Implementing Real-Time Calibration in Advanced LIGO Control Software

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Outline

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The interferometer

- The interferometer measures changes in the spacetime interval between test masses to detect GWs.
- The arms of a detector are 4 km-long Fabry-Perot resonant cavities.
- When these cavities are held on resonance, small changes in differential arm (DARM) length can be used to reconstruct GW signals.
- A negative feedback control loop, the DARM loop, works to keep the DARM length $\Delta L = L_X - L_Y$ constant.

Outline

The DARM loop

- The DARM feedback loop suppresses external differential displacements, ΔL_{ext}, to keep the detector on resonance.

Sensing function, C:

Transforms residual displacement into a digitzed error signal, d_{err}.

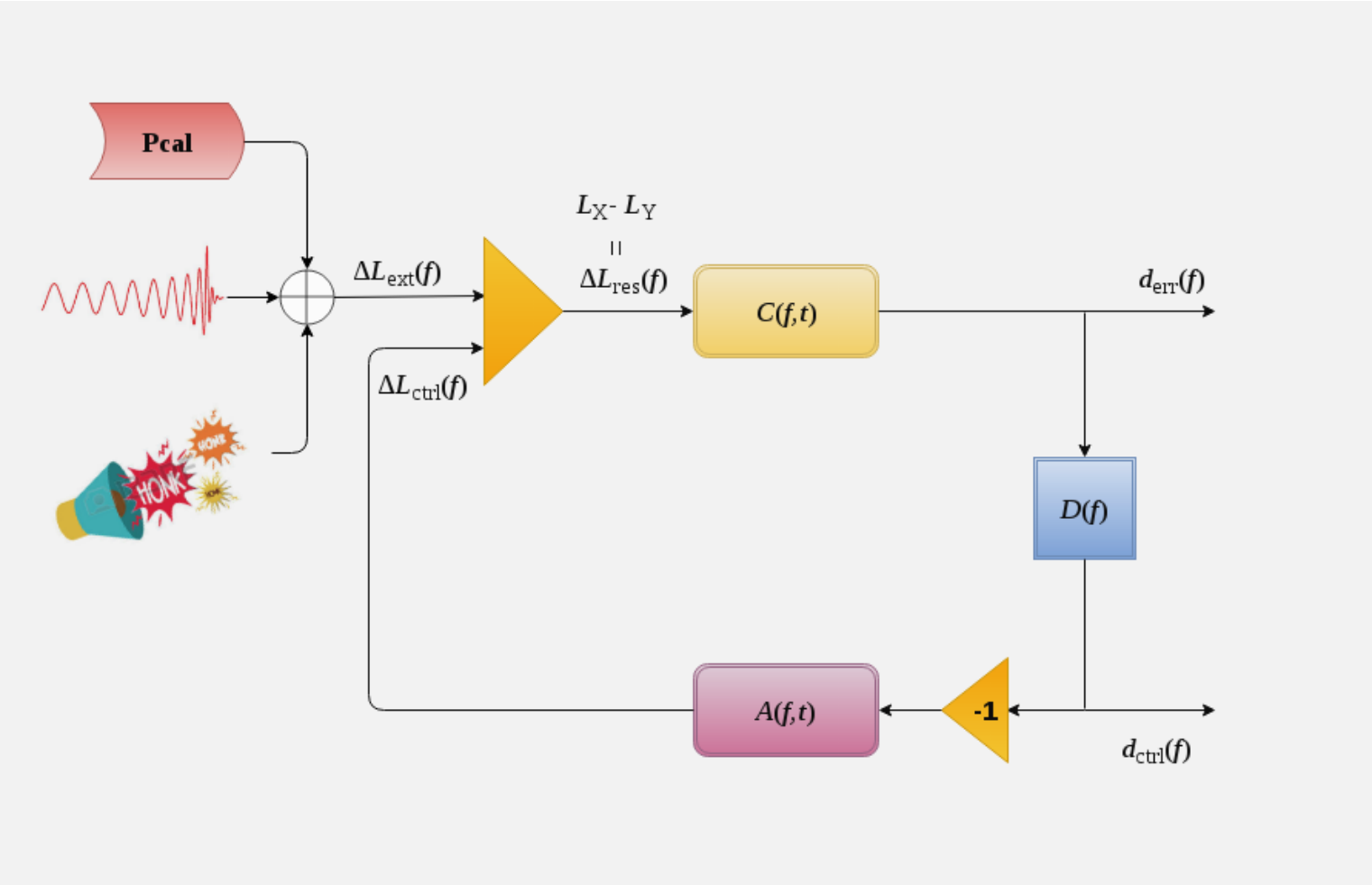
Digital filter bank, D:

Converts d_{err} into d_{ctrl}.

Actuation function, A:

Takes d_{ctrl} and transforms it into a control displacement which opposes the sensed external displacement of the detector.

The DARM loop



Outline

Current calibration process

CALCS (online)

Calibration system running in the front end computers' real-time processors. Uses infinite impulse response (IIR) filtering to produce partially calibrated data: $\Delta L_{\mathrm{PU}}, \Delta L_{\mathrm{T}}, \Delta L_{\mathrm{res}}$, and ΔL_{ext}.

GDS (online)

Takes output of CALCS and applies corrective finite impulse response (FIR) filters A_{corr} and C_{corr}^{-1} and time-dependent correction factors (kappas) to produce refined $h(t)$.

DCS (offline)

Picks off d_{err} and d_{ctrl} and uses FIR filtering to produce $h(t)$ in high-latency.

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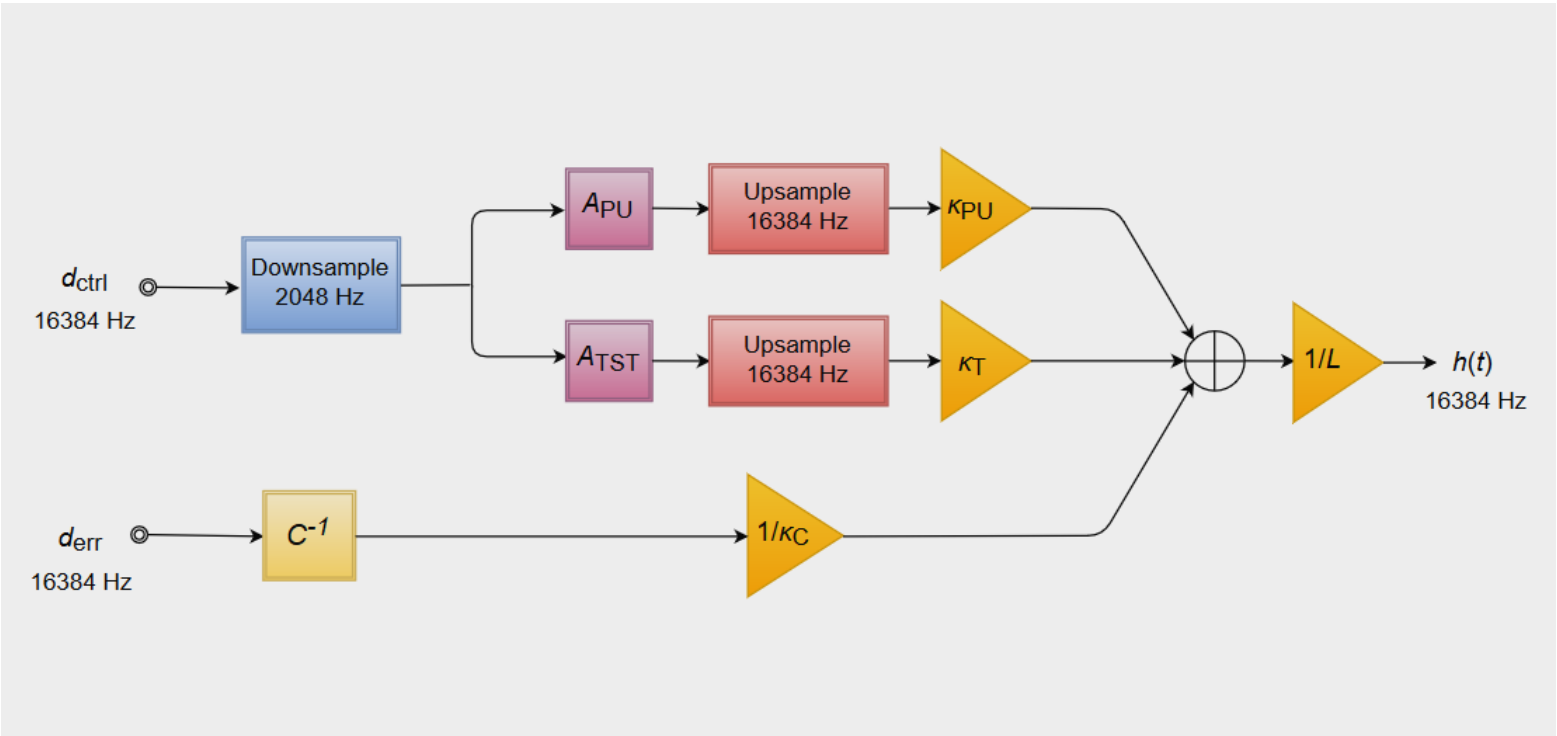
Project motivation

- CALCS introduces systematic errors into ΔL_{ext}, and the GDS pipeline makes corrections before it outputs calibrated GW strain.
- The GDS pipeline operates within the Data Monitoring Tool, which are computers distinct from the front end computers.
- A complete calibration pipeline located in the front end computers would provide operators in the control room with "best possible" calibrated $h(t)$ in very low-latency and remove the redundancy of the dual-system currently in place.

Outline

New front end calibration model



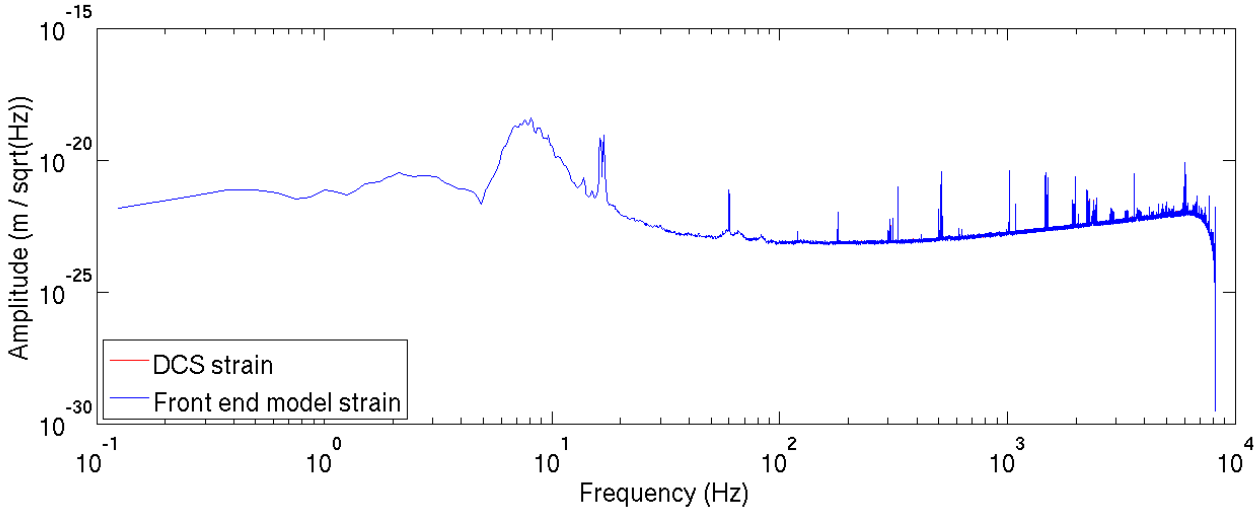
- Note: we use FIR filters identical to those used in DCS pipeline.

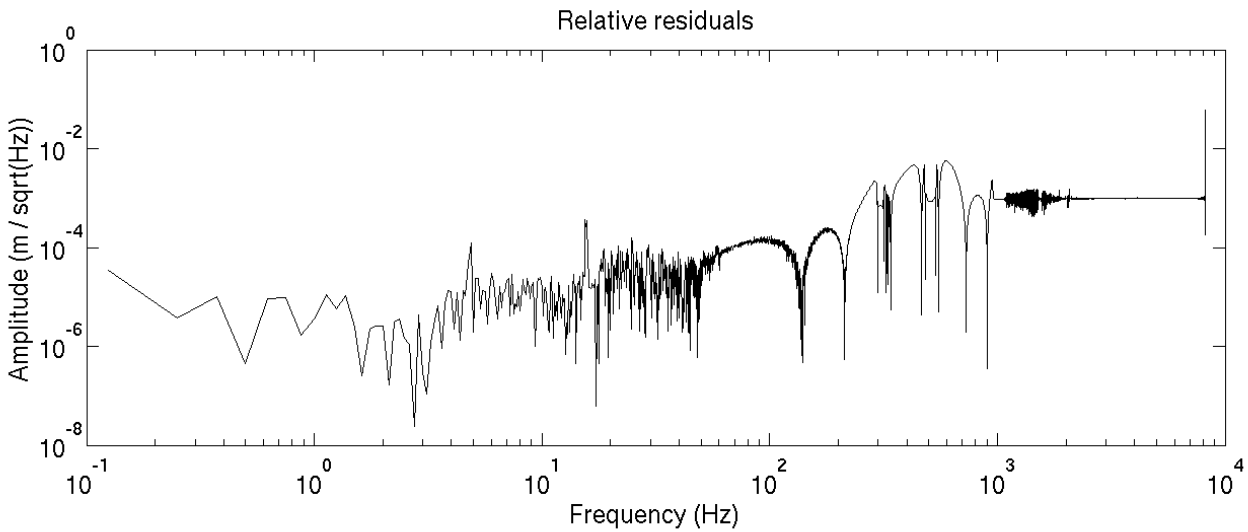
Outline

Testing new pipeline

- Each FIR filter was coded in C on dedicated testing computers. This includes A_{PU}, A_{TST}, C^{-1}, as well as the sinc table downsampling and cubic spline upsampling. These filters were then installed in a front end model.
- To check the viability of the new front end model, we injected a 600 second sample of past data and compared the strain it calculated with the actual strain output by the DCS pipeline for this GPS time.
- An amplitude spectral density (ASD) plot shows how the amplitudes of each pipeline's strain compare across the entire frequency band of Advanced LIGO searches.

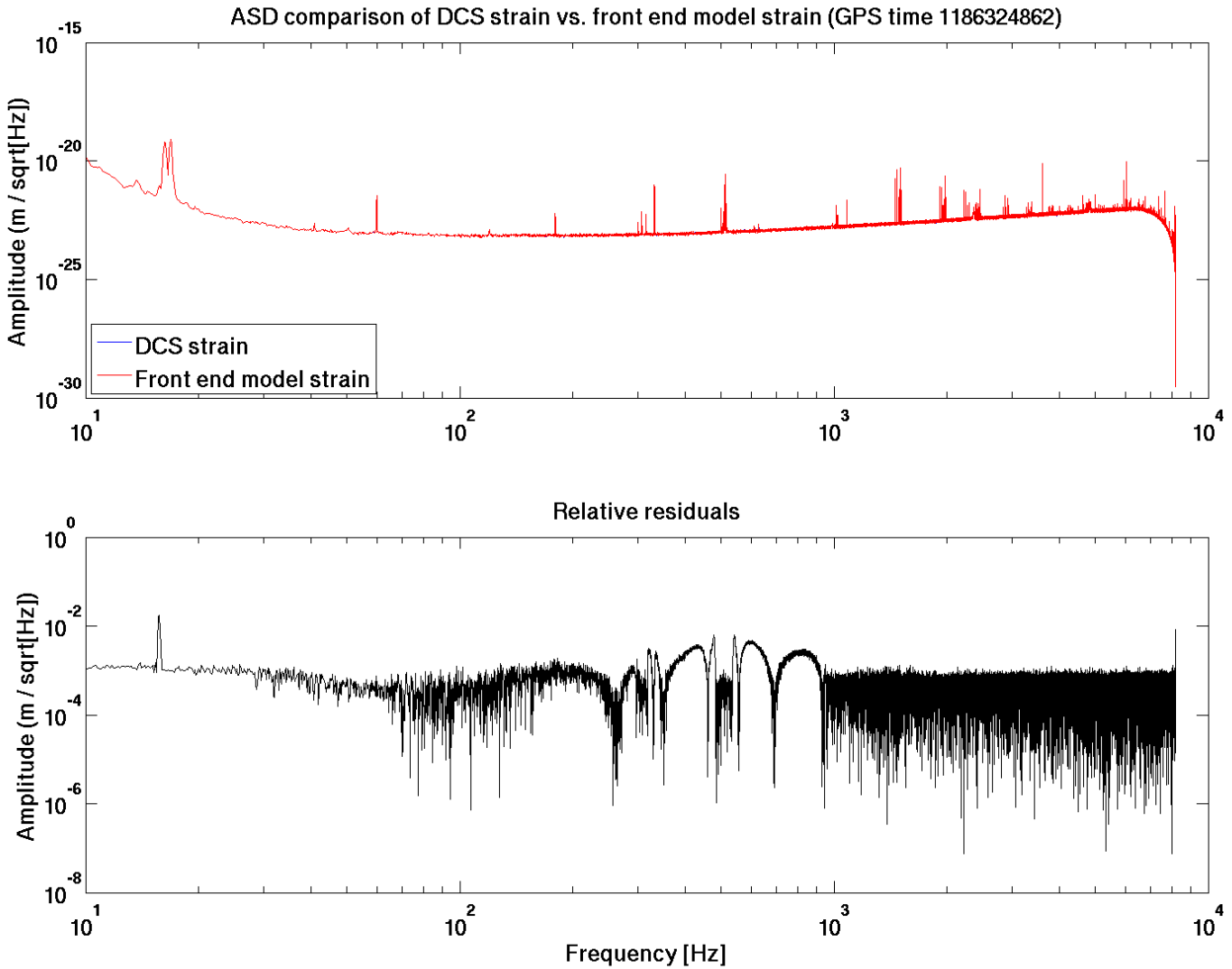
ASD comparison





Outline

Final strain comparison



Summary

- We have built and installed a new calibration pipeline to run in the front end computers.
- It uses identical FIR filters as the ones in the DCS pipeline.
- This pipeline will replace CALCS and GDS as the primary online system to produce $h(t)$ with latency ≈ 3 seconds.

Summary

- We have built and installed a new calibration pipeline to run in the front end computers.
- It uses identical FIR filters as the ones in the DCS pipeline.
- This pipeline will replace CALCS and GDS as the primary online system to produce $h(t)$ with latency $\approx$ 3 seconds.

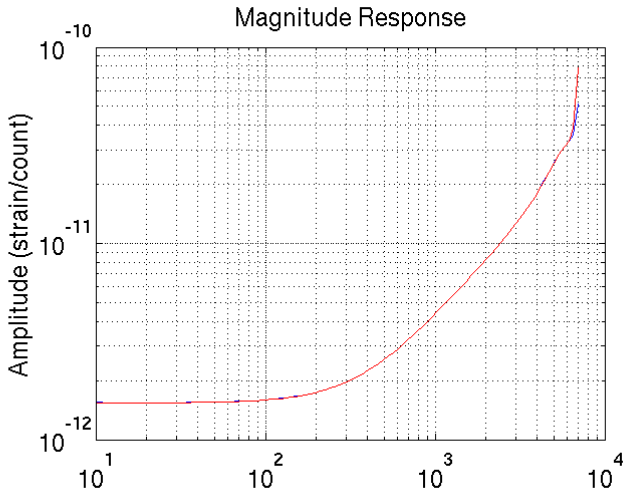
Any questions?

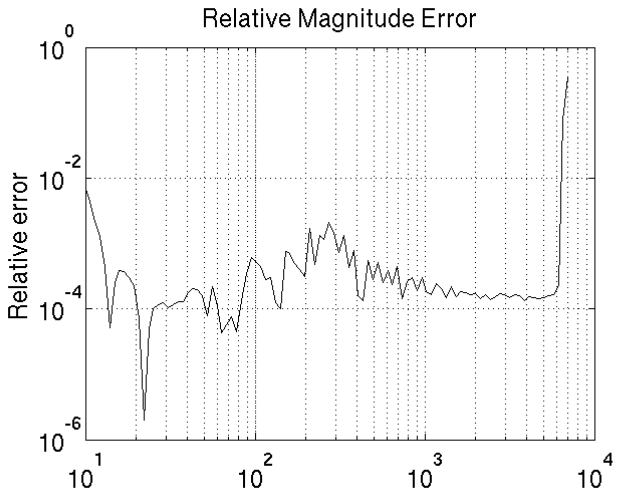
Outline

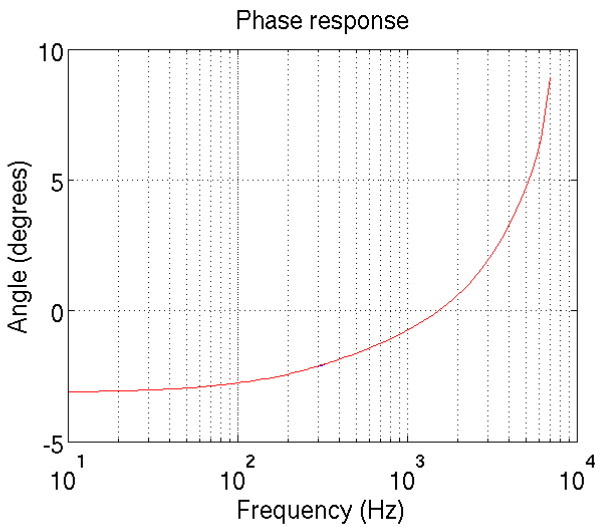
FIR filter comparisons

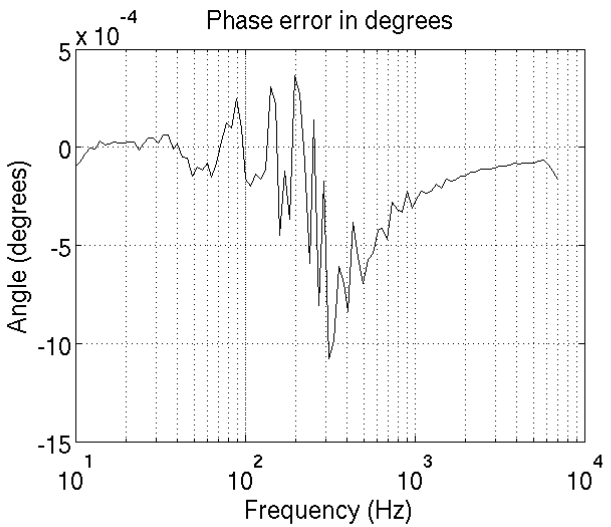
- Modeling the transfer functions of the DARM loop as FIR filters is an approximation.
- The frequency response of each FIR filter is compared against the frequency domain model of the corresponding function in the DARM loop.
- This is accomplished by running injections through the model and taking transfer functions between appropriate points.

Inverse sensing filter

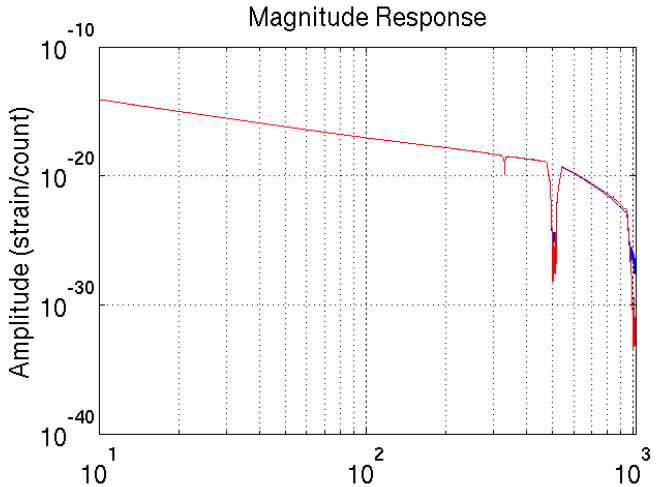


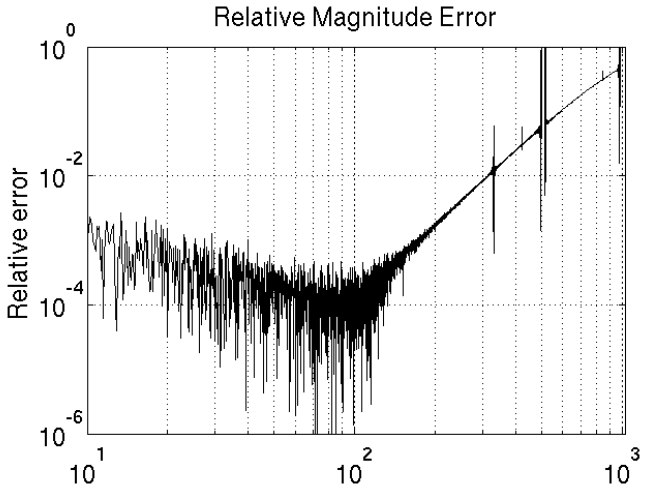


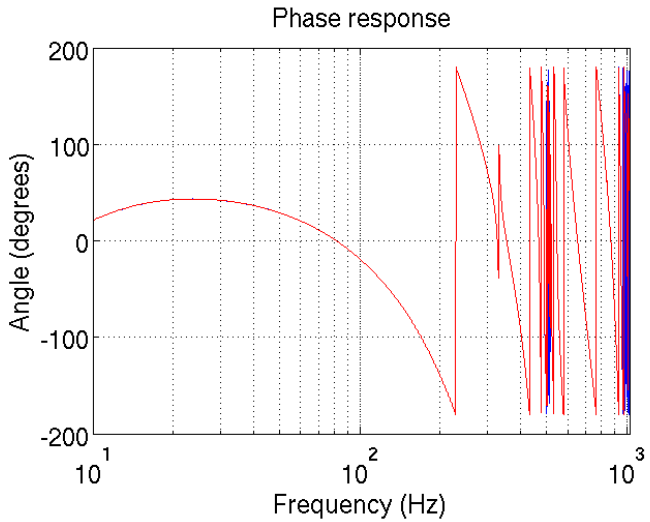


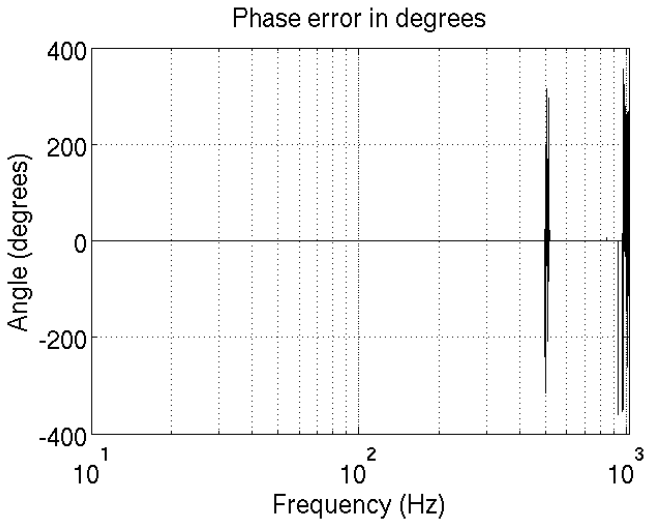


Actuation PU filter

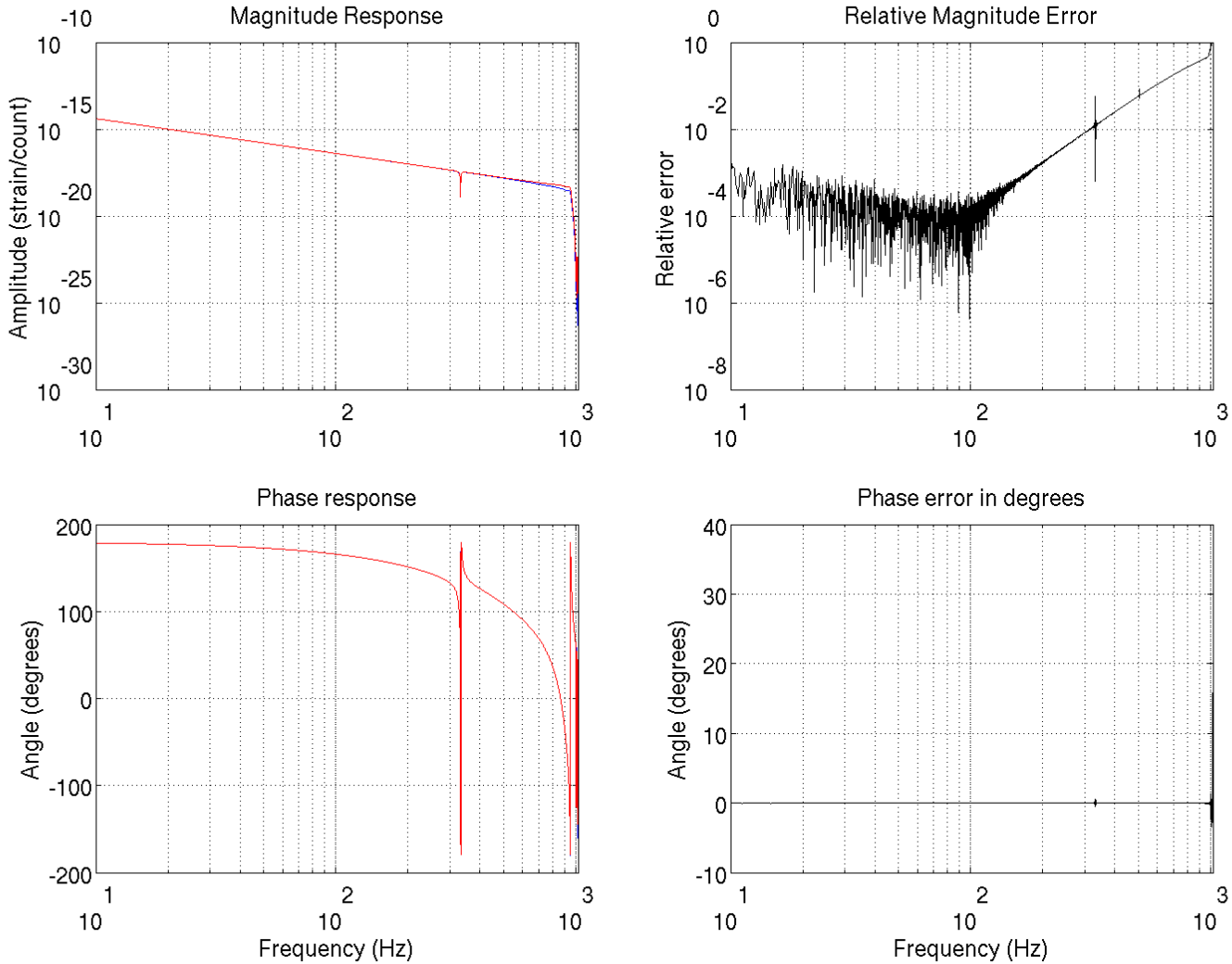








Actuation TST filter



Outline

PCAL ratios

- At LLO, a photon calibrator (PCAL) device at the end test mass of the Y arm is used to calibrate detector response.
- These devices shoot laser light of known wavelength onto the mirrors and generate large displacements.
- A relationship between laser power and test mass displacement can be established.

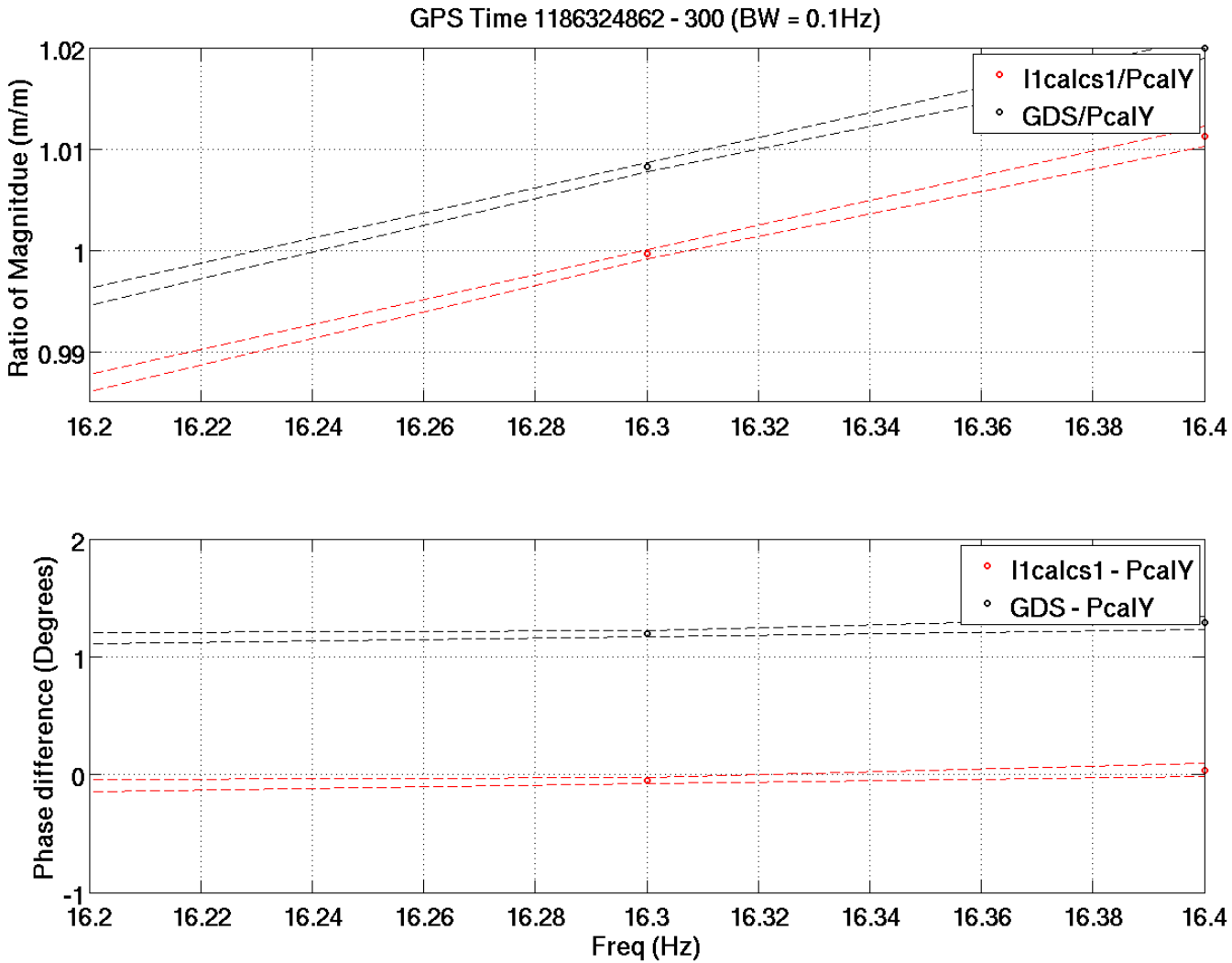
PCAL ratios, continued

- Laser power fluctuations at the auxiliary photodetector are recorded.
- These readings are converted into a voltage to displace the test mass according to the detector's response function.

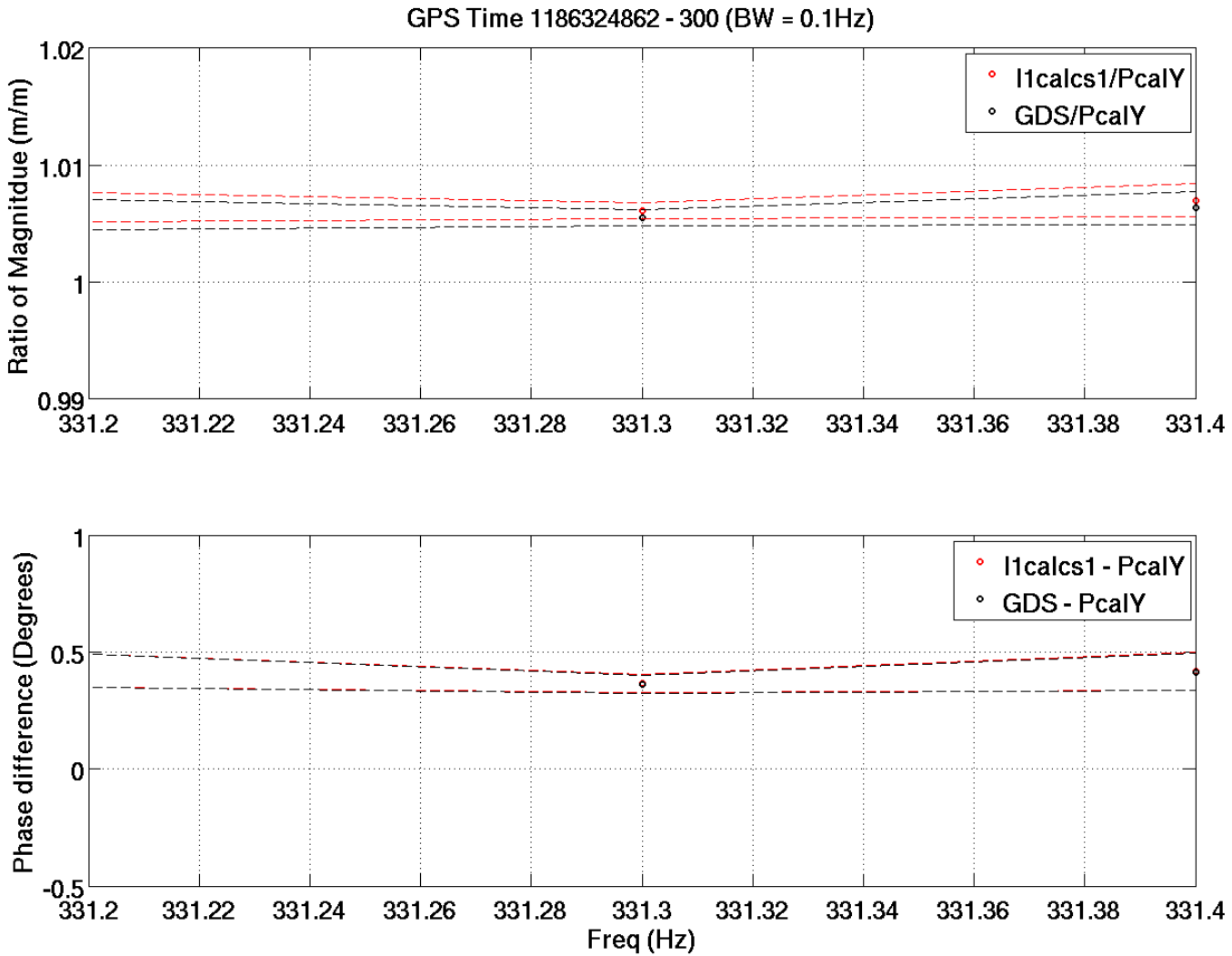
Front end model strain vs. PCAL strain

Ideally, the ratio of the mangnitudes of the two strains at the calibration line frequencies should be 1 and the difference in phase should be 0.

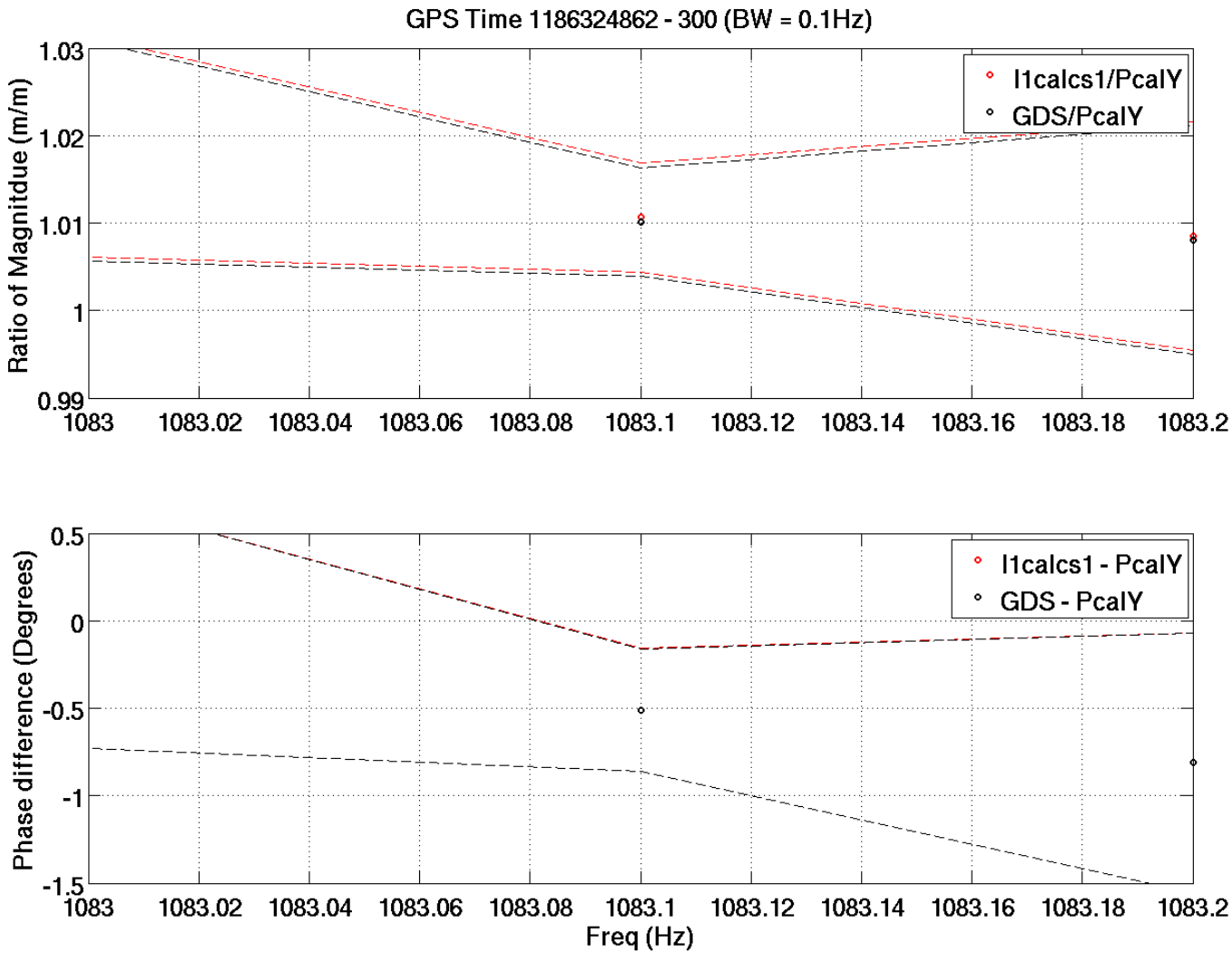
16.3 Hz line comparison



331.3 Hz line comparison



1083.1 Hz line comparison



Outline

FE/DCS strain transfer function