Detector Installation and Commissioning

Stan Whitcomb

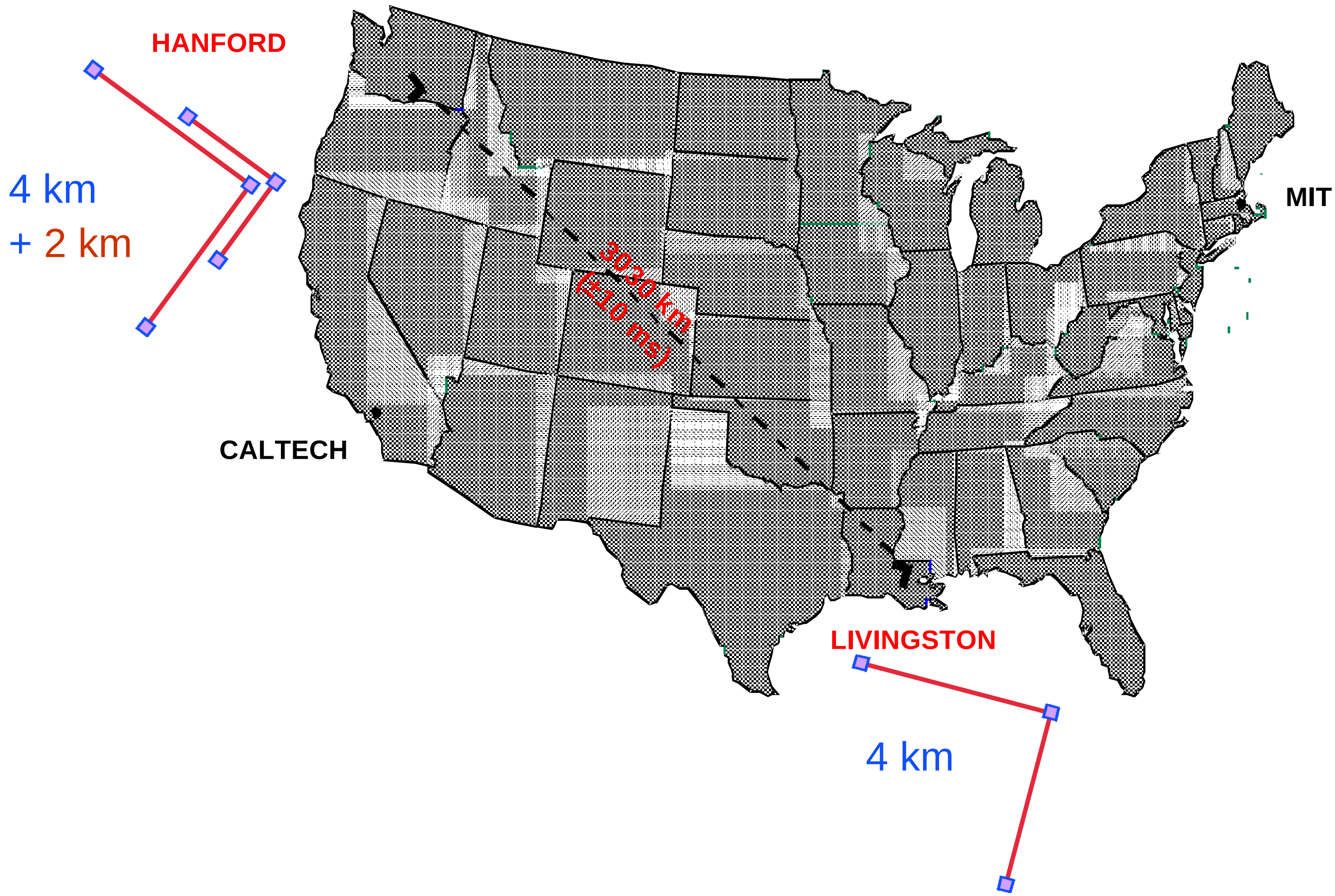
NSF Annual Review

30 April 2001

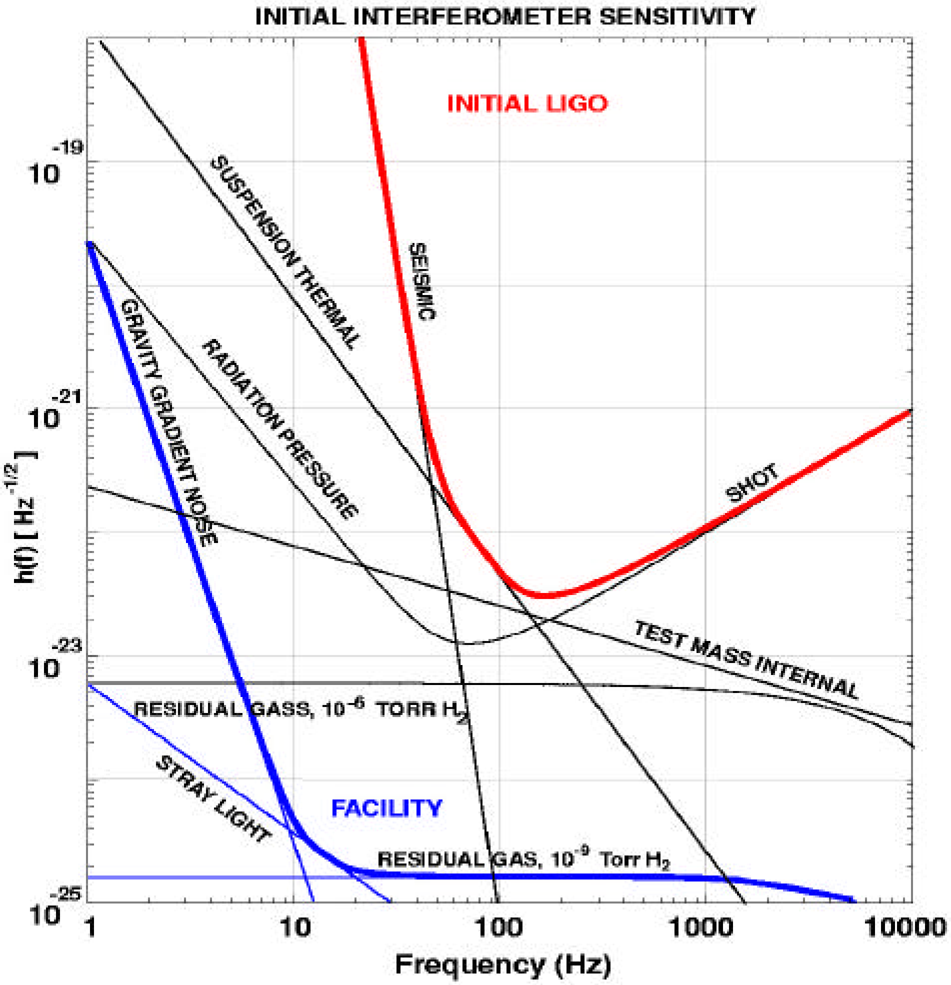
Caltech

LIGO-G010184-00-D

LIGO Observatories



Initial LIGO Sensitivity Goal



- Strain sensitivity $<3\times10^{-23}$ $1/Hz^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

Installation/Commissioning Philosophy

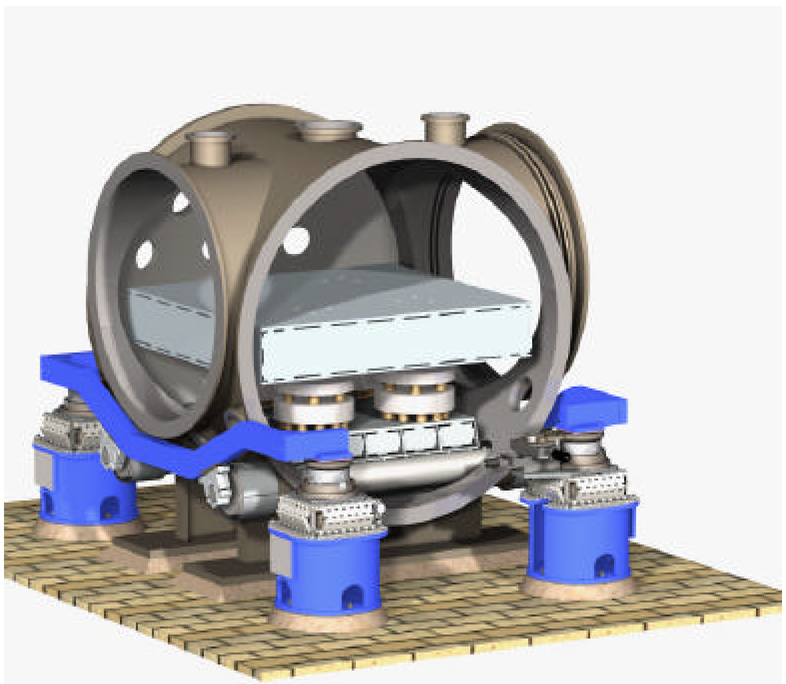
- Each interferometer has a specific role in commissioning
  - 2 km Interferometer: "Pathfinder", move quickly, identify problems, move on
  - LLO 4 km Interferometer: Systematic characterization, problem resolution
  - LHO 4 km Interferometer: Scheduled so that all fixes can be implemented prior to installation
- Stagger the installation and commissioning activities to make optimal use of available staff

Installation Status

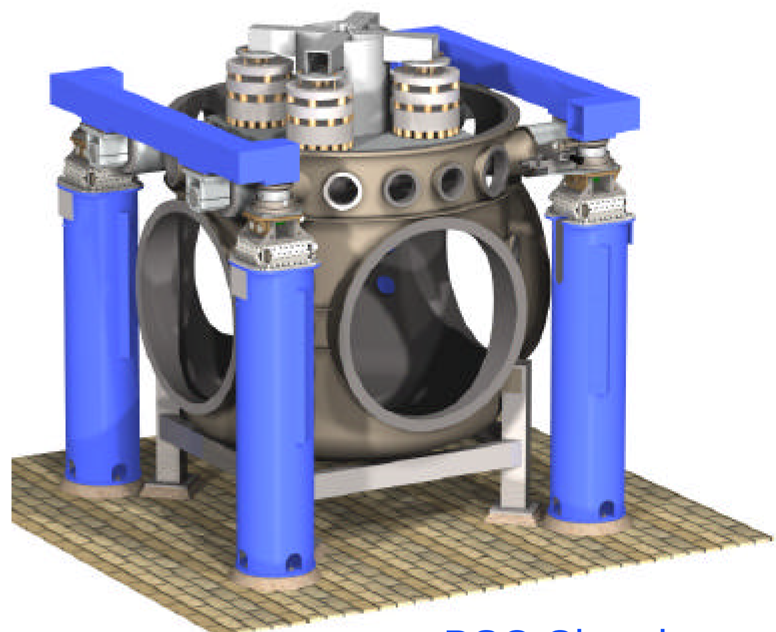
- All installation complete for LHO 2km and LLO 4km interferometers
  - » Commissioning underway
- LHO 4km interferometer
  - » Seismic isolation complete
  - » Prestabilized laser installation complete
  - » In-vacuum optics installation nearly complete
- Data Acquisition/Control Network infrastructure complete at both sites
  - » Basic functionality all in place; still working on reliability, enhancements
- Olympia earthquake forced repairs and realignment of 2 km LHO interferometer
  - » Magnets broken off some suspended optics

Vibration Isolation Systems

- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Large range actuation for initial alignment and drift compensation
- Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

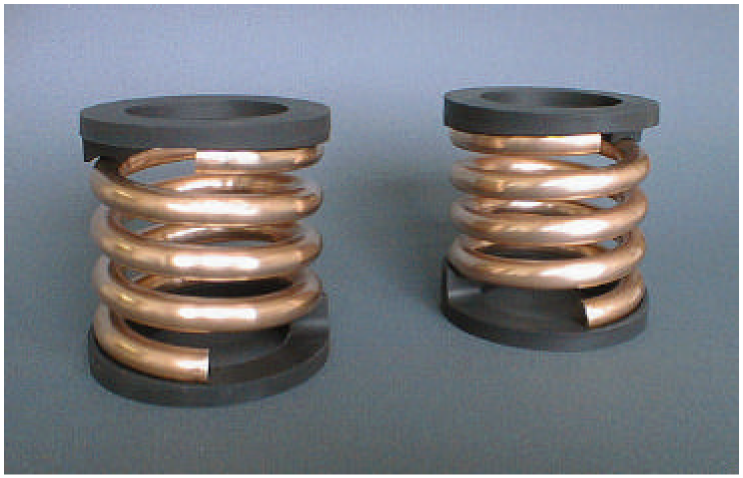


HAM Chamber

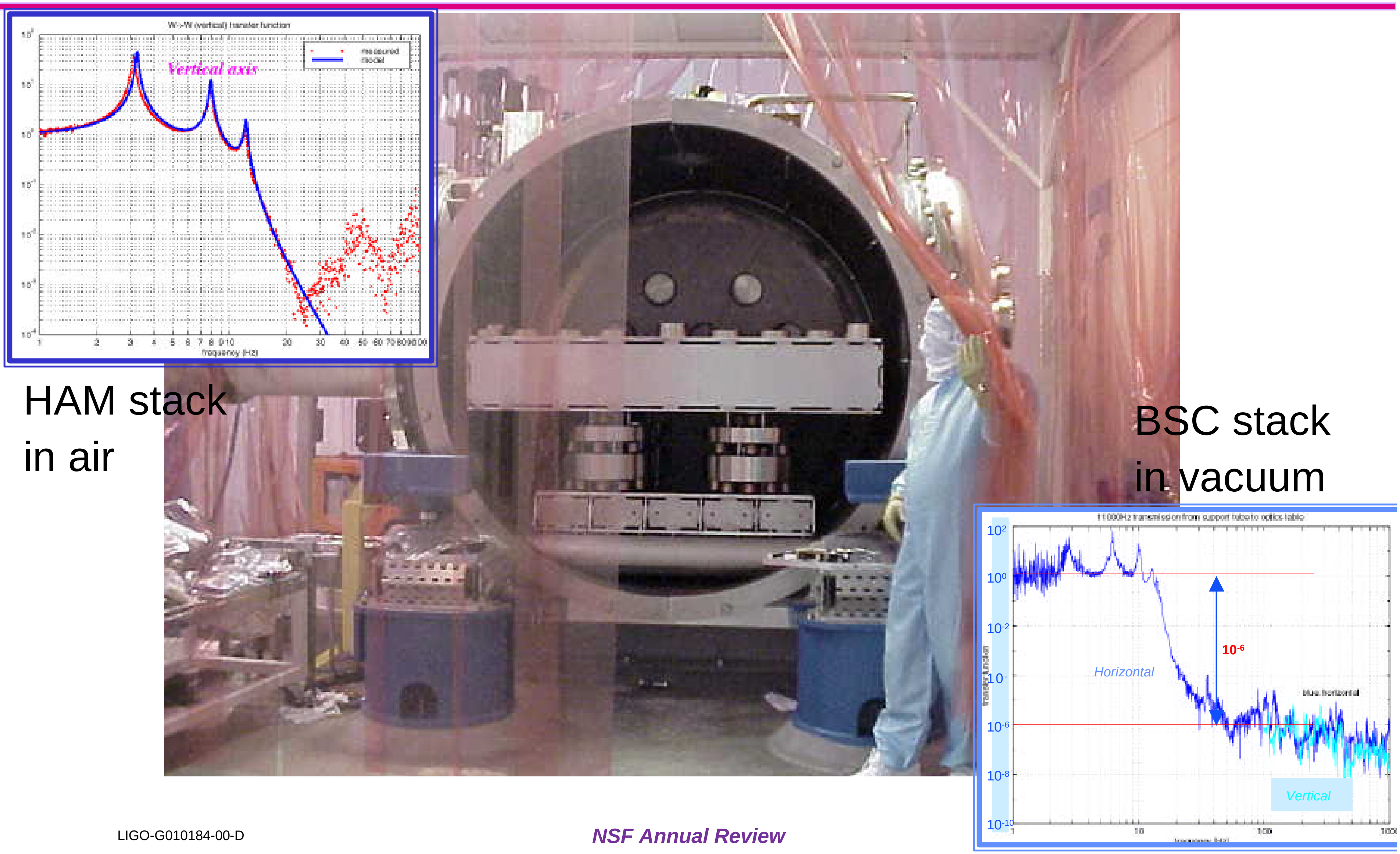


BSC Chamber

Seismic Isolation – Springs and Masses



Seismic System Performance

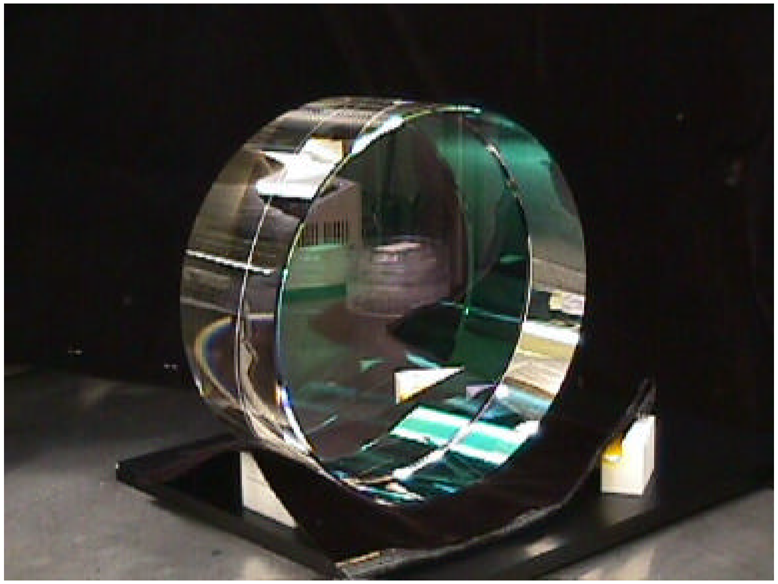


HAM stack in air

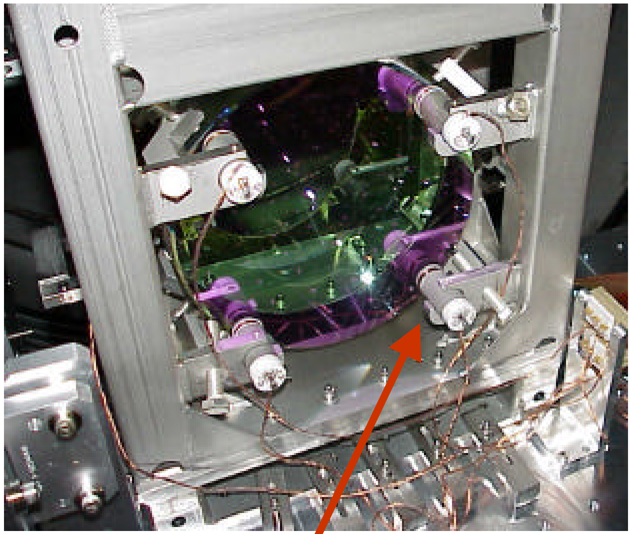
BSC stack in vacuum

Core Optics

- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity $< 5 \times 10^{-7}$
  - » Internal mode Q's $> 2 \times 10^{6}$
- Polishing
  - » Surface uniformity < 1 nm rms
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity $<10^{-3}$
- Successful production involved 6 companies, NIST, and the LIGO Lab
- All optics for three interferometers delivered to sites

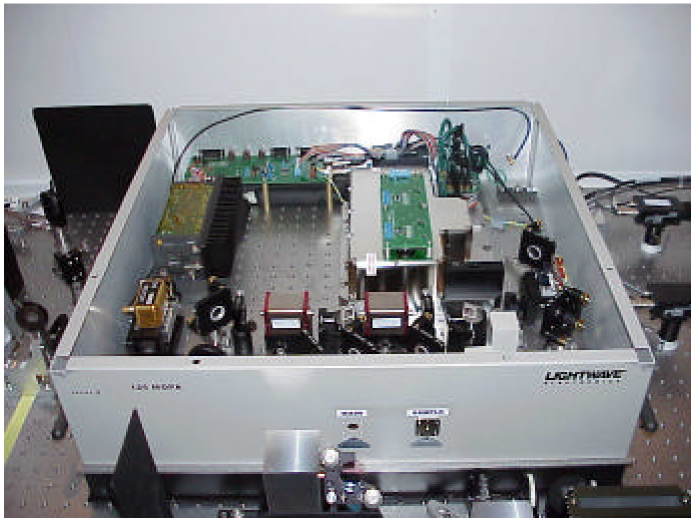


Core Optics Suspension and Control

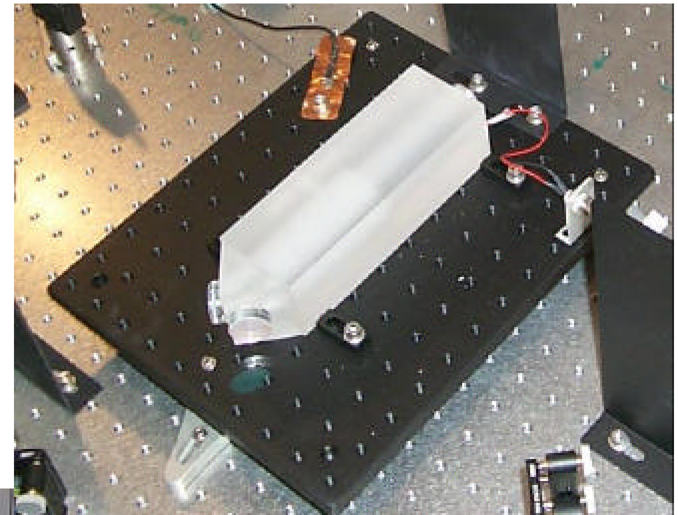


- Optics suspended as simple pendulums
- Local sensors/actuators for damping and control
- Problem with local sensor sensitivity to laser light

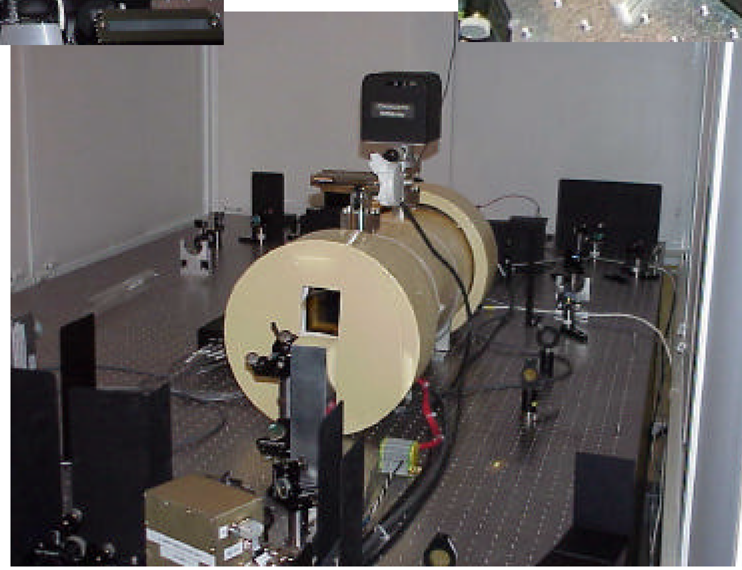
Pre-stabilized Laser



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



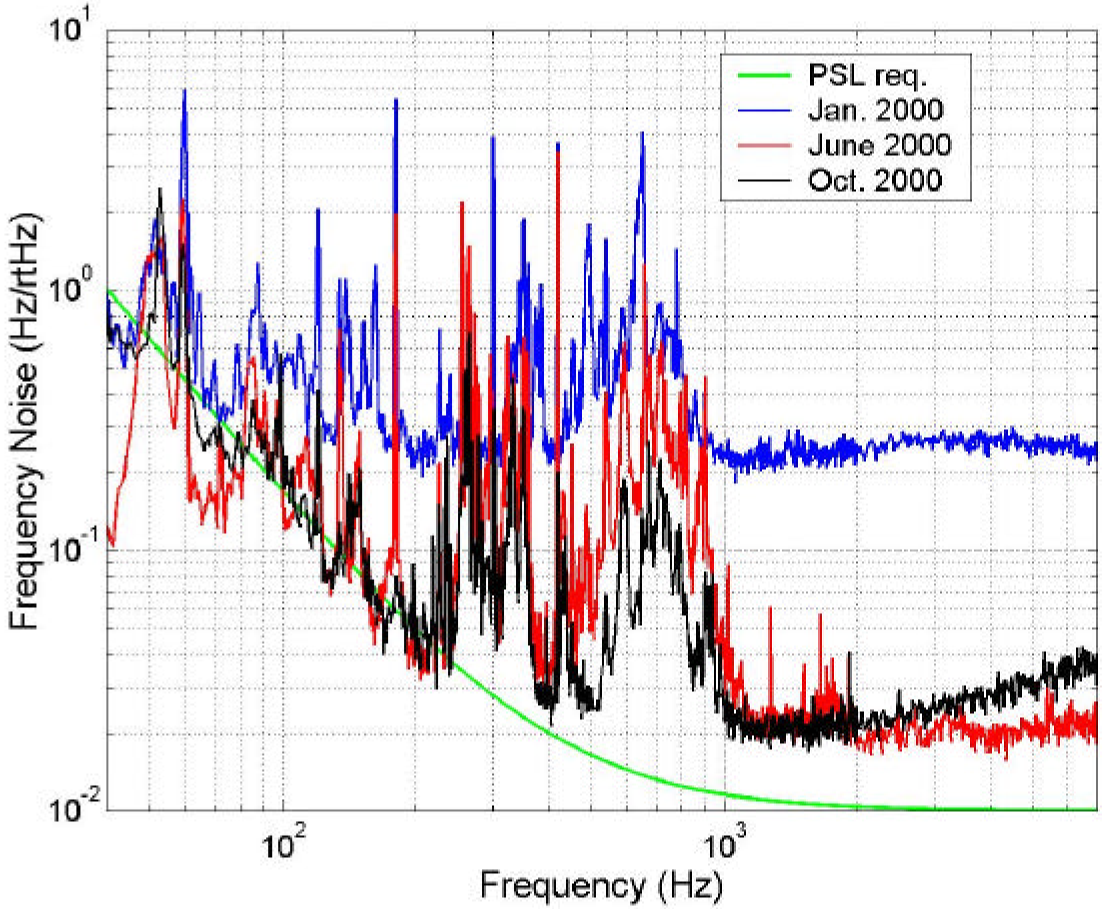
Cavity for
defining beam geometry,
joint development with
Stanford



Frequency stabilization
cavity

WA 2k Pre-stabilized Laser Performance

- > 20,000 hours continuous operation
- Frequency lock typically holds for months
- Improvement in noise performance
  - » electronics
  - » acoustics
  - » vibrations



Control and Data System

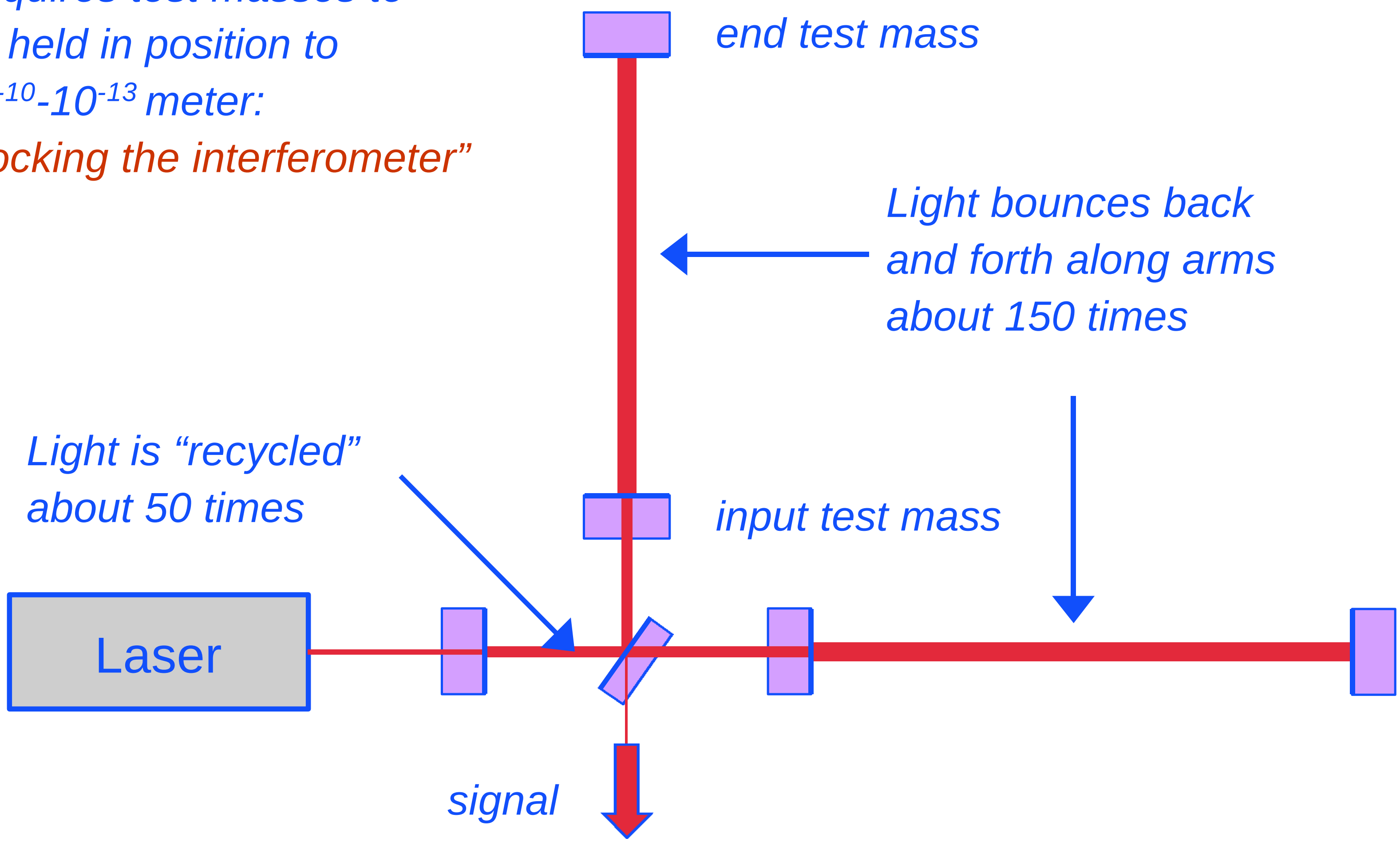
- EPICS-based distributed realtime control system
  - » ~50 realtime processors, ~20 workstations per site
  - » ~5000 process variables (switches, sliders, readings, etc) per interferometer
  - » Fiber optic links between buildings
- Data acquisition rate of 3 MB/s per interferometer
  - » Reflective memory for fast channels, EPICS for slow ones
  - » Synchronized using GPS
  - » Data served to any computer on site in realtime or playback mode using same tools
- Multiplexed video available in control room and next to the interferometer
- Starting to see maintenance costs for CDS computers/electronics

Commissioning Status

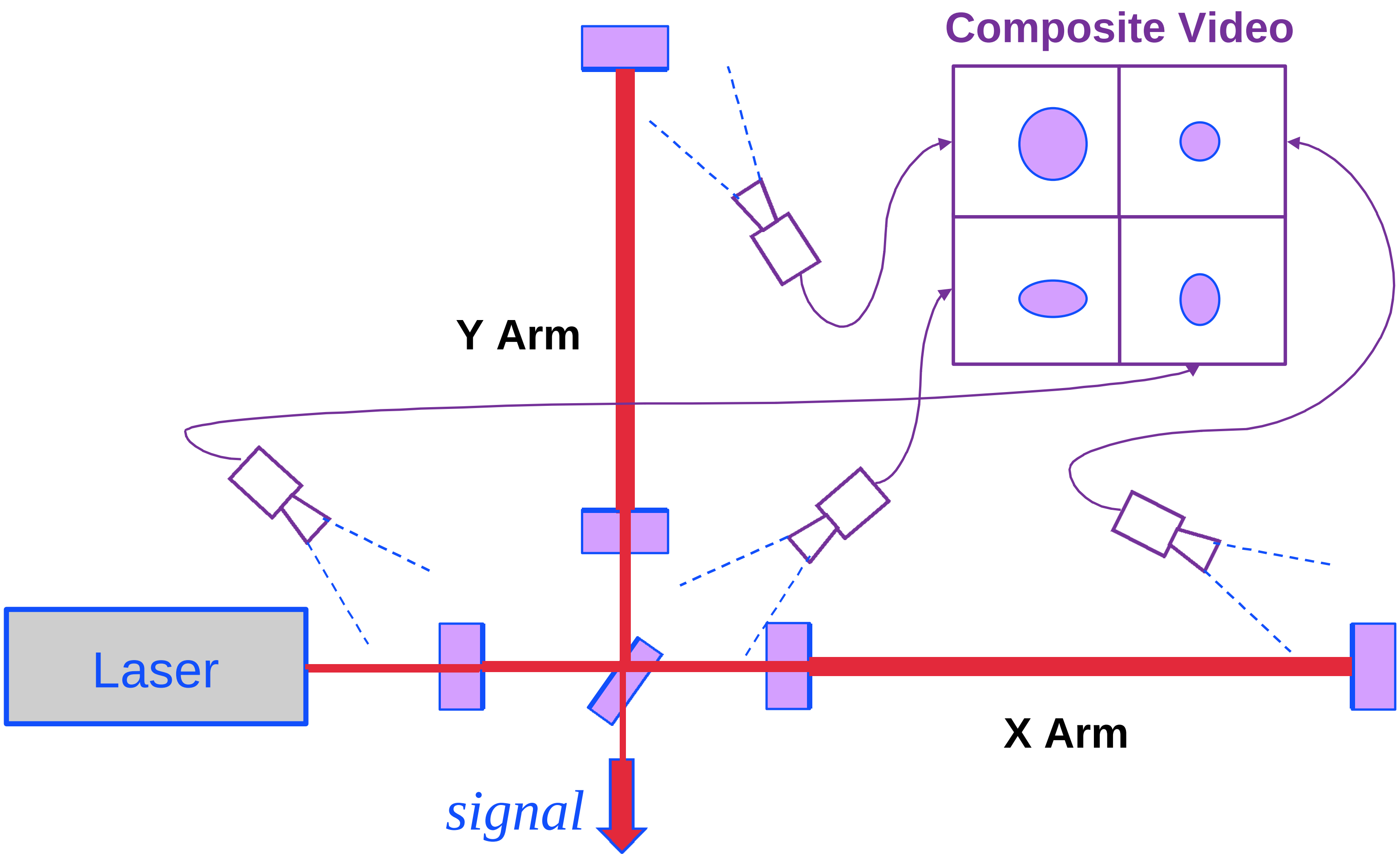
- LHO 2 km interferometer
  - » Identified problem with scattered light in suspension sensors during modecleaner testing – moved to lower power and continued on
  - » Early test of individual arm cavities performed before installation was complete
  - » Full interferometer locked at low input power (100 mW)
    - All longitudinal degrees of freedom controlled
    - Partial implementation of wavefront-sensing alignment control
  - » Commissioning interrupted by earthquake repairs/suspension sensor replacement
- LLO 4 km interferometer
  - » Careful characterization of laser-modecleaner subsystems
  - » Single arm testing complete (both arms locked individually)
  - » Recombined Michelson with Fabry-Perot arms locked successfully
  - » Repetition of 2 km integrations taking much less time than (I) expected (10 times shorter to date, but probably can't continue)

Locking an Interferometer

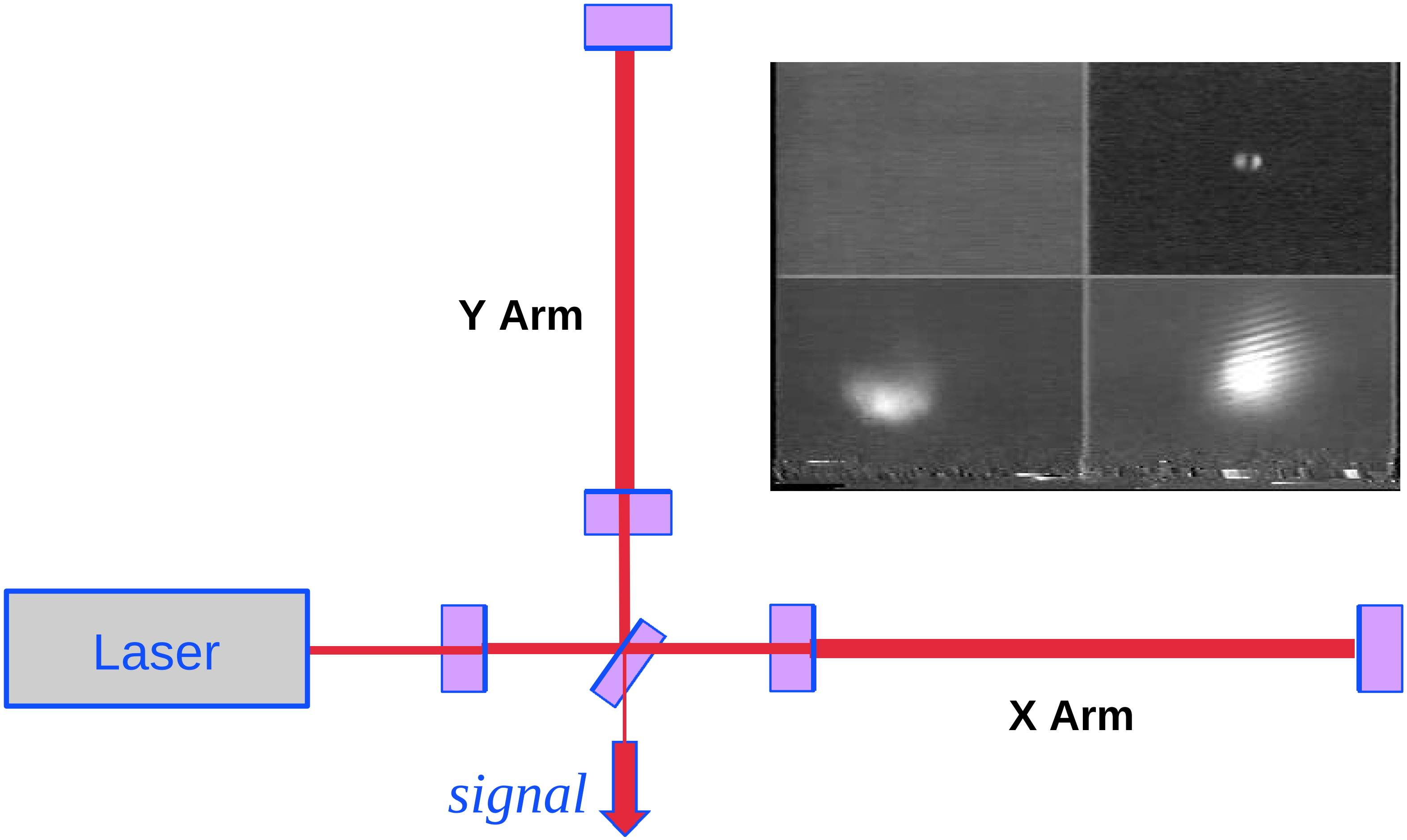
Requires test masses to be held in position to 10^{-10}-10^{-13} meter:
"Locking the interferometer"



Steps to Locking the Interferometer



Watching the Interferometer Lock

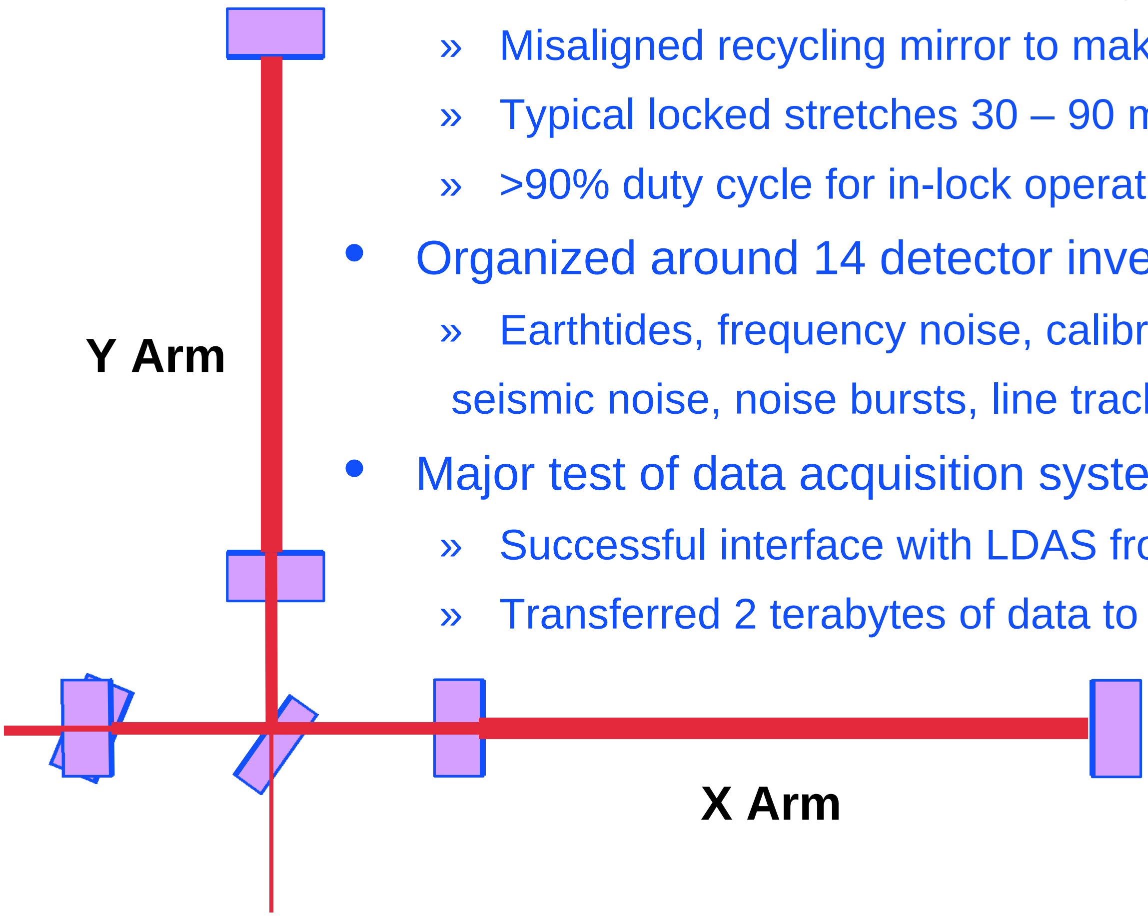


Engineering Runs

- Means to involve the broader LSC in detector commissioning
  - » Major benefit to commissioning, but also requires Lab resources
- Engineering Runs are a key part of our commissioning plan
  - » Test interferometer stability, reliability
  - » Well-defined dataset for off-site analysis
  - » Develop procedures for later operations
- First Engineering Run (E1) in April 2000
  - » Single arm operation of 2 km interferometer with wavefront sensing alignment on all angular degrees of freedom
  - » 24 hour duration
  - » Lots of interest, seven LSC groups made arrangements for data access

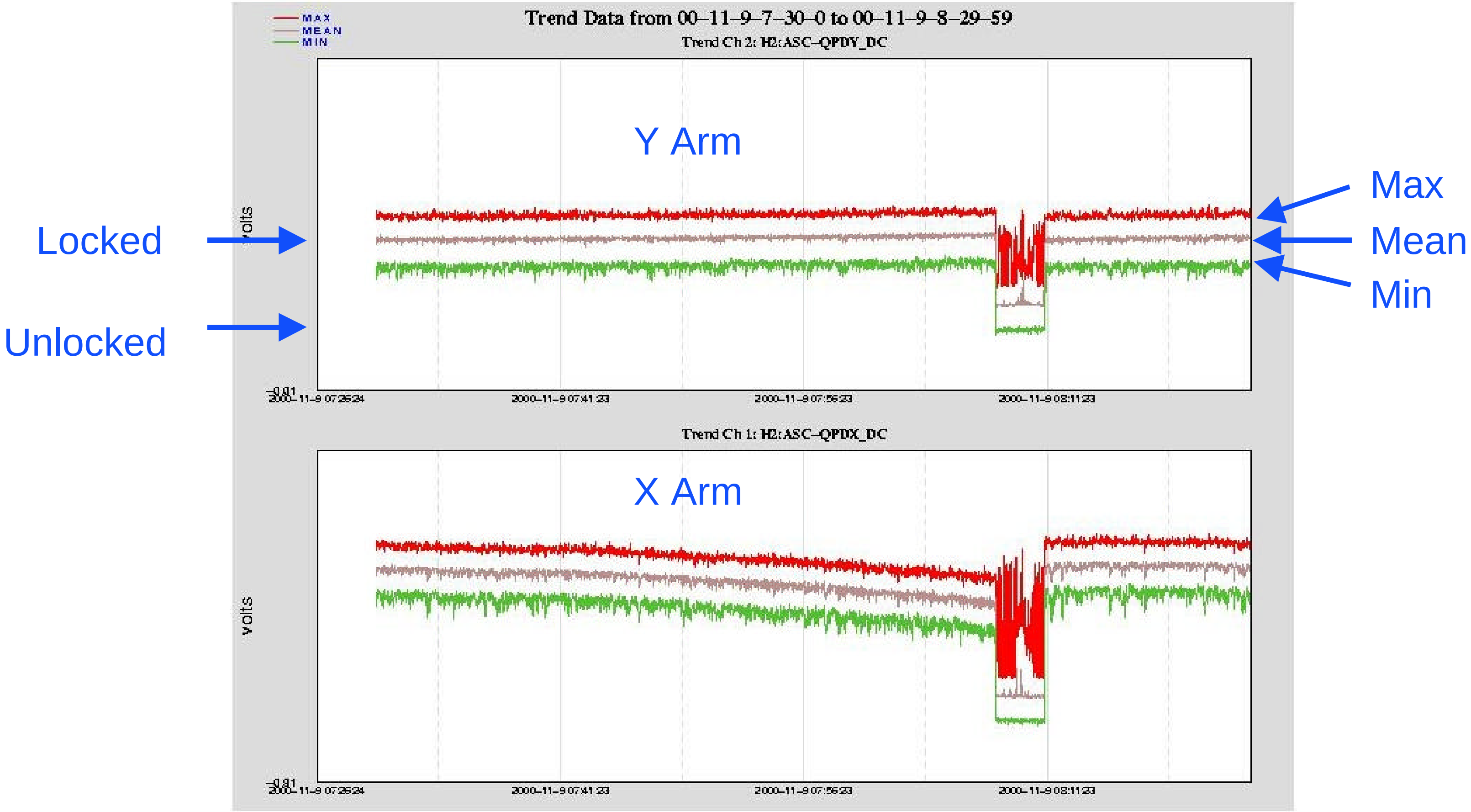
Second Engineering Run (E2)

- November 2000
  - » One week of 24/7 operation of 2 km interferometer
  - » Approximately 35 scientists participated on site
- Recombined Michelson with Fabry-Perot arms
  - » Misaligned recycling mirror to make for more robust locking
  - » Typical locked stretches 30 – 90 minutes (longest ~ 3 hours)
  - » >90% duty cycle for in-lock operation
- Organized around 14 detector investigations
  - » Earthtides, frequency noise, calibration, noise stationarity, seismic noise, noise bursts, line tracking, …
- Major test of data acquisition system
  - » Successful interface with LDAS front-end
  - » Transferred 2 terabytes of data to Caltech archive



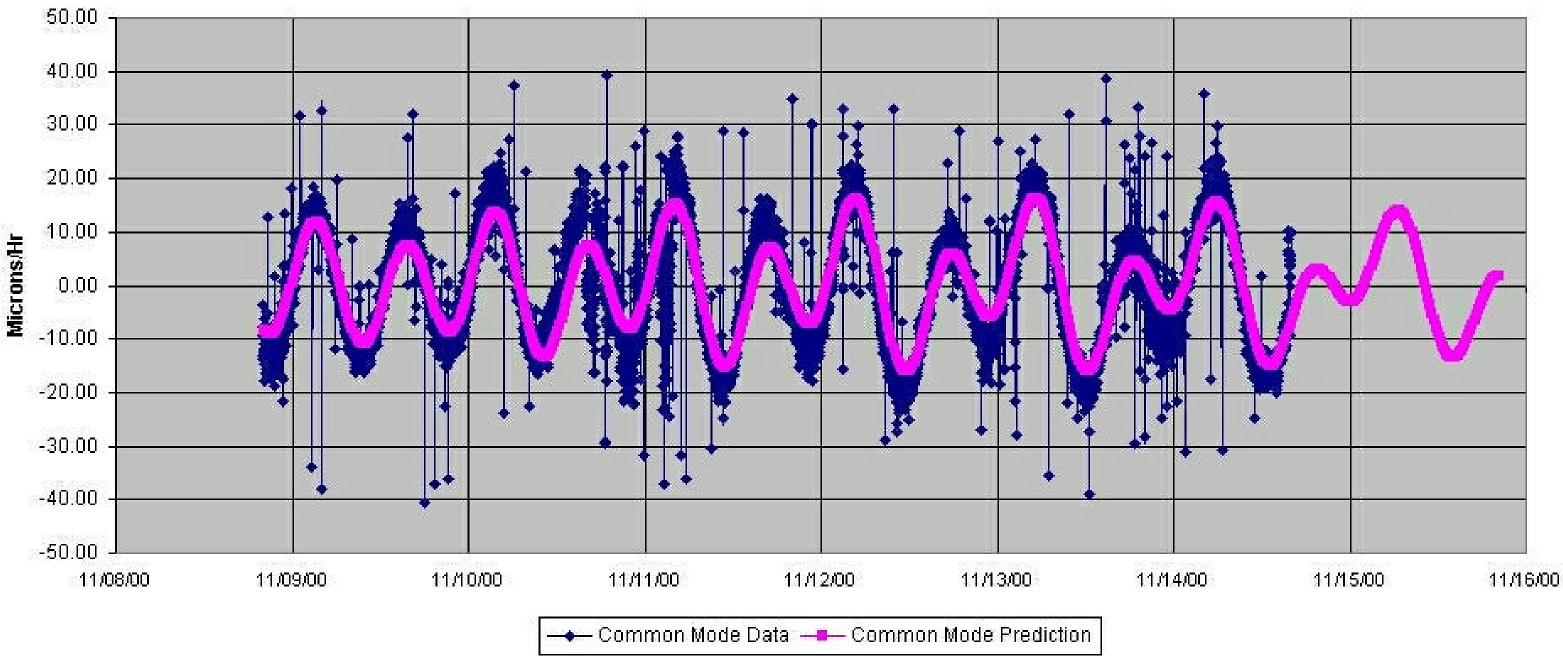
E2: Recombined Michelson Robustness

Randomly chosen hour from recent engineering run

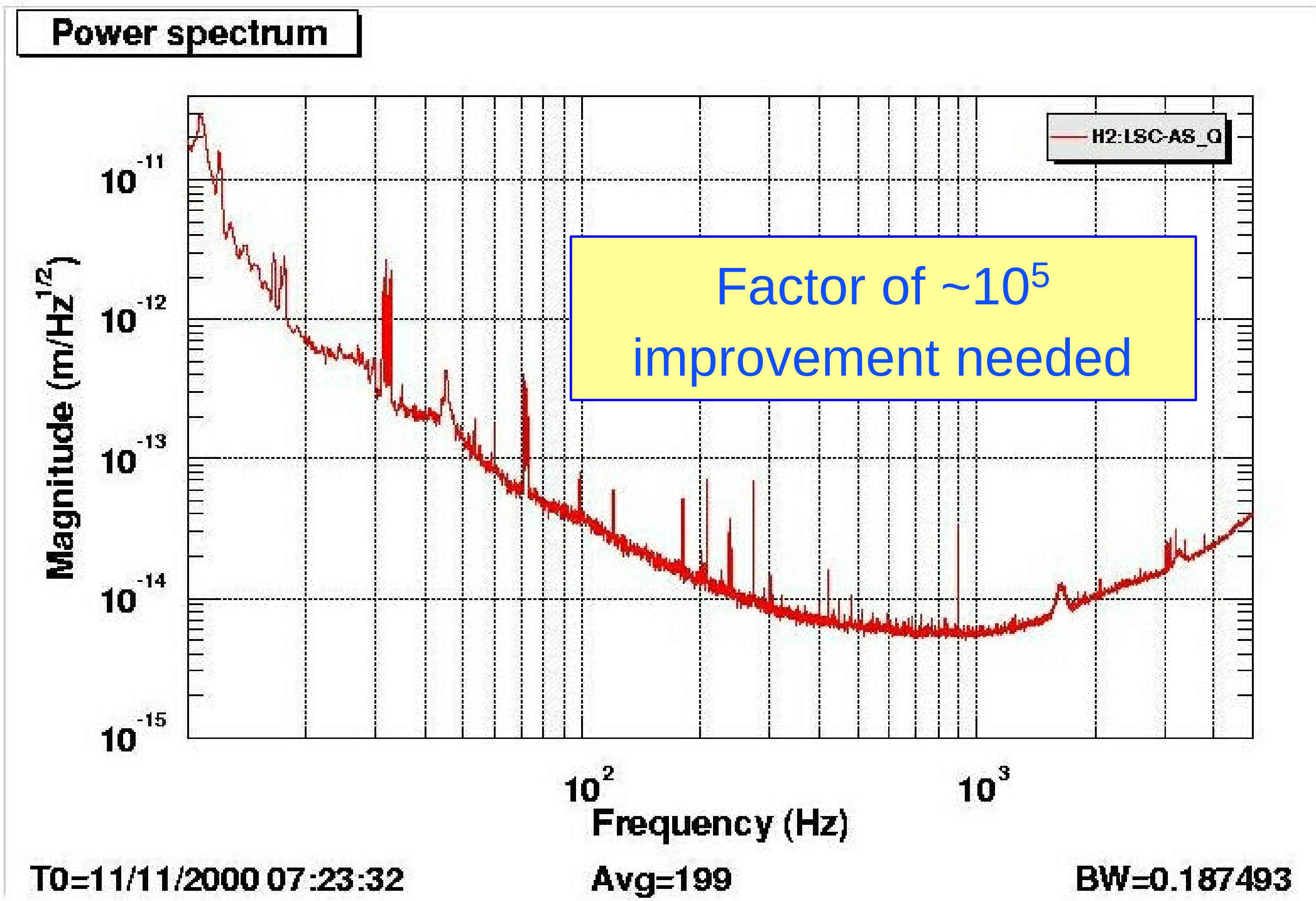


E2: Earthtide Investigation

- Observed in earlier E1 Run
- Main cause of loss of lock in E2 run: ~200 microns p-to-p
- Tidal actuator being commissioned for continuous lock
- Common mode (both arms stretch together) and differential mode (arms stretch by different amounts)



E2: Recombined Interferometer Spectrum



First differential arm spectrum, Nov. 2000

E3 Engineering Run

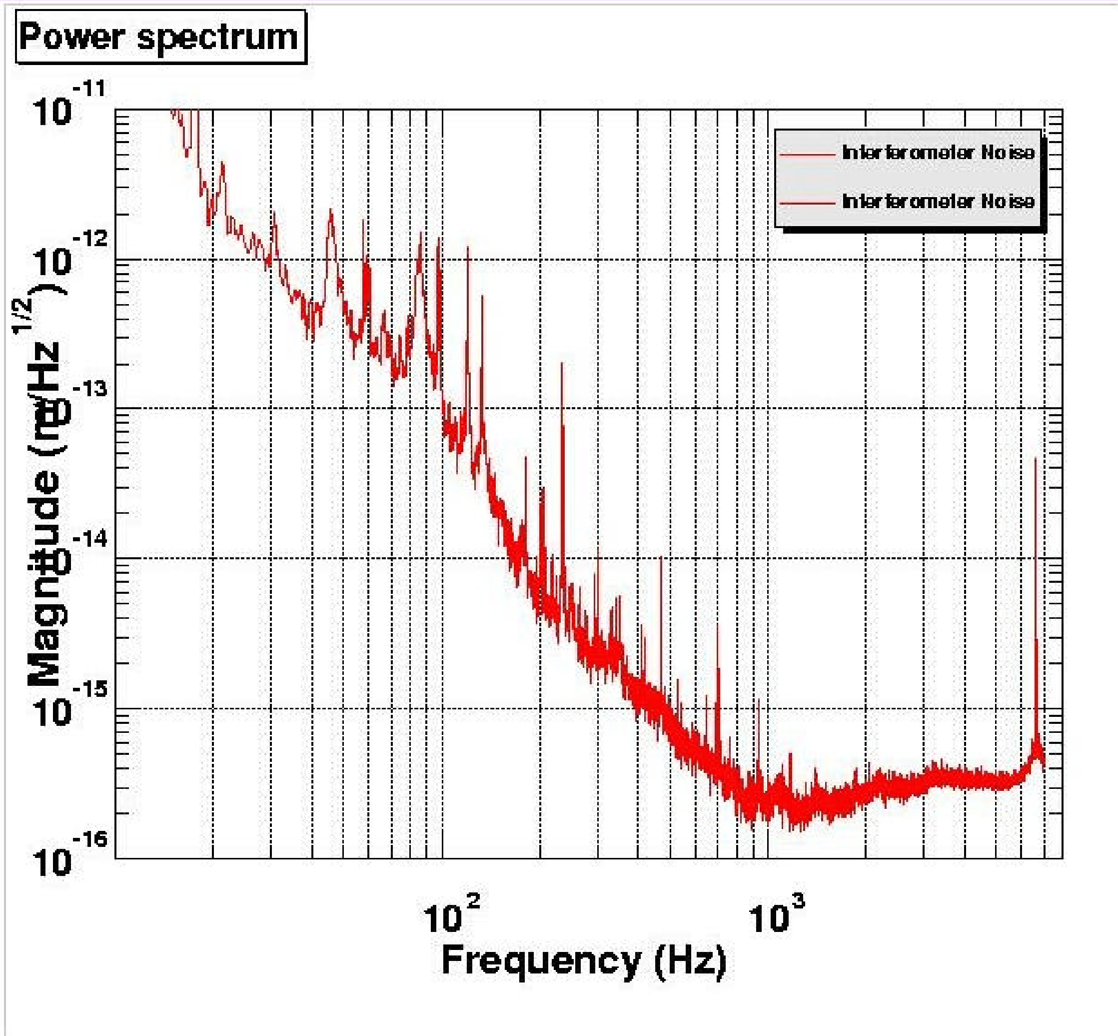
- Held March 9-12
- Planned as first coincidence run between LHO 2 km interferometer (full recycled configuration) and LLO 4 km interferometer (single arm)
- Earthquake (10 days before start) reduced LHO to PEM data only
- Again organized around investigations
- Specific goals
  - » Correlations between environmental signals
  - » Integration of data streams from two sites (including timing)
  - » (First operation of full recycled F-P Michelson interferometer)

Work on Interferometer Noise

Pretty much what we expected from first noise spectrum:

- Electronics noise dominant at high frequencies in E2 spectrum (due to low input power)
- Laser frequency noise dominates in mid frequency band (stabilization servos still being tuned up)
- Low frequencies seismic noise?
- Many resonant features to investigate and eliminate
- No showstoppers!

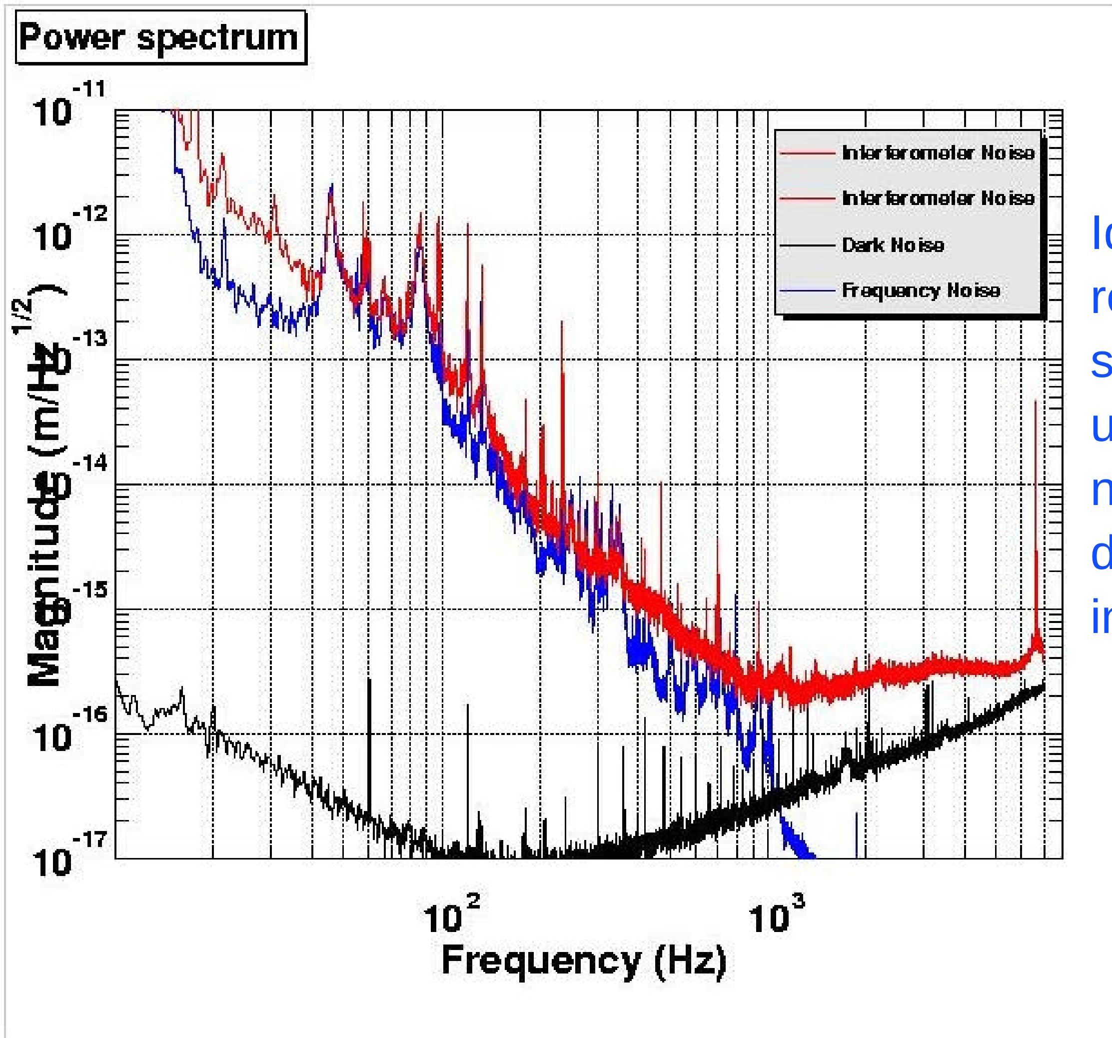
2 km Noise Spectrum (pre-earthquake)



Factor of 20 improvement (over E2 spectrum):

- Recycling
- Reduction of electronics noise
- Partial implementation of alignment control

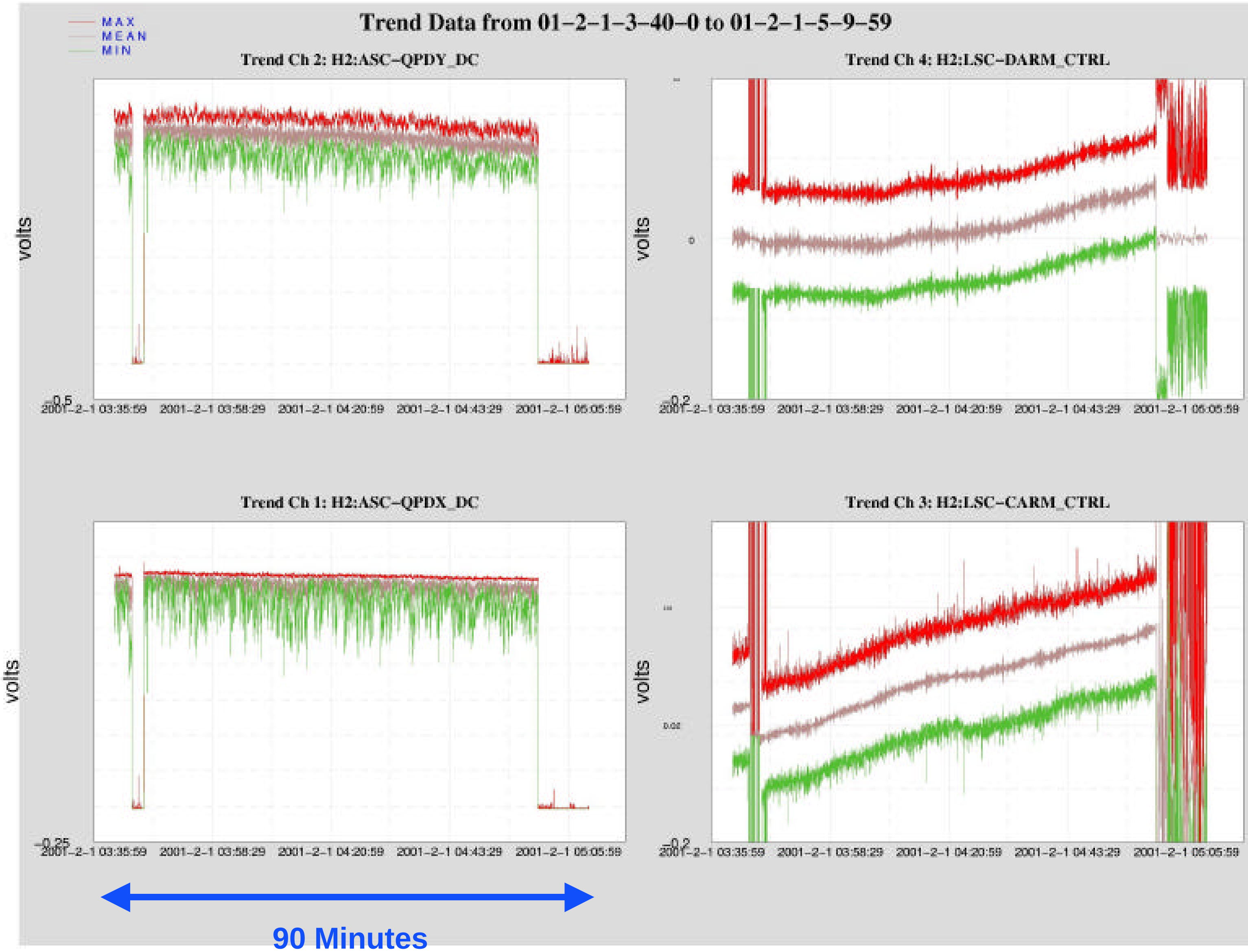
Known Contributors to Noise



Identification and reduction of noise sources underway using well-established noise-hunting techniques developed on prototype interferometers

Progress Toward Robust Operation

- Different measure of interferometer performance (in contrast with sensitivity)
  - Interferometer lock duration goal is 40 hours
- 2 km Prestabilized Laser
  - Two years continuous operation with ~20% loss in power (recovered in recent tune-up)
  - Locks to reference cavity and premodecleaner for months
- Mode Cleaner
  - Locks for weeks at a time, reacquires lock in few seconds
- Data Acquisition and Control
  - Data Acquisition and Input Output Controllers routinely operate for days to months without problems
  - Tools in place for tracking machine state: AutoBURT, Conlog



Trend Data from 01-2-1-3-40-0 to 01-2-1-5-9-59
MAX
MEAN
MIN
Trend Ch 2: H2:ASC-QPDY_DC
Trend Ch 4: H2:LSC-DARM_CTRL
Trend Ch 1: H2:ASC-QPDX_DC
Trend Ch 3: H2:LSC-CARM_CTRL
volts
-0.5
-0.25
-0.2
2001-2-1 03:35:59
2001-2-1 03:58:29
2001-2-1 04:20:59
2001-2-1 04:43:29
2001-2-1 05:05:59
90 Minutes

Plan to Reach Science Run

- March 9-12
  - » E3 (engineering run): coincidence run between LHO PEM and single arm at LLO
- mid-March to mid-May
  - » LHO 4k, complete installation, lock modecleaner
  - » LHO 2k, repair, suspension sensor replacement, resurrect PRM
  - » LLO 4k, lock full interferometer, sensitivity/robustness
- May
  - » E4 run: LLO 4 km, operating in recombined mode (recycling?) + LHO PEM
- May - June
  - » LHO 2k, bring full interferometer back on-line, sensitivity studies
  - » LLO 4 k suspension sensor replacement, bring back on-line
  - » LHO 4k, PRM locking (no arms yet)

Plan to Reach Science Run, Part 2

- July
  - » E5: LHO 2k in full recycled configuration, LLO 4k in full recycled configuration(?), LHO 4k in PRM mode
- July - Sept
  - » LLO 4k, improve full interferometer lock, sensitivity studies
  - » LHO 2km sensitivity studies, 4k lock full interferometer
- late Sept – early Oct
  - » E6: triple coincidence run with all 3 interferometers in final optical configuration (“upper limit run”)
- Oct – early 2002
  - » Improve sensitivity and reliability
  - » Alternate diagnostic testing with engineering runs

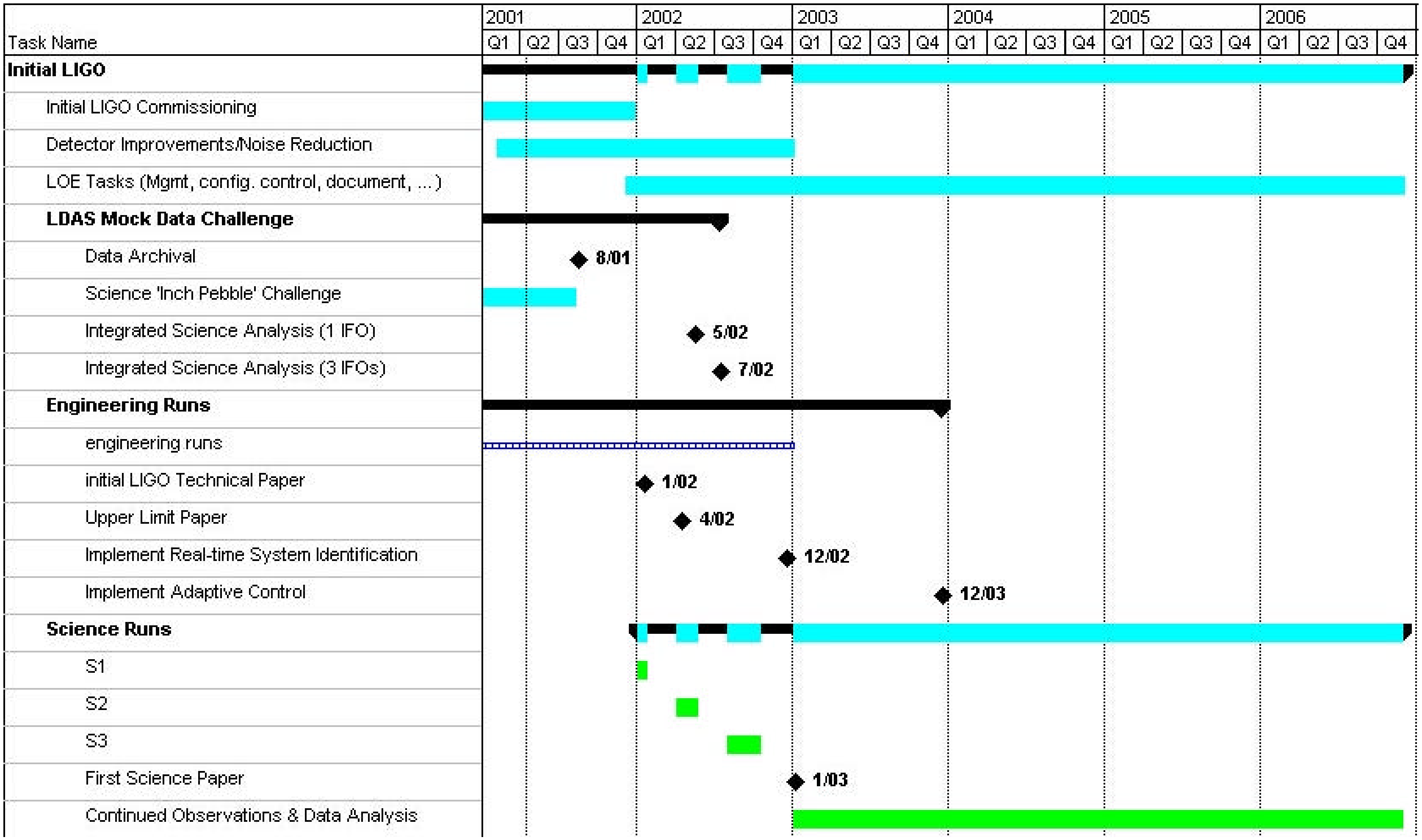
Upgrades to Initial Detector

- Upgrades in progress
  - » Redesigned Damping Sensor/Actuator Heads (increased immunity from the laser light)
  - » Digital Suspension Controllers (frequency dependent diagonalization)
- Planned detector upgrades
  - » Improved interferometer sensing & control servo electronics (noise reduction)
  - » Servo-control and diagnostic software modifications (continuous)
  - » On-line system identification (enable controls improvement)
  - » Adaptive interferometer control (for improved control robustness)

Detector Upgrades (continued)

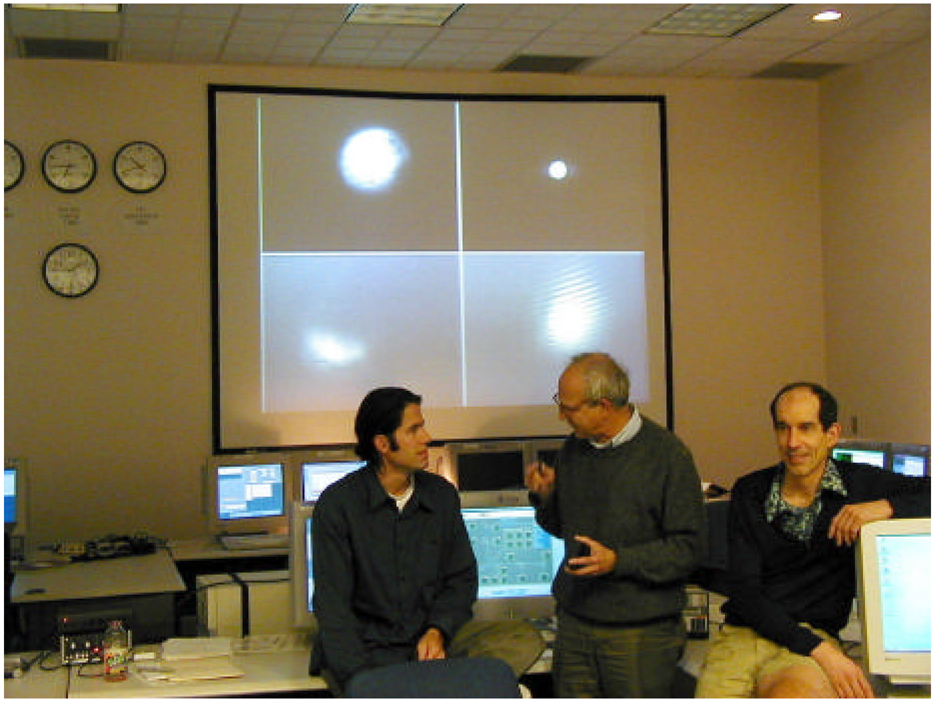
- Possible Future Detector Upgrades
  - » Modulated damping sensor electronics (increased immunity to laser light)
  - » Improved laser frequency stabilization servo electronics (noise reduction)
  - » Redesigned pre-mode cleaner (enable higher bandwidth control)
  - » Additional physics environment monitoring (PEM) sensors (after correlation analyses indicate useful deployment)
  - » TBD -- as commissioning and characterization studies determine needs

Initial Detector Milestones



Summary

- Detector installation is nearly complete
- Commissioning is proceeding well
- 2001
  - » Improve sensitivity/reliability
  - » First coincidence operation
  - » Initial data run ("upper limit runs")
- 2002
  - » Begin Science Run
  - » Interspersed data taking and machine improvements
- 2003-2006
  - » Minimum of one year of integrated data at 10^{-21} sensitivity



First Lock in the Hanford Observatory control room