AOS: Photon Calibrator

Technical Status

NSF Review, April 25-27, 2011

Rick Savage

(and Jonathan Berliner)

Functions

Project cost for Pcal is $1.22M

- Provide an independent, absolute length fiducial via photon radiation pressure
  - » Conceptually simple, one-step calibration method
  - » Displacements on order of what is expected for gravitational waves
  - » Power measurement standard calibrated at NIST
- Provide an independent timing standard by driving the Photon Calibrator (Pcal) with a function generator locked to GPS 1pps signal.
  - » One or all of the injected Pcal lines
- Calibrate and assess the stability of the End Test Mass electrostatic drive actuators
  - » Suitability for use in interferometer calibration

Requirements

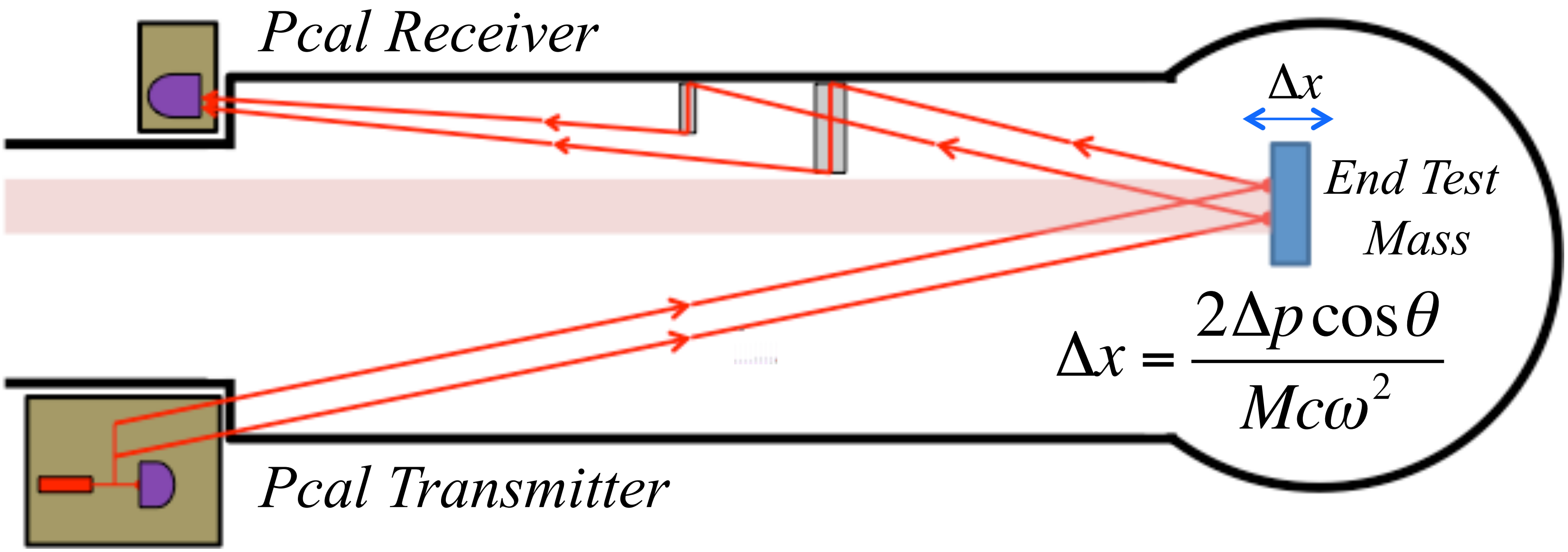
Functional Requirements:

- 5% absolute length modulation accuracy, for modulation frequencies from 10 Hz to 1.5 kHz.
- Three simultaneous excitations with SNR > 20 with 1-second DFTs (~ 50 Hz, ~ 400 Hz, ~ 1 kHz)
- ~ 2 kHz excitation with SNR > 20 with 60-second DFTs.
- Swept-sine measurements of interferometer response from 10 Hz to 1 kHz with good SNR in less than 1 hour.

Noise Requirements:

- Harmonic noise < 10% of aLIGO design sensitivity with 60-second DFTs
- RIN-induced displacement < 10% of aLIGO design sensitivity.

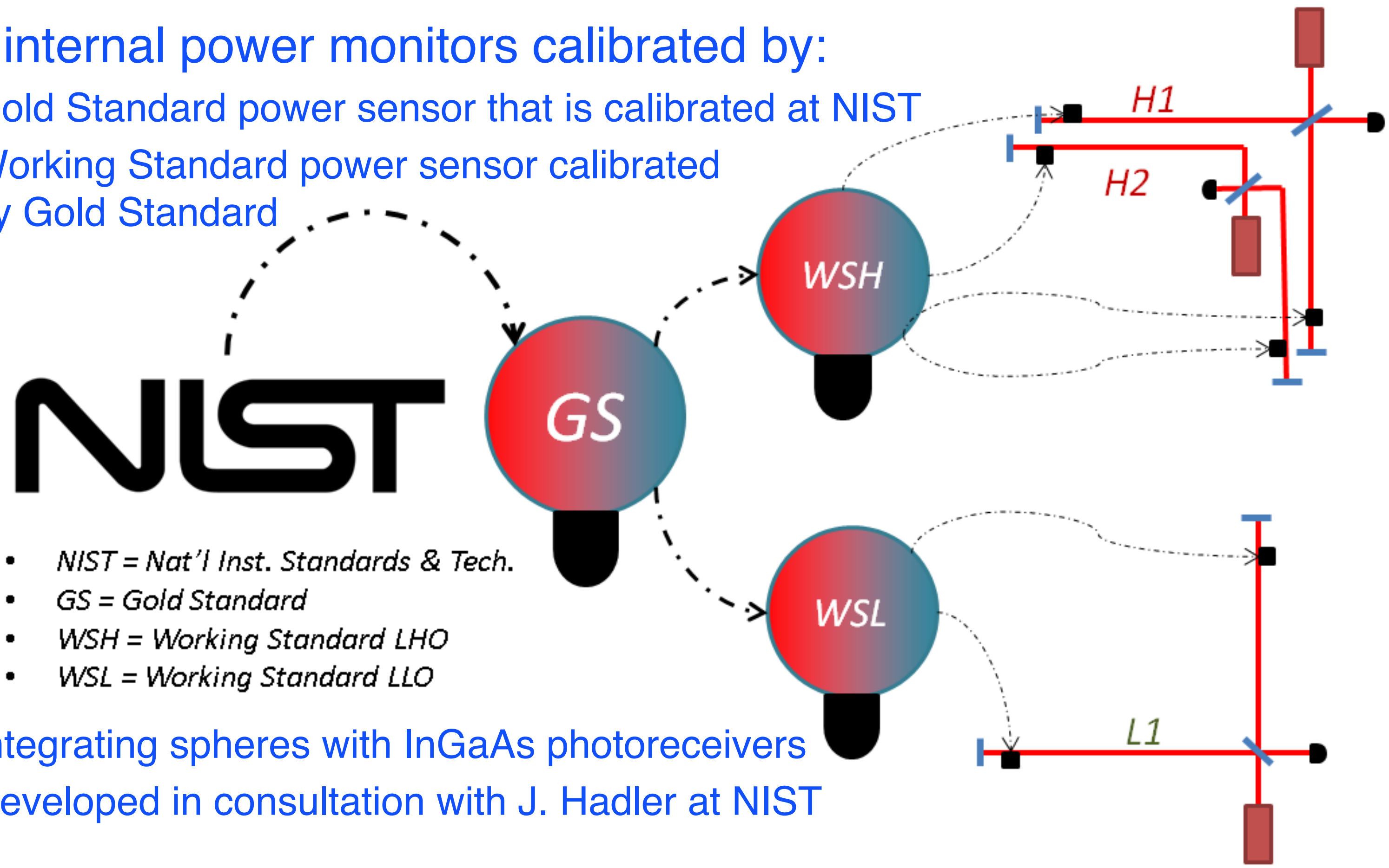
Overall Concept



- Power-modulated auxiliary laser induces modulated displacement of End Test Mass.
- Two-beam configuration to minimize impact of elastic deformation of surface of optic.

Absolute Power Calibration

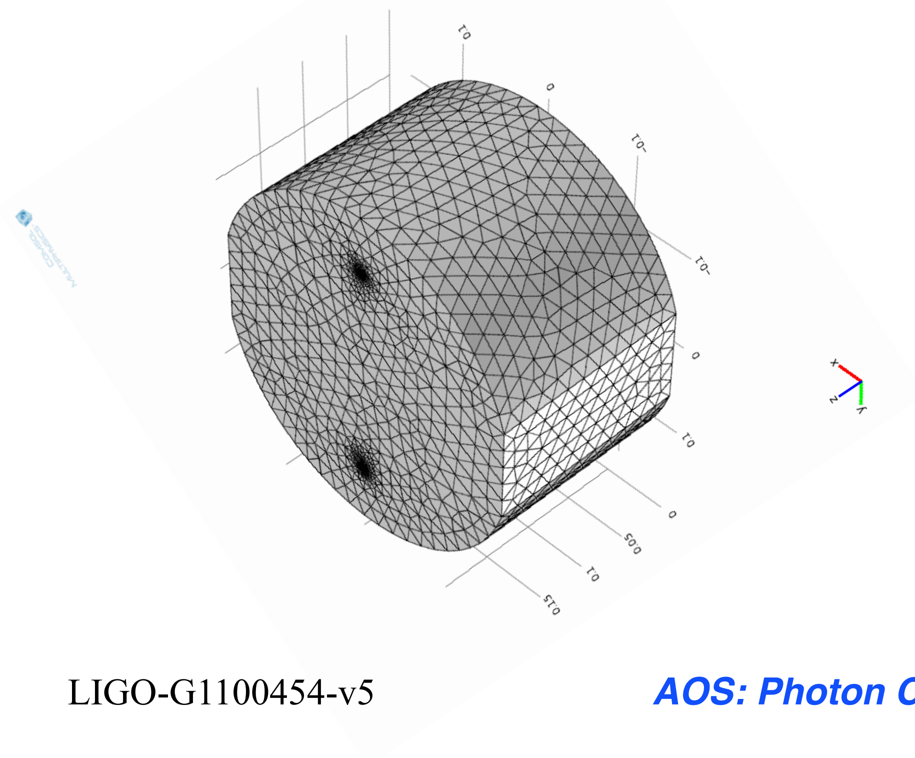
- Pcal internal power monitors calibrated by:
  - » Gold Standard power sensor that is calibrated at NIST
  - » Working Standard power sensor calibrated by Gold Standard

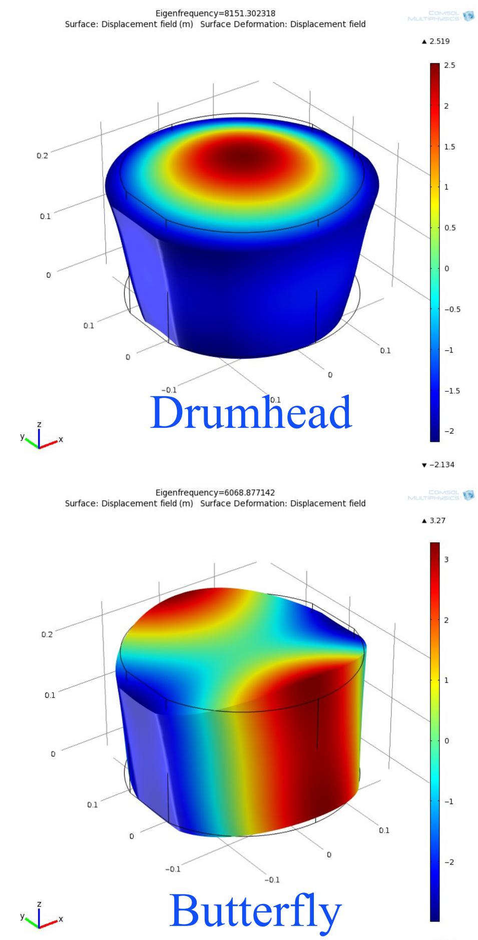


  - » Integrating spheres with InGaAs photoreceivers
  - » Developed in consultation with J. Hadler at NIST

Elastic Deformation of Test Mass

- Comsol finite element modeling (P. Daveloza)
  - » Locate two beams at radial positions that minimize excitation of the drumhead mode

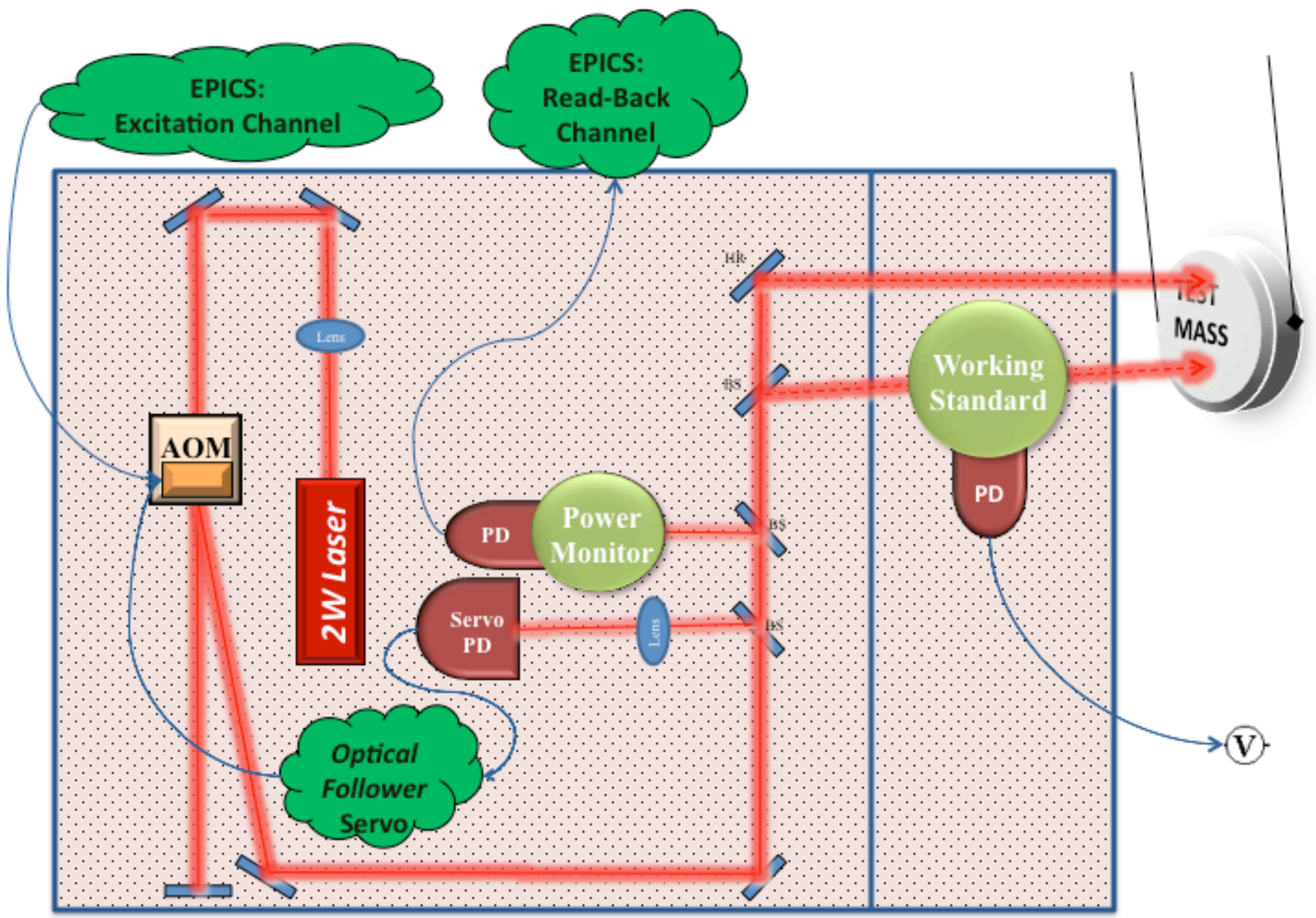




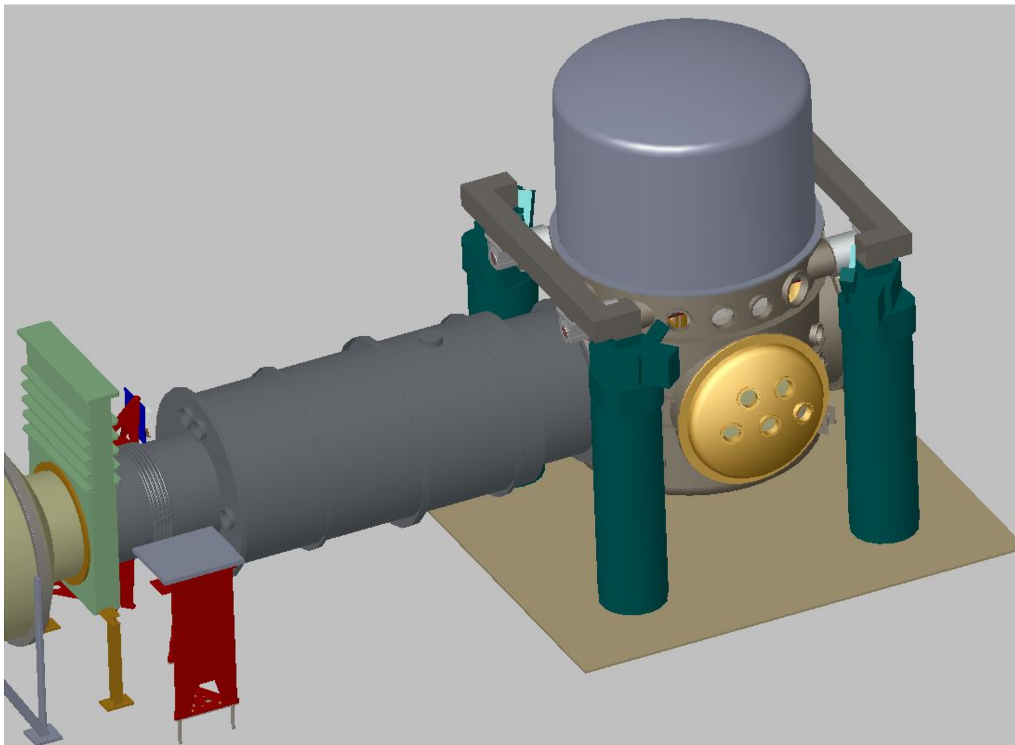
Development History

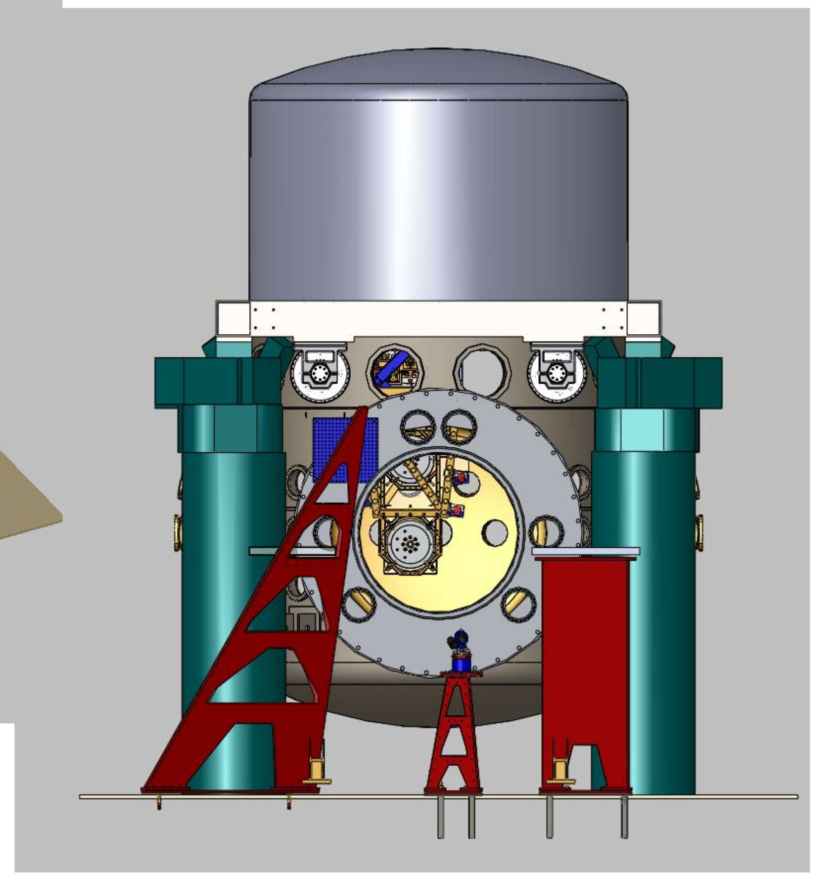
- Conceptual Design Review – June 2007 (P. Willems and M. Smith)
- Preliminary design deferred – 2007 to Feb. 2011
- iLIGO Pcals fabricated, installed (H1, H2, and L1), and operated – (with E. Goetz)
- eLIGO Pcals designed, fabricated, installed, and operated during S6 (with M. West) – Jul 2009 to Oct 2010
- Currently finishing preliminary design (with J. Berliner and I. Romero)

aLIGO Transmitter Layout

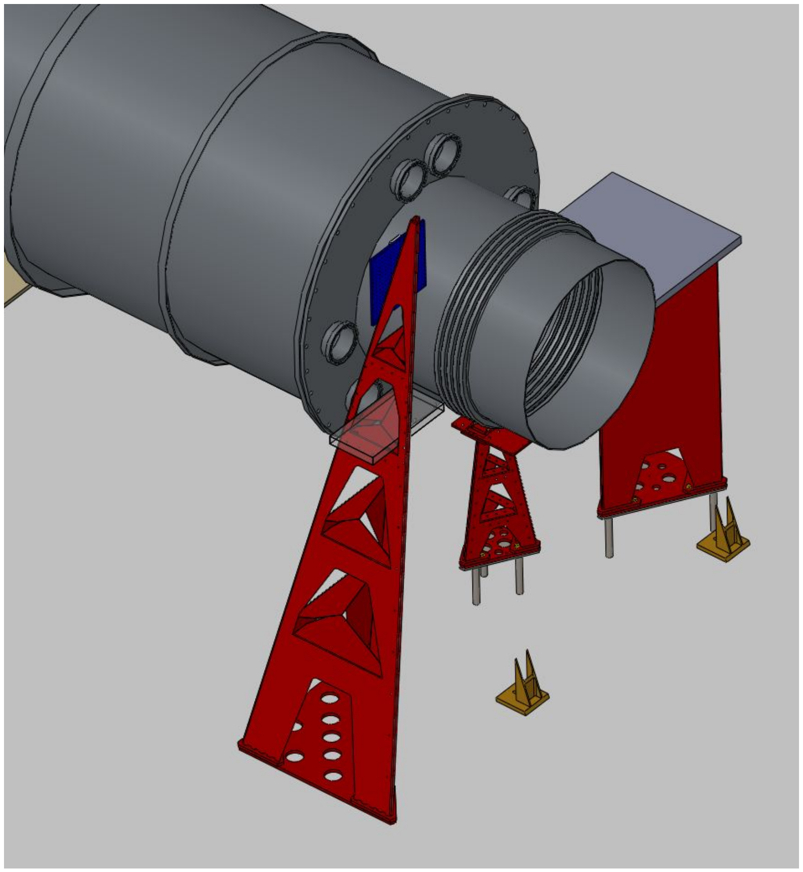


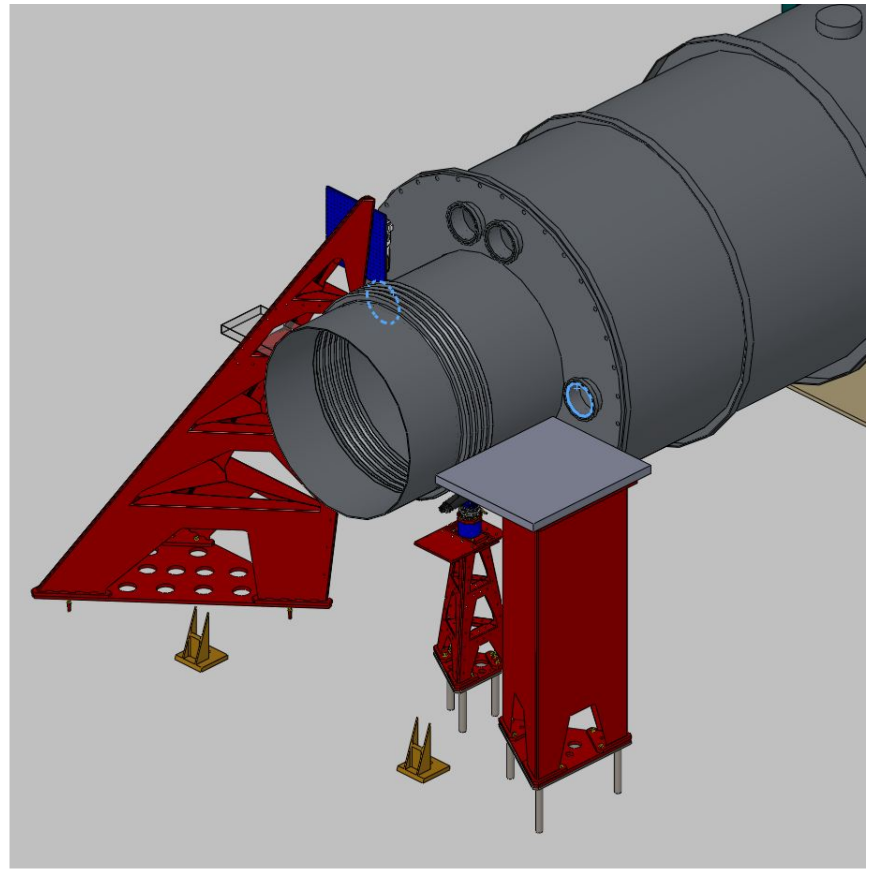
H1, L1 Hardware Locations



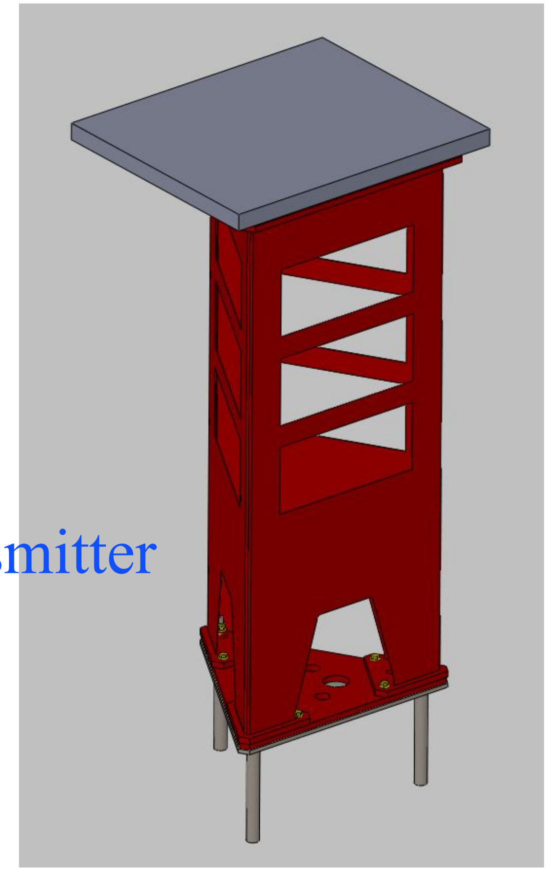


Support Pylons

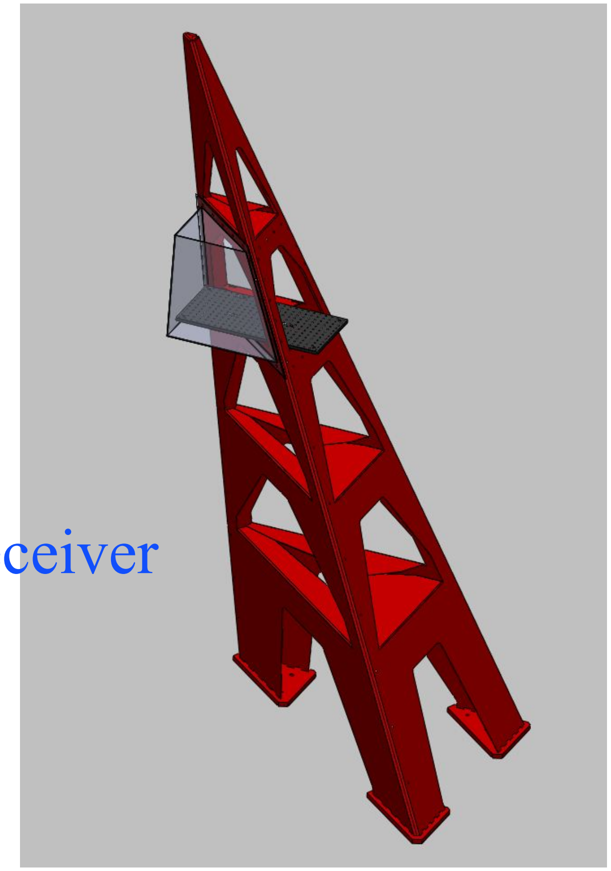




Transmitter and Receiver Pylons



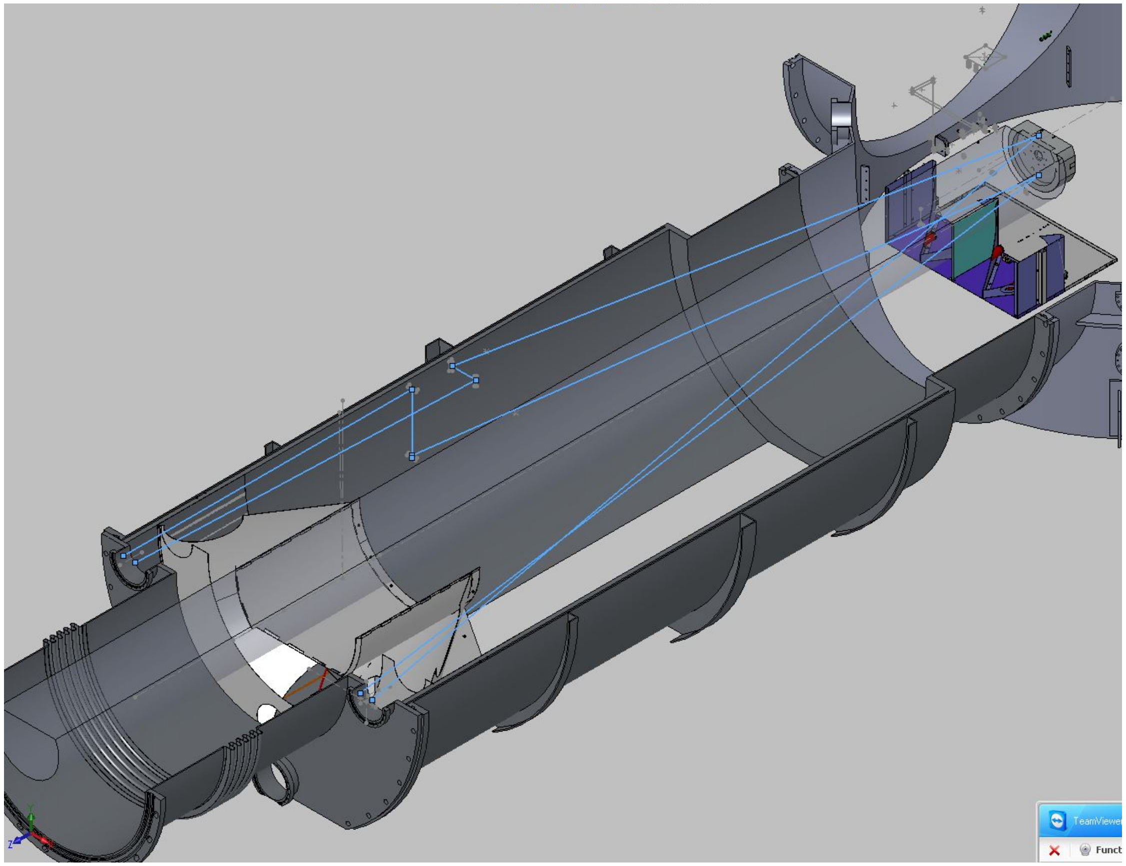
Transmitter



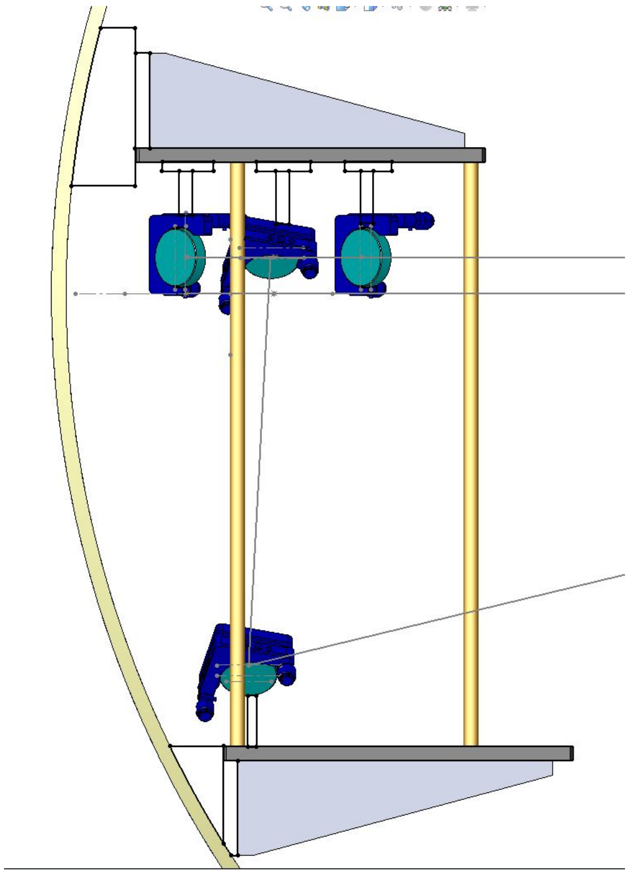
Receiver

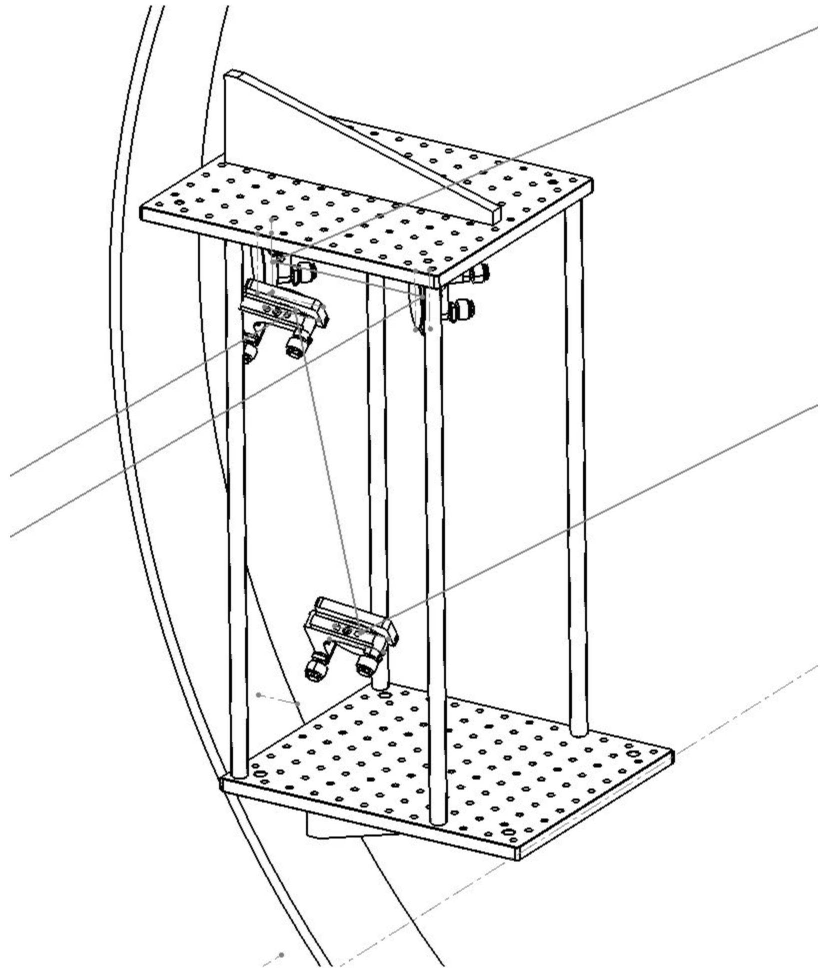
Design: R. DeSalvo, et al.

H1, L1 Optical Paths

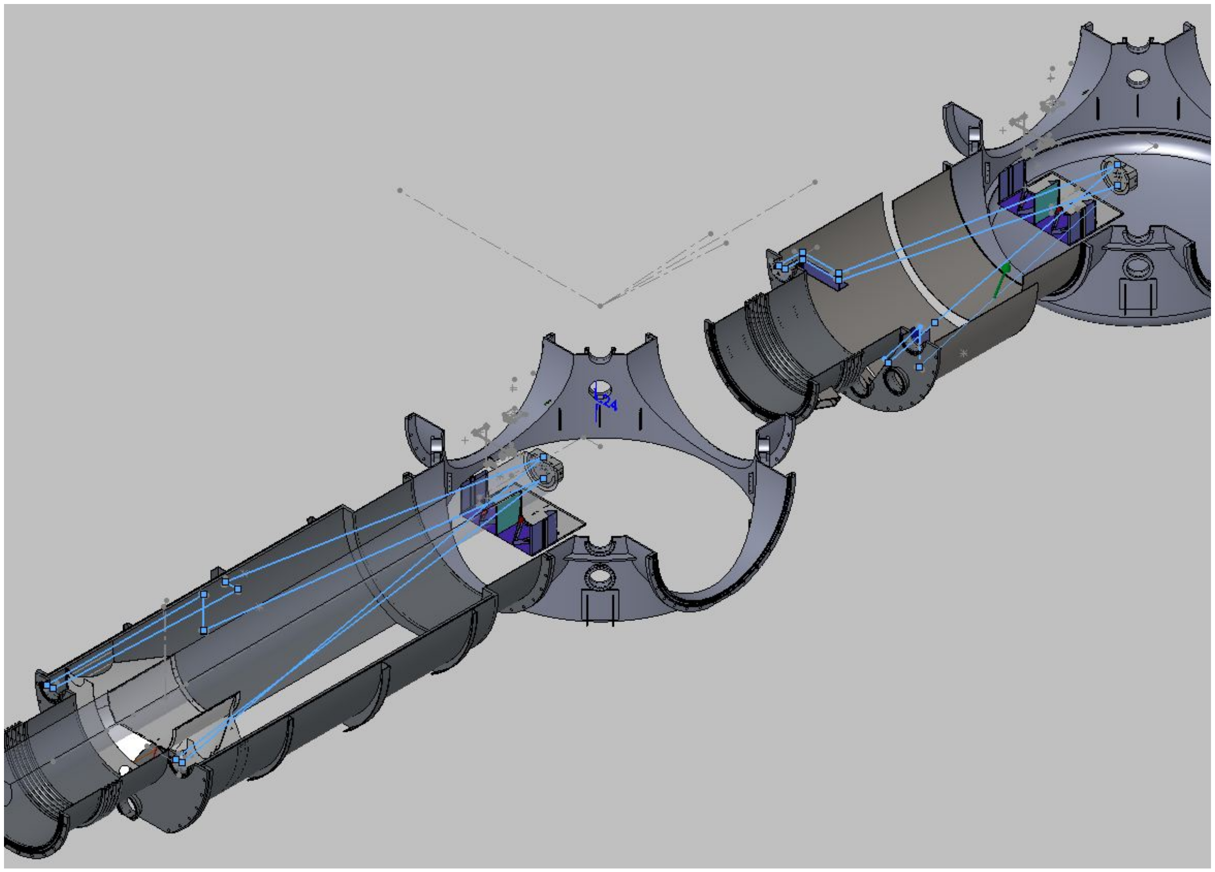


H1, L1 In-Vacuum Periscopes

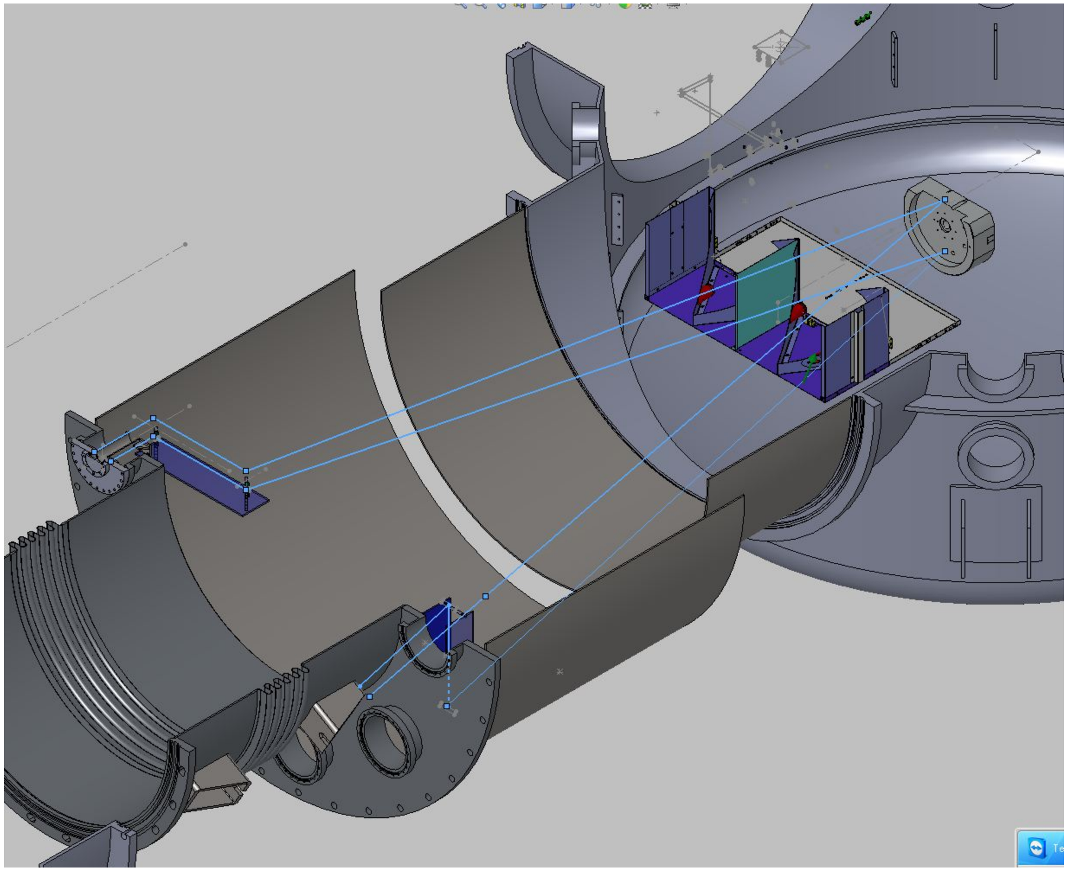




H1, H2 Optical Layouts

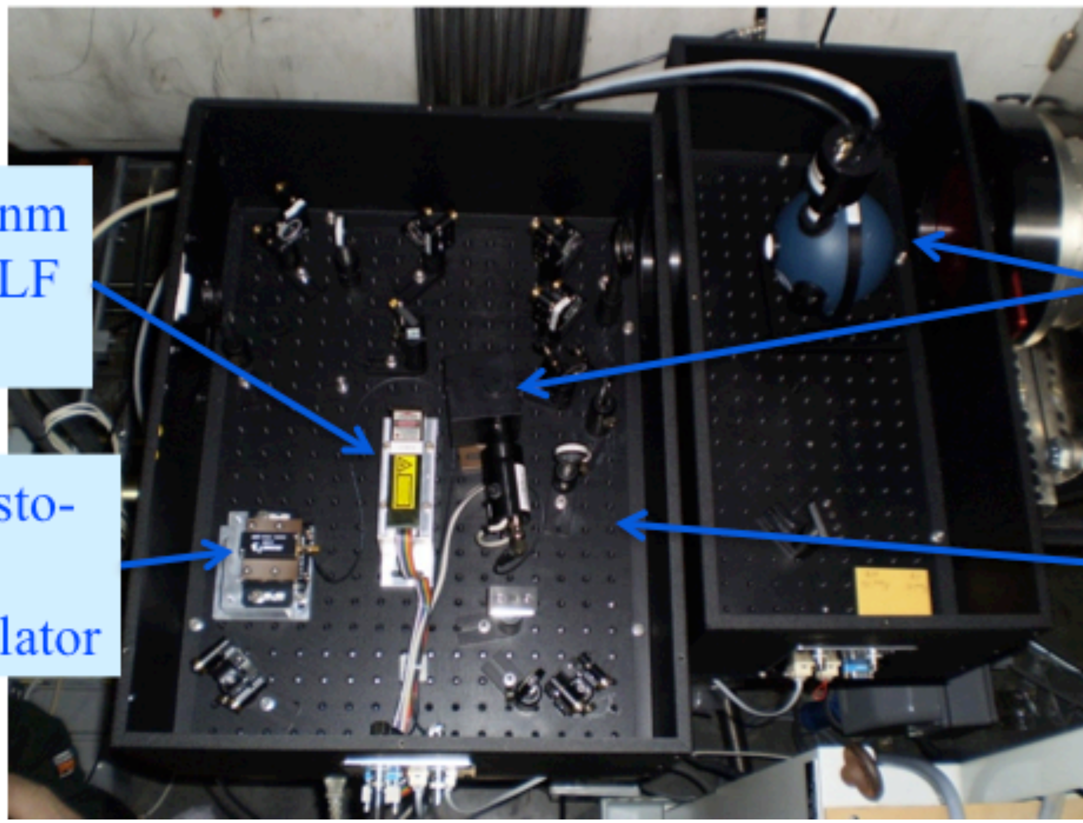


H2 Optical Paths

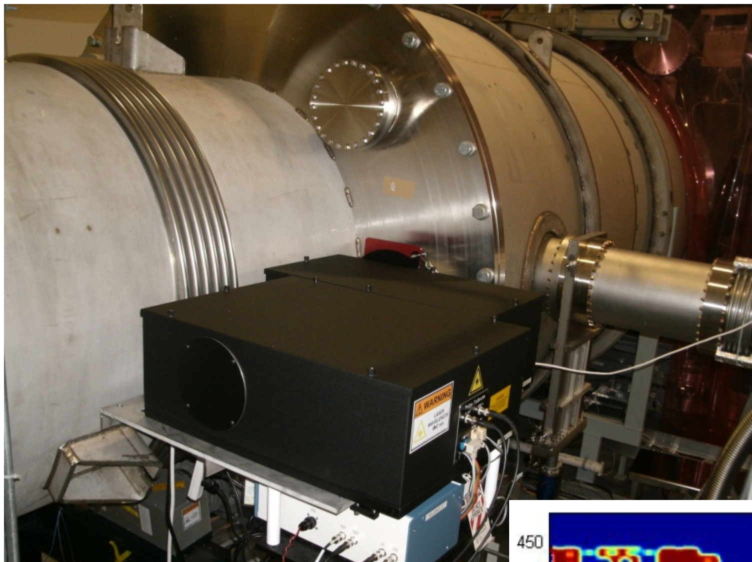


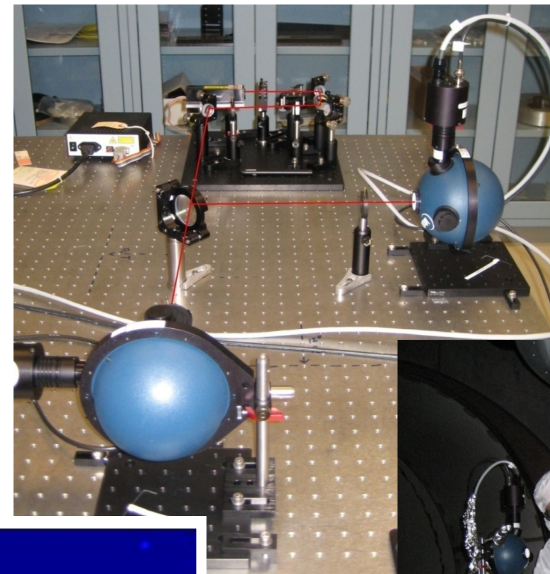
Accomplishments
eLIGO Pcal Upgrade

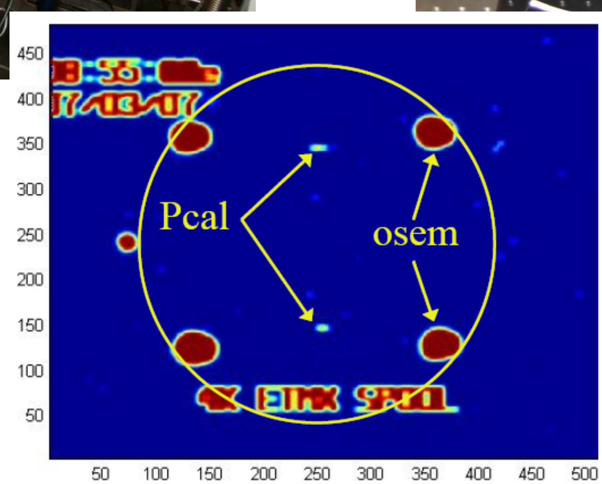
- Upgraded Pcals installed for S6. H1 and L1 X-arm end test masses (Matt West, Ryan DeRosa, Michael Sakosky



eLIGO Implementation

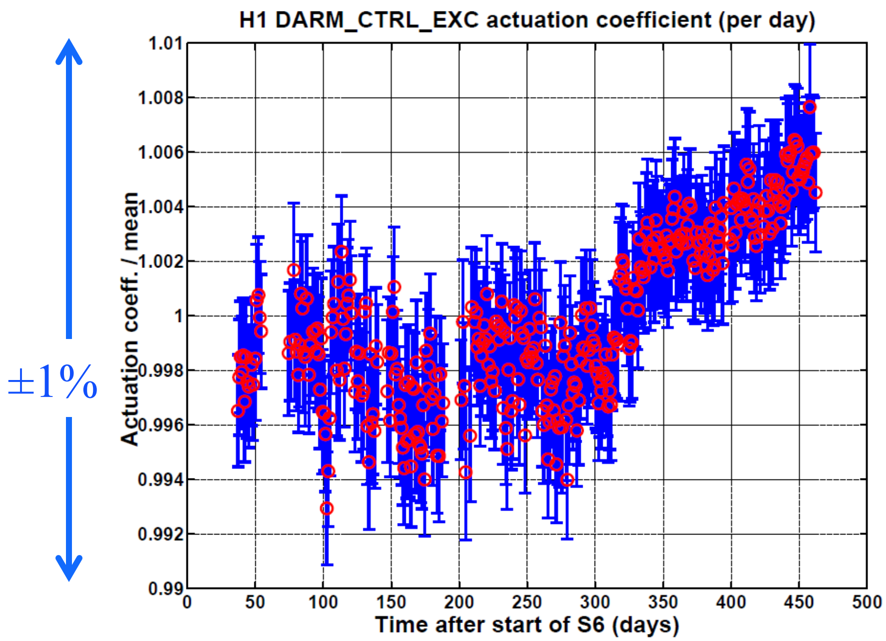


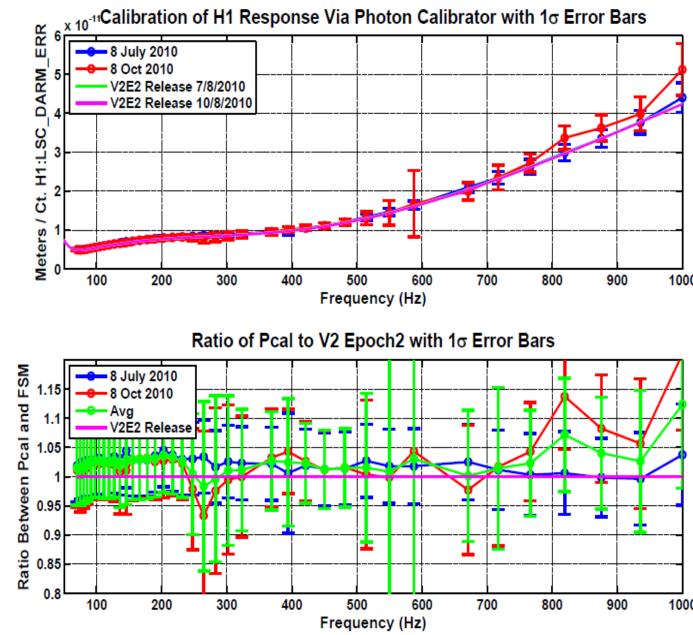




Accomplishments: Actuator Stability, Swept-Sines

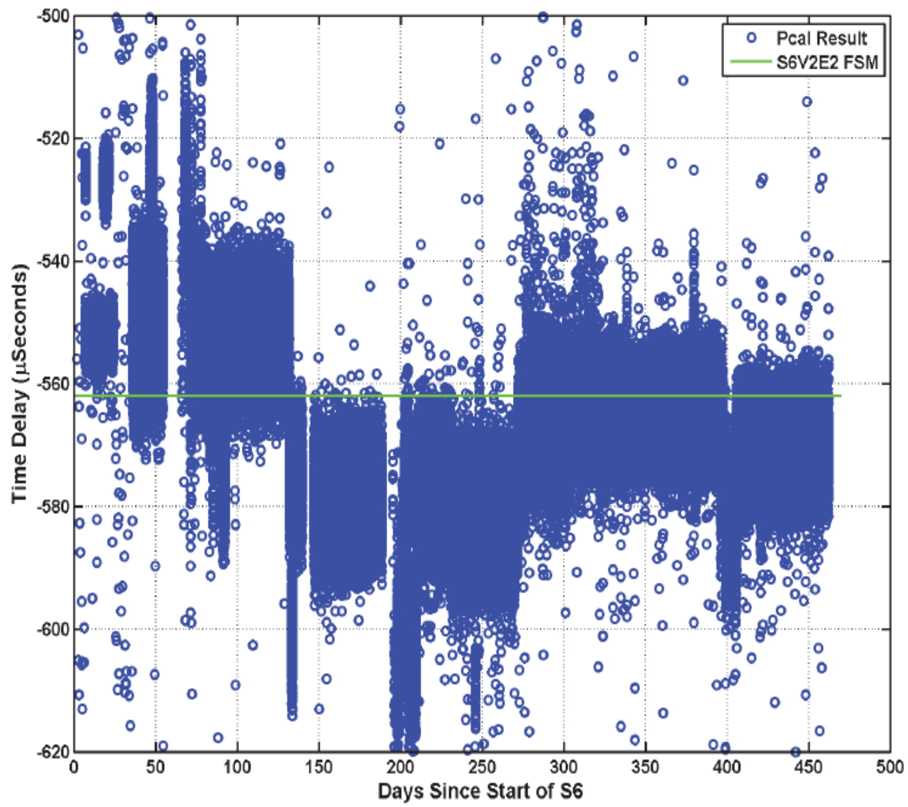
- Stability of Actuation
- Swept-sine Analysis





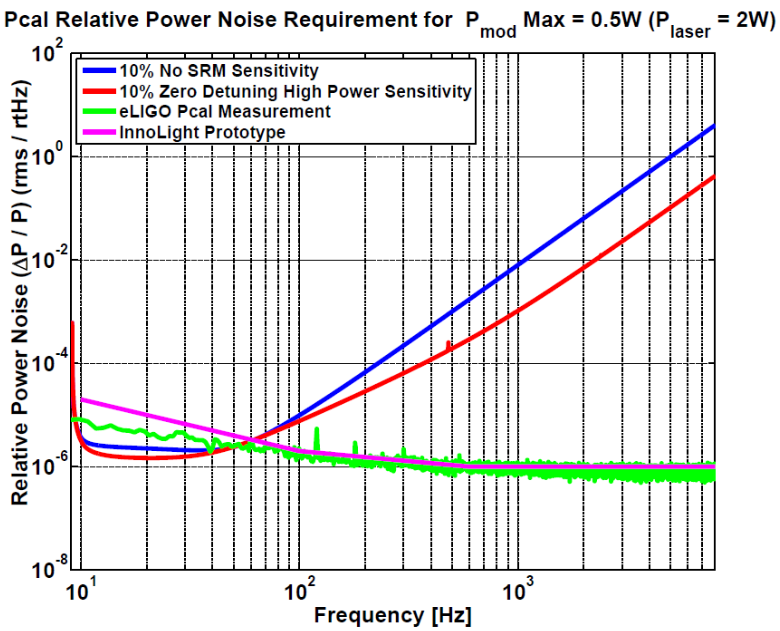
Accomplishments: eLIGO Timing

- Independent timing assessment during eLIGO - DuoTone (with I. Bartos).
- Revealed jumps in H1 OMC timing.

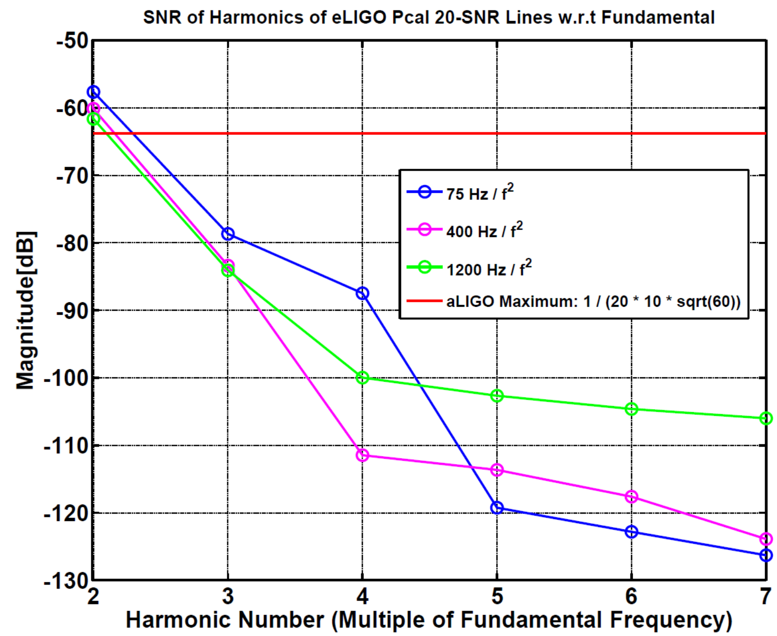


Challenges: Laser Noise

- Intensity Noise



- Harmonic Noise



Solution: “Optical Follower” Servo

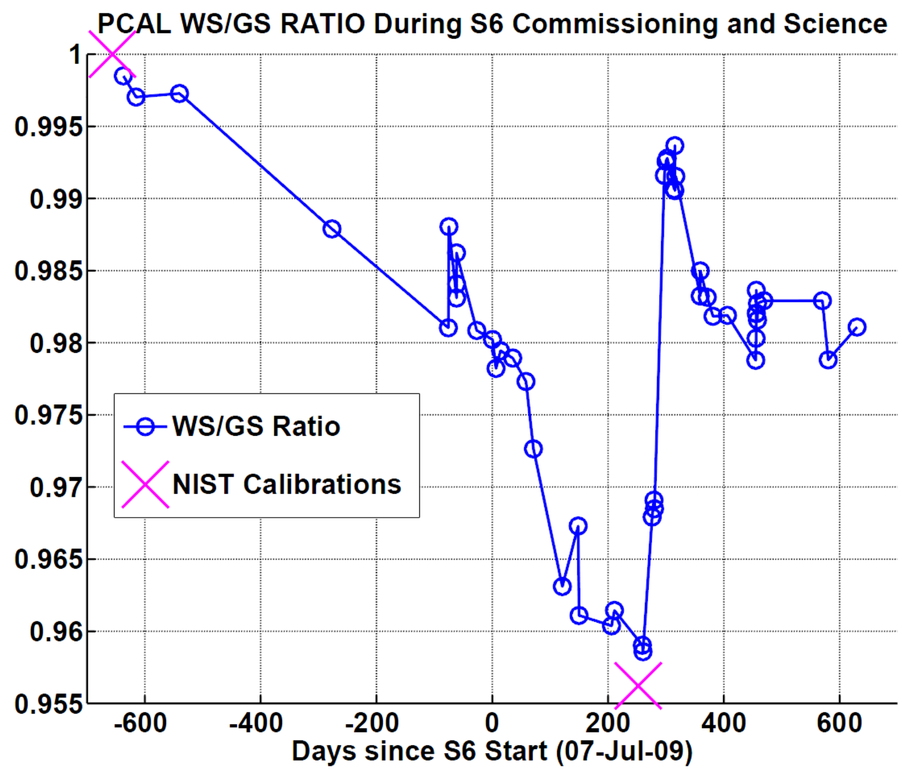
Challenges: Calibration Accuracy

ISSUE:

- Gold Standard drifted ~ 4.5% over 3 years
  - » Working Standard drifted only ~0.5% between NIST calibrations.

MITIGATION:

- Change to EO Systems photoreceiver (tested on H1 and L1 during eLIGO)
- Maintain Working Standards at both LHO and LLO.
- Calibrate Gold Standard at NIST at least once per year ($7k per calibration)



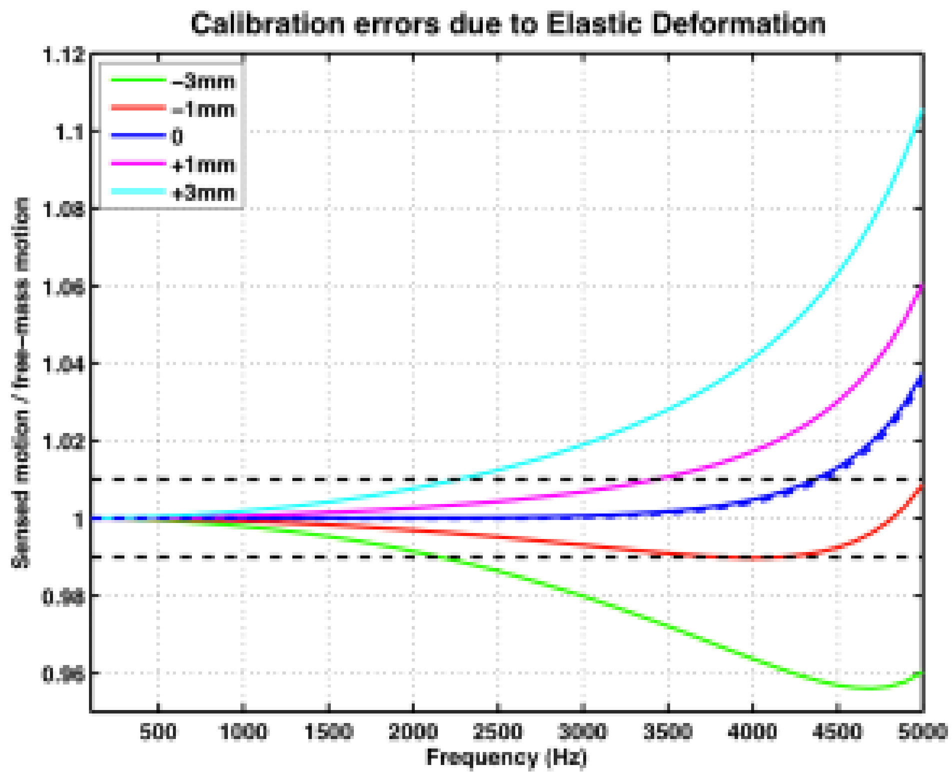
Challenges: Beam Positioning

ISSUE:

- Deviation in beam position yields calibration error
- Elastic deformation of Test Masses by Pcal forces
  - » >1% error at frequencies above 3.5 kHz for ±1 mm beam position error.

MITIGATION:

- Accurate and precise beam centering method (TBD)



Development and Installation Plan

- Preliminary design review – May 2011
- Final Design – May to Nov. 2011
  - » Early procurement of first-article laser for long-term testing?
- In-vacuum hardware
  - » First article test atH2 Y-end: Aug. 2011
  - » Install in-vacuum hardware
    - – L1 X-end: Mar. 2012 L1 Y-end: May 2012
    - – H2 X-end: Nov. 2012 H1 Y-end: Jan. 2013
    - – H2 Y-end: Feb. 2013 H1 X-end: Jun. 2013
- Install and align transmitter and receiver
  - » L1: Jun. 2013 H1: Jan. 2014 H2: Jun. 2014

Staffing

- *Rick Savage* – Lead; Scientist (LHO)
- *Jonathan Berliner* – Fab, Install, Test, LHO Liaison; Operator (LHO)
- *Chris Guido* – LLO Liaison, Operator (LLO)
- *Paul Schwinberg* – Electronics; Scientist (LHO)
- *Ignacio Romero* – CAD (CIT)
- *Pablo Daveloza* – Finite Element Analysis; Graduate student (UTB/LHO)

References

- **Accurate calibration of test mass displacement in the LIGO interferometers**, E. Goetz et al., *Class. Quant. Grav.*, Vol.27, pp. 084024-33, 2009.
- **Precise calibration of LIGO test mass actuators using photon radiation pressure**, E. Goetz et al., *Class. Quant. Grav.*, Vol. 26, pp. 245011-23, 2009.
- **Calibration of the LIGO displacement actuators via laser frequency modulation**, E. Goetz and R. L. Savage, Jr., *Class.Quant.Grav.*, Vol. 27, pp. 215001-10, 2010.
- **Accurate measurement of the time delay in the response of the LIGO gravitational wave detectors**, Y. Aso et al., *Class. Quant. Grav.*, Vol. 26, pp. 055010-22, 2009.
- **Calibration of the LIGO Gravitational Wave Detectors in the Fifth Science Run**, J. Abadie et al., *Nucl.Instrum.Meth.*, Vol. A624, pp. 223-240, 2010.
- **Optimal calibration accuracy for gravitational-wave detectors**, L. Lindblom, *Phys. Rev. D* **80**, 042005, pp. 1-7, 2009.

Backup slides

Comparison of Calibration Methods

- Three fundamentally different methods employed to measure the test mass actuation coefficients in meters per DAC count
  - Free-Swinging Michelson
  - Voltage Controlled Oscillator
  - Photon Calibrator
- Measured coefficients agree at the +,- 5-10 % level

Class. Quantum Grav. **27** (2010) 084024 E Goetz *et al*

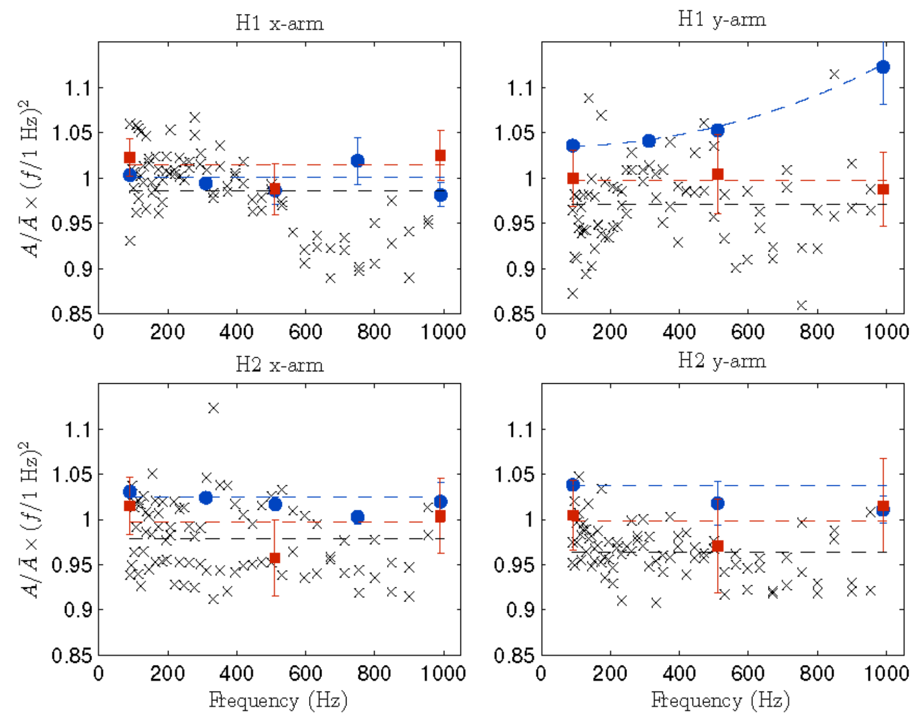


Figure 6. Comparison of ETM actuation coefficients measured with three techniques: free-swinging Michelson (black crosses), photon calibrator (blue circles), and frequency modulation (red squares). The data are multiplied by the square of the measurement frequency and normalized to the average of the three weighted mean values (dashed horizontal lines) for each method, $\overline{A}$. The free-swinging Michelson data are plotted without error bars; for visibility, 3σ statistical error bars are plotted for the other two methods. The single-beam H1 y-arm photon calibrator data show the influence of local elastic deformation by photon radiation pressure.