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Earth Tide Prediction and Compensation for Advanced LIGO

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LIGO-G1300834-v1

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Project Goals

- Characterize the effect of solid earth tides on the aLIGO interferometers through analytical prediction
- Determine whether an on-line feed-forward system is necessary to remove these effects
- Provide a conceptual design and implement such a system if necessary
- Develop an operational diagnostic tool to display tidal predictions if not, for direct comparison to real time feedback compensation

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Tidal Model of the Earth

- Tidal displacement of a point on earth determined in proportion to tidal potential at that point
- General case for $A(r, \phi, \lambda)$ on earth's surface and object at $O(r, \delta, \alpha)$ of the form

$$U_{\{r=a\}} \propto C_1(\phi, \delta)\cos(2H) + C_2(\phi, \delta)\cos(H) + C_3(\phi, \delta)$$

where $H = H_0 - \alpha - \lambda$

Elastic Earth Model (Love)

Assume isotropy and elasticity as defined by:

$$u_r = h\frac{U(A)}{g}$$ Vertical Displacements

$$u_\theta = \frac{l}{g}\frac{\partial U(A)}{\partial \theta}$$

$$u_\lambda = \frac{l}{g}\frac{1}{\sin\theta}\frac{\partial U(A)}{\partial \lambda}$$

Horizontal Displacements

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Computation Methods

- Two methods to compute tidal deformation:
  - » Displacement - Use tidal displacements of corner and end stations to calculate longitudinal displacement
  - » Strain - Use tidal displacement equations to derive strain tensor, and project strain elements along arms
- Which is better?
  - » Strain simpler conceptually, makes more assumptions
  - » Displacement more robust, more prone to computational error
- Both currently implemented, for future comparison

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Prediction Code

- Can use either method to predict tidal strains at Hanford and Livingston either for one time or a time range.
- Employs high-precision simulation data to predict location of moon and sun (from JPL)
- Computes YARM, XARM, CARM, and DARM
- Outputs predictions either to file or terminal

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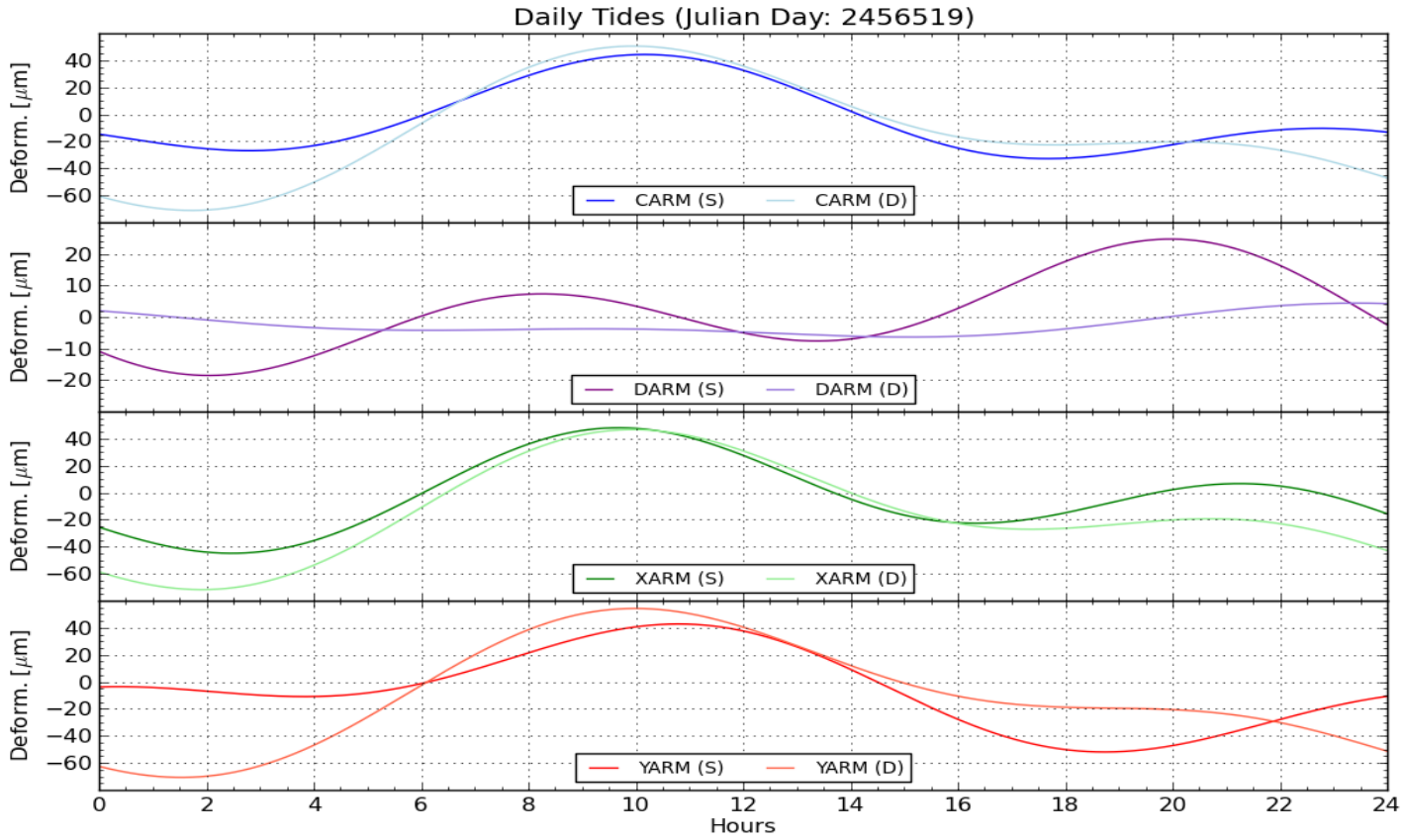
Daily Tides



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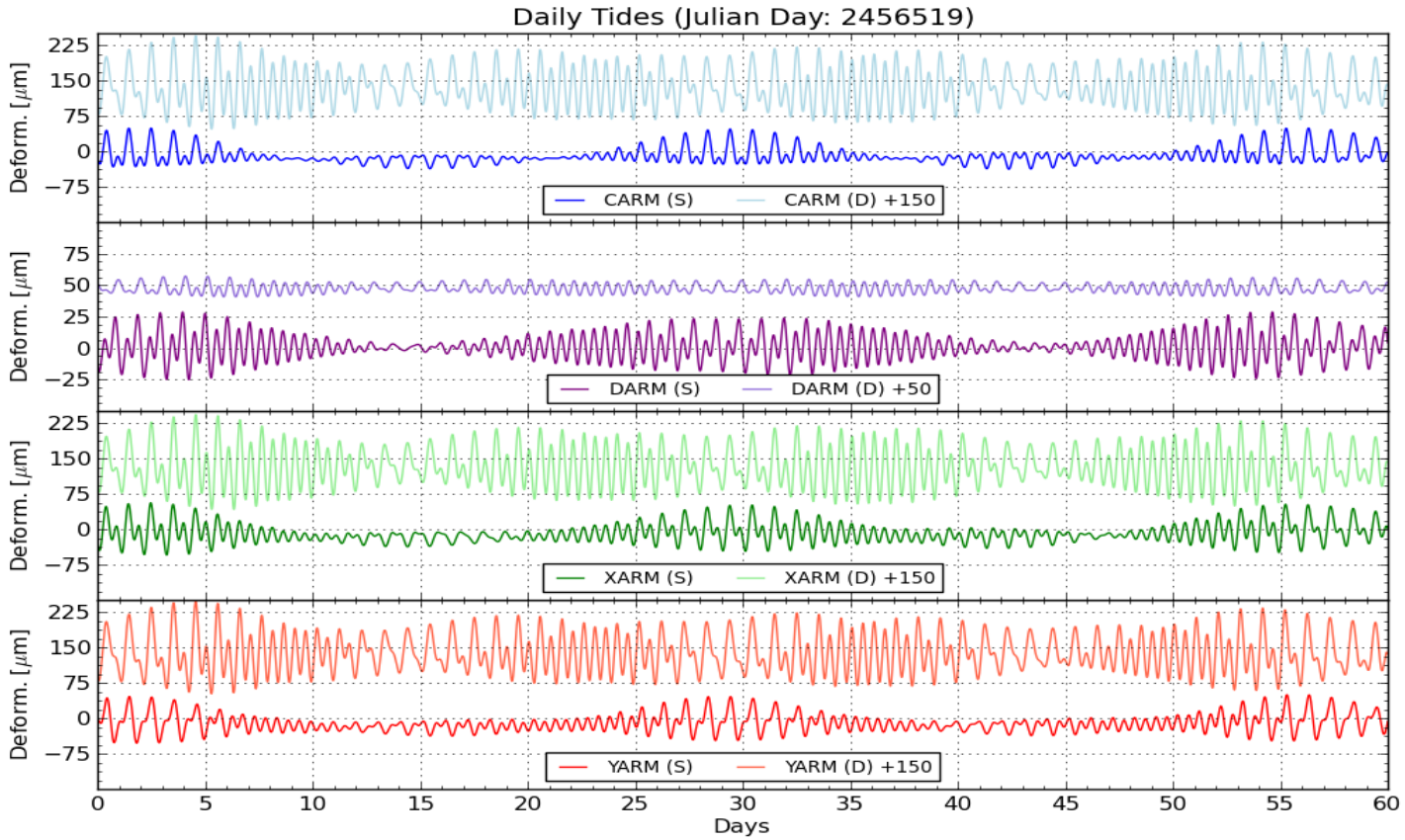
Monthly Tides



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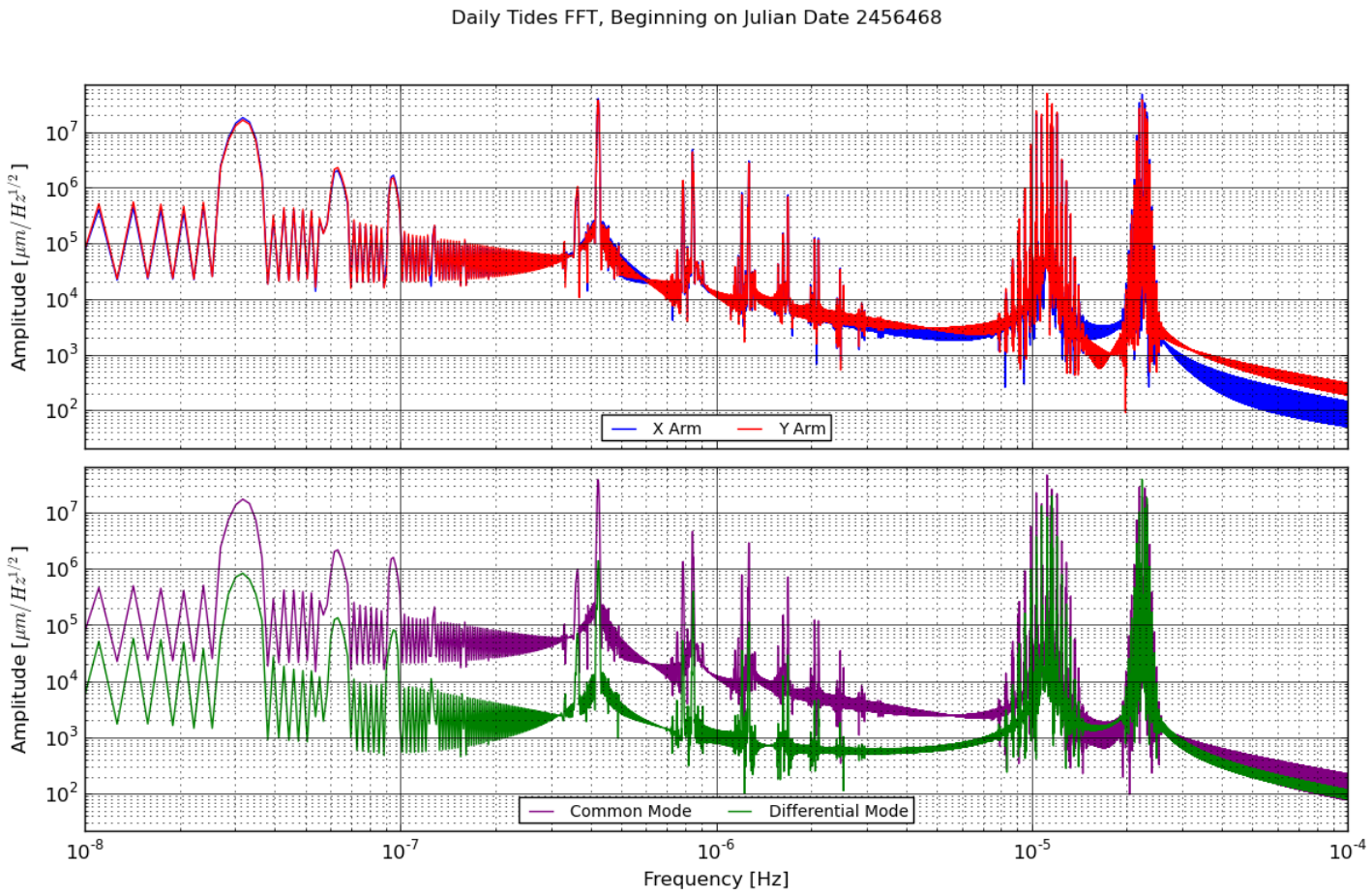
Tidal Power Spectrum



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Previous Tidal Analysis

- Previously discussed HIFO-Y ALS system and ongoing analysis of long-term stability
- HIFO “instability” highly correlated with reference cavity temperature fluctuations
- HIFO-Y ALS not designed for long-term operation, lacks ability to separate CARM and DARM
- LSC system main compensation system for long-term drifts, e.g. Tidal effects

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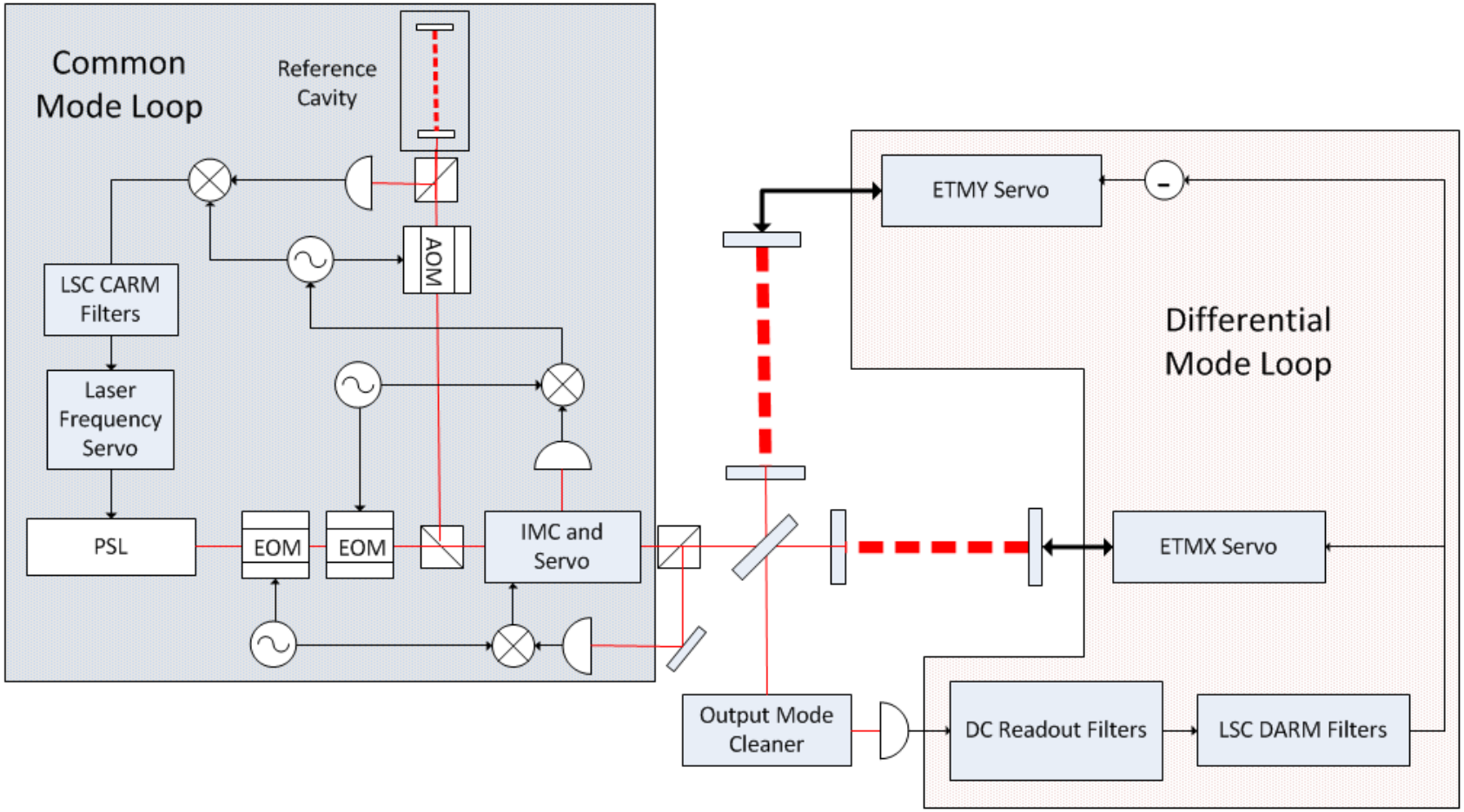
Is Feed-Forward Necessary?

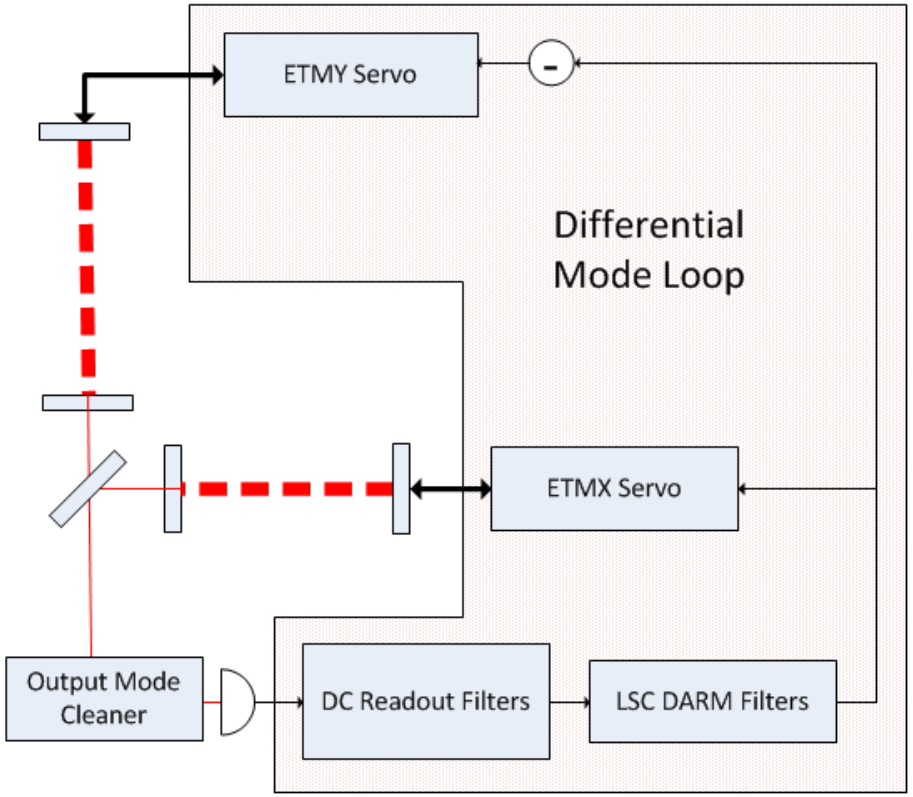
- Know from HIFO analysis that HEPI feedback loop very stable at near-DC and no resonances near frequencies of interest
- Can use worst case tidal predictions to set requirements for feedback system:
  - » DARM – 100 microns peak to peak
  - » CARM – 300 microns peak to peak
  - » Twelve Hour Timescale

LSC Overview



Differential Mode Compensation

- DC Readout (comparison to dark port offset)
- Limited by response of HEPI actuation loop
- Feedback O.K.

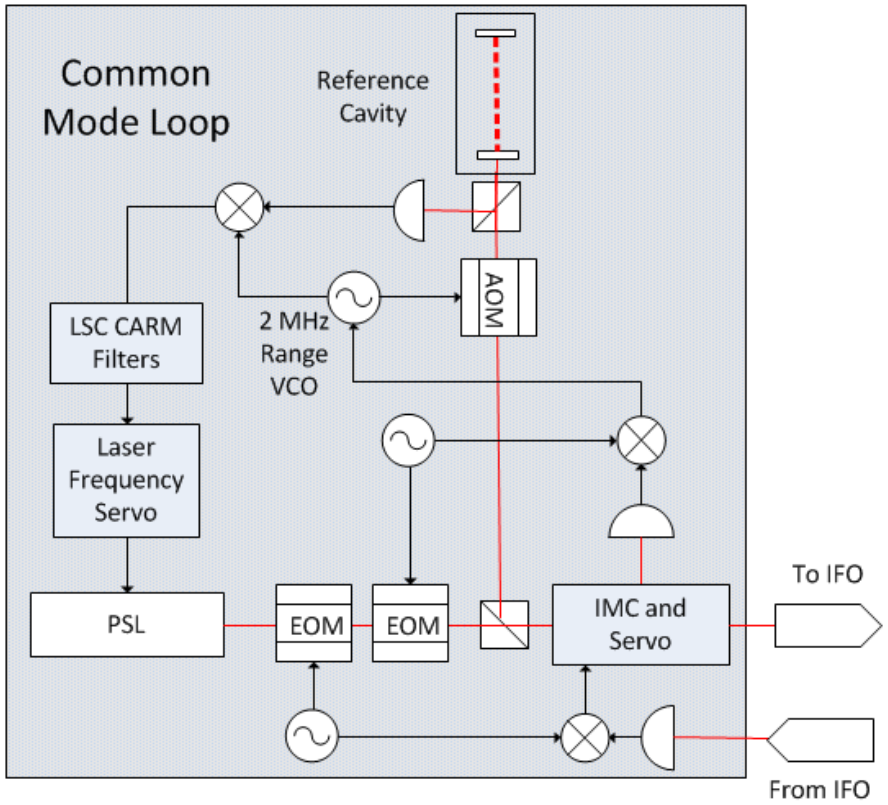


Common Mode Compensation

- RF Readout (PDH)
- VCO Range ≈ 2 MHz used to offset laser frequency
- Tidal signals will saturate VCO range:

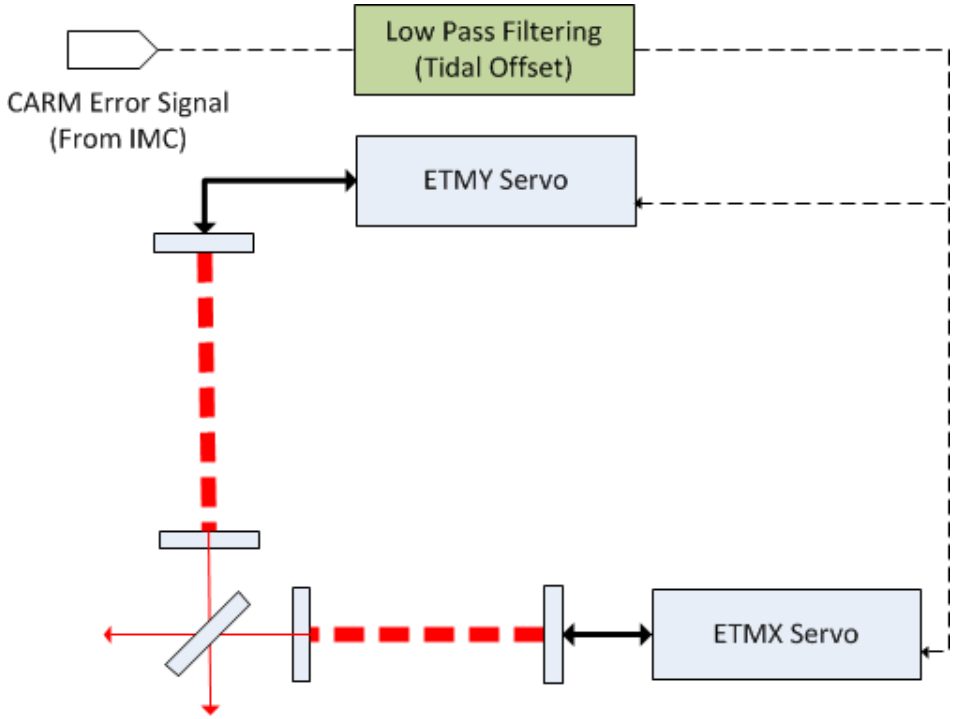
$$\Delta f = f\left(1 - \frac{\mathrm{L}}{\mathrm{L} + \Delta L}\right) \approx 23 \text{ MHz}$$

- Exiting Feedback Inadequate

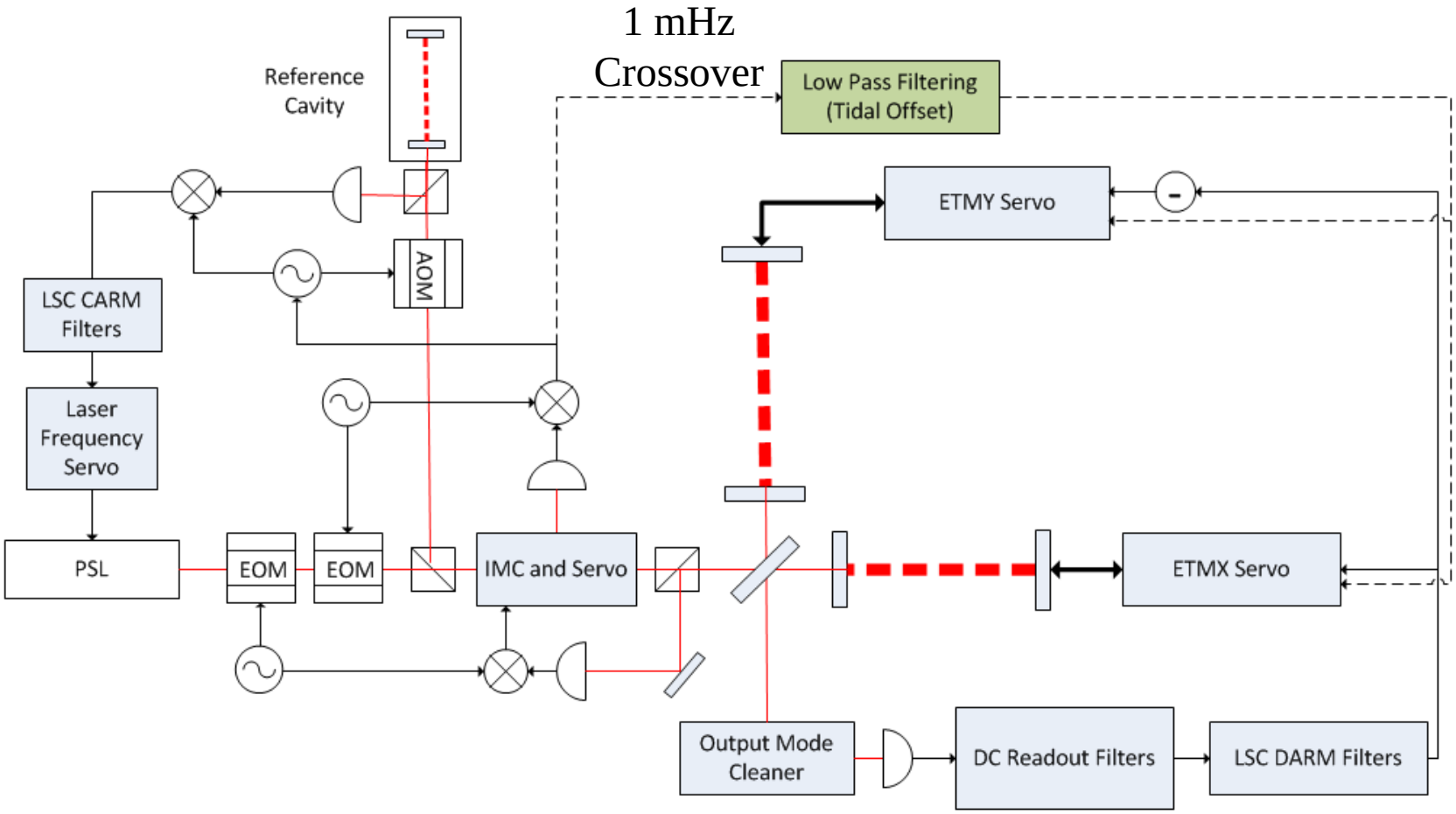


Common Mode Compensation

- DC common mode signal can be fed back to HEPI actuators without saturation
- Requires low pass filtering and crossover analysis
- *Modified* feedback: O.K.



Proposed LSC Modification



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Is Feed-Forward Necessary?

- Know from ALS analysis that HEPI feedback loop very stable at near-DC and no resonances near frequencies of interest
- Can use tidal predictions to set requirements for feedback system:
  - » DARM – 100 microns peak to peak **O.K.**
  - » CARM ***(Modfied)*** – 300 microns peak to peak (worst case) **O.K.**

No feed-forward required

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EPICS Tidal Prediction Integration

- Tidal predictions ported to EPICS for future comparison with error signals
- Tidal prediction code has been modified to run continuously, predicting tidal displacements using both methods given current system time
- Device support/IOC implemented for Hanford and Livingston
- Currently running on h0epics2

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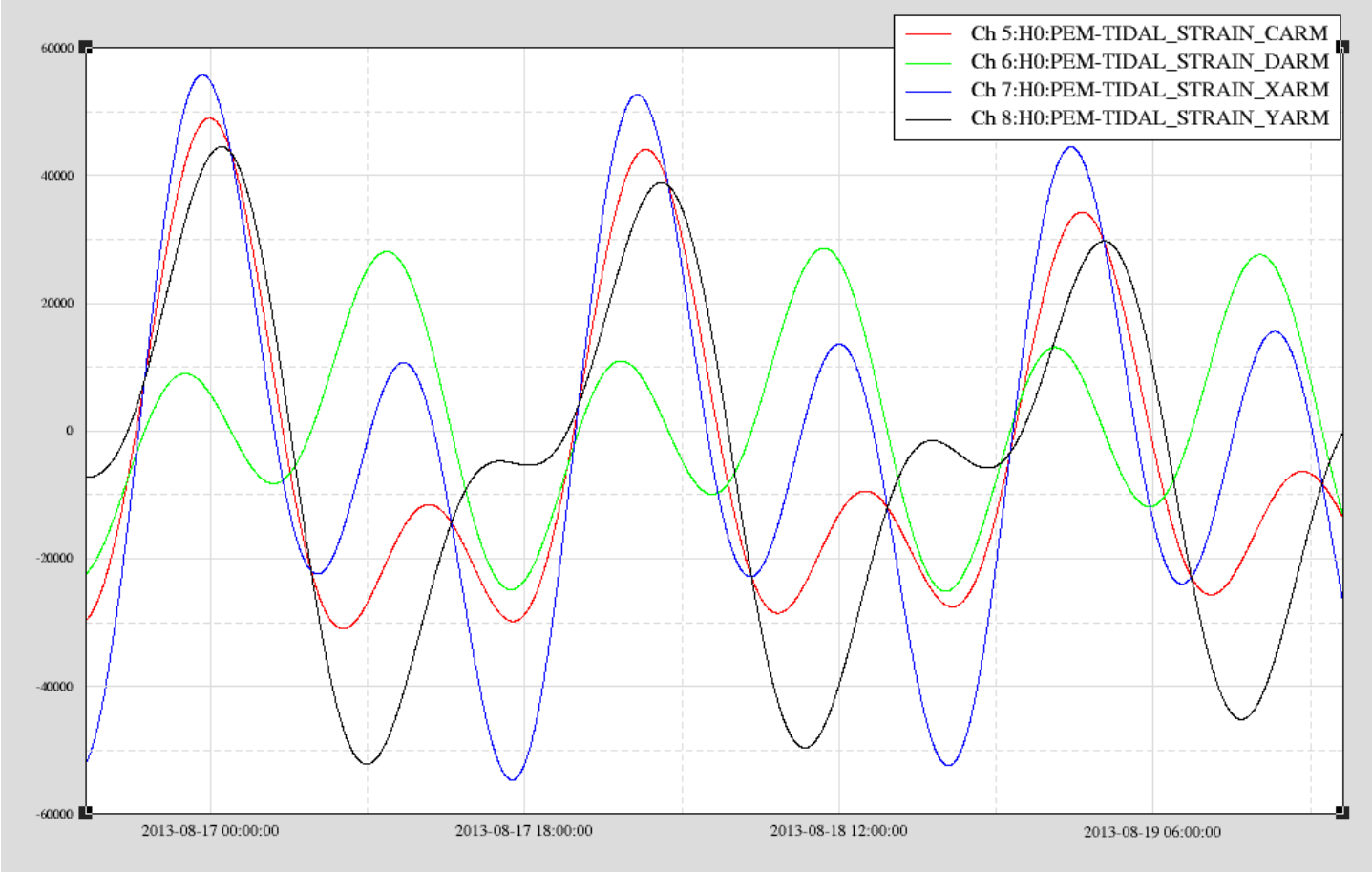
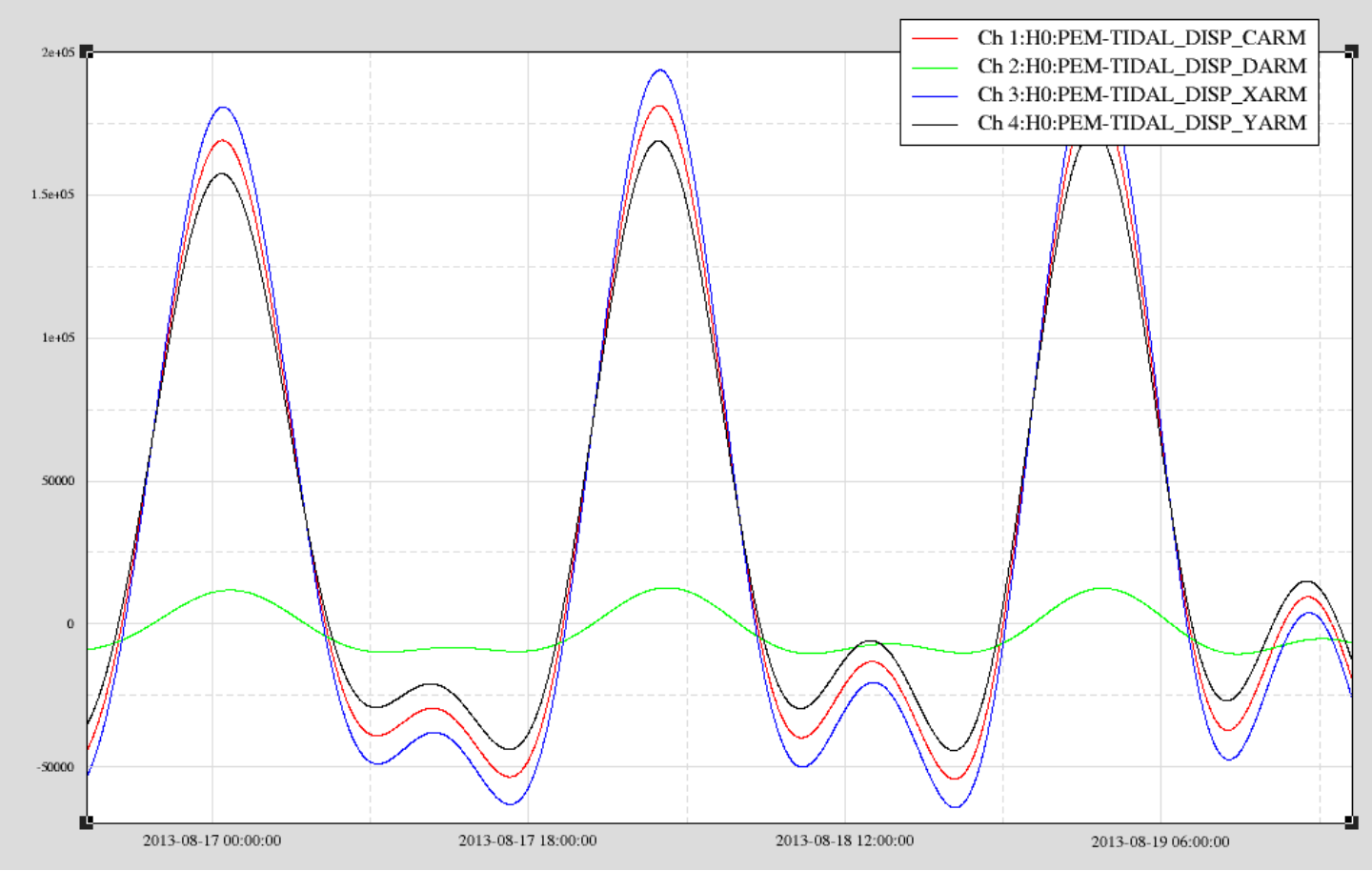
EPICS Signals

- Signal Names:
  - » H0:PEM-TIDAL_DISP_CARM
  - » H0:PEM-TIDAL_DISP_DARM
  - » H0:PEM-TIDAL_DISP_XARM
  - » H0:PEM-TIDAL_DISP_YARM
  - » H0:PEM-TIDAL_STRAIN_CARM
  - » H0:PEM-TIDAL_STRAIN_DARM
  - » H0:PEM-TIDAL_STRAIN_XARM
  - » H0:PEM-TIDAL_STRAIN_YARM
  - » H0:PEM-TIDAL_UNIXTIME
- Actively updated, stored in FRAMES

EPICS Signals in DataViewer (STRAIN)



EPICS Signals in DataViewer (DISP)



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Tidal Prediction: Future Plans

- Test models, verify predictions, determine accuracy
  - » HIFO-Y ALS system too unstable on long timescales to test tidal predictions
  - » LSC system not operational, as only one arm fully commissioned
  - » Is tidal prediction the chicken or the egg?
- So far, models mostly un-tested against real data, aside from general comparison to past observations

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In Conclusion

- The aLIGO interferometers are capable of offloading tidal deformations through feedback alone
  - » This will require development of ultra-low frequency bypass loop
- Earth tide predictions can be monitored in real time in the control room and compared to observed longitudinal displacements
- If a feed-forward system is desired for a later aLIGO system, its implementation will be very easy and efficient due to this effort

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References

- D. C. Agnew. *Earth Tides*, 2007.
- Paul Melchior. “The Tides of Planet Earth”, 1987
- R. Adhikari. *Sensitivity and Noise Analysis of 4 km Laser Interferometric Gravitational Wave Antennae*. PhD thesis, Massachusetts Institute of Technology, 2004.
- E. Morganson. *Developing an Earth-Tides Model for LIGO Interferometers*. Technical Report, 1999
- D. Sigg. Arm Length Stabilization at LHO. Technical Report LIGO-G1300258-v1, March 2013.
- K. Somiya et. al. *Length Sensing and Control for AdLIGO* Technical Report LIGO-T060272, November 2006

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EXTRA SLIDES

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Future Projects

- Fully design and characterize proposed feedback loop, or opt to implement feed-forward
- Compare tidal predictions to DARM and CARM error signals, once IFO fully commissioned
- Decide whether discrepancies are due to model errors or control system inadequacies (should be based on long-term lock stability)
- Determine whether strain or displacement method is more accurate, or whether numerical method should be used