Violin mode amplitude glitch monitor for the presence of excess noise: from GEO 600 to aLIGO

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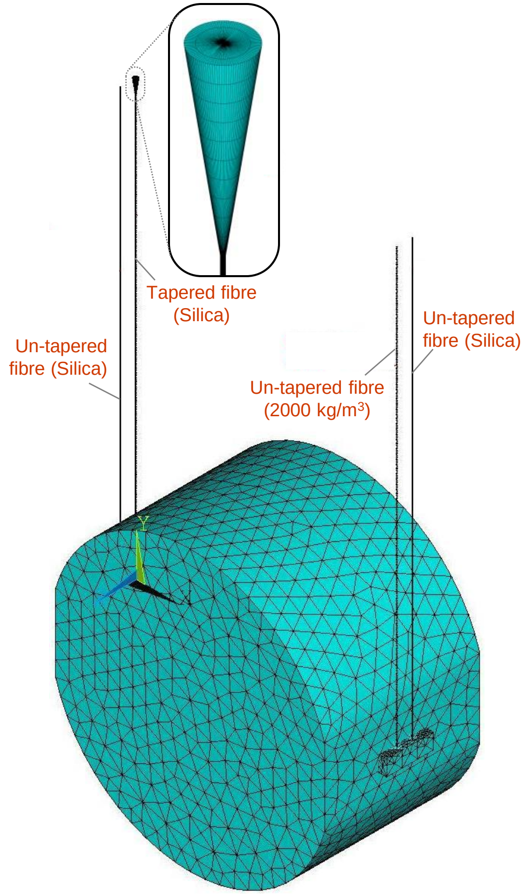
Summary of the analysis applied to GEO 600

- Thermal noise is dominant noise source near the “violin modes”.
- Assuming thermal fluctuations as only excitation of these modes → Brownian motion of the test masses.
- The randomness of the Brownian motion shows as changes in the amplitude of the violin modes with a normal (or Gaussian) distribution.
- **We focus on events that excite the violin modes such that their amplitude variation with time is inconsistent with thermal noise.**

Finite elements model of GEO 600 suspension

University of Glasgow

- **Establish that observed violin mode amplitude is consistent with thermal fluctuation excitation.**
- FE model of GEO 600 monolithic suspensions.
- Fibres were modeled with ideal geometry, and slightly different properties to break degeneracy.
- The energy of motion and displacement of the anti-node of the mode and of the mass at the fundamental violin mode was obtained (relative numbers, arbitrary excitation).
- Assuming that the system energy is entirely due to thermal noise we calculate the calibration factor.

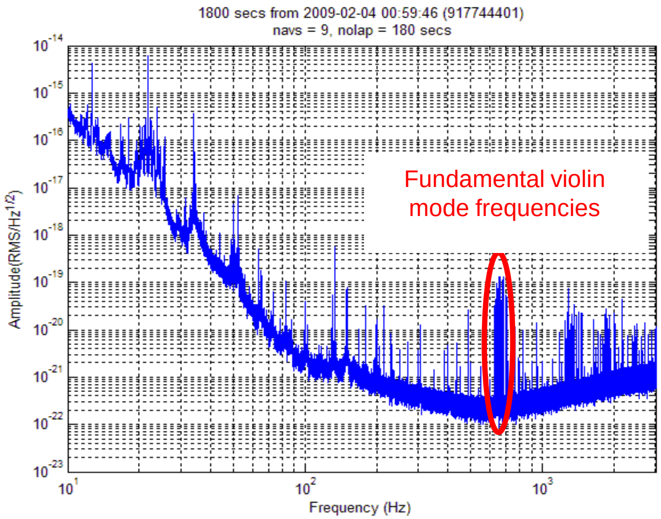


Fibre design	Mode frequency (Hz)	System displacement (m)	System energy (J)	Mass energy (J)	Calibrated violin mode amplitude *rms* (m)
Un-tapered fibre 1	718.5	292.9	$1.02 \cdot 10^{7}$	8.68	$5.6 \cdot 10^{-18}$
Un-tapered fibre 2	730.7	292.9	$1.05 \cdot 10^{7}$	9.0	$5.5 \cdot 10^{-18}$
Un-tapered fibre (2000 kg/m^3)	753.9	307.4	$1.12 \cdot 10^{7}$	8.68	$5.05 \cdot 10^{-18}$
Tapered fibre	783.7	303.4	$1.21 \cdot 10^{7}$	10.03	$5.06 \cdot 10^{-18}$

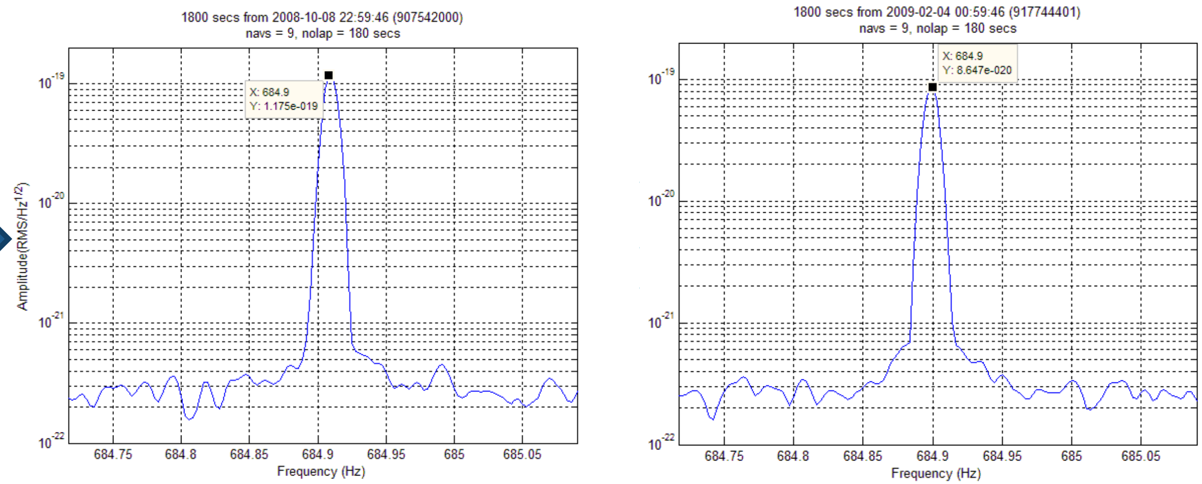
- Spread of the violin mode amplitude between simulated fibres is less than 10%. Experimental violin modes range from 627 Hz to 713 Hz.
- Frequencies of simulated fibres a few percent higher than experimental ones, due to lack of precise knowledge of GEO 600 fibre diameter and presence of damping material.

Experimental violin mode amplitude in GEO 600

GEO spectrum 2009

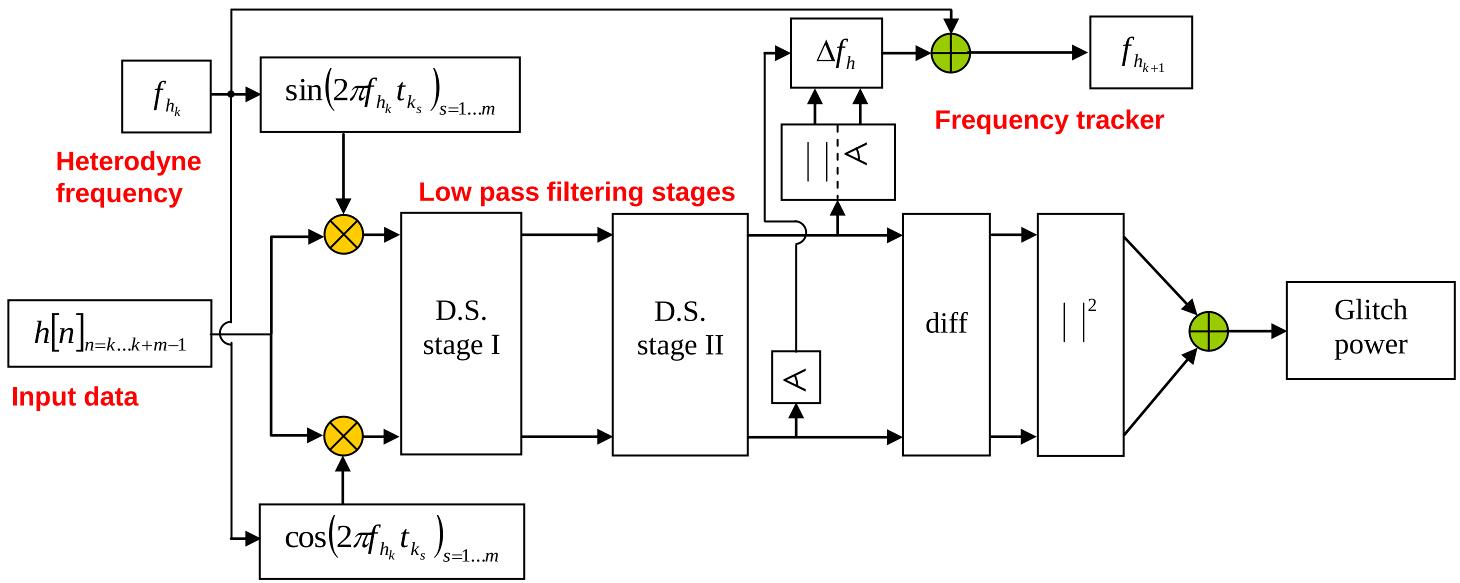


Looking at East end mirror violin mode amplitude 4 months apart



- The experimental strain amplitude, after settling, of a fundamental violin mode in GEO 600 oscillated by a factor of about 2 depending on time of measurement.
- As an example we look above at violin mode at 684.9 Hz associated to (MFe):
  - Amplitude of violin mode lies between $7\cdot10^{-20}$ and $12\cdot10^{-20}$ *rms*/$\sqrt{Hz}$ *(Bw=0.012 Hz).*
  - Amplitude *rms* of violin mode oscillates between $4.5\cdot10^{-18}$ and $7.9\cdot10^{-18}$ m.
- FE model values are within experimental range. Reasonable to assume that observed violin mode amplitude in GEO 600 is consistent with thermal noise.

Violin mode amplitude monitor algorithm



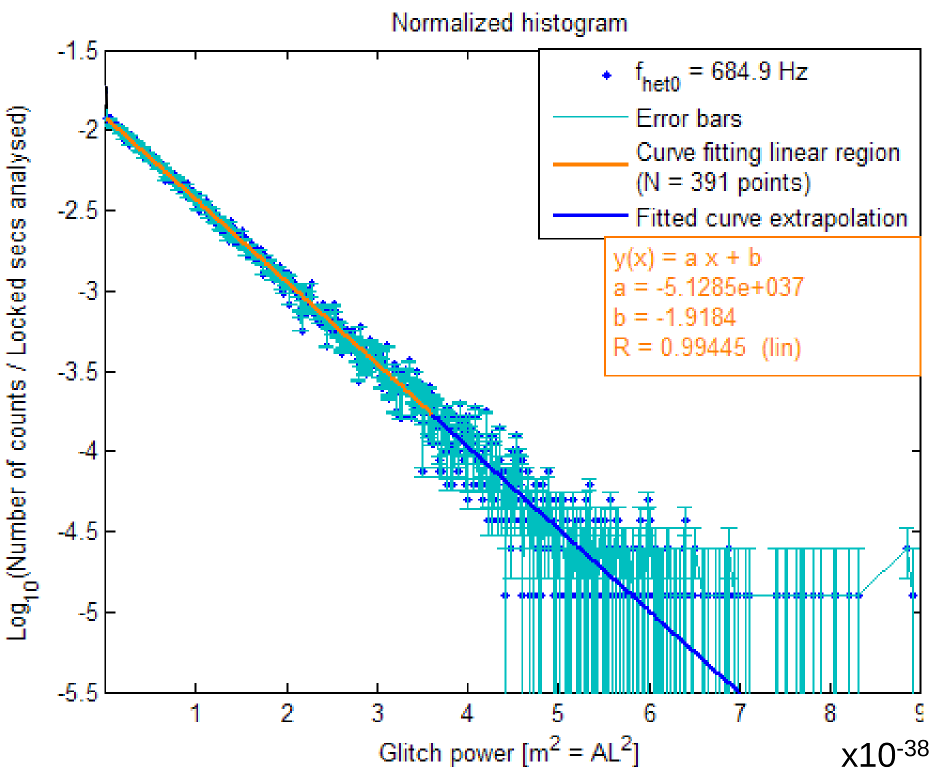
- Objective is to **monitor and record short-term perturbations** or "glitches'" **in the amplitude of** the selected **violin modes**. The approach employs a heterodyning, filtering and down-sampling procedure followed by differencing to reveal changes in the complex amplitude of the mode (implemented in MATLAB).

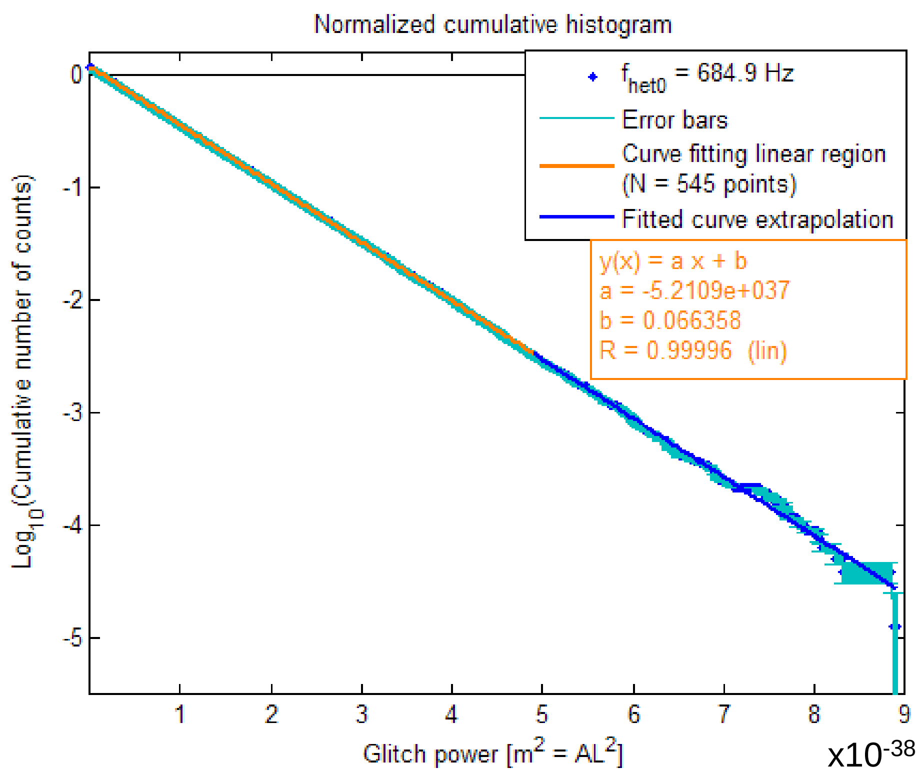
Analysis: Input data and violin mode selection

- Selection of analysed h(t) data:
  - Detector locked and no maintenance carried out.
  - No disturbance due to other processes within the frequency range of the violin modes.
- Selection of violin modes:
  - Those without control forces applied; Far east and far north mirrors and beamsplitter.
  - Suitable violin modes do not change in amplitude during an interferometric re-lock.

Analysis results: Glitch power histograms, ex. 1

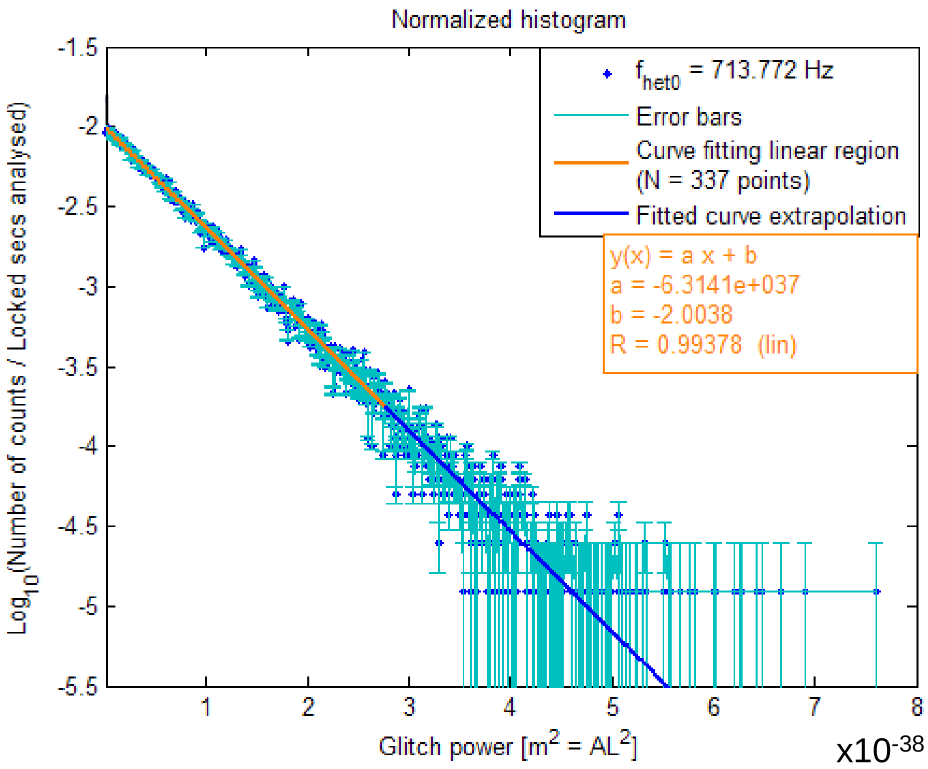
Violin mode at 684.9 Hz

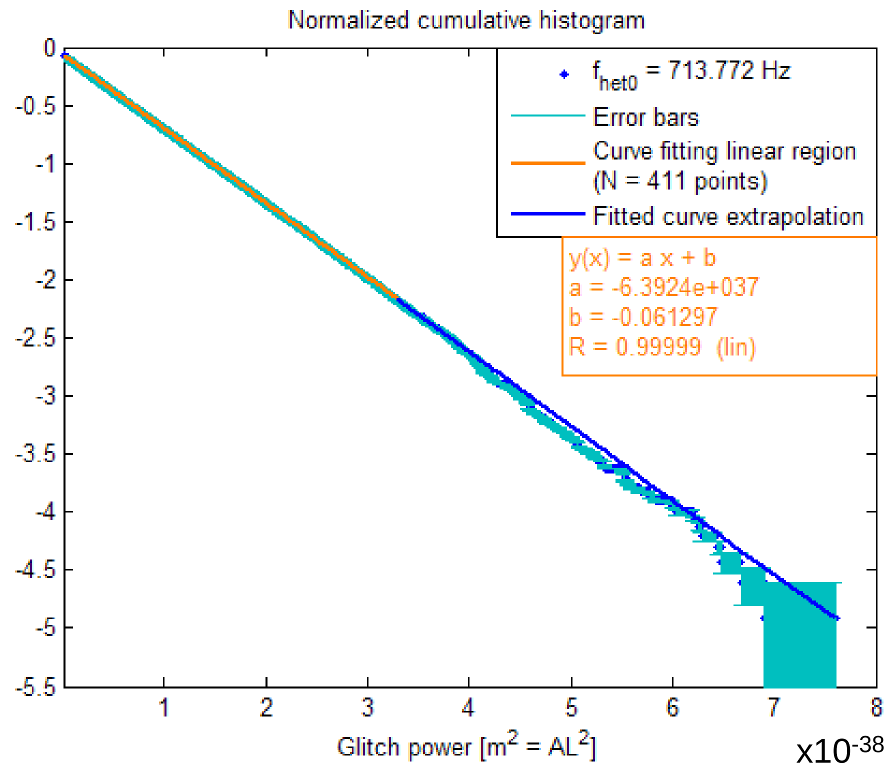




Analysis results: Glitch power histograms, ex. 2

Violin mode at 713.8 Hz



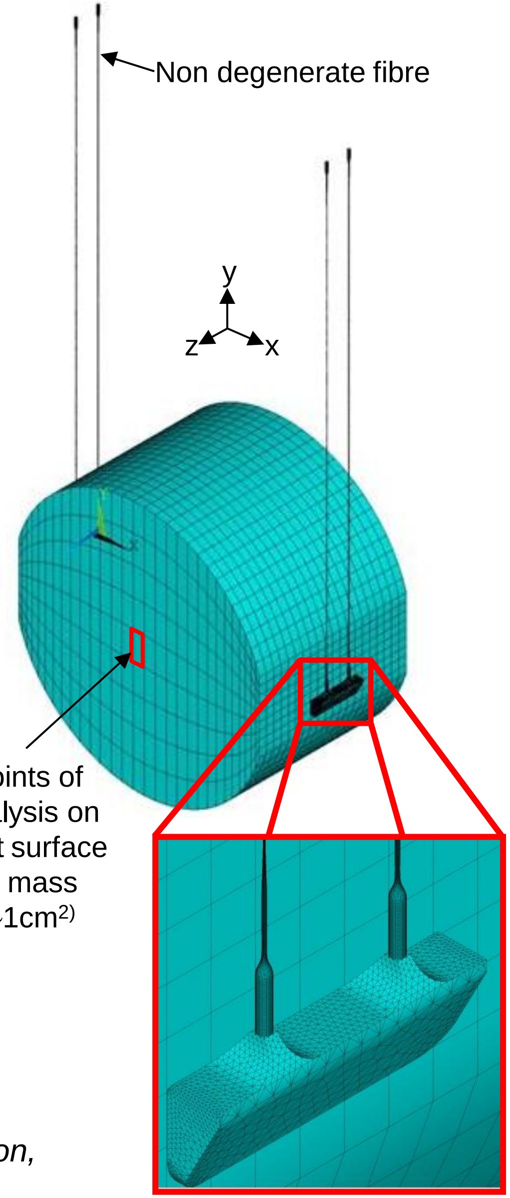


Analysis results: Conclusions

- The good linear fits of the logarithmic normalized histograms indicate a Gaussian distribution as expected if the source of glitches is thermal noise.
- No deviation from a Gaussian distribution is seen to exceed the error bars, therefore **no excess of glitches is observed that would correspond to non thermal excitations of the suspensions, at least at a rate of 1 glitch per day**.
- More details in publication http://iopscience.iop.org/0264-9381/27/15/155017/pdf/0264-9381_27_15_155017.pdf

Application to aLIGO - FEA

- The previous analysis is the baseline for the current work being done for aLIGO. Initial investigations discussed next.
- ANSYS simulations use full aLIGO fibre geometries [1].
- To decouple violin mode frequencies we increased by 2.5% the density of 3 fibres providing a similar spread in frequencies to those observed at LLO.
- Two modes very close in frequency (order of 0.1 Hz) are seen in the non degenerate fibre, with orthogonal motion. This is due to very slight ellipticity in the fibre shape.

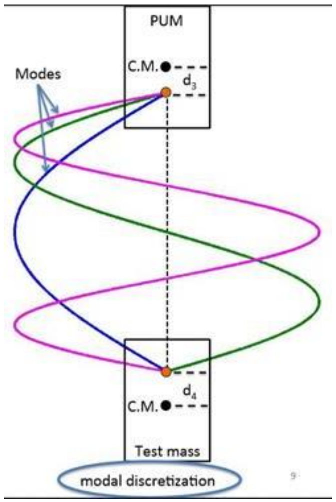


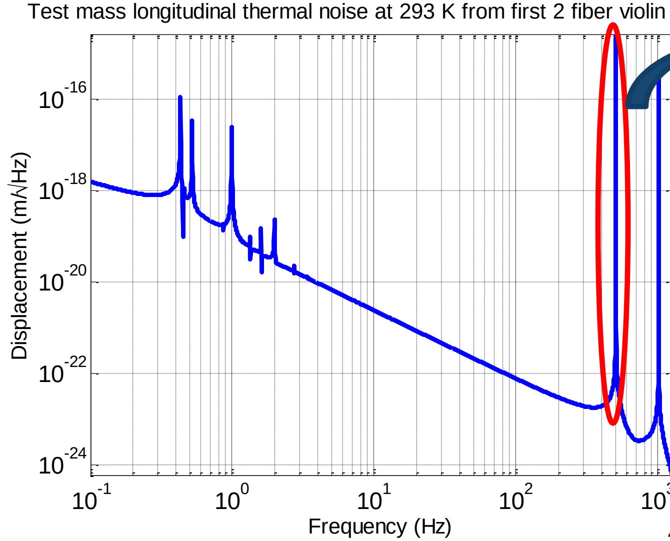
Mode Frequency [Hz]	Uncal. system energy (J)	Displacement of the fibre antinode [m] (calibrated RMS)			Surface displacement of mass (range for 4 nodes of mesh central square) [m] (calibrated RMS)		
		X	Z (long.)	Angle to long. [deg]	X	Z (long.)	Average (Z)
510.6	5.147e06	5.80e-13	1.48e-12	21.4	[3.79 - 3.82]e-18	[1.67 – 2.19]e-18	1.93e-18
510.9	5.152e06	1.48e-12	5.80e-13	68.6	[0.38 – 0.42]e-18	[0.63 – 0.89]e-18	0.76e-18

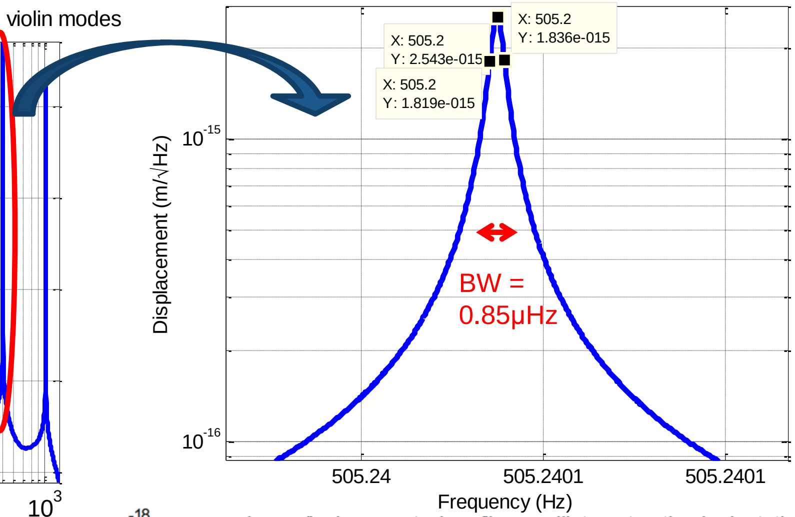
[1] A. Cumming, et. al., *Design and development of the advanced LIGO monolithic fused silica suspension*, CQG **29**, 035003, 2012

Application to aLIGO – Matlab QUAD model

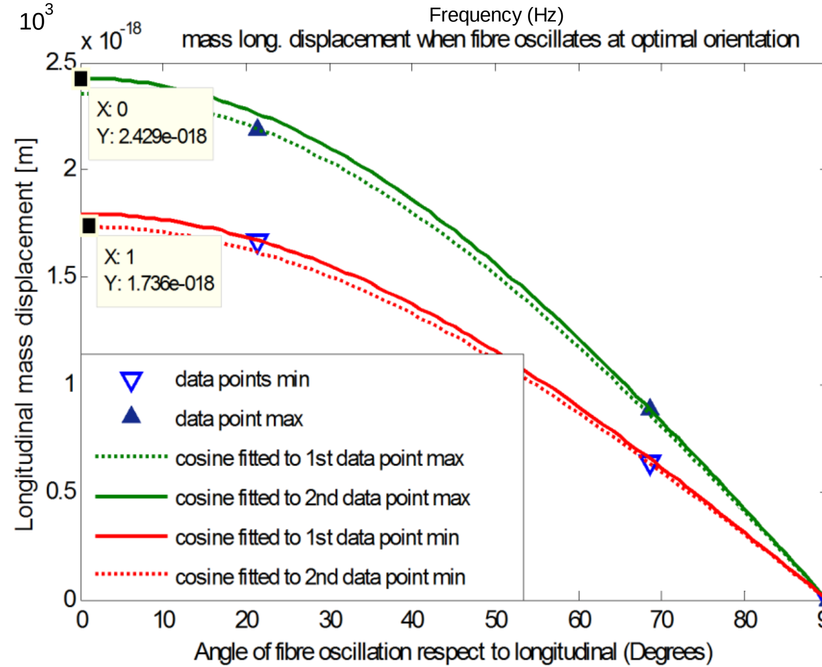
- We compared our results with those from B. Shapiro's Matlab model of the QUAD suspensions (G1401132, T1400587) which also includes violin modes.





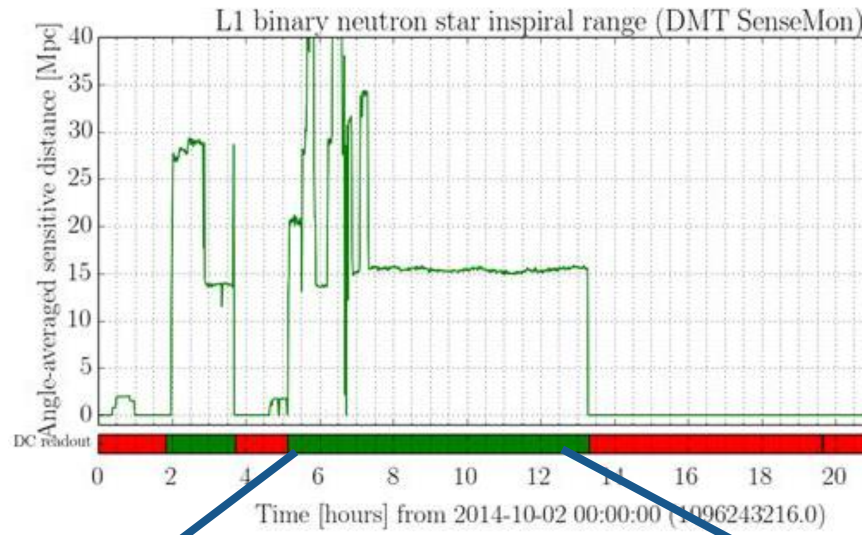


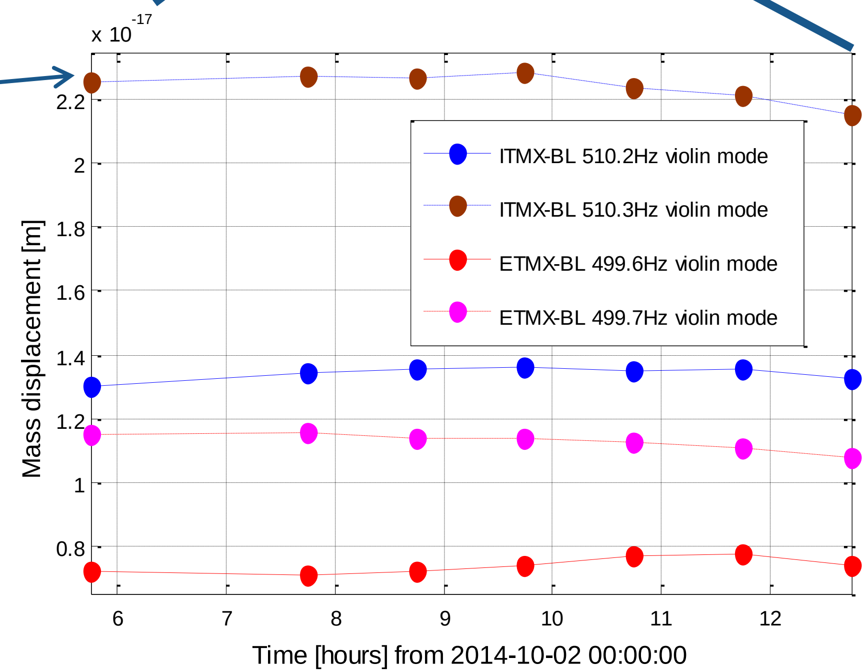
- The longitudinal mass displacement due to violin mode excited with thermal noise is **2.35e-18 m (RMS)**.
- Matlab model assumes longitudinal oscillation of fibre, while ANSYS model has a realistic non optimal orientation. Extrapolate to compare results: **[1.74 – 2.43]e-18 m (RMS)**



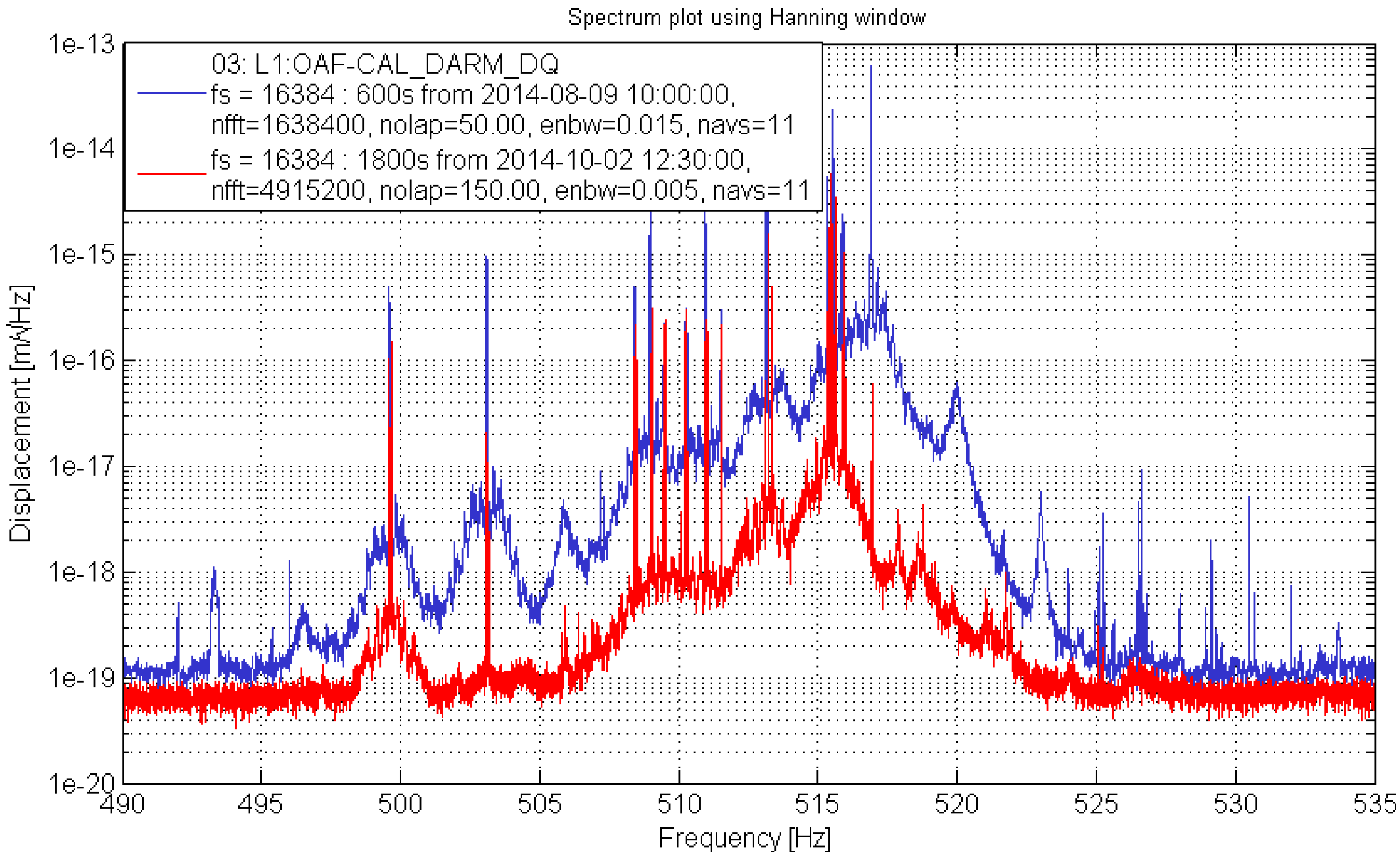
Application to aLIGO – Experimental data

- 2nd October LLO locked for 8 hours (with a short out-of-lock within) providing best sensitivity so far.
- Any excitation of the violin modes, during a relock, takes 1 week to decay (1/e in amp) due to the high Q ~1e9.
- We look at the violin mode amplitude of fibres associated with a mass that has no control forces applied (ITM).
- The experimental violin mode amplitude is up to one order of magnitude higher than expected due to thermal noise excitation.
- One possible source of excess noise is radiation pressure during relocks.





aLIGO fast sensitivity improvements



- Encouraging fast noise hunting progress, by aLIGO commissioners, around the violin mode frequencies (and other frequency bands). Above data only 2 months apart.

Conclusions

- Current LLO locks show that violin modes are excited above thermal noise. Radiation pressure could be one source of excess noise, as well as inputs from actuators.
- We will investigate above possible sources to identify the origin of the excess noise.
- Brett's Matlab model for the QUAD suspensions and ANSYS simulations will play an important role on identifying the origin of the excess noise.
- The violin mode amplitude algorithm has the potential to be used as a real-time monitor of the state of the suspensions as a data quality flag. This flag could be used as a veto channel for glitches due to the suspensions.