aLIGO BSFM "Level 2" Damping Loop Design (Supplemental to LHO aLOG 6392)

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aLIGO BSFM "Level 2" Damping Loop Design

Mission Statement

The damping loops installed during the SUS testing phase

Level 1

- merely to prove that the suspensions *could* be damped
- damped quickly and robustly
- little-to-no regard to re-injection of sensor noise
- very aggressive, but poorly placed elliptic filters to rolloff noise

The mission here was to design a set of loops, that

Level 2

- doesn't take you years to design and tweak
- isn't on the hairy edge of instability
- doesn't require any "Brett Shapiro" trickery (damping in Modal, Global bases)
- doesn't require and new infrastructure (which Modal and Global damping would),

but still

- designed with what modeling experience we've gained
- gets us *close* to what we'll need for aLIGO, primarily focusing on Longitudinal
- will be sufficient for the first several stages of integrated testing

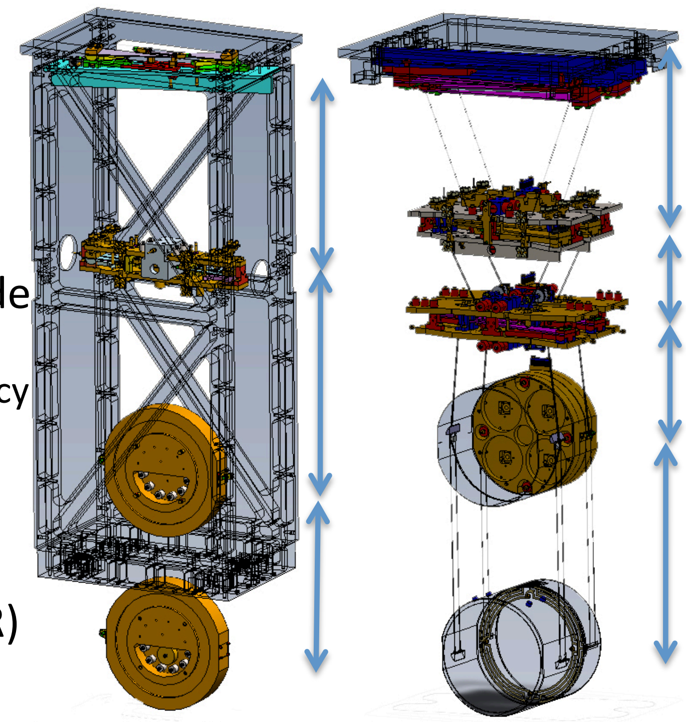
Damping Loop Design

Model Figures of Merit

- **Stability**: Bode plots of Open and Closed Loop Gain Transfer Functions
- **Cross-Coupling**: The above, Modeled both as SISO and MIMO systems, the below as MIMO
- **Modeled Performance**: Compute all DOF's of Top Mass sensor noise contribution to Optic degree of freedom of interest
- **Compare**: with other noise sources, requirements, coupling to DARM, etc.
- **Measured Performance**: With what we can: Closed Loop TOP2TOP Open and Closed Loop TFs, TOP Sensor ASDs, TOP Control Signal ASDs

(Check out G1300537 and LLO aLOG 6949 for a more thorough description; I assume from here on that you've seen and understand what they mean, so I can get right to the points.)

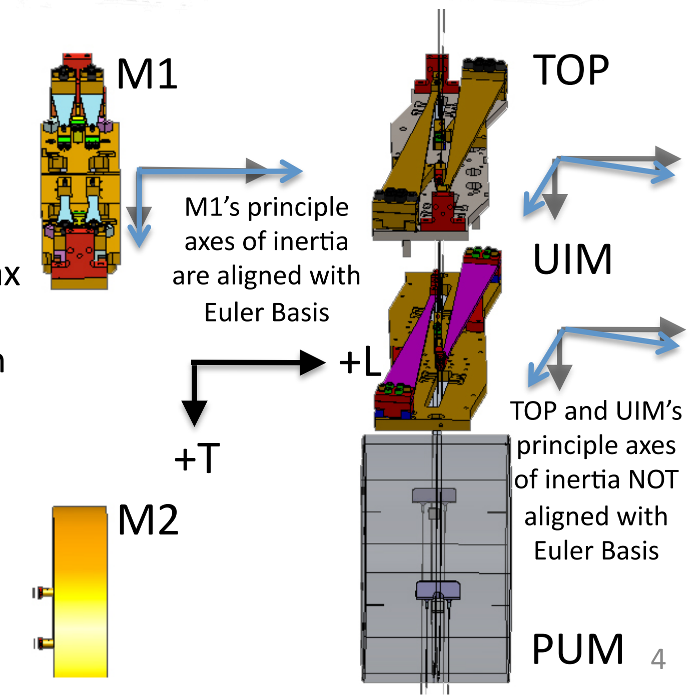
BSFM vs QUAD



Important differences between BSFM and QUAD:

1. BSFM is a long, triple suspension, so (L/P) and (T/R) mode frequencies are, in general, lower
   - ⇛ Plenty more phase to play with between the highest frequency resonance and 10 [Hz] requirements
2. BSFM's lower blades are aligned with the T - V plane, so there's no fundamental coupling between (L/P) and (T/R) like there is for the QUADs
   - ⇛ Don't have to consider sensor noise of 4 different loops to improve L
3. Though BSFM (L and P) or (T and R) are (independently) coupled, respectively, damping a resonance in one DOF damps it in both
   - ⇛ Can again play the "take advantage of the MIMO" game to relax the design where needed.
   - ⇛ E.g. Highest to T/R modes at 2.1 and 3.2 [Hz] can be damped in R, where there are no noise requirements

These three points mean that the L, T, R, and P loops are ***significantly easier*** to design and meet requirements (not to mention the requirements are less stringent, of course)



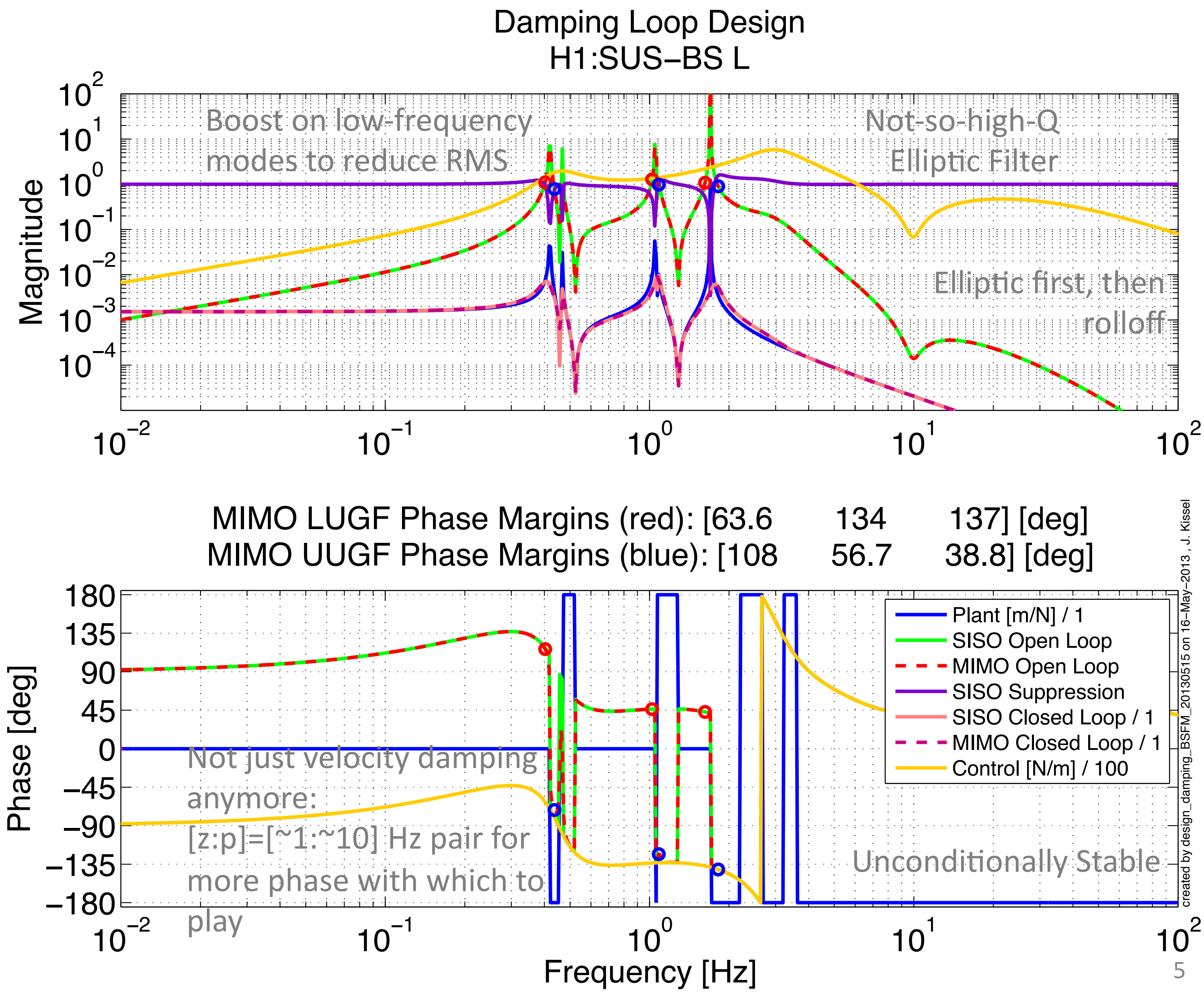
Damping Loop Design

Stabililty (New Filters -- L)

I started out by using the same general design features as the Level 2 QUAD filters,

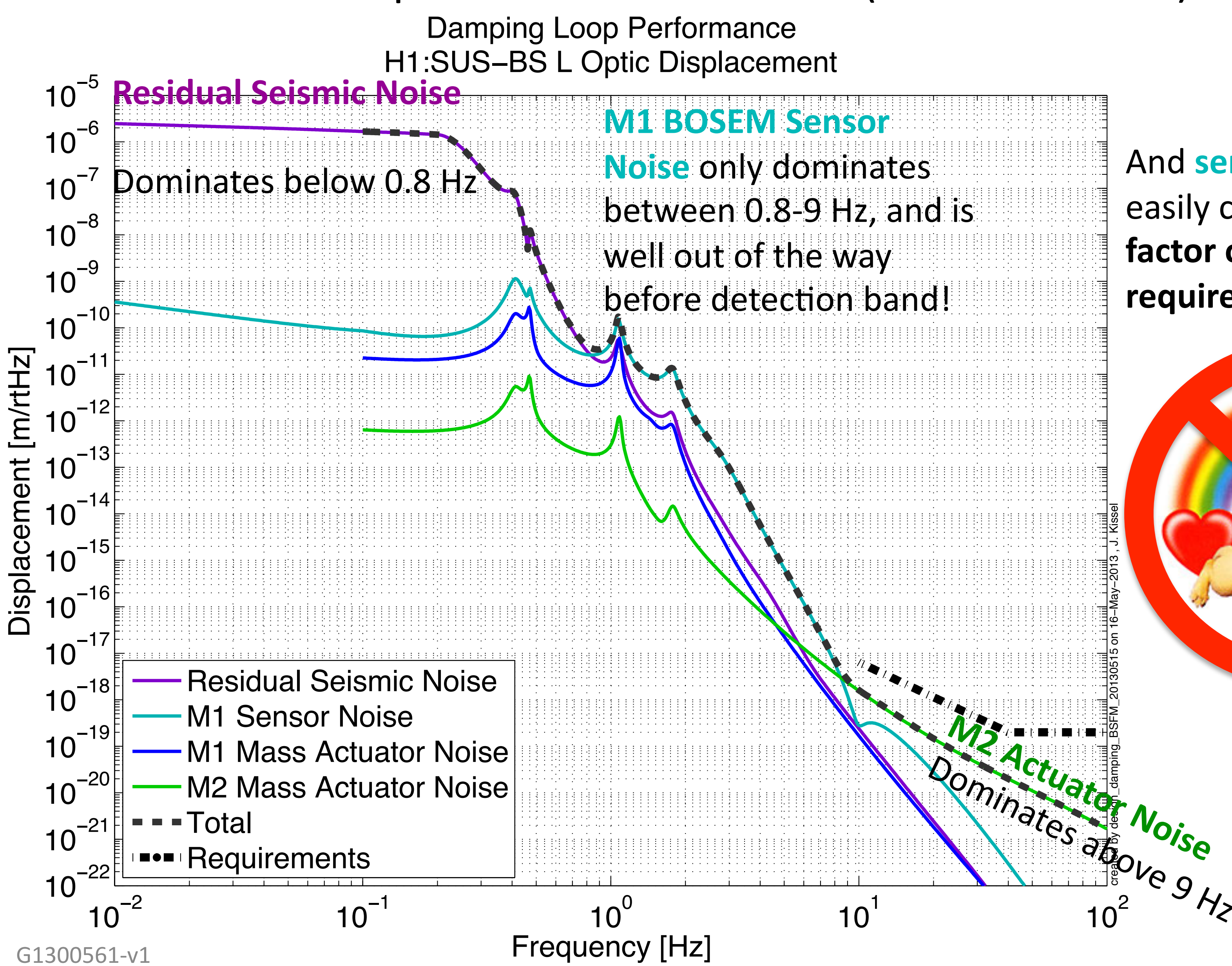
but
because resonances are lower, I had more phase with which to play.

So
- Elliptic filters start at lower frequency
- Qs of boosts elliptic notches are a little higher
- More dBs of isolation on elliptic's stop-band



Damping Loop Design

Compare with other Noises (New Filters -- L)



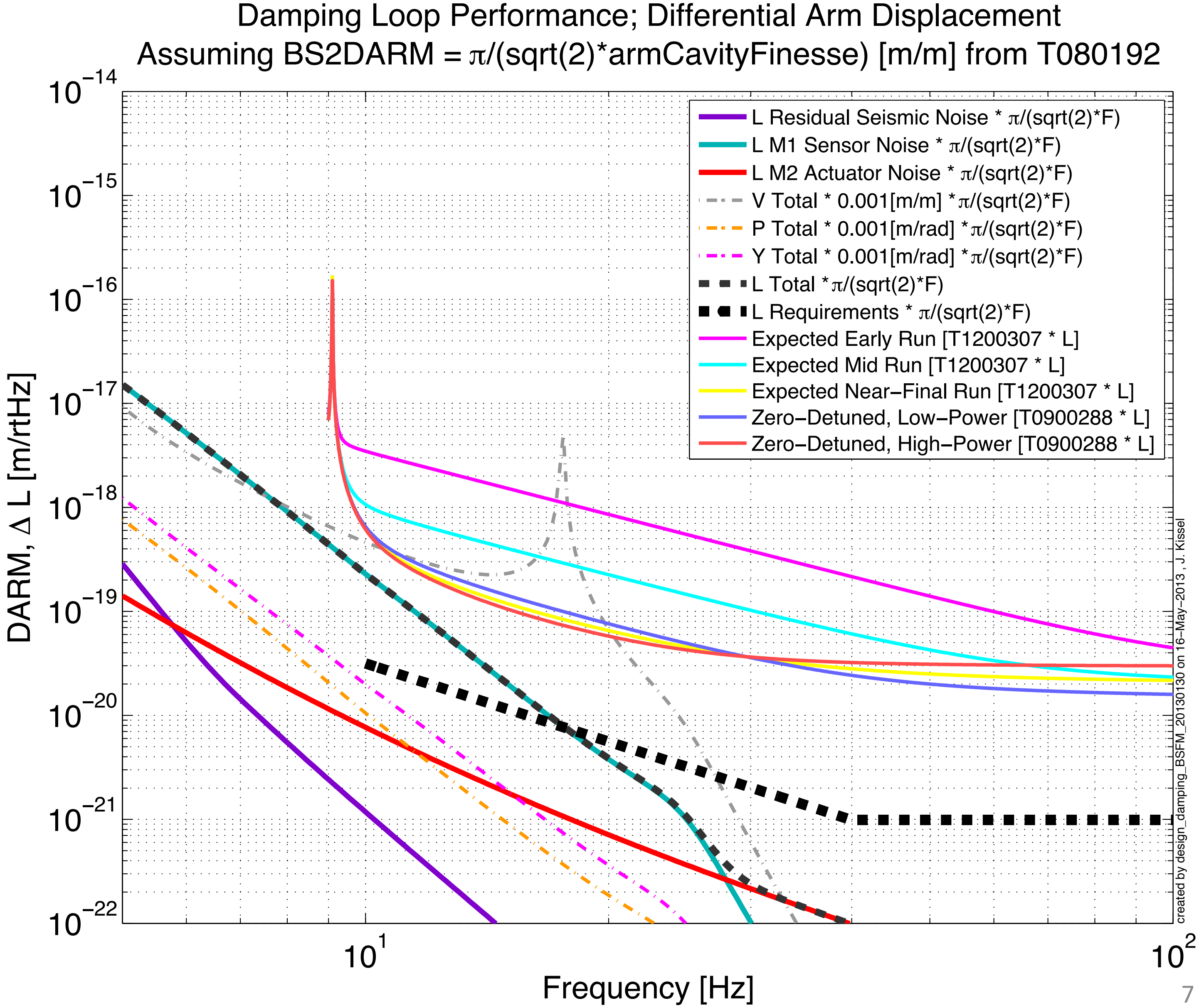
And **sensor noise** easily comes in **a factor of 10 below the requirements** at 10 Hz.

but it's not all puppies and rainbows…

Damping Loop Design

Coupling to DARM (OLD Filters)

Even with the **Level 1** filters, we see it's ***VERTICAL*** that's the worst offender when it comes to contribution to DARM



Damping Loop Design

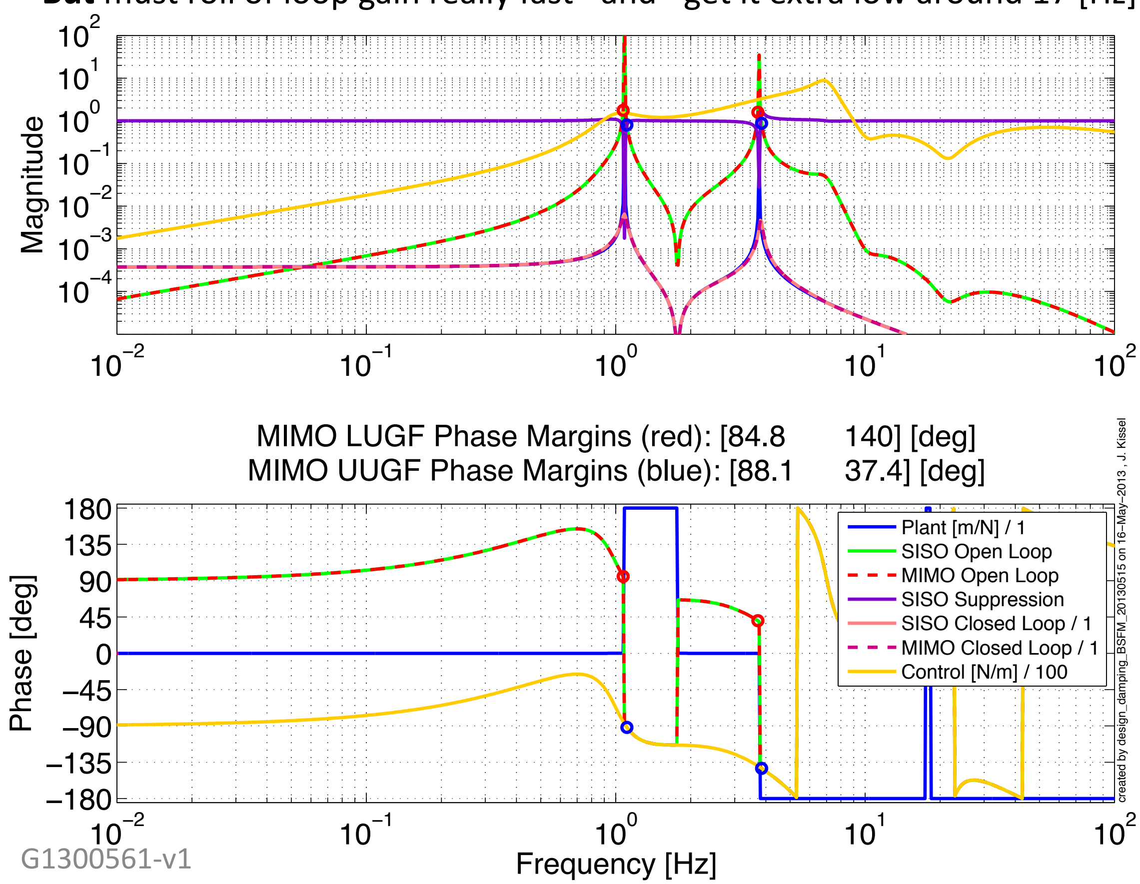
Stabililty (New Filters -- V)

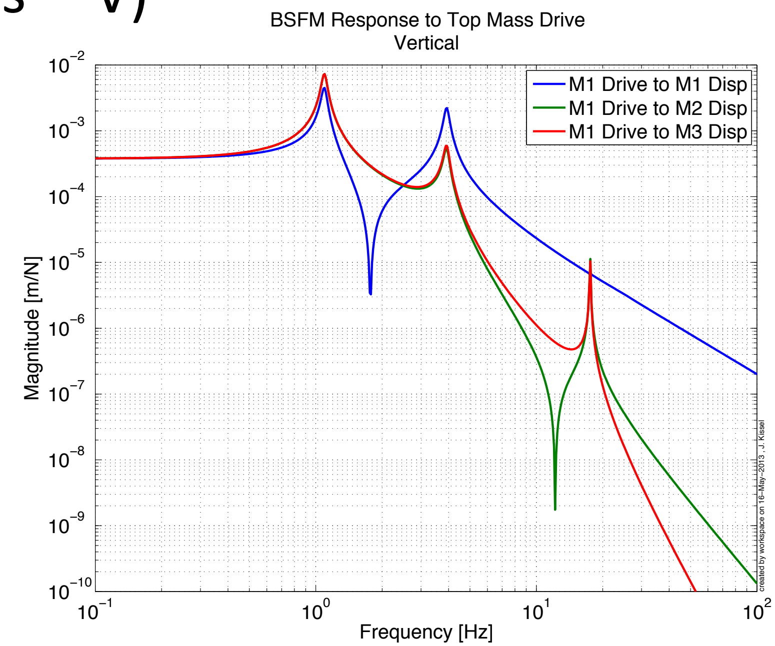
• M2 and M2 response to M1 force shows the highest V mode at 17.5 [Hz]. But ***M1 to M1 doesn't.***

• BSFM is pretty stiff in vertical, so all modes are relatively high compared to 10 [Hz] requirement, so

- Boost for extra gain at lowest-mode has to be high in frequency
- Very little phase left with which to play

• **But** must roll of loop gain really fast *and* get it extra low around 17 [Hz]





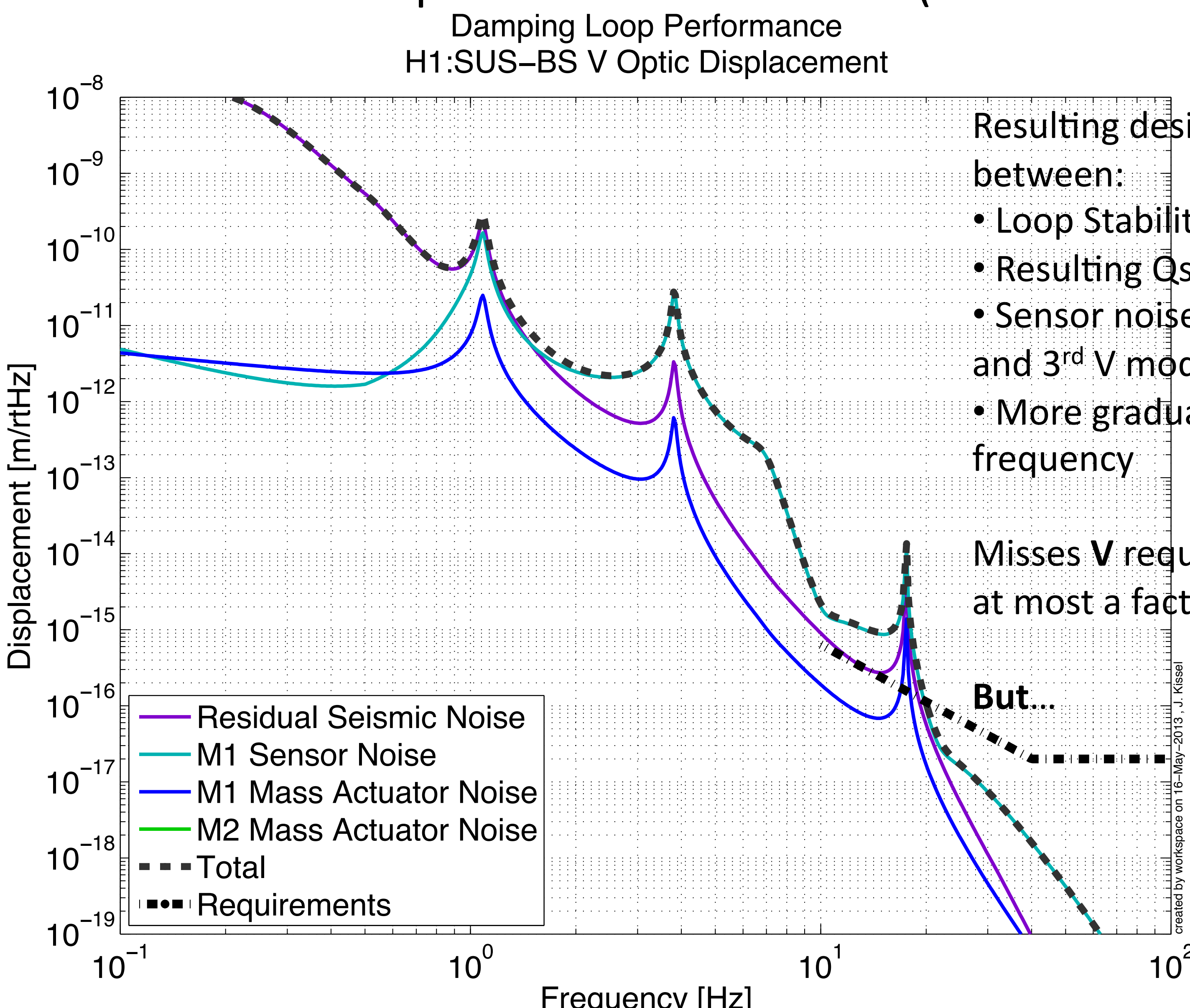
Solution:

• Forced to use more complex filter design (i.e. 4th order elliptic instead of 3rd order)

• Get 2nd elliptic notch as close to 17.5 Hz as possible

Damping Loop Design

Compare with other Noises (New Filters -- V)



Resulting design is a compromise between:

- Loop Stability
- Resulting Qs of 1st and 2nd V modes
- Sensor noise level between 10 Hz and 3rd V mode
- More gradual rolloff at high-frequency

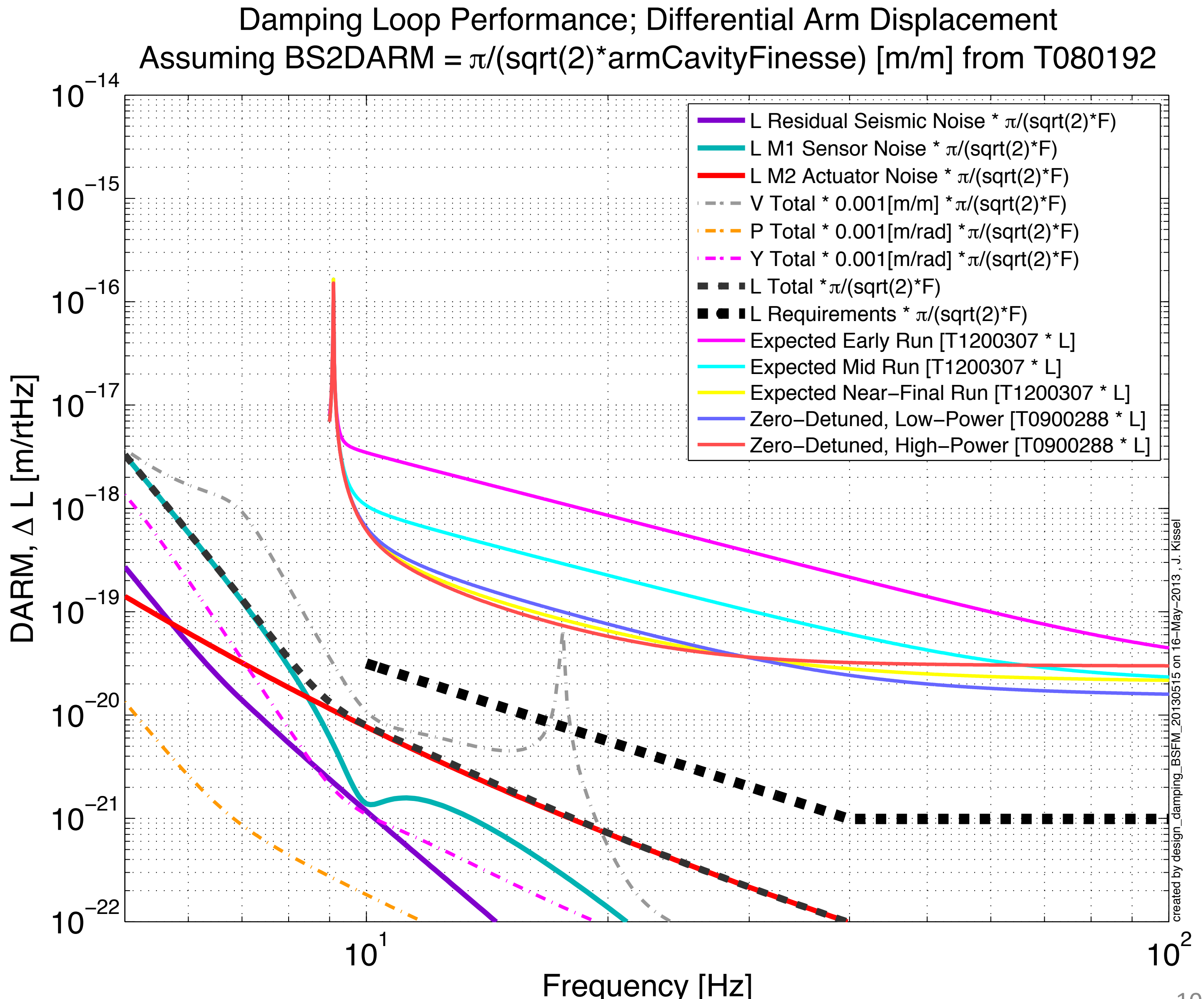
Misses **V** requirement for BSFMs by at most a factor of 5.

But…

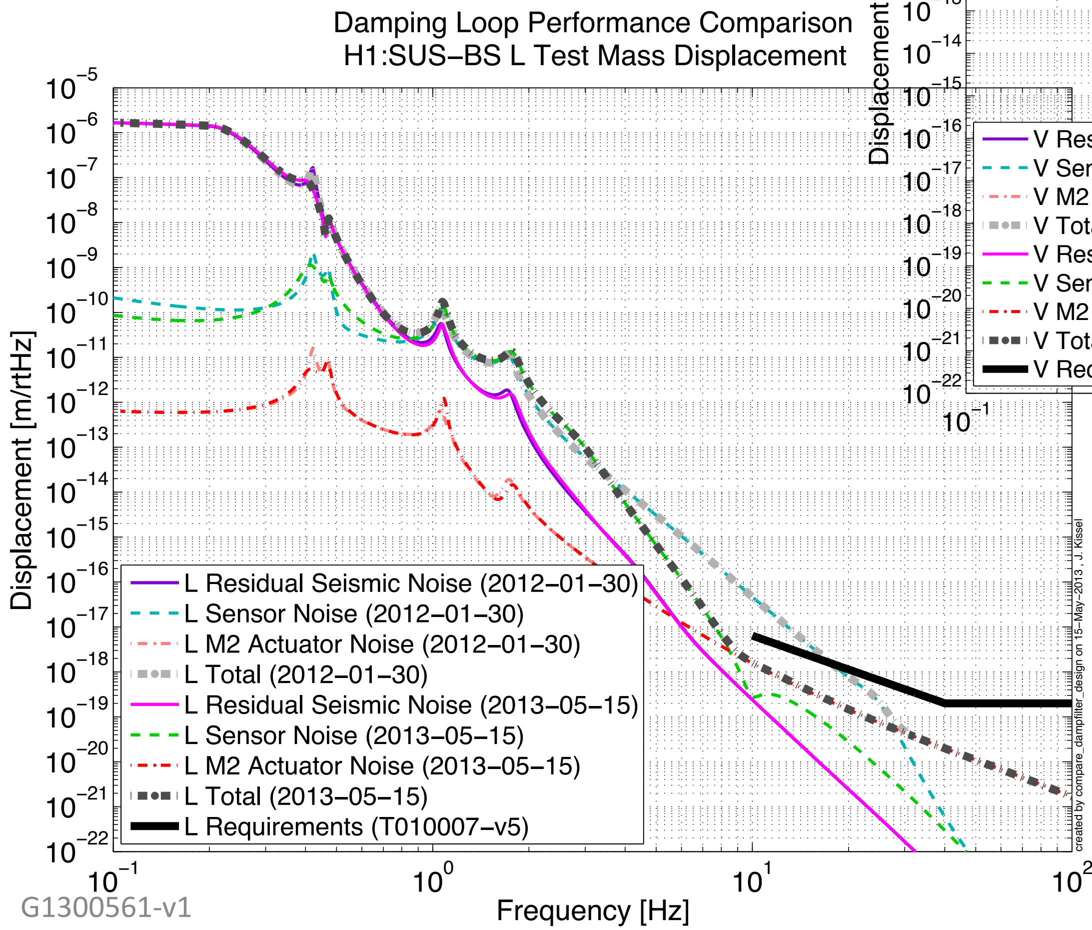
Damping Loop Design

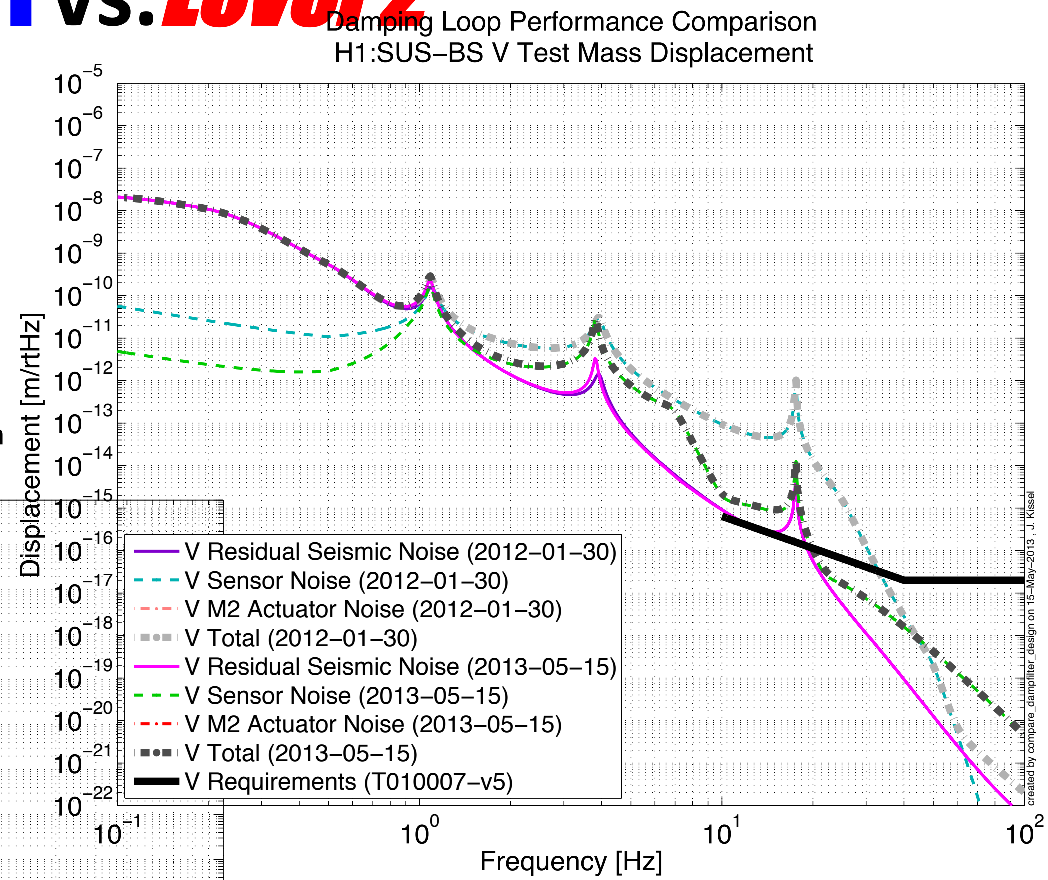
Coupling to DARM (NEW Filters)

… assuming a V2L coupling factor of 0.001, the resulting total ***VERTICAL*** noise is still well below any of the expected DARM sensitivities!

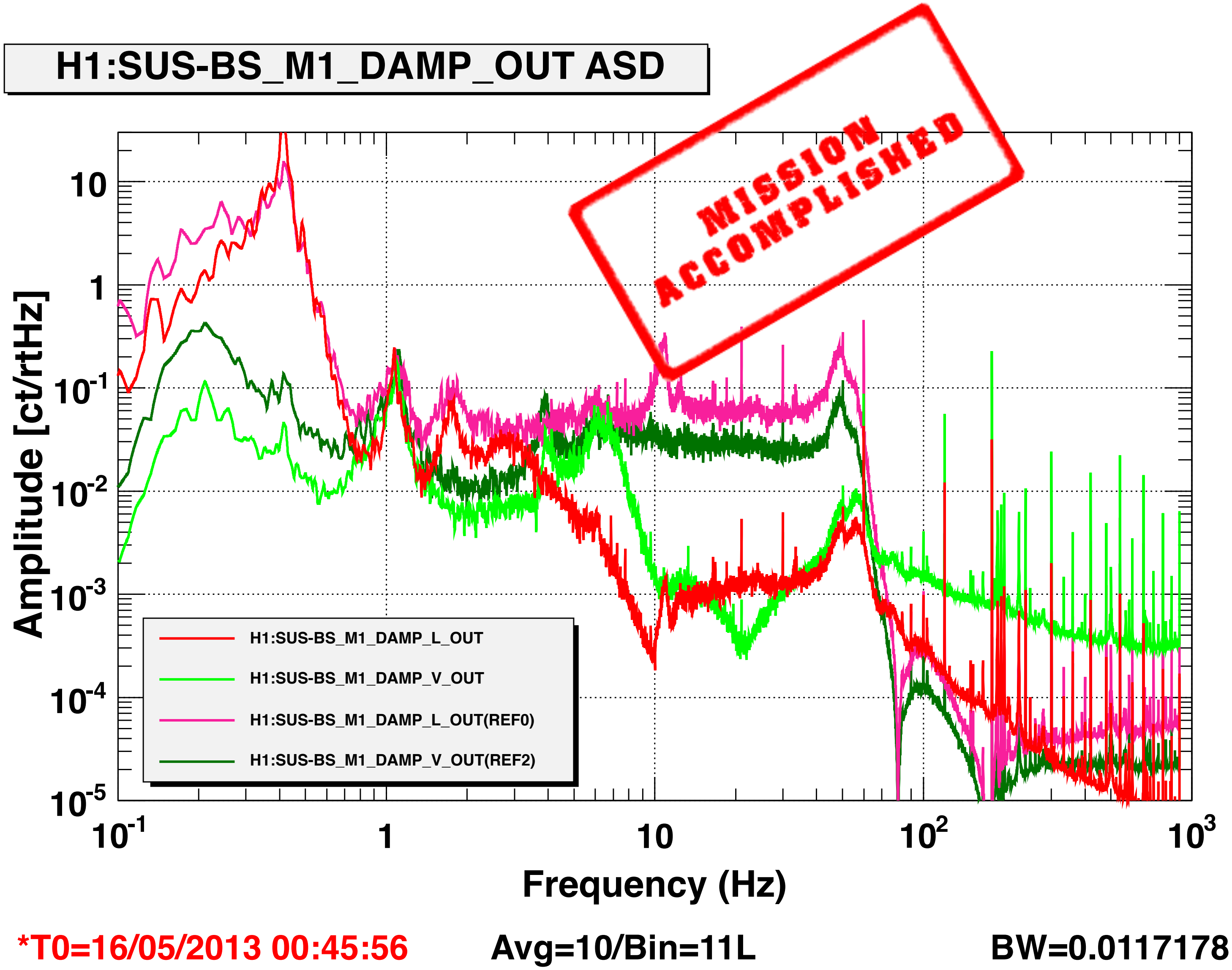


Level 1 vs. Level 2





Level 1 vs. Level 2



Can't measure Optic noise improvement directly yet…

If **sensor noise** dominates above ~0.5 [Hz] both before and after, then M1 control signal should be **~100 times less** at 10 Hz.

And it is!

Concluding Remarks

- BSFM Level 2 damping filters beat almost all aLIGO requirements

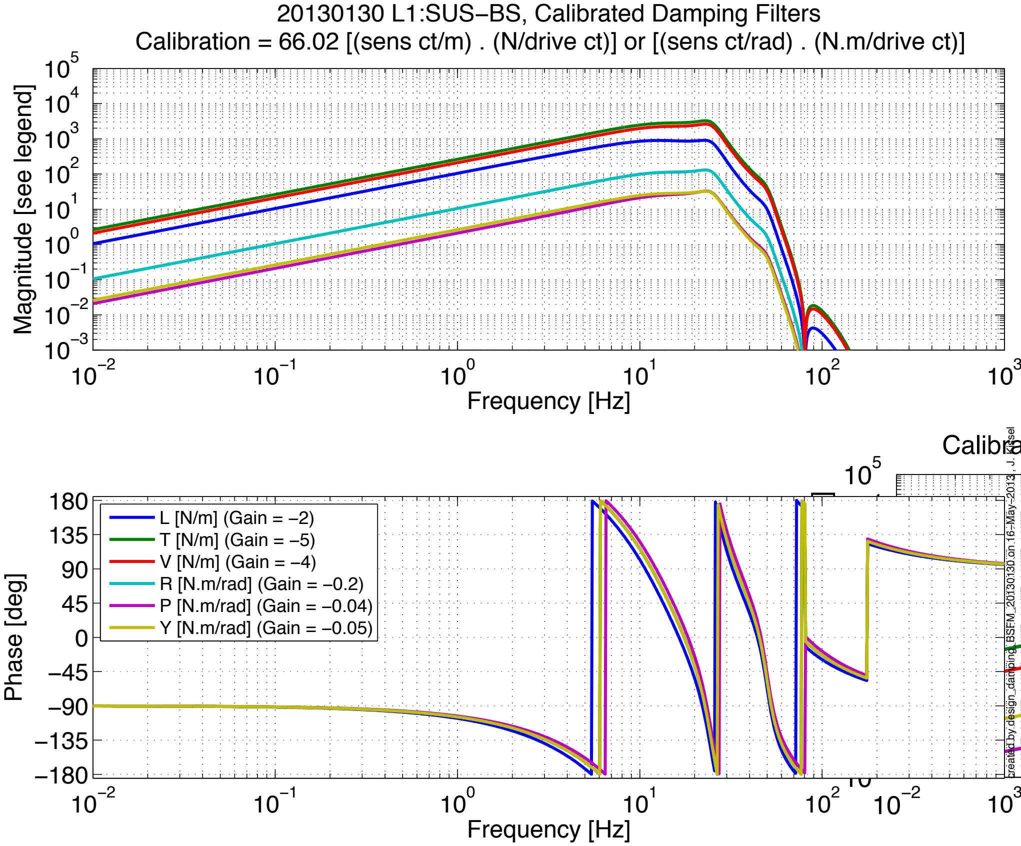
- BSFM design, in general was easier than the QUAD; Vertical is the toughest

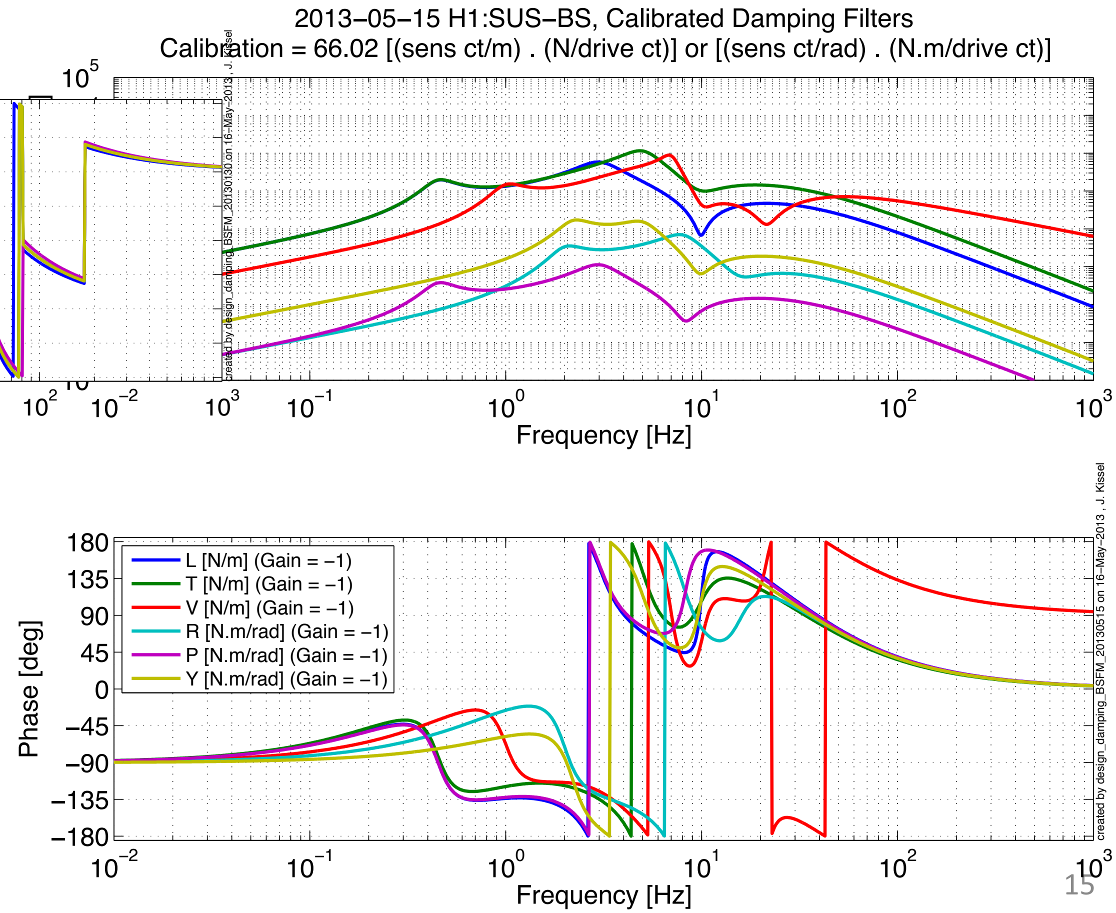
- Design choices
  - Chose to absorb over all gain into boost filter
  - Chose to move boost filters up in frequency on some DOFs
- Proof of design measurements
  - I didn't measure the open loop gain transfer functions
    - the experience with the QUAD has shown
      - the measurements to be more confusing than they're worth
      - the measurements confirm the cross-coupled MIMO model works
    - So in the interest of time, I've nixed them
  - Will get closed loop transfer functions and spectra over the course of phase 3a testing

Bonus Material For the Curious

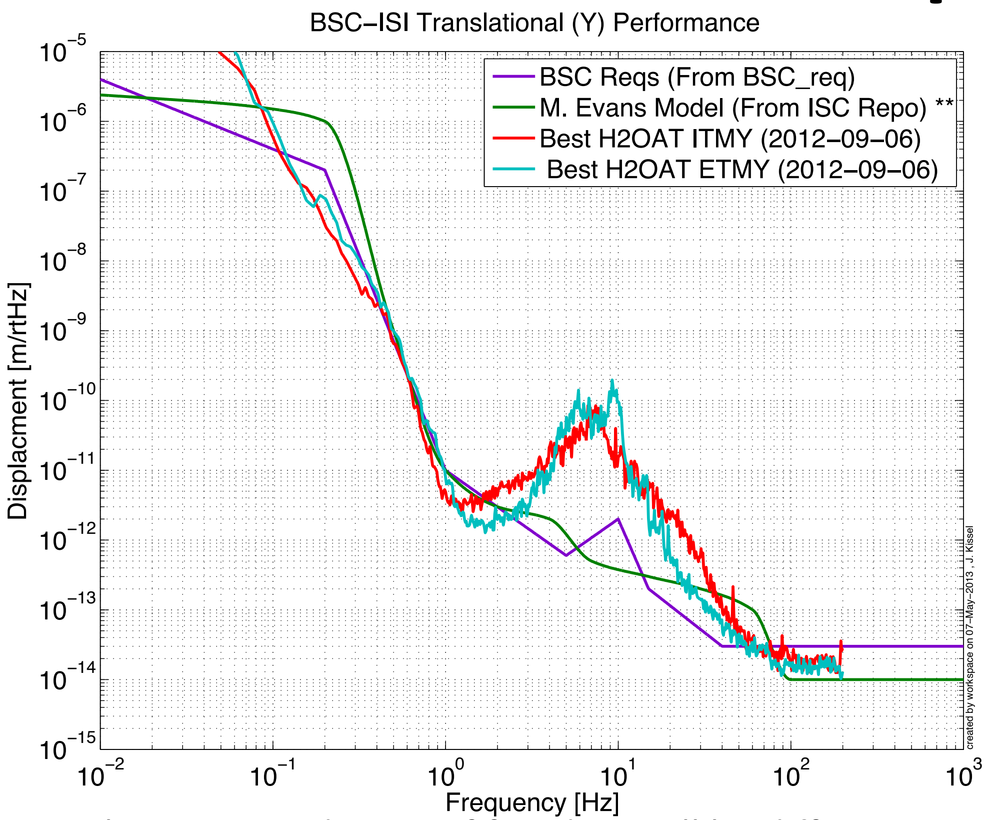
Remember, for even more text, plots, details see LHO aLOG 6392

Level 1 vs. Level 2





Seismic Input Motion



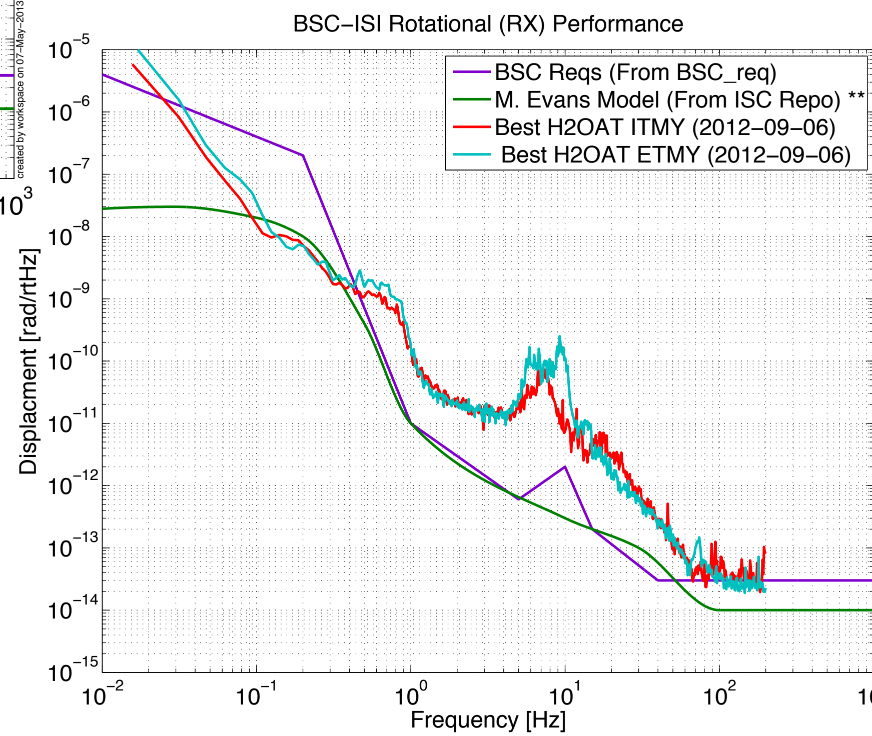
In the absence of real, best-possible performance data from the BSC-ISIs, there are a few choices for Residual Ground Input Motion to the QUAD:

- Use the **Requirements** for all DOFs
- Use **M. Evans' Model** of the "Translation" (same for X, Y, Z) and "Rotational" (same RX, RY, RZ)
- Use not-yet-awesome, but real **H2OAT data** (different for every DOF, and even between ISIs)

We know every degree of freedom will be different, so I don't like using the **Reqs**.

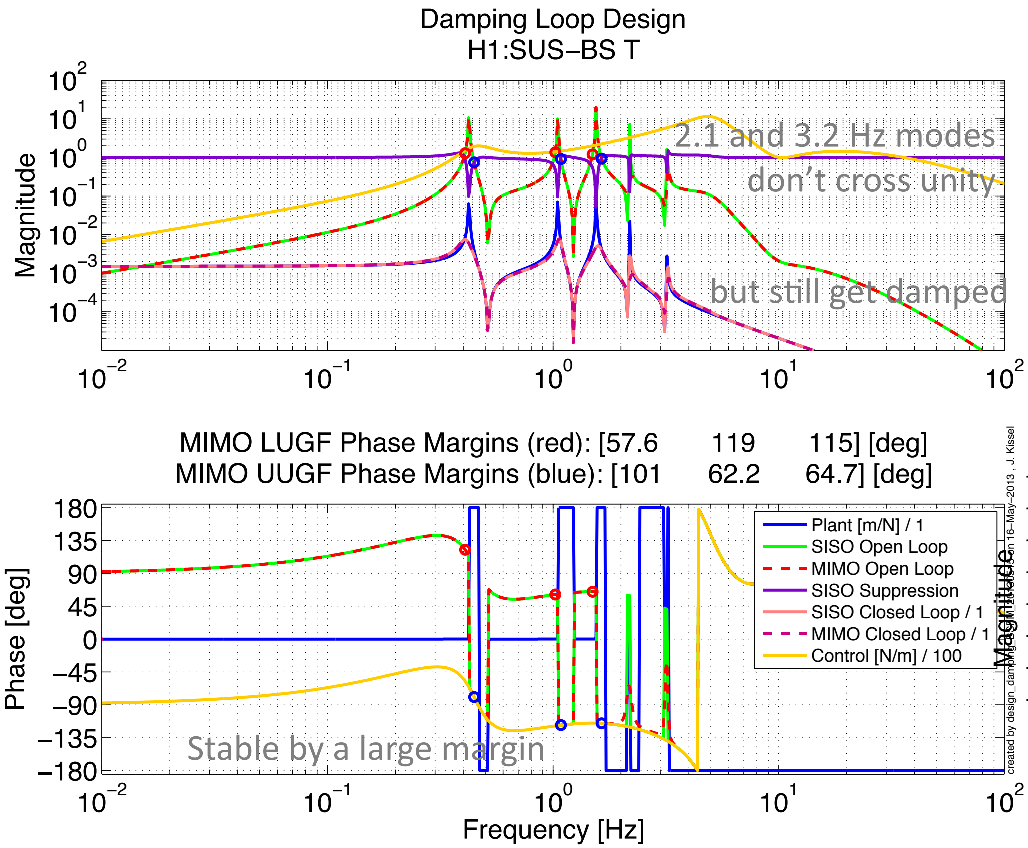
We know the very low frequency data of the **H2OAT data** is all tilt (if not sensor noise), and we know the mid-frequency band will be better

So I went with **Matt's Model** since it seems to fold in the most (optimistic?) realism

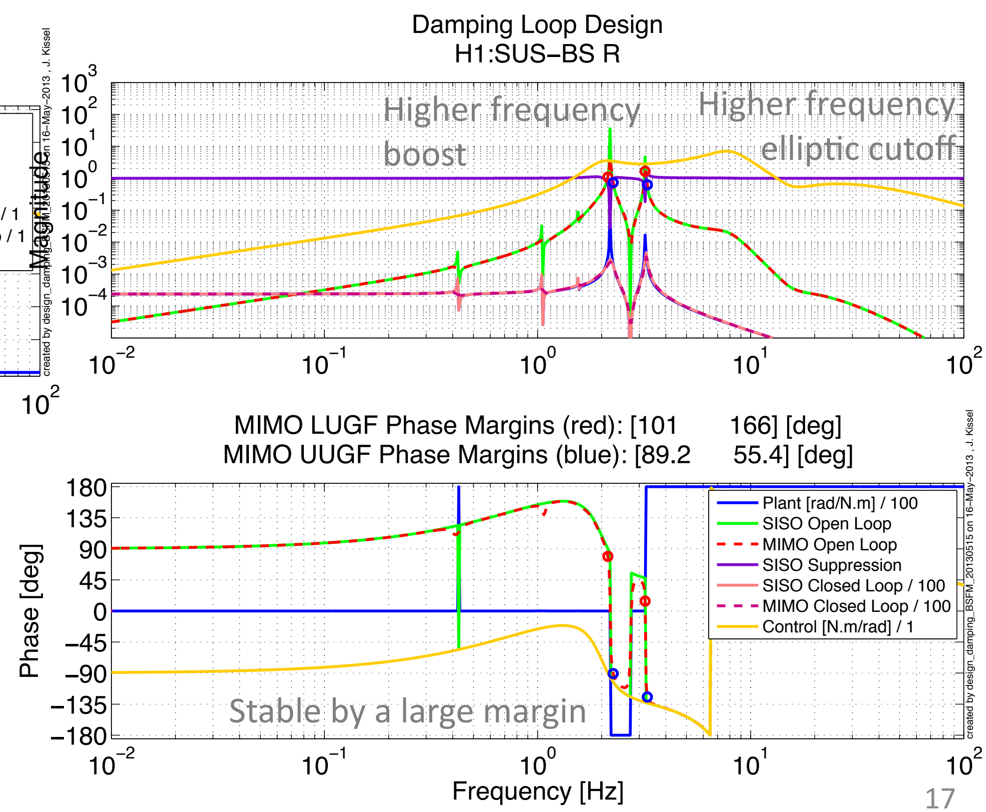


Damping Loop Design

MIMO Games (New Filters – T/R)



- Highest two T/R modes at 2.1 and 3.2 Hz would be trouble if T plant was SISO
- Turns out they can be damped in R
- So, push up the boost frequency in R (and subsequently the elliptic cutoff frequency), "skipping" the first three T/R modes, since they don't couple well to the R plant



- Then ***ignore*** them in the T design, since R has squashed them below unity gain