S5 Calibration Status and Comparison of S5 results from three interferometer calibration techniques

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for the LSC Calibration committee

LIGO-G070472-00-W

Outline

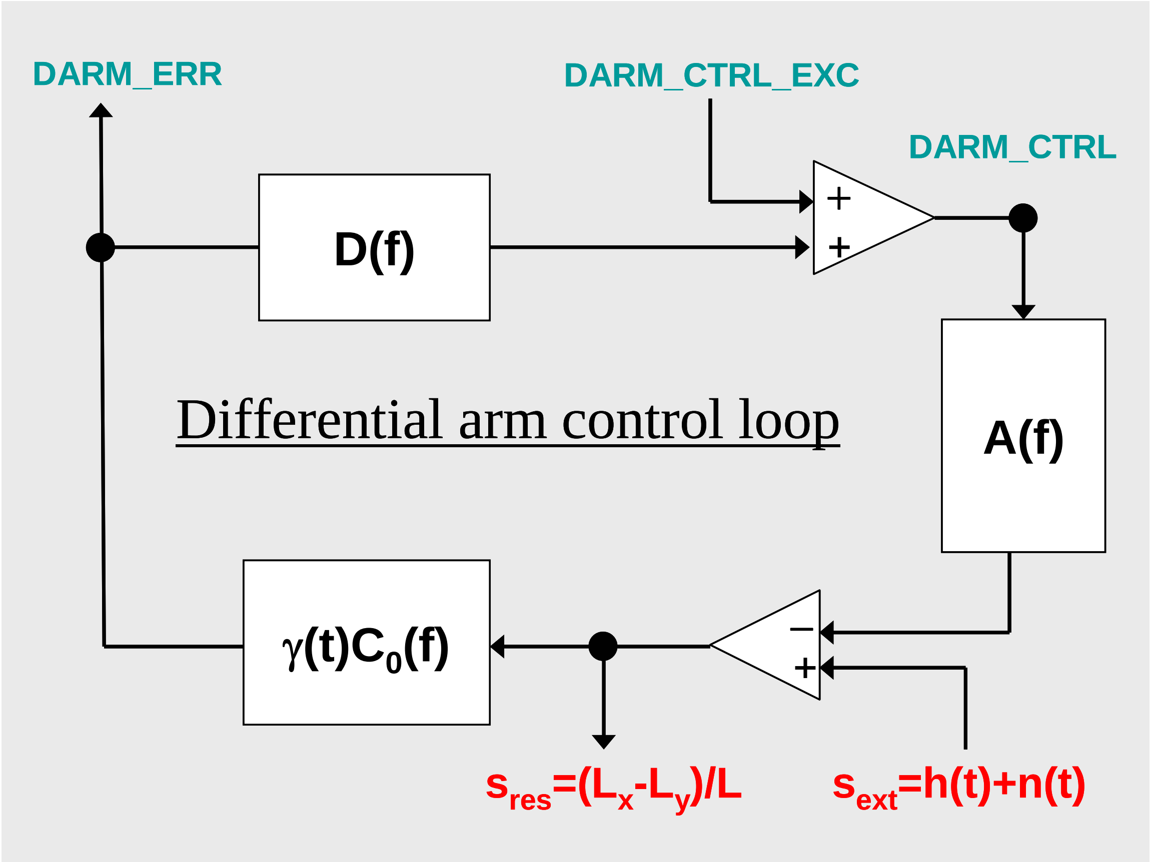
- Status of S5 Calibration
  - » Progress since Cascina meeting – May 21-25,2007
- Comparison of ETM actuation factors from the official calibration with measurement results from
  - » Photon calibrators
  - » New frequency modulation technique
- Overview of plans for post-S5 calibration-related measurements

People working on calibration

- Calibration committee
  - S. Giampanis, E. Goetz, G. González, M. Hewitson, S. Hild, E. Hirose, P. Kalmus, M. Landry, E. Messaritaki, **B. O'Reilly**, R. Savage, X. Siemens, M. Sung
  - **Virgo**: F. Marion, B. Mours, L. Rolland

- Calibration review committees
  - Frequency domain: S. Fairhurst, **K. Kawabe**, V. Mandic, J. Zweizig
  - Time domain : S. Fairhurst, **K. Kawabe**, V. Mandic, B. O'Reilly, M. Sung, S. Waldman
  - High frequency : K. Kawabe, M. Rahkmanov, **R. Savage**, D. Sigg

DARM_ERR calibration



Track height of calibration lines to determine calibration coefficients

Measure open-loop gain at reference time t_0:

$$G_0(f) = C_0(f) \times D(f) \times A(f)$$

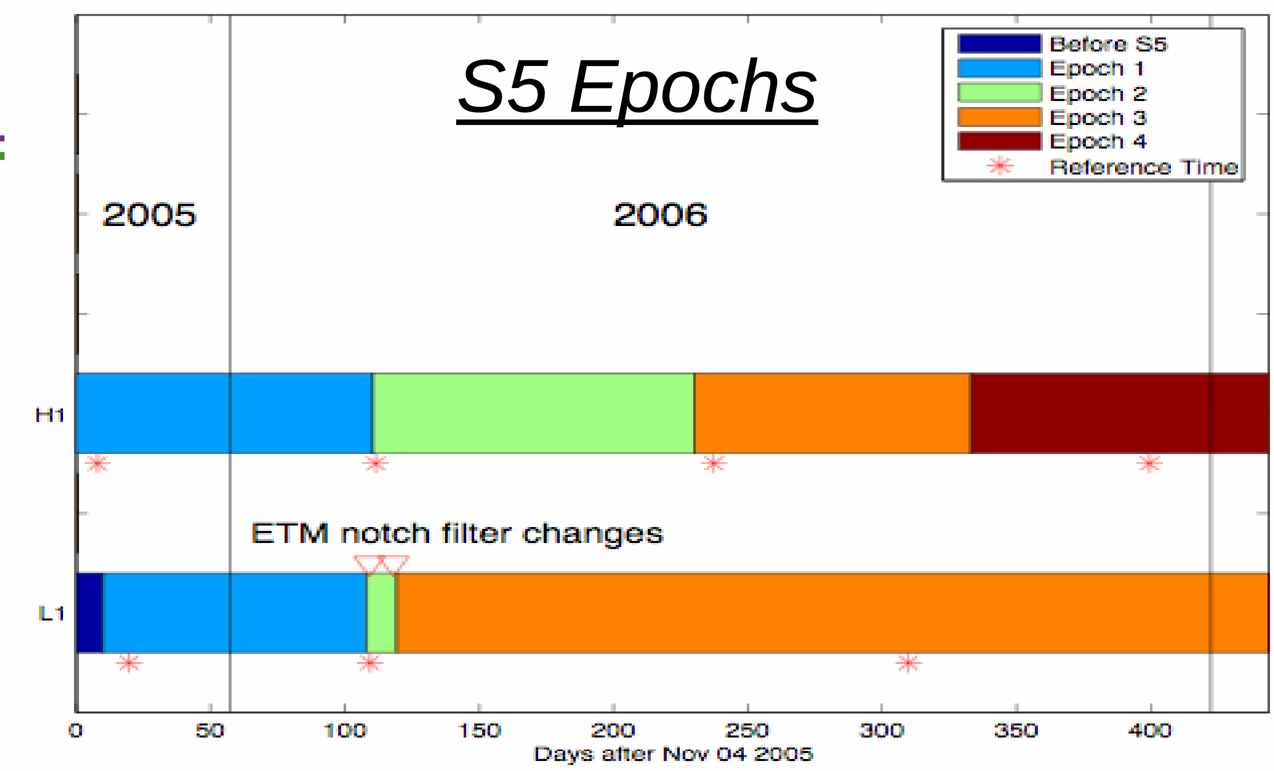
Measure D(f) and calibrate A(f) - this gives $C_0(f)$

Response function:

$$R_{DERR}(f,t) = \frac{1+\gamma(t)G_0(f)}{\gamma(t)C_0(f)}$$

GW signal:

$$h(f,t) = R_{DERR}(f,t) \times DARM\_ERR(f,t)$$



- New epoch defined when interferometer configuration changes – DARM loop gain, filters changes, etc.
  - » Four epochs at LHO; three epochs at LLO
- Each version of calibrations covers all epochs prior to release

Status of the S5 calibration

- S5 V3 calibration released and being used by analysis groups
  - » Valid from beginning of run through Jan 22, 2007
  - » Details of calibration epochs and products:
    MyungkeeS's S5 Calibration talk at March LSC meeting, Baton Rouge LIGO-G070120
    MichaelL's S5 Calibration at May LSC-Virgo meeting, Cascina LIGO-G070312
  - » Calibration home page (password protected): https://gold.ligo-wa.caltech.edu/engrun/Calib_Home
- Expect the final calibration release to be V4 and that it will be released after S5 and cover whole S5 run
  - » Will require post-S5 calibration measurements

Progress since Cascina meeting

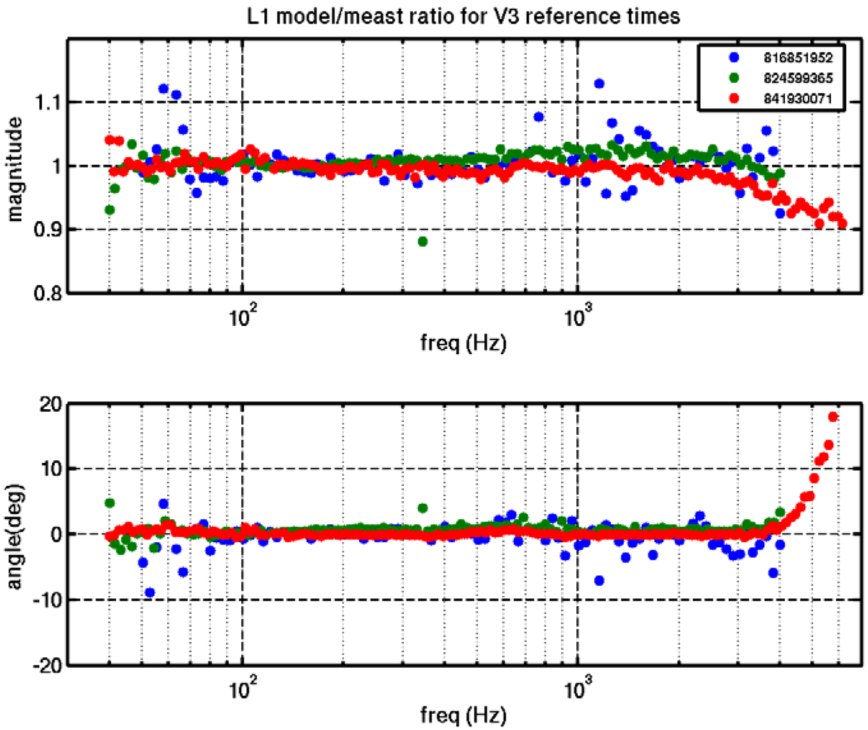
- S5 V3 h(t) data generated through Jan 22, 2007. On-line h(t) based on V3 calibration Jan 22, 2007 to present (XaviS, EiichiH, et al.)
  - » Details: http://www.lsc-group.phys.uwm.edu/~siemens/ht.html
- V3 calibration frames have been generated, but not yet validated (EiriniM)
- V3 calibration factors have been generated and follow-up studies are in progress (MyungkeeS)
  - » Looking for sudden changes in $\gamma(t)$ and reconciling with elog
  - » Consistency of $\gamma(t)$ between h(f) and h(t). Differences < 0.1%
  - » Tagging segments where calibration lines are not present
- GRB070201 calibration validation (MichaelL, EvanG, EiichiH, MyungkeeS, et al.) LIGO-T070100
- V3 h(f) review completed [*almost*] (KeitaK, et al.)

S5 V3 calibration review: almost complete (from KeitaK)

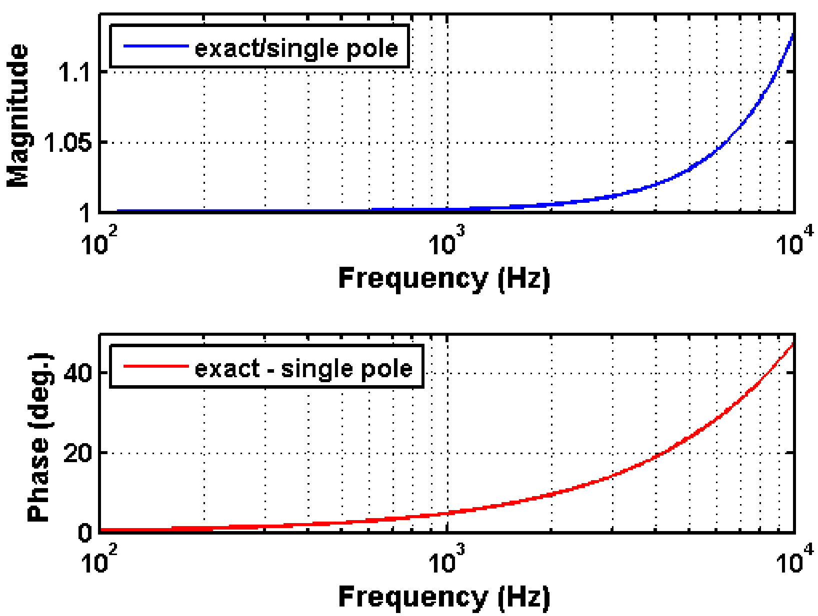
- Five+ meetings so far of reviewers (SteveF, KeitaK, VukM, JohnZ) and reviewees (GabrielaG, MichaelL, BrianO, and MyungkeeS, among others)
- Changes in the IFOs have been properly tracked and documented by checking calibration coefficients, ilog, and CDS filter archive throughout S5 (*kudos to calibration team!*)
- No serious mistake was found so far in V3 calibration technique, model, or measurement data (f<2kHz)
- Reviewers expect to be able to close V3 review very soon
- Many recommendations for verification and/or improvement of S5 calibration (i.e. V4)
  - » These necessitate new measurements during post-S5 period

Issue: high frequency discrepancy in OLG

- Agreement between model and measurements degrades significantly above 1 or 2 kHz (all three interferometers)



- Possible causes?
  - » Single pole vs. full length response
  - » Elastic deformation of TM (PhilW)



- Plan to investigate during post-S5 measurement period

Comparison of alternate techniques for calibration of the coil actuator coefficients

with Evan Goetz (at LHO from U of M)

(and Peter Kalmus, Malik Rakhmanov, Keita Kawabe, Michael Landry, Brian O'Reilly, Gabriela Gonzalez, et al.)

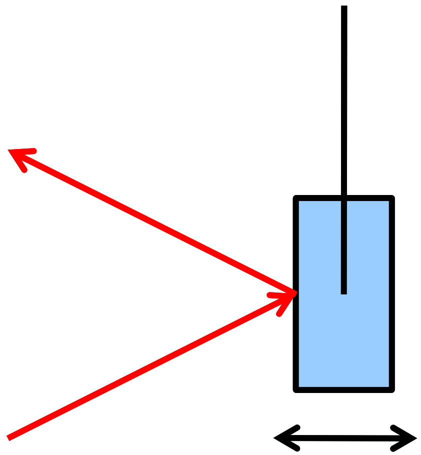
Three techniques

- Used to calibrate the test mass coil actuation coefficients in meters per count of excitation

1. The **"free-swinging Michelson" technique** (FSM) utilized for the official S5 calibration
   - » Uses the wavelength of the laser light as yardstick
2. **Photon calibrator (Pcal)**– power-modulated laser beams reflecting from the end test masses
   - » Relies on absolute measurement of the modulated laser power (and the mass of the test mass)
3. **Frequency modulation** via the voltage controlled oscillator (VCO) in the pre-stabilized laser (PSL) system
   - » Relies on laser frequency to length transfer function $$\Delta L \cong L \times \frac{\Delta \nu}{\nu}$$

FSM and Pcal techniques

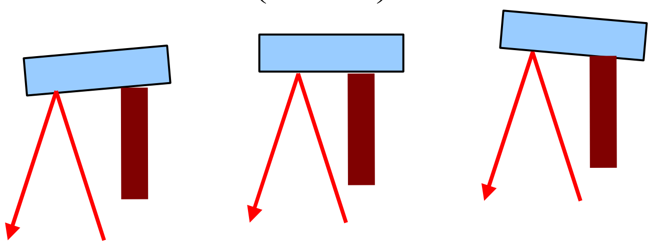
- Free-swinging Michelson technique
  - » *Calibration of the LIGO detectors for S4*
    LIGO-T050262
  - » *Calibration of the LIGO detectors for S5*
    draft in Calibration CVS archive
- Photon calibrators
  - » *Status of the LIGO photon calibrators*
    LIGO-T070026
  - » *Comparison of the photon calibrator results with the official calibration*
    LIGO-T070050
  - » *Photon calibrator upgrade proposal*
    LIGO-T070094
  - » (Advanced LIGO) *Photon calibrators conceptual design*
    LIGO-T070167

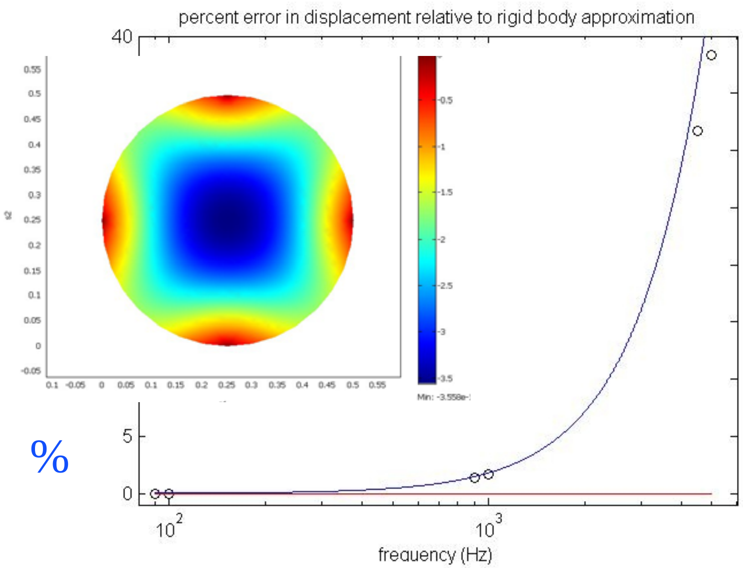


Pcal investigations/improvements

Ifo. and Pcal centering offsets

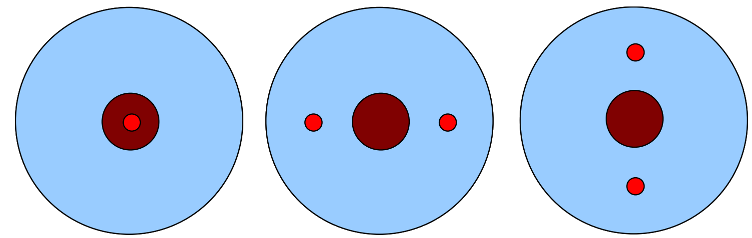
$$x(\omega) = -\frac{2\cos(\theta)}{Mc\omega^2}\left(1 + \frac{abM}{I}\right)P(\omega)$$

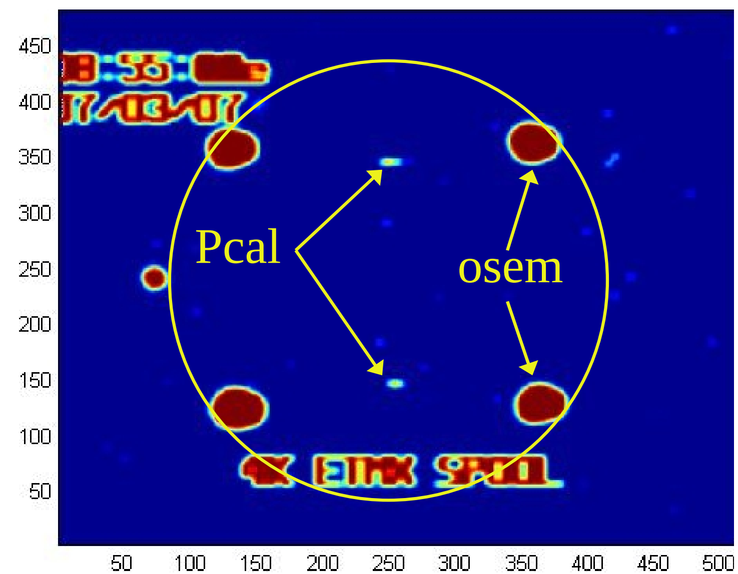




Elastic deformation
(StefanH, PhilW, et al.
LIGO-P070074-00-Z)

Two-beam configurations to avoid interaction with ifo beam



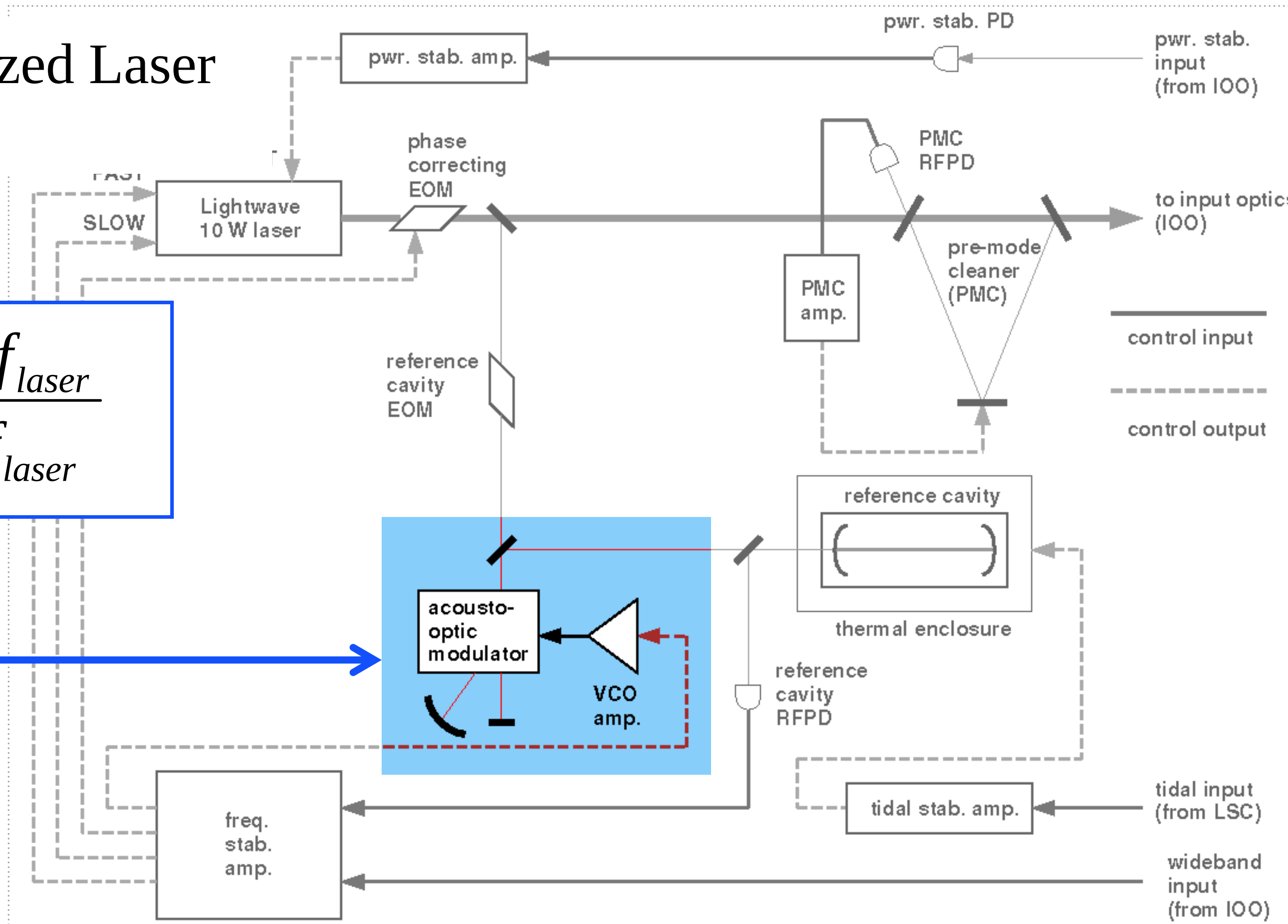


Frequency modulation (VCO) technique

Pre-stabilized Laser System

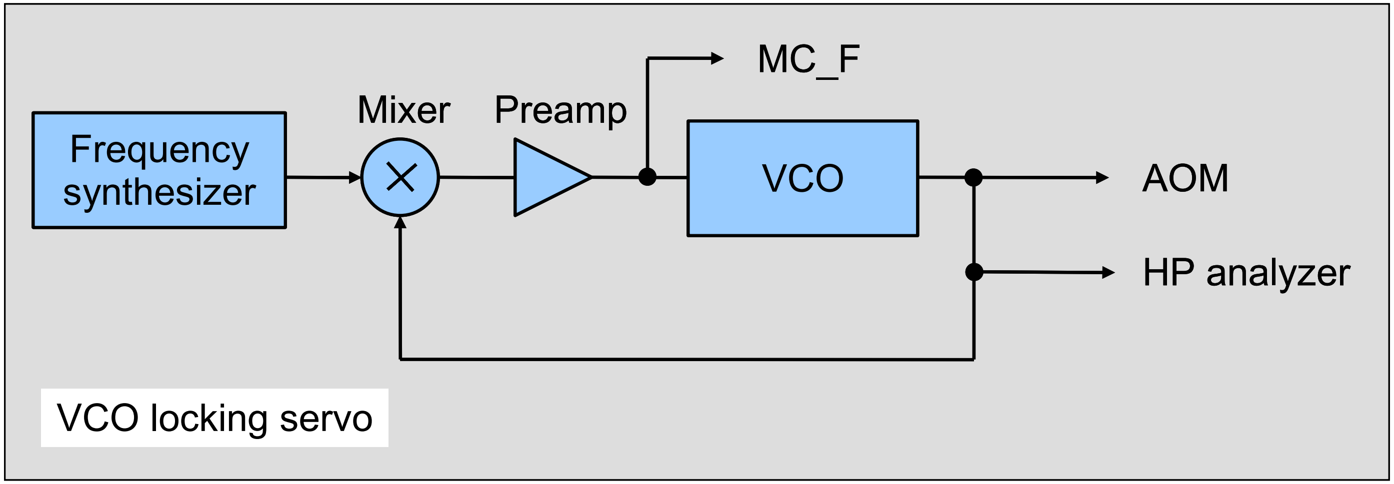
$$\Delta L = L \frac{\Delta f_{laser}}{f_{laser}}$$

frequency shifter

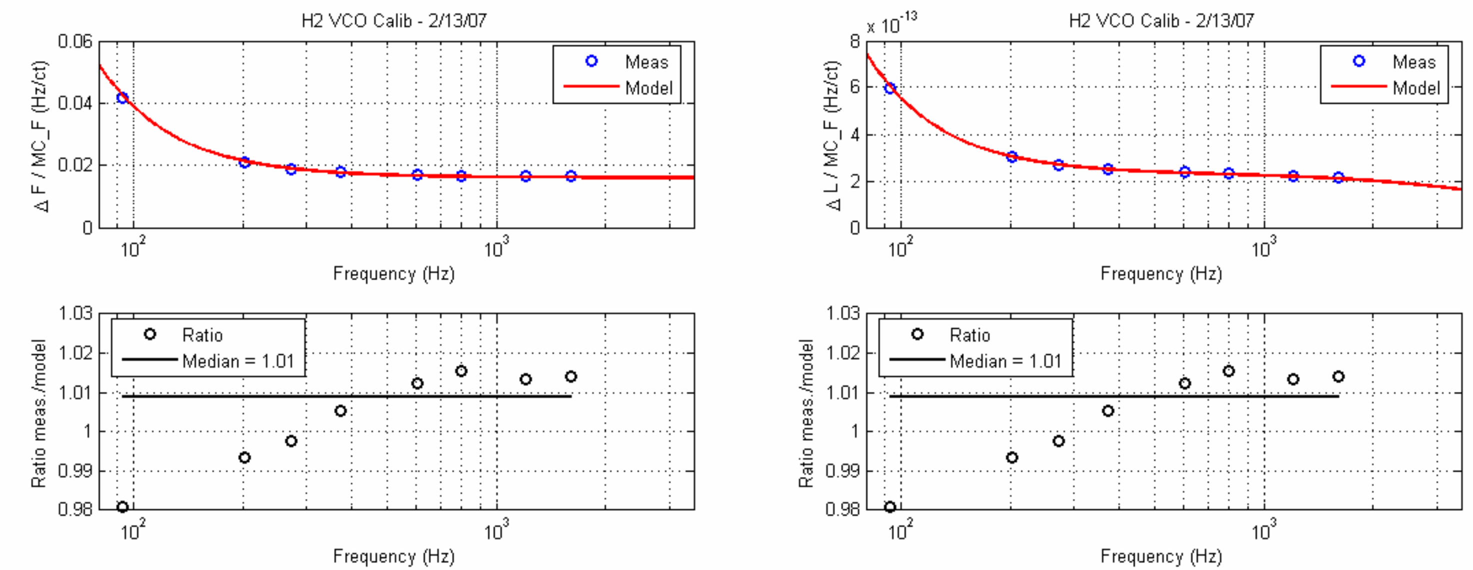


Outline of frequency modulation (VCO) technique

- First, calibrate the frequency modulation coefficient of the voltage controlled oscillator in the PSL
  - » Lock the nominal 80 MHz VCO modulation frequency to freq. synthesizer
  - » Inject a frequency modulation signal and measure the modulation sidebands to 80 MHz carrier amplitude ratio using an RF spectrum analyzer
  - » $\frac{P_{SB}}{P_{carrier}} = \frac{J_1(\Gamma)^2}{J_0(\Gamma)^2}$ $\quad \frac{J_1(\Gamma)}{J_0(\Gamma)} \cong \frac{\Gamma}{2} = \frac{\Delta f}{2 f_{\mathrm{mod}}}$ VCO calibration in Hz/count



Frequency modulation technique (cont.)

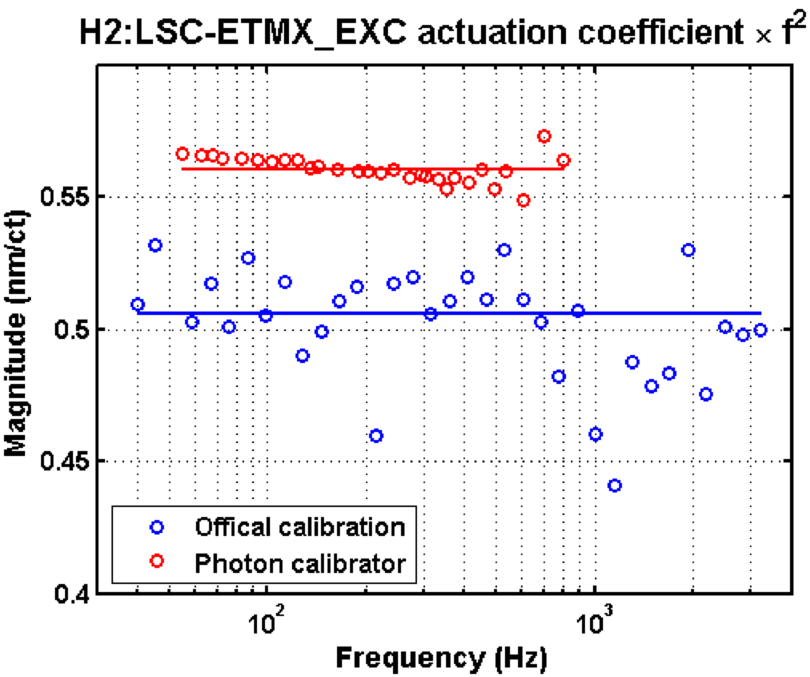


- Second, lock a single arm (in acquire mode) and drive both the VCO and the ETM coils with sine waves separated by 0.5 Hz. Take ratios, swap frequencies, and average ratios as for the Pcal measurements
  - » Correct the VCO modulation amplitude for the filtering by the modecleaner ~ single pole at about 4.6 kHz for H1, 3.6 kHz for H2
  - » $\Delta L = L \dfrac{\Delta f_{laser}}{f_{laser}}$ gives calibration of the coil actuators in m/count

Comparison of calibration parameters

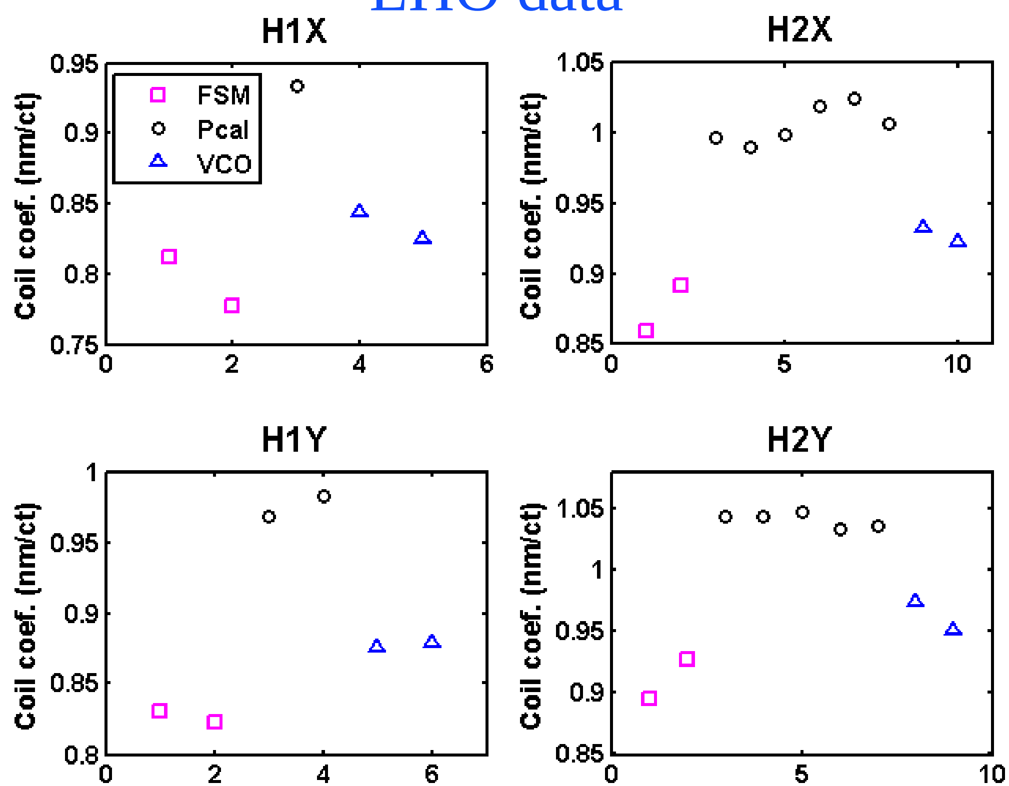
	Free-swinging Michelson	Photon calibrators	Frequency Modulation
Interferometer configuration	Unlocked/Locked Michelson Single arm low power	Full lock Full power (SM config.)	Single arm low power
ETM drive configuration	Acquire	Run	Acquire
Appl. length modulation (at 100 hz)	3e-6 m/6e-13m 2e-12m	4e-18 m	4e-12 m
Critical parameter(s)	Laser wavelength	Modulated laser power Mass of TM	frequency modulation amplitude

Comparison of S5 actuation coefficient meas.



Frequency sweeps

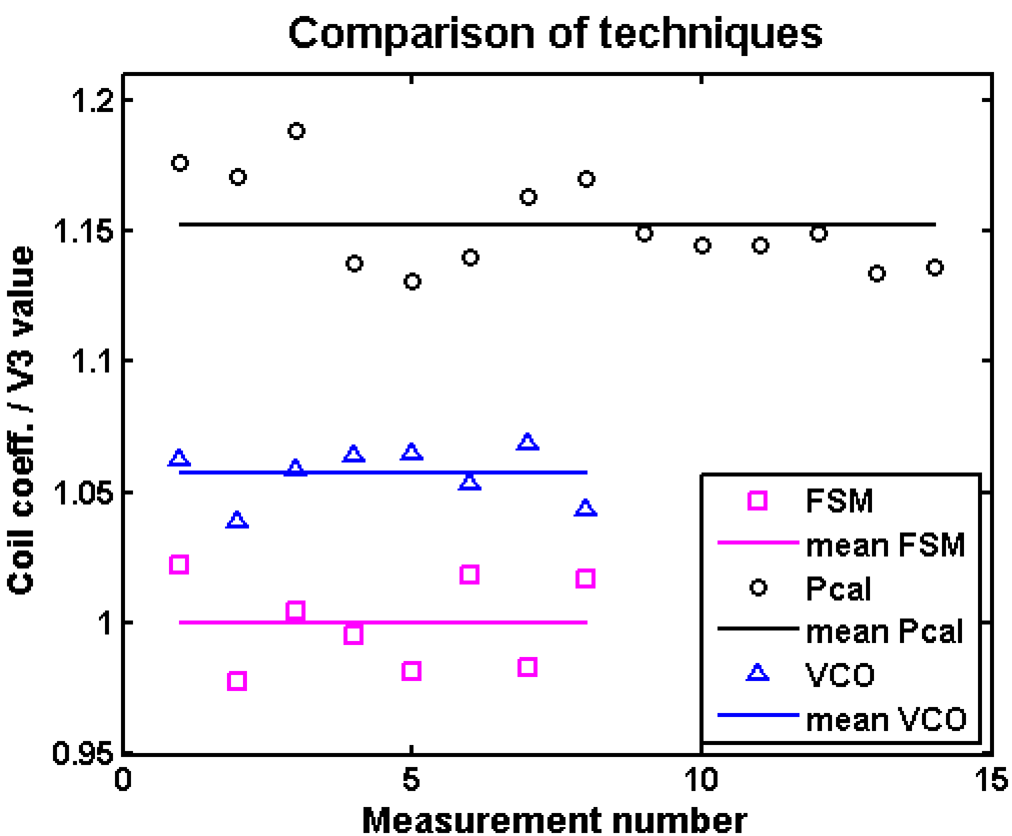
LHO data



Mean coil actuation coefficients

LLO Pcal data show similar behavior, but with greater uncertainty in the power calibration. VCO measurements at LLO will be made during the post-S5 period.

Comparison of calibration methods



- Pcal data over 10 mos. in various configurations
  - » One beam, two beam horiz., two beam vertical, diffracted or non-diffracted beam

FSM data from V3 calibration

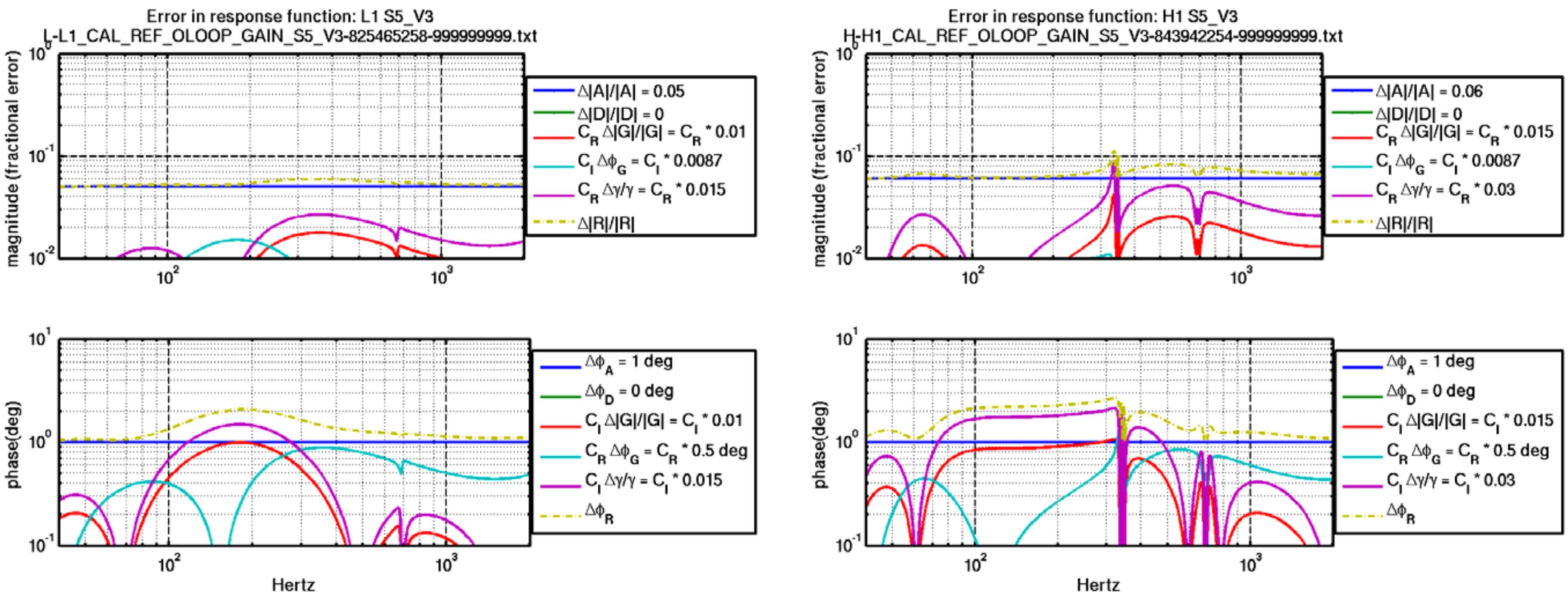
- » Two measurements,
- » Separated by 13 mos.
  - – Representative of other sweeps

VCO data from H1ETMX, H1ETMY and H2 ETMX

- » Calibration of VCO and measurements repeated over past 7 mos.

Official calibration error budgets

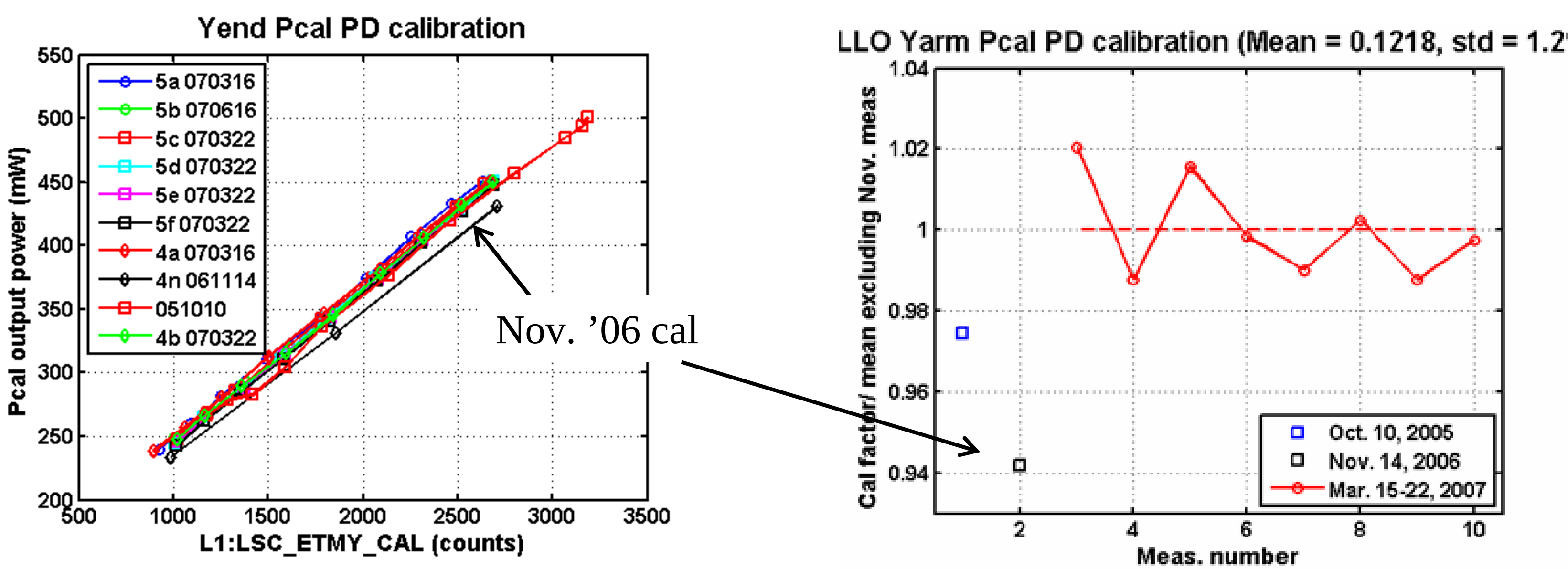
- Statistical errors and measured systematic variation in actuation function are ~5% (1 sigma) and < 5 deg. of phase (below 1 kHz).
- However …. extrapolation of actuation coefficient over:
  - » Six orders of magnitude in actuation force
  - » Factor of ~2000 in laser power (single arm vs. full interferometer lock)
  - » Run vs. Acquire configuration, whitening filters, etc.



Potential source of systematic errors

Pcal – measurement of absolute laser power reflected from mass

- » By far the largest potential for systematic errors
- » Thermal power meters
  - Calibrations drifting by 7% over ~ 6 months
  - ~10% variation between different manufacturers
  - Unexplained ~6% variations in different locations (temperature, air currents?)
- » Planning to upgrade to temperature-controlled InGaAs PDs on integrating spheres with calibrations at NIST
  - – **Hope to have ready for post-S5 measurement period**



LIGO *Summary of calibration method comparisons*

- Three fundamentally different calibration techniques agree at the 15% level
- Mean systematic discrepancy of ~15% between free-swinging Michelson technique and photon calibrators
  - » Photon calibrators indicate lower sensitivity (lower inspiral range)
- Frequency modulation results ~6% higher than FSM calibrations (lower sensitivity).
- Some of the post-S5 investigations will be aimed at reconciling the three techniques

Post-S5 calibration-related measurements

- Calibration team estimates that 100-150 hours of post-S5 measurements will be required for calibration-related work

Overview of proposed measurements (under development)

- Standard (full) official calibration run on all three ifos.
  - » Used to generate the final (V4) S5 calibration
- Interferometer configuration validation
  - » Carefully measure all input parameters to our current model.
  - » Double check expected cancellations in electronics transfer functions.
  - » Check de-whitening filters and run/acquire filter compensation.
  - » Measure AI, AA and whitening filters
  - » Measure PD response (shot noise limited).
  - » Measure time delay in loop
- Sign and Timing using Photon Calibrator
- Measurements of the Cavity Pole
  - » Unlocked arm cavities.
  - » Photon Calibrator sweep with a fully locked IFO.
  - » Ringdown measurements.

Post-S5 measurements (cont.)

- Investigation of high frequency discrepancy > ~2 kHz
  - » Incorporate exact length response into model
  - » Scrutinize delays/phase in model
- Investigations aimed at resolving discrepancy between Pcals and free-swinging Michelson
  - » Upgraded Pcal power measurement/calibration
- Calibration/validation of FAST channels (262 kHz)
- Other techniques
  - » Asymmetric Michelson
  - » Virgo technique
  - » VCO Calibration
  - » HEPI or Fine Actuators
  - » Fringe Fitting
  - » Sign Toggling
- Lots of work to make sure we understand as much as we can about the calibration of the interferometers during S5 before we take them apart.

end

Outline of Free-Swinging Michelson (FSM) technique

- First, measure the AS_Q (one ASPD) sensing coefficient in the free-swinging Michelson configuration
  - » P-P AS_Q signal corresponds to $\lambda/4$ motion of ITM
  - » This gives the FSM sensing coefficient, S, in m/count
- Second, lock the Michelson configuration and measure the open loop transfer function, G(s)
- Third, measure ITM coil actuation transfer function to AS_Q in the locked Michelson configuration
  - » Correct for the loop gain – multiply by 1+G(s), and divide by the sensing coefficient, S
  - » This gives the ITM coil actuation coefficient in m/count
- Third, lock a single arm (in acquire mode)
  - » Measure ITM to AS_I and ETM to AS_I transfer functions
  - » Bootstrap ETM coil actuation coefficient from ITM coil actuation coefficient via ratio of the transfer functions.
  - » This gives the ETM coil actuation coefficient in m/count calibrated with the FSM technique

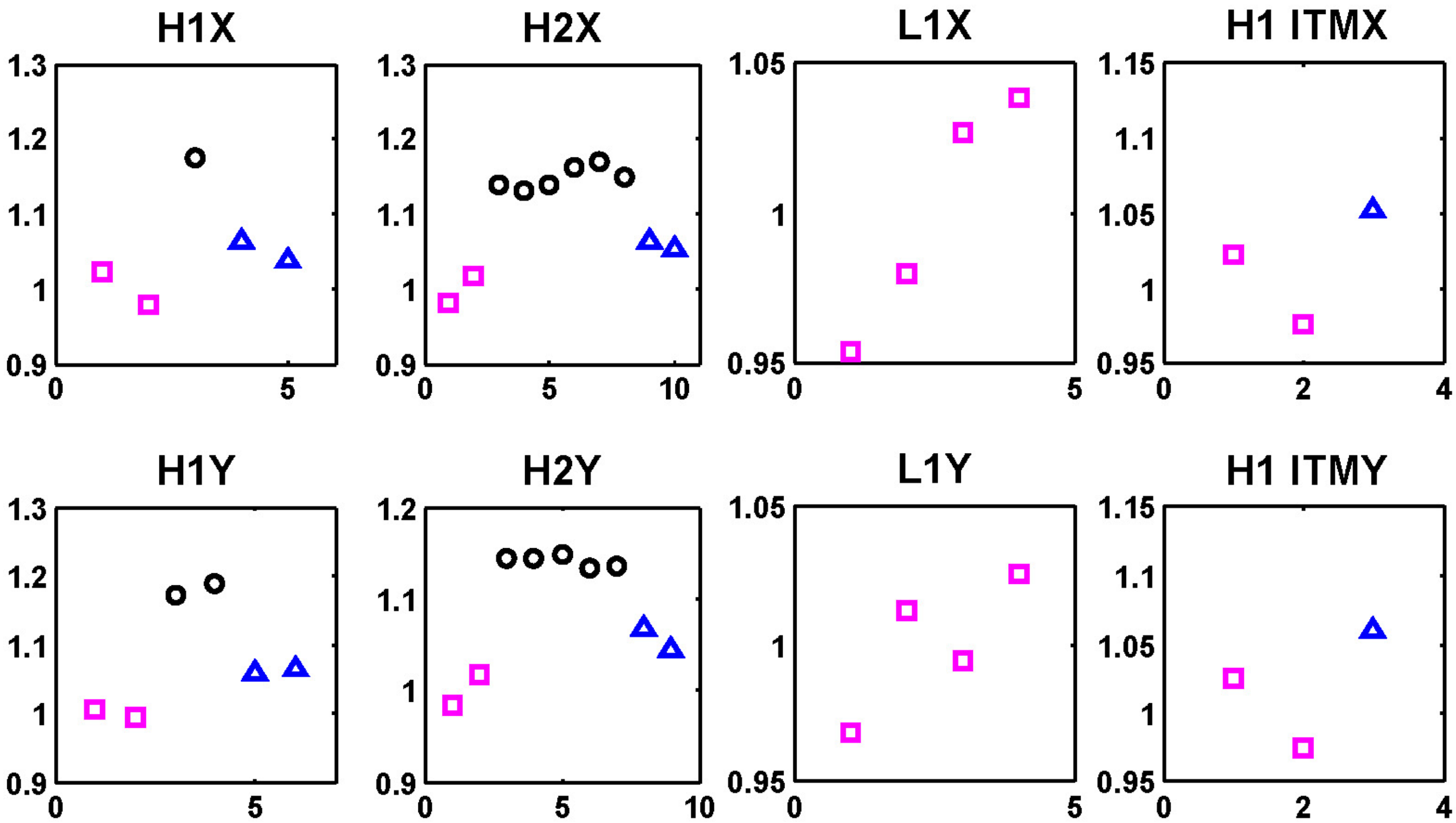
Outline of Photon calibrator (Pcal) technique

- First, calibrate the Pcal internal photodetector using an external power meter
  - » This gives a calibrated monitor of the modulated laser power delivered to the ETM
- Second, lock the ifo. (full power, Run mode) and simultaneously drive both the Pcal and the ETM coil actuators with sine waves separated by 0.5 Hz and take the ratio of the transfer coefficients from the readbacks of the drives to DARM_ERR
  - » Swap the drive frequencies and average the ratios from the two measurements
- Third, calculate the induced test mass motion due to the Pcal beam

$$\Delta x = \frac{2\Delta P \cos\theta}{Mc\omega^2}$$

  - » Ratio of transfer coefficients times the calculated Pcal-induced motion gives the ETM coil actuation coefficient in m/count calibrated using the Pcal

Actuation coefficients normalized to V3 values



Magenta – FSM, Blue – VCO, Black Pcal