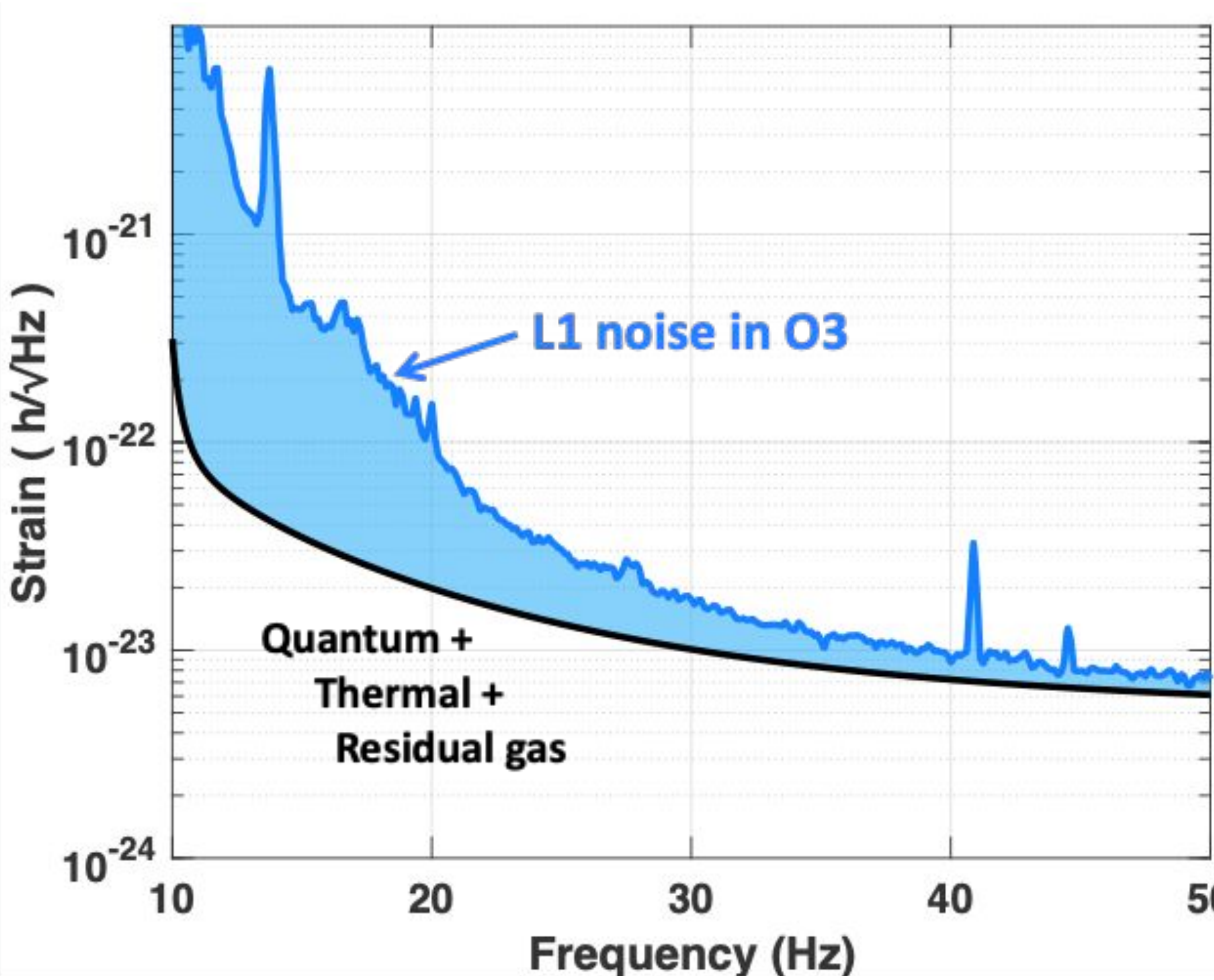
Review of the LSC 2021 Low Frequency Workshop

Brian Lantz, Peter Fritschel, May 19, 2021, G2101094

2 day conference, April 6 & 7
Talks and Agenda in DCC @ conf. 1091
Report is L2100055



Importance for aLIGO:

- More range, help w/ stable operation
- Early warning of inspirals ($t_{merge} \propto f_{low}^{-8/3}$)
- Detection of intermediate black holes (> 100 M_{sun})
  f_{merger} ~ 60 Hz for 100 + 100 system
  (recall excitement for ~ 4 cycles of GW190521)
- Low frequency pulsars

Also, for 3G

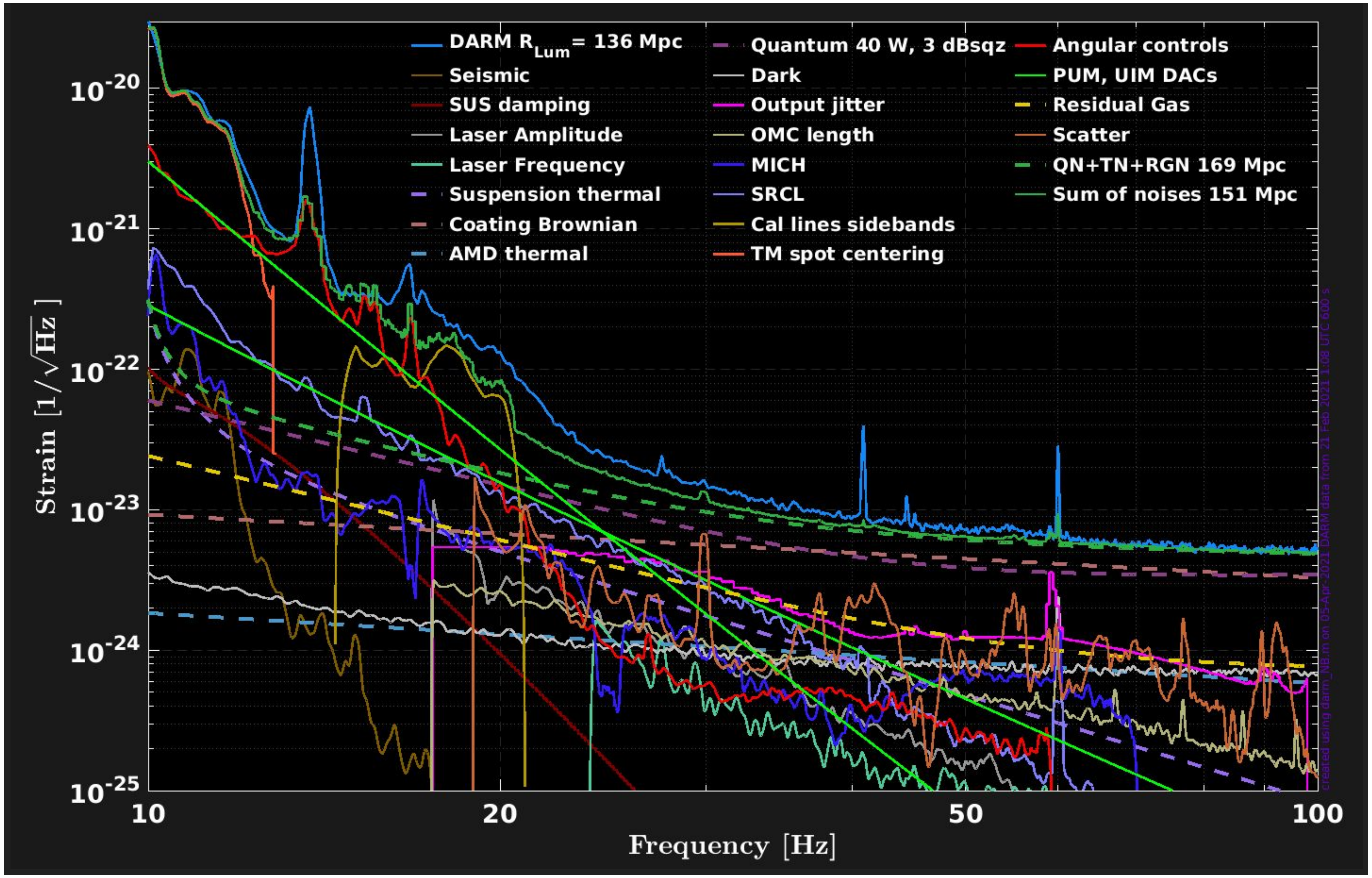
- Show that the 3G LF designs are achievable

High level view

- Good noise budgets
- Good instrument development
- A few examples of how instruments could improve pieces of the detector (improve ISI, improved SUS)
- Did not have end-to-end analysis of how to bring many pieces together to improve Advanced LIGO.
- Did generate a set of recommendations for next steps along this path.
- Peter Fritschel is chairing a new committee to evaluate plans for post A+ upgrades,
  see his talk from Monday LIGO-G2101000

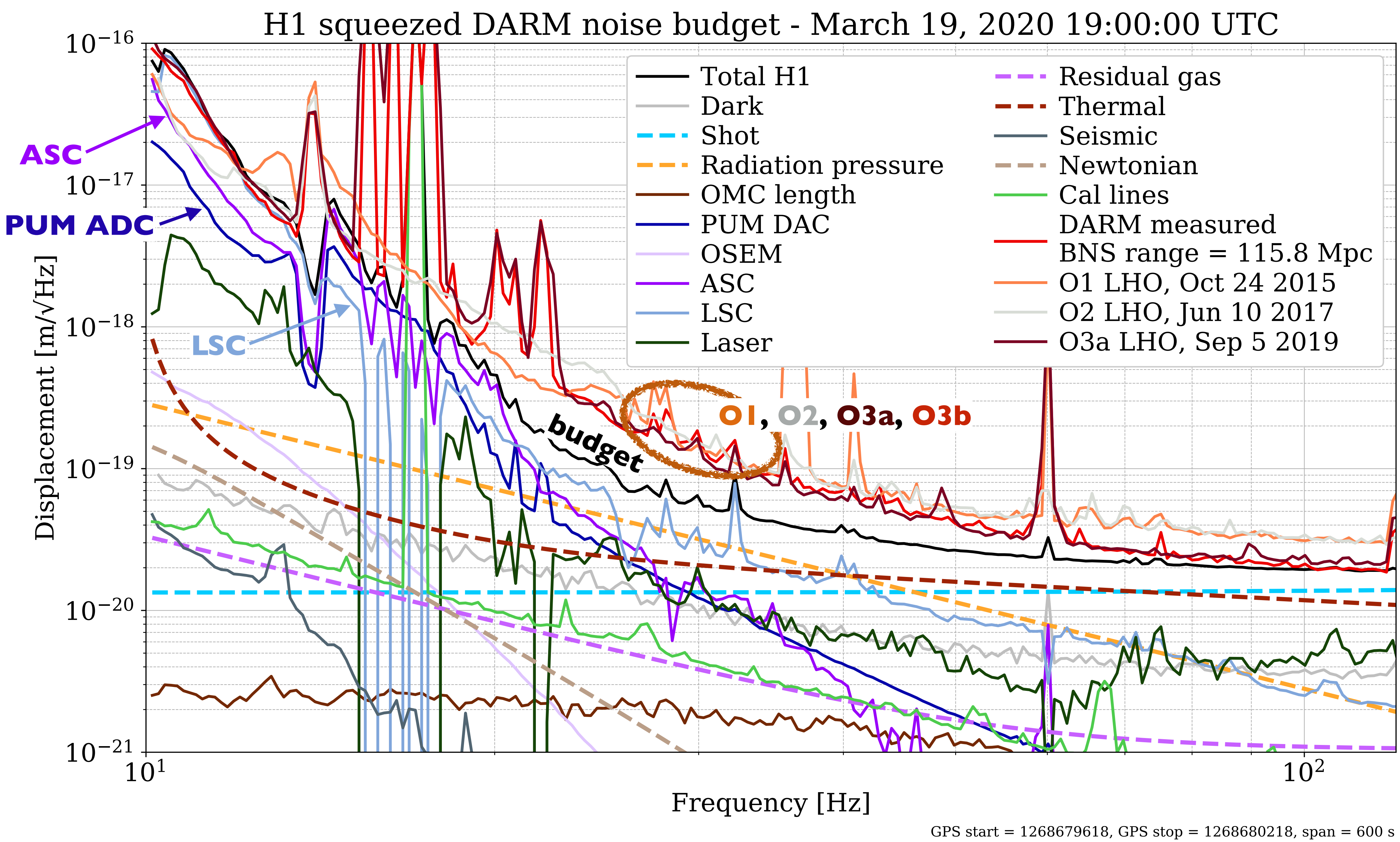
Noise budgets

- LLO noise budget from O3b - excellent recorded discussion at G2100763
- Includes lots of known technical noise and some mystery noise at low frequency.
- Total excess noise cost is 33 MPc, $(169/136)^3 = 1.92$



A. Effler, V. Frolov, G2100746

Noise budgets



C. Cahillane, S. Dwyer, G2100737

New Instrumentation

Compact interferometers

- Many groups are working on compact IFOs
- Some are general, some are components for a particular instrument
- Also development of improved OSEMs
- Strong effort with many clear opportunities in ISI and SUS

Compact IFO development from L2100055

Group	Type	Comments
U of Birmingham	HoQI: Homodyne Quadrature Interferometer	Laser is fiber-coupled to the sensor. New compact version being p'typed: 6x8.5x2.4cm
U of Birmingham	Customized commercial sensor coupled w/ DFM	Compact sensor head from SmarAct, fiber coupled to source and detectors.
U of Hamburg	Deep-Frequency Modulation (DFM) Interferometry	Compact optical head in development, includes diodes. Fiber coupled source.
Texas A&M (TAMU)	Two-beam, compact heterodyne IFO	Being developed for reading out their fused-silica resonator inertial sensor.
U of Brussels	Homodyne IFO (no fringe counting).	Developed for reading out their inertial sensors.
UC Louvain	Cryogenic Homodyne IFO.	Developed for reading out cryogenic, Watt's linkage inertial sensor.

New Instrumentation

- Many groups are working on new inertial sensors, translation & rotation
- Some are direct upgrades to ISI components (GS-13 with IFO readout)
- Some represent new capabilities (compact vibration sensors, in-vacuum rotation sensors)
- Some are quite novel (e.g. Rasnik 2D optical sensor)
- Improved commercial sensors (Nanometrics T360, MicroSense HV capacitive sensor)
- Seismic Platform Interferometer systems - both phase meter & digital interferometry

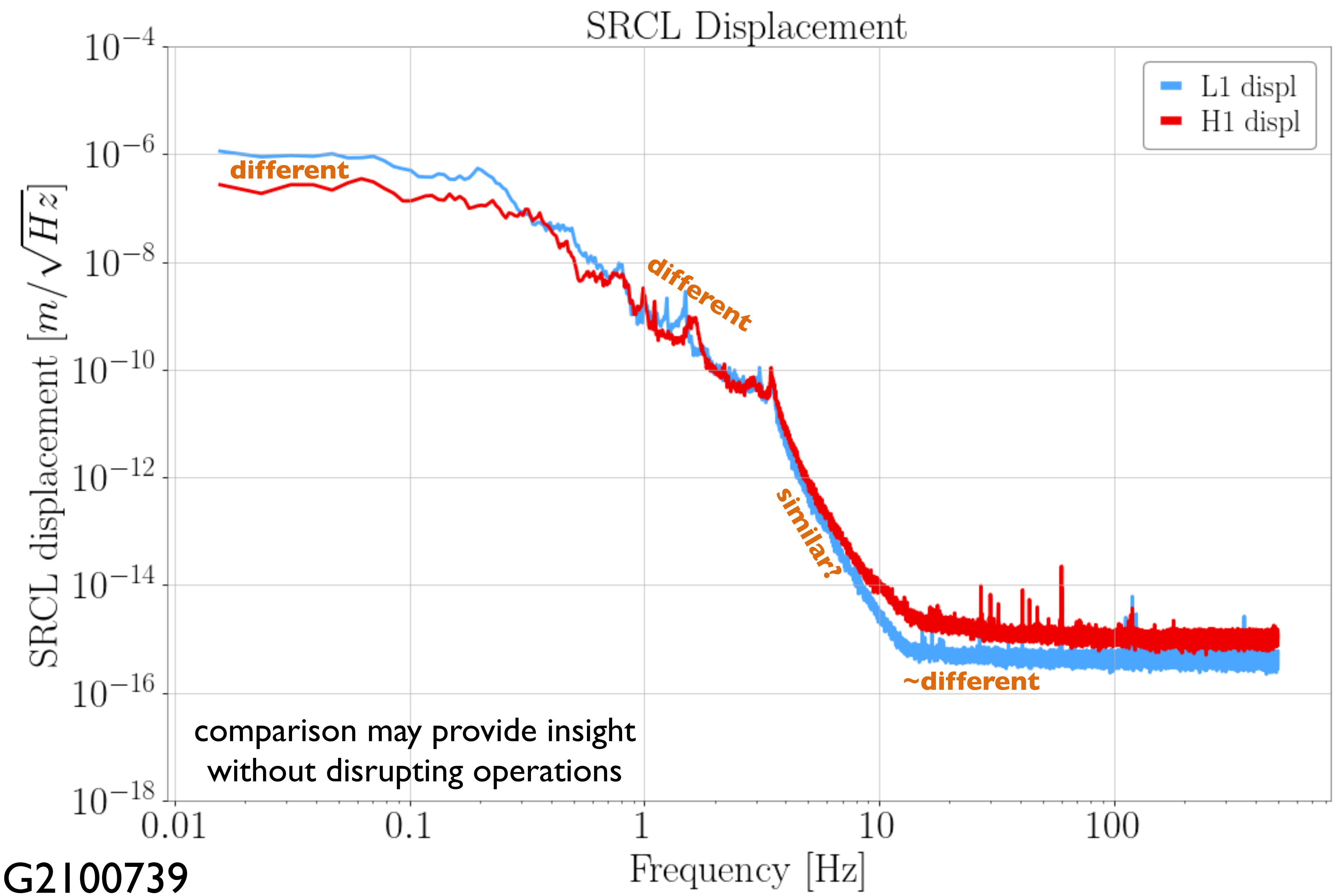
Inertial sensor developments from L2100055

Group/ reference	Type	Comments
U of Birmingham	L-4C and GS-13 with HoQI readout	Adding the HoQI readout has/ should improve the low frequency noise for the L-4C/ GS-13
Texas A&M (TAMU)	Fused silica resonator at several hertz	Being developed in conjunction with the compact IFO. Very compact.
U of Brussels	Inertial sensor	STS-1 mechanics retrofitted with commercial IFO readout. New vertical unit with glass flexure and STS-1 style leaf spring.
U of Washington	cBRS - In-vacuum rotation sensor	Version 2 of the compact BRS is in development. 30 cm scale. Has a cylindrical reference mass and uses HoQI readouts.
Paroscientific	QRS - In-vacuum rotation sensor	Similar to the CRS, but uses a proprietary quartz readout
OzGrav/ UWA	Alfra - In-vacuum rotation sensor	78 cm scale balance beam with optical walk-off sensor
U of Birmingham	6D sensor	Scaled down version of the 6D isolator. In early development.

Recommendations

1. Further investigate the output beam jitter noise (into the OMC). Repeat the measurements made on L1 to estimate this noise on the H1 detector. Understand the source of the beam jitter -- e.g., is it HAM platform noise filtered by the Tip-tilt suspensions? Or Tip-tilt suspension actuator noise?

2. Continue the comparison between L1 and H1 of LSC and ASC channels (noise levels) and control loop designs (from Jenne's start).



J. Driggers, G2100739

Recommendations

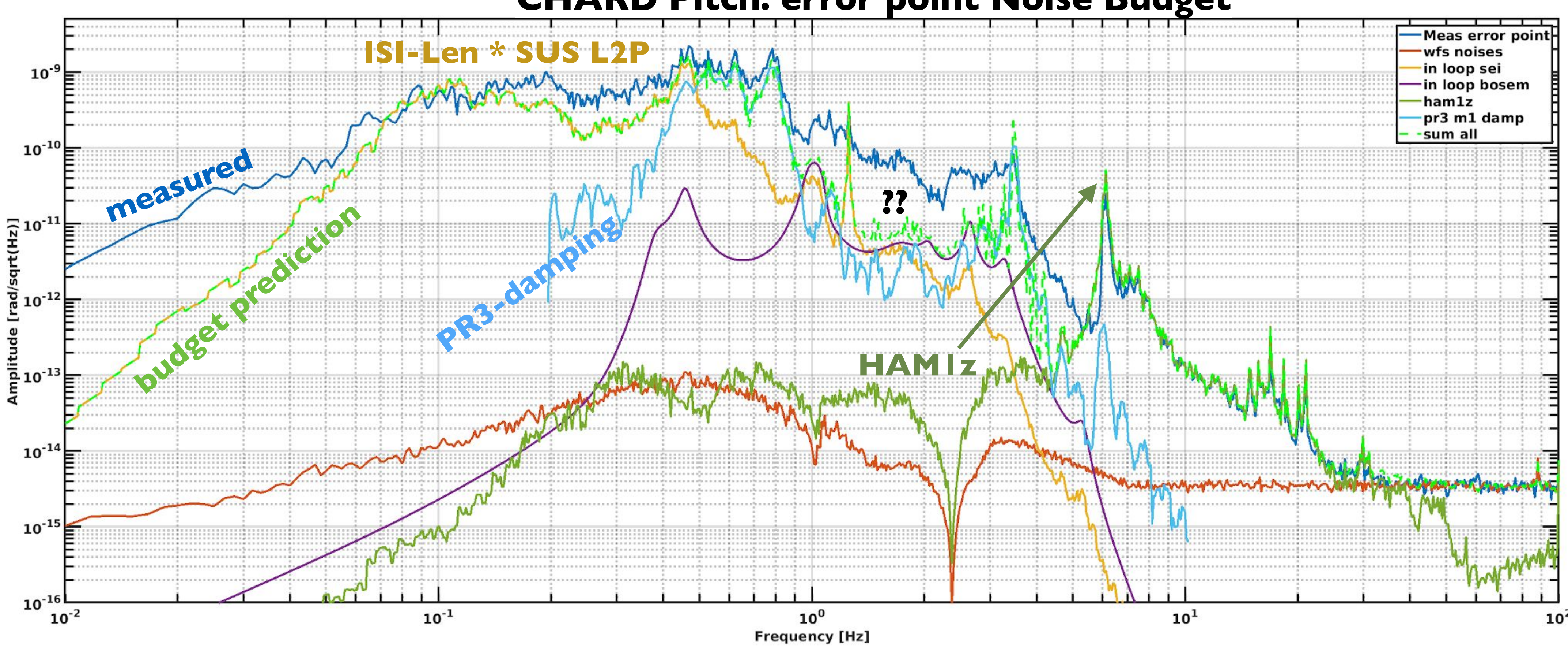
Angular motion & WFS

3. Explore ways to mitigate the coupling of motion to the REFL WFS signals. For example, by modifying the Tip-Tilts: improve vertical damping, or short-out the vertical compliance (to eliminate the 6 Hz vertical mode). On a longer time scale, evaluate the benefits of using a HAM Double Suspension (HDS) on this path in lieu of the Tip-Tilts.

4. Try to understand the source of the WFS noise in the 1-20 Hz band, which is currently mostly unexplained. Also try to understand the mechanism(s) of the coupling of angular control signals to test mass longitudinal motion (DARM): the measured coupling is around 1-2 mm/rad, but the typical test mass residual angular motion of 1 nrad-rms produces spot motion on the test masses of 20-30 um -- so why is the coupling so big?

5. a) Study ways to reduce the coupling of length drive to angular motion in the auxiliary suspensions. Solutions may arise from better understanding of couplings identified above, or they may arise from more general techniques, e.g. reducing the Q of angular modes of the suspensions used to control the lengths.
   b) Study ways to reduce ISI table motion, in order to minimize the length drive applied to the auxiliary suspensions (to reduce angular motion). Note, a table of measurements to reduce the SUS cross couplings can be found at https://tinyurl.com/LIGOSUSActuatorTuning

CHARD Pitch: error point Noise Budget



M. Kasprzack, G2100751

Recommendations

SUS and ISI modeling

6. Make a test of Shapiro's suspension modal damping. One of the large triple suspensions (HLTS) would be a good test case, or possibly one of the new Filter Cavity suspensions.

7. Look into the applicability of the type of complementary filters that are used in seismic controls for blending sensor signals, for use in the suspension controls (to split controls between suspension stages).

8. Look into potential benefits of applying local damping of the test masses in the basis of the arm alignment DoF (CHARD, DHARD, CSOFT, DSOFT) rather than at the individual test mass basis.

9. Make some tutorials for how to use the Matlab suspension models.
   The CSWG may be a good place to advertise/market this task.

10. Develop a simple, common tool to allow the Matlab suspension models to be used in Python noise budgeting tools.

11. Investigate potential benefits of lower noise sensors for suspension local damping (i.e., lower noise BOSEMs). Currently SUS damping noise in DARM is rather low above 10 Hz (cf. L1 and H1 noise budgets), nor is quad SUS damping noise dominant in the alignment DoF in the control band (0.5-10 Hz), at least for CHARD and DHARD pitch. But some other DoF do seem to be limited by damping noise -- e.g., CHARD via PR3 damping, and SRCL via SRx damping. A more complete study should be made of where suspension damping noise is limiting performance. Include in this study the option of lower noise sensors at lower stages of the suspension.

12. a) Extend the BSC-ISI and HAM-ISI models to more than the X and RY (Y and RX) DoF, to include RZ and Z.
    b) Extend the BSC-ISI and HAM-ISI models to help quantify the the tilt coupling below about 0.2 Hz.

Recommendations

ISI sensors, optical sensors

13. Noise in the ISI capacitive position sensors (CPS) is clearly a limiting factor, particularly for the HAMs but also (to a lesser degree) for the BSCs. On the HAMs, swapping the coarse-CPS with fine-CPS would provide a significant improvement, and the new HAM-ISIs for the filter cavity will provide a good test of this solution. The full scope of upgrading all HAM-ISI CPS to 'fine' versions should be studied and documented: the required design changes; hardware costs; time/personpower required for retrofitting. This study should include the option of upgrading to the lower-noise (higher voltage) CPS model currently still under test. For the BSC-ISIs, the scope of upgrading to these lower-noise CPS should also be documented.

14. Study what would be needed to run all the rX rY isolation loops on stage 2 of the BSC-ISIs.

15. The LSC efforts on interferometric displacement sensors should continue and their progress should be tracked by the LIGO Lab. The timescale for expecting significant progress is probably about a year (i.e., early 2022).

16. In vacuum rotation sensors. Development of in-vacuum rotation sensors should continue. Predictions for improved isolation performance of the ISIs should be tested in one of the prototype facilities, e.g. Stanford or LASTI. A trial of a single rotation sensor in a LIGO interferometer could be an option for O5, or possibly even for installation in an O4 commissioning break.

Recommendations

17. Model various sensing upgrades for the ISIs to improve the performance below 1 Hz.
Questions to consider include - where does the stage 1 tilt originate?
How much of the current issues come from BSC motion, how much from HAM motion, and how much from relative motion?
Do we need to improve the motion at the end stations, or just in the LVEA?
What could we do to reduce the platform motion at 0.4-0.5 Hz, where the first quad suspensions modes lie.

    Possible upgrades include:

    a) Replace the T240s on the BSC-ISI with T360s
    b) Add rotation sensors to the BSC-ISI and/or the HAM-ISI
    c) Replace the HAM-ISI GS-13s with better inertial sensors, e.g. GS13s with IFO readouts
    d) Use lower noise CPSs
    e) Add SPI relative sensors between the tables.
    f) SPI sensors plus some sort of improved rotation sensing, either direct rotation sensors or improved Z sensors on adjacent platforms

18. Start discussions between Stanford/Hannover and LIGO Lab on the practicalities of integrating the HAM platform-to-platform sensors that have been developed at AEI-Hannover.

19. In addition to ISI motion, the auxiliary DOFs are also limited by suspension motion above 0.7 Hz. We should have a system level discussion of how to approach these DOFs.

Conclusions

- Workshop generated many recommendations.
- Noise budgets give good direction for where we need Low Frequency improvements, but mysteries remain.
- LSC instrument development is strong, provides lots of opportunities.
- Many recommendations on how to improve the our modeling, particularly system modeling.
- Problems we see have several steps, involve cross-couplings, and encompass several sub-systems - challenge for 3G designs
- As we know, the "Control System" and the "System to be Controlled" is not an ISI, or CHARD-P, it's multiple ISIs + multiple SUSs + ISC. Need better tools (see next talk?)
- (outside of workshop, but interesting to consider) For major upgrades, some design modifications are worth exploring - lower relative motion at 0.1 Hz? Lower cross-coupling in SUS? ASC?
- As we move towards O5 and beyond, we look forward to implementing many of these recommendations