Thoughts on Damping the UIM

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1 Summary

We describe a simple calculation to damp the UIM (Upper Intermediate Mass) of the quad suspension. We start with the damped, production model of the quad. We use the original damping filters, not the damping filters currently in use at the sites. This is to simplify the bookkeeping. The production model also has good noise at 10 Hz, even though the damping could be better.

```
>> options    (this is a single chain suspension with the 'legacy' damping)
    singleChainBuildType: 'fiber'
           reacBuildType: []
         importFromSites: 0
                     IFO: 'H1'
                   Optic: 'ITMX'
          topMassDamping: 'default'
```

The modeling is all done with the code 'quad_calcs_for_proposal_v2.m' in the directory '{SeismicSVN}/seismic/Common/Documents/T1800504-damping-UIM'

For the code, we assume that the damping sensors will measure relative to the suspension cage, and will therefore couple in the motion of the seismic platform. This coupling impacts the angular motion at the first pendulum modes. This motion is likely to be a problem, and so we make a new motion target for the BSC ISI. This is 2x lower at 0.2 Hz, and flat to low frequency. In fact, this should be pretty simple to get with the frequency noise Leo Hollberg can achieve. The 0.4 Hz motion is 10x lower than the current requirement, but about the same as the current performance.

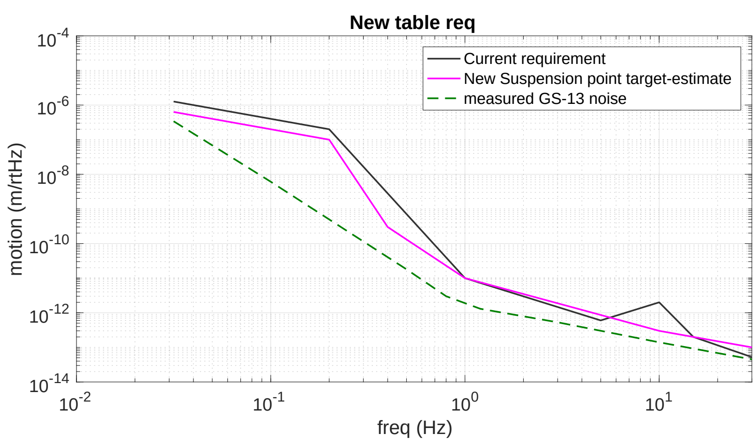

Figure 1: BSC-ISI requirements. The current requirement is shown in black. A new motion requirement needs to be established to take advantage of the improved tilt-sensing enabled by the optical levers on the SPI. For this calculation, we assume an ISI motion given by the magenta curve.

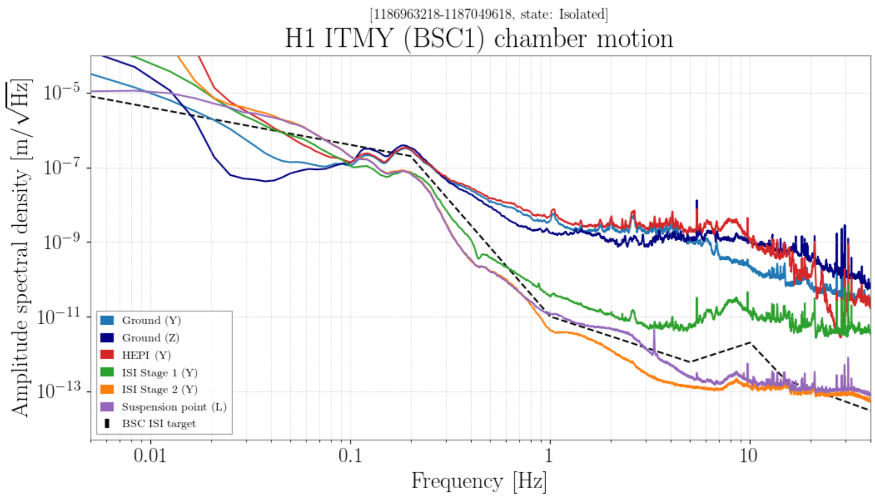

Figure 2: Motion of the BSC-ISI table, at the Suspension Point for the ITMY optic. This spectrum is from Hanford, and is the average performance on Aug 17, 2017 (the day we measured the Binary Neutron Star merger).

2 Pitch damping

The pitch plant is measured from the torque input on the UIM to the UIM displacement in radians. The plant is shown in figure 3. The pitch controller we model is very simple. It is called tiny_damp_P and the bode plot is shown in figure 4. The matlab definition is:

```
tiny_damp_P = zpk(-2*pi*[0],-2*pi*[10,10],800);
```

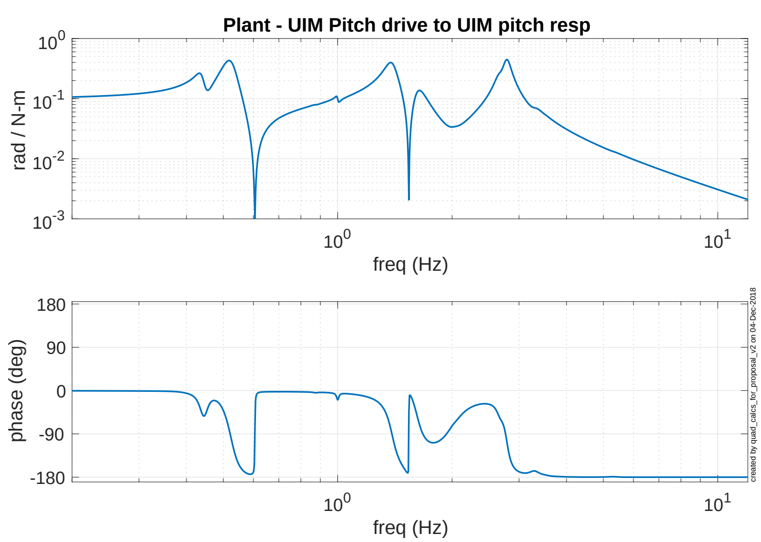

Figure 3: Pitch Response of the UIM when driven by a torque. This is the 'pitch plant' we will damp.

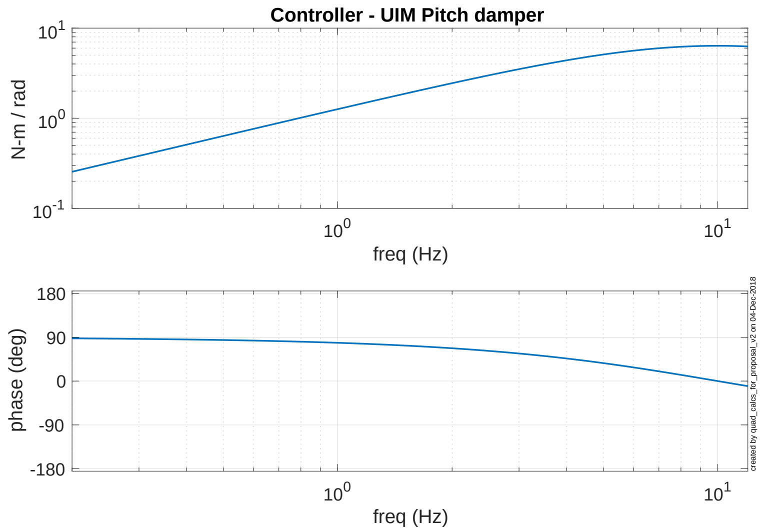

Figure 4: This is the damping control we apply. The input is radians, measured at the UIM, and the drive is a torque on the UIM.

The open loop controller for the UIM pitch is the product of the UIM plant and the UIM controller, as shown in figure 5. This is clearly not doing very much, and has not been optimized generally. However, the damping of the highest frequency mode is close to optimal. Additional damping for this mode is seen to increase the Q of the pitch when seen at the test-mass.

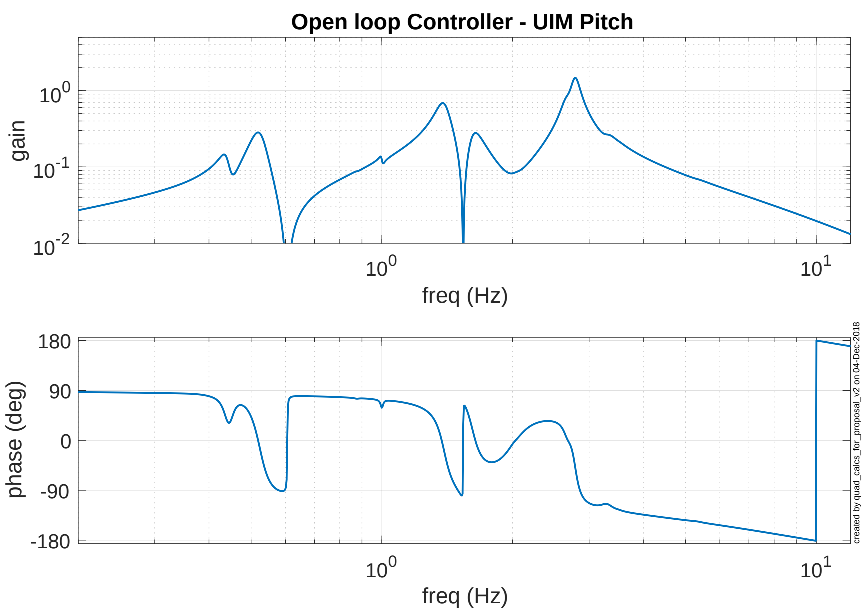

Figure 5: Open loop pitch control for the UIM. It only adds damping to the highest frequency mode. It has not been optimized.

3 Longitudinal Damping

The longitudinal (beam-line) damping (or the length damping) is similar to the pitch damping. It is called tiny_damp_L. Like the pitch control, it is basically a velocity damper, but includes a bit of shaping to get a bit more gain at the first resonance, and it also includes a 2nd-order elliptic filter with a damped zero at 10 Hz to help reduce the noise coupling. The Length plant in shown in figure 6 and the damper is shown in figure 7. The matlab definition of the damper is:

```
ellip10E = 10^(2.5/20) * myellip_z(5.2,2,2.5,15,8);
ellip_rolloff = ellip10E;
tiny_damp_L = zpk(-2*pi*[0,.8],-2*pi*[0.5,20,20],1.6e6) * ellip_rolloff;
```

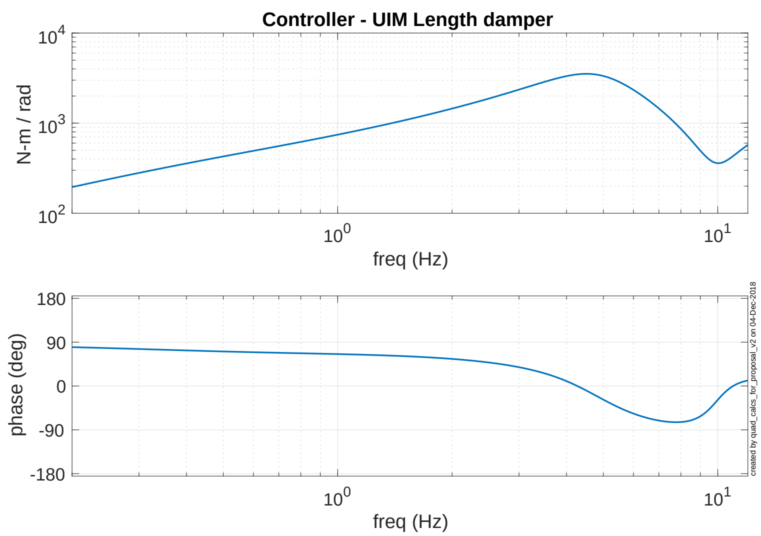

Figure 6: Longitudinal response of the UIM when driven by a force. This is the ‘length plant’ we will damp.

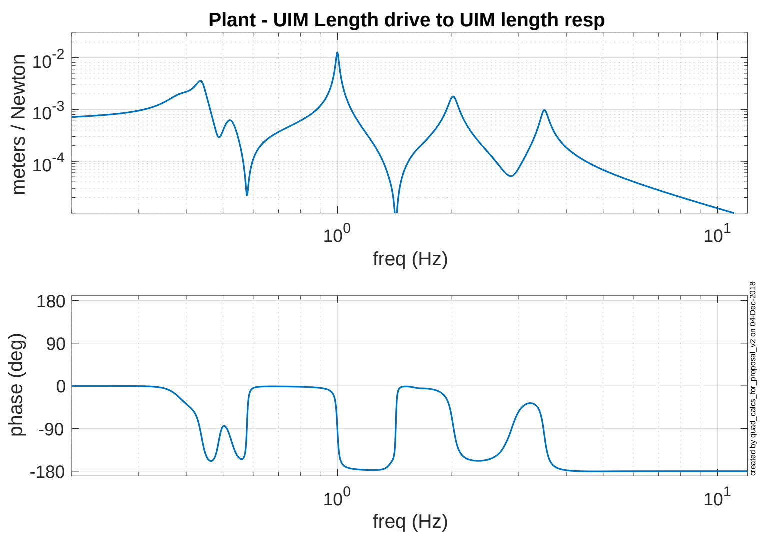

Figure 7: This is the longitudinal damping control we apply. The input is meters, measured at the UIM, and the drive is a force on the UIM.

The open loop control is show in figure 8. This controller is damping several of the modes.

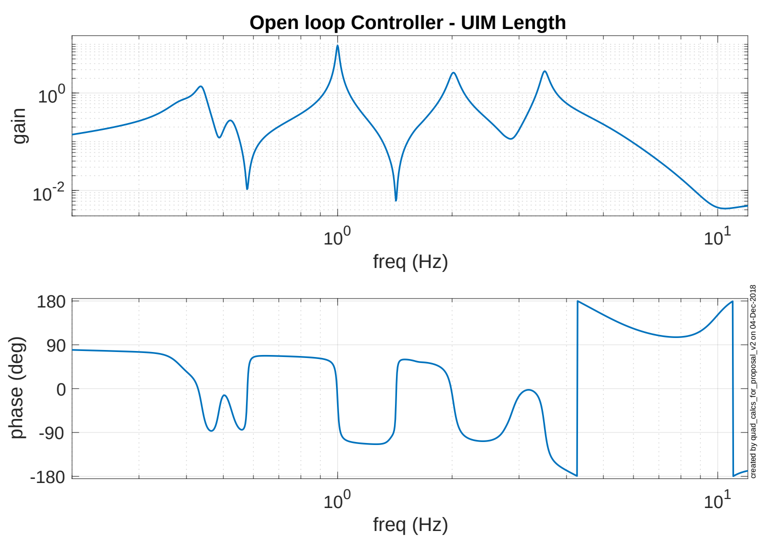

Figure 8: Open loop length control for the UIM.

4 New closed-loop response

The loops were close with simple matlab commands:

```
tiny_damp_both = parallel(tiny_damp_L, tiny_damp_P,[],[],[],[]);
d2_LP = feedback(QMD.dampedss, ...
    tiny_damp_both, ...
```

```
[QMD.dampedin.uim.drive.L,QMD.dampedin.uim.drive.P],...
[QMD.dampedout.uim.disp.L, QMD.dampedout.uim.disp.P]);
```

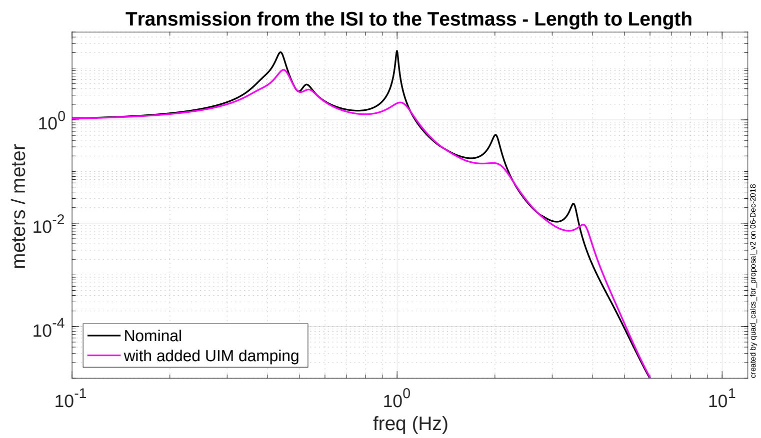

Figure 9: Longitudinal Transmission of the suspension with nominal damping (black) and with the added UIM damping (magenta).

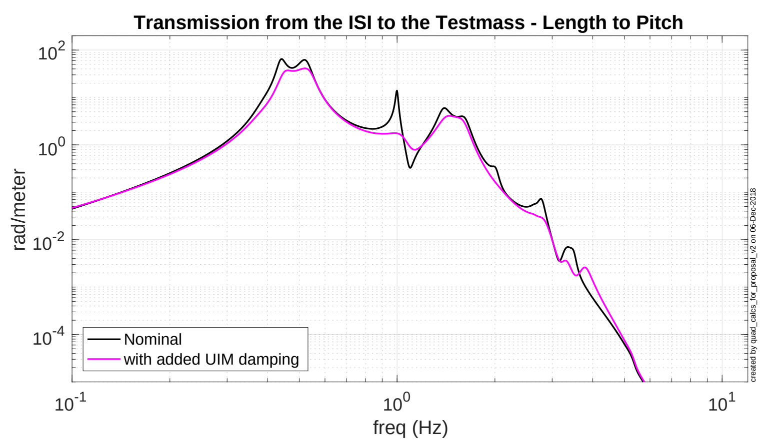

Figure 10: Coupling from ISI translation to test-mass pitch with nominal damping (black) and with the added UIM damping (magenta).

5 Noise Coupling to the Test mass

The UIM damping controllers have input in units of motion (meters or radians), because they are defined to observe the motion outputs of the SUS model. Input noise for these controllers is therefore in units of displacement, or displacement $/\sqrt{\text{Hz}}$.

```
coupling.uim_Lnoise2tstL = abs(squeeze(freqresp(...
     d2_LP(QMD.dampedout.tst.disp.L,  QMD.dampedin.uim.drive.L) * tiny_damp_L, 2*pi*freq)));
coupling.uim_Lnoise2tstP = abs(squeeze(freqresp(...
     d2_LP(QMD.dampedout.tst.disp.P,  QMD.dampedin.uim.drive.L) * tiny_damp_L, 2*pi*freq)));
```

```
coupling.uim_Pnoise2tstL = abs(squeeze(freqresp(...
     d2_LP(QMD.dampedout.tst.disp.L,  QMD.dampedin.uim.drive.P) * tiny_damp_P, 2*pi*freq)));
coupling.uim_Pnoise2tstP = abs(squeeze(freqresp(...
     d2_LP(QMD.dampedout.tst.disp.P,  QMD.dampedin.uim.drive.P) * tiny_damp_P, 2*pi*freq)));
```

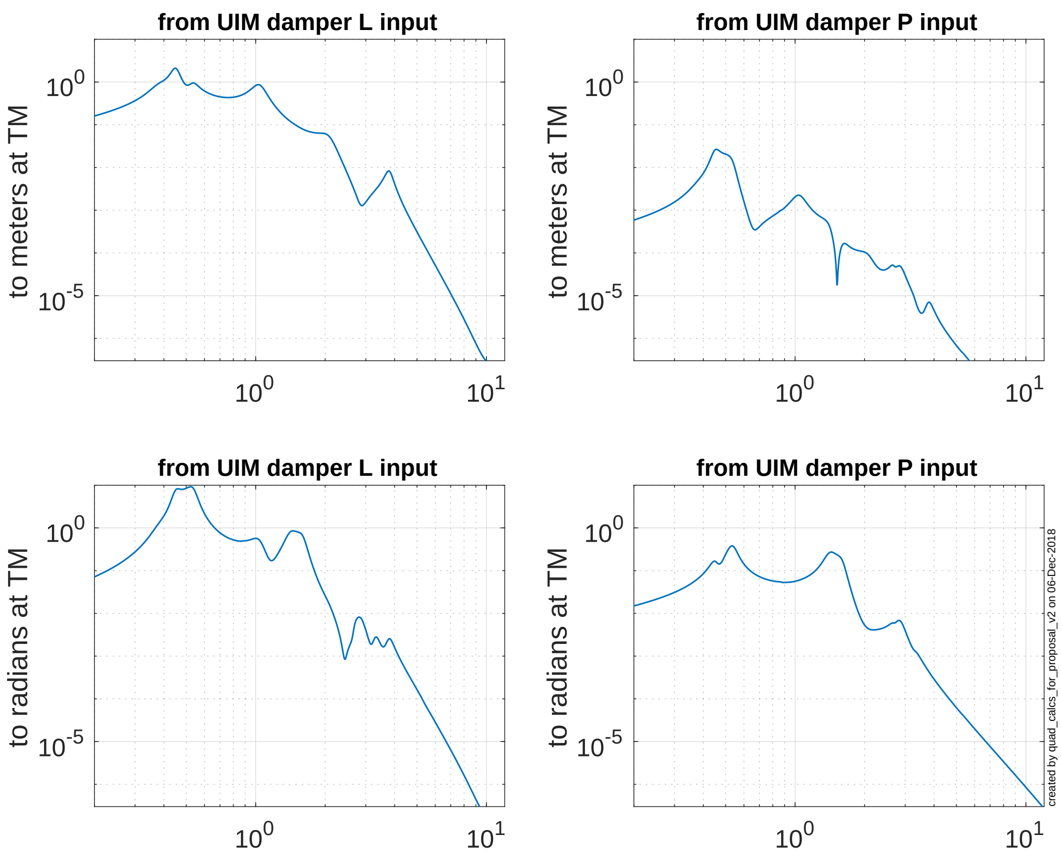

Figure 11: Coupling to motion at the test-mass from input referred noise at the UIM damper.

The coupling from the UIM dampers to the test mass is shown in figure 11. At the test-mass, the allowed motion at 10 Hz is about 10^{-19} m/$\sqrt{\text{Hz}}$ and 10^{-17} rad/$\sqrt{\text{Hz}}$. Using these couplings, this implies that the allowed sensor noise and platform motion (at the UIM sensor location) at 10 Hz is about $3 \cdot 10^{-13}$ m/$\sqrt{\text{Hz}}$ and $1 \cdot 10^{-11}$ rad/$\sqrt{\text{Hz}}$.

Figure 12 shows the motion of the test-mass when driven by the ISI motion and sensor noise at the UIM damper. At 10 Hz, these noises are below the 10^{-19} m/$\sqrt{\text{Hz}}$ target. This demonstrates that a UIM damper system could be used to improve the damping of the test-mass without compromising the test-mass motion.

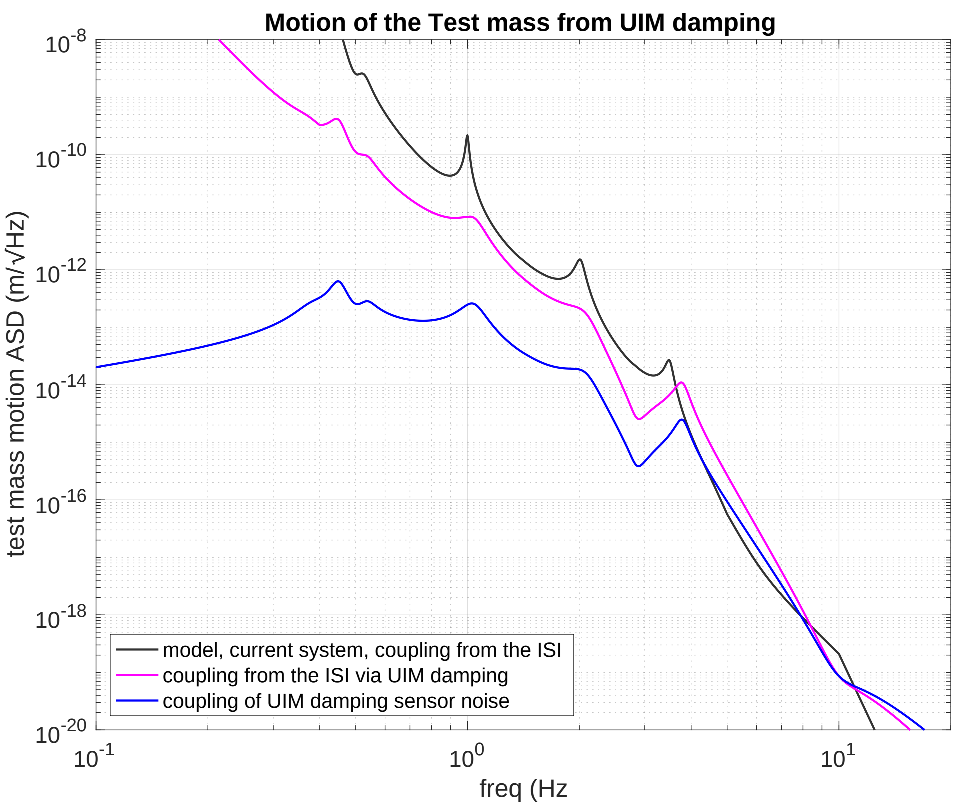

Figure 12: Longitudinal Motion of the test-mass. Inputs include: **black:** current ISI motion requirement * current damped transmission of the suspension from L to L. **magenta:** New ISI motion target * transmission of the suspension from UIM damper coupling to L with added UIM damping. **blue:** Flat sensor noise of $3 \cdot 10^{-13}$ m/$\sqrt{\text{Hz}}$ * transmission through the UIM damper to the test-mass.