LIGO

Status of LIGO Simulation

Hiro Yamamoto
LIGO Laboratory / California Institute of Technology

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

- Scientists
  - » Hiro Yamamoto
  - » Matt Evans
  - » Biplab Bhawal
  - » Virginio Sannibale 1/3
  - » Luca Matone
    - – LHO liaison
- Programmers
  - » Bruce Sears
  - » Melody Araya

LIGO End to End Simulation

the motivation

- Assist detector design, commissioning, and data analysis
- To understand a complex system
  - » ***back of the envelope is not large enough***
  - » complex hardware : pre-stabilized laser, input optics, core optics, seismic isolation system on moving ground, suspension, sensors and actuators
  - » feedback loops : length and alignment controls, feedback to laser
  - » non-linearity : cavity dynamics to actuators
  - » field : non-Gaussian field propagation through non perfect mirrors and lenses
  - » noise : mechanical, thermal, sensor, field-induced, laser, etc : amplitude and frequency : creation, coupling and propagation
  - » wide dynamic range : $10^{-6} \sim 10^{-20}$ m
- As easy as back of the envelope

E2E perspective

- e2e development started after LIGO 1 design completed (1997 ~)
- LIGO 1 lock acquisition was redesigned successfully using e2e by M.Evans (2000 ~ 2001)
- Major on going efforts for LIGO I (2001 ~)
  - » Realistic noise of the locked state interferometer
  - » Effect of the thermal lensing on the lock acquisition
  - » Effect of the train and logging activity at LLO to lock acquisition and lock stability
- Efforts for Advanced LIGO (2000 ~)
  - » Development of optics and mechanics modules
  - » Trying to expand users who can contribute
    - – A.Weinstein (CIT), J.Betzwieser (MIT), M.Rakmanov (UF), M.Malec (GEO)

End to End Simulation overview

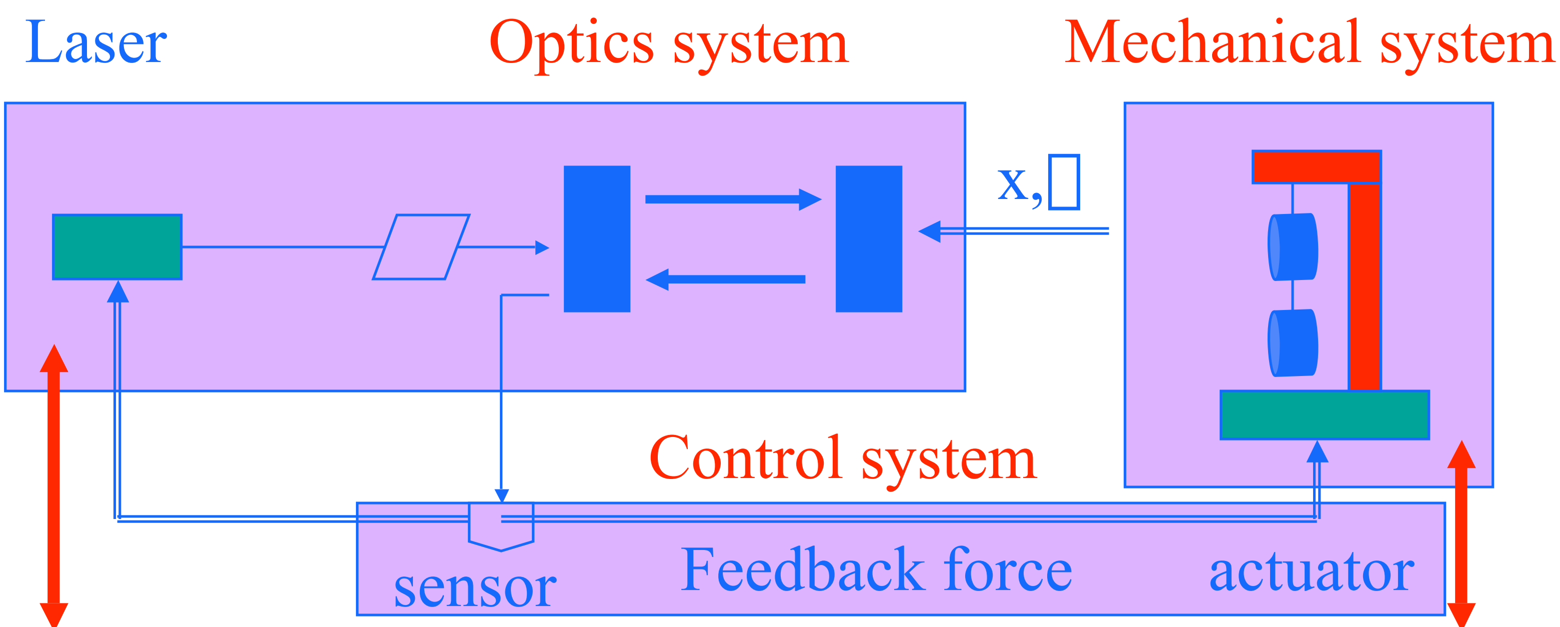
- General purpose GW interferometer simulation framework
  - » Generic tool like matlab or mathematica
  - » Time domain simulation written in C++
    - – Speed and flexibility
  - » Optics, mechanics, servo, ...
    - – time domain modal model, single suspended 3D mass.
    - – analog and digital controller - ADC, DAC, digital filter, etc
- End to End simulation environment
  - » Simulation engine - modeler, modeler_freq
  - » Description files defining what to simulate - Simple pendulum ~ full LIGO (constituent files are called “box files” or simply “boxes”)
  - » Graphical Editor to create description files - alfi
- LIGO I simulation packages
  - » Han2k : used for the lock acquisition design
  - » SimLIGO : to assist LIGO I commissioning

End to End Simulation
e2e vs matlab

	e2e	matlab
General purpose calculator	Laser+2 mirrors = FP	1+2 = 3
Language	Easy construction of LIGO like opto-mechanical system	Quick prototyping of wide variety of problems
Built-in function	Primitive modules : Mirror, michelson cavity, 3d mass, digital_filter, etc FUNC - expression parser	math functions, strings, graphics, etc
User programs	Execute box files in modeler, (compound module)	execute m-files in matlab
GUI	Alfi	simulink

End to End Simulation

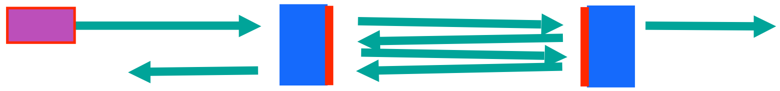
coarse view

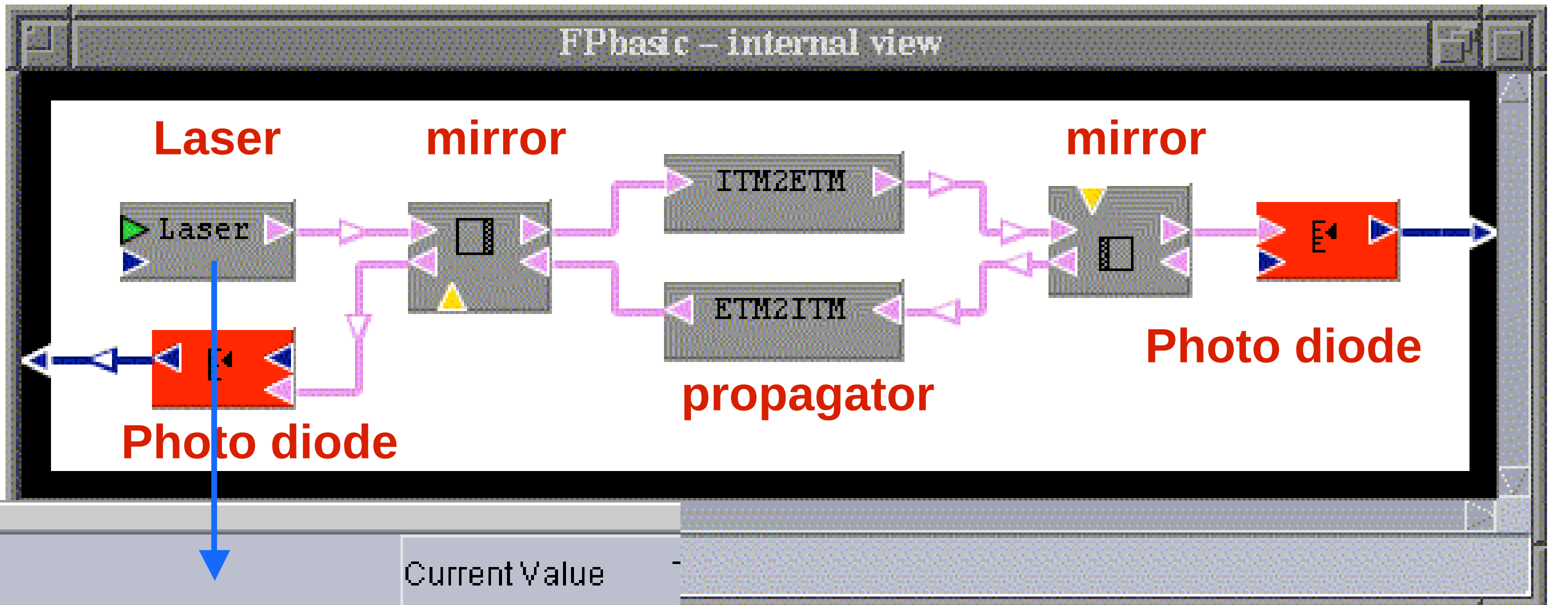


- Time domain modal model
- Objects : laser, mirror, photo diode, …
- Any planar interferometer
  - Fabry-Perot, Mode cleaner,LIGO I,
  - Advanced LIGO,…

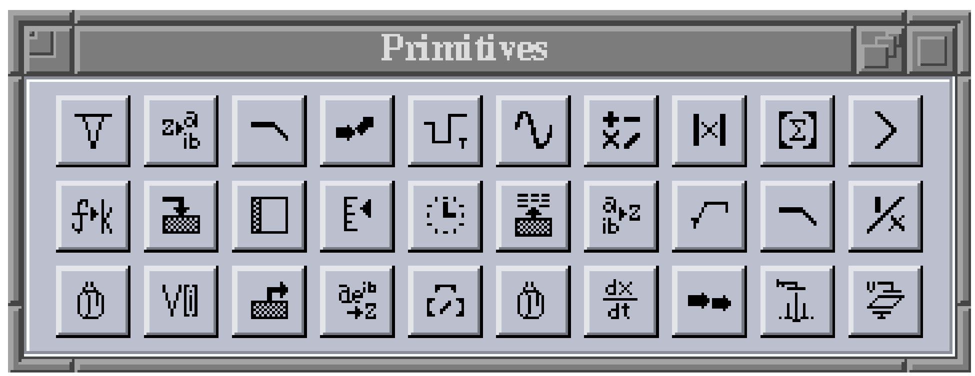
- Transfer function using Digital filter
- Single Suspended mirror
- Mechanical Simulation Engine (object-oriented)

e2e Graphical Editor





	Current Value
lambda	DEFAULT
waist_size_X	w0
waist_size_Y	w0
distance_waist_X	z_dist
distance_waist_Y	z_dist
angle_resolution	DEFAULT
compute_mismatch_curvature	DEFAULT
max_mode_order	1



e2e primitives
Mirror module - an example

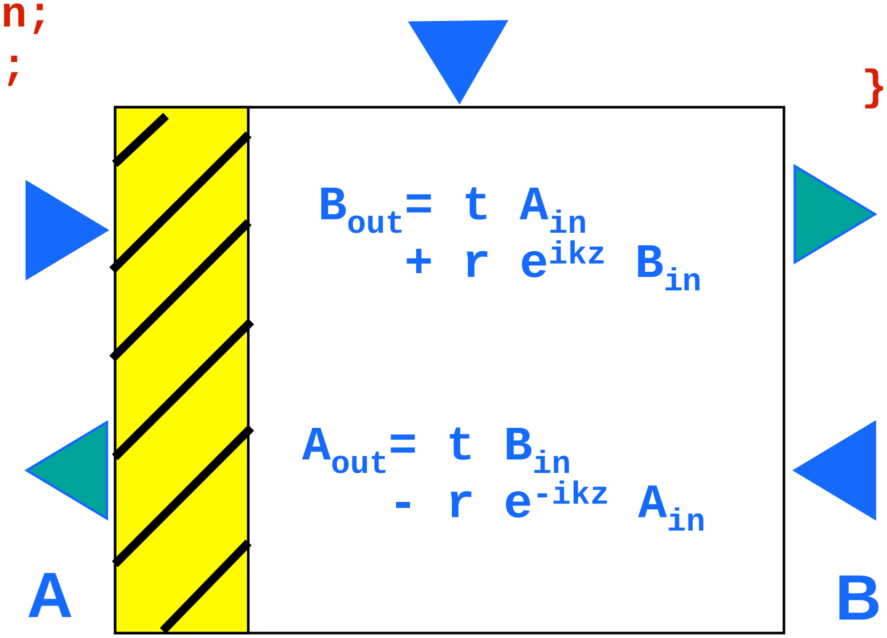
```
struct field
{ double amps[n];
  int mode;
  int polarization;
  double waistPos;
}
```

Mass position and orientation

```
struct clamp
{ double x, y, z;
  double thetax,…
  int statusBits;
}
```

Input field to coated side

output field from substrate side

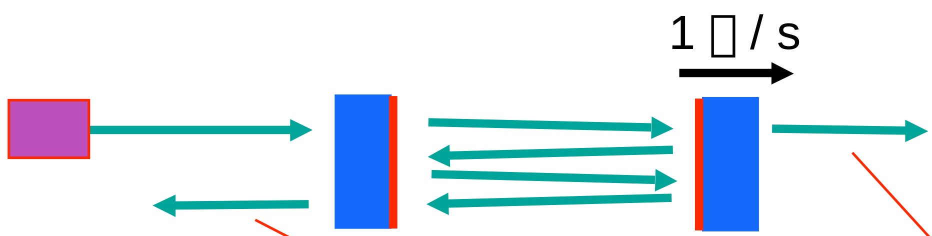


output field from coated side

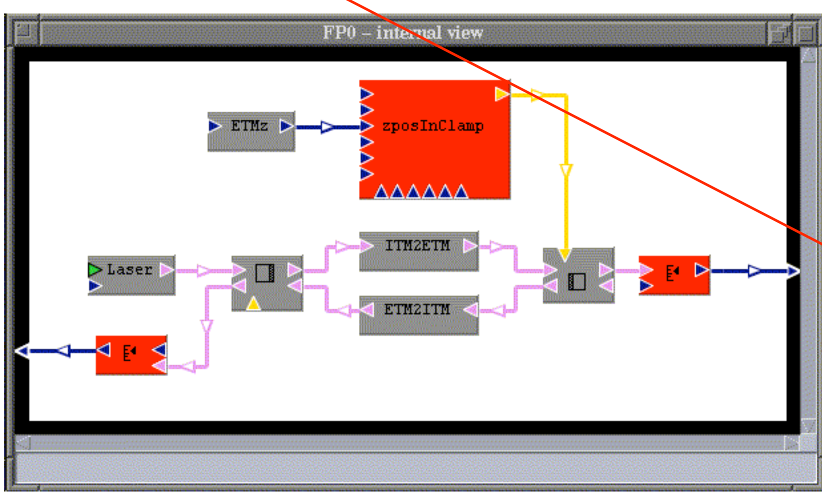
Input field to substrate side

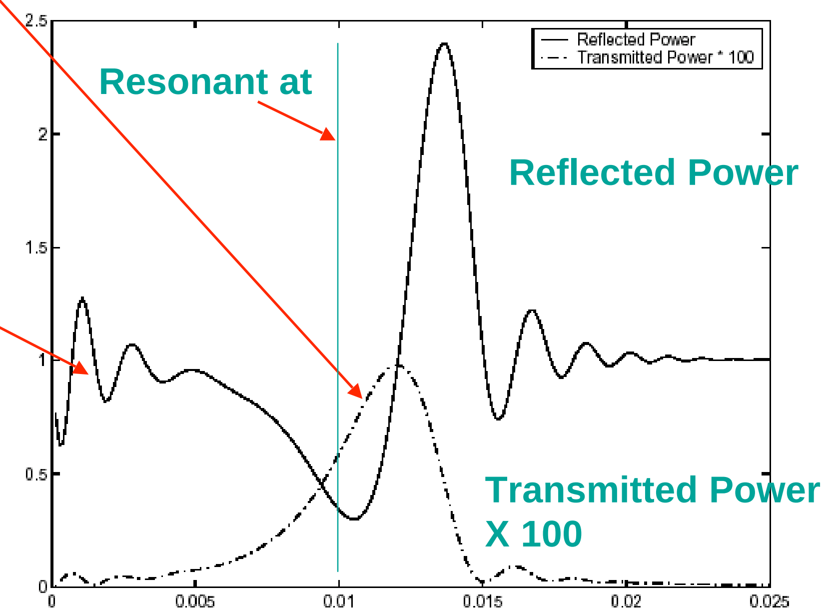
Static parameters : Reflectivity, transmittance, surface curvature, etc

e2e example - 1
Fabry-Perot cavity dynamics



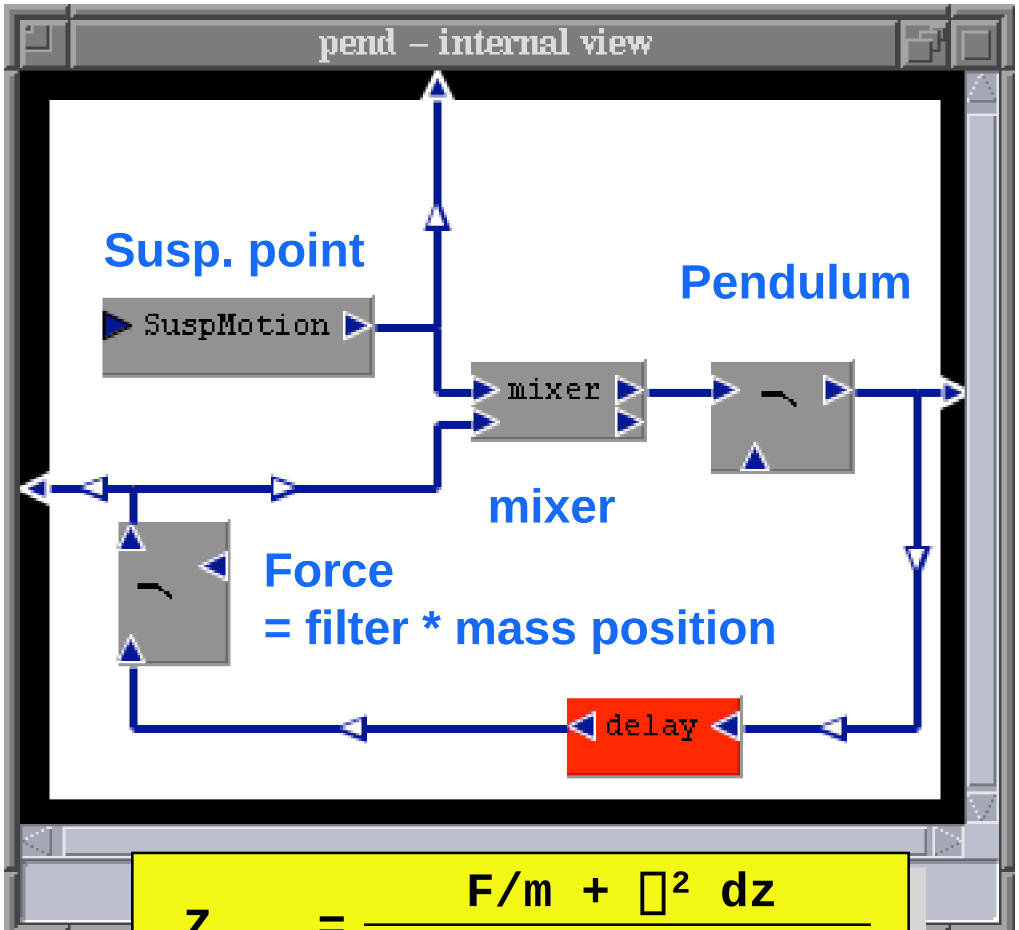
ETMz = $-10^{-8} + 10^{-6}$ t



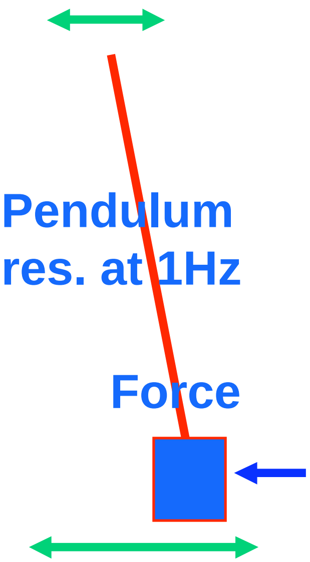


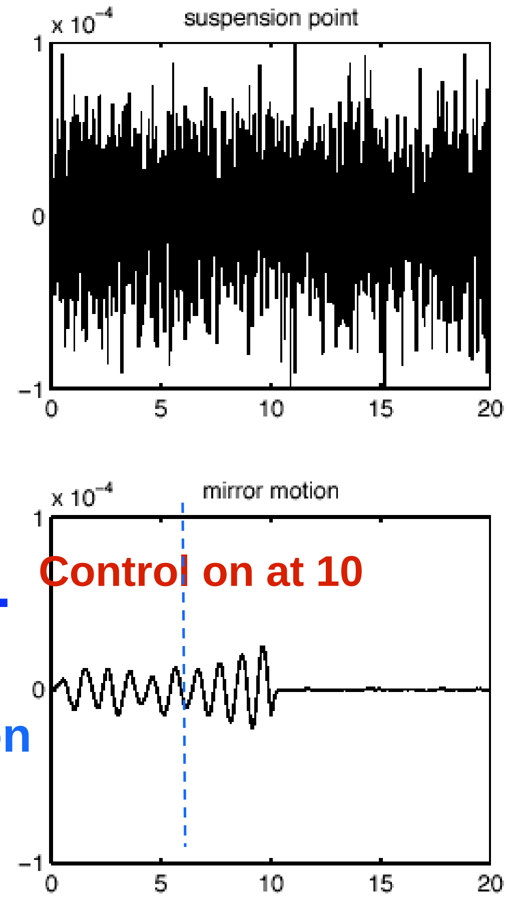
Power = 1 W, T_{ITM}=0.03, T_{ETM}=100ppm, L_{cavity} = 4000m

e2e example - 2
Suspended mass with control



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





FUNC primitive module
- command liner in GUI -

- GUI is not always the best tool
- FUNC is an expression parser, based on c-like syntax
- all basic c functions, bessel, hermite
- special functions : time_now(), white_noise, digital_filter(poles, zeros), fp_guoypahse(L,R1,R2), …
- predefined constants : PI, LIGHT_SPEED, …
- inline functions : leng(x,y) = sqrt(x*x+y*y); L = leng(2,3);

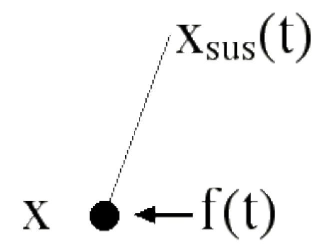
mixer module

```
gain = -5; lockTime = 10;
out0 = if ( time_now()<lockTime , in0, in0+gain*in1 );
```

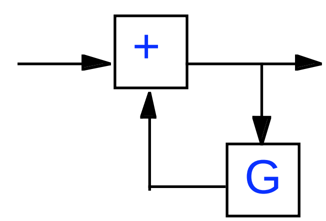
e2e physics
Time domain simulation

- 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
  - » e2e DF = PF's pziir.m (bilinear trans (s->z) + SOS) + CDS filter.c
  - » Transfer function -> digital filter
  - » Pendulum motion
  - » Analog electronics

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

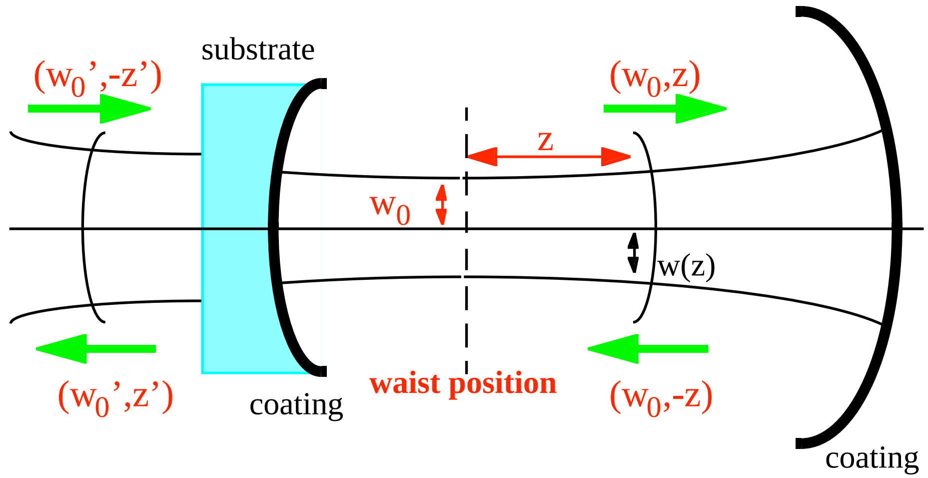


- Easy to include non linear effect
  - » Saturation, e.g.
- A loop should have a delay
  - » Need to put explicit delay when needed
  - » Need to choose small enough time step



e2e physics
Fields and optics

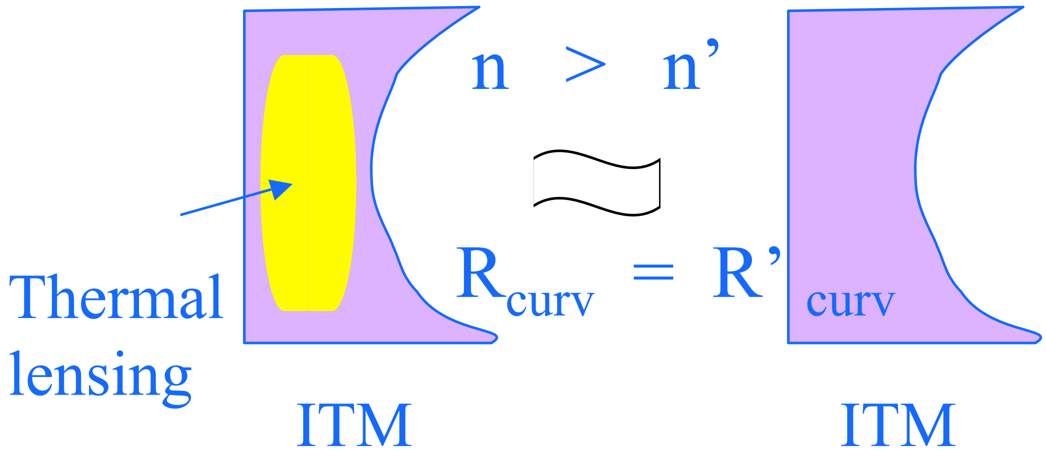
- Time domain modal model
  - » field is expanded using Hermite-Gaussian eigen states
  - » number of modes (n+m) <=4 for now, no limit in the future
- Reflection matrix
  - » tilt
  - » vertical shift
  - » curvature mismatch
- Completely modular
  - » Arbitrary planar optics configuration can be constructed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



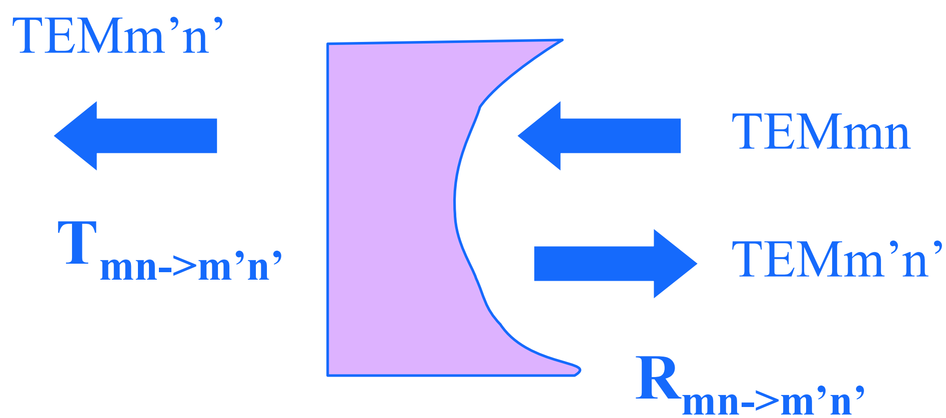
- Photo diodes with arbitrary shapes can be attached anywhere
- Adiabatic calculation for short cavities for faster simulation

e2e physics
optics imperfection

- Simple lens model
  - » LIGO 1
    - – lock, mode mixing



- Mode decomposition matrix - tbd
  - » LIGO 1
    - – actual mirror phase map
    - – more accurate
  - » Adv. LIGO



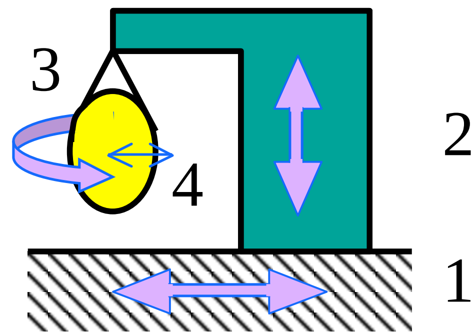
e2e physics
Mechanics simulation

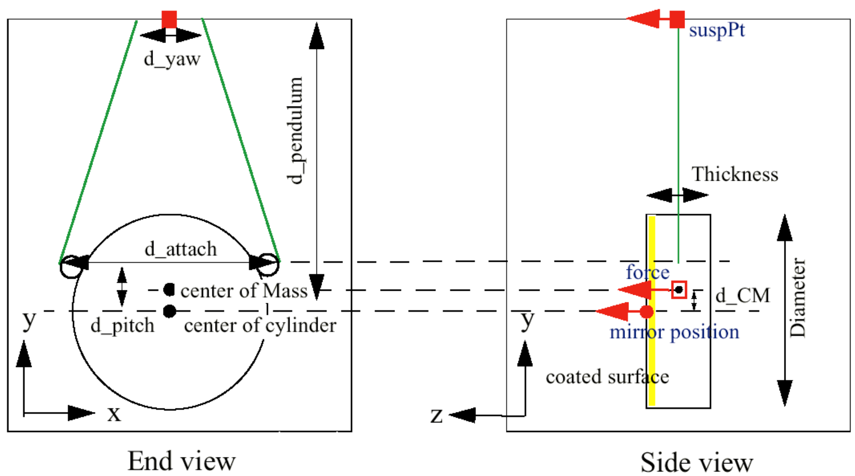
(1) Seismic motion from measurement
- » correlations among stacks
- » fit and use psd or use time series

(2) Parameterized HYTEC stack
- » Ed Daw

(3) Simple single suspended mirror
- » M.Rakmanov, V.Sannibale
- » 4/5 sensors and actuators
- » couple between LSC and ASC

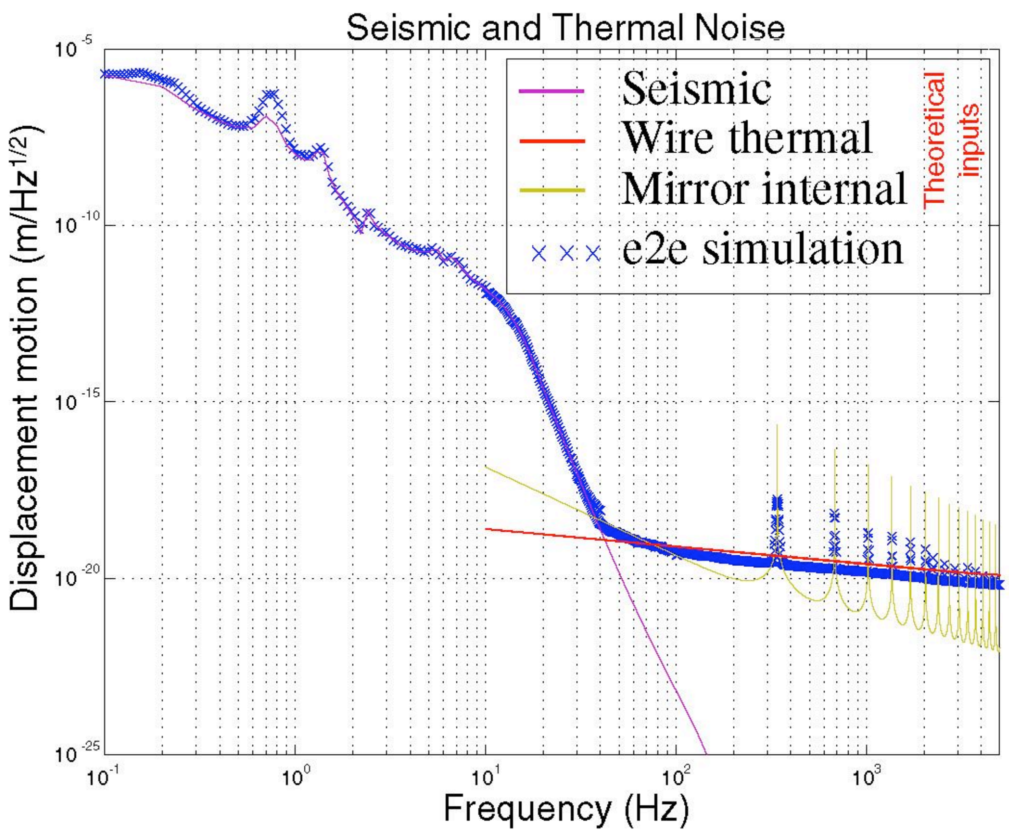
(4) Thermal noise added in an ad hoc way
- » using Sam Finn's model

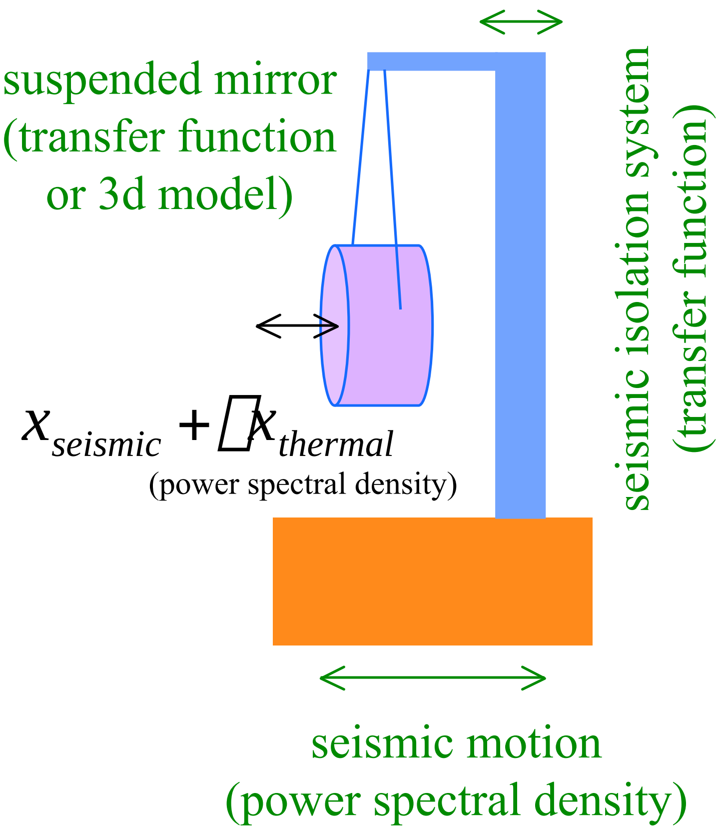




Mechanical noise of one mirror

seismic & thermal noises





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

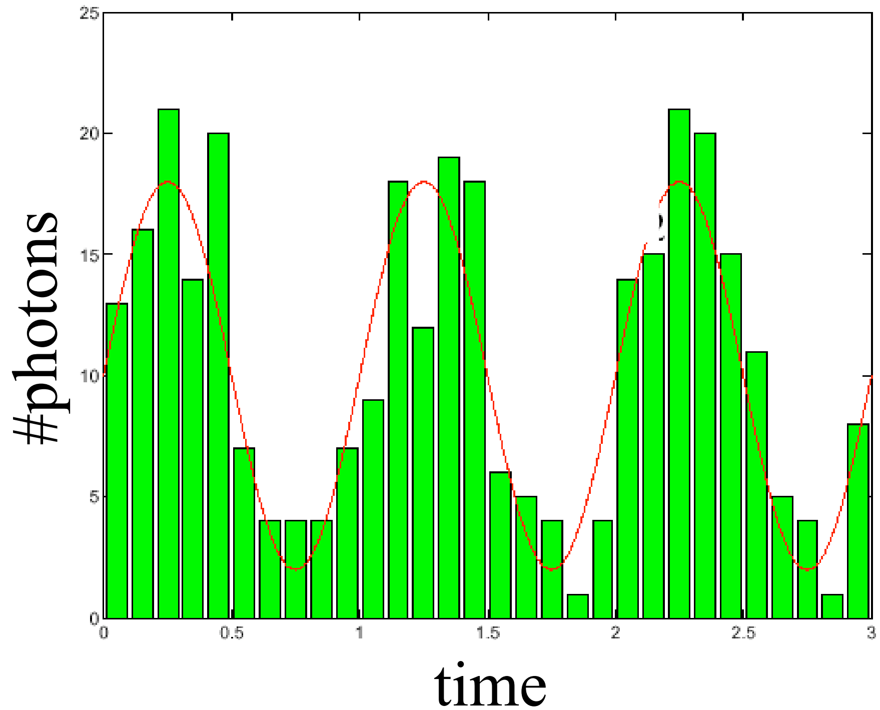
$$n(t) = Poisson(n_0(t))$$

Simulation option

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

Average number of photons by the input power of arbitrary time dependence

Actual number of photons which the detector senses.



First LIGO simulation
Han2k

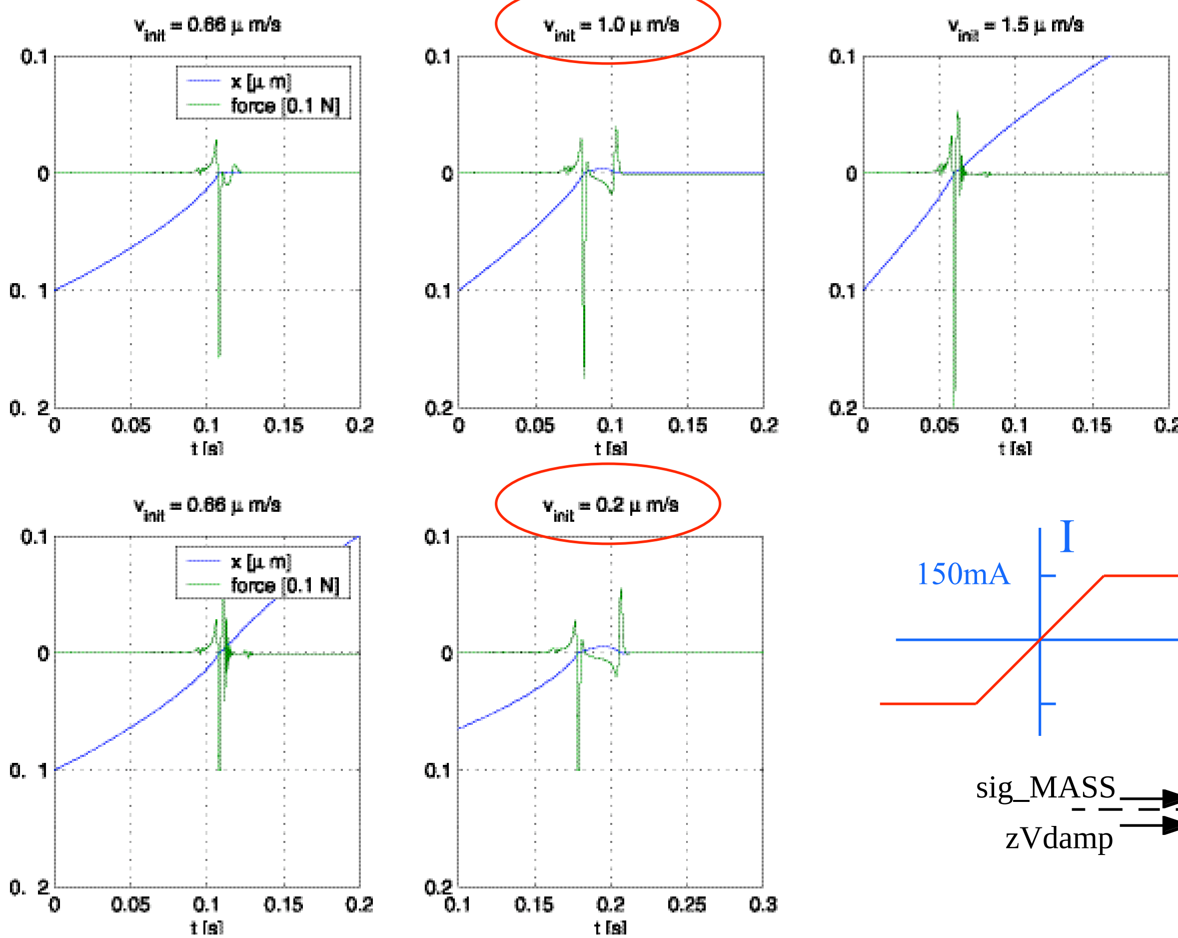
- Matt Evans Thesis
- Purpose
  - » design and develop the LHO 2k IFO locking servo
  - » simulate the major characteristics of length degree of freedom under 20 Hz.
- Simulation includes
  - » Scalar field approximation
  - » 1 DOF, everywhere
  - » saturation of actuators
  - » Simplified seismic motion and correlation
  - » Analog LSC, no ASC
  - » no frequency noise, no shot noise, no sensor/actuator/electronic noise

Fabry-Perot

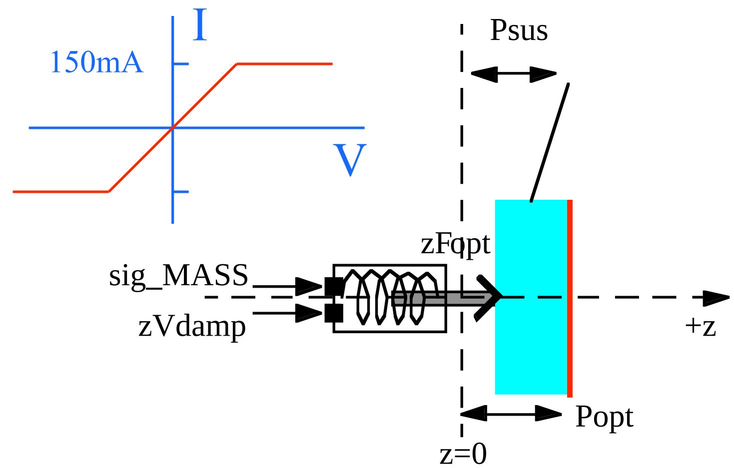
ideal vs realistic

ideal

realistic



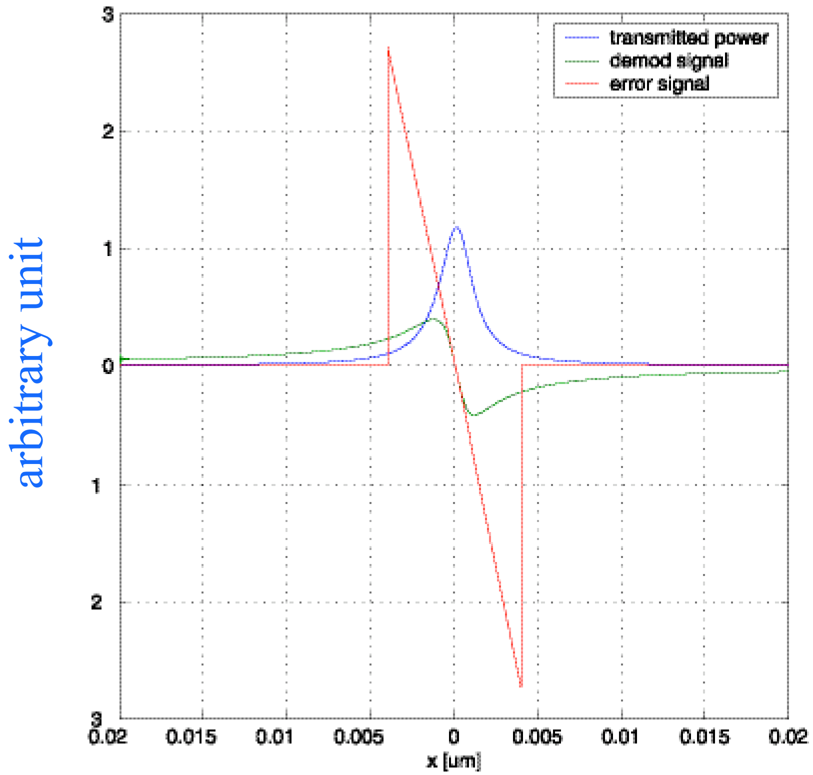
Linear Controllers: Realistic actuation modeling plays a critical role in control design.

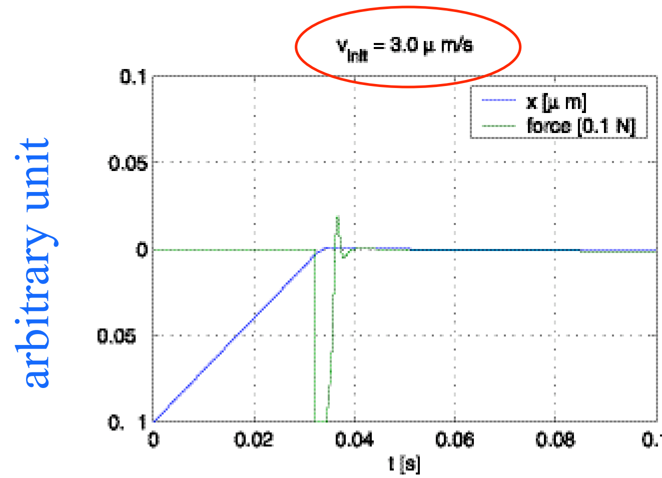


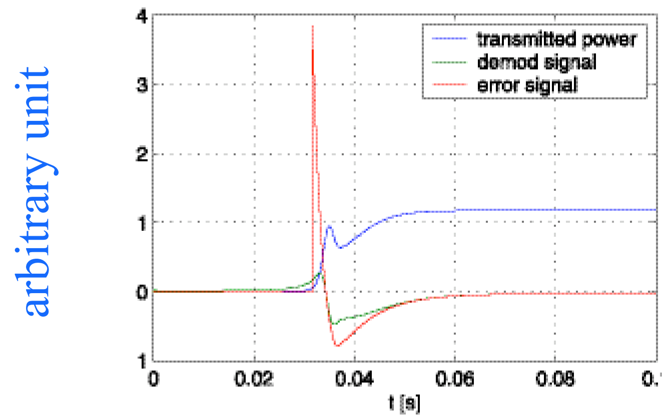
Fabry-Perot

Error signal linearization

$$S = \frac{S_{PDH}}{|A_{tr}|^2} = \square \frac{r_{ETM}}{t_{ETM}^2} \sin \square$$



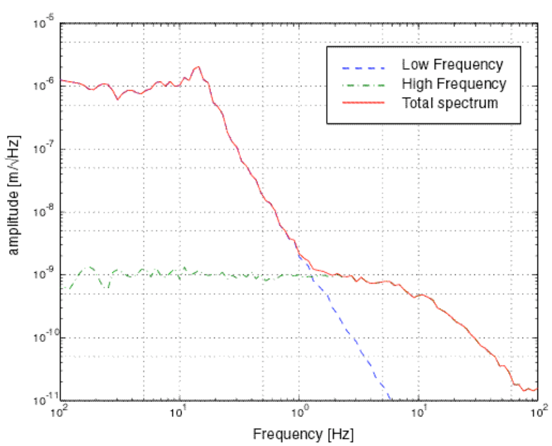


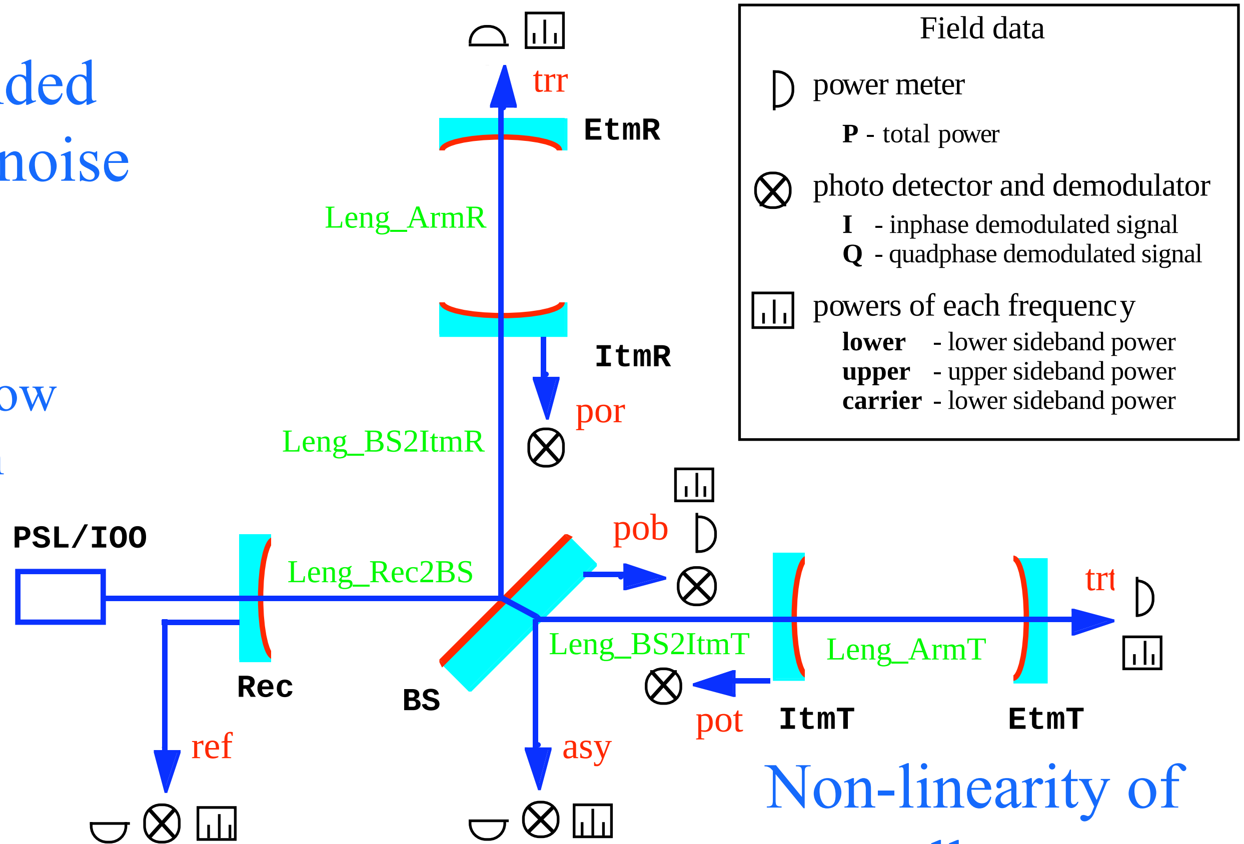


Hanford 2k simulation setup

6 independent suspended mirrors with seismic noise

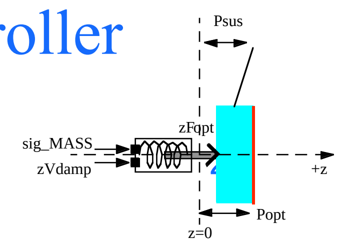
corner station :
strong correlation in the low frequency seismic motion





Han2k optics setup

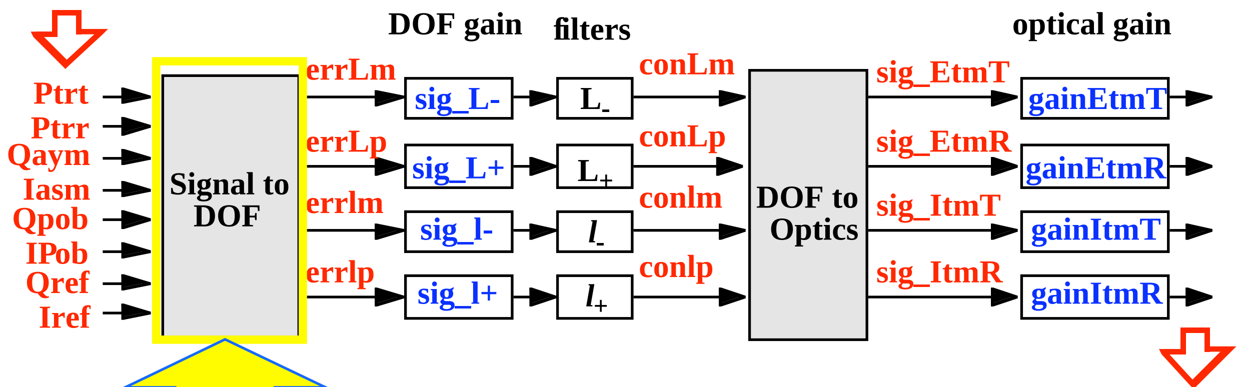
Non-linearity of controller



Automated Control Matrix System

LIGO T000105 Matt Evans

Field signal

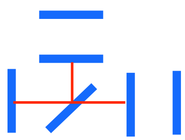


Same c code used in LIGO servo and in simulation

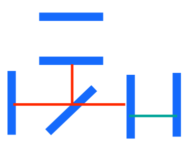
Actuation of mass

Multi step locking

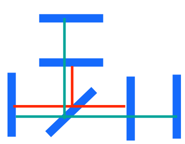
State 1 : Nothing is controlled. This is the starting point for lock acquisition.



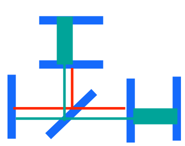
State 2 : The power recycling cavity is held on a carrier anti-resonance. In this state the sidebands resonate in the recycling cavity.



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.

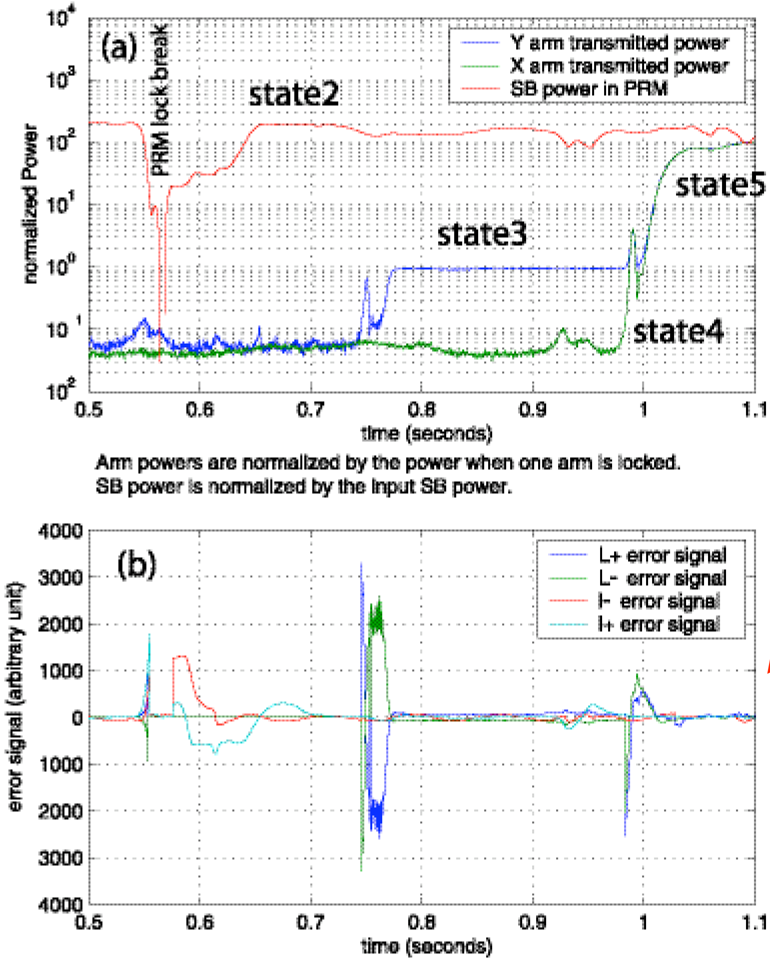


State 5 : The power in the IFO has stabilized at its operating level. This is the ending point for lock acquisition.

Lock acquisition

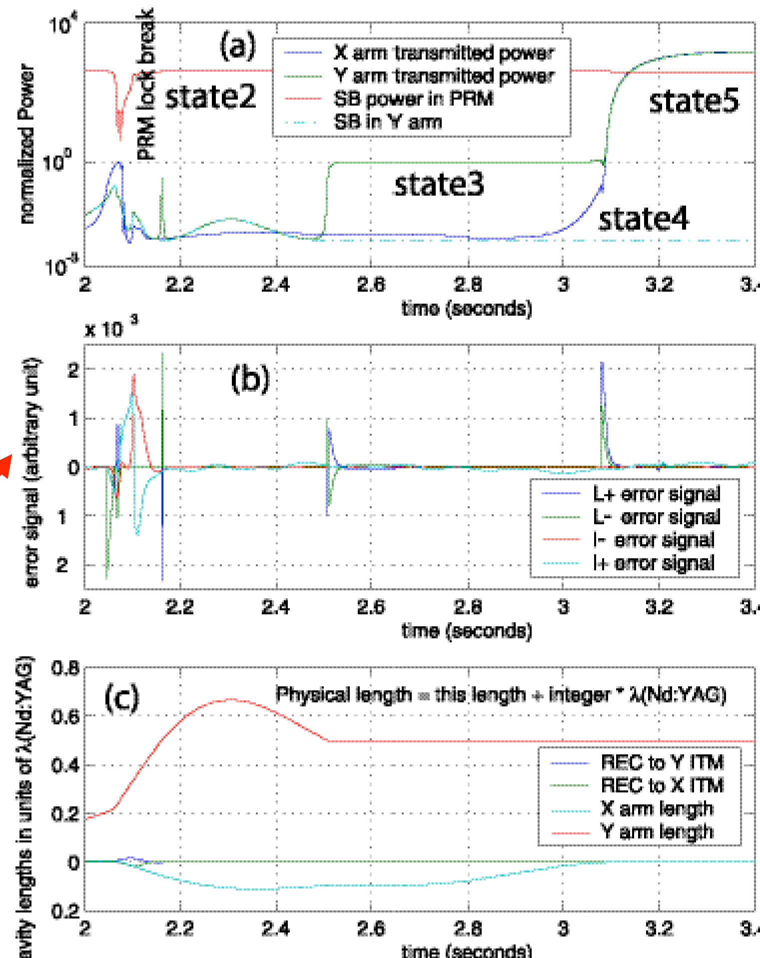
real and simulated

Figure 1. LHO 2k IFO data



observable

Figure 2. Simulated signal



Not experimentally observable

LIGO 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

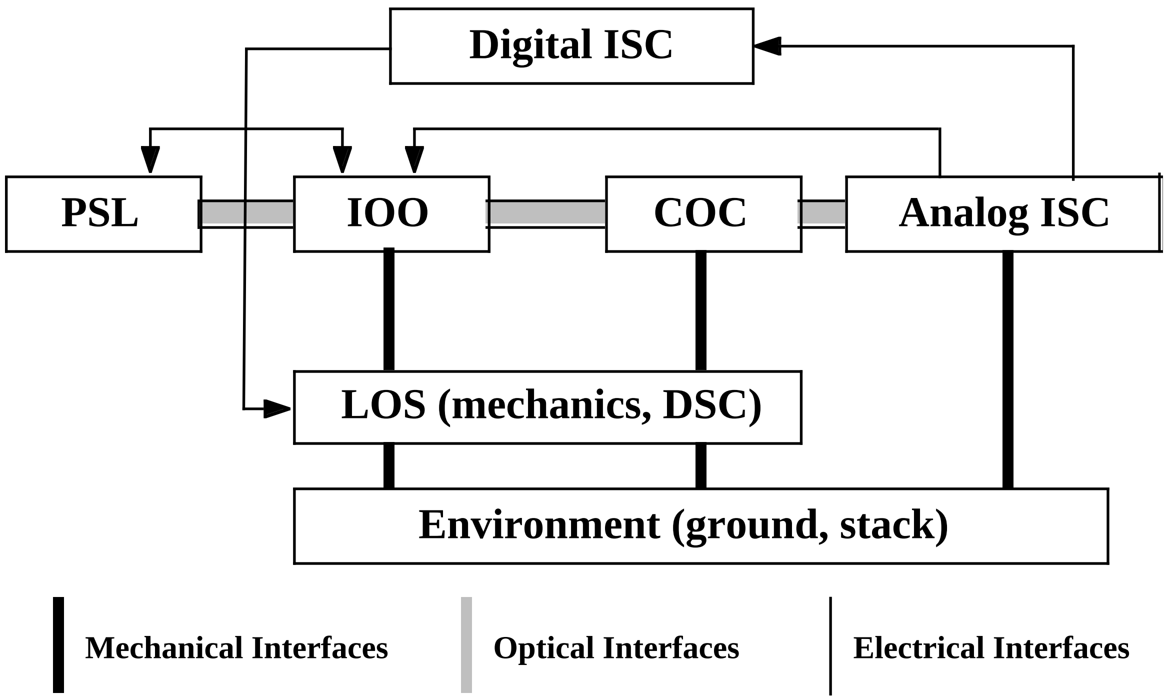
SimLIGO
A Detailed Model of LIGO IFO

- Modal beam representation
  - alignment, mode matching, thermal lensing
- 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
  - Wave Front Sensors
  - “Noise characterization of the LHO 4km IFO LSC/DSC electronics” by PF and RA, 12-19 March 2002 included

SimLIGO
Noise sources

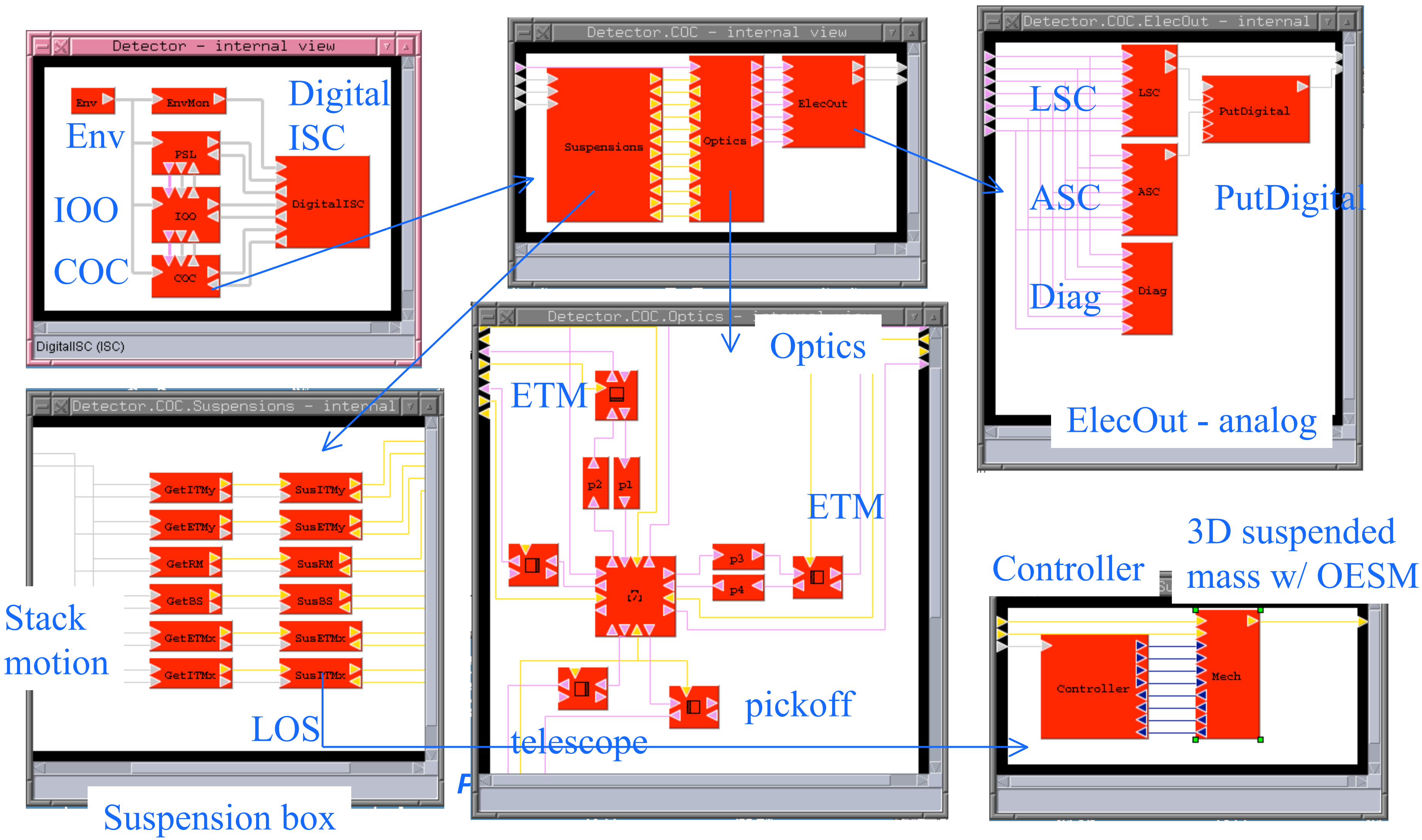
- All major noise sources
  - seismic, thermal, sensing, laser frequency and intensity, electronics, mechanical
- IFO
  - optical asymmetries (R, T, L, ROC)
  - non-horizontal geometry (wedge angles, earth's curvature)
  - phase maps
  - scattered light
- Mechanics
  - wire resonances, test mass internal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

SimLIGO
System structure

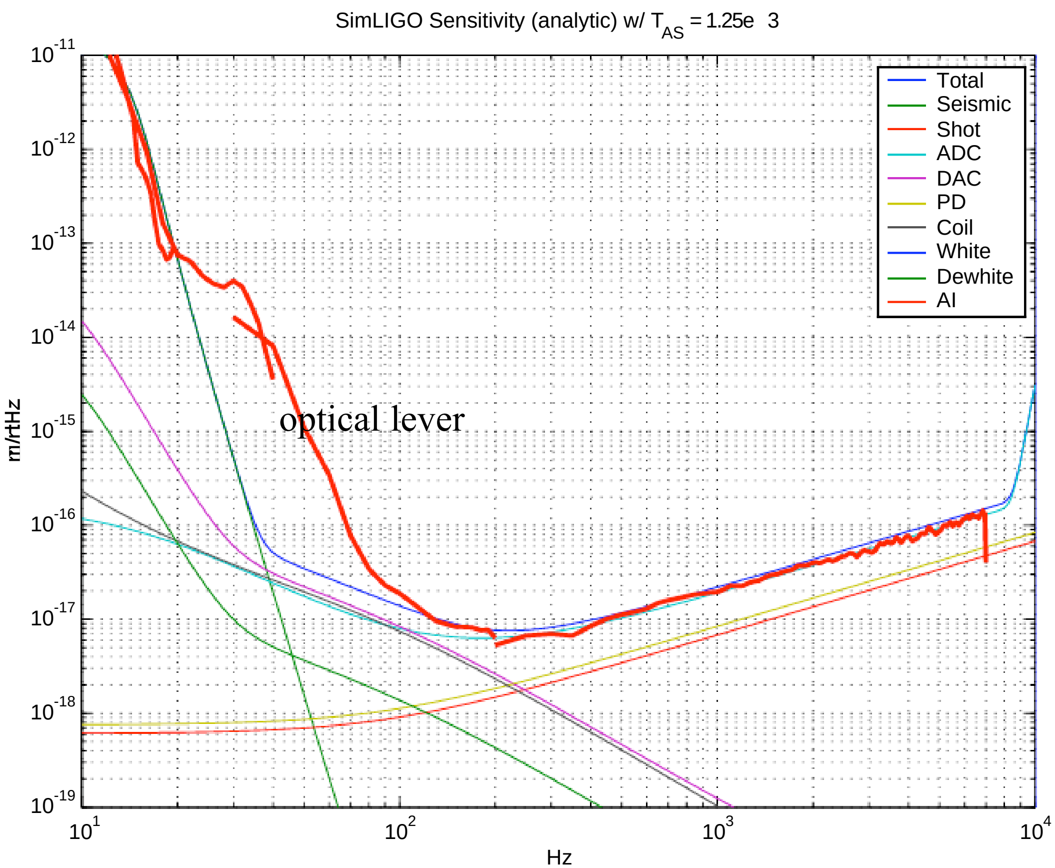


SimLIGO

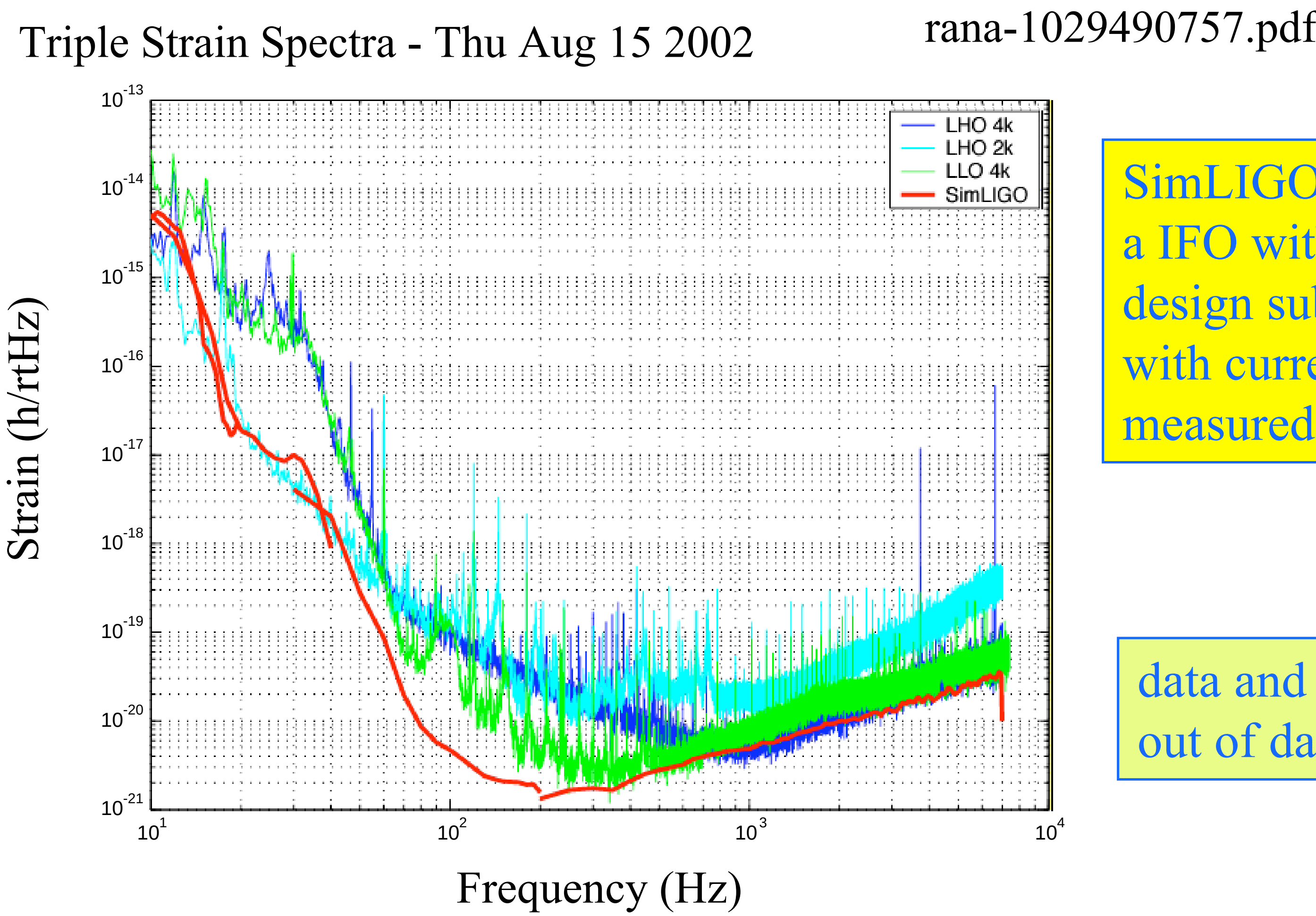
more realistic LIGO simulation



SimLIGO
Noise components



LIGO data vs SimLIGO



SimLIGO simulates a IFO with all final design subsystems with current measured noises

data and simulation out of date

SimLIGO sensitivity curve

- Calculated from a time series of data
  - » Major ingredients of the real LIGO included
  - » Interferometer, Mechanics, Sensor-actuator, Servo electronics
  - » Known noises
  - » Signal to sensitivity conversion
- Demonstration of the capability to simulate the major behavior of LIGO
  - » Reliable tool for fine tuning a complex device
  - » Almost any assumptions can be easily tested - at least qualitatively
  - » Trade study
  - » Subsystem design
  - » …

LIGO

LIGO simulation without programming

- Package distributed
  - » SimLIGO box files
  - » auxiliary files
    - – macro files, run instructions, support apps
  - » matlab files for easy analysis of e2e outputs
  - » modeler < run.in to generate time series and psds
  - » **5 lines in unix terminal to generate the sensitivity curve**
- Macro files - text file
  - » lengths and mirror quantities
  - » noise : on-off
  - » control : on-off
  - » shaking mirrors : length and angle - linear, periodic, random
  - » configurations : FP, PRM, full LIGO

SimLIGO
what's TDB - we do

- Simulation code improvements
  - » Add physics
    - – mirror phase map, radiation pressure, scattering noise, etc
  - » Improve existing physics simulation
    - – better field-optics implementation, etc
  - » Code improvements
    - – better data manipulation, speed, multi thread, etc
- SimLIGO
  - » Update common mode servo
  - » Better mechanical system model
  - » Lock acquisition support

SimLIGO
what's TDB - we need help

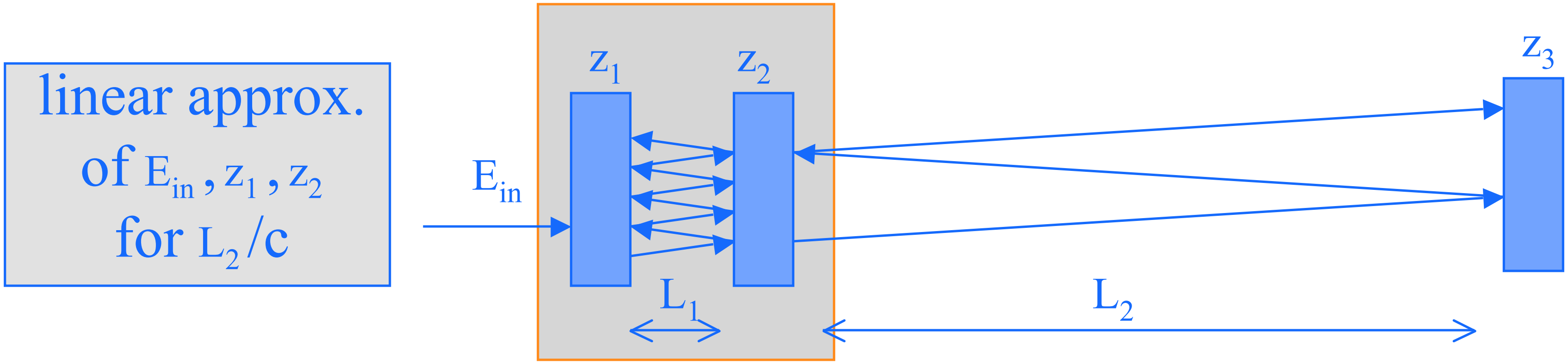
- LIGO 1 hardware/software data NEEDED
  - » Seismic data
    - – only LHO data now
    - – S.Yoshida (SLU) is helping us
  - » Noise data
    - – updated noises of laser frequency, amplitude, electronic, etc
  - » Updated servo design
- **More USERs**
  - » why simulation is useful
  - » how simulation can be used

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

Dual recycling cavity simulate FAST

- Can be simulated today, but slow…
- simulation time step = cavity length / speed of light
- Module based on an approximate calculation of fields in a short cavity runs 500 ($\sim L_2 / L_1$) faster than simulation using primitive mirrors.
- M.Rakmanov (UF) worked on a dual recycling cavity formulation and did its validation using matlab and e2e primitive optics. Not completed.



Mechanical Simulation Engine(MSE)

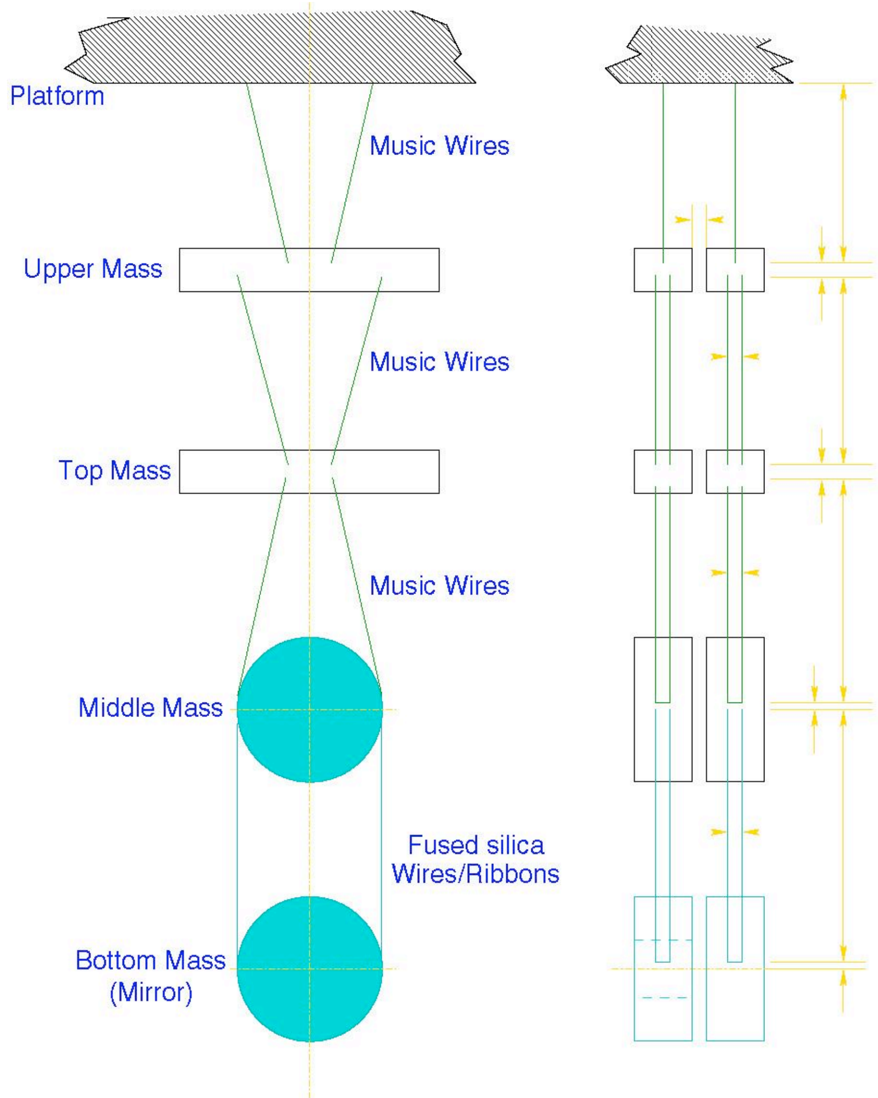
- Delivered by Dr.G.Cella of Univ.Pisa
  - » C++ mechanics class library
  - » Developed for LIGO based on his work at Virgo
- Fully three dimensional model
- Modular design with flexibility
- Time domain and frequency domain simulation
- Easy integration with the optics and control parts of the End to End model
- Interface to external models, like stack models by other group

Quadruple Pendulum

- Virginio Sannibale based on MSE (1/3 of his time)
- The two chains of the quadruple pendulum suspension implemented.
- Main geometrical parameters of each element included.
- Complete three-dimensional simulation. All the geometrical possible couplings can be taken into account.
- Rigid body D.O.F. completely described.
- Internal mode implementation in progress (wire violin mode, blade, …)
- Small oscillation or a linear regime.
- Viscous Damping for the longitudinal modes.
- Force actuators can be placed anywhere.
- Not completed

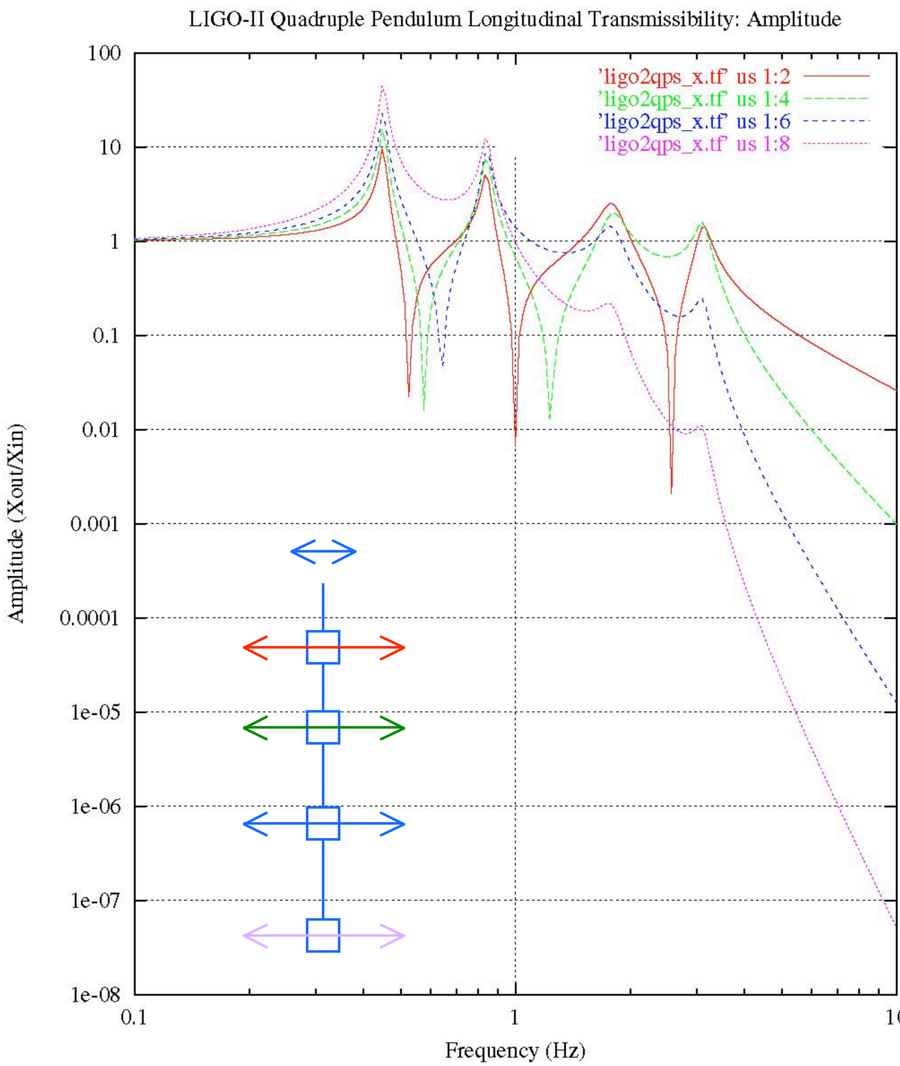
Adv. LIGO Mechanics

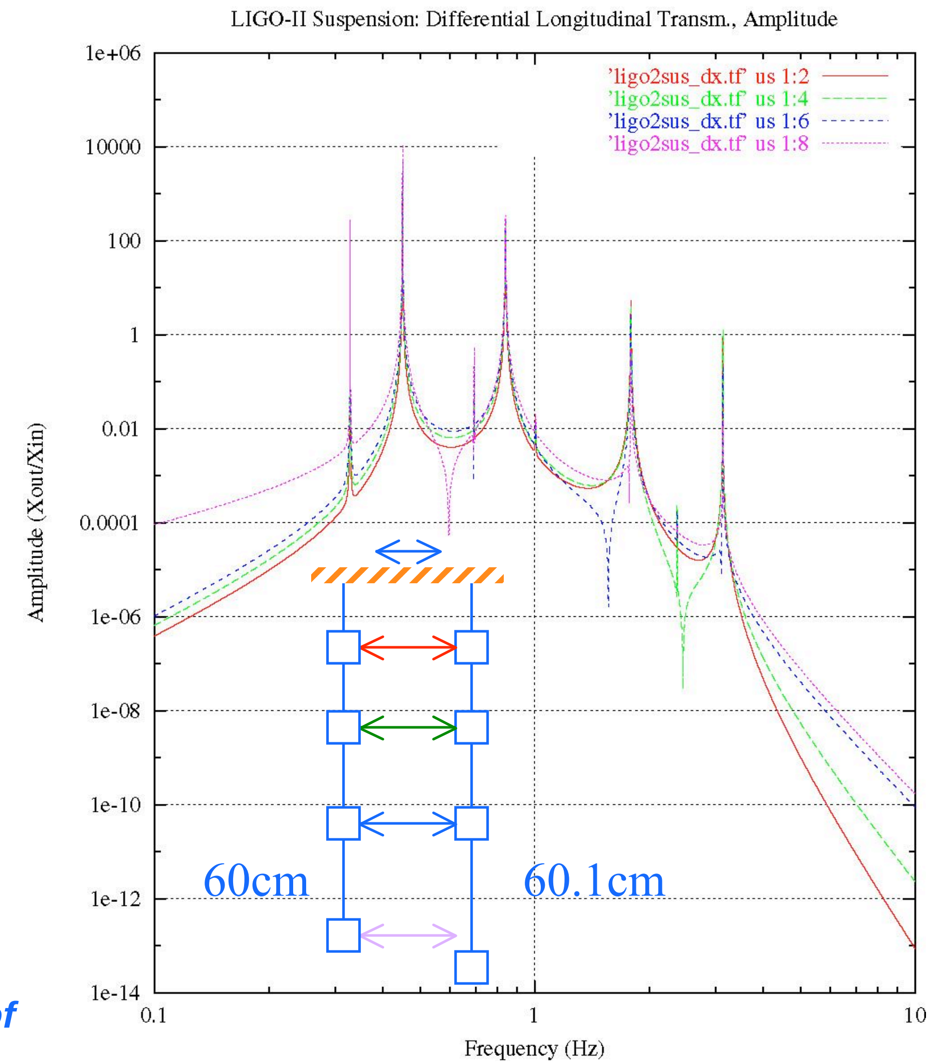
Quadruple Pendulum structure



Adv. LIGO Mechanics

Transfer functions





of

Information about End to End simulation package

- Platform supported
  - » JAVA 1.4, gcc 2.95.2
  - » Sun Solaris, Intel Linux, MacOSX (tbd)
- Homepage
  - » www.ligo.caltech.edu/~e2e/
- 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