System Identification for LIGO Seismic Isolation

Brett Shapiro

GWADW – 19 May 2015

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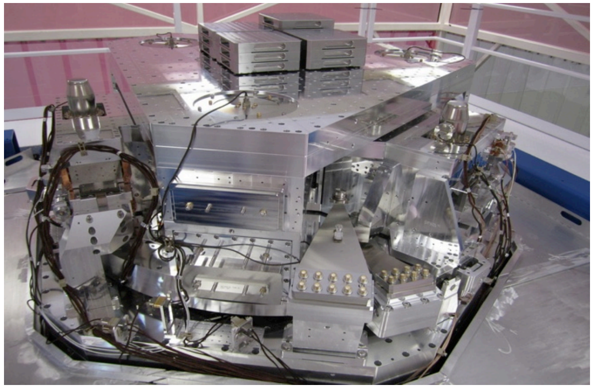
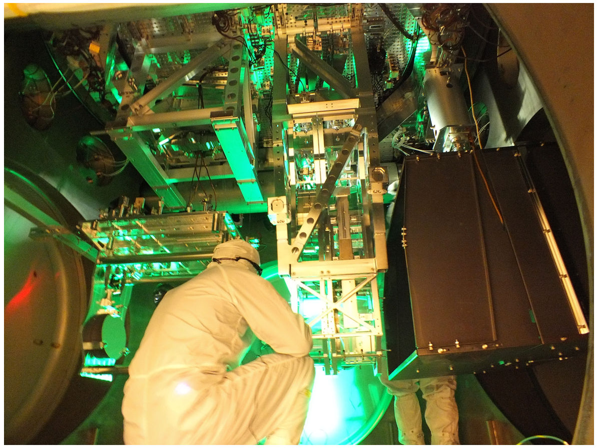
- Internal Seismic Isolation (ISI)
  - Measurements
  - Modeling

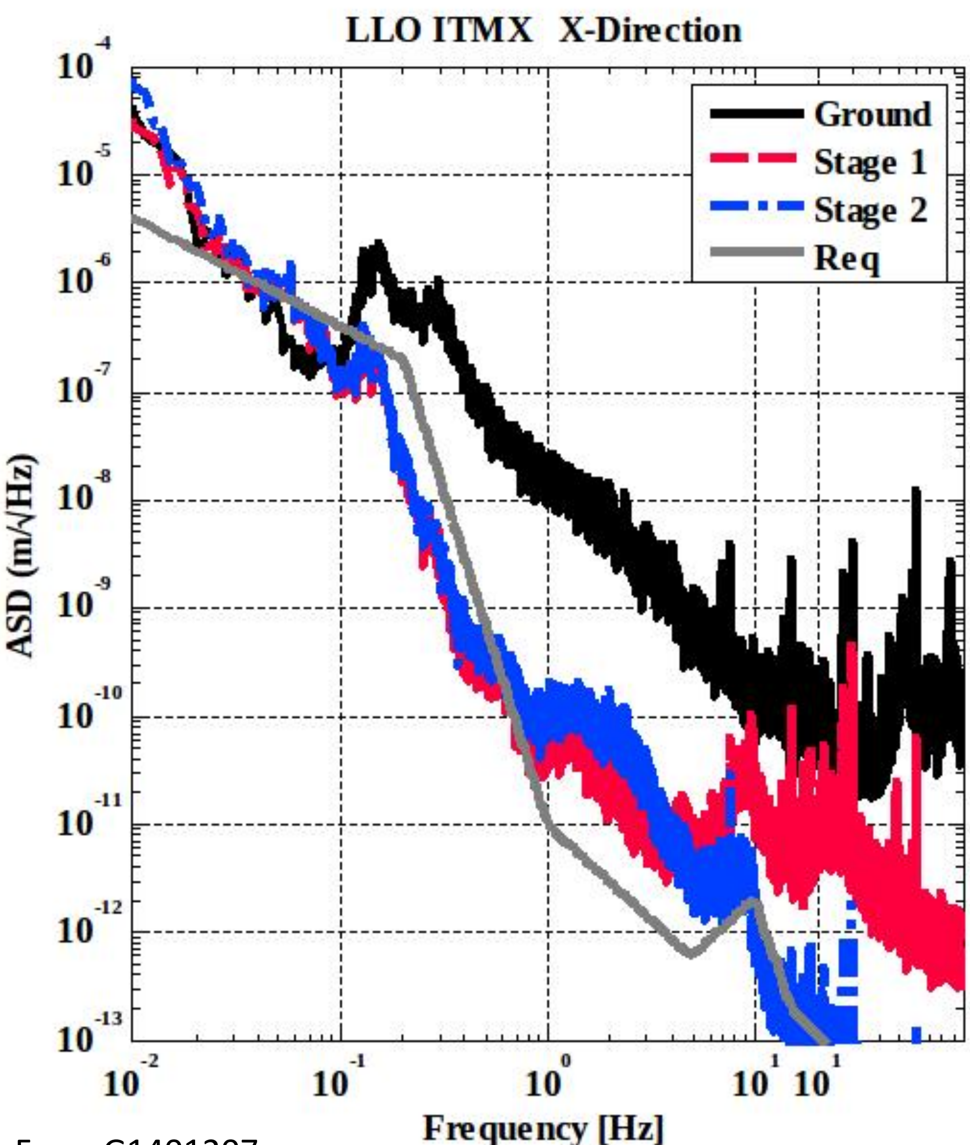


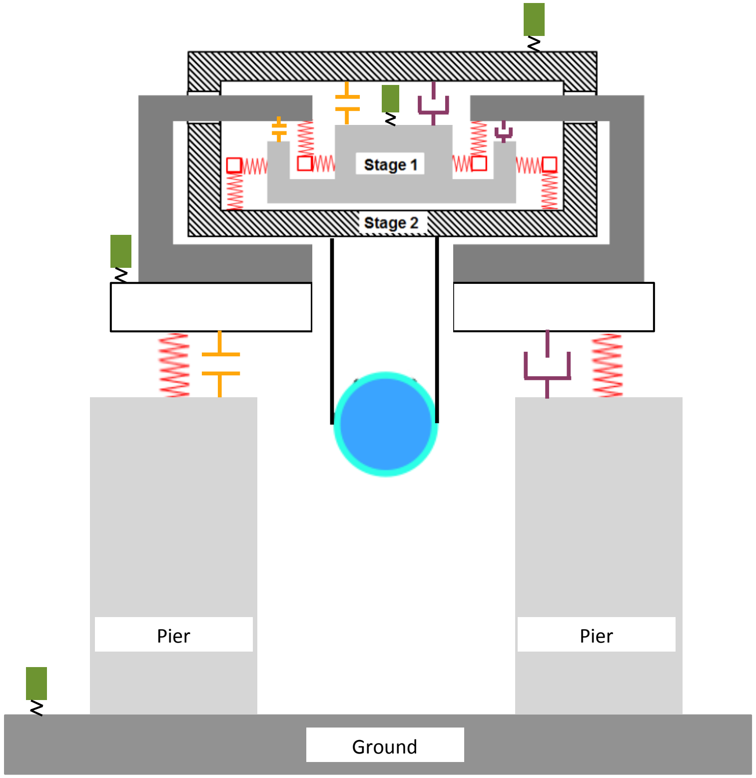
- Suspensions
  - Measurements
  - Modeling

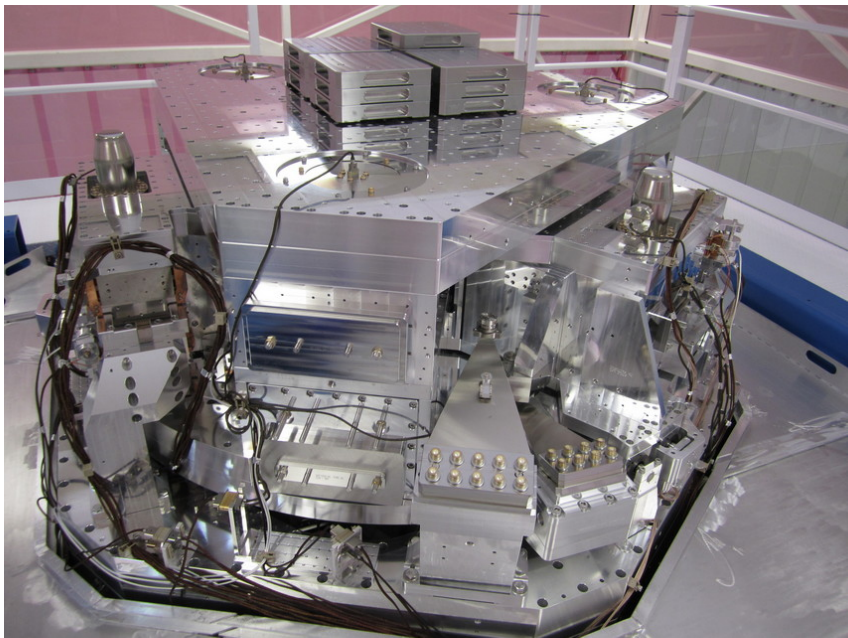


Internal Seismic Isolation (ISI)

BSC chamber (core optics) configuration and performance

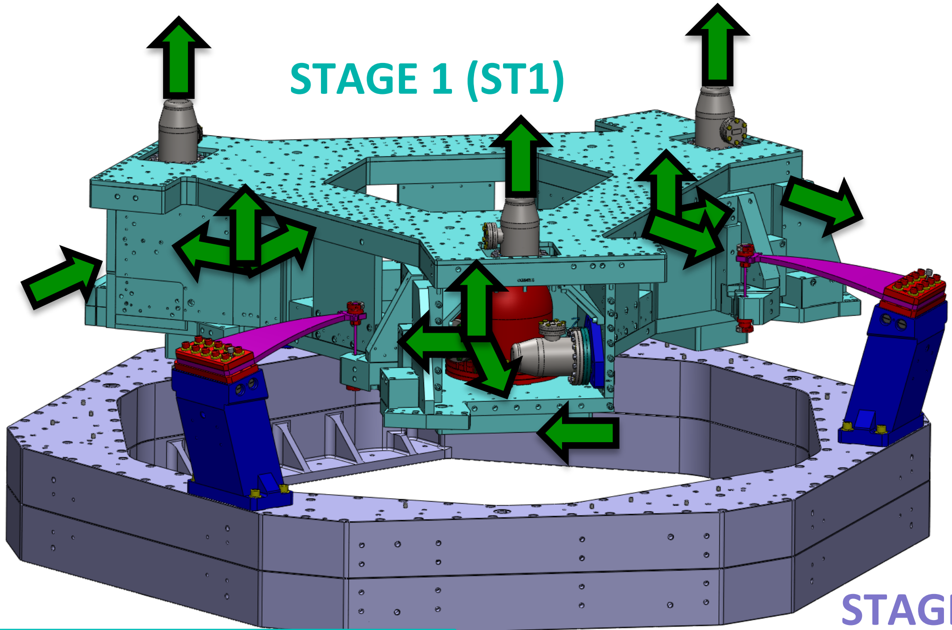


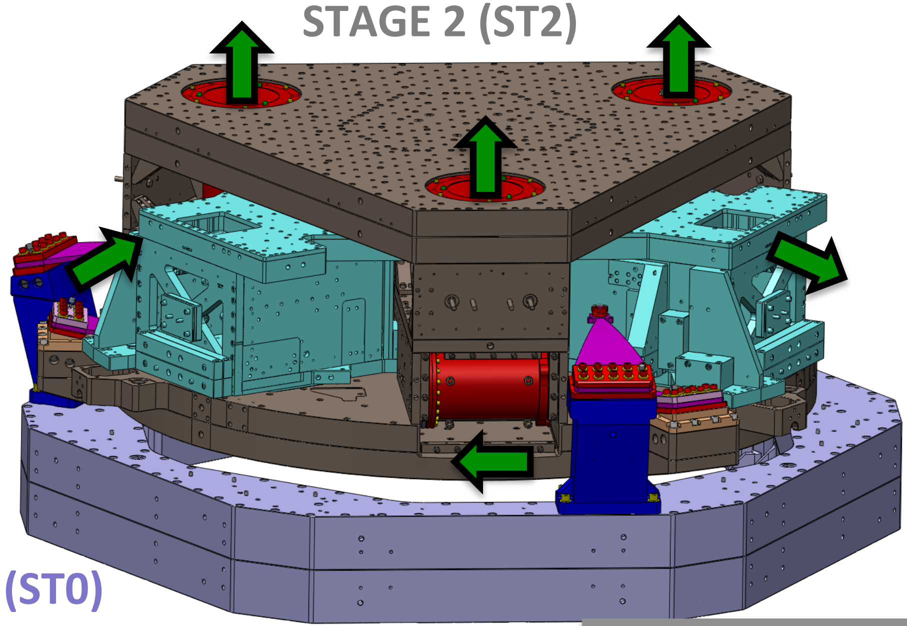




From G1401207

Where stuff is on a BSC-ISI





STAGE 0 (ST0)

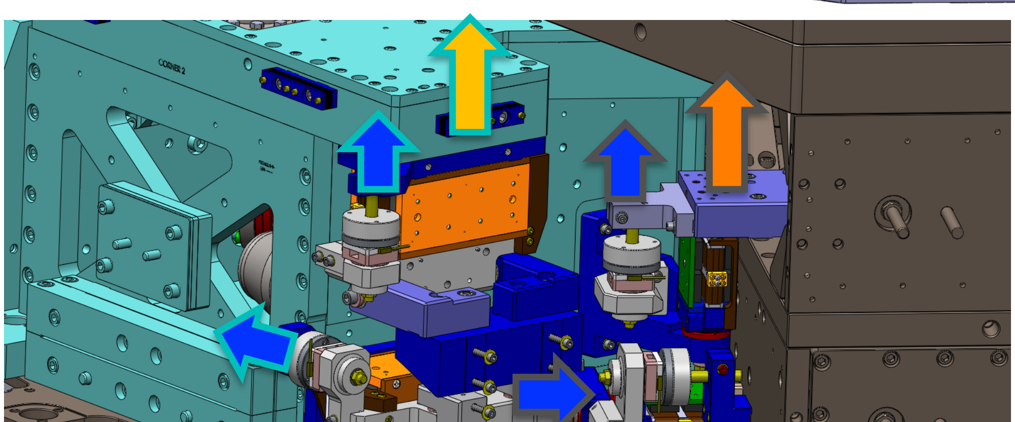
L4C

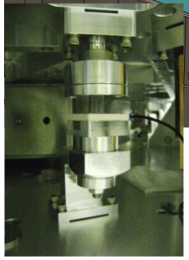
f = ~1 Hz

T240

f = ~5 mHz

Inertial Sensors

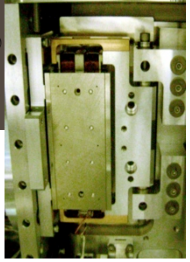




CPS

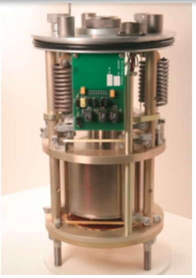
Displacement Sensor

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



ACT

Electromagnetic Actuators

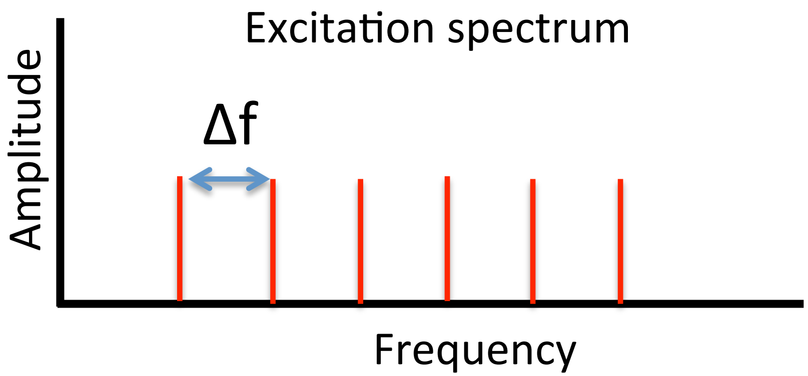


GS13

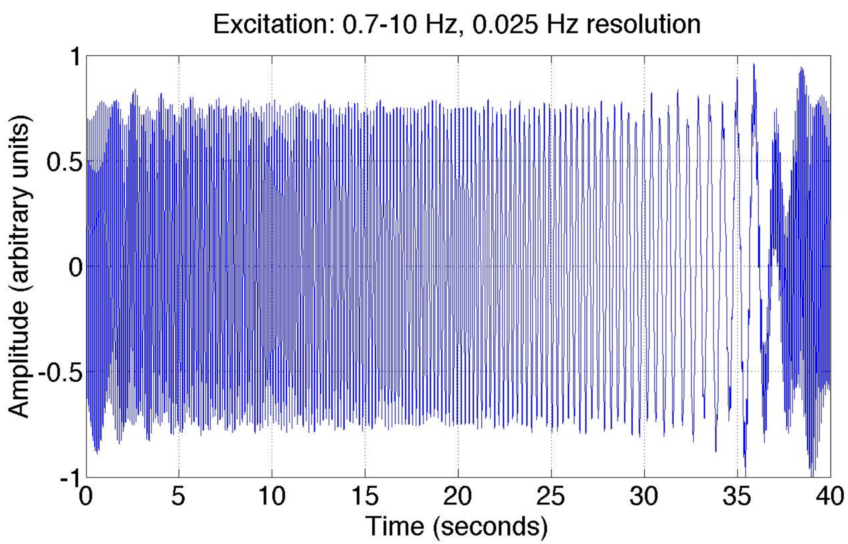
f = ~1 Hz

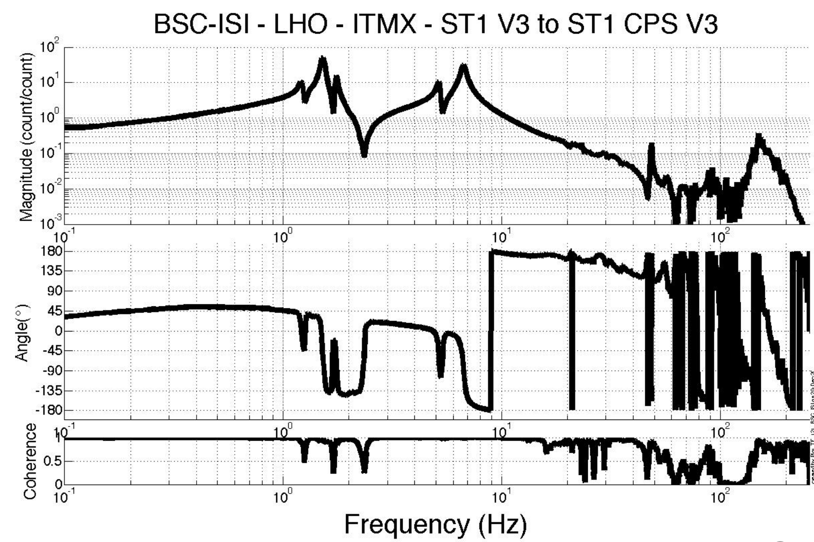
Inertial Sensor

Schroeder Phase TFs

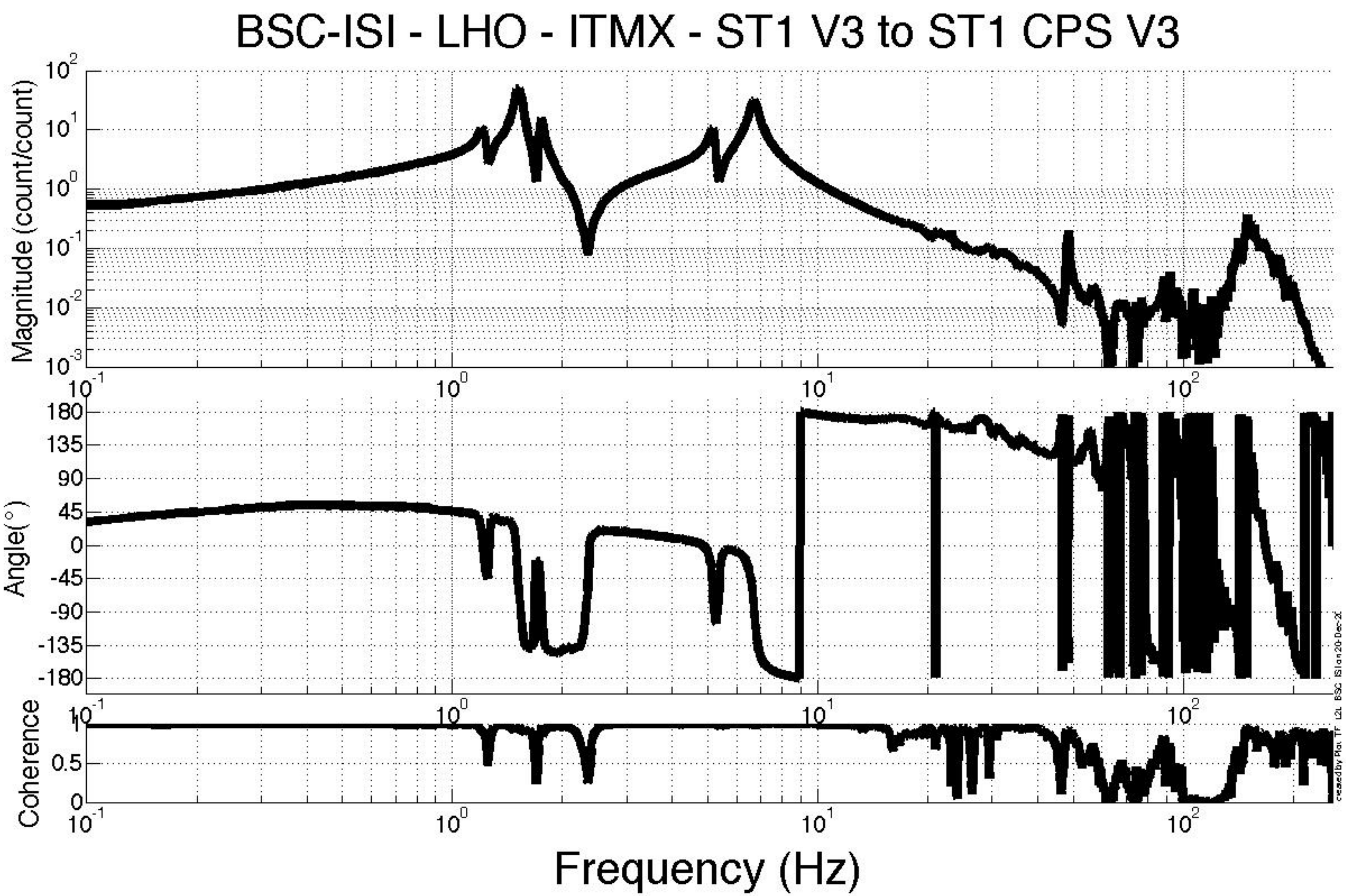


- The excitation consists of a frequency comb with a spacing of Δf
- The phase of each sine wave is set to minimize the largest excitation value
- All within MATLAB

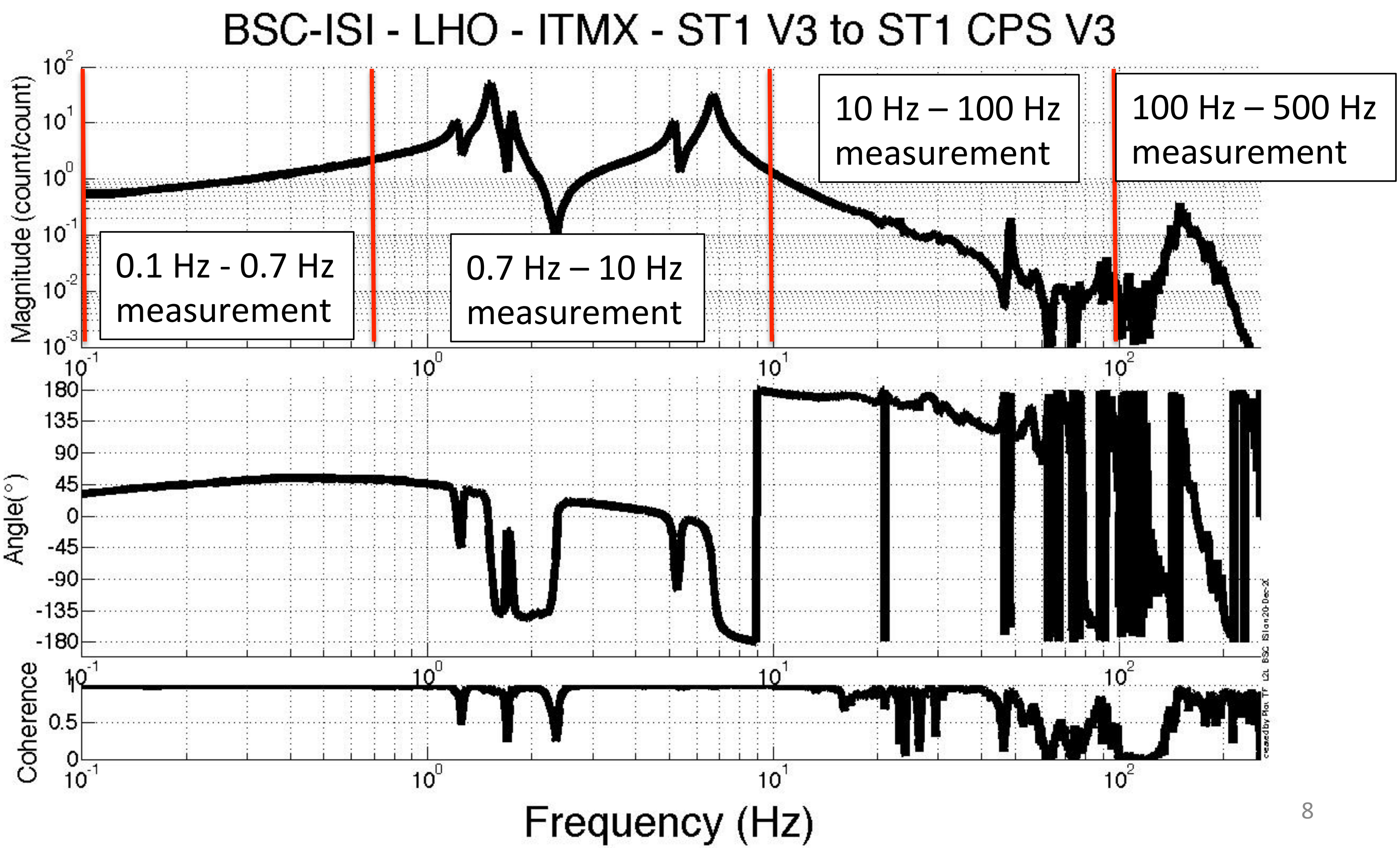




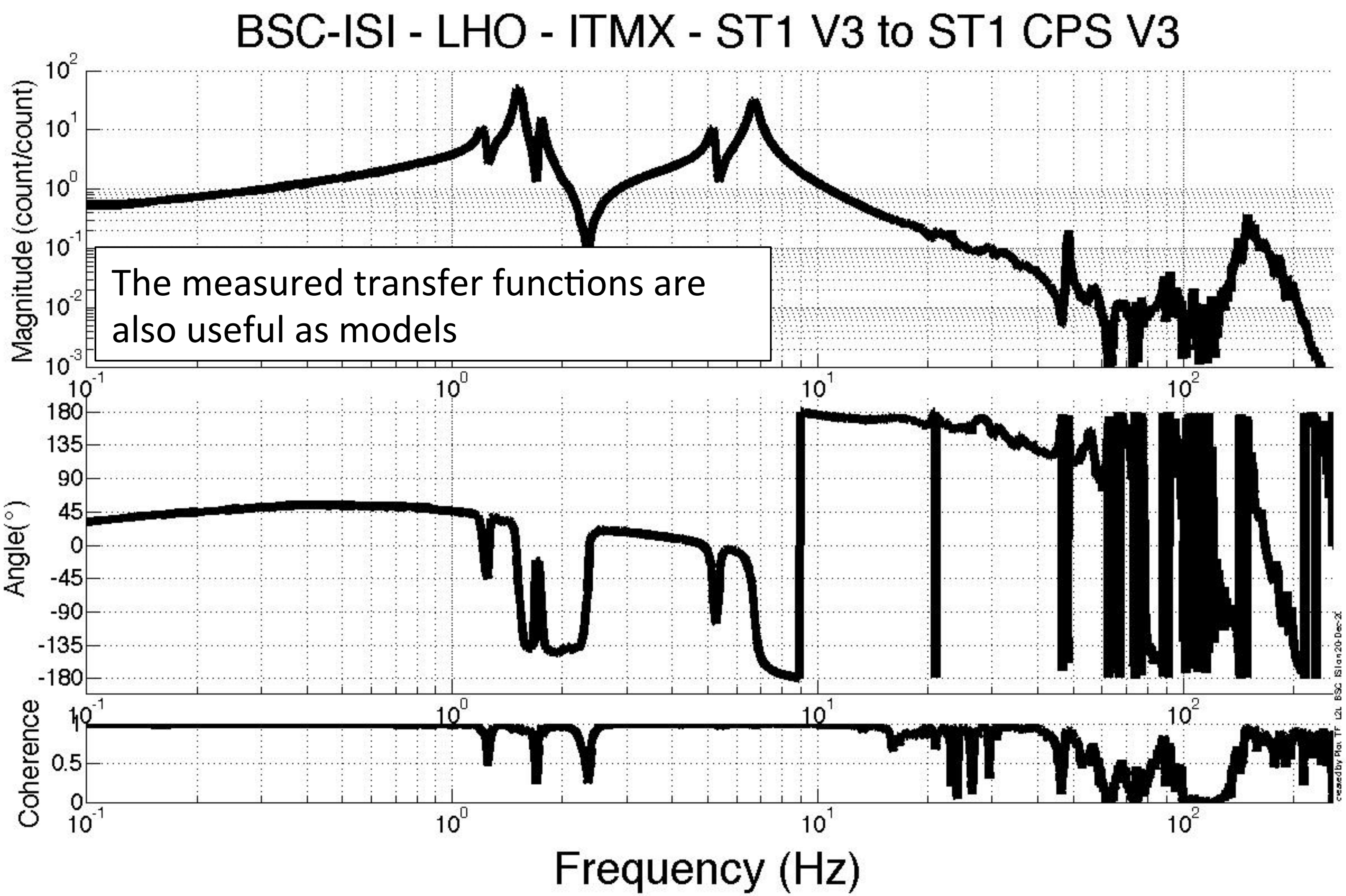
Example TF from BSC-ISI



Example TF from BSC-ISI

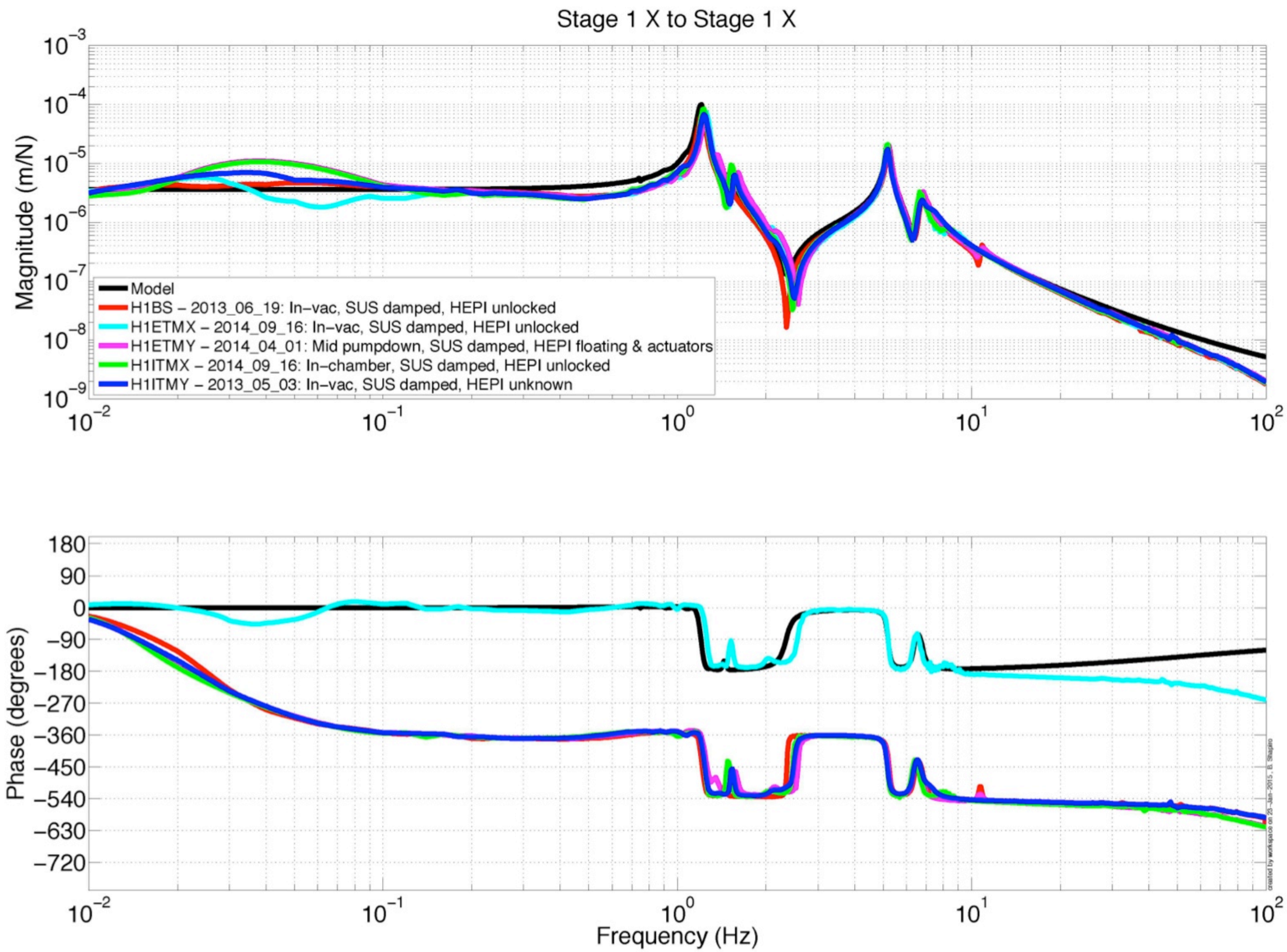


Example TF from BSC-ISI



The measured transfer functions are also useful as models

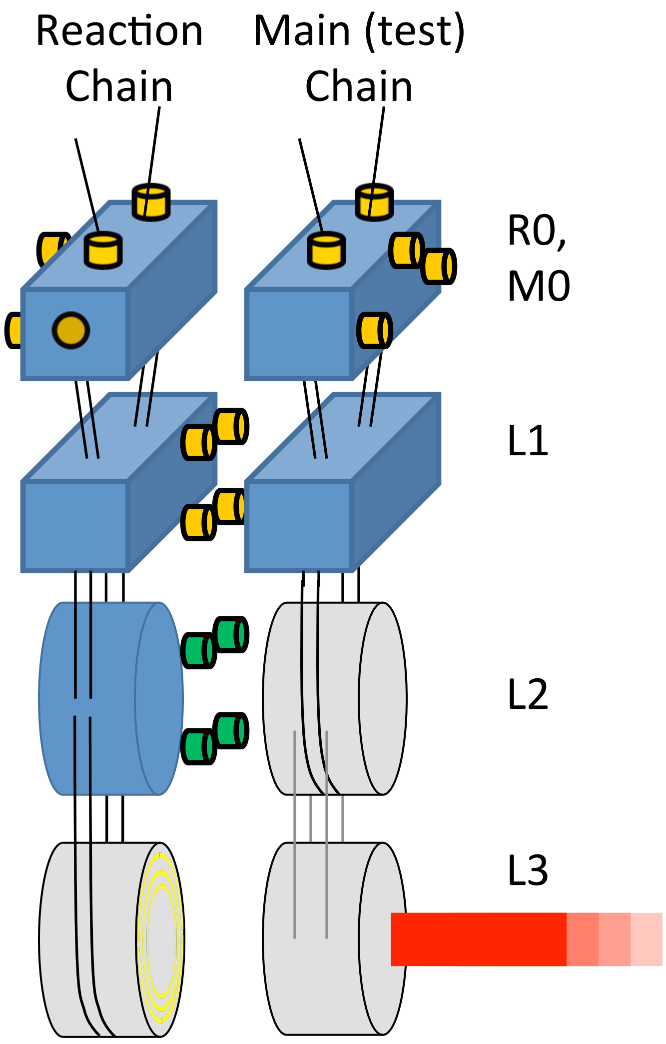
Model fit to Measurements



Fit using MATLAB's N4SID – frequency domain or time domain. Generates state space model.

Suspensions

Quadruple Suspension (Quad)



Purpose
- Input Test Mass (ITM, TCP)
- End Test Mass (ETM, ERM)

Location
- End Test Masses, Input Test Masses

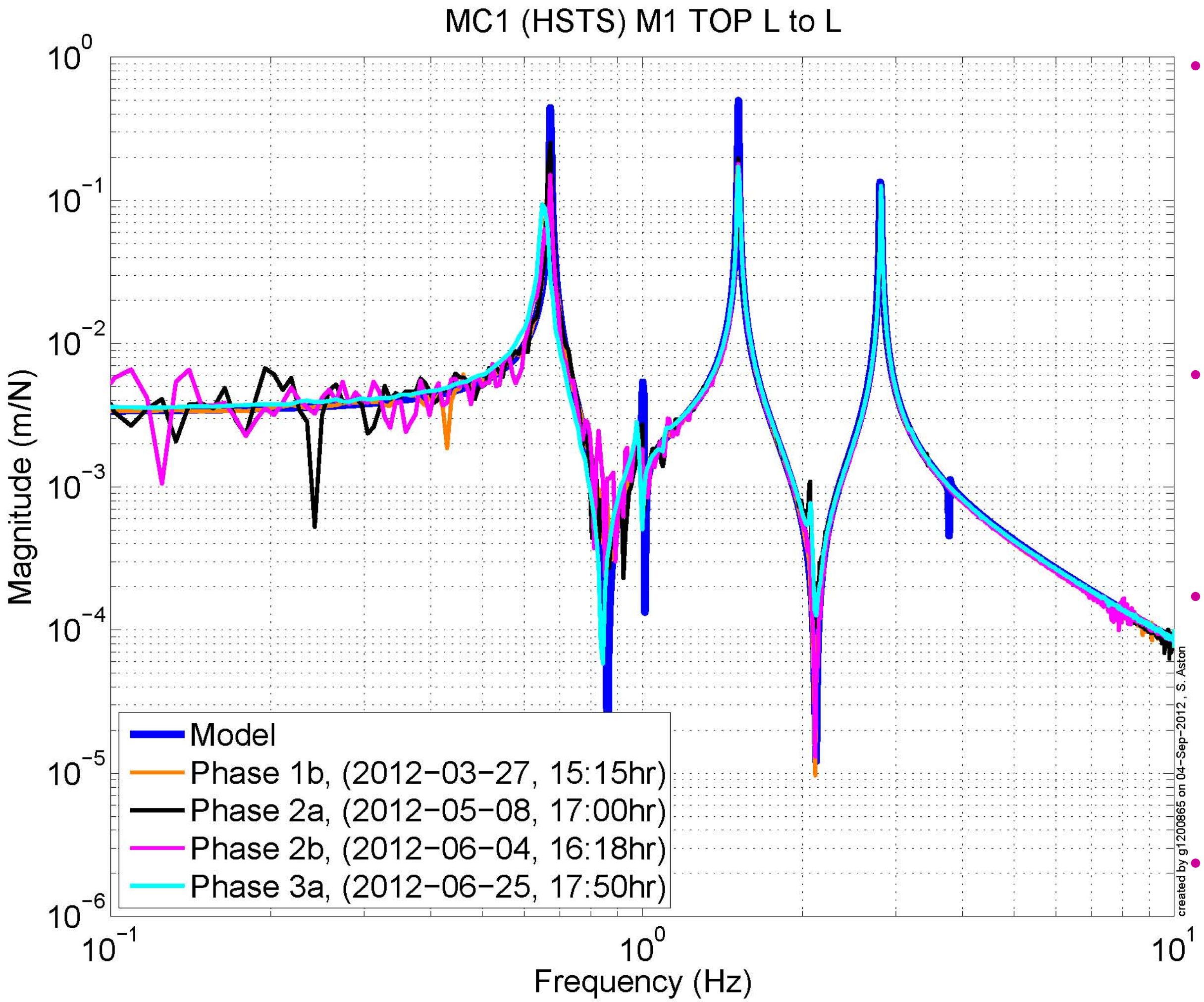
Control
- Local – damping at M0, R0
- Global – LSC & ASC at all 4

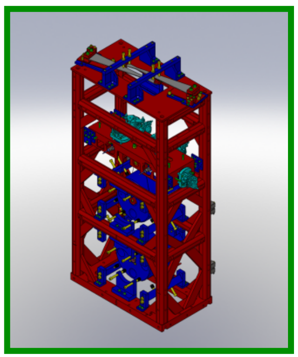
Sensors/Actuators
- (yellow) BOSEMs at M0, R0, L1
- (green) AOSEMs at L2
- Optical levers and interf. sigs. at L3
- Electrostatic drive (ESD) at L3

Documentation
- Final design review - T1000286
- Controls arrang. – E1000617

SUS Schroeder Phase Transfer Functions

- Consistent performance for suspensions between testing phases and sites



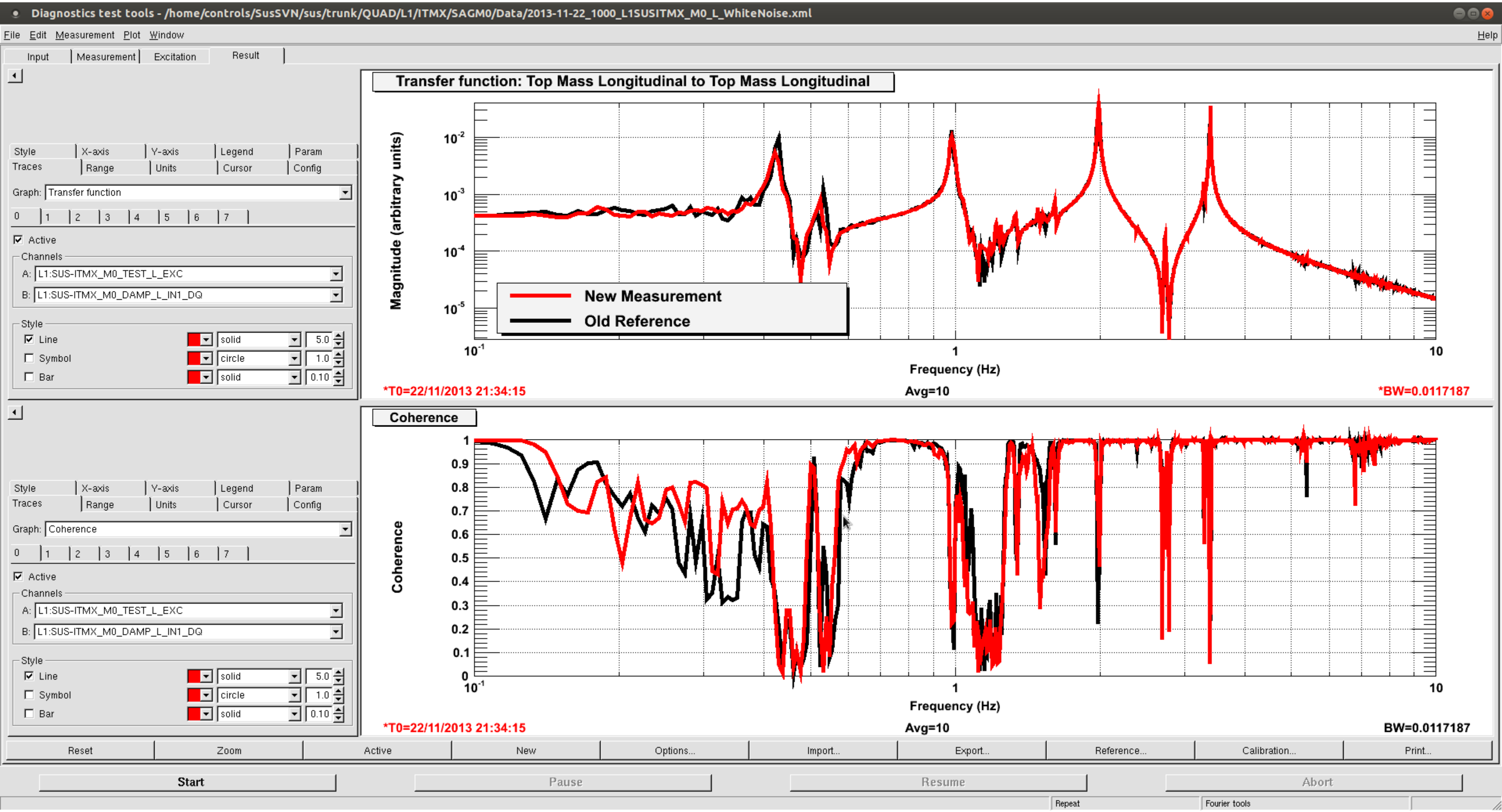


HSTS

- **Allows comparison of the "as-built" suspension resonances against an analytical model of the mechanics**
- **To give us confidence that the suspension works as designed**
- **Aiming for repeatability for suspensions throughout all Phases of testing**
- **Also want to maintain repeatability from site to site**

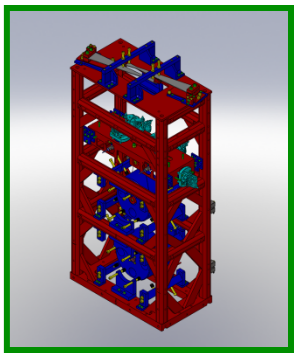
Ref - G1300132

SUS DTT White Noise Measurement

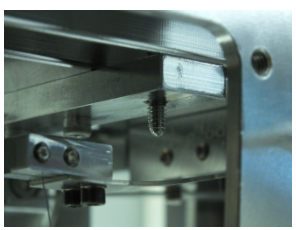


Testing - Transfer Functions Find Bugs

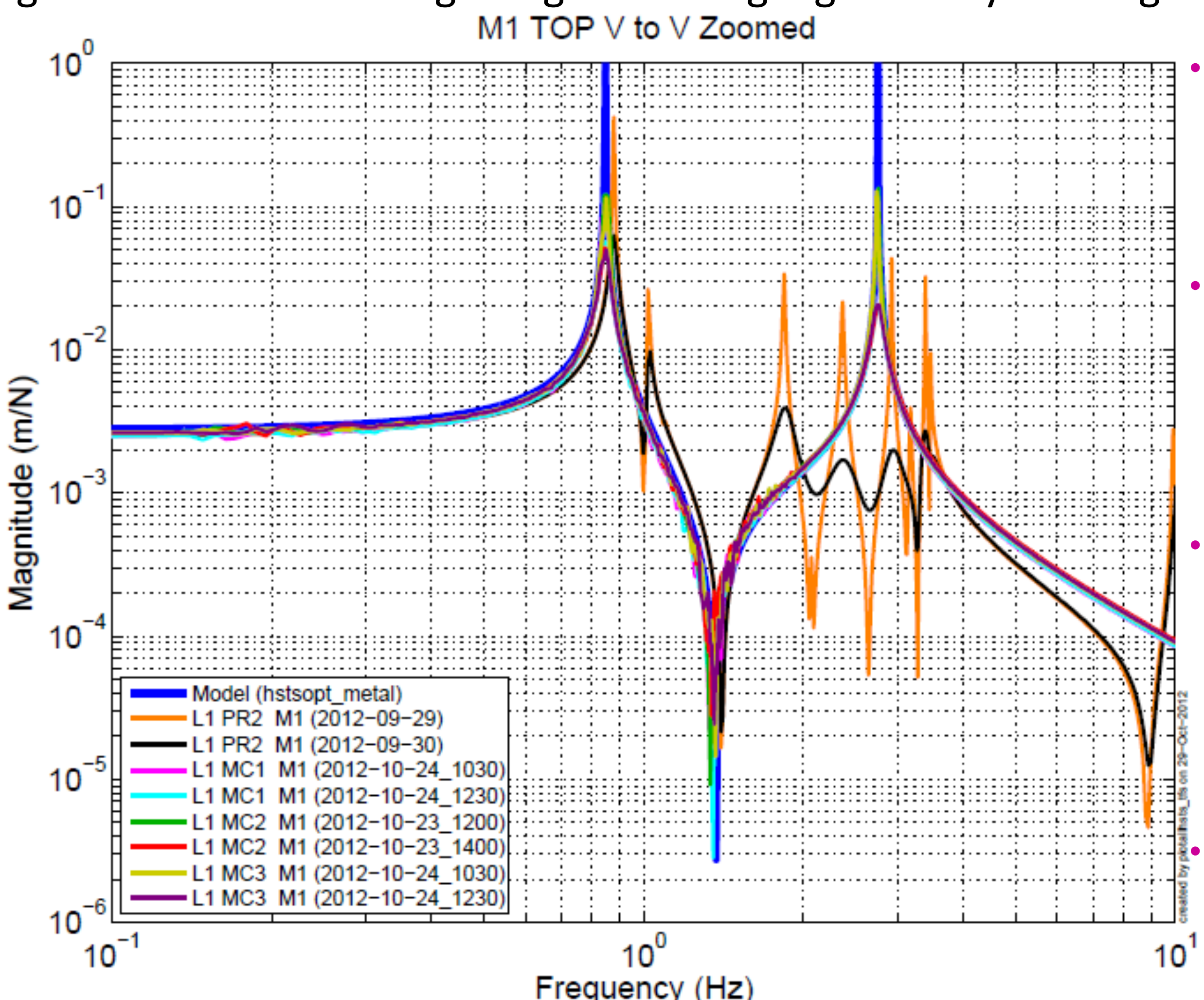
- Help diagnose when something has gone wrong e.g. identify rubbing source



HSTS



Lower blade-stop



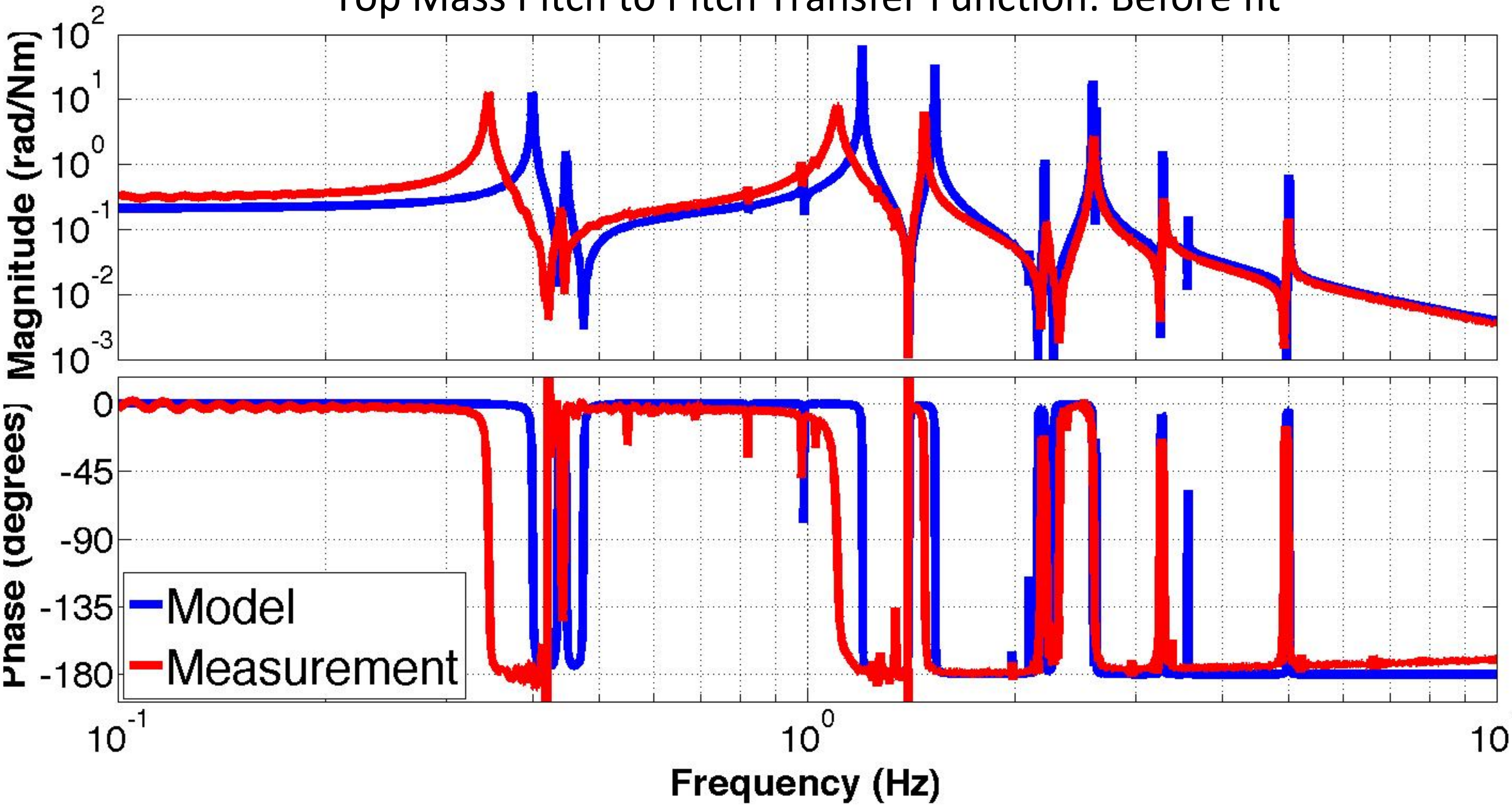
- **PR2 showed no signs of rubbing during Phase 3a (free-air)**
- **But following pump-down, Phase 3b, only PR2 shows severe rubbing (orange)**
- **After venting, still exhibited identical vertical rubbing, suggesting no t buoyancy related (T1100616)**
- **Visual inspection identified it to be a lower blade stop interfering**

Ref - G1300132

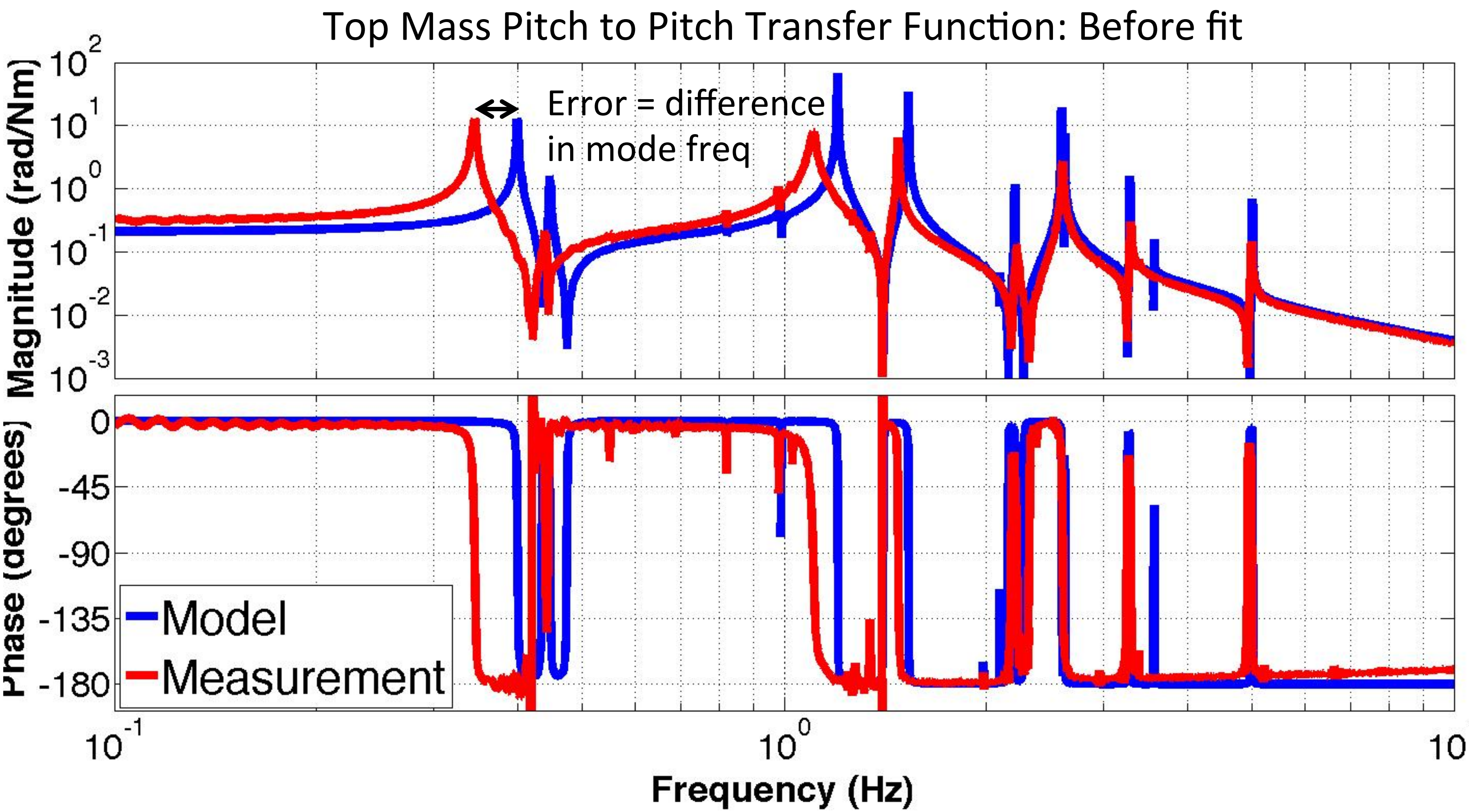
Suspension Model Parameter Estimation

Model vs Measurement

Top Mass Pitch to Pitch Transfer Function: Before fit

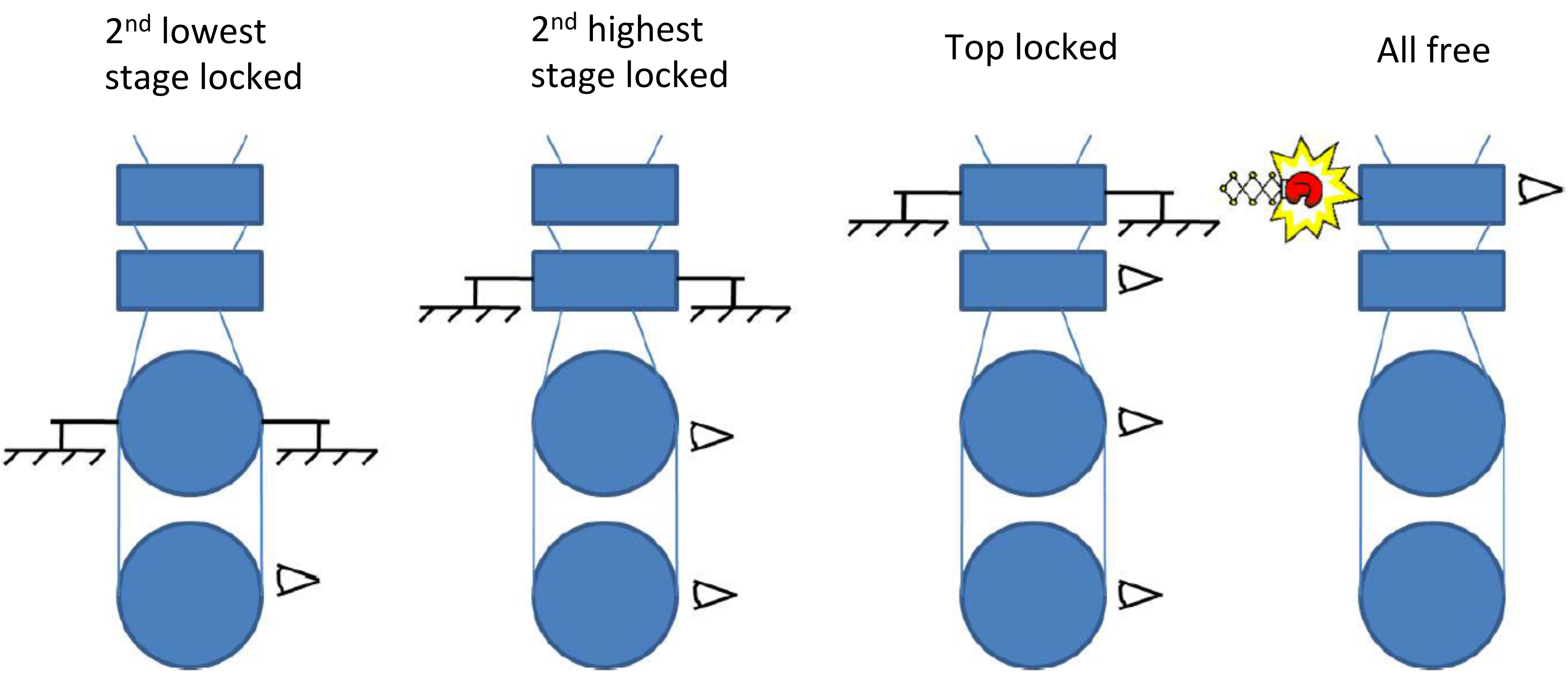


Error Measurement



- High Q resonant frequency measurements are not subject to calibration errors or noise.
- The measurement 'noise' is the data resolution, which only depends on time.

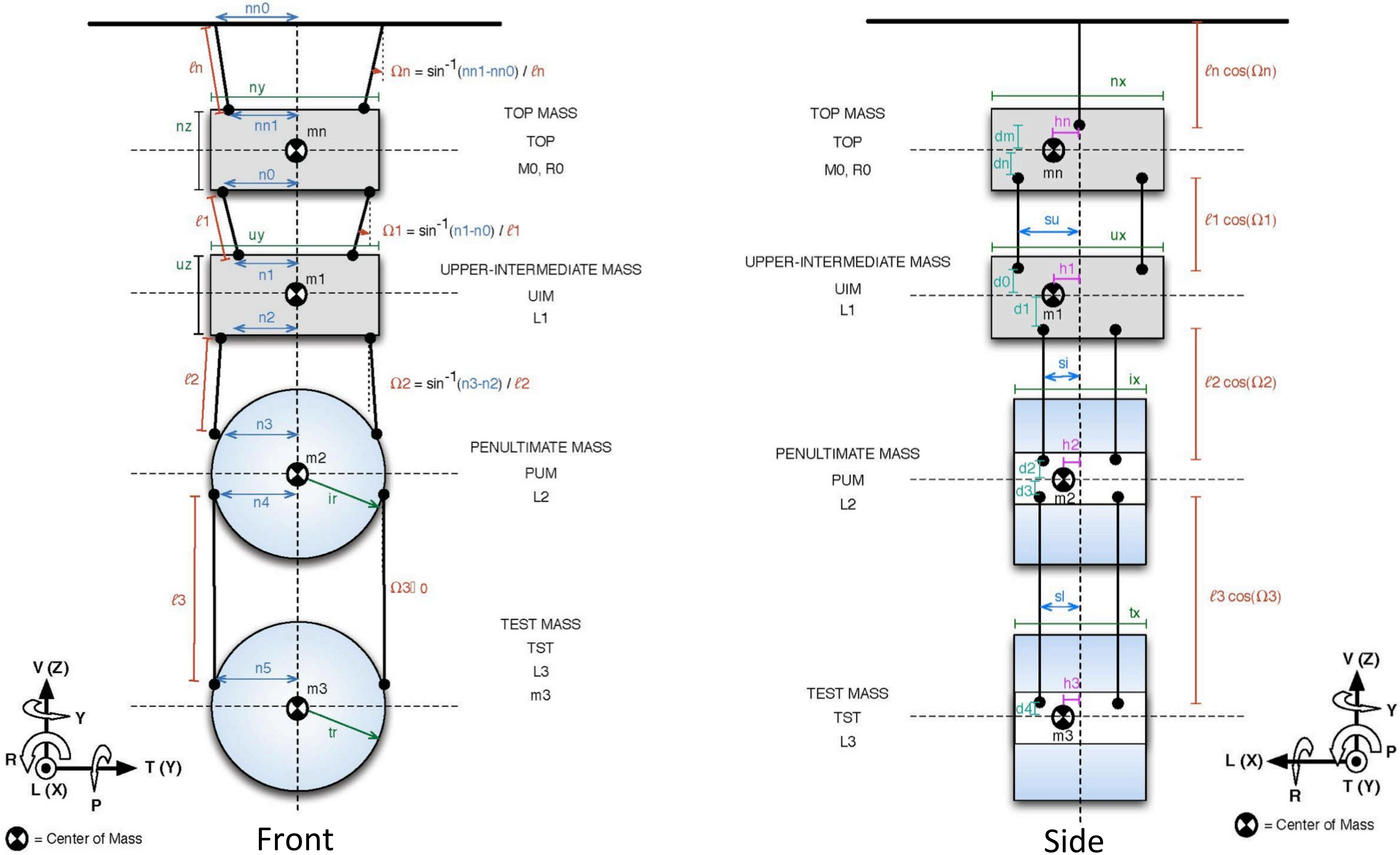
Maximizing the Measurements



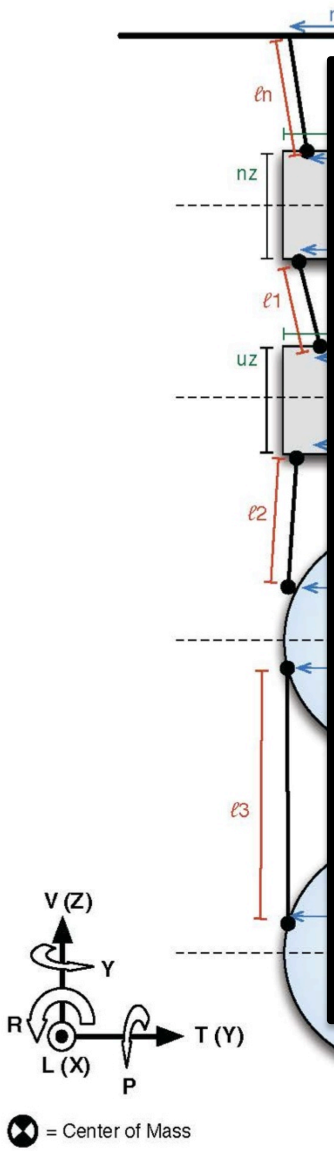
6 resonances | 12 resonances | 18 resonances | 24 resonances

6 + 12 + 18 + 24 = 60 resonant frequencies

Quad Model – 67 unique parameters

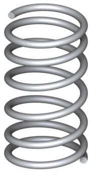


Quad Model – 67 unique parameters

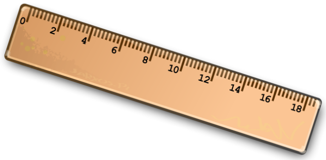


Physical parameters include:

Inertia



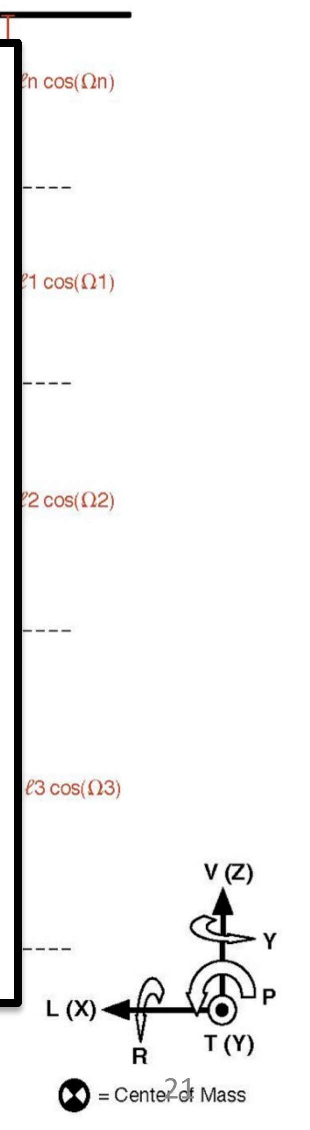
Spring stiffness



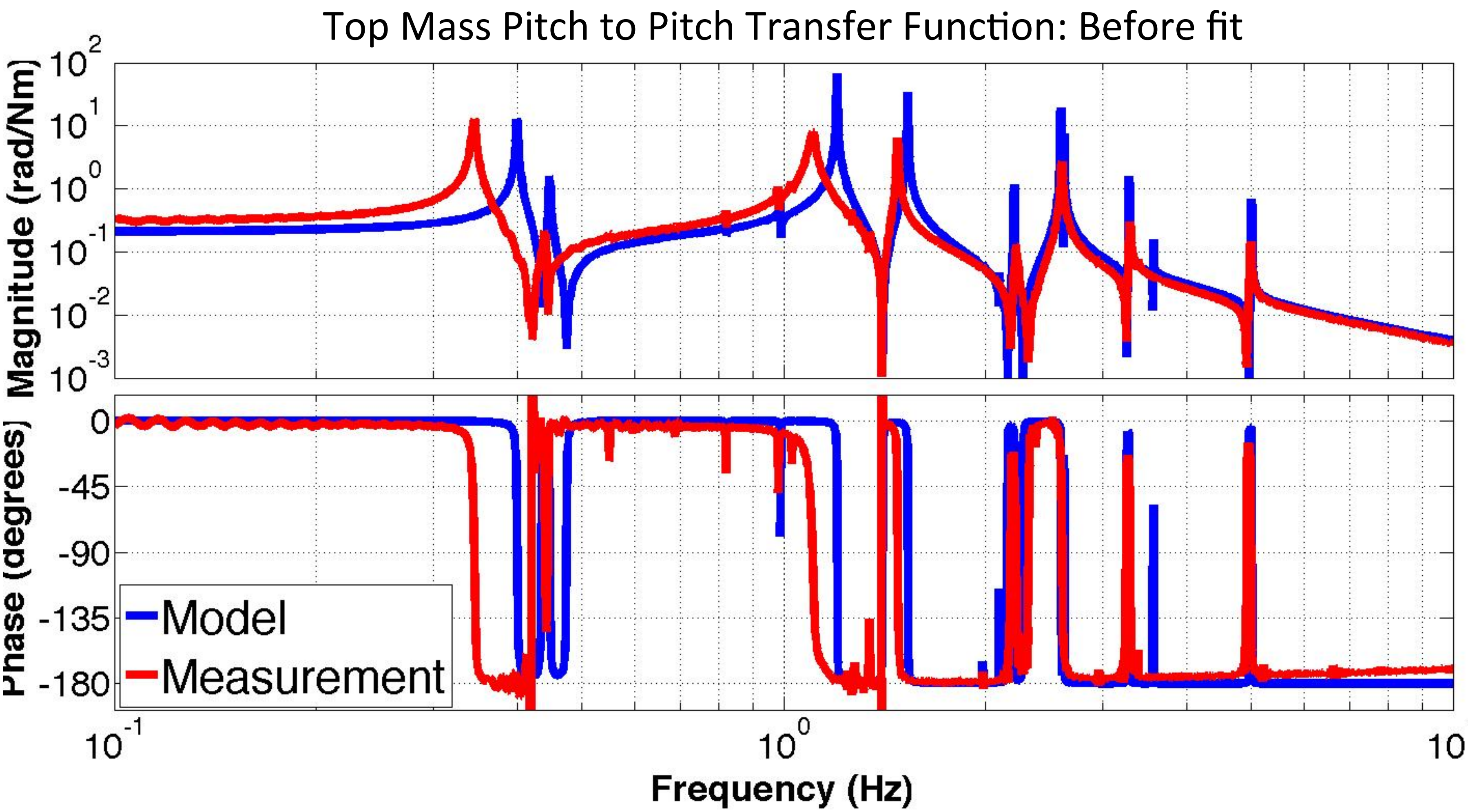
Wire dimensions

…

Etc…

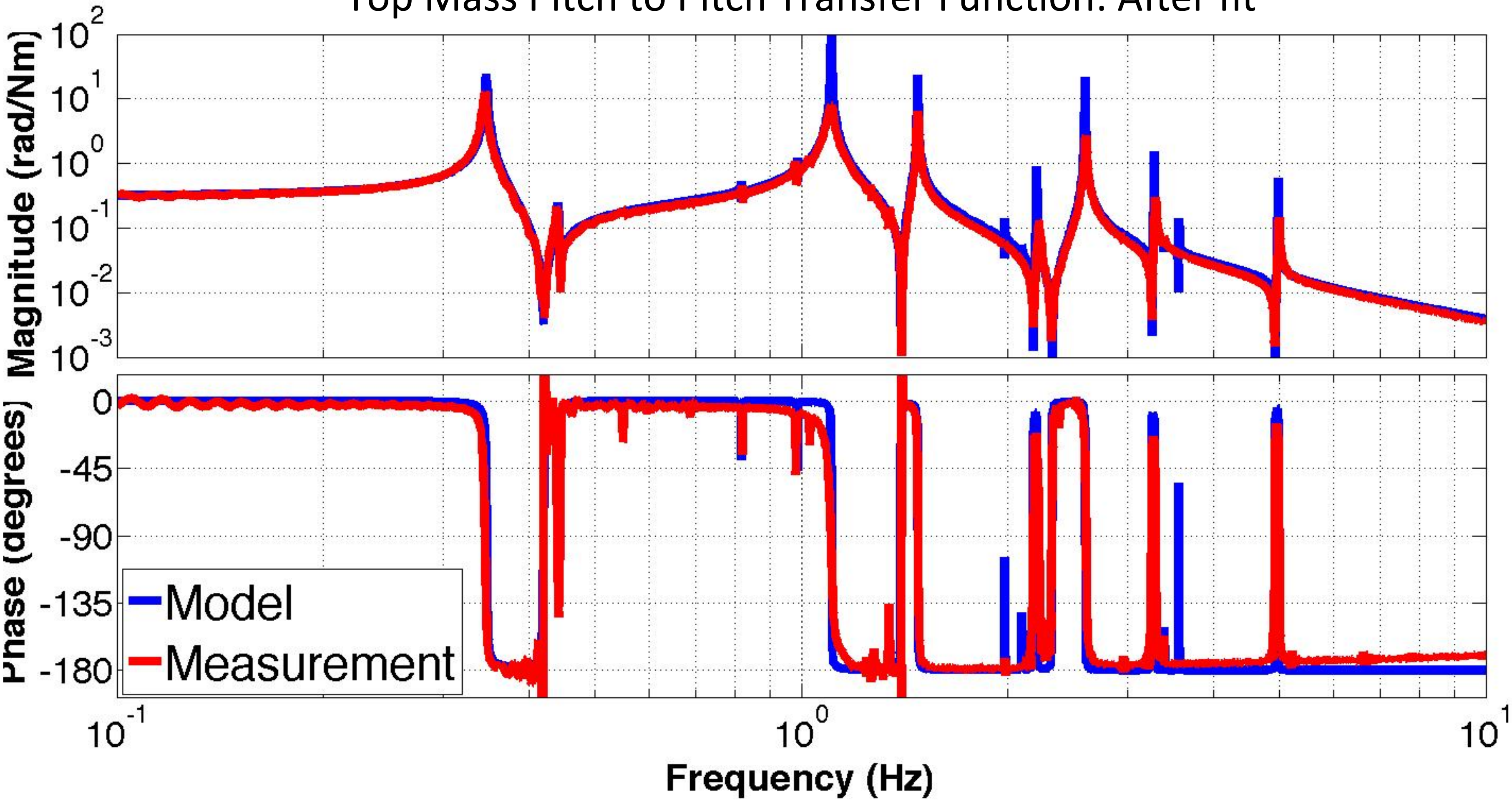


Before Parameter Estimation



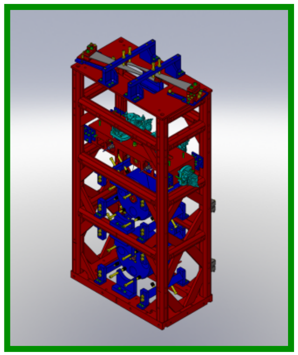
After Parameter Estimation

Top Mass Pitch to Pitch Transfer Function: After fit



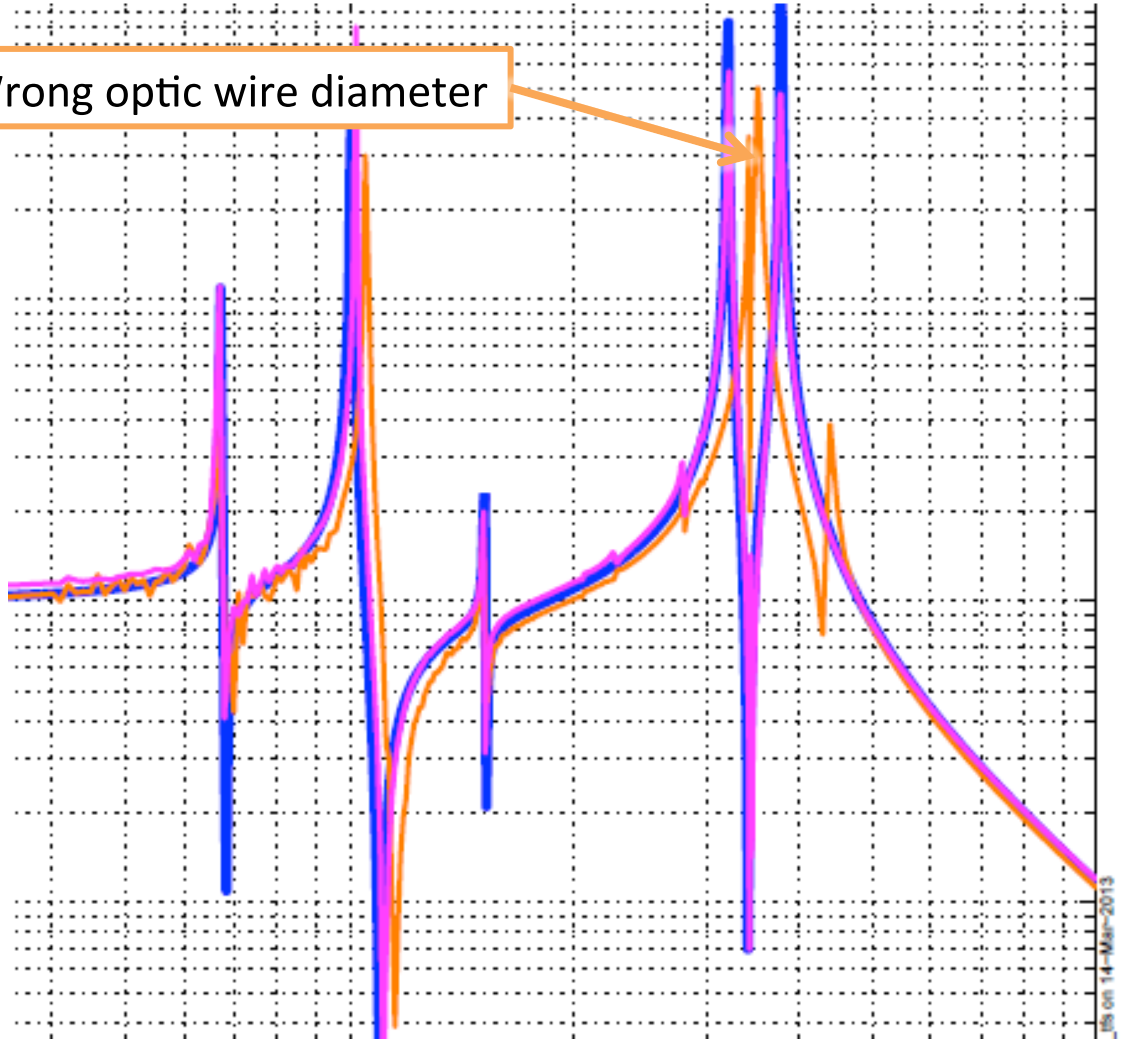
References: T1000458 and "Selection of Important Parameters Using Uncertainty and Sensitivity Analysis", Shapiro et al.

Parameter Estimation Can Diagnose Errors



HSTS

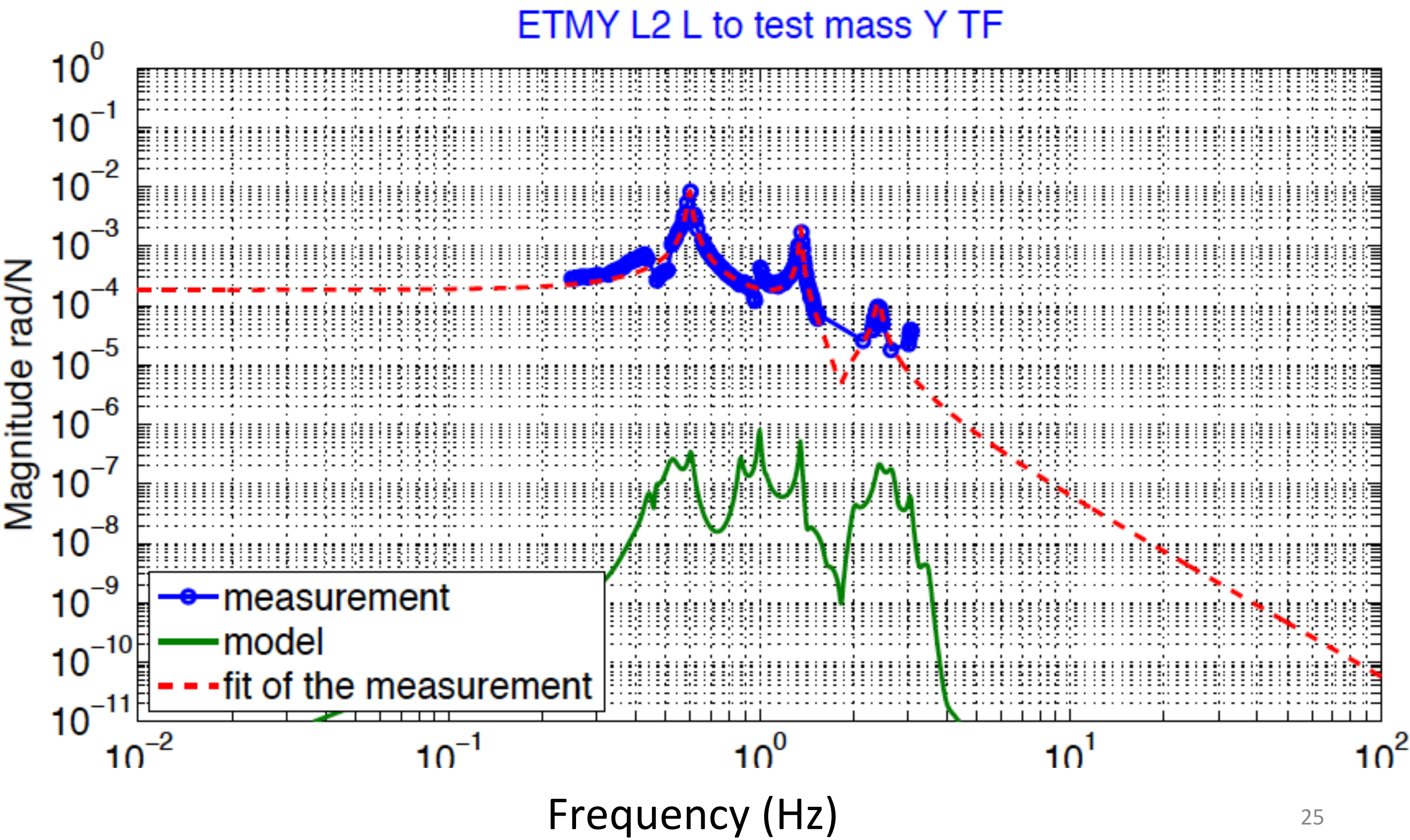
Measuring lower wire diameter



- All DOFs for SRM (HSTS) looked good, except for an ugly feature in Pitch (orange)
- Modeling suggested that most likely the incorrect diameter lower wire could be the culprit (see LLO aLOG 4766 i.e ø = 152 µm instead of ø = 120 µm
- This was later confirmed, and replaced with the correct wire diameter (magenta)

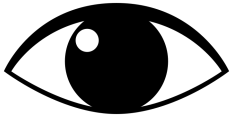
Ref - G1300132

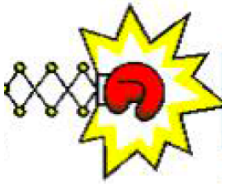
Model Misses Cross-Couplings



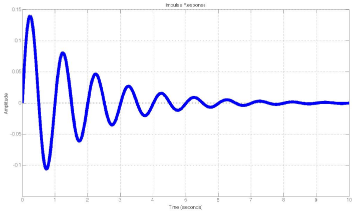
Homework: find ways to improve measurements of future suspensions

- Examples





  - More sensors
    & actuators

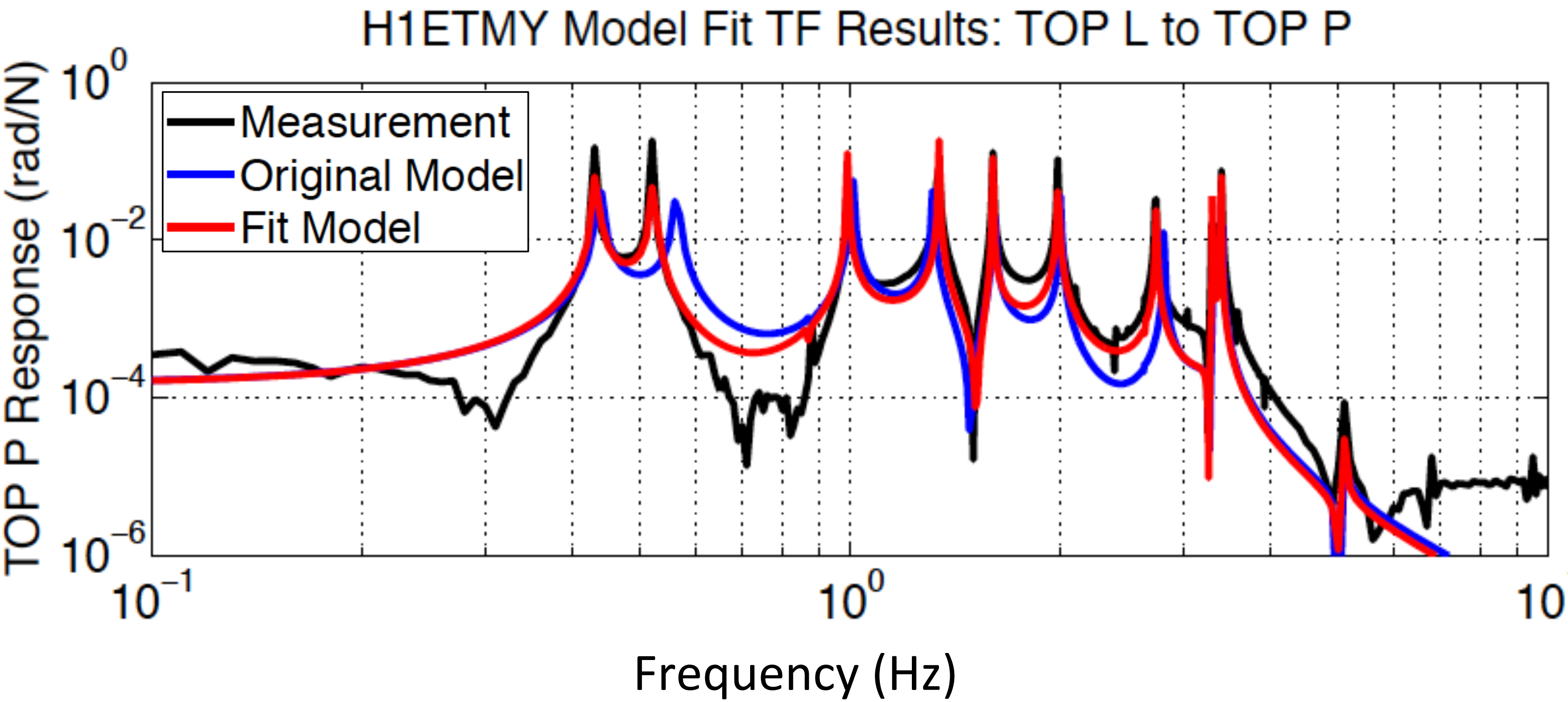


  - Different dynamics
    - e.g. lower bounce mode frequency

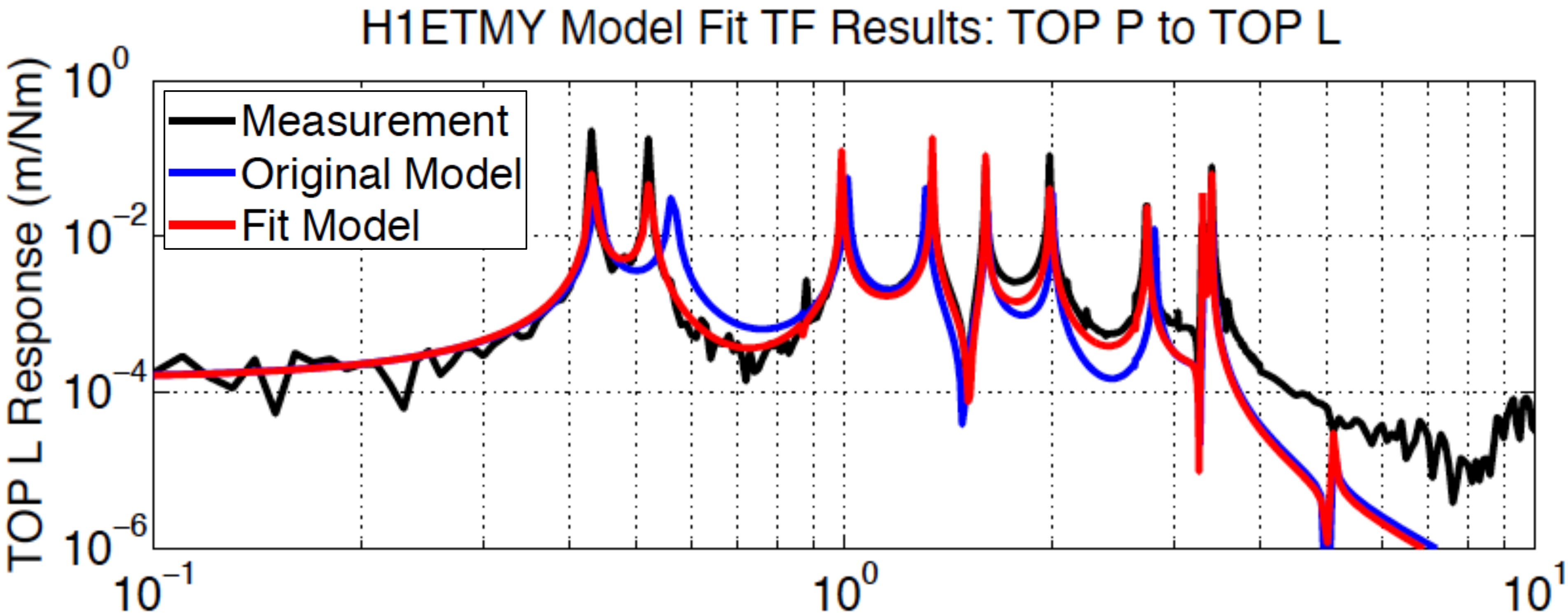
- Many solutions will help ***both*** sys-id and control

Back Ups

Model Misses Cross-Couplings

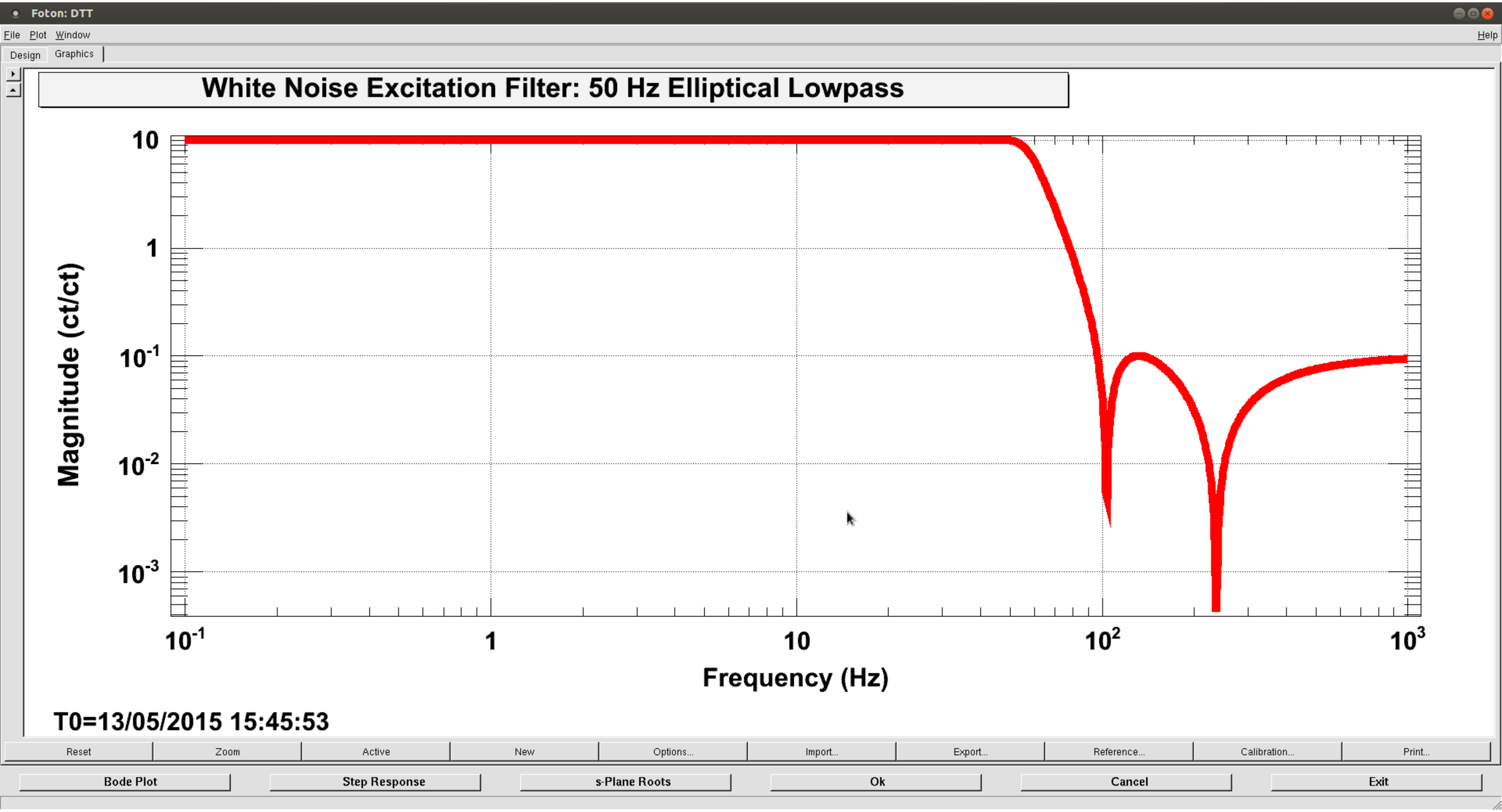


Model Misses Cross-Couplings



Frequency (Hz)

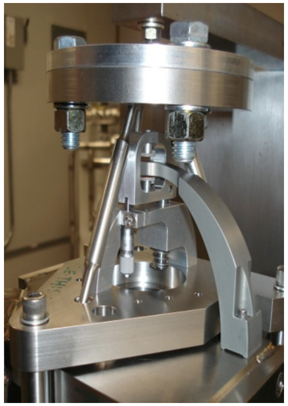
SUS DTT White Noise Filter



SEI Sensors and Their Noise

“Low” Frequency

DC



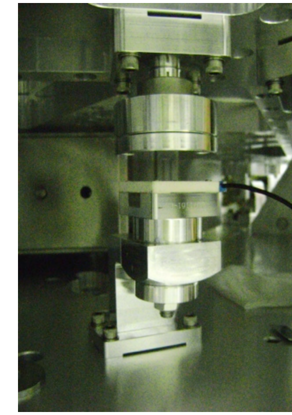
IPS

Kaman’s Inductive Position Sensors

Used On: HEPIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used ‘cause: Reasonable Noise, Long Range



CPS

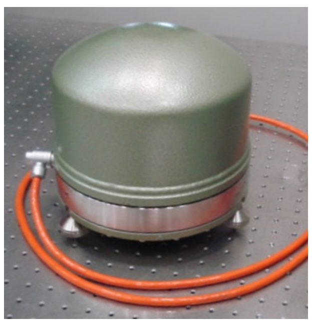
MicroSense’s Capacitive Displacement Sensors

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

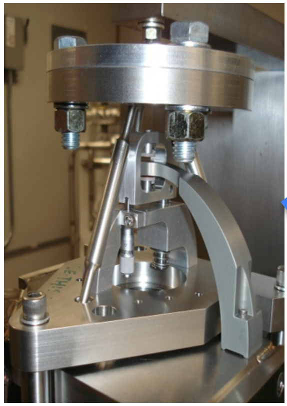
800 Hz

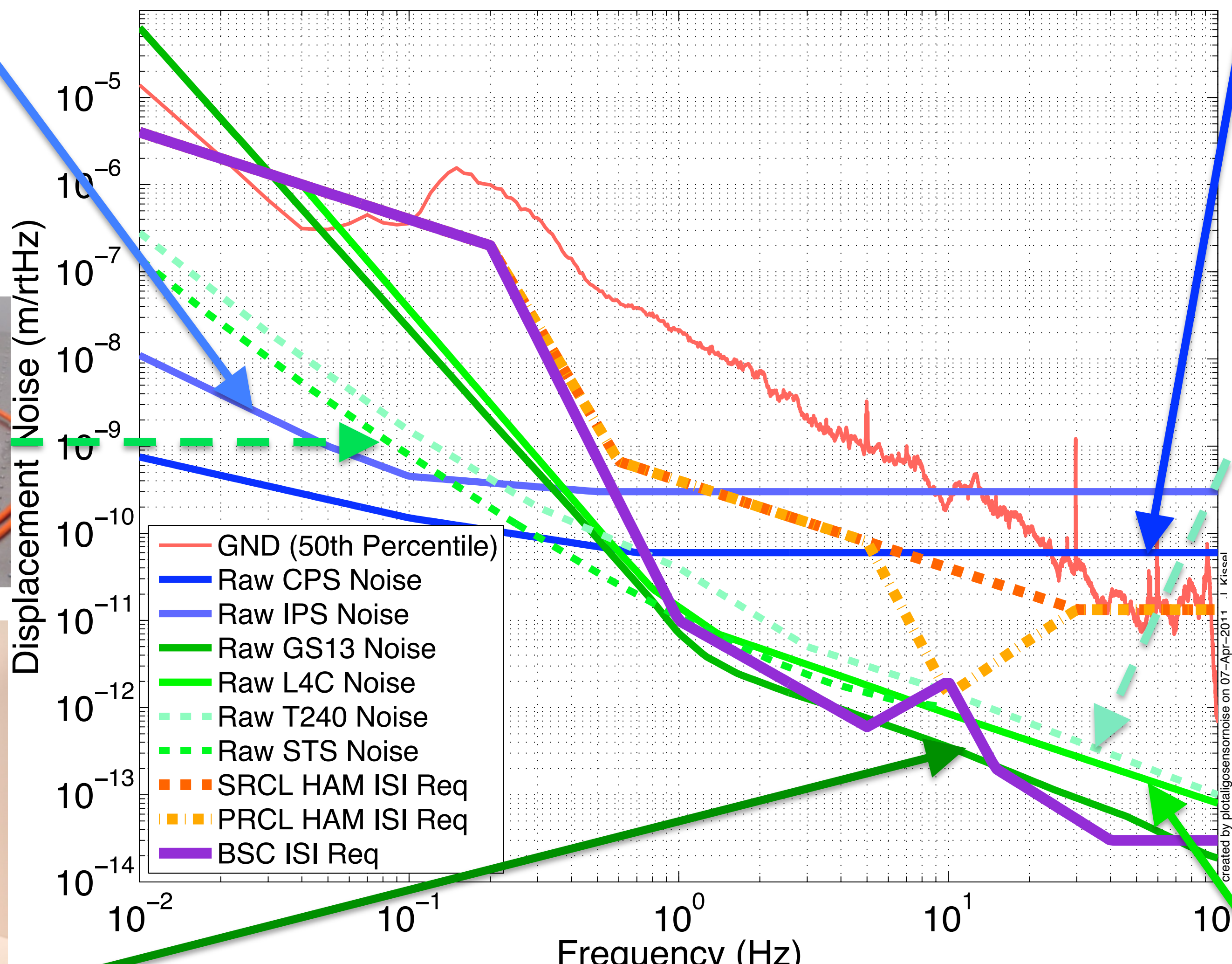
“High” Frequency

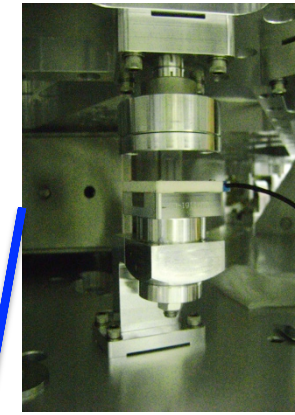
J. Kissel, Apr 7 2011

Ref: G1100431

SEI Sensors and Their Noise







Ref: G1100431

What is System Identification?

"System Identification deals with the problem of building mathematical **models** of dynamical systems based on **observed data** from the system."

- *Lennart Ljung, System Identification: Theory for the User, 2nd Ed, page 1.*

References

- Lennart Ljung, System Identification: Theory for the User, 2nd Ed
- Dariusz Ucinski, Optimal Measurement Methods for Distributed Parameter System Identification