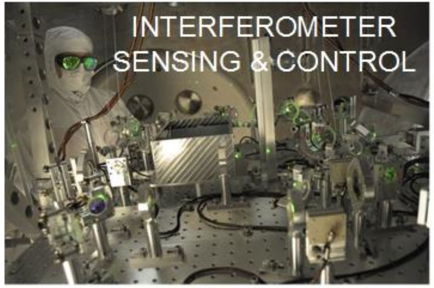
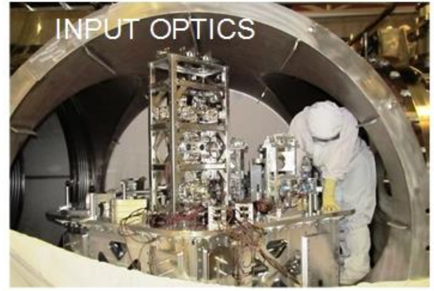




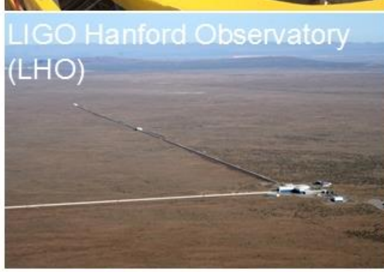
Brief LIGO Controls Overview

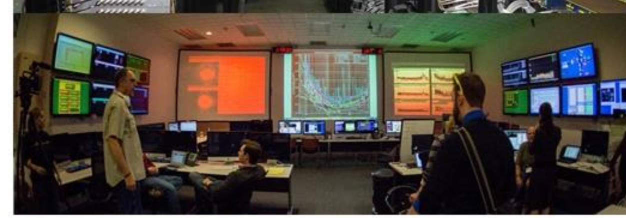
Dennis Coyne

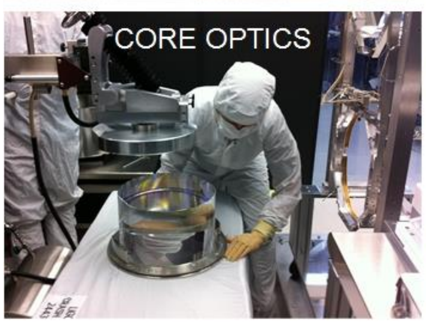
LIGO Laboratory, Caltech

26 Aug 2017

LIGO-G1701594-v1







outline

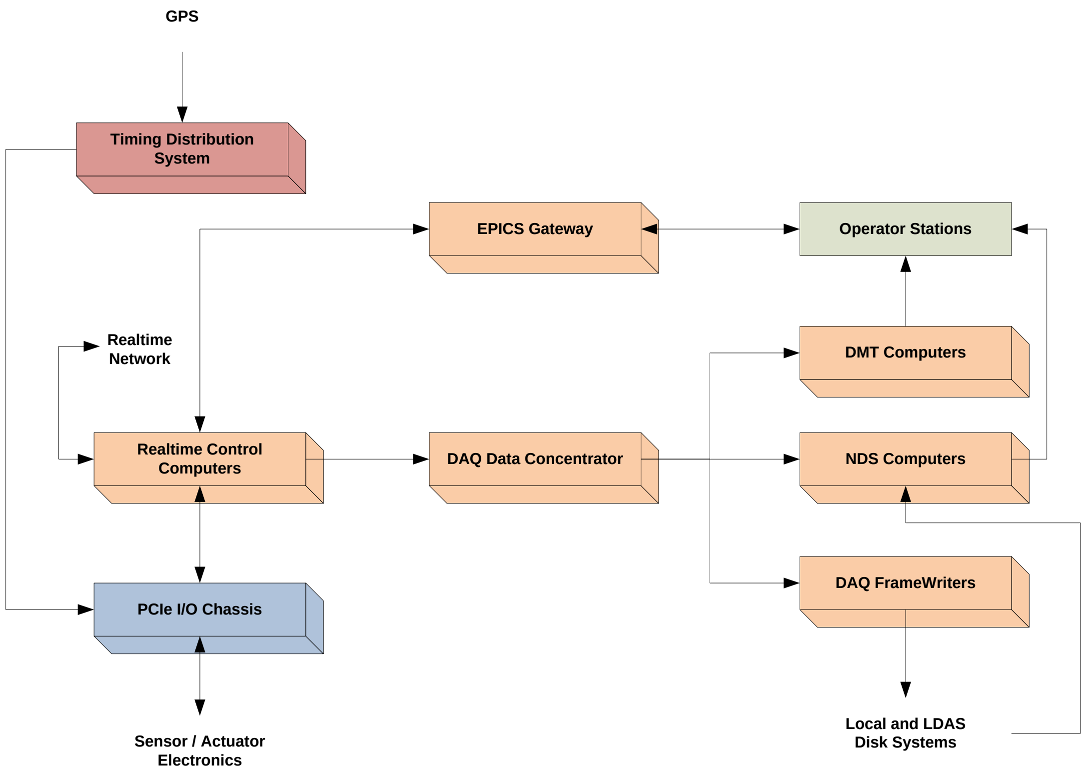
- **Hardware architecture**
- **Software architecture**
- **“Plants” to be controlled**
- **Control group focus areas/priorities**

Overall references on the Advanced LIGO detector:

- *Advanced LIGO, LIGO-P1400177*, https://arxiv.org/abs/1411.4547
- *The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy, LIGO-P1500260, https://arxiv.org/abs/1604.00439, Phys. Rev. D 93, 112004,June 2016.*

Control & Data System Hardware Architecture Overview

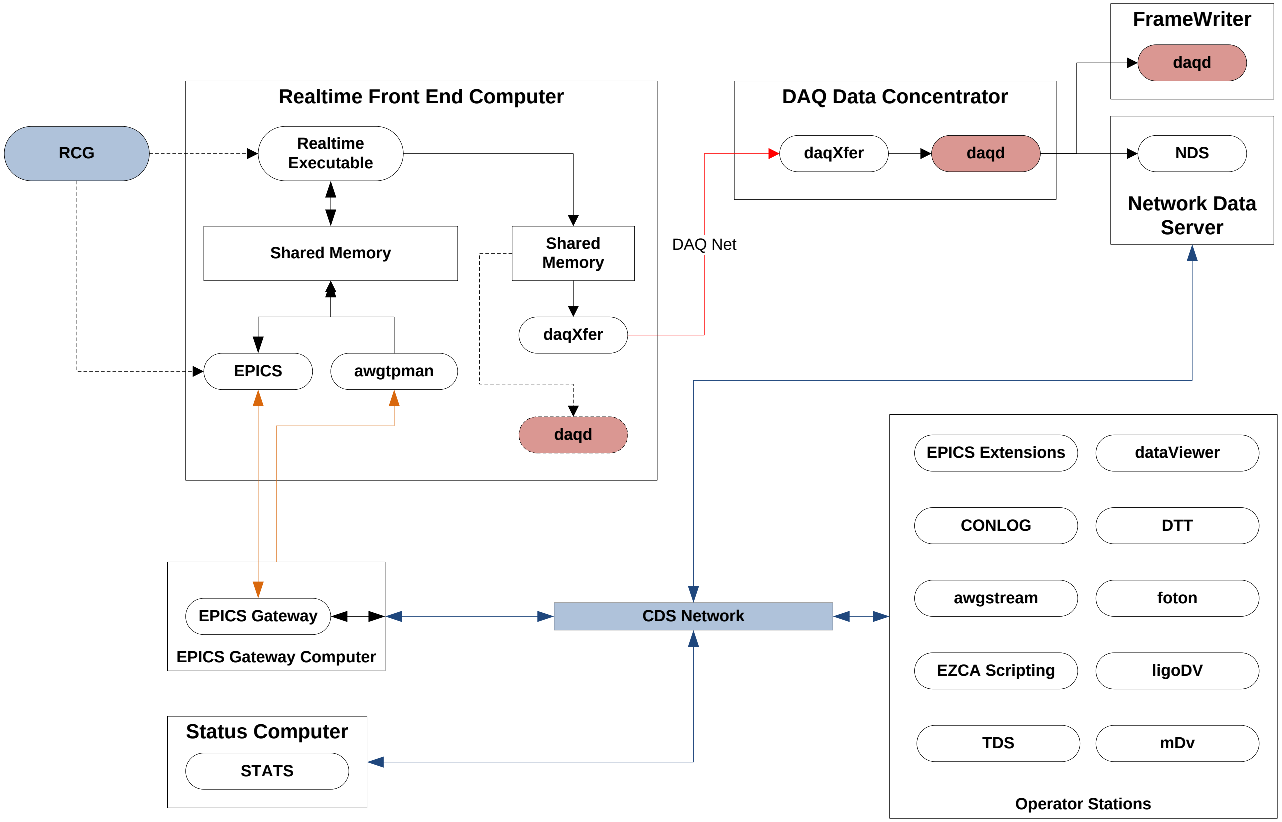
- Timing derived from GPS
- Front-End Computers
  - hard, real-time
  - Linux real-time OS
  - multi-core, server class
- Fiber-linked PCIe I/O bus with 18-bit ADC/DAC
- Servo loop rates up to 65 kHz
- Synchronous, deterministic operation to within a few microseconds



- *AdvLIGO CDS Design Overview, LIGO-T0900612*
- *New Control and Data Acquisition System in the AdvLIGO Project, LIGO-P1100052*

Control & Data System Software Architecture Overview

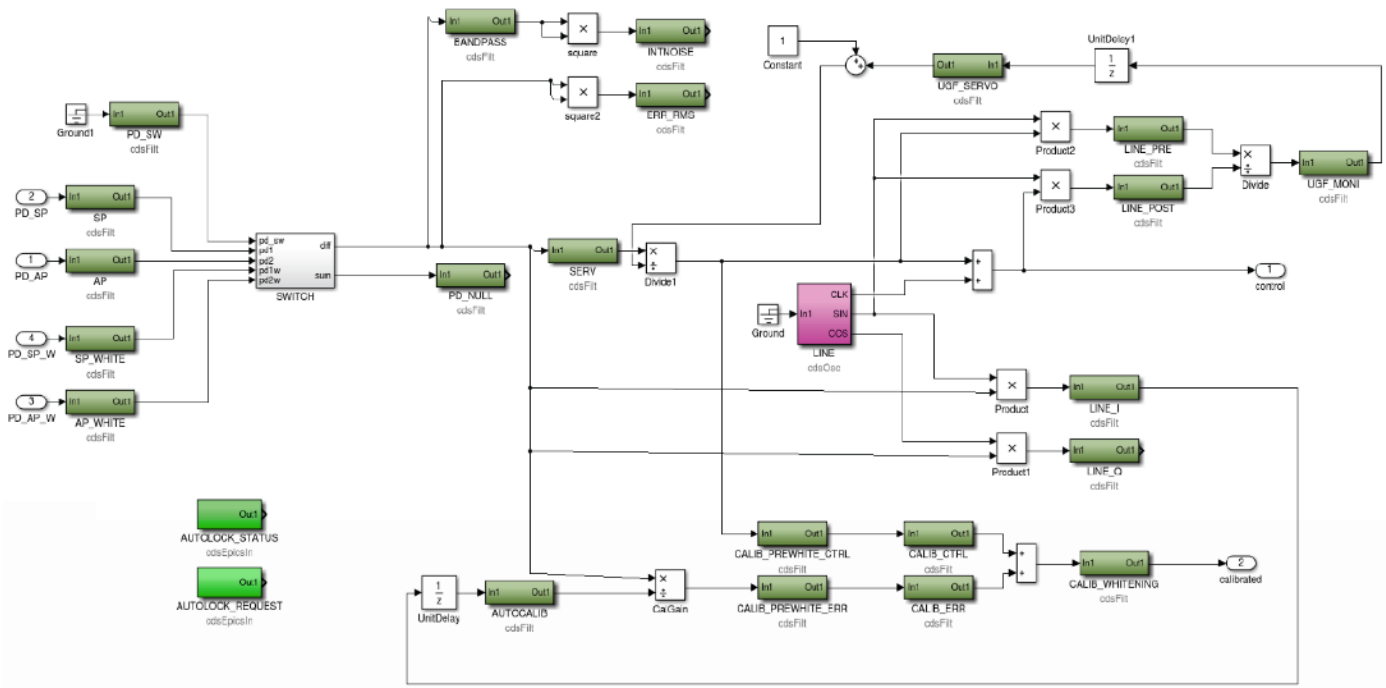
- **Real-Time Code Generator (RCG)**
  - Matlab Simulink graphical interface used to sketch control
- **EPICS**
  - Interface for setting parameters
- **Guardian**
  - State machine for sequencing



- *aLIGO, DAQ, Software Design Documentation, LIGO-T1000625*

Real-time digital control

- Matlab/Simulink used as a graphical interface to sketch control system using standard blocks
- Generates real-time code to run on linux front-end machine

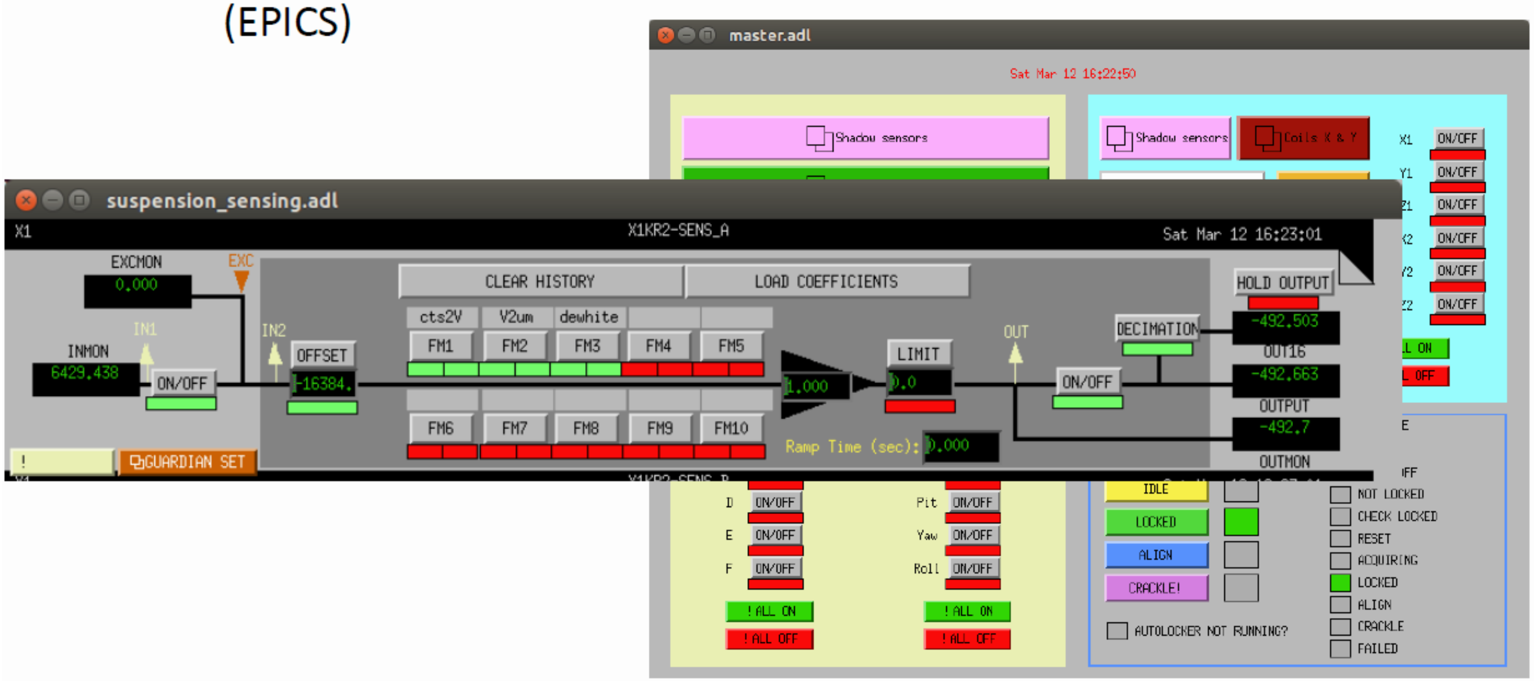


- *Real-time Code Generator (RCG) Software Component Overview, LIGO-T1200291*

Real-time digital control

- **Interface to the front-end, real-time "models" is via EPICS**
- **Change filters, gains, parameters**
- **Set Point Definition/Monitor software automates configuration control for the ~100k servo system parameters**

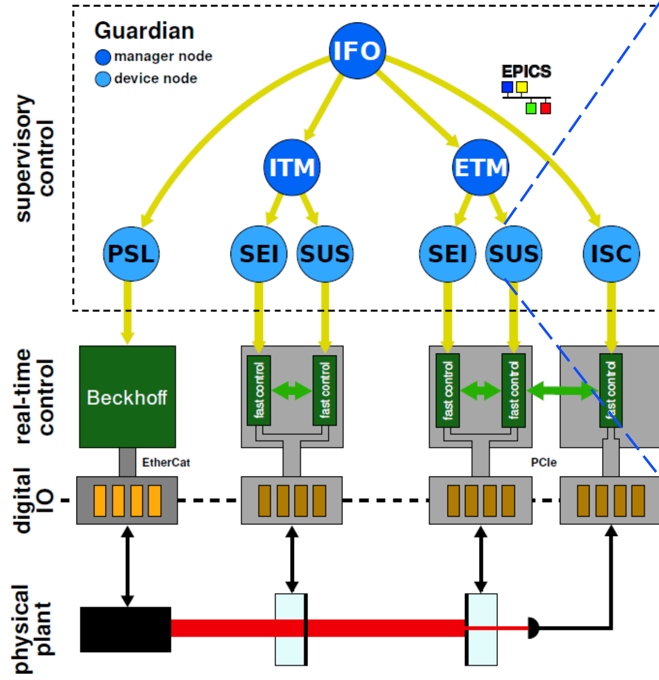
(EPICS)

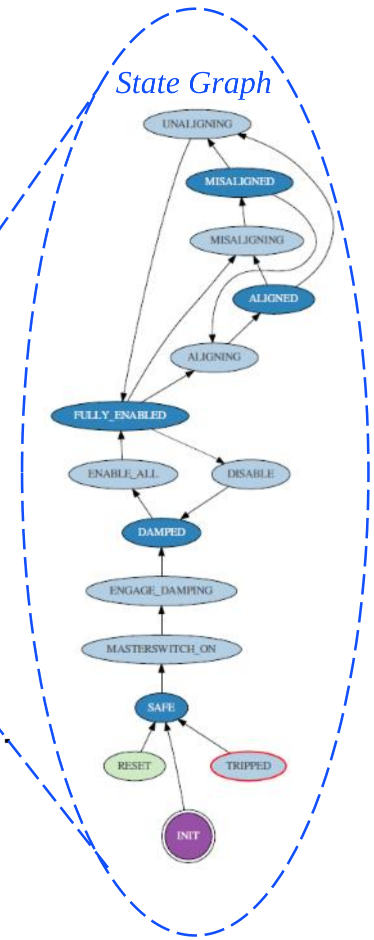


- *Real-Time Code Generator (RCG) SDF Software, LIGO-T1500115*

the Guardian

- Robust framework for automation of the interferometer & all subsystems
- Hierarchical, distributed, finite state machine
- Each node executes a state graph for its subsystem
- Supports commissioning & operation
- EPICS interface
- Python code
- Adopted & adapted by Virgo

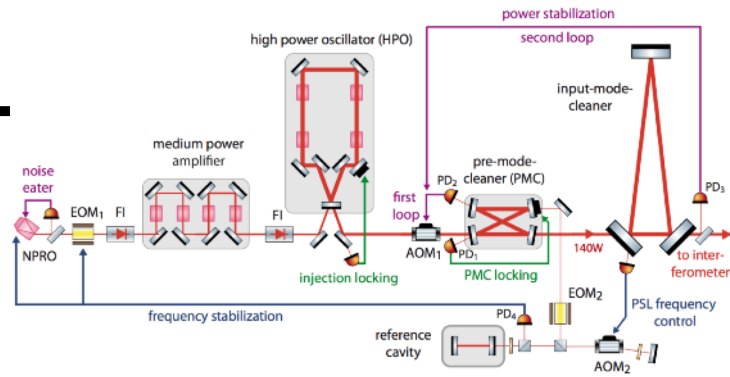




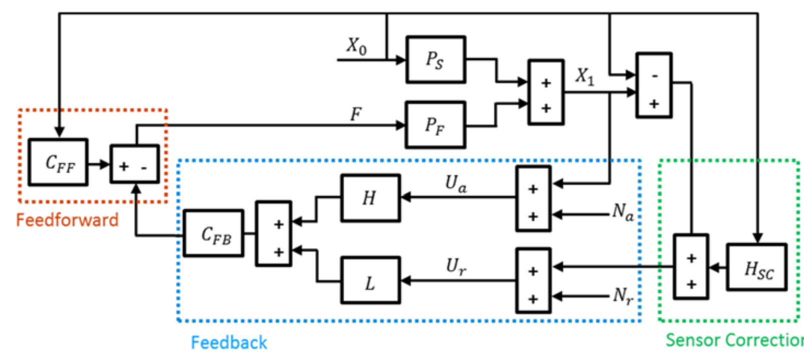
- *Advanced LIGO Guardian Documentation, [LIGO-T1500292]*
- *Distributed State Machine Supervision for Long-baseline Gravitational-wave Detectors with the Guardian Automation Platform, [LIGO-P1600066], [https://arxiv.org/abs/1604.01456], Rev. Sci. Instrum. 87 (2016) 094502*

The principal “Plants”

- **Pre-Stabilized Laser (PSL)**
  - **Frequency, pointing & intensity stabilization**
- **Seismic Isolation System (SEI)**
  - **Isolated platforms for optics**
  - **3 stages x 6 dof each = 18 dof**
  - **EM actuators inner stages**
  - **Hydraulic, actuator outer**
  - **Blended position & velocity sensing**
  - **MIMO, feed-forward and feedback control**
- **Suspensions (SUS)**
  - **Single, double, triple & quadruple pendulum suspensions**
  - **Quad Test Mass (TM) suspensions with reaction chain**
  - **2 x 4 x 6 = 48 degrees of freedom each TM SUS**
  - **Position sensors & EM actuators on upper stages**
  - **Electro-static actuation at TM stage**
  - **Damped at low frequency with rapid roll-off to prevent control loop noise injection in-band**
  - **SUS are length and angle actuators for global interferometer control**
- **Interferometer Sensing & Control (ISC)**
  - **Length**
  - **Angle**



Multi-stage frequency isolation. Initial frequency stabilization has 400 kHz BW (PZT, EOM, Crystal heating)

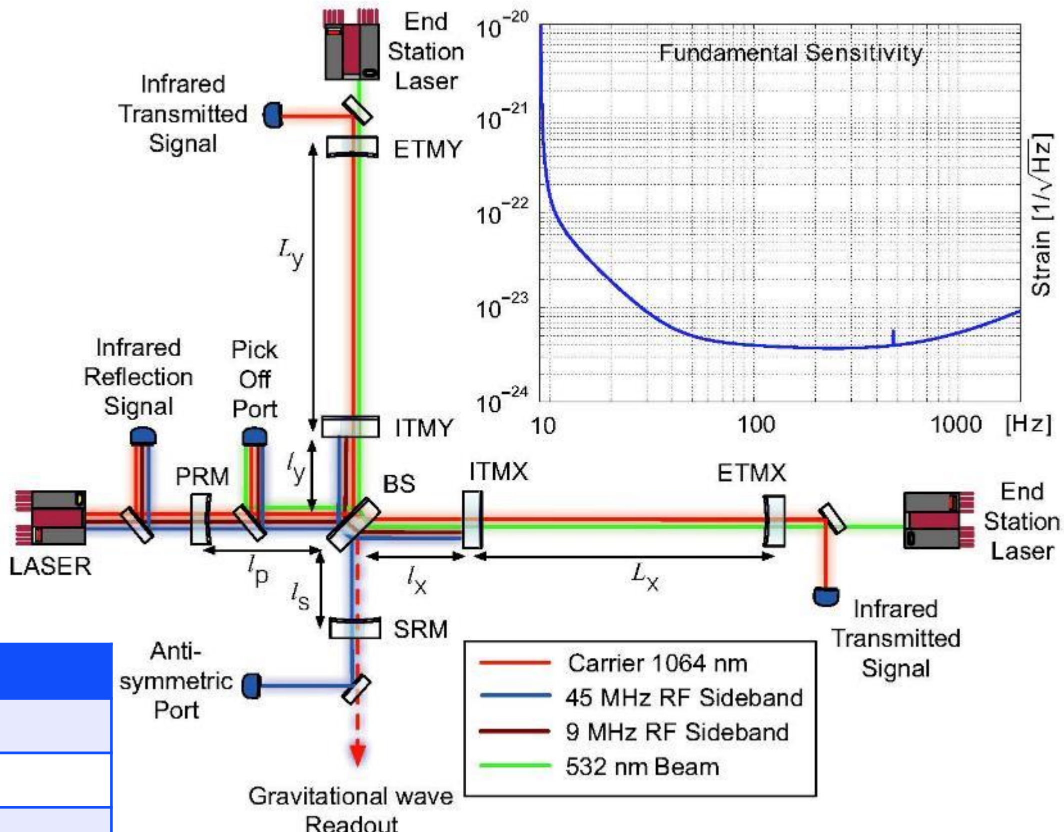


Control topology for each SEI dof.
(40 dB of isolation with bandwidths ~25 Hz, dof dependent)

- *Stabilized high-power laser system for the gravitational wave detector Advanced LIGO, LIGO-P1100192, Optics Express, Vol. 20 Issue 10, pp.10617-10634 (2012)*
- *Seismic Isolation of Advanced LIGO: Review of Strategy, Instrumentation, and Performance (CQG 2015), LIGO-P1200040, https://arxiv.org/abs/1502.06300*
- *Noise and Control Decoupling of Advanced LIGO Suspensions, LIGO-P1400085, 2015 Class. Quantum Grav. 32 015004 doi:10.1088/0264-9381/32/1/015004*

Interferometer *Length* *Sensing & Control*

- Nonlinear cavity lock acquisition control
- Length derived from RF demodulated signals
- Five resonant cavity lengths
- Arm Length Stabilization (ALS)
  - Acquire lock with lower finesse at doubled frequency (green wavelength) first

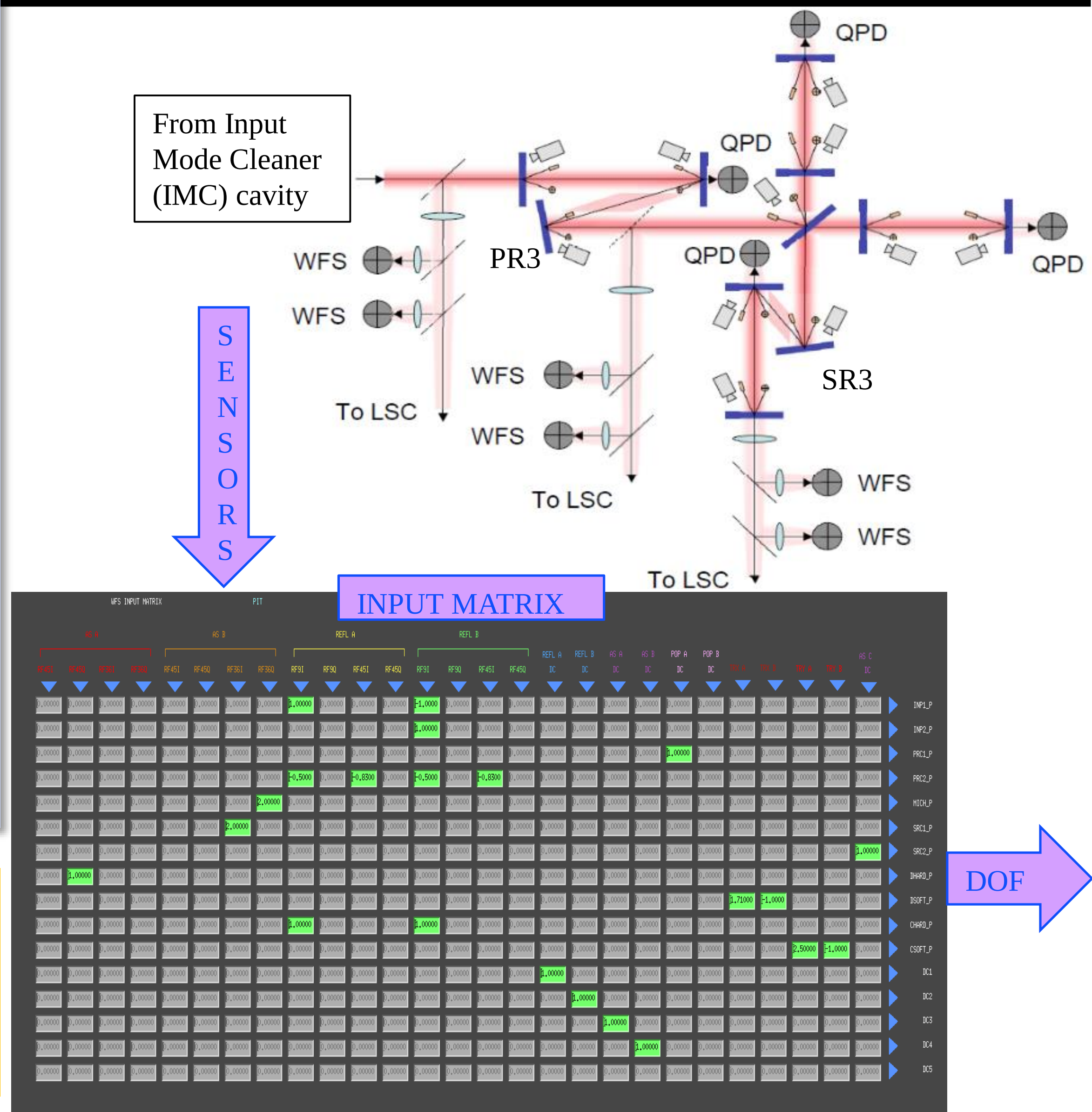


Mode	Definition
Common arm length (CARM)	(Lx+Ly)/2
Differential arm length (DARM)	Lx-Ly
Power recycling cavity length (PRC)	lp+(lx+ly)/2
Signal recycling cavity length (SRC)	ls+(lx+ly)/2
Michelson length (MICH)	lx-ly

- *Achieving Resonance in the aLIGO Interferometer, LIGO-P1400105, Class. Quantum Grav. 31 (2014) 245010*
- *CARM/ALS Electro-Optical Controls Diagram, LIGO-G1500456*

Interferometer Angle Sensing & Control

- Modulation sidebands:
  - 9 MHz mostly sees PRC
  - 45 MHz seeS PRC and SRC
- Quadrant Photo-Diodes (QPD)
  - Relative position → pitch & yaw
- Wavefront Sensors (WFS)
  - RF QPD yields In-Phase and Quadrature Phase pitch & yaw
  - Placed at different Gouy phases (near vs far field)
- 26 degrees-of-freedom
  - Input beam (pos + angle)
  - 11 optics form the PRC, SRC, FP arm cavities (yaw, pitch)
- 20 dof controlled
  - IMC pointing
  - SR3, PR3 are just damped
- Input & Output Matrices are used to project the sensing to the controlled dofs

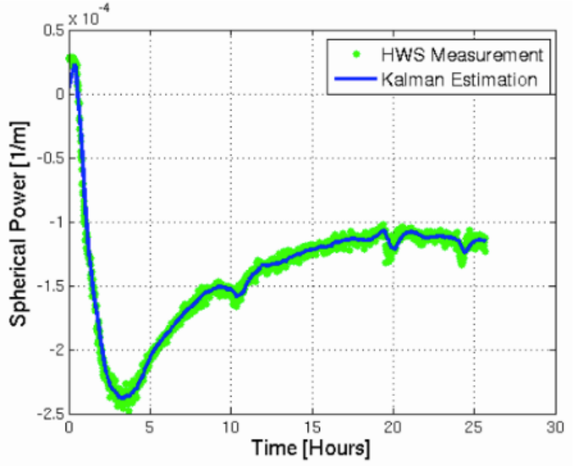


- *Alignment Sensing and Control in Adv. LIGO, LIGO-P0900258, Class. Quantum Grav. 27 (2010) 084026*
- *Advanced LIGO Angular Control System (ASC), LIGO-G1500923*

Auxiliary Loops

Many additional, essential loops, many of which are not completely independent of the global interferometer controls:

- **Earth tidal correction**
- **Output Mode Cleaner (OMC) alignment**
- **Wavefront Sensor (WFS) centering**
- **Input Mode Cleaner (IMC) alignment**
- **Arm Length Stabilization (ALS)**
- **Thermal Compensation System (TCS)**
- **Fiber "violin" mode damping loops**
- **…**

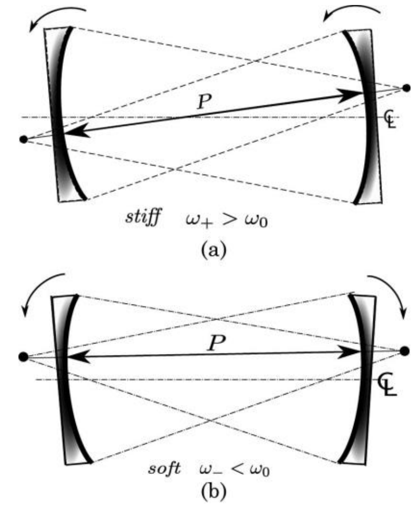


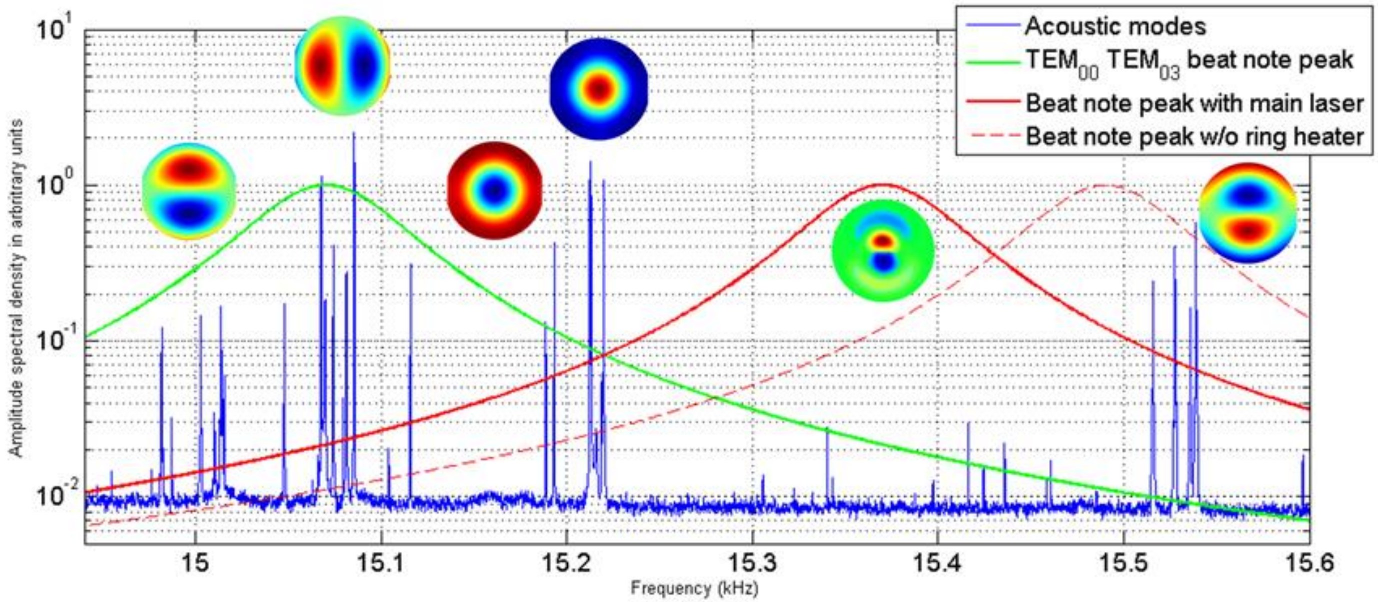
Wavefront sensor measurement and Kalman estimator

- *The Adv. LIGO Input Optics, LIGO-P1500076,* http://dx.doi.org/10.1063/1.4936974, *Rev Sci Instrum vol. 87 pg. 014502.*
- *Locking the Advanced LIGO Gravitational Wave Detector: with a focus on the Arm Length Stabilization Technique,* *LIGO-P1500273*, http://dx.doi.org/10.7916/D8X34WQ4
- *Kalman Filter for the Thermal Compensation System, LIGO-G1501532*

Interferometer Plant Changes with Optical Power

- "Stiff" and "Soft" modes
  - Radiation pressure in the Fabry-Perot arm cavities can result in instability
  - Control Hard modes with ETMs only at high bandwidth
  - Control Soft modes with ITMs only, at low bandwidth
- Parametric Instabilities
  - Overlap of high order optical modes & test mass acoustic modes
  - Shift off resonance with thermal tuning (ring heaters)
  - Damp with electro-static actuators
  - Research on passive, broadly tuned dampers

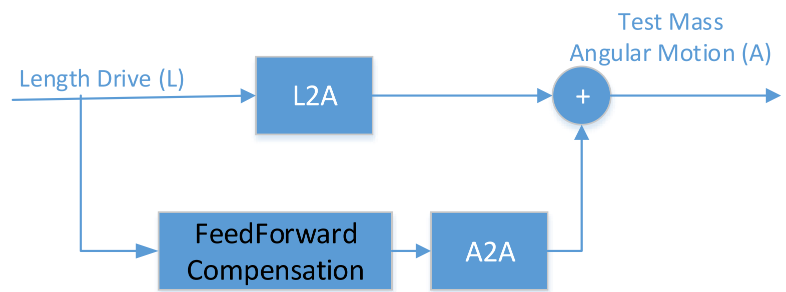


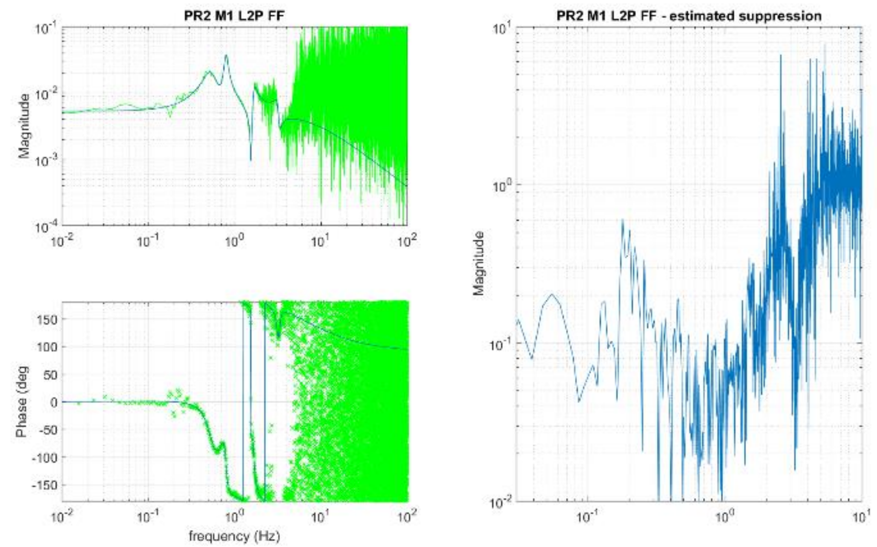


- *Angular instability due to radiation pressure in LIGO, LIGO-P0900086, https://arxiv.org/abs/0909.0010, Applied Optics, Vol. 49, No. 18*
- *First Demonstration of Electrostatic Damping of Parametric Instability at Adv. LIGO, LIGO-P1600090, https://arxiv.org/abs/1611.08997, Phys. Rev. Lett. 118, 151102 (2017)*

LSC Control Systems Working Group (CSWG[1]) Priorities/Focus Areas

- **Applications of Machine Learning (ML) to Controls**
  - **Lock Maintenance**
  - **Lock Acquisition[2]**
- **Length to Angle (L2A) decoupling**
- **Feedback optimization (esp. applied to angular controls)**
- **System Identification**
- **Interferometer robust configuration for earthquakes[3]**
- **State space control for the Real-Time Code Generator (RCG) Software**
- ***More generally, we are working to inject more modern control techniques to improve performance & robustness***





1) *CSWG wiki page: https://wiki.ligo.org/viewauth/CSWG/WebHome*
2) *LSC-Virgo August 2017 Meeting @CERN, Deep leaning applied to lock acquisition, LIGO-G1701589*
3) *LSC-Virgo August 2017 Meeting @CERN, Earthquake early warning & response, LIGO-G1701593*