# Commissioning

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# Interferometer Status

- All 3 interferometers have been operating in power recycled configuration since early 2002
  - All had comparable sensitivity during S1
- LHO 2k
  - Currently being upgraded with new coil drivers & digital suspension controls
- LHO 4k
  - Currently has best sensitivity in 100-200 Hz band (some improvement since S1)
- LLO 4k
  - Best sensitivity for S1
  - Currently being upgraded with new coil drivers & digital suspension controls

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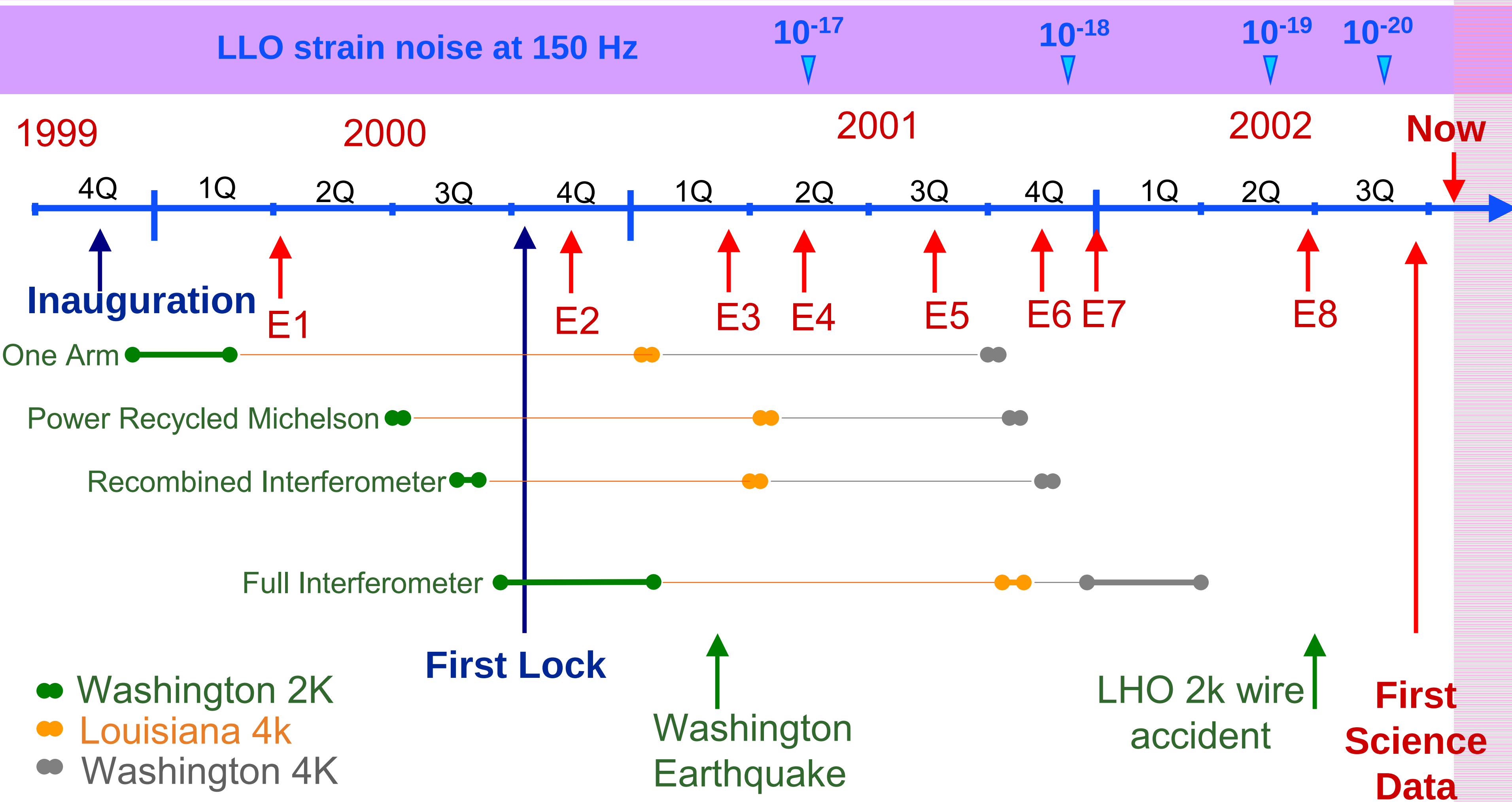
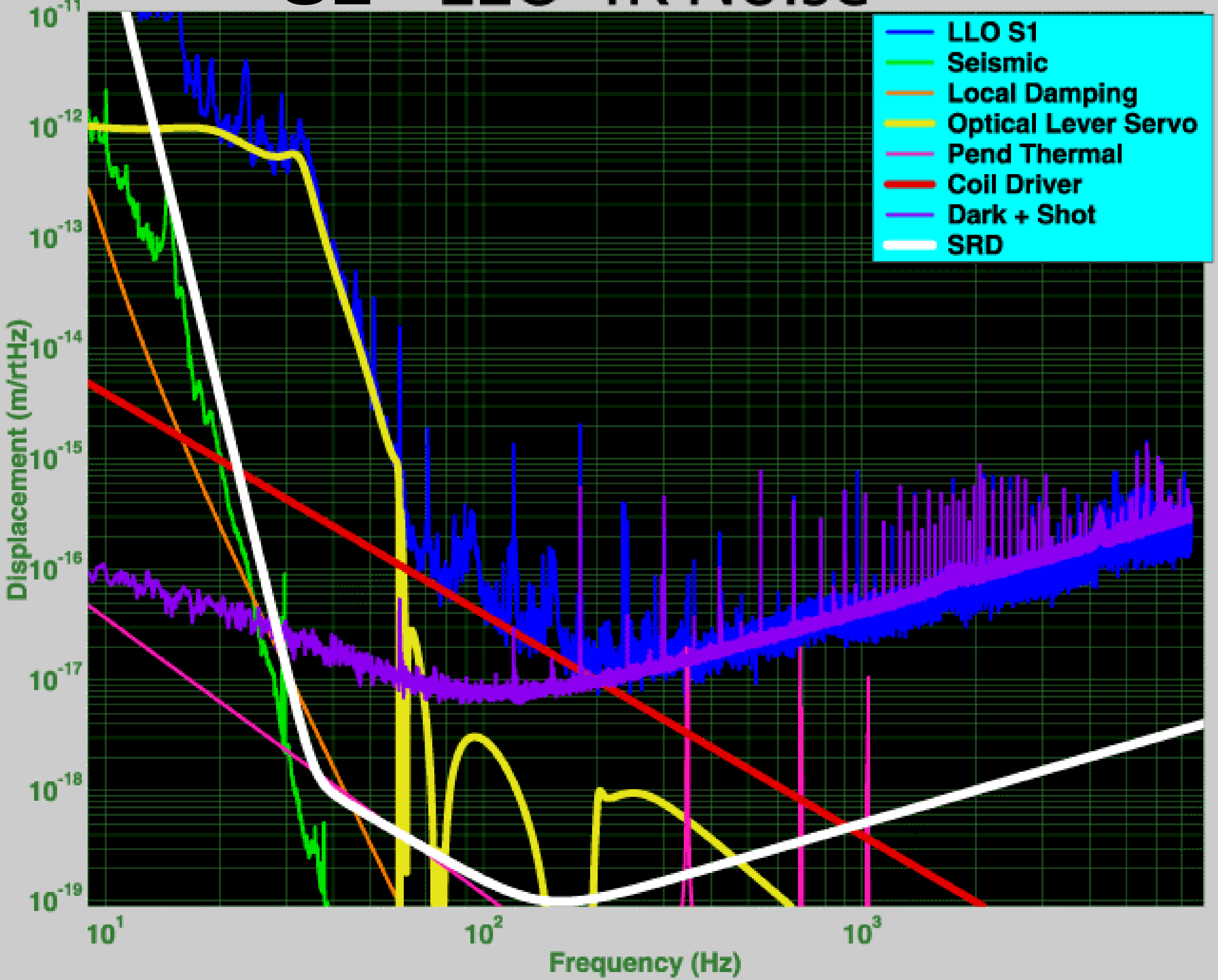
# Time Line



# Commissioning strategy

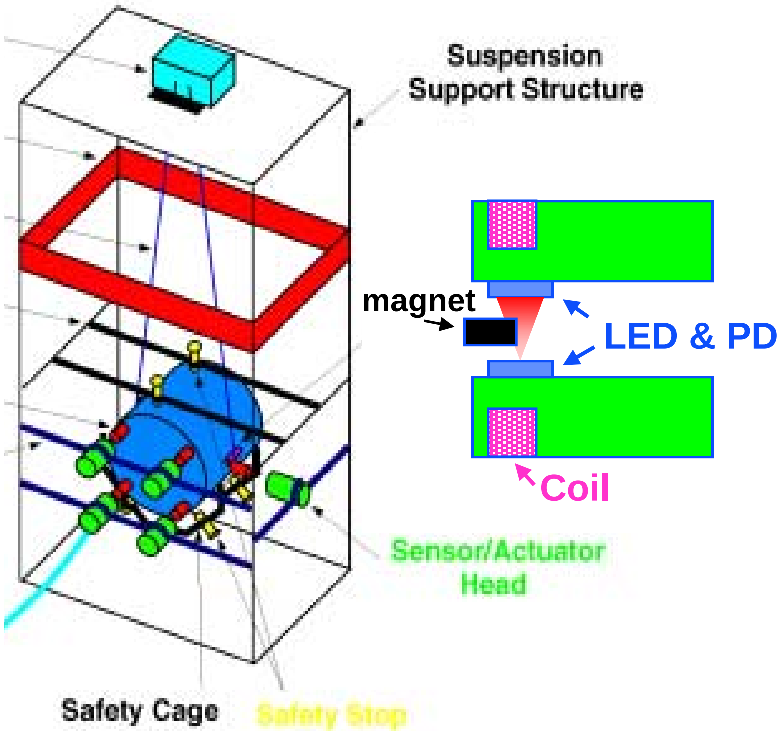
- Installation and early commissioning was staggered, with specific roles for each interferometer
  - First interferometer, LHO 2km: 'Pathfinder' – move quickly, identify problems, move on
  - LLO 4km interferometer: systematic characterization, problem resolution
  - LHO 4km interferometer: scheduled so that fixes/revisions can be implemented at the start
- This strategy has evolved over the last 1-2 yrs
  - LHO 4km was the first to implement new suspension controls
  - LLO had to adapt control systems to deal with much higher ground noise
  - All interferometers now at a similar stage:
    - Noise reduction
    - Stability/robustness improvements
  - Interferometer operation (Eng. & science runs) interspersed with commissioning

# S1 LLO 4K Noise



# Completed design modifications & additions

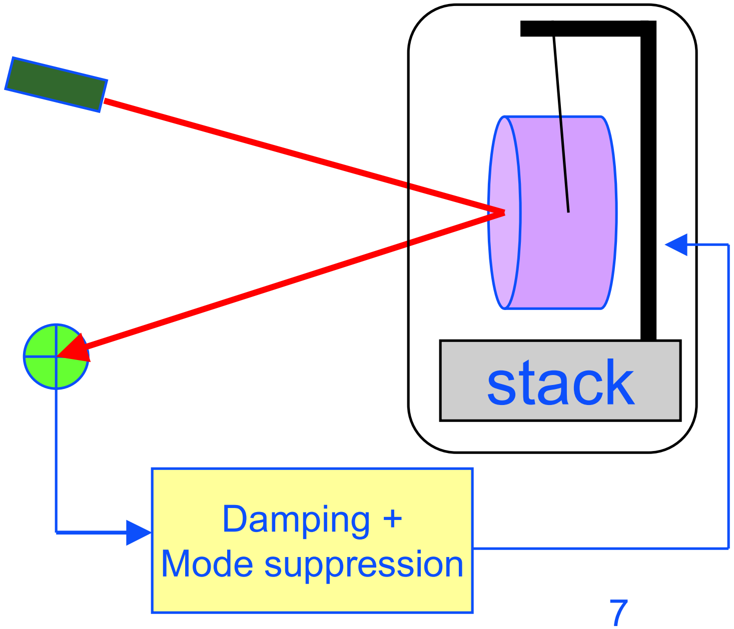
- New suspension local sensors
  - Initial sensors picked up scattered laser light, prevented high power operations
  - New sensors developed in parallel with low power commissioning, now installed on all interferometers and tested at full power



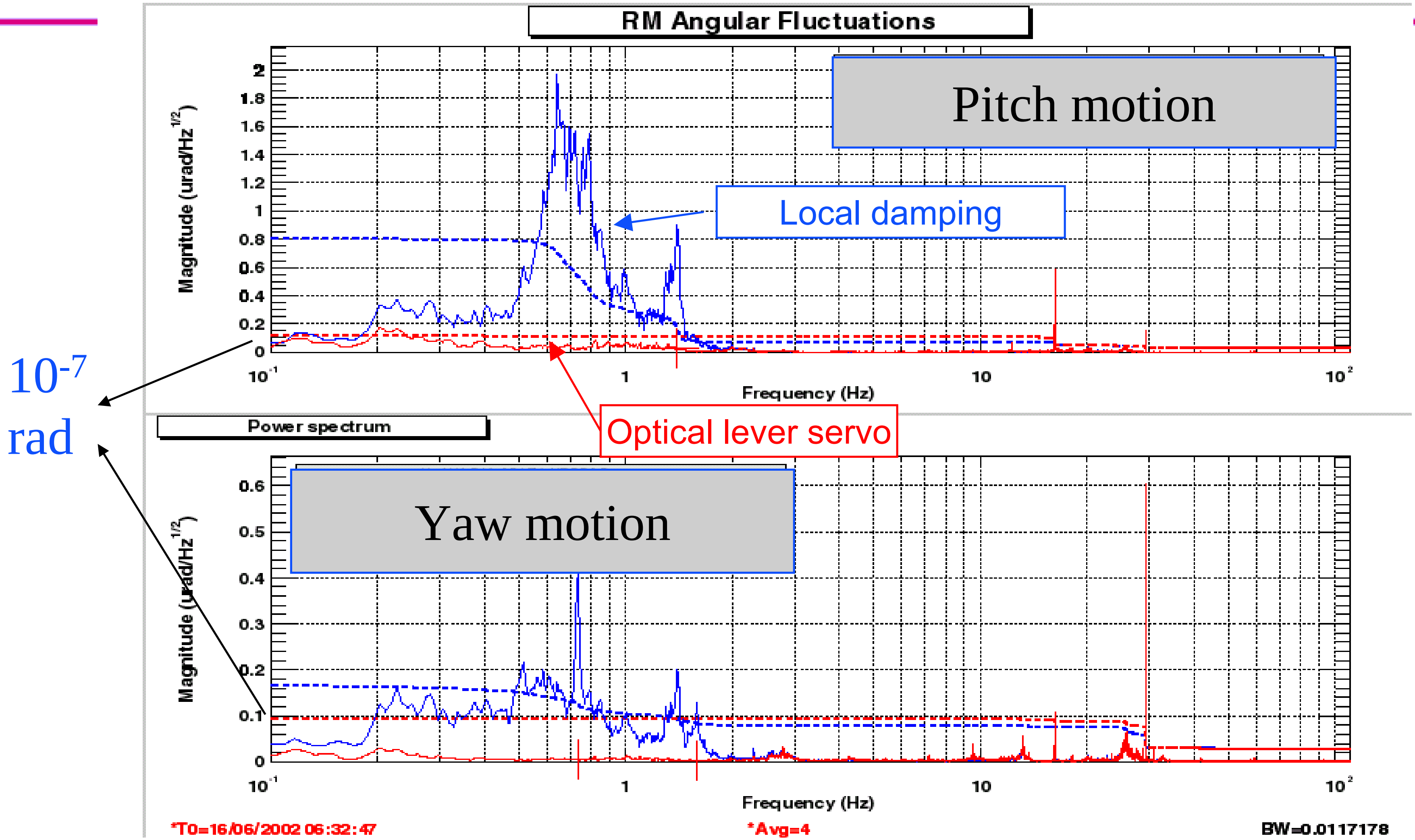

- Suspended optic angular stabilization using optical levers
- Seismic noise attenuation at LLO
- New suspension controls
- Enhancements of real-time digital control systems

# Stability improvements: reduction of angular fluctuations

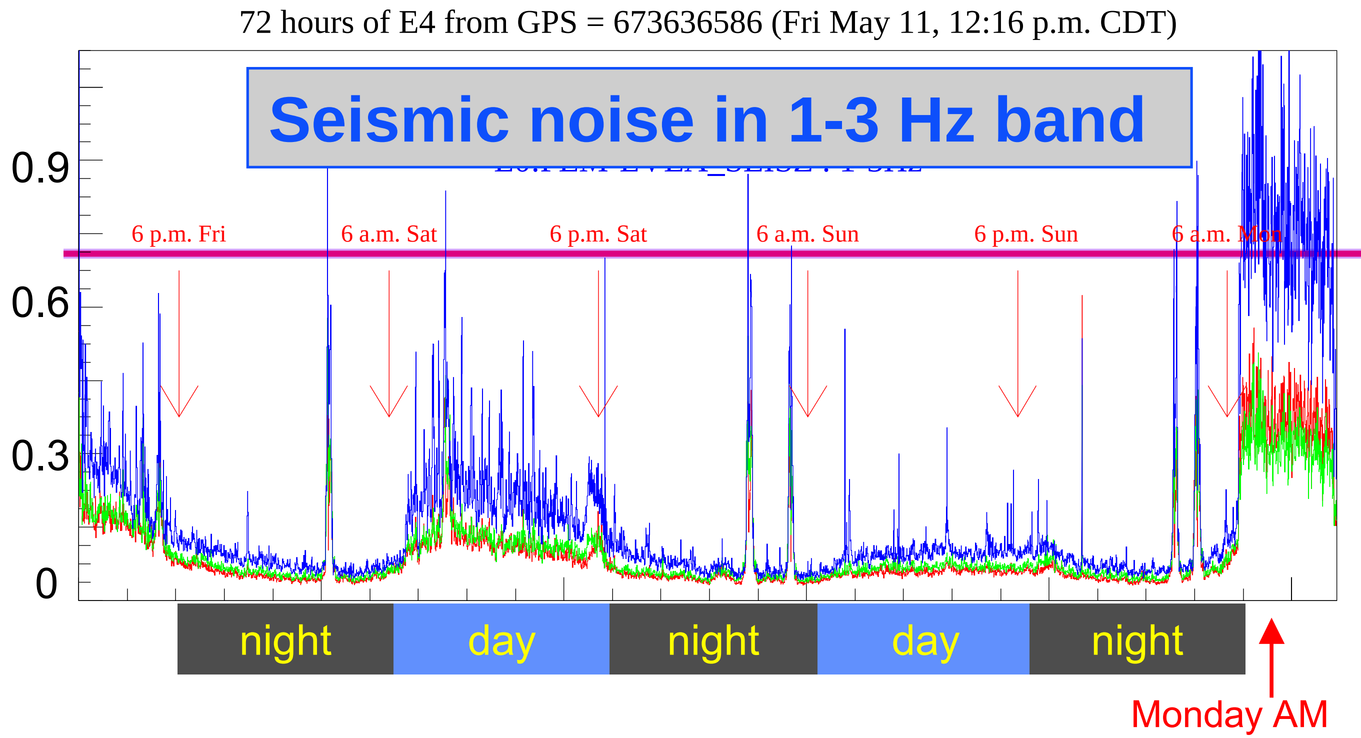
- Angular fluctuations of core optics lead to difficulty in locking and large power fluctuations when locked
  - Fluctuations dominated by low-frequency isolation stack and pendulum modes
  - Suspension local sensors damp the pendulum modes, but have limited ability to reduce the rms motion
- Optical lever sensors:
  - initially meant as an alignment reference and to provide long term alignment information
  - they turn out to be much more stable than the suspended optic in the ~0.5-10 Hz band
  - wrap a servo around them to the suspended optic, with resonant gain peaks at the lowest modes
  - tradeoff: increased noise in GW band

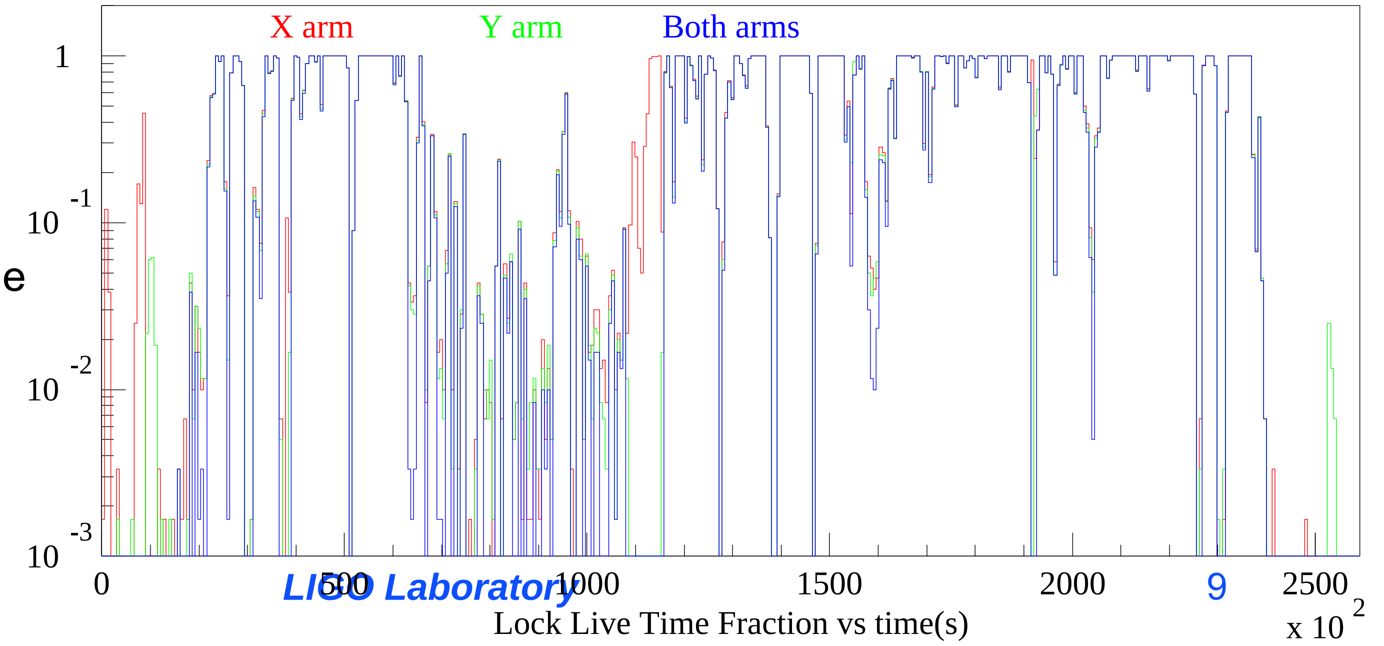


# Optical lever servo results



# Seismic Situation at LLO



# Seismic Situation at LLO (2)

- Spiky seismic noise 1-3 Hz band
  - Related to human activity – mostly lumber industry, but also trains, highway traffic … most likely to grow with time
  - Coincident with stack resonances
  - Precludes IFO locking during weekdays
- Dealing with the noise
  - Short term: Coil drivers with extended range
    - Increase maximum current to the coils, needed to acquire lock
    - Cannot reach ultimate LIGO noise floor
  - Long term: active external compensation system
    - 2 D.O.F. feedback stabilization of test mass supports (next talk)
    - 6 D.O.F. feedback stabilization of all suspended optic supports (next talk)
    - Feed forward reduction of microseism

# μSeismic Feed-forward System (LLO)

- Standing ocean gravity waves driven by storms excite double frequency (DF) surface waves that traverse large distances on land
  - Amplitude: from fractions to several microns; frequency: ~0.15 Hz
  - Wavelength: several kilometers ➔ LIGO arm length changes of several microns
- Seismic design provides an external fine actuation system (FAS)
  - Single DOF flexure design, ±90 μm range for each end (or mid) station BSC payload
  - Principally intended for tracking tidal arm stretching
- Streckeisen STS-2 seismometer signals collected from each building
  - filtered to produce arm length correction signals that are applied to the FAS, largely removing the microseism independently of global interferometer servos
  - Filters are derived using system-identification tools, & represent a compromise between high performance at the microseism and minimal added noise elsewhere.

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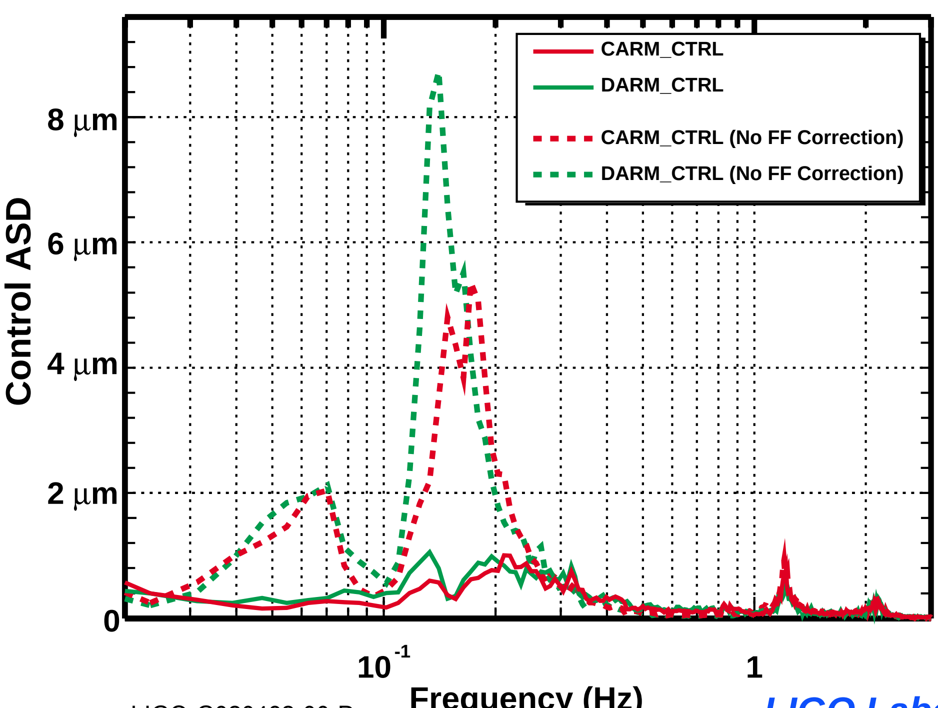
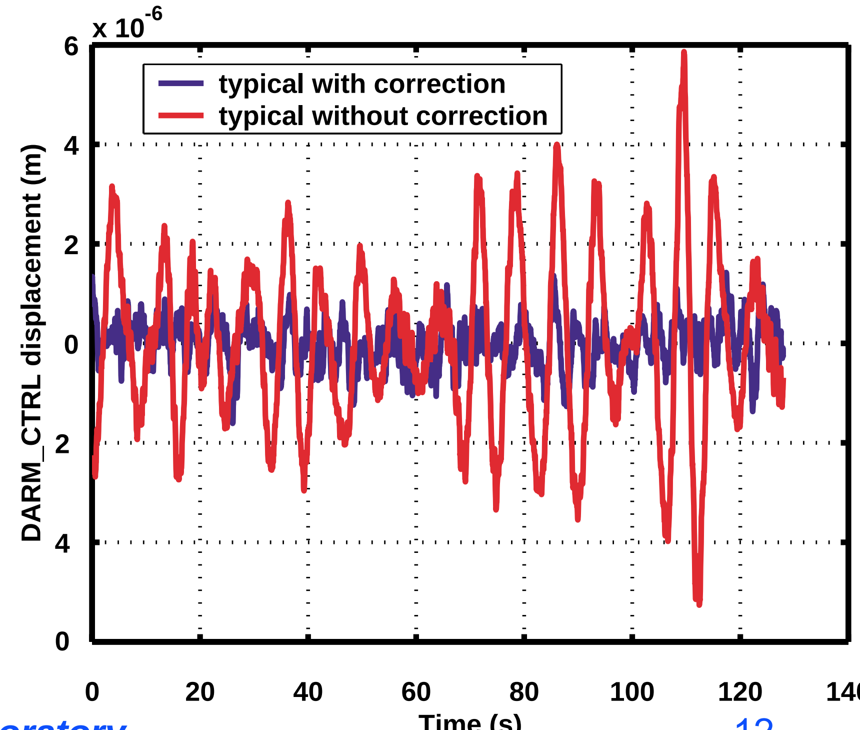
# Noise Reduction during E6

- E6 was during a period of very high microseism, allowing a good test.
- Test mass RMS (0.03 - 0.5 Hz) reduced by ≈ 85% , so that this spectral band no longer dominates the control signal.



# LHO 4k: Development ground for new suspension controls

- **Why a new suspension controls system?**
  - Coil driver design limitation:

| Acquisition currents: 100 – 300 ma | Alignment currents: 10 – 30 ma | In-lock length control: ~3 ma |
| --- | --- | --- |

    – Coil driver design made it impractical to reduce longitudinal control range after lock ⇨ couldn't achieve the noise benefits of a smaller range
  - Local sensing & damping electronics, and coil drivers (including LSC & ASC input conditioning) made all on one board
    – Made changes very difficult to implement; more modularity desired
- **Moved to a system with a digital processing core & more modular analog components**
  - Much easier to implement & change digital filtering; low freq filters don't require big C's
  - Suspension signals digitally integrated w/ global length and alignment controls
  - Alignment bias currents are generated and fed in, well filtered, independently of the feedback signals

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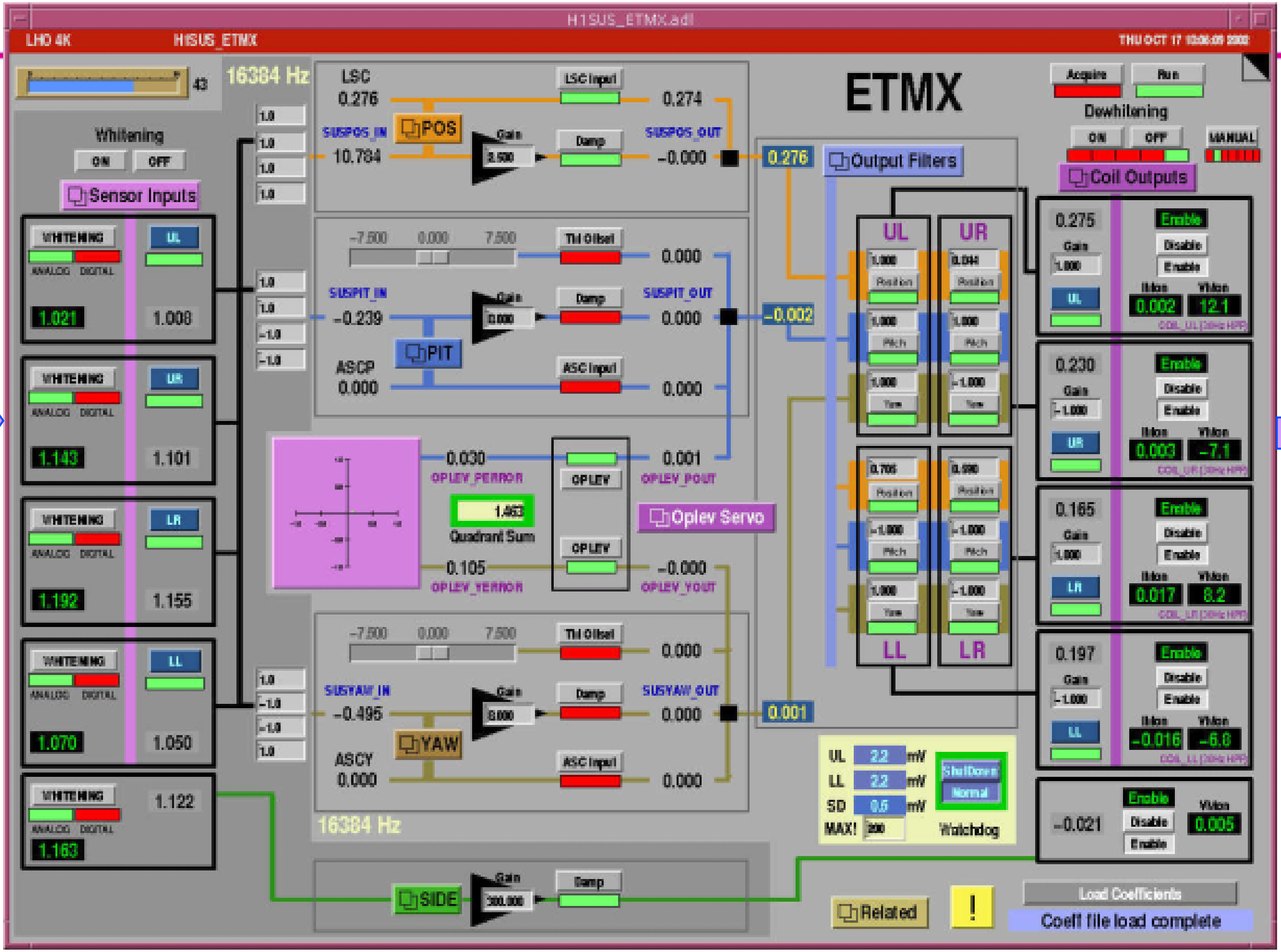
# Digital Controls screen example

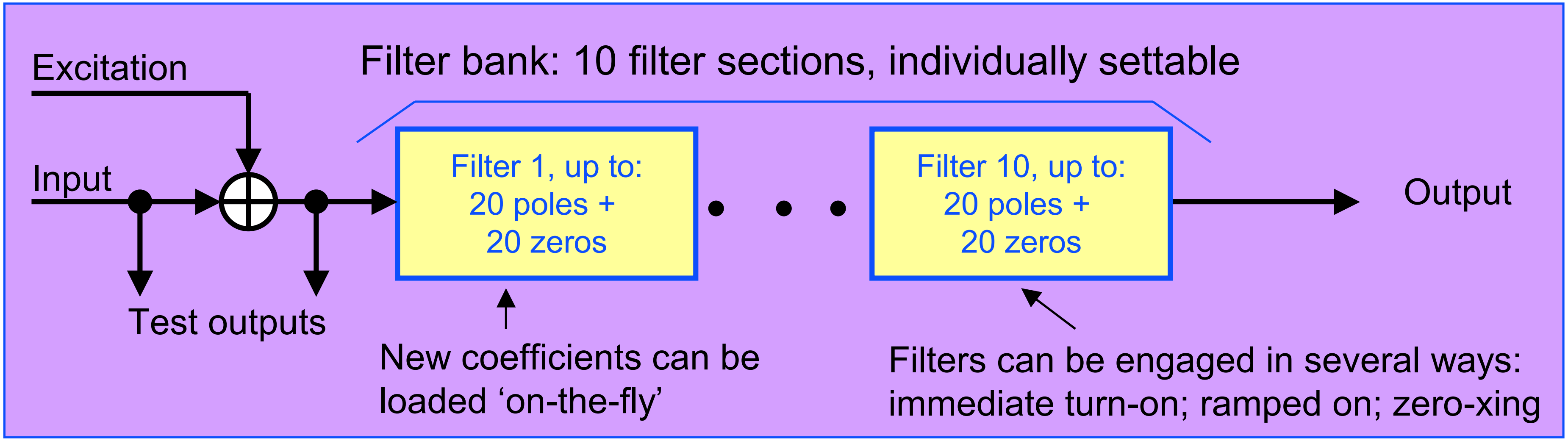
Analog In




Analog Out

# Real-time digital filtering

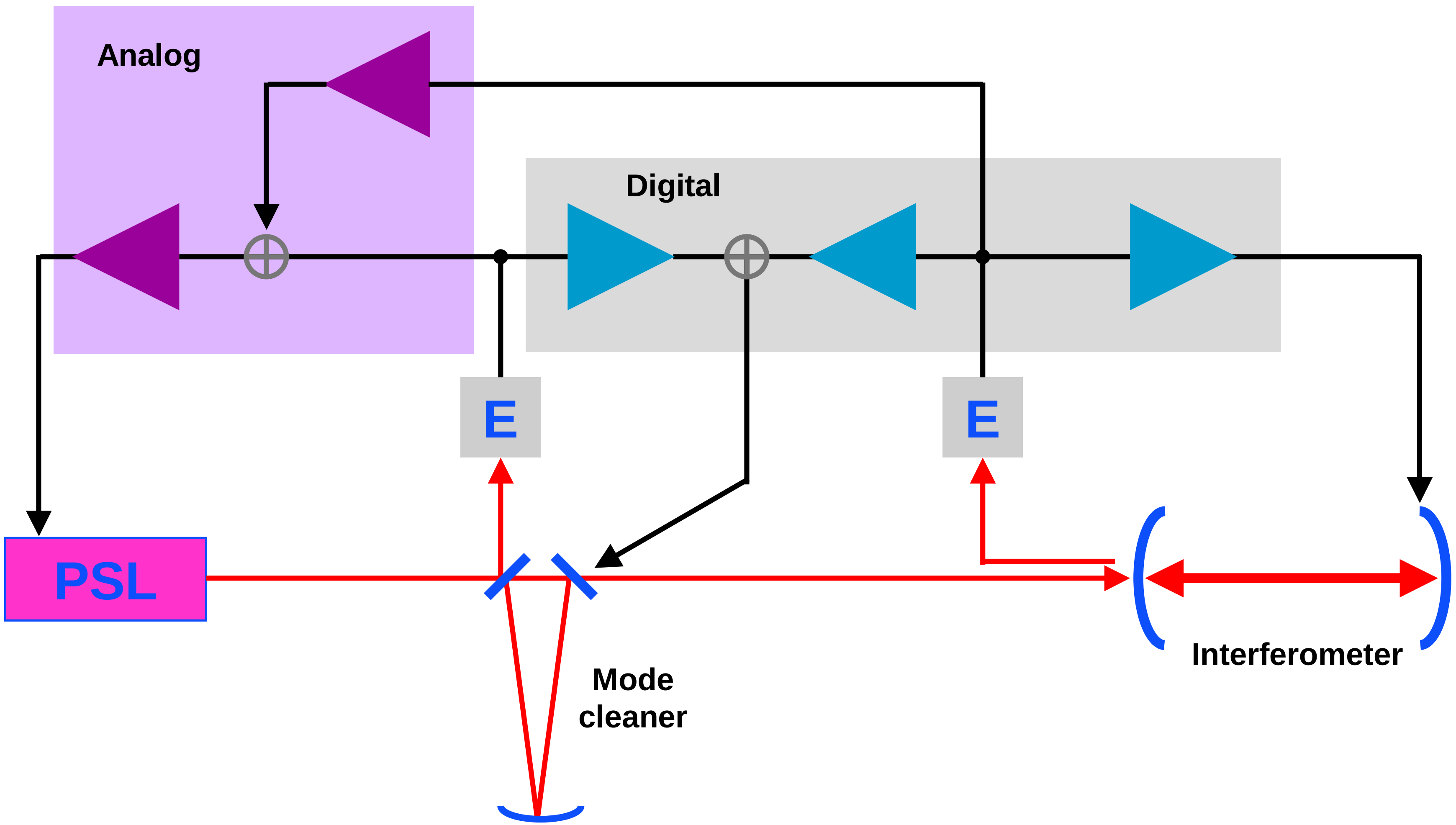
- Servos based on digital filtering a crucial part of improvements
  - Can suppress features that account for rms fluctuations (typically f < 10 Hz)
  - Can filter out noise coupled into the gravity wave band
- Recent real-time code enhancements have made it much easier to implement complex digital filters
  - Reductions in processing & I/O time allow us to do more
  - All digital feedback systems (LSC, ASC, DSC) now use a new 'generic filter module'



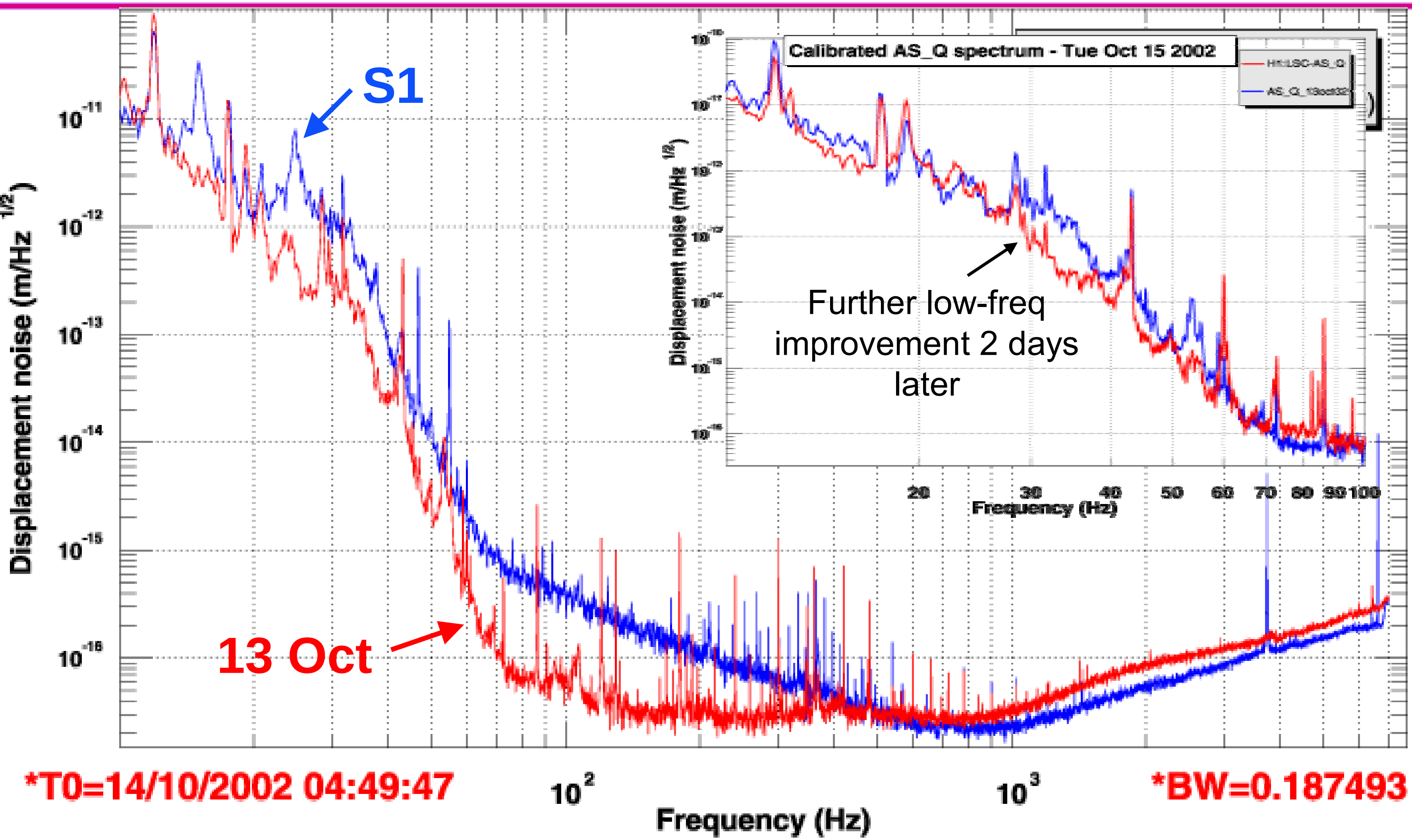
# Noise reduction: interferometer frequency stabilization

- Feedback loop from the 'common mode' error signal – error between the average arm length and the laser frequency – to the laser frequency
  - Provides the final level of frequency stabilization, after the prestabilization and mode cleaner stages
  - Ultimately, need a stability of $3 \times 10^{-7}$ Hz/rtHz at 150 Hz
  - Lock is acquired with feedback only to the end mirrors …
  - the tricky operation is then to transfer the common mode feedback signal to the laser frequency, with multiple feedback paths
- Status
  - Operational on all 3 ifo's during S1
    - Removed all coherence between common and differential D.O.F.
  - Frequency coupling measured on LHO 2k: 300:1 rejection ratio! (100 Hz)

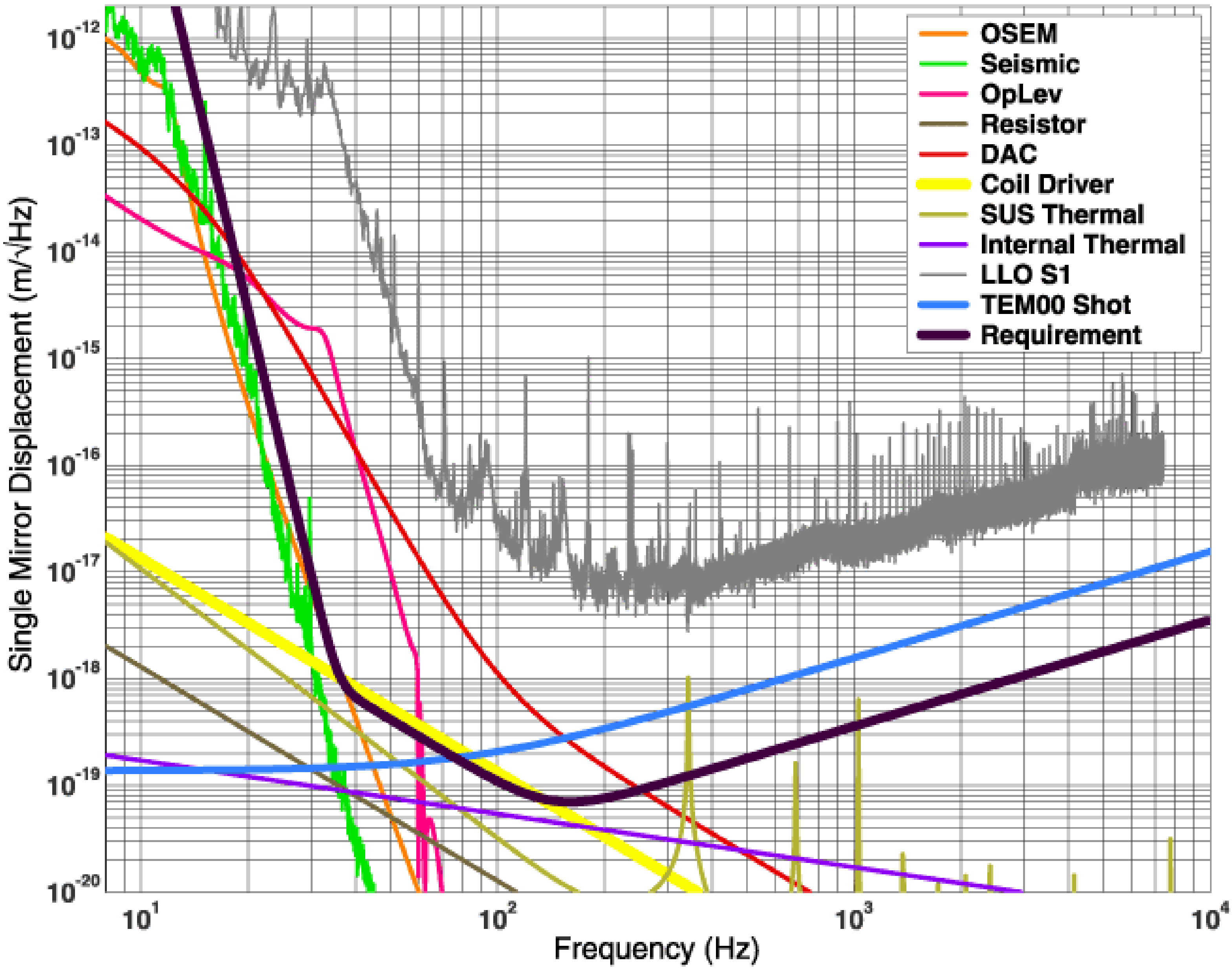
# Frequency stabilization feedback configuration



# Improvements to LHO 4k noise



# Estimated Noise limits for S2



# Ongoing subsystem integration

- Laser power stabilization servo
  - First stage operational, achieving a relative intensity noise of ~$10^{-7}/Hz^{1/2}$
  - Second stage of stabilization in the works ⇨ $10^{-8}/Hz^{1/2}$
- Wave-front sensor (WFS) based alignment system
  - Optical lever servos reduce the fluctuations, but they don’t find the right alignment point
  - Wave-front sensors are referenced to the cavity axes, indicating the optimal alignment point for 10 degrees-of-freedom
  - Being interferometric sensors, they have lower sensing noise than the optical levers ⇨ *reduce low-frequency noise*
  - Single sensors have functioned so far to align the end test masses, full system is being commissioned

# Summary: what works

- Initial alignment: surveying good to ~25 μradians
  - No searching for beams!
- Lasers: 2+ yrs of continuous operation
  - Prestabilized frequency noise meets requirement
- Seismic isolation stacks: isolate as designed
- Suspensions: thermal excitation of wire resonances observed
- Core optics quality
  - power recycling gains of ~40
  - Internal mode quality factors as expected (~$10^6$)
- Interferometer lock acquisition: acquisition times within few minutes
- Global diagnostics system: now an indispensable tool
- Digital control systems:
  - Critical to noise & stability improvements
  - Can deal with dynamic range limitations

# Summary: major accomplishments

- First Science Run completed with good sensitivity and uptime
- Systems integration is nearing completion
- Significant noise improvements on all interferometers over the last year
- Stability improvements: optical lever stabilization, external preisolation
- Seismic isolation fine actuators used successfully to:
  - Compensate for tidal stretching of the arms
  - Compensate for the microseismic arm fluctuations
  - Attenuate ground noise at LLO
- Suspensions:
  - Mechanical robustness improved
  - New improved control electronics implemented
- Operator training
  - operators now an integral part of day-to-day commissioning

# Summary: future plans

- Plans for near term
  - Recover full operation of LLO and LHO 2k interferometers following suspension controls upgrade
  - Full wavefront sensor alignment control
    - Enable power increase at detection port
  - Begin effort to improve the electronics infrastructure, EMI/RFI environment
  - Focus on robustness & stability
    - Planning a longer stabilization period – ‘configuration freeze’ – prior to second science run (S2)
    - Need to increase duty cycle from ~60% to >90%
  - Noise hunting …