Advanced Interferometer Sensing & Control (ISC)

- Responsible for the GW sensing and overall control systems
- Addition of signal recycling mirror increases complexity
  - Permits 'tuning' of response to optimize for noise and astrophysical source characteristics
  - Requires additional sensing and control for length and alignment
- Shift to 'DC readout'
  - Rather than RF mod/demod scheme, shift interferometer slightly away from dark fringe; relaxes laser requirements, needs photodiode develop
- Requires both proof-of-principle and precision testing (40m)
- Schedule Highlights:
  - 2Q01: Design Requirements Review
  - 2Q02: Tabletop DC readout test results
  - 2Q03: GEO 10m prototype test results/review
  - 4Q03: Final design complete

Advanced Interferometer Sensing & Control (ISC)

- Subsystem Scope:
  - optoelectronic sensors*
  - signal conditioning electronics *
  - servo-control electronics (analog & digital) *
  - control topology & laws *
  - locking algorithm
  - interferometer supervisory controls
  - interferometer system diagnostics
  - calibrated strain readout signal

* except local PSL loops

Advanced Interferometer Sensing & Control (ISC)

- Research Scope:
  - low noise ADC & DAC research
  - segmented, high frequency RF, wavefront sensor
  - high frequency, low noise RF photodiodes
  - DSP investigation (to allow more computation-intensive filter techniques and enhance control robustness and timing margins)
  - Control law/topology design
  - Controls and electronics testing (definition & assist to GEO 10m & LIGO 40m experiments)
  - Simulation extensions & modeling

Advanced Interferometer Sensing & Control (ISC)

- Signal- & power-recycled interferometer has 8 independent optical path lengths, one identical to re-scaling the wavelength
- independent and significant alignment degrees of freedom:
  - 12 angular & 2 centering dof for the core optics
  - 2 angular & 2 centering dof for the input mode cleaner
  - 2 angular dof for the input mode cleaner
- 28 'global' degrees of freedom

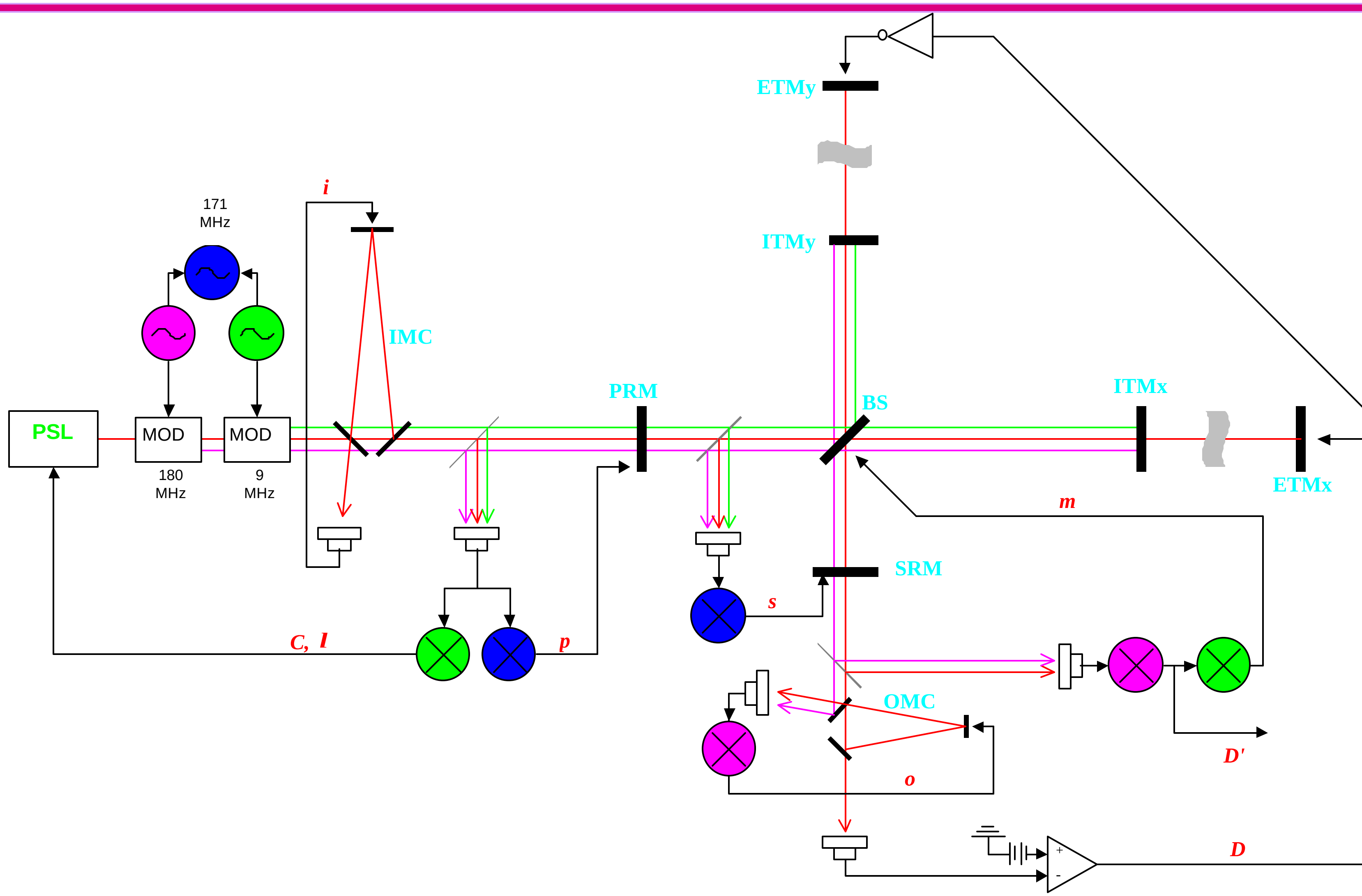
Symbol	*was*	*Description*	*Definition*
D	L_-	*Arm cavity differential (a strain)*	*(ETMx-ITMx) - (ETMy-ITMy)*
C	L_+	*Arm cavity common mode*	*(ETMx-ITMx)/2 + (ETMy-ITMy)/2*
m	l_-	*Michelson differential*	*(ITMx-PRM) - (ITMy-PRM)*
p	l_+	*Michelson common mode*	*(ITMx-PRM)/2 + (ITMy-PRM)/2*
s	~	*Signal recycling cavity length*	*(ITMx-SRM)/2 + (ITMy-SRM)/2*
l	***l***	*Laser wavelength*	
i	l_{MC}	*Input mode cleaner length*	
o	~	*Output mode cleaner length*	

Advanced Interferometer Sensing & Control (ISC)

- Schnupp asymmetry/frontal modulation method (used in initial LIGO) is extended by adding a second set of resonant sidebands
- The three auxiliary cavity lengths *p*, *m* and *s* are measured with minimal interaction from the arms, by looking at beat notes between the two sideband systems:
  - directly at the difference frequency, in the reflected port
  - by double demodulation, at the antisymmetric port
- The arm cavity mean length ***C*** is readily derived from interference of the 9 MHz sidebands with the returning carrier at the reflected port
- 'DC readout' of the gravitational wave signal *D*, rather than the traditional RF homodyne detection
- robust separation is achieved between the internal coordinates

Port	*Frequency*	***C***	***D***	***p***	***m***	***s***
Reflection	171 MHz	-0.4	0	**80**	-1	40
PRC Sample	171 MHz	-2	0	72	-63	**960**
Antisymmetric	171 MHz	0	0	0.1	**-1**	**1.95**
Antisymmetric	189 MHz	0	0	-0.3	**-1**	**-1.95**

Servo Controls



Advanced Interferometer Sensing & Control (ISC)

- preliminary modeling:
  - with the planned advanced SEI & SUS attenuation
  - damping and control of the auxiliary ***p***, ***m*** and ***s*** lengths (< 10^{-10} m RMS, adequate to reject optical noise effects) requires only ~1 Hz unity-gain loop bandwidths
- allows a full frequency decade below the noise-critical sensing band for aggressive signal filtering
- If actuation for auxiliary lengths are applied to the BS, PRM & SRM, contamination of the gravitational wave readout ***D*** will be minimal:
  - Noise figures in the range of 10^{-14} m/Hz$^{1/2}$, some million times noisier than the strain readout, could be tolerated
  - depends, on the development of adequate low-noise (e.g., passive eddy-current) damping for the suspension eigenmodes of the cavity mirrors to obviate the need for interferometric damping feedback.

Servo-Controls Research Tasks

- advanced SEI & SUS systems will have radically different controller interfaces
  - actuation to upper stages which are separated from the mirror position (readout variable) by complex mechanical transfer functions
  - anticipate significant work required to define pre- and post-conversion signal processing for each of these stages, with the goal of building a composite virtual "super actuator" for each degree of freedom
  - controllability issues may play a strong role in the suspension actuator selection
- Software tools for control algorithm construction & maintenance:
  - initial LIGO control loop software is implemented in compiled C code
  - successful and efficient, but cumbersome to adapt to new purposes and depends on a high degree of programming expertise
  - intend to preserve our substantial investment in the EPICS/VxWORKS architecture
  - propose to develop dynamic libraries, programming tools and user interface layers for our existing realtime operating systems and application environments

Servo-Controls Research Tasks (continued)

- Modeling & Analysis: extend to signal recycled configuration
  - MELODY
  - FFT Propagation Code
  - Modal Model
  - Matlab IFO Control Model
  - End-to-End (E2E)
  - validate models with 10m and 40m experiment results
- Servo-control topology and control law development
  - robust control approach, with initial LIGO experience in modeling uncertainties and plant & disturbance variability
  - define control laws & deliver code to 40m experiment

Advanced Controls & System Identification (SID)

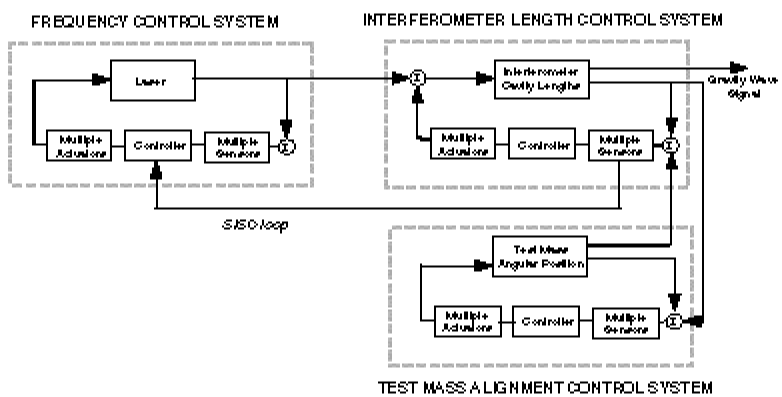
- Programmatic Scope:
  - Integrated with the ISC design effort
  - Initial LIGO
  - Advanced LIGO
  - interfaces with existing infrastructure
- Technical Scope:
  - Robust modern control approach
  - Optimal controls approach
  - System identification
  - Adaptive control

Advanced Controls & SID Motivation

- Challenging LIGO detector availability goals:
  - Single interferometer operations > 90% of the time with 40 hr. min. continuous lock periods
  - Double coincidences > 85% time and triple coincidences > 75% time with 100 hr. min. continuous lock periods
- 40 m prototype experience:
  - 40m prototype lock durations vary from seconds to a few hours
  - Control system instabilities caused by drifts in the interferometer system parameters
  - Displacement noise events which kick the interferometer out of lock
- Initial LIGO experience:
  - Lock durations currently limited by tidal drift to ~hours; with tidal actuation may be limited to a few days between earthquakes that knock cavities out of lock
  - Too early to tell if alignment or parameter drift is a serious problem or not; system is ‘maturing’ and becoming (or perceived as?) more stable with time

Advanced Controls & SID

- LIGO has frequency, length and alignment servo-control loops
  - The optical model for the core optics length control system is a 4x4 matrix of transfer functions
- The interferometer optical alignment model is a 10x10 matrix of transfer functions whose elements have a similar form

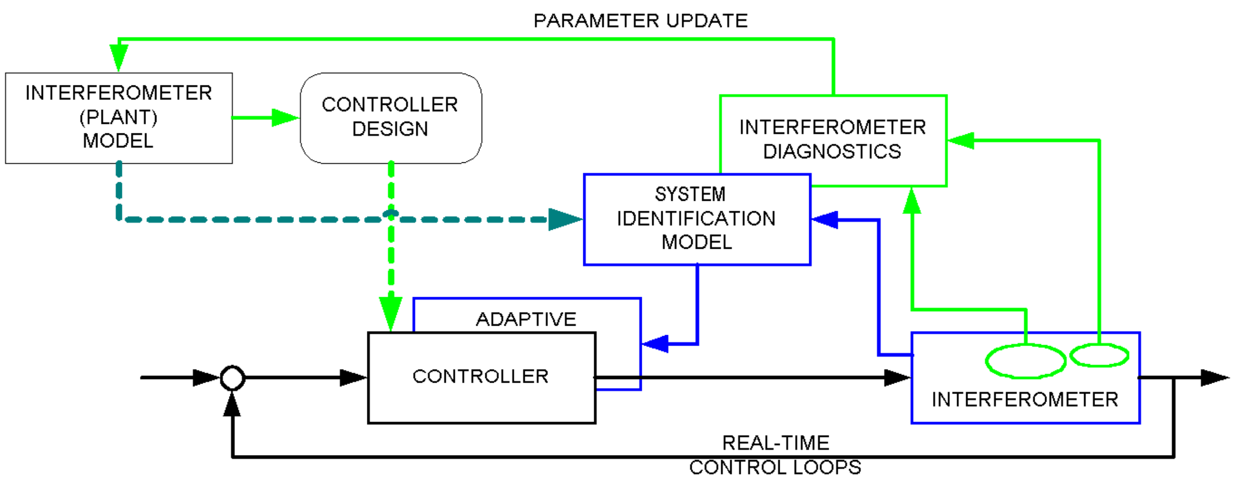


Advanced Controls & SID

- Potential hardware imperfections, model errors, unknowns or parameters subject to drift which could effect control system robustness include:
  - Beamsplitter reflectivity $\neq$ 50%
  - Mixer phase error
  - Deviations from resonance
  - Visibility variation
  - Fabry-Perot cavity input and end test mass absorption (resulting in radius of curvature changes)
  - Sensor & actuator cross-talk (optical, mechanical & electrical)
  - Alignment/length Coupling
  - Modulation depth & phase variation
  - etc.

Strategy

- System identification will be used in conjunction with subsystem diagnostic and measurement techniques to update our understanding of the system and its control
- Once the system susceptibilities are understood, an adaptive controller can be formulated to compensate
- SID and Adaptive Control are mature technologies; The application to Interferometry is unique

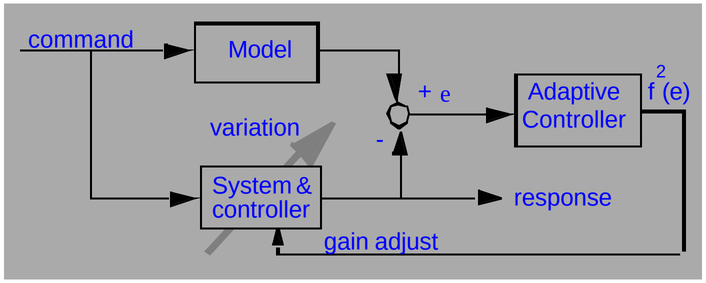


System Identification

- System Identification (SID) is an empirical approach to modeling interferometer system dynamics
  - Non-parametric identification (i.e. frequency response estimation)
  - Parametric system models (e.g. state space representation)
- For LIGO we seek a recursive, real-time parameter identification of the multi-input/multi-output optical response of the interferometer in Detection Mode
- Many techniques are available and will be explored; Potential candidates include:
  - Generalized Least Squares and Maximum Likelihood Estimators (e.g. the Prediction Error Method) are computationally simple
  - Observer/Kalman Filter Identification (OKID) -- time domain based, can be extended to identification of closed loop effective controller/observer combination (Observer Controller Identification, OCID)
  - State-Space Frequency Domain (SSFD) identification -- frequency domain based (can use spectrum analyzers)

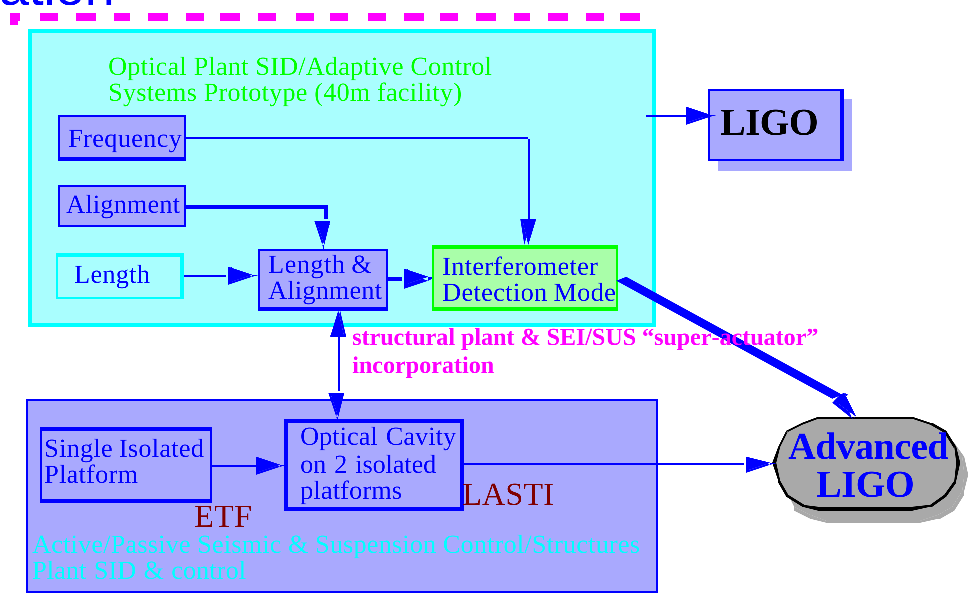
Adaptive Control

- Adaptive Control can improve sensitivity while maintaining robustness to
  disturbances and plant variations
- Adaptive control time scales:
  - milliseconds for the ordinary feedback
  - many minutes for updating the control parameters and performing SID
- Possible adaptive control algorithm: Model Reference Adaptive Control



Collaborators & Responsibilities

- Stanford Univ. plans to explore system identification and adaptive control on advanced seismic isolation and suspension subsystems
- LIGO will concentrate on identification and control (length, alignment and frequency) of the optical plant for a power recycled configuration
- GEO plans to explore adaptive control for autonomous and tele-remote operation



Advanced Controls & SID

- Schedule Highlights
  - 4Q02: System identification for the initial LIGO detector
  - 4Q03: Adaptive control for the initial LIGO detector
  - 1Q04: Application to 40m configuration testbed
  - 2Q05: System identification for the advanced LIGO configuration

Advanced Interferometer Systems, Sensing & Control (ISC, 40m, SID, SYS)

FY02

	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)		
Advanced Interferometer Systems, Sensing & Control (ISC)						
Sci & PD	MIT	0	0			6.87
	CIT	2	0	3.2	5.2	
UG & Grads	MIT	1	0	1	2	5
	CIT	3	0	0	3	
Eng & Techs	MIT	0	0	0.75	0.75	10.23
	CIT	0	0	9.48	9.48	
Totals (FTE):		6	0	16.1	**22.1**	
Equip. & Supplies ($K)		$275	$0	$0	**$275**	

N.B.: Does not include LSC research staff.