LIGO Detector Commissioning

Reported on behalf of LIGO colleagues by

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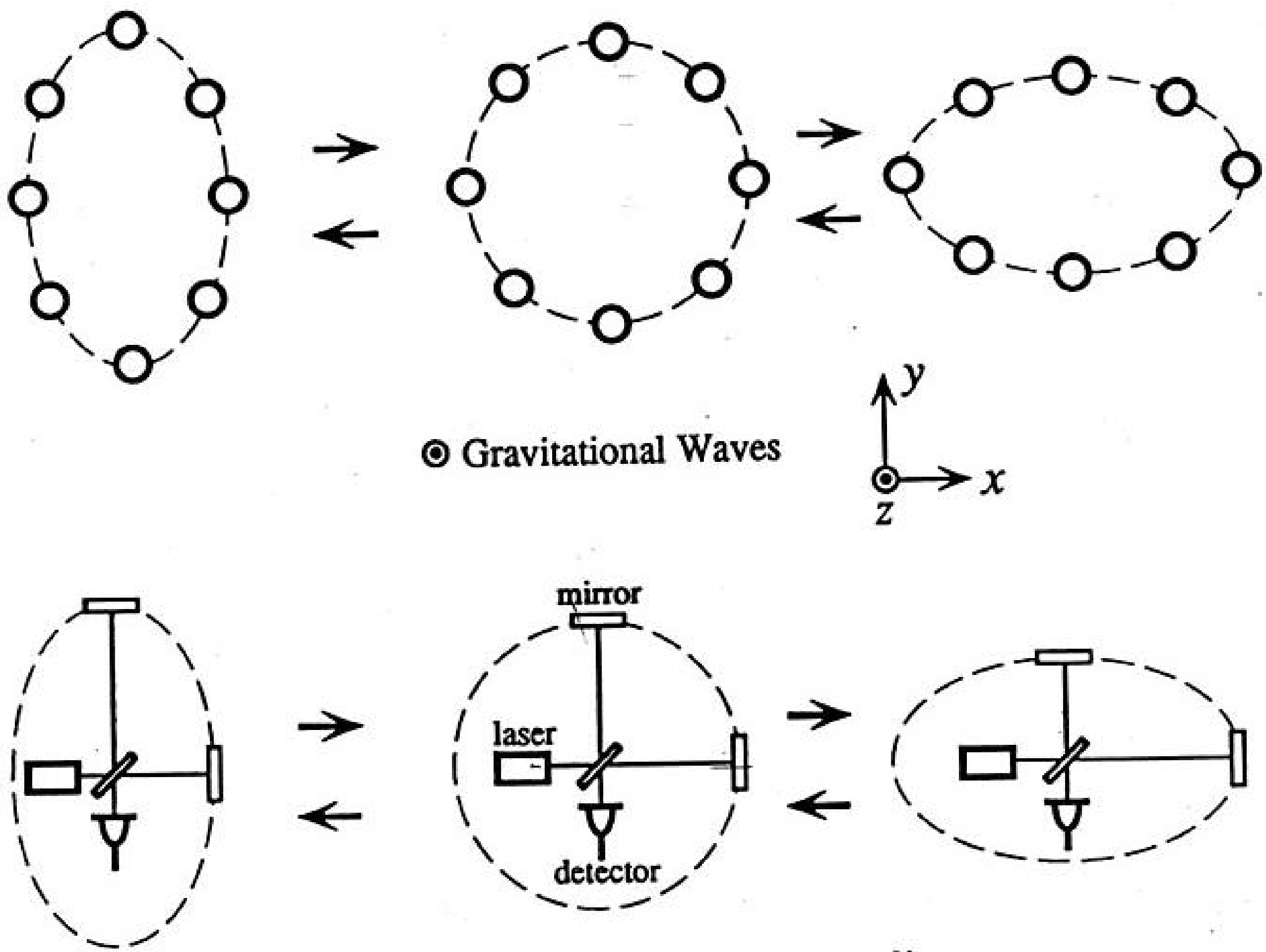
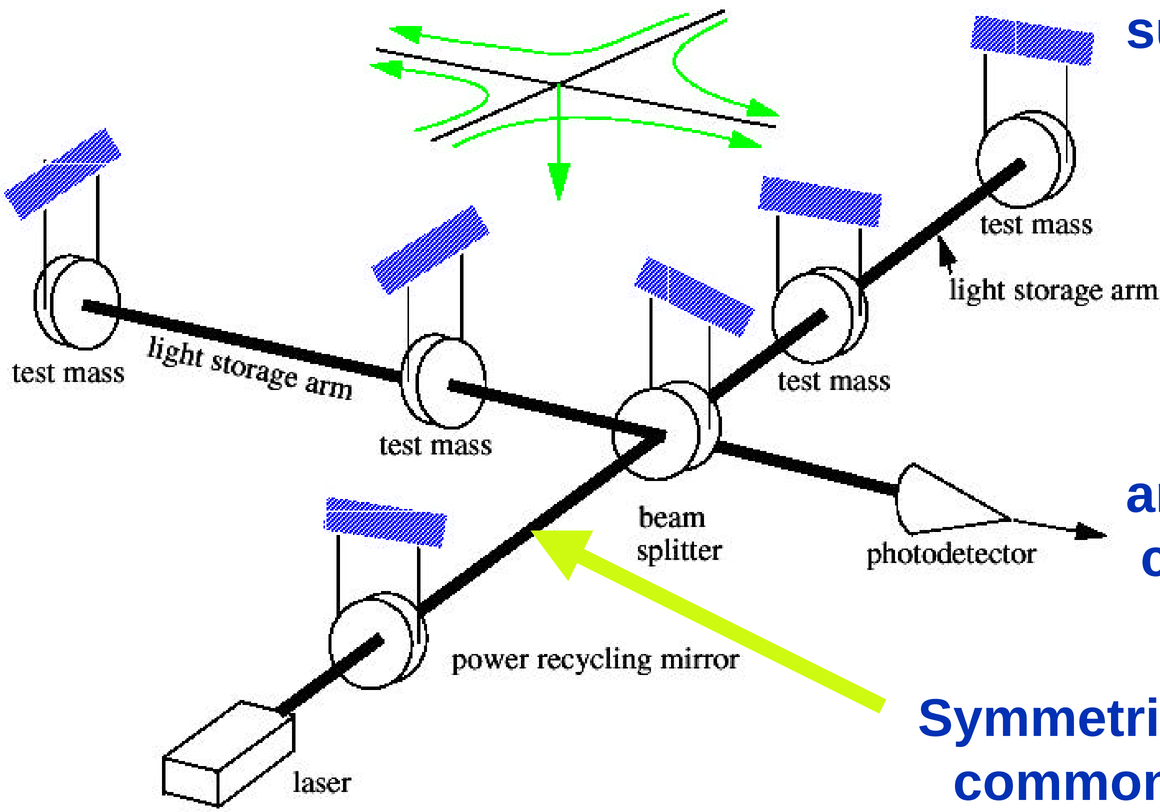
LIGO-G030169-02-W

Basic Signature of Gravitational Waves



Power-Recycled Fabry-Perot-Michelson Interferometer

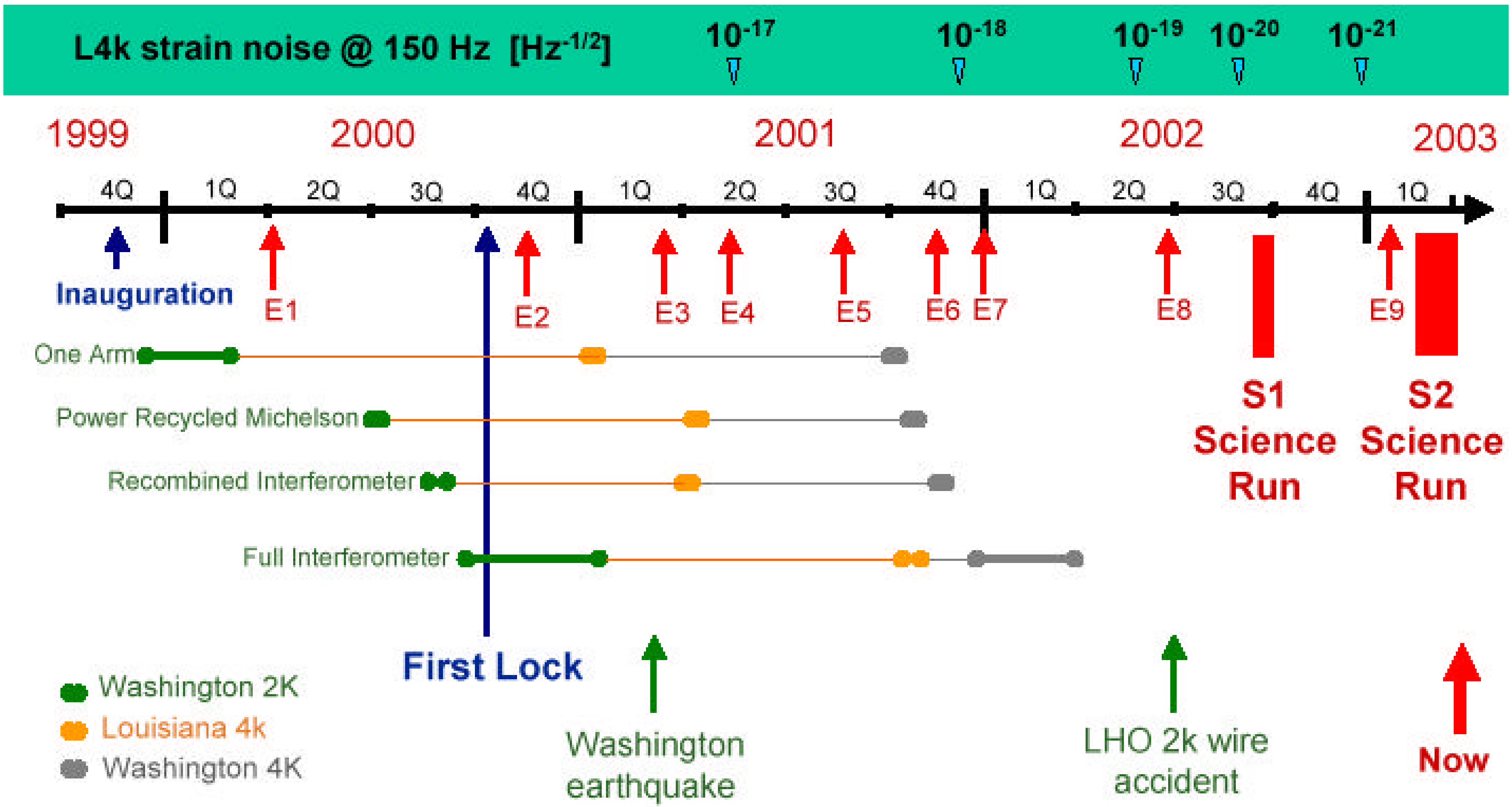


suspended mirrors mark inertial frames

antisymmetric port carries GW signal

Symmetric port carries common-mode info

Commissioning Time Line

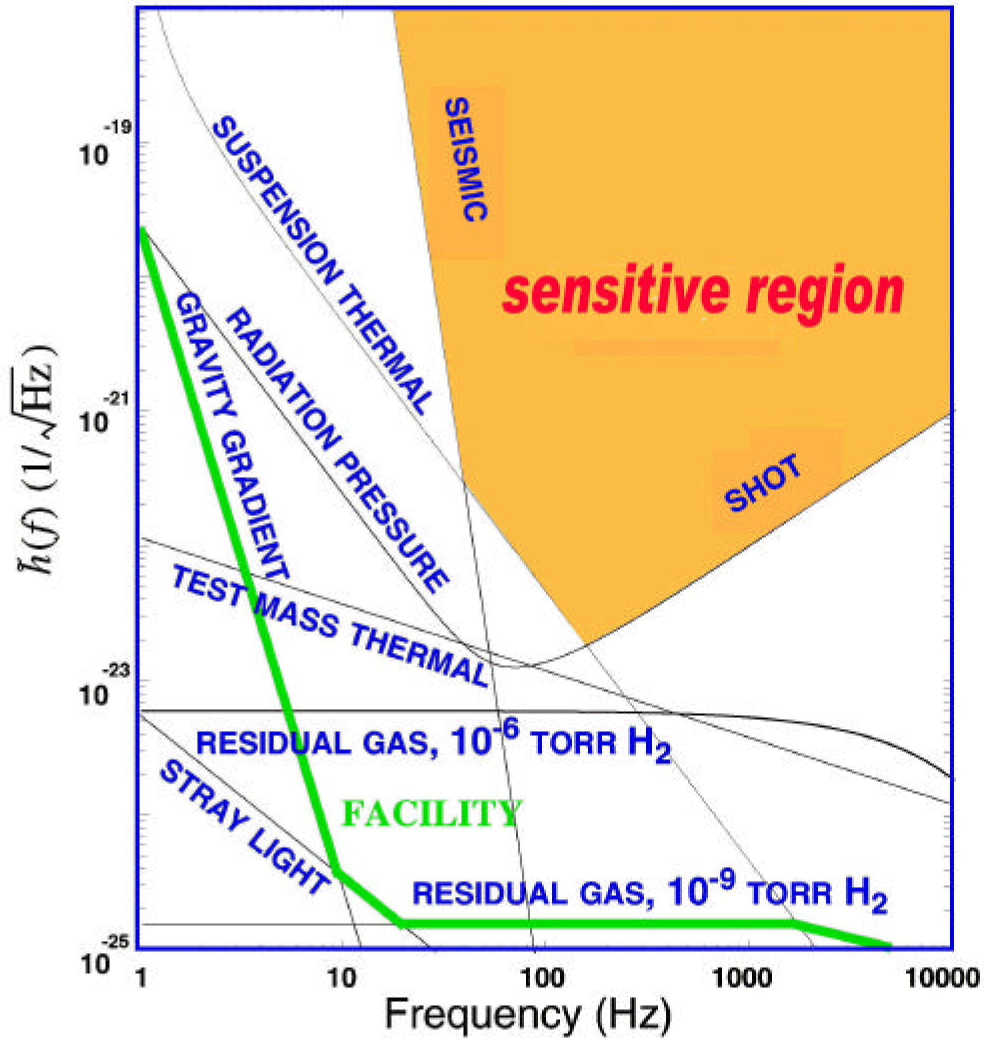


Some of the Technical Challenges

- Typical Strains < 10^{-21} at Earth ~ 1 hair's width at 4 light years
- Understand displacement fluctuations of 4-km arms at the millifermi level (1/1000th of a proton diameter)
- Control arm lengths to 10^{-13} meters RMS
- Detect optical phase changes of ~ 10^{-10} radians
- Hold mirror alignments to 10^{-8} radians
- Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors

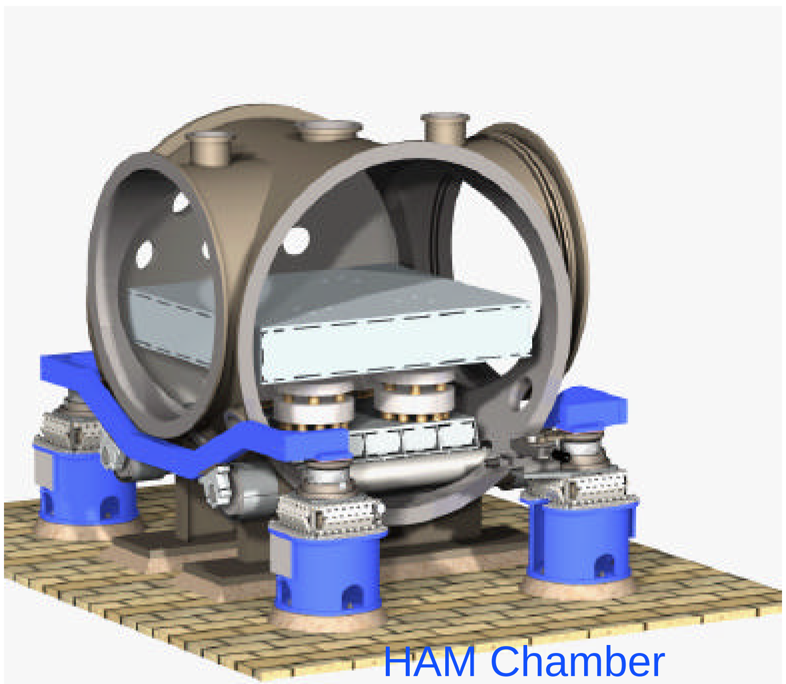
What Limits Sensitivity of Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

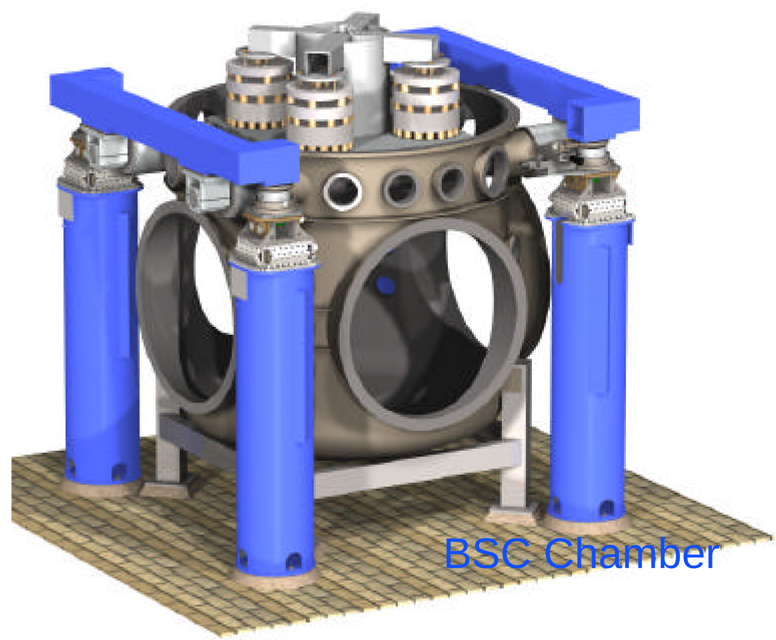


Vibration Isolation Systems

- » Reduce in-band seismic motion by 4 - 6 orders of magnitude
- » Little or no attenuation below 10Hz
- » Large range actuation for initial alignment and drift compensation
- » Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

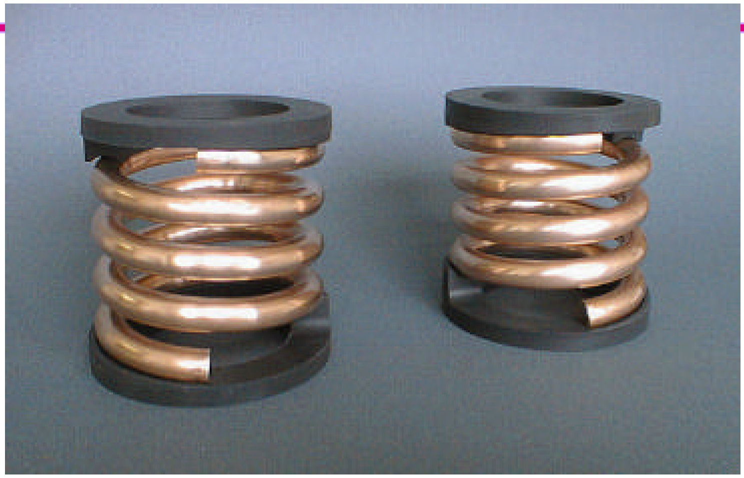


HAM Chamber

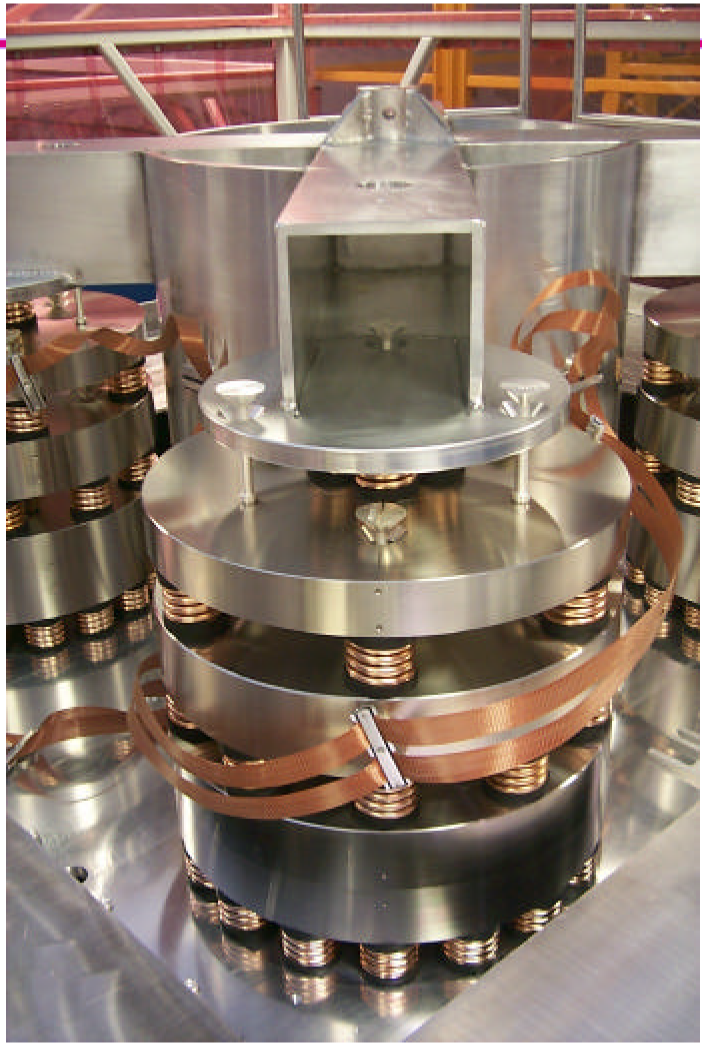


BSC Chamber

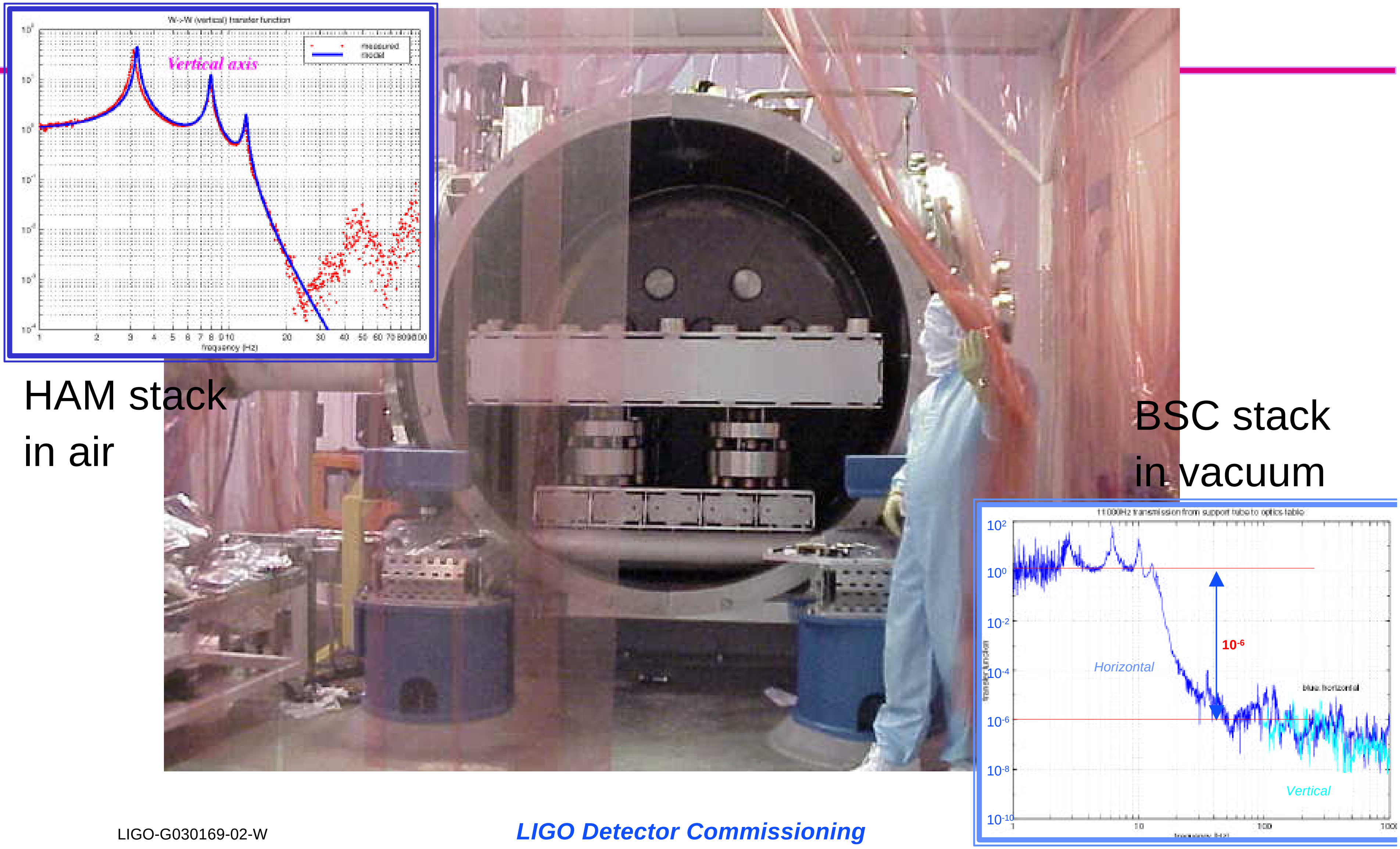
Seismic Isolation – Springs and Masses



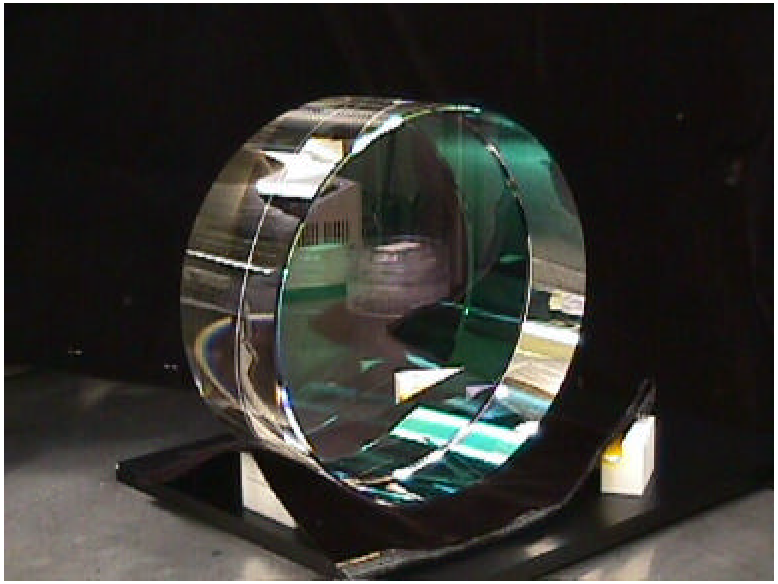
damped spring
cross section



Seismic System Performance

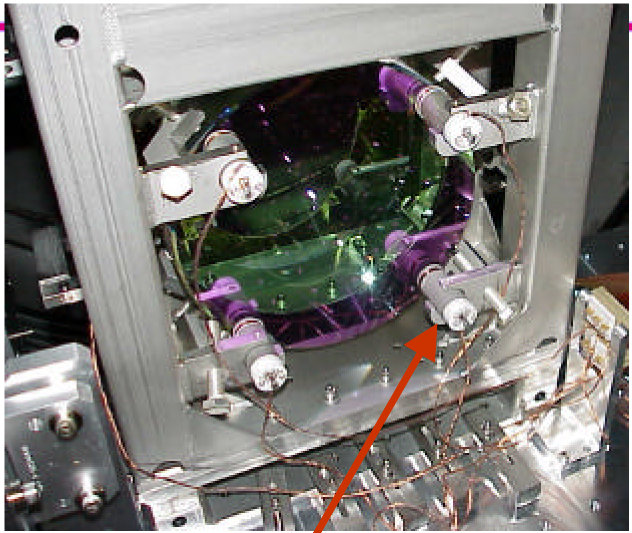


Core Optics

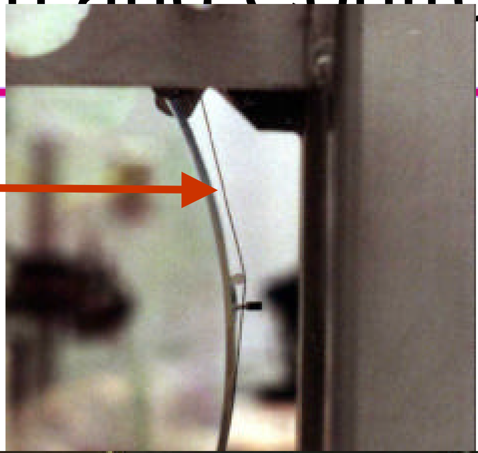


- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5 x 10^{-7}
  - » Internal mode Q's > 2 x 10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}
- Production involved 6 companies, NIST, and LIGO

Core Optics Suspension and Control



Optics suspended as simple pendulums



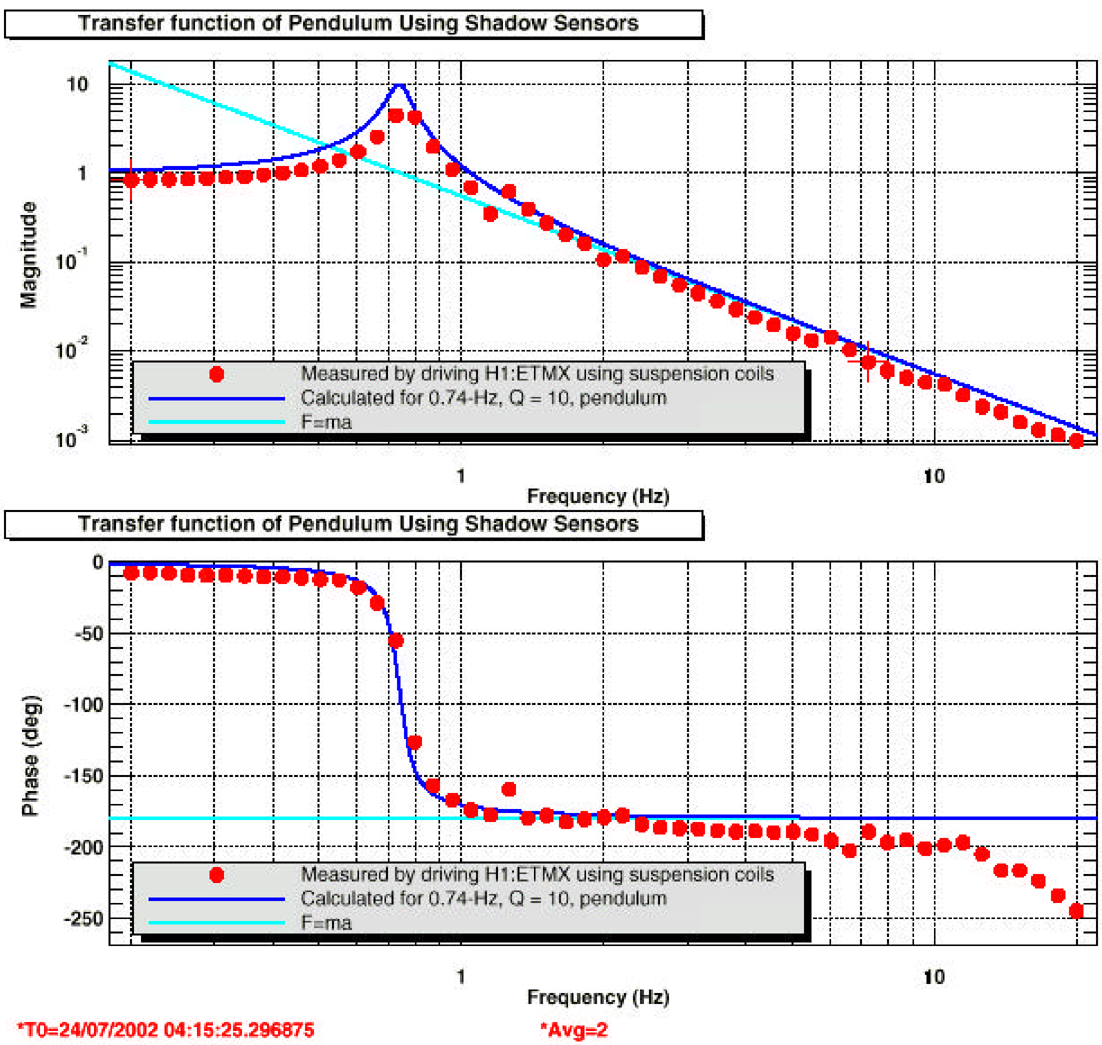
Shadow sensors & voice-coil actuators provide damping and control forces

Mirror is balanced on 30 micron diameter wire to 1/100th degree of arc

Feedback & Control for Mirrors and Light

- Damp suspended mirrors to vibration-isolated tables
  - » 14 mirrors × (pos, pit, yaw, side) = 56 loops
- Damp mirror angles to lab floor using optical levers
  - » 7 mirrors × (pit, yaw) = 14 loops
- Pre-stabilized laser
  - » (frequency, intensity, pre-mode-cleaner) = 3 loops
- Cavity length control
  - » (mode-cleaner, common-mode frequency, common-arm, differential arm, michelson, power-recycling) = 6 loops
- Wave-front sensing/control
  - » 7 mirrors × (pit, yaw) = 14 loops
- Beam-centering control
  - » 2 arms × (pit, yaw) = 4 loops

Suspended Mirror Approximates a Free Mass Above Resonance



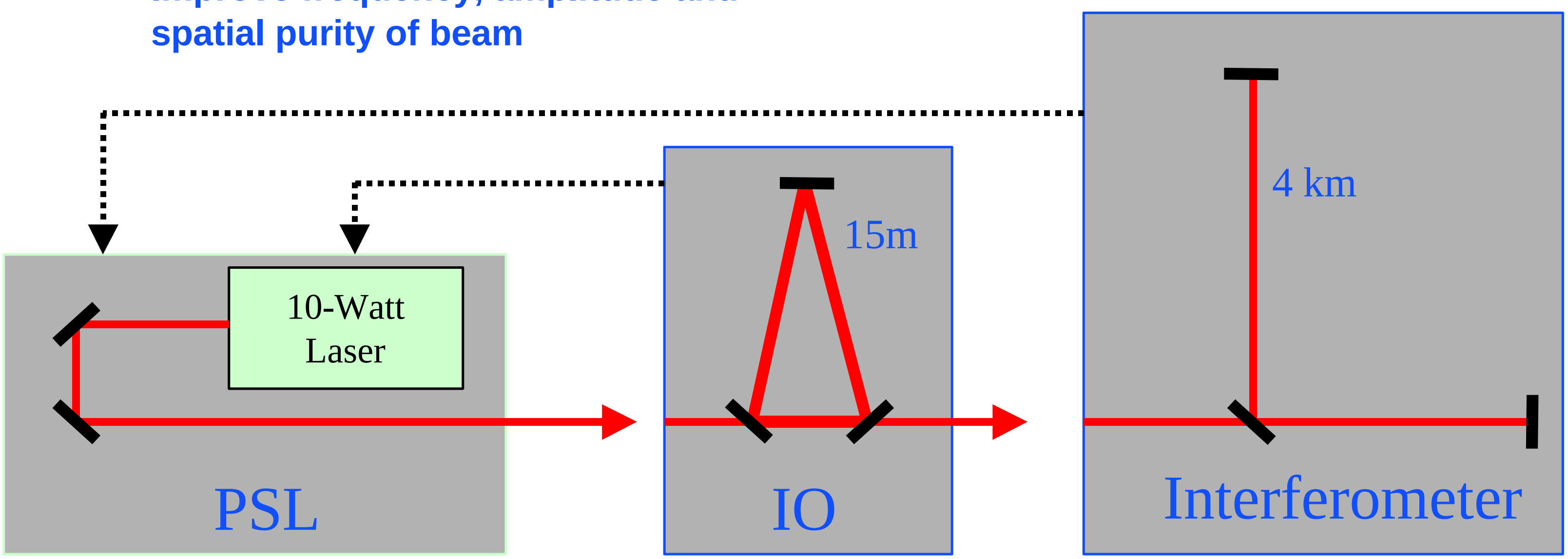
Blue: suspended mirror XF

Cyan: free mass XF

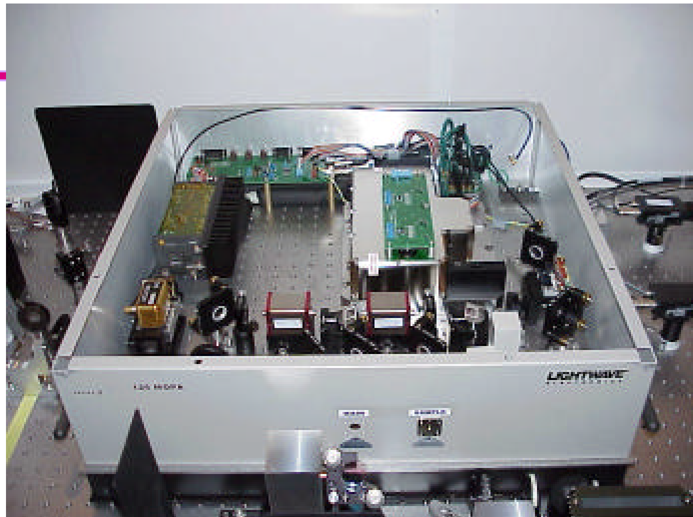
Data taken using shadow sensors & voice coil actuators

Frequency Stabilization of the Light Employs Three Stages

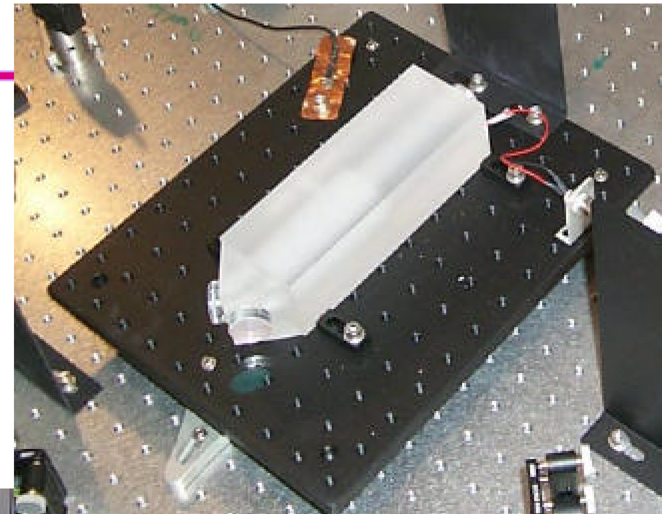
- Pre-stabilized laser delivers light to the long mode cleaner
  - **Start with high-quality, custom-built Nd:YAG laser**
  - **Improve frequency, amplitude and spatial purity of beam**
- Actuator inputs provide for further laser stabilization
  - **Wideband**
  - **Tidal**



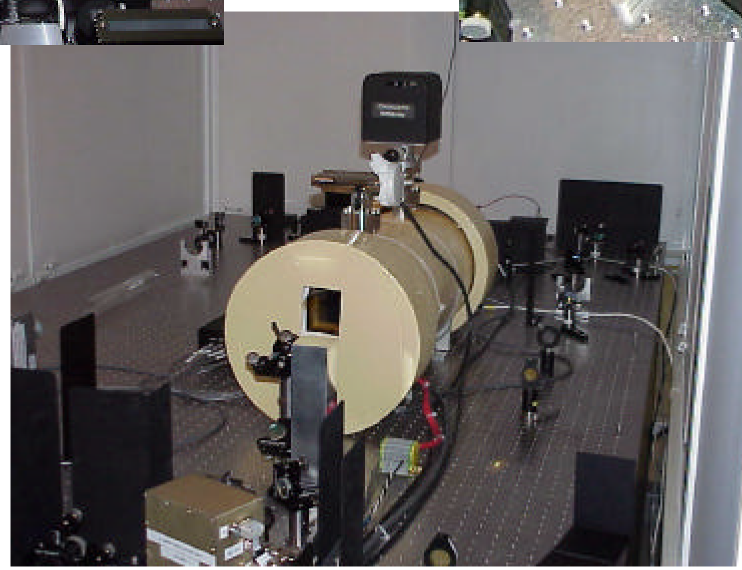
Pre-stabilized Laser (PSL)



Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)

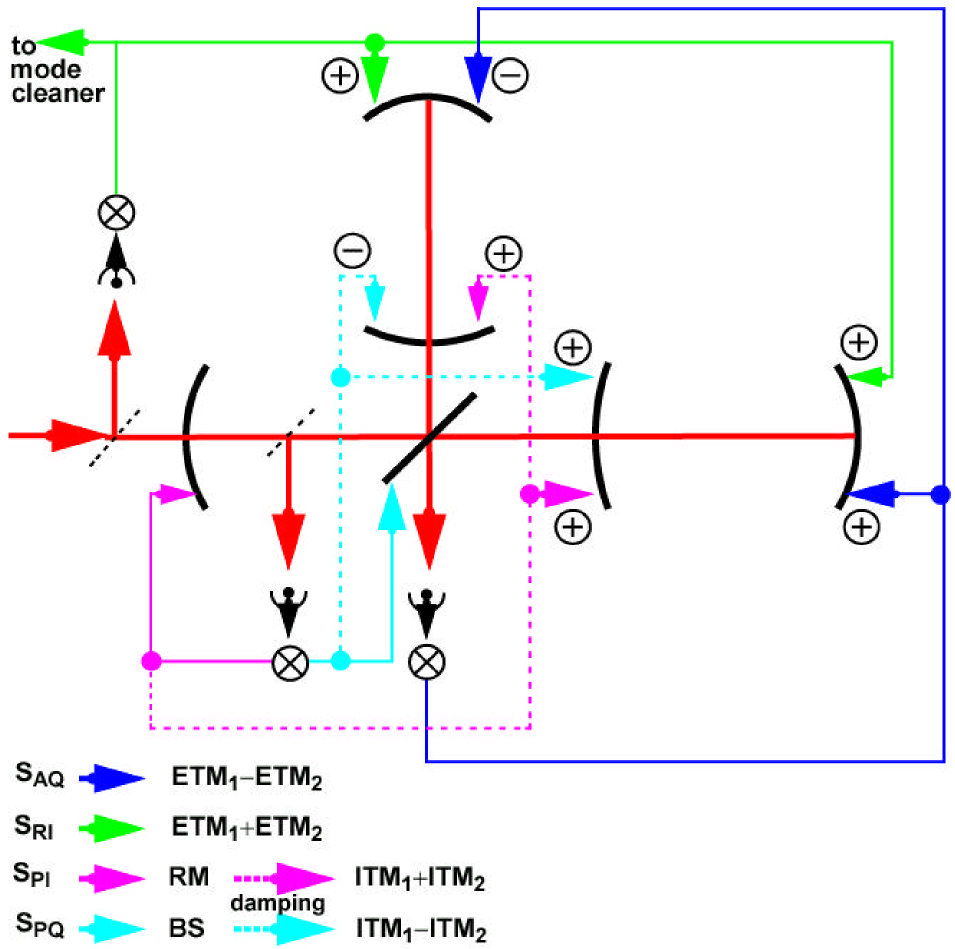


Cavity for
defining beam geometry,
joint development with
Stanford



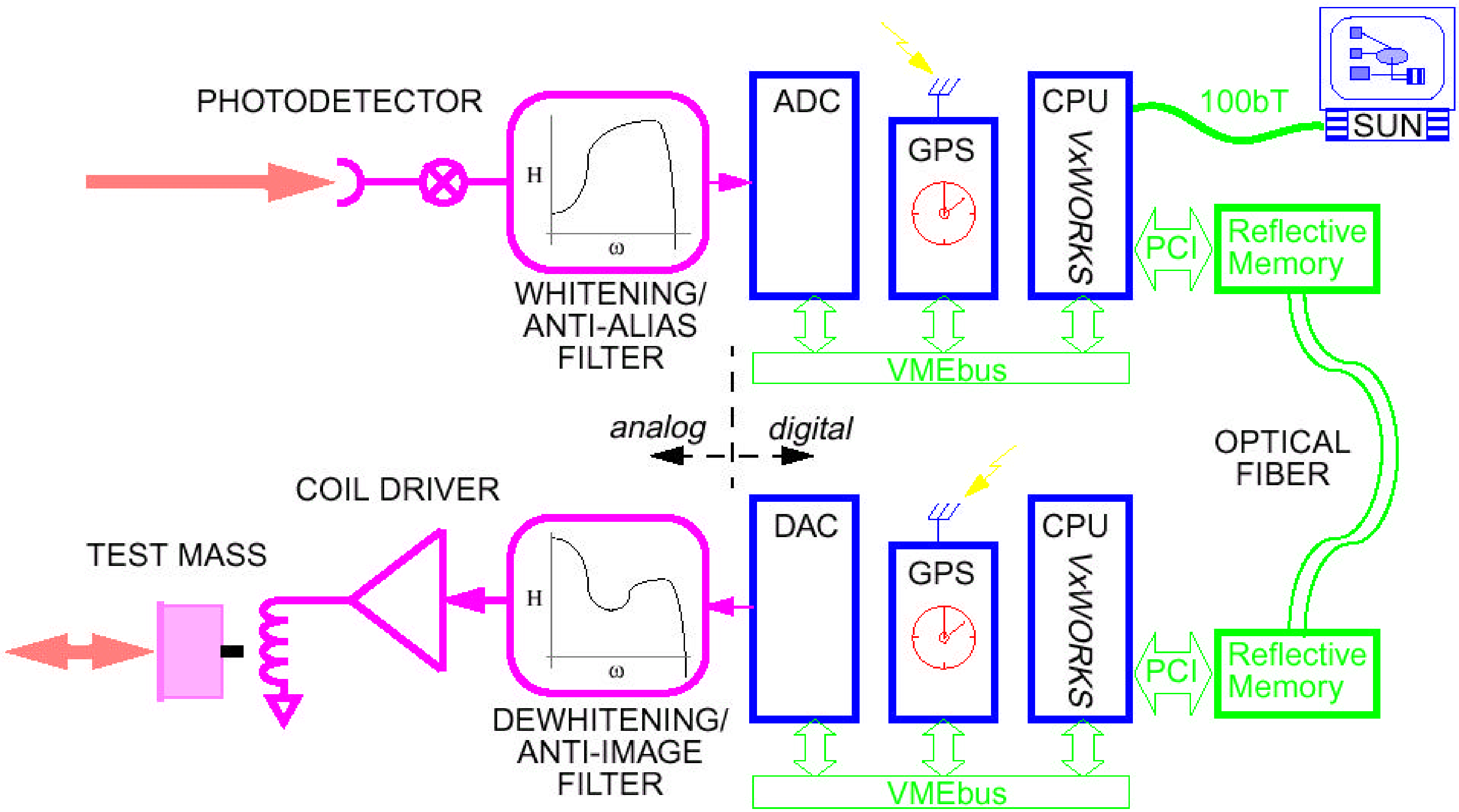
Frequency reference
cavity (inside oven)

Interferometer Length Control System

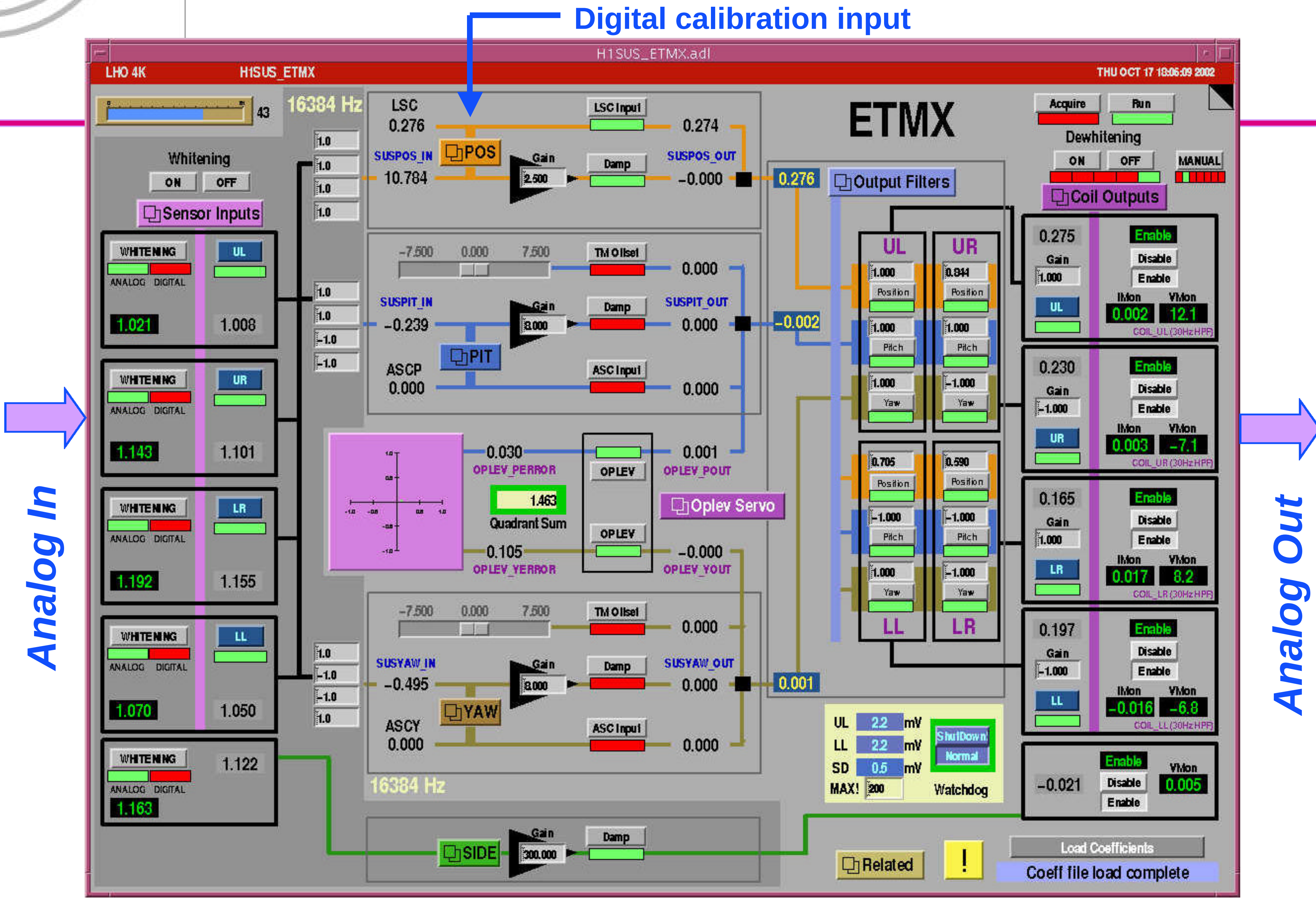


- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Ill-conditioned (off-diagonal) plant matrix
- Highly nonlinear response over most of phase space
- Transition to stable, linear regime takes plant through singularity
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition

Digital Interferometer Sensing & Control System

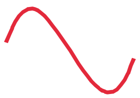
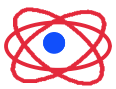
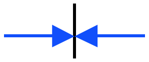


Digital Controls screen example

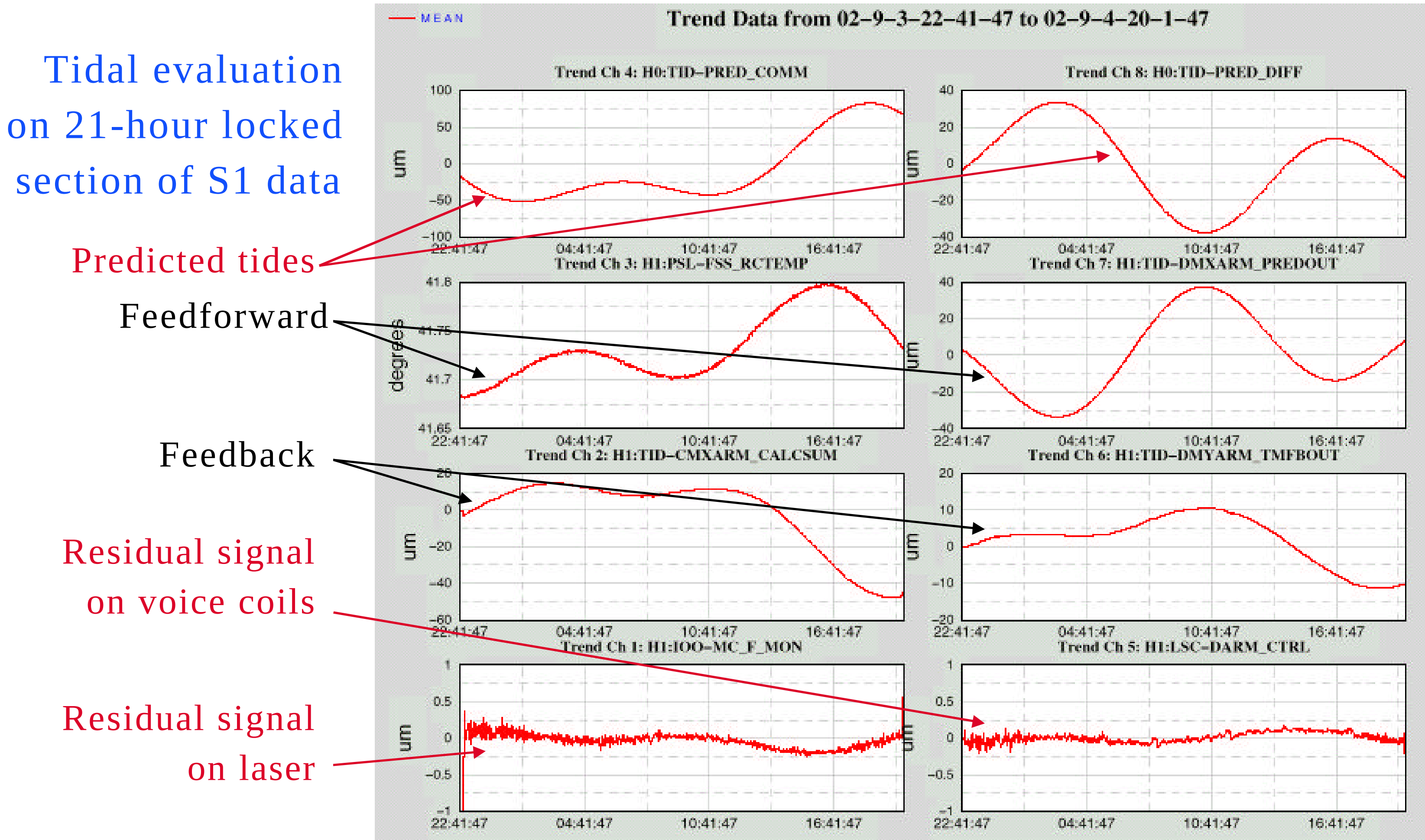


Why is Locking Difficult?

One meter

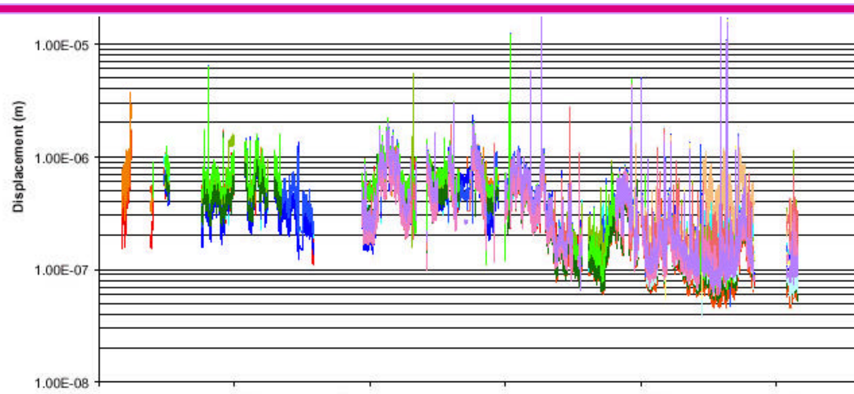
÷10,000		*Earthtides, about 100 microns*
÷100		*Microseismic motion, about 1 micron*
÷10,000		*Precision required to lock, about 10^{-10} meter*
÷100,000		*Nuclear diameter, 10^{-15} meter*
÷1,000		*LIGO sensitivity, 10^{-18} meter*

Tidal Compensation Data



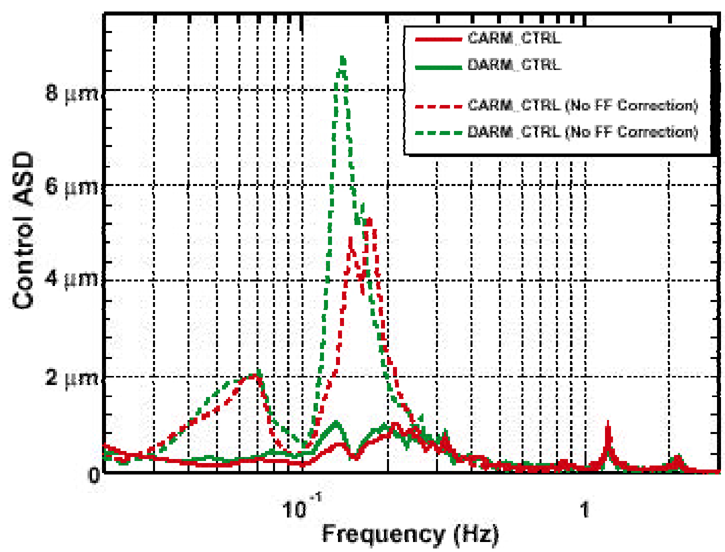
Microseism

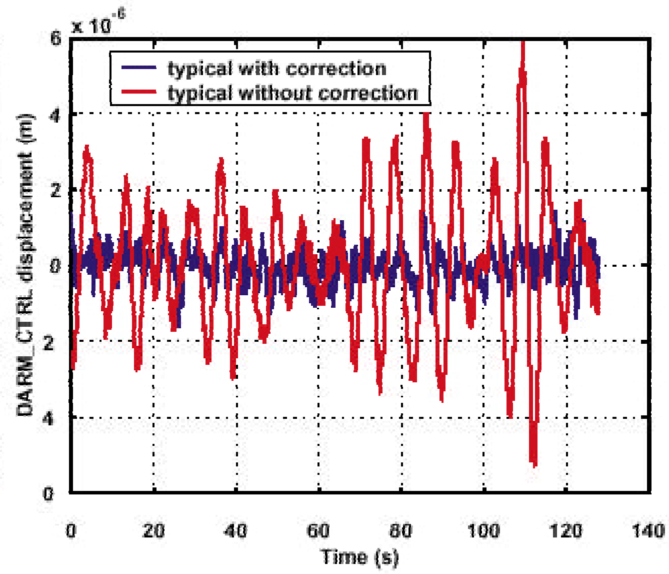
Microseism at 0.12 Hz dominates ground velocity



Trended data (courtesy of Gladstone High School) shows large variability of microseism, on several-day- and annual- cycles

Reduction by feed-forward derived from seismometers

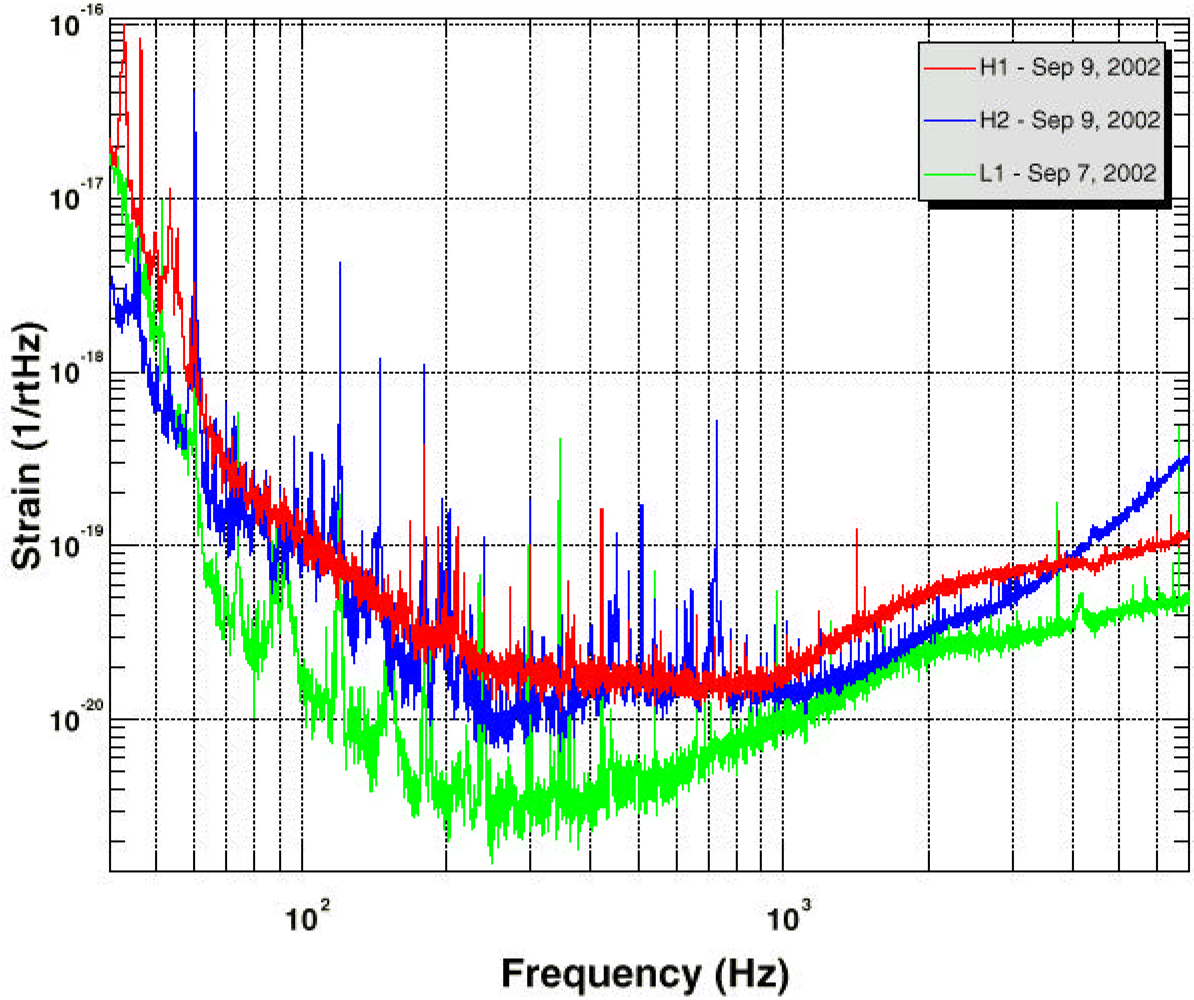




Calibration of the Detectors

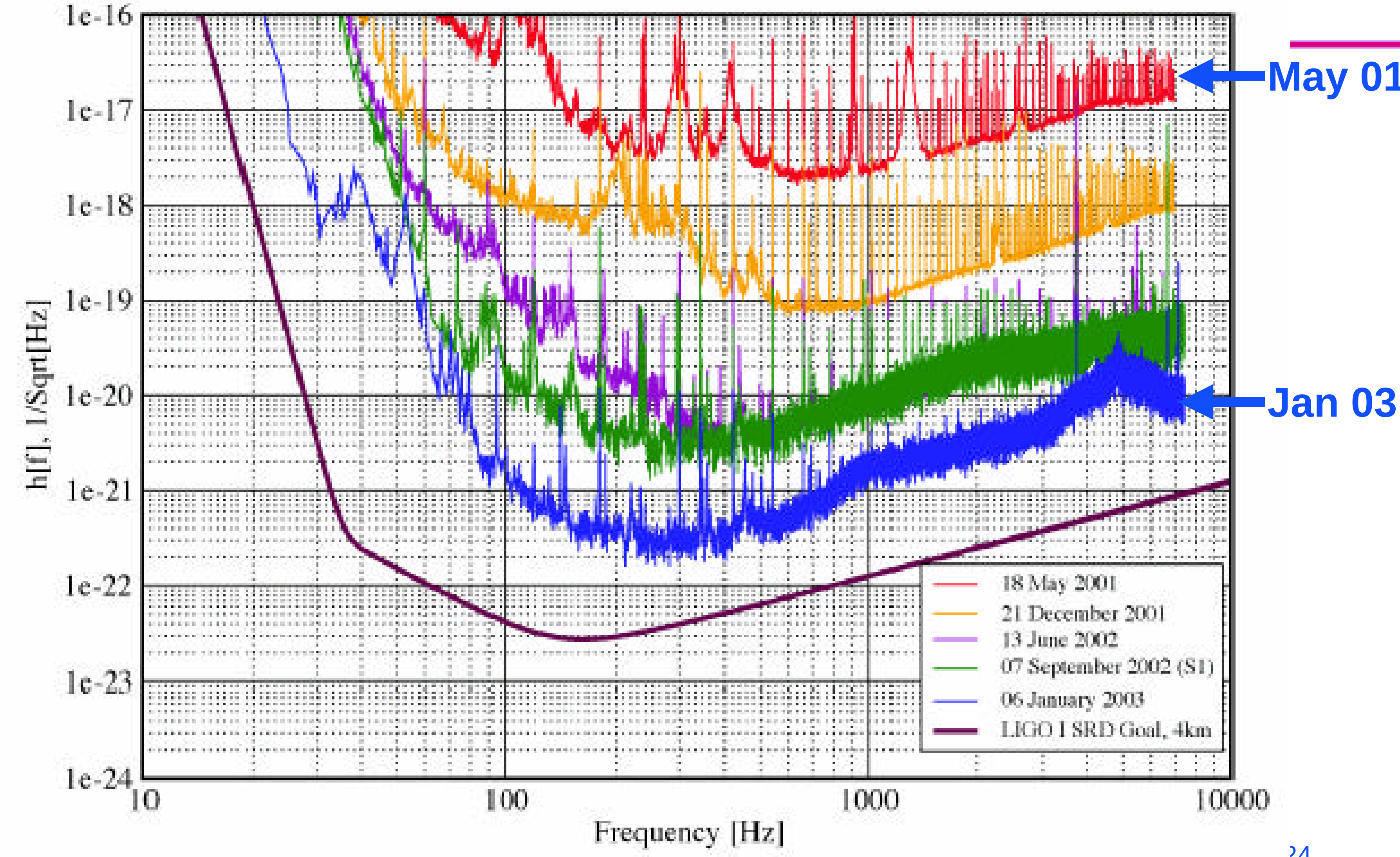
- Combination of DC (calibrates voice coil actuation of suspended mirror) and Swept-Sine methods (accounts for gain vs. frequency) calibrate meters of mirror motion per count at digital suspension controllers across the frequency spectrum
- DC calibration methods
  - » fringe counting (precision to few %)
  - » fringe stepping (precision to few %)
  - » fine actuator drive, readout by dial indicator (accuracy to ~10%)
  - » comparison with predicted earth tides (sanity check to ~25%)
- AC calibration measures transfer functions of digital suspension controllers periodically under operating conditions (also inject test wave forms to test data analysis pipelines
- CW Calibration lines injected during running to monitor optical gain changes due to drift

Noise Equivalent Strain Spectra for S1

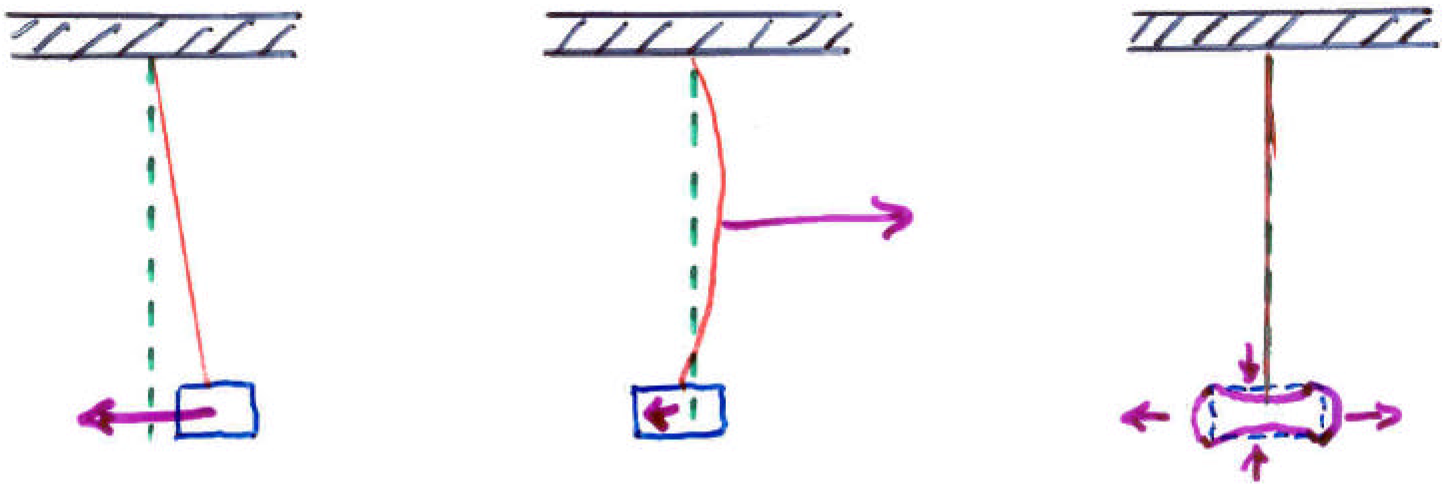


LIGO Sensitivity Over Time

Livingston 4km Interferometer



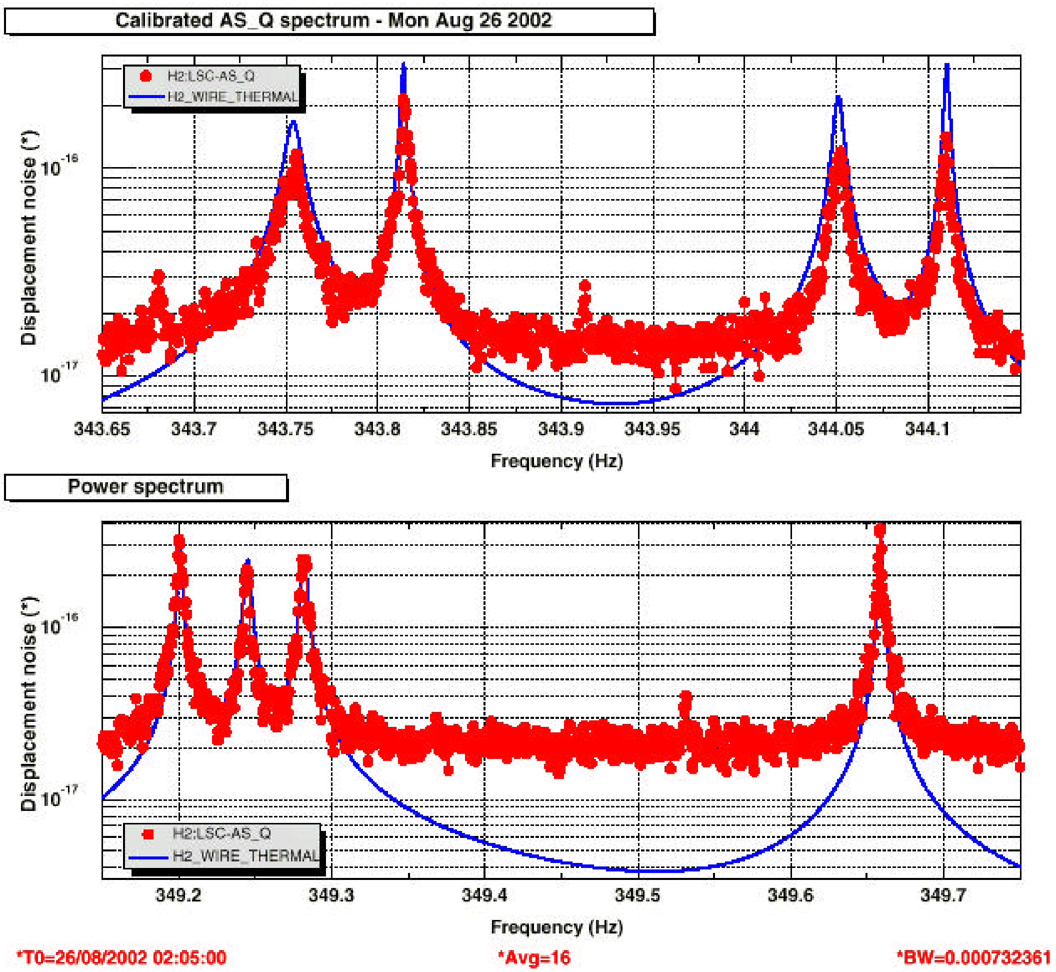
Background Forces in GW Band = Thermal Noise ~ $k_B T$/mode



pendulum mode	violin mode	test mass vibrational mode
$x_{rms} \approx 10^{-11}$ m	$x_{rms} \approx 2\times10^{-17}$ m	$x_{rms} \approx 5\times10^{-16}$ m
$f < 1$ Hz	$f \sim 350$ Hz	$f \geq 10$ kHz

Strategy: Compress energy into narrow resonance outside band of interest ⇒ require high mechanical Q, low friction

Thermal Noise Observed in 1st Violins on H2, L1 During S1



~ 20 millifermi RMS for each free wire segment

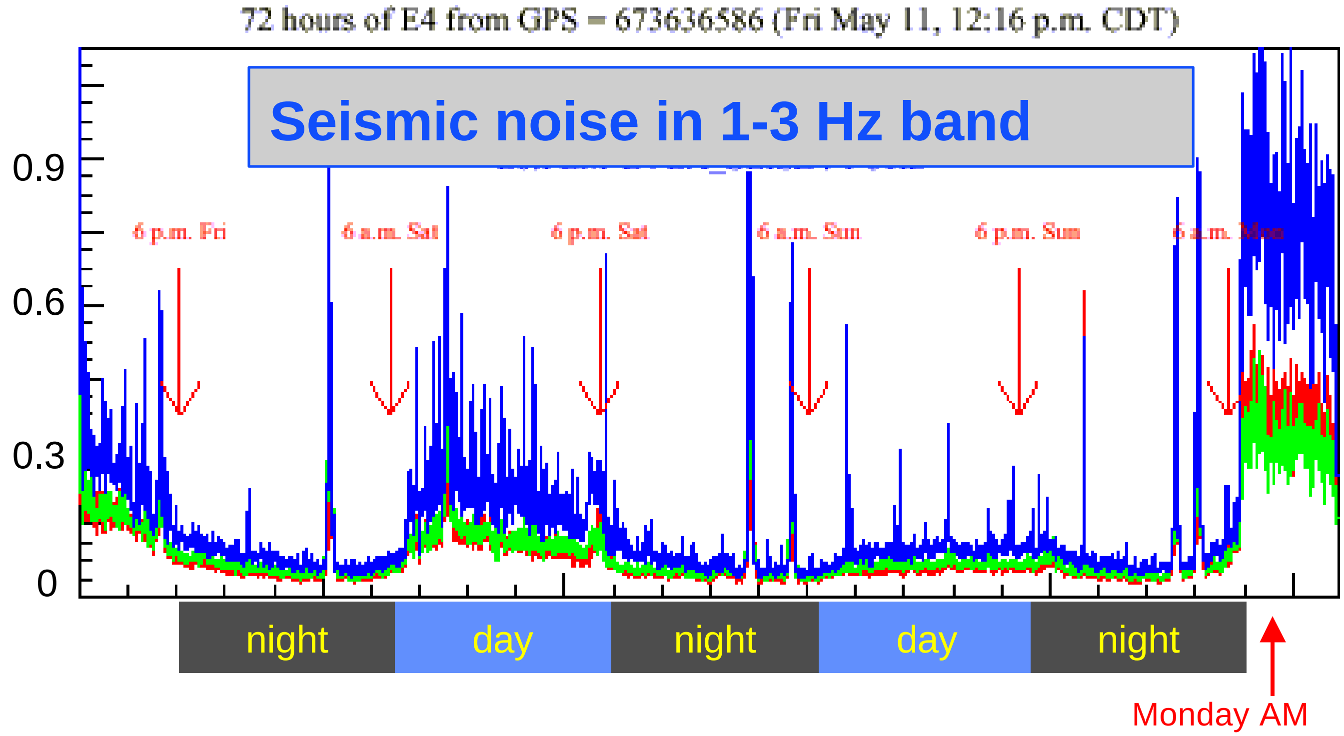
Commissioning Achievements

- Stable locking of 4-km interferometers with power recycling factors of ~40 and lock durations up to 66 hours
- Achievement of 10^{-13} m RMS arm length stabilization
- Steadily improving sensitivity
- Development of digital suspension controllers provides agility in tailoring control-loops
- Partial implementation of wave-front sensing & alignment control stabilizes sensitivity to within several % over 1/2-day time scales
- Tidal and Microseism compensation systems work
- Initial look at thermal-noise parameters exhibit expected properties
- Optical characterization of losses in long arm cavities look good

Commissioning Tasks Remaining

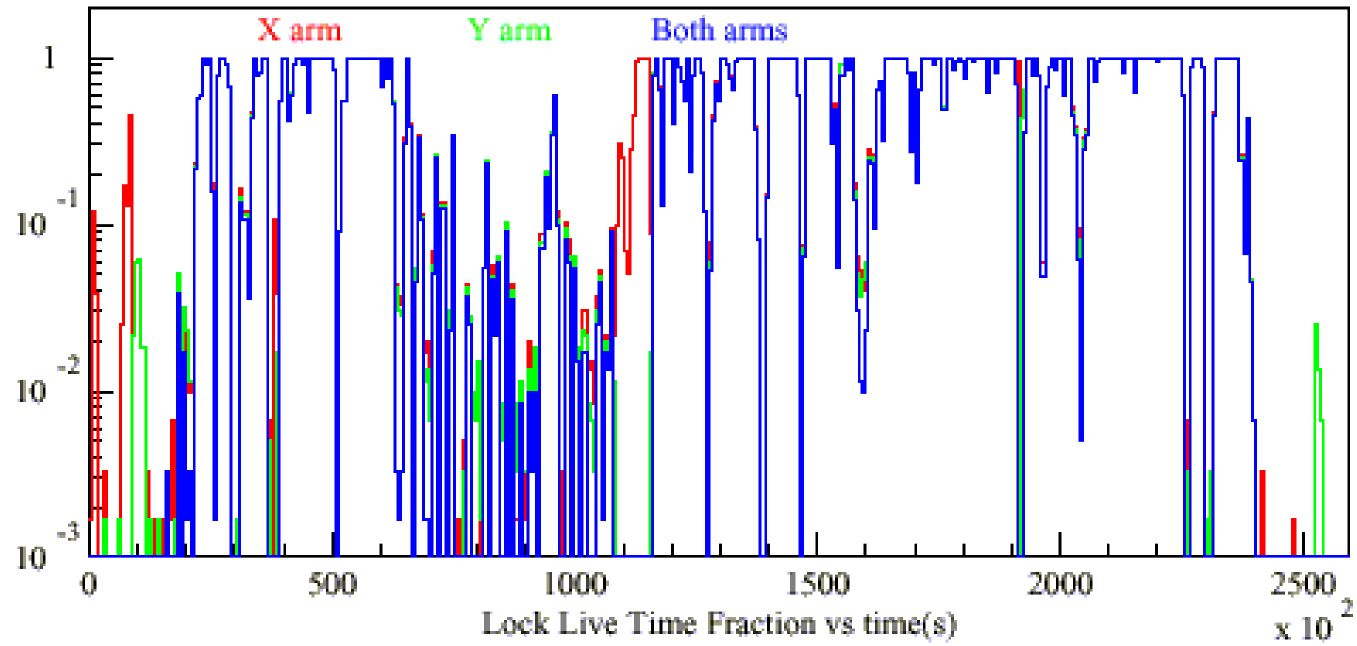
- Complete commissioning of wave-front & beam-centering control systems to stabilize alignment
- Commission intensity stabilization system
- Operate interferometers at full laser power
- Improve RFI immunity
- Install active seismic pre-isolators in Livingston to extend duty cycle
- Compensate for degeneracy issues in recycling cavity

Microns/sec



Active Seismic Isolation to be installed at Livingston to extend duty cycle

Fractional time in lock



Despite a few difficulties, science runs started in 2002.