The LIGO End-to-End Simulation Program

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- End to End simulation
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  - » Physics
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- Past
  - » Lock acquisition
- Present
  - » Noise simulation
- Future
  - » Advanced LIGO

For the E2E team:

- Scientists
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  - » Matt Evans
  - » Virginio Sannibale 1/3
- Programmers
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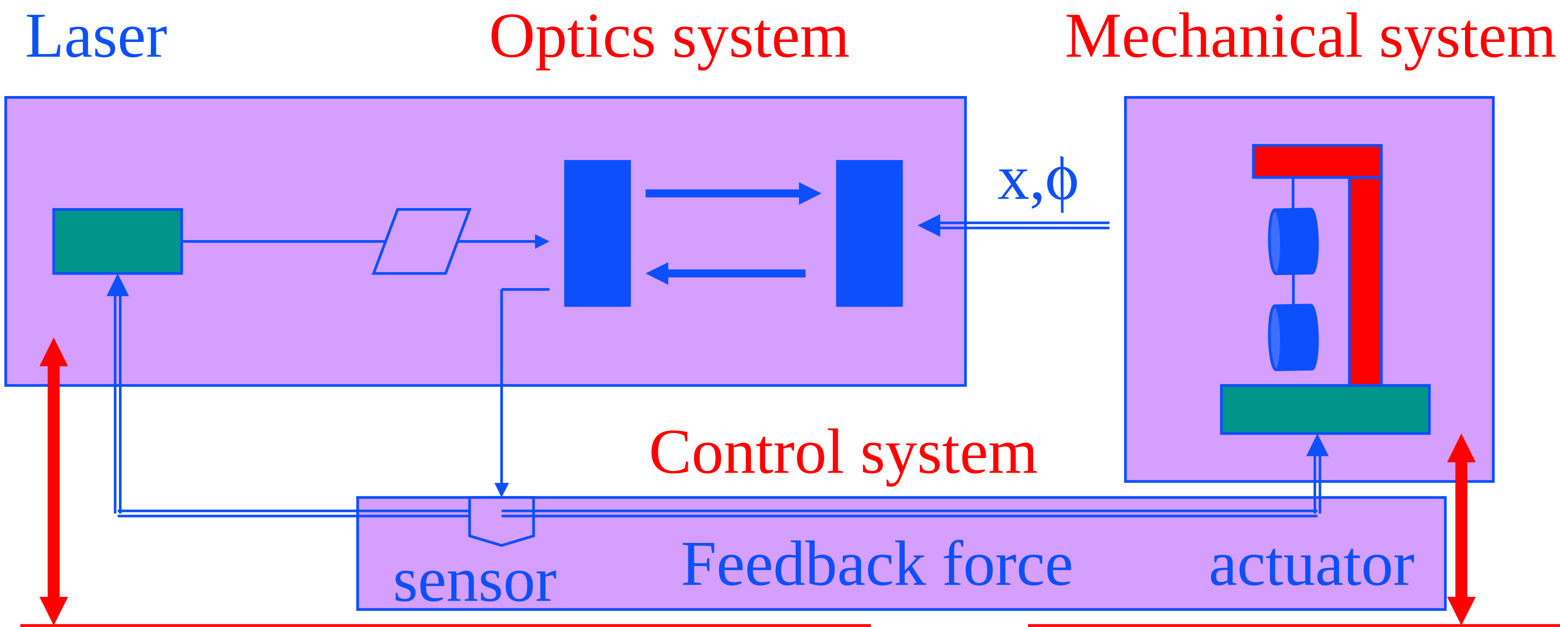
End-to-End Model Overview

- A general simulation framework for time-domain simulation studies of optical, mechanical and electronic components and their interaction in interferometer-based GW detectors
- General tool-box like Matlab or Mathematica
- Precedence: SIESTA (VIRGO)
- LIGO I simulation package:
- Han2k: used for the lock-acquisition design
- SimLIGO: To assist LIGO I commissioning

- Modularity & Flexibility
- You can study any configuration
- You can look at field at any port and analyze
- You, as user, donot need to know C++ or even programming or to touch the original code
- You, as developer, can introduce new physics modules easily without touching the rest of the code but utilizing full advantage of that.

End to End Simulation
coarse view



- Time domain modal model
- Objects : laser, mirror, photo diode, …
- Any planar interferometer
    - Fabry-Perot, Mode cleaner,LIGO I,
    - Advanced LIGO,…

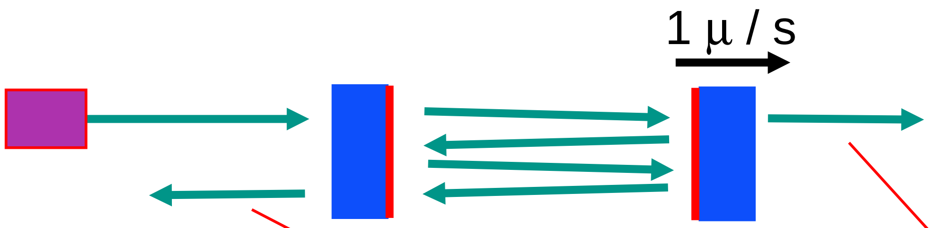
- Transfer function using Digital filter
- Single Suspended mirror
- Mechanical Simulation Engine (object-oriented)

LIGO End to End Simulation

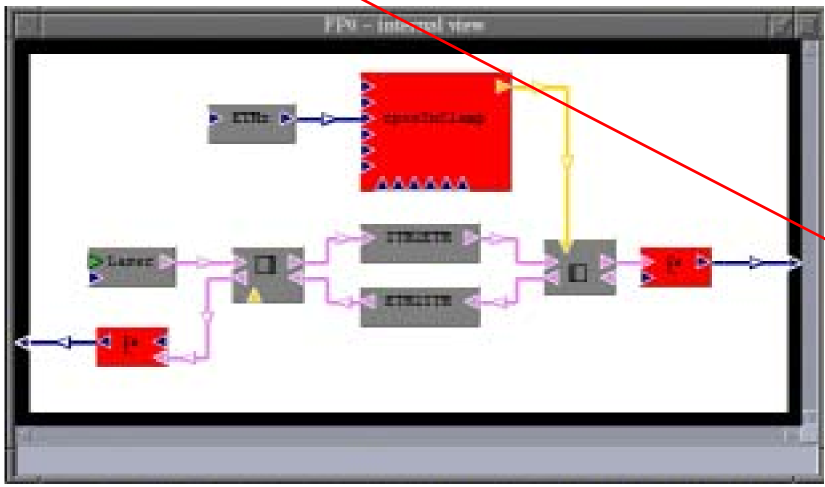
the motivation

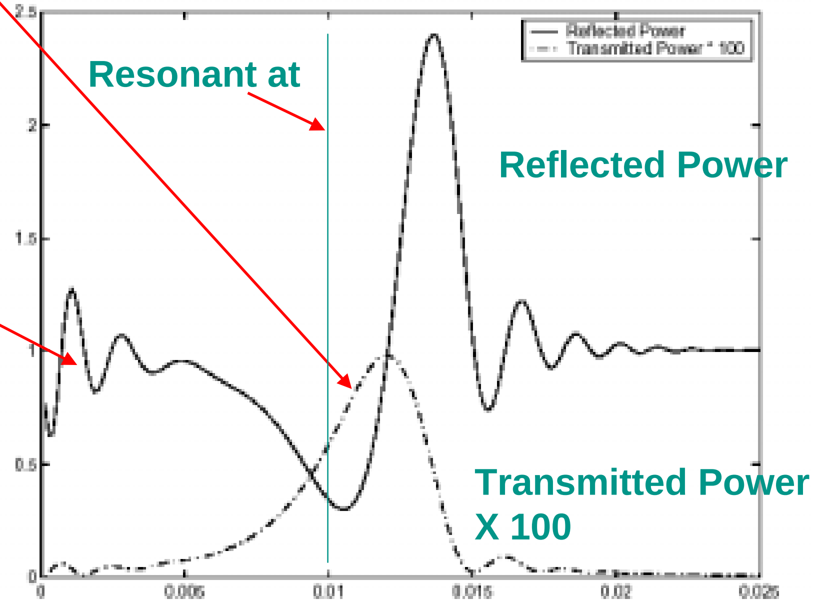
- Assist detector design, commissioning, and data analysis
- To understand a complex system
  - » complex hardware : pre-stabilized laser, input optics, core optics, seismic isolation system on moving ground, suspension, sensors and actuators
  - » field : non-Gaussian field propagation through non perfect mirrors and lenses, misalignment and modal mismatch ..
  - » feedback loops : length and alignment controls, feedback to laser
  - » non-linearity : cavity dynamics to actuators
  - » coupling : alignment and longitudinal, frequency and motion, between arms
  - » noise : mechanical, thermal, sensor, field-induced, laser, etc : amplitude and frequency : creation, coupling and propagation
  - » wide dynamic range : $10^{-6} \sim 10^{-20}$ m

e2e example - 1
Fabry-Perot cavity dynamics



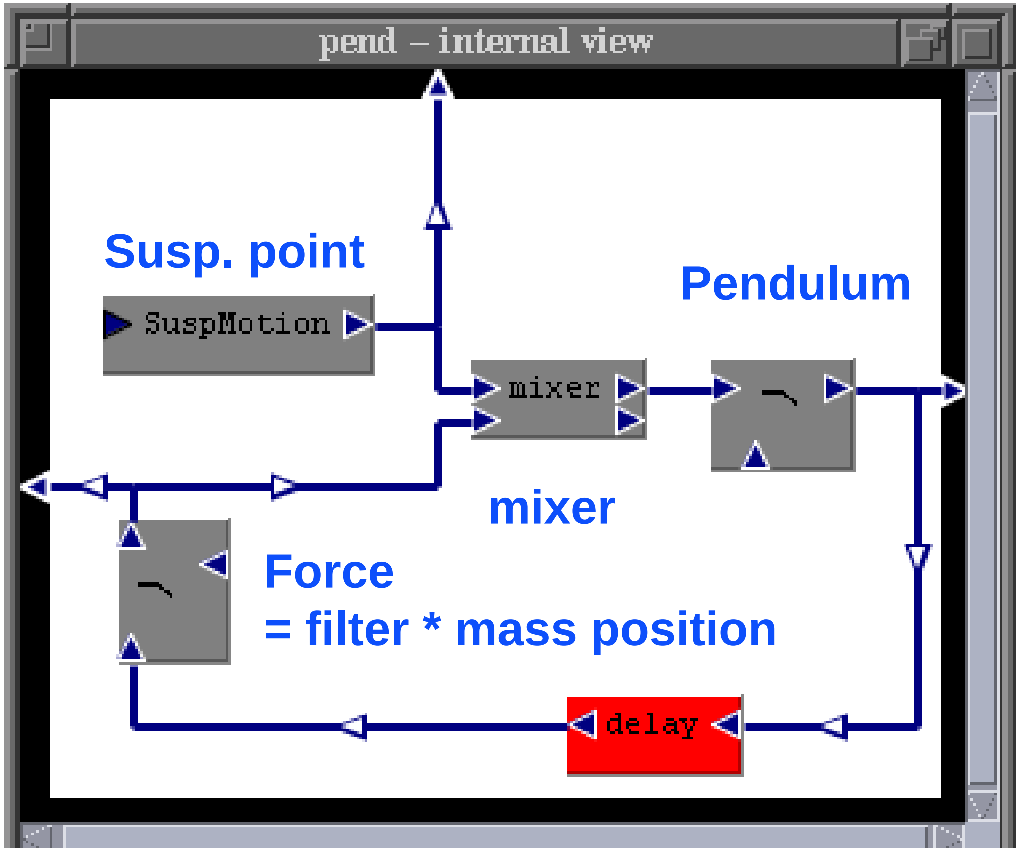
ETMz = $-10^{-8} + 10^{-6}$ t



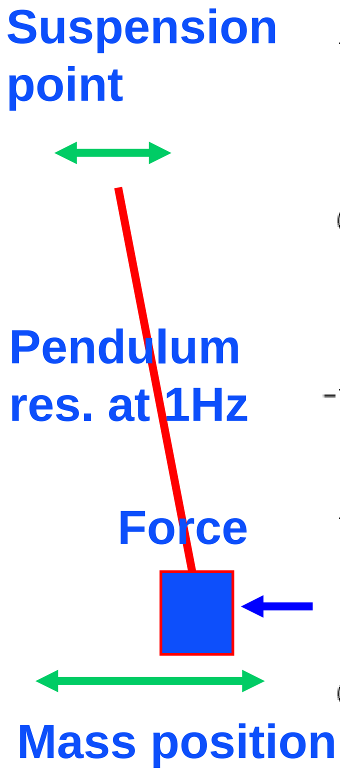


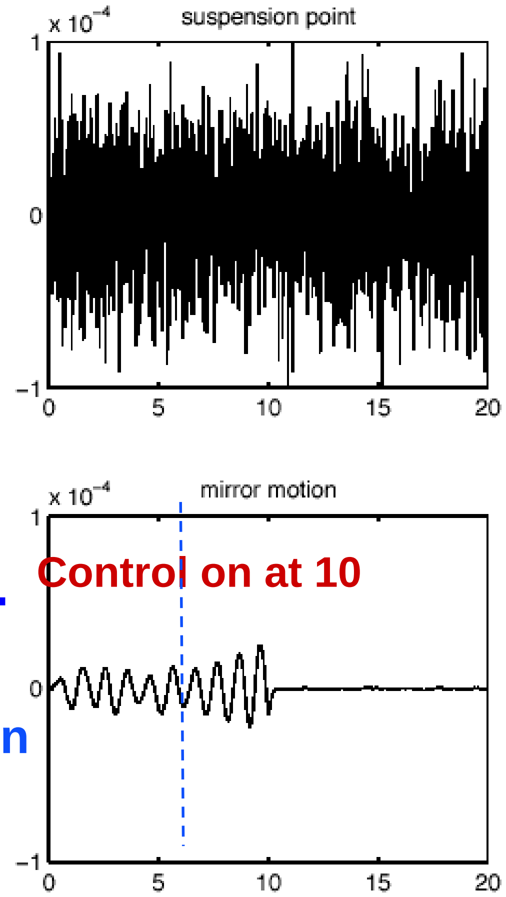
Power = 1 W, T_{ITM}=0.03, T_{ETM}=100ppm, L_{cavity} = 4000m

e2e example - 2
Suspended mass with control



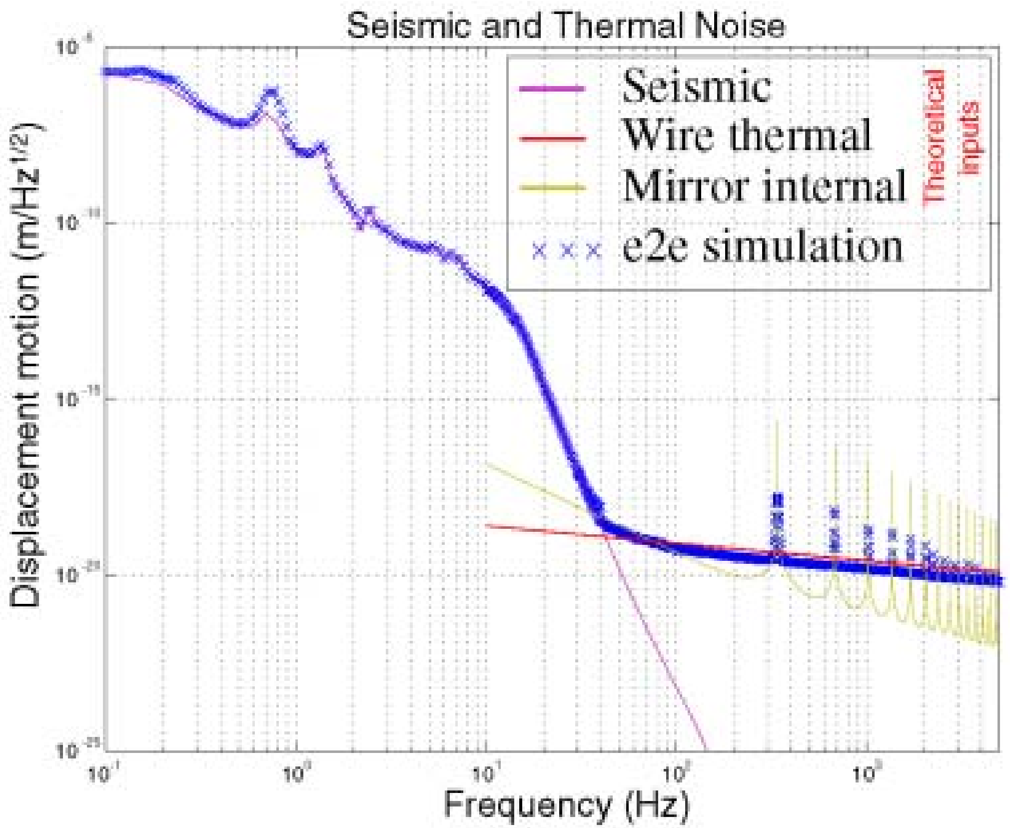
$$Z_{mass} = \frac{F/m + \omega^2\, dz}{S^2 + a\,S + \omega^2}$$

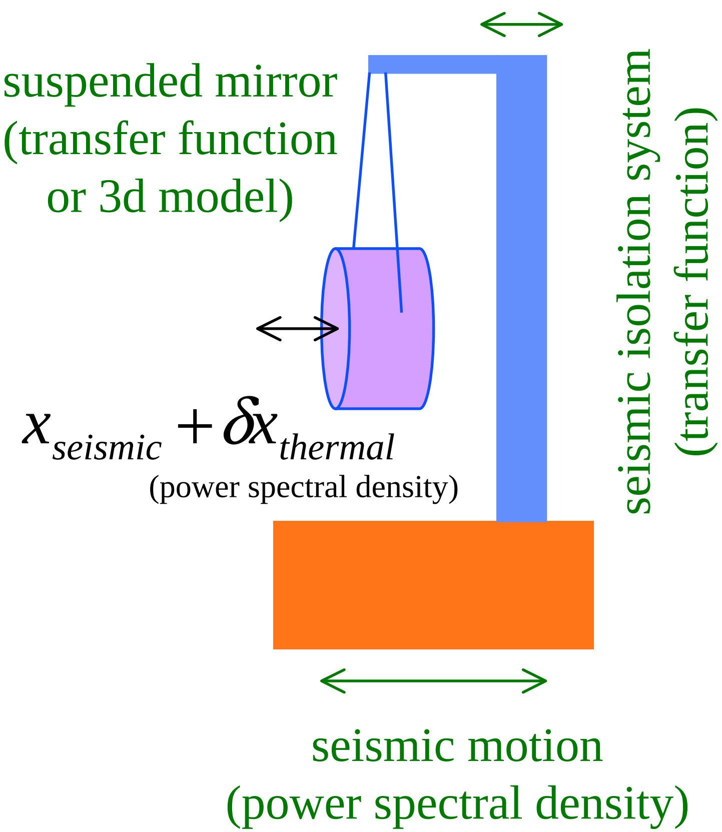




Mechanical noise of one mirror

seismic & thermal noises

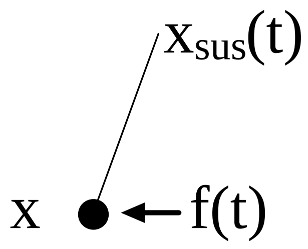




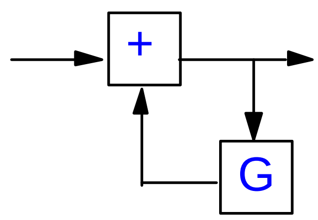
e2e physics
Time domain simulation

- Analog process is simulated by a discretized process with a very small time step (10^{-7}~ 10^{-3} s)
- Linear system response is handled using digital filter
  - » Transfer function -> digital filter
  - » Pendulum motion
  - » Analog electronics

$$x = \frac{1}{s^2 + \gamma s + \omega_0^2}\left(\frac{f}{m} + \omega_0^2 x_{sus}\right)$$

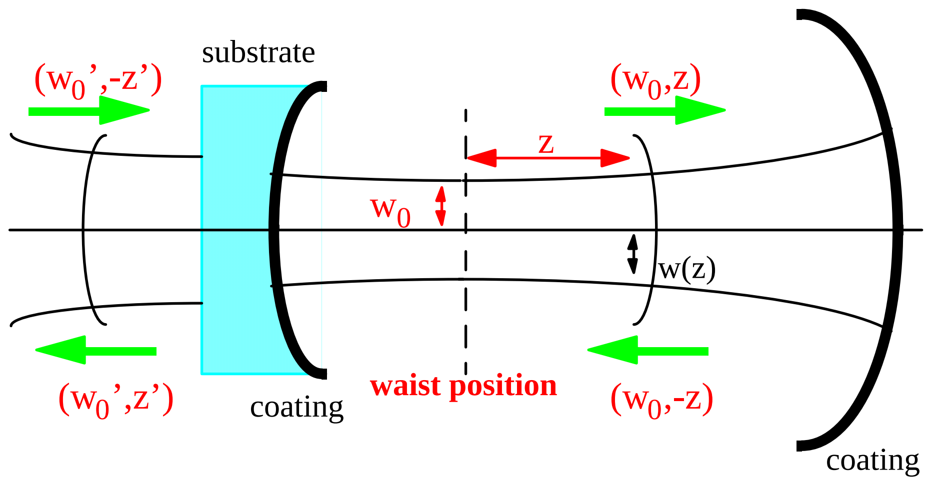


- Easy to include non linear effect
  - » Saturation, e.g.
- A loop should have a delay
  - » Need to put explicit delay when needed
  - » Need to choose small enough time step



e2e physics
Fields and optics

- Time domain modal model
  - field is expanded using Hermite-Gaussian eigen states
  - number of modes (n+m) <=4 for now, no limit SOON
- Reflection matrix
  - tilt
  - vertical shift
  - curvature mismatch
- Completely modular
  - Arbitrary planar optics configuration can be constructed by combining mirrors and propagators



- Photo diodes with arbitrary shapes can be attached anywhere
- Adiabatic calculation for short cavities for faster simulation

Sensing noise
Shot noise for an arbitrary input

Average number of photons

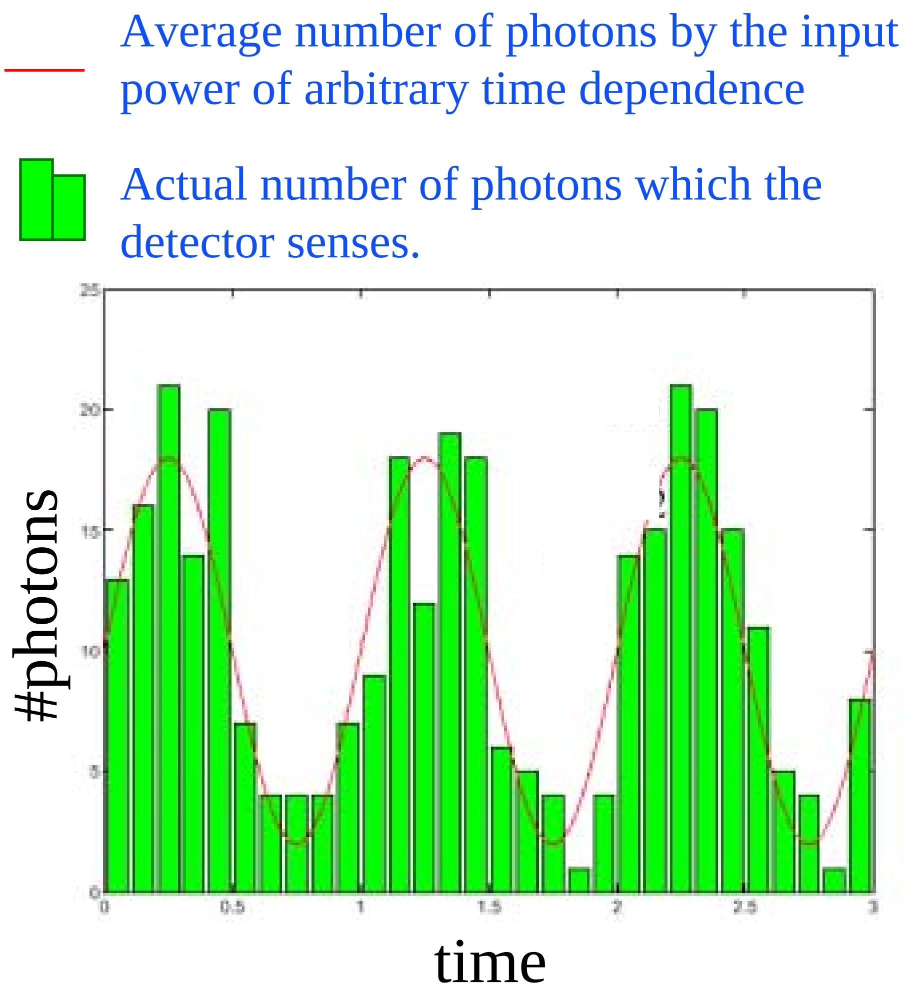
$$n_0(t) = \frac{\eta \cdot P(t) \cdot \Delta t}{h \cdot \nu}$$

Actual integer number of photons

$$n(t) = Poisson(n_0(t))$$

Simulation option

Shot noise can be turned on or off for each photo diode separately.



First LIGO simulation
Han2k

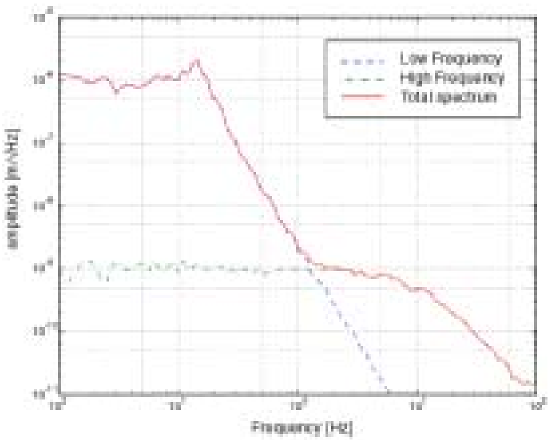
- Matt Evans Thesis
- Purpose
  - » design and develop the LHO 2k IFO locking servo
  - » simulate the major characteristics of length degree of freedom under 20 Hz.
- Simulation includes
  - » Scalar field approximation
  - » Only longitudinal DOF in each mirror
  - » saturation of actuators
  - » Simplified seismic motion and correlation
  - » Analog LSC (Length Sensing Control), no Alignment SC
  - » no frequency noise, no shot noise, no sensor/actuator/electronic noise

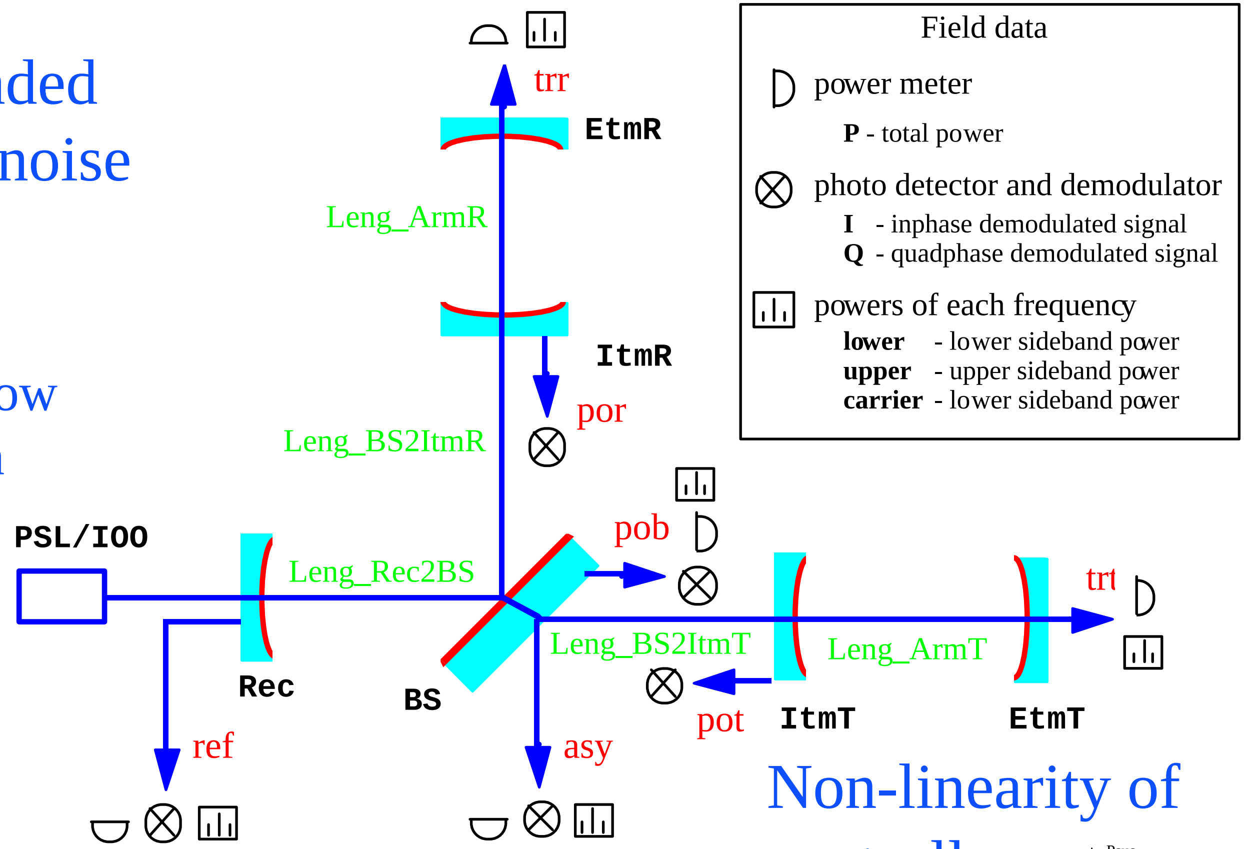
Hanford 2k simulation setup

6 independent suspended mirrors with seismic noise

corner station :

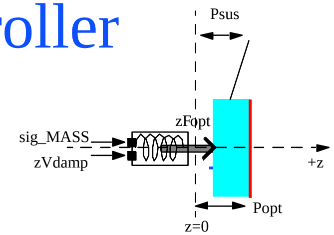
strong correlation in the low frequency seismic motion





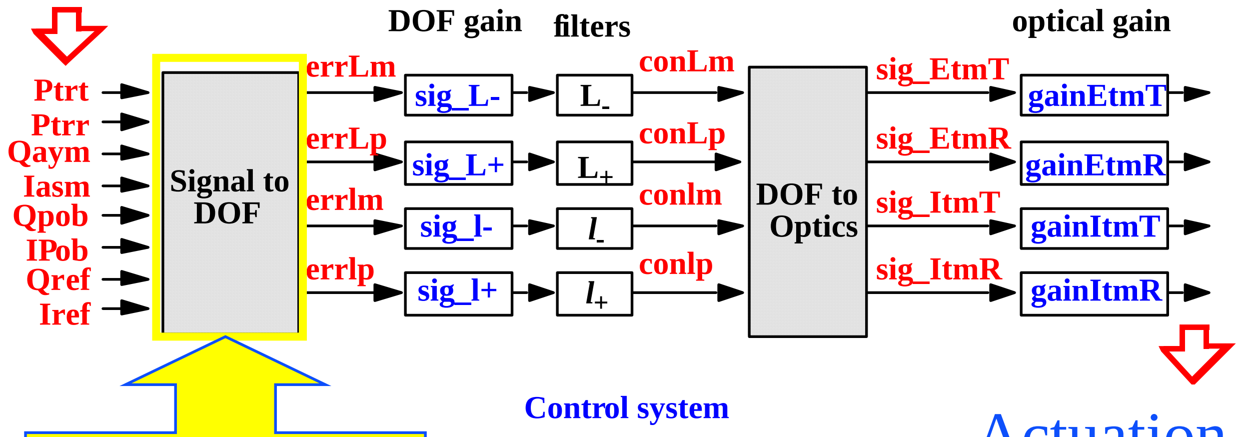
Han2k optics setup

Non-linearity of controller



Automated Control Matrix System

Field signal

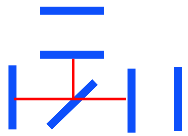


Same c code used in LIGO servo and in simulation

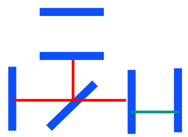
Actuation of mass

Multi step locking

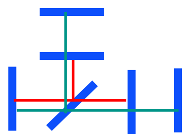
State 1 : Nothing is controlled. This is the starting point for lock acquisition.



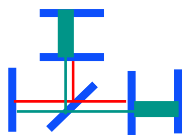
State 2 : The power recycling cavity is held on a carrier anti-resonance. In this state the sidebands resonate in the recycling cavity.



State 3 : One of the ETMs is controlled and the carrier resonates in the controlled arm.



State 4 : The remaining ETM is controlled and the carrier resonates in both arms and the recycling cavity.



State 5 : The power in the IFO has stabilized at its operating level. This is the ending point for lock acquisition.

Lock acquisition
real and simulated

Second generation LIGO simulation SimLIGO

- Assist noise hunting, noise reduction and lock stability study in the commissioning phase
- Performance of as-built LIGO
  - » effect of the difference of two arms, etc
- Noise study
  - » Non-linearity
    - – cavity dynamics, electronic saturations, digitization, etc
  - » Bilinear coupling
- Lock instability
- Sophisticated lock acquisition
- Upgrade trade study

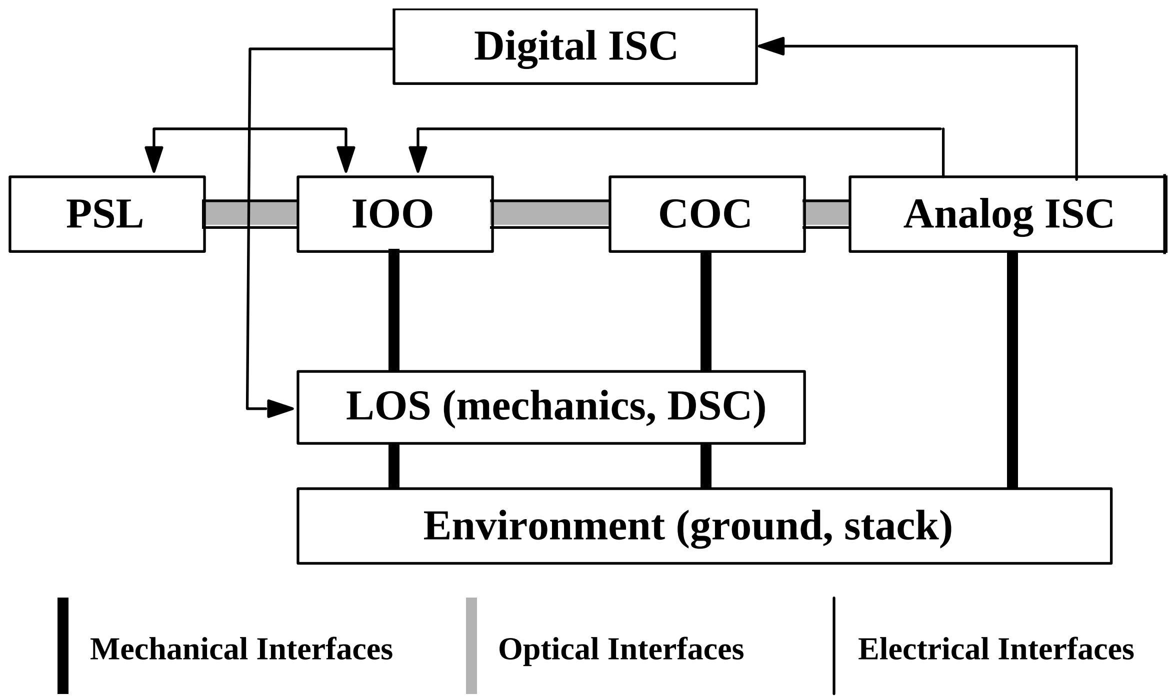
SimLIGO
A Detailed Model of LIGO IFO

- Modal beam representation
  - » alignment, mode matching, thermal lensing
- Alignment Control
  - » Optical lever, Wave Front Sensor
- 3D mechanics
  - » Correlation of seismic motions in corner station
  - » 6x6 stack transfer function
  - » 3D optics with 4/5 local sensor/actuator pairs
- Complete analog and digital electronics chains with noise
  - » Common mode feedback
  - » “Noise characterization of the LHO 4km IFO LSC/DSC electronics” by PF and RA, 12-19 March 2002 included

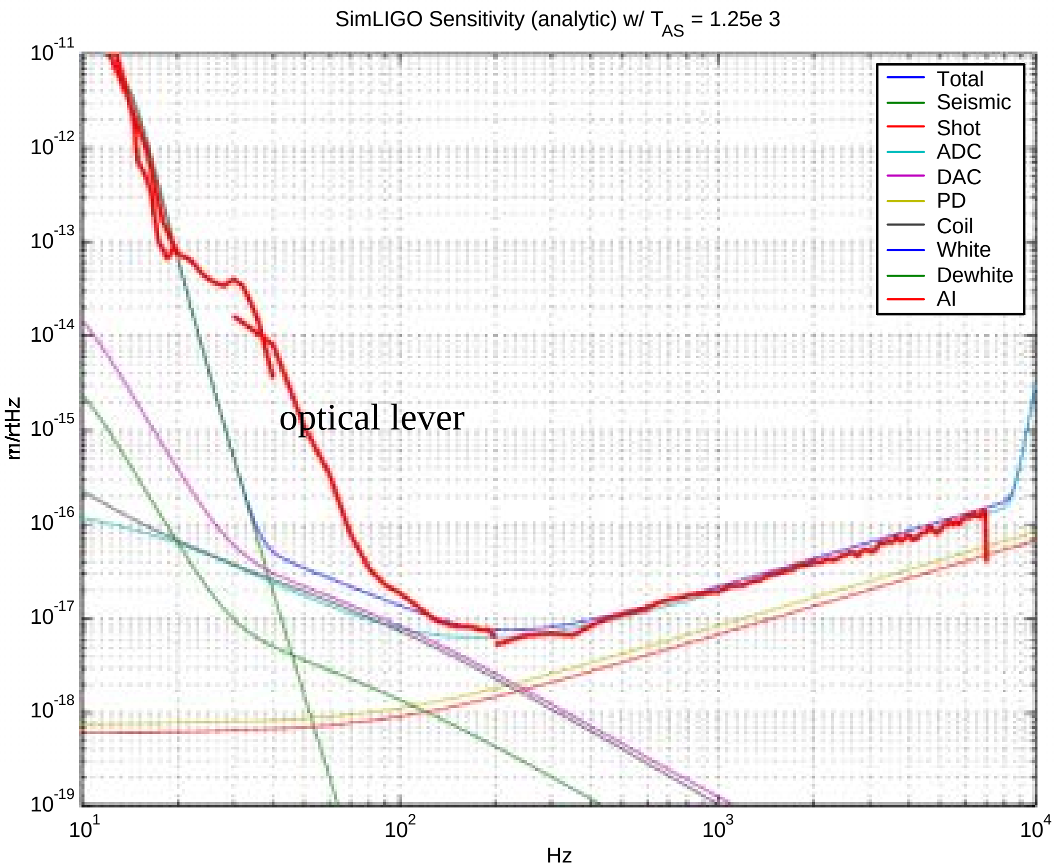
SimLIGO
Noise sources

- All major noise sources
  - » seismic, thermal, sensing, laser frequency and intensity, electronics, mechanical
- IFO
  - » optical asymmetries (R, T, L, ROC)
  - » non-horizontal geometry (wedge angles, earth's curvature)
  - » phase maps
  - » scattered light
- Mechanics
  - » wire resonances, test mass internal modes
- Sensor
  - » photo-detector, whitening filters, anti-aliasing
- Digital system
  - » ADC, digital TF, DAC
- Actuation
  - » anti-imaging, dewhitening, coil drivers

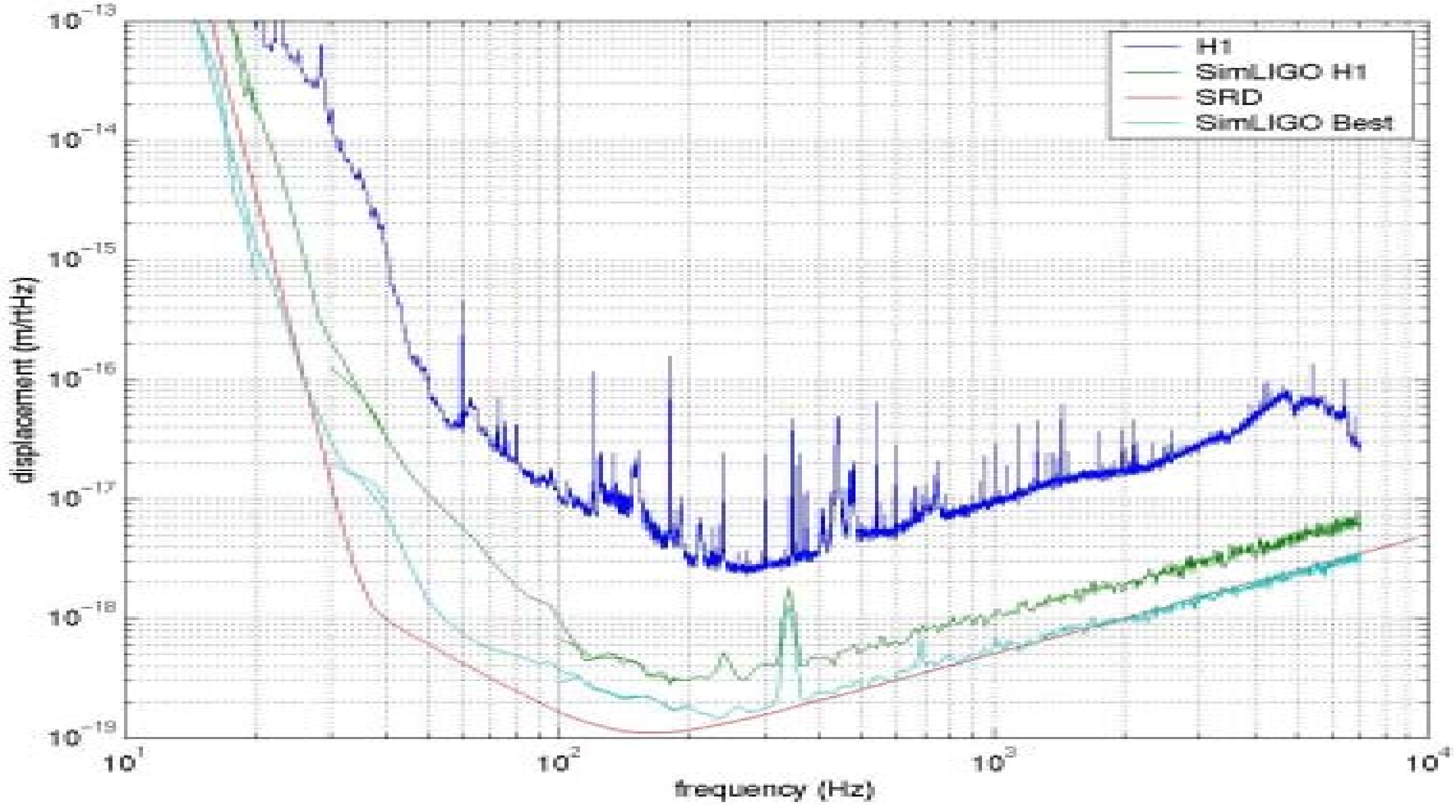
SimLIGO
System structure



SimLIGO
Noise components



SimLIGO Sensitivity Curve vs S2 representative curve



Future work
Advanced LIGO

- Optics and Field
  - » Fast simulation of dual recycling configuration
  - » Thermal lensing effects
  - » Method handling complex profile field - more sophisticated modal model or FFT?
- Mechanics
  - » Simulation of quad pendulum
  - » Interfacing with stack models by other group
- Noises
  - » thermo elastic
  - » radiation pressure, …
- Others
  - » “seismic noise whitening”, otherwise, 64 bit real is not enough
  - » speedup

Information about End to End simulation package

- Homepage
  - » www.ligo.caltech.edu/~e2e/
- Platform supported
  - » JAVA 1.4, gcc 2.95.2
  - » Sun Solaris, Intel Linux, MacOSX (tbd)
- e2e tarbal downloadable from e2e homepage
  - » e2e-version.tar.gz, SimLIGO.tar.gz, Han2k.tar.gz
- Documentations
  - » all downloadable from e2e homepage
  - » Han2k users manual
  - » SimLIGO
    - – 1) System structure, 2) How to guide, 3) Physics (to be completed)
- Maillist
  - » ligo-e2e-announce, physics, GUI, programming