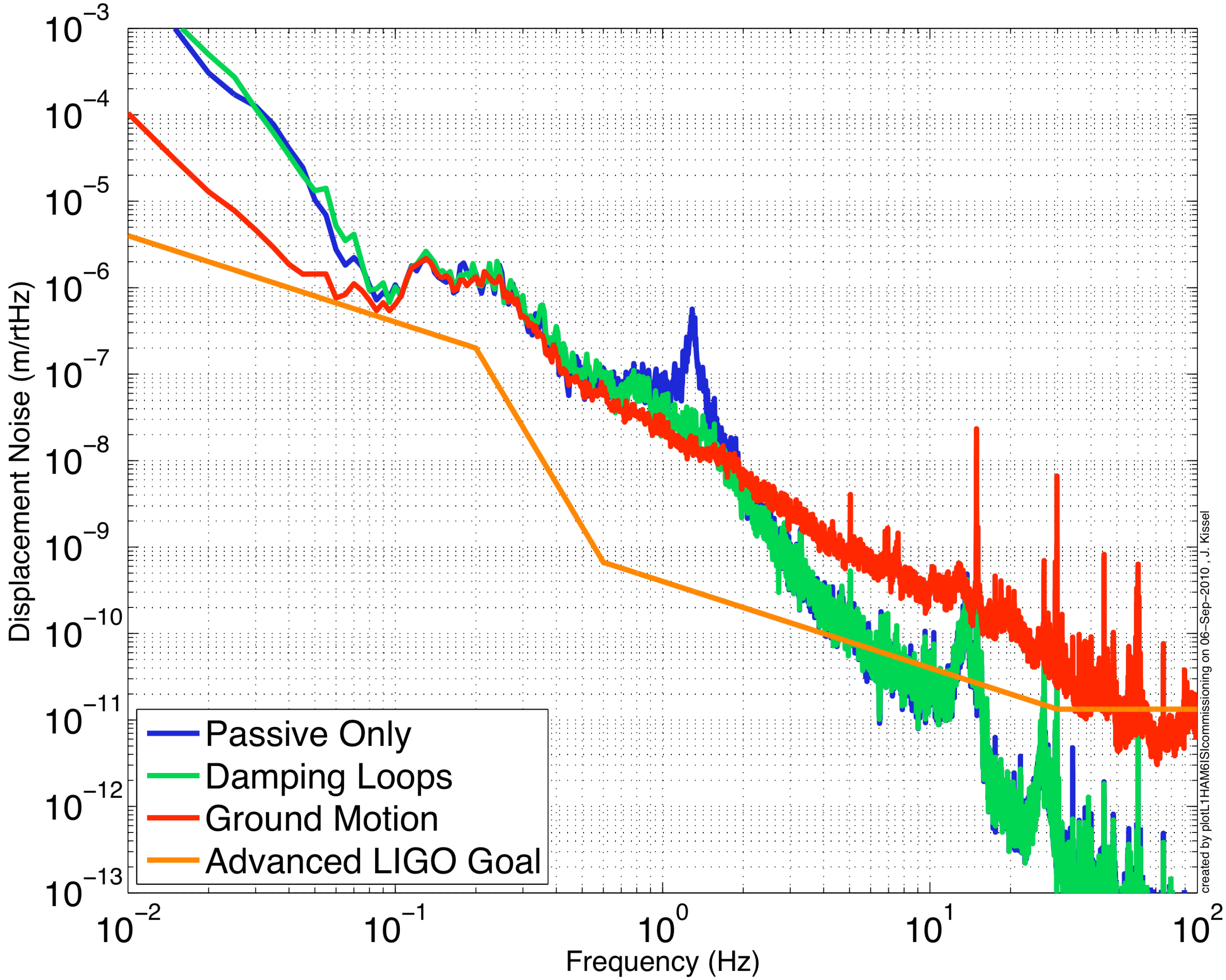




Active Isolation – Successive Loop Closure







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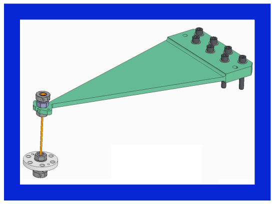
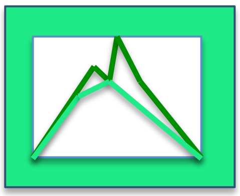
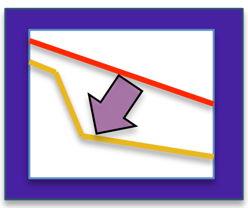
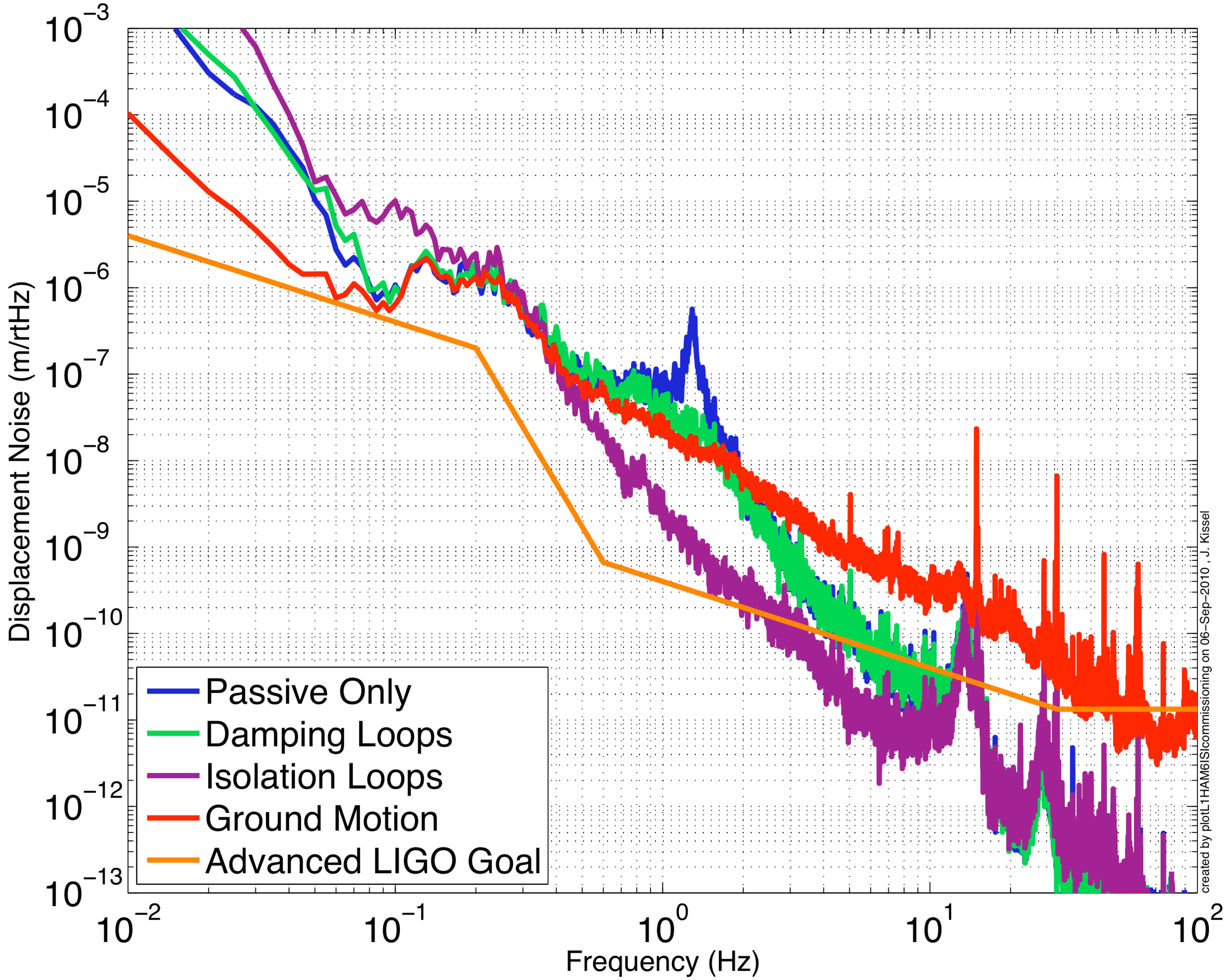
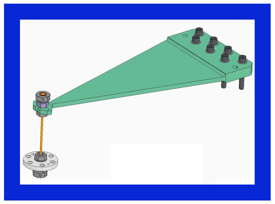


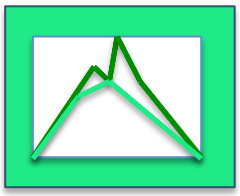


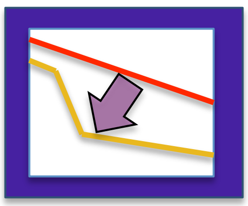


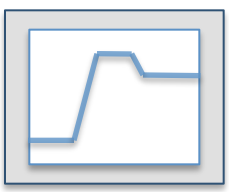


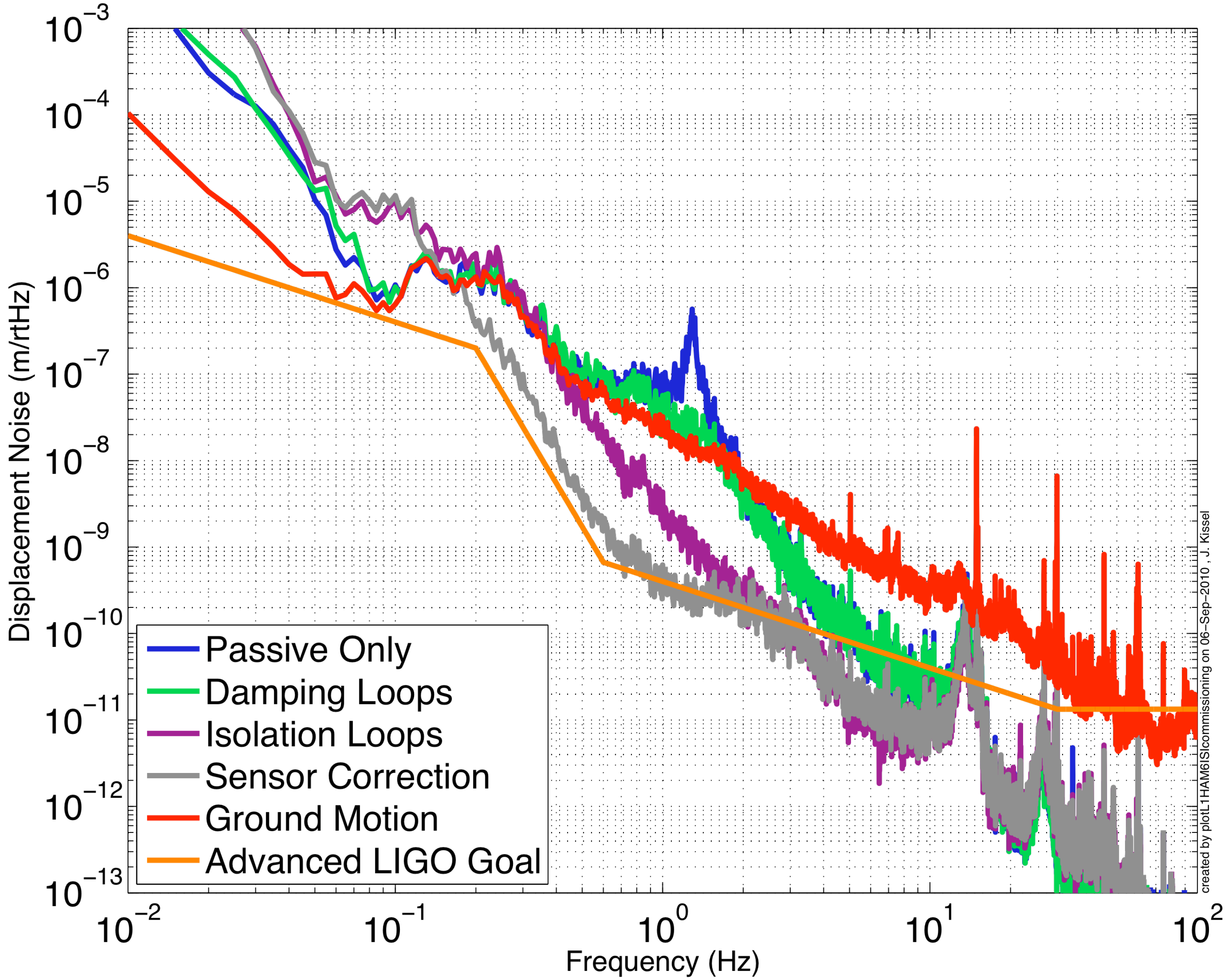
Active Isolation – Successive Loop Closure



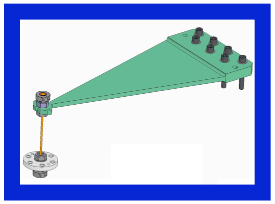


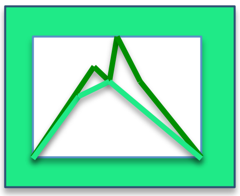


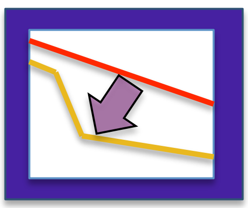


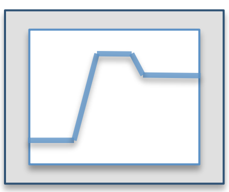


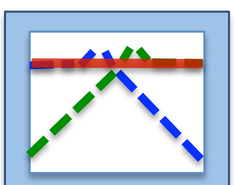
Active Isolation – Successive Loop Closure

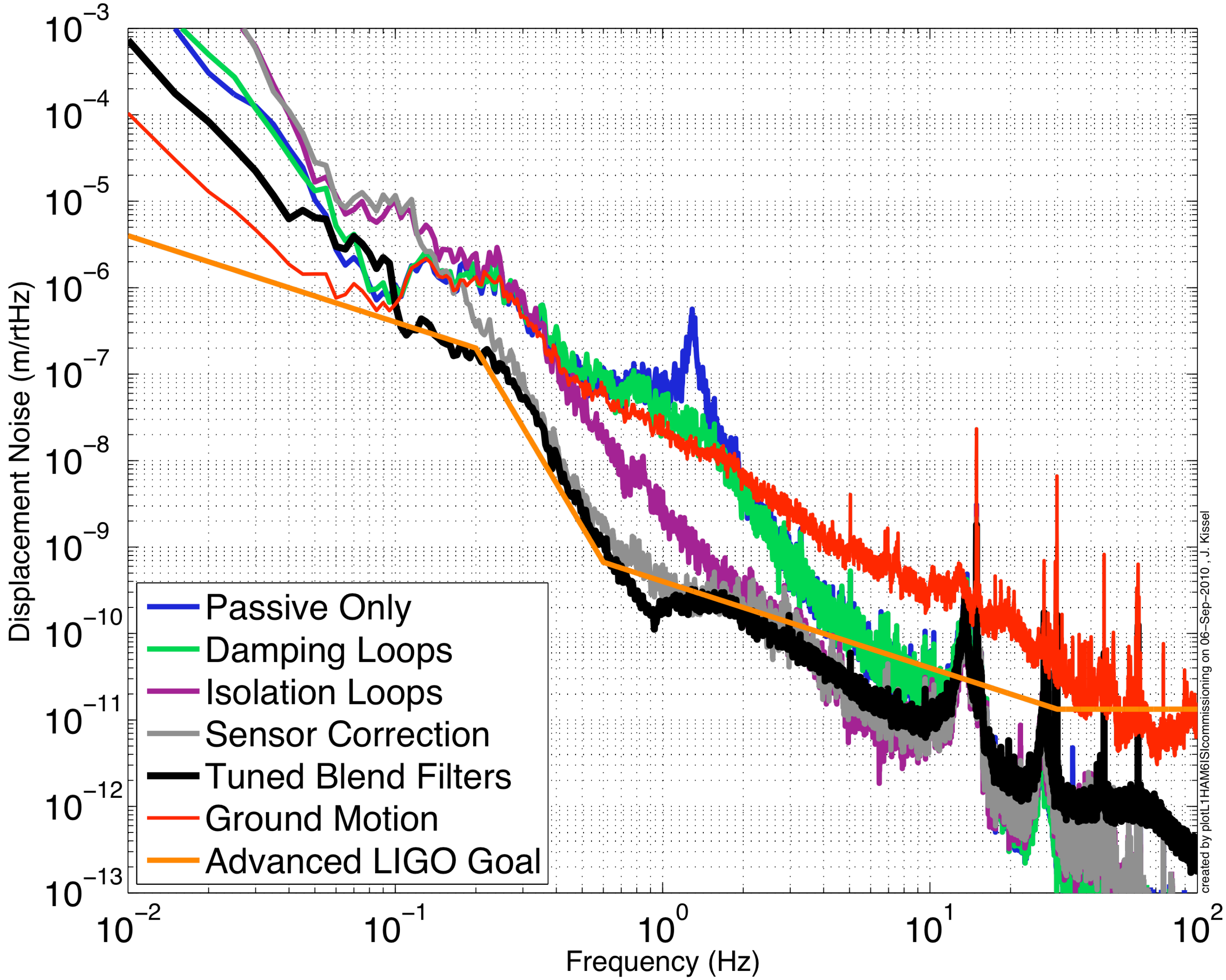












Who to bug when you're confused

- Brian Lantz – Lead Scientist for all SEI (Stanford)
  BLantz@stanford.edu
- Fabrice Matichard – Lead Mechanical Engineer (MIT)
  fabrice@ligo.mit.edu
- Ken Mason – Lead Mechanical Engineer (MIT)
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- Jeff Kissel – Post-Doc (MIT)
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- Celine Ramet – Engineer (LLO)
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- Vincent Lhuillier – Engineer (LHO)
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- Ben Abbott – Engineer (CalTech)
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What you can do to help

Some Ideas…

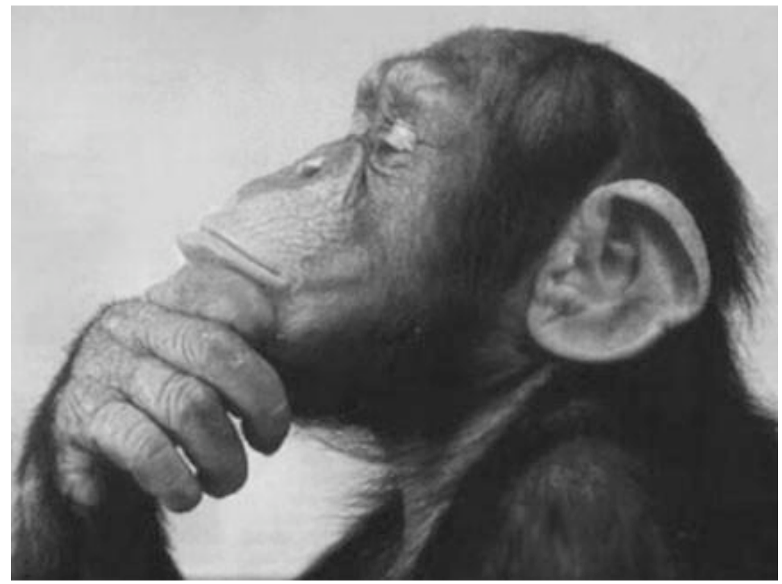
- Gather information on how the ground motion and platforms behave over month/year timescales
- Generalize eLIGO HAM6ISI NoiseBudget for all aLIGO Seismic Platforms
- Study platform glitchy-ness by implementing an OmegaGram on in-loop channels
- Help us write some general-user software (especially if you like perl!)
- Gather long term info on pod pressure

Just ask! Suggestions welcome!

What Channels Matter to You

Things you should ask yourself before you look:

- Where is the sensor?
- Is the “sensor” composed of many sensors?
- Is it an in-loop sensor?
- At what frequency can I trust this sensor?
- Is it calibrated into physical units?
    - If yes – over what frequency range to I trust the calibration?
    - If no – what is the calibration?



What Channels Matter to You

Channels will have the following basic naming convention:

[IFO]:[Sub-system]-[Chamber/Optic]-[Isolation Stage]-[Filter Bank Function]-[Degree of Freedom]-[Standard Extension]

[IFO] = H1, H2, or L1

[Sub-system] = ISI for BSC-ISI and HAM-ISI, SEI for HEPI

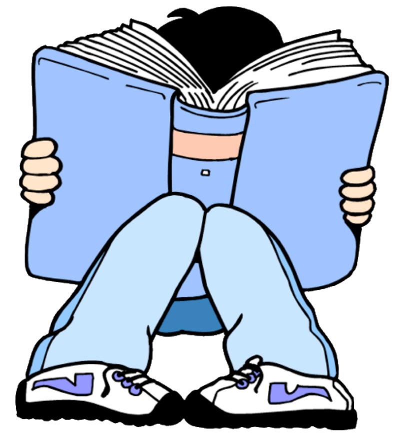
[Chamber/Optic] = For HAM Chambers, always by chamber; for BSC Chambers always by Core Optic

[Isolation Stage] = ST0, ST1, ST2 for Stage 0, Stage 1, and Stage 2 (May not exist for HEPI and HAM-ISIs which only have one stage of isolation)

[Degree of Freedom] = Colocated basis: H1, H2, H3, H4, V1, V2, V3, V4
Cartesian basis: X, Y, RZ, RX, RY, Z
Euler Basis: L, T, V, R, P, Y

[Standard Extensions] = IN1_DAQ, IN2_DAQ, OUT_DAQ

Some Good Reading Material



- Brian’s NSF Review <G0900312>
- Brian’s “Simple Platform” Calculation <T080119>
- Brian’s Sensor Noise Document <T0900450>
- Brian’s Tilt Paper <P080073>
- Jeff/Fabrice’s ISI Orientation Drawings <G1000125>
- Jeff’s Electronics Cartoon <D1001575>
- Ben’s Electronics Schematics
- Fabrice’s BSC-ISI Prototype Paper <P1000029>
- Fabrice’s BSC-ISI FDR Presentation <G0901006>
- Lantz’s HAM ISI Training <G0900421>
- Jeff’s Thesis (Chaps 4 and 5) <P1000103>
- Shyang’s Thesis <P0900021>
- Corwin’s Thesis <T020047>