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THE LIGO END-TO-END SIMULATION PROGRAM

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The End-to-End (E2E) simulation package has been developed to model the full LIGO detector, its advanced design-variants and subsystems in order to help the design and commissioning. The E2E package simulates the time-evolution of fields, optics, mechanical structures and electronic and control systems. A simulation setup of the Hanford 2 km LIGO interferometer played a crucial role in the first lock-acquisition design of the interferometer. Another LIGO simulation setup has been built recently which contains all the important hardware and softwares features of the LIGO detector. This is capable of generating realistic noise spectra and studying both the length control and alignment control through wave-front sensors and various other physics issues for a LIGO-like complex coupled system.

1 Introduction

The joint Caltech-MIT LIGO (Laser Interferometer Gravitational-wave Observatory) project [1] started the first science run of its three long-baseline interferometers (two at Hanford, Washington of baselines 4 km and 2 km and one at Livingston, Louisianna of baseline 4 km) in August-September, 2002 for a duration of 17 days. The second science run of continuous 2 months' operation was completed in February-April of 2003.

Some interesting features of LIGO detectors, as sketched in Fig.1, are as follows: (i) Fabry-Perot (FP) cavities are used in arms to increase the storage time of light, (ii) The recycling cavity lengths, l_x, l_y are adjusted such that the output port remains on the dark fringe in order to maximize the signal-to-noise ratio, (iii) In order to reduce photon shot noise, a high power laser is used and, under dark-fringe operation, the constructively interfered component of light that travels toward the laser source is recycled back to the interferometer by placing a suitable mirror in front of the source, thus enhancing laser power, (iv) All six mirrors are suspended to

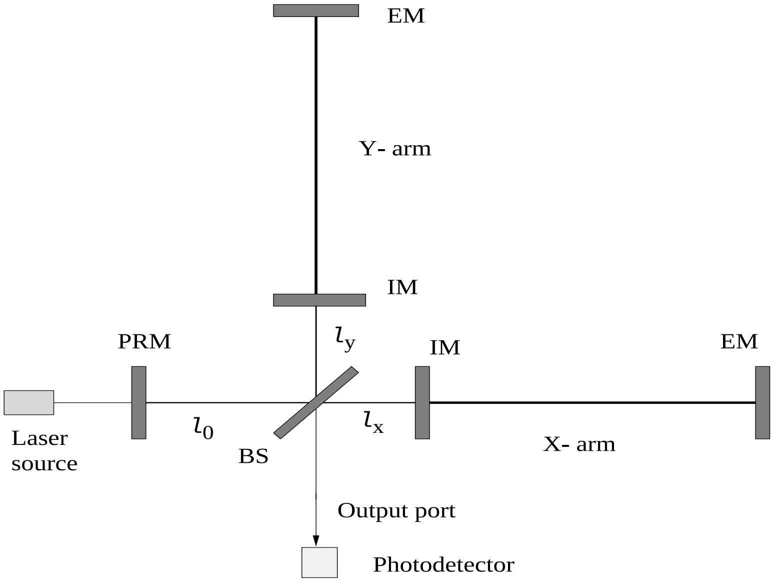

Figure 1: Configuration of power-recycled interferometer. BS, beam-splitter; EM, end mirror; IM, input mirror, PRM, power recycling mirror. Recycling cavity lengths, l_0, l_x, l_y are of the order of a few meters whereas arms are of 2 or 4 km length

filter out seismic noise letting the mirror to move as free masses above the resonant frequency of the pendulum.

In a future advanced detector another mirror will be placed at the output port for dual-recycling [2] or resonant sideband extraction [3] modes of operation. The optical configurations of these detectors, with dynamics of mirrors involved, thus represent coupled nonlinear multi-length systems with complicated dynamical responses. In order to control the interferometer and keep it in locked state, radio frequency modulation and demodulation techniques are employed.

Computer simulation is thus expected to play a crucial role in understanding and improving the performance of these detectors. As has been demonstrated in the field of experimental high energy physics, a detailed computer simulation is crucial for successful operation and analysis of large complex experiments. So, with that aim a simulation package with various modeling tools has been developed at Caltech. This simulation program called LIGO End-to-End (E2E) model [4] allows us to perform computer experiments on LIGO or its advanced design-variants or on some subsystem of it. A similar simulation program called SIESTA [5] was developed by the French-Italian VIRGO project.

The E2E software has been developed mainly for the following purposes: (i) detector diagnostics during the commissioning and operating phases, (ii) trouble-shooting for hardware or unknown noise sources, (iii) pseudo data production for running and testing data analysis techniques, (iv) design of advanced detectors.

The E2E package simulates the time-evolution of fields, optics, mechanical structures and electronic and control systems. It can be viewed as a software toolbox, like MATLAB [6], and complex systems can be simulated by combining building blocks. The package consists of two parts: the simulation engine software and description files which keeps information about the simulation setup. E2E is written in C++ and its modular design makes it possible to simulate wide variety of experimental configurations and processes (with different description files) using the same simulation engine. A JAVA-based graphical user interface has been developed. Using that it is quite easy to create, modify and maintain the simulation configuration setup even for complex systems, such as LIGO interferometer with all its optical, mechanical and control system components. The flexibility of the underlying simulation environment makes it easy to maintain, extend or introduce new physics or functionalities in a streamlined way.

In the next section we give some outline of the physics tools included in the E2E software package. In last two sections we would describe two available models of LIGO: “Han2k” which was successfully used for the design of lock acquisition of LIGO interferometer and more detailed “SimLIGO” which is currently being used to understand various noise sources.

2 Physics Tools of E2E

The optical configurations of LIGO detectors, with dynamics of mirrors involved, represent coupled nonlinear systems with complicated dynamical responses. The multilength aspect of the cavities add more difficulties in handling the simulation. The aim of E2E was to properly represent such complex systems and try to understand their behavior especially when effects are coupled to each other.

The simulation effort needed to take care of at least the following issues and complexities: (i) Complex hardware: pre-stabilised laser, input optics, core optics, seismic isolation system on moving ground, stacks, suspension system, sensor and actuators. (ii) Feedback loops: length and alignment control, feedback to laser. (iii) Nonlinearity: Cavity dynamics to actuators. (iv) Field: Gaussian or Non-Gaussian field propagation through imperfect mirrors and lenses. Effects of thermal lensing and misalignments. (v) Noise: mechanical, thermal, sensor, amplitude and frequency noise of laser; Their creation, propagation and coupling. (vi) Wide dynamical range : $\sim 10^{-6}$ to $\sim 10^{-20}$ meter.

For simulation of optics and electronic components, a number of fundamental objects (called *modules*) have been created: laser source, mirror, propagator, modulator, demodulator, telescope, power meter, digital filter, algebraic and logic functions etc [7]. The evolution of the field and its perturbative interaction with optical media are calculated using a modal model [8] that takes into account spatial modes upto some finite order.

In order to solve simulation speed problem posed by LIGO cavities’ multilength issue (which mainly originates from the fact that the recycling cavity is much smaller than the arm cavities) an approximation method[9,10] is used for the small cavities. In this approximation the field evolution over multiple reflections is calculated analytically by assuming all inputs change linearly during each time step. These equations are used to develop what we call *summation cavities*. Currently, three summation cavity modules are available: Fabry-Perot cavity, triangular cavity and recycled Michelson cavity. A dual-recycled summation cavity is under development.

These various modules are combined together to set up a simulation experiment of optics or opto-electronic system involving control loops. The simulation of mechanical systems involves: seismic ground motion, seismic isolation systems, suspension systems and actuation force driven by the control system. The computation by these modules give the motion of the mirrors in all 6 degrees of freedom (3 rotational and 3 translational) in time-domain. These mechanical motion are used in the corresponding optics modules, like mirrors in a FP cavity or LIGO. The responses of such a complete dynamical system are calculated by programs of the simulation engine.

We took much effort in validating various modules of the code by comparing with other available codes, like the frequency-domain program, *Twiddle* [11] for studying transfer functions of the longitudinal modes, the LIGO FFT model [12] and the Mathematica-based Modal model [8,13] for studying misalignment or mode-mismatch issues. Apart from that various tests have been performed to check self-consistencies among various effects on these modules.

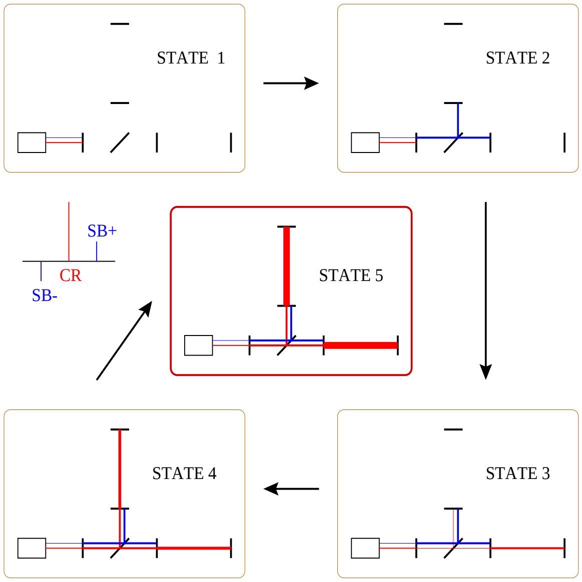

Figure 2: States of lock acquisition. *State 1:* Light just enters through the recycling mirror; Nothing is controlled. *State 2:* Sidebands(SB) resonante in the recycling cavity; The same cavity is held on a carrier(CR) anti-resonance. *State 3:* One of the End mirrors is controlled and carrier resonates in that controlled arm. *State 4:* The other ETM is controlled and carrier resonates in both arms and the recycling cavity. *State 5:* Power in the full interferometer is stabilized at its operating level.

3 Han2k Model and Lock Acquisition of LIGO

In January 2001 the Hanford 2 km interferometer became the first LIGO detector to achieve the locked state in its full power-recycled configuration. Due to reasons described above, the problem of achieving the desired locked state starting from the first entry of light through the recycling mirror is not a trivial problem. It needs a good step-by-step algorithm that takes into account evolution of fields due to mirror motion and changing resonant conditions of various cavities that are coupled to each other.

In order to help LIGO commissioners in this effort, a model of the interferometer, designated "Han2k" [14] was built up in the latter half of 2000. Its purpose was to design and develop the Hanford 2 km interferometer locking servo and simulate the major characteristics of length degrees of freedom under 20 Hz.

This model took the following into consideration: (i) Only longitudinal degrees of motion were considered everywhere (Field evolution with scalar field approximation). (ii) Effects of saturation of actuators, (iii) Simplified seismic motion and correlation, (iv) Analog Length Sensing and Control (LSC) system; The alignment sensing and control system was not modeled. (v) Frequency noise, shot noise and sensor, actuator and electronic noise were not included.

Figure 2 shows the step-by-step locking procedure followed for the full interferometer. The corresponding lock-acquisition code was developed in E2E. Essentially this code calculates signals at different states and invert those to the force necessary to move the mirrors in appropriate direction depending on the current state of the interferometer and in that way proceed toward the final operating condition. This code was directly ported to the real interferometer control system. When the actual interferometer acquired locked state, any typical field-evolution curve, as shown in Fig.3, followed essentially the same pattern in going from state to state as is observed in time-domain simulation runs of the "Han2k" model.

The lock-acquisition of LIGO interferometer had been the first major contribution of the time-domain simulation effort to the LIGO commissioning [15,16].

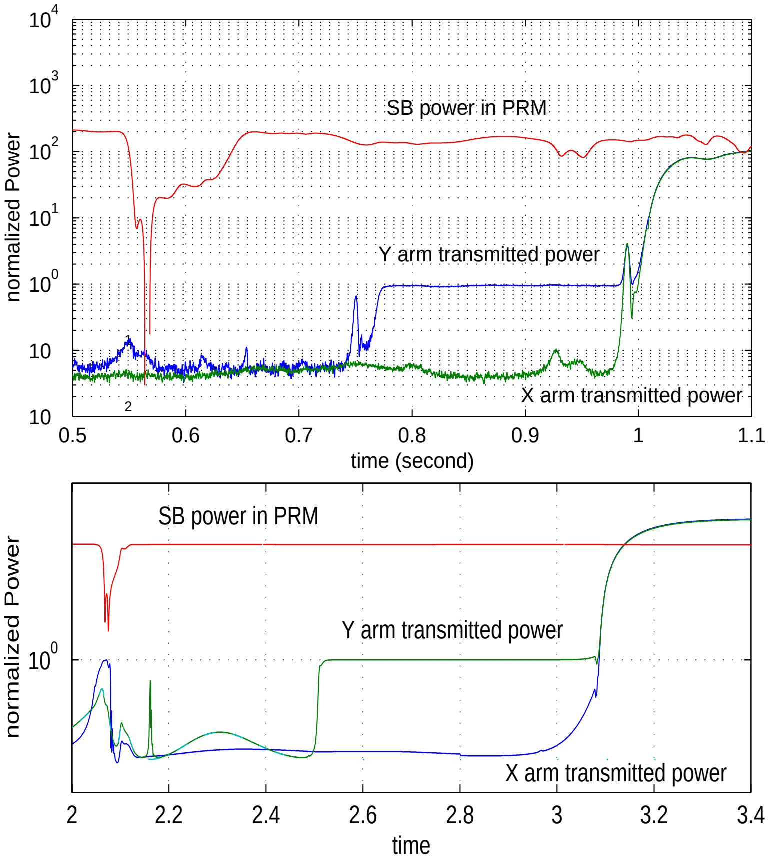

Figure 3: The lock-acquisition of Hanford 2 km interferometer. The top plots are from the actual lock acquisition process in the physical interferometer and the bottom plots correspond to those from E2E's simulation set-up. Both plots show changes in power as the interferometer goes from one state to other for finally acquiring the full locked state. The sideband (SB) power in PRM (Power Recycling Cavity) is normalized to the input sideband power multiplied by the RM transmittivity, whereas the other two curves in both plots are normalized to the one arm transmitted power in absence of RM.

4 SimLIGO Model and Study of LIGO Noise Sources

SimLIGO is the second generation LIGO simulation package. Han2k package was developed and used for the lock acquisition design, based on a scalar field calculation with minimal content in Interferometer Sensing and Control (ISC) system. SimLIGO is designed to be used for the noise simulation as well as the lock stability study of the as-built LIGO. One of its important objectives is to investigate the noise coupling mechanisms. Like a frequency-domain model, the time-domain simulation can be used to study the linear coupling of noise sources to the gravitational-wave signal. Unlike a frequency-domain model, it can also be used to look into bilinear or other more general nonlinear effects. Since these rather subtle and not well-understood nonlinear effects would be the main sources of difficulty in attempts to reduce the noise level in the physical interferometers, it is hoped that SimLIGO would be of good use for that effort.

In order to achieve that the following features have been included:

- Realistic correlation of seismic motions and 6x6 stack transfer functions of 3 translational plus 3 rotational degrees of freedom from ground to suspension point.
- Three dimensional mirrors, actuated by 4 OSEMs (Optical Shadow Sensor and Magnetic Actuator), with noisy coil drivers, enabling the simulation of the coupling between length and alignment degrees of freedom.

- Thermal noise: pendulum, wire and internal.
- Photon shot noise.
- Frequency and Intensity noise.
- Digitized Interferometer Sensing and Control (ISC) and digital suspension controler
- Realistic servo: Common mode servo implemented; Analogue to Digital Converter and vice versa (ADC-DAC) running at 16k and 2k, with whitening-dewhitening filter; Includes measured electronic noise sources.
- Alignment Sensing Control (ASC) system based on optical levers and Wave-Front Sensors (WFS).

Of course , a large number of other noise effects are not implemented in SimLIGO. Some important examples are: scattering, beam clipping, acoustic noises, noise originated from mode mismatch.

The simulation of the the Pre-Stabilized Laser (PSL) system and the Input Optics (IOO) system uses simple models based on their designed responses. Since these systems have too wide control bandwidth, the simulation takes too long computational time as compared to the simulation time of the interferometer itself. So, a design decision was made to use a simple model for the main interferometer simulation and a more sophisticated and detailed model of IOO is used to study specific problems of the mode cleaner. The building tool is ready and can be easily expanded.

Most of the major noise sources can be simulated as of now. The running conditions, including the noise levels and IFO parameters, can be easily tuned by editing a few input database files. Another advantage is that the user can easily switch on or off one or more noise sources for some specific studies in which (s)he wants to concentrate on some effects in which those noise sources may not be of consideration.

At present the speed of the simulation for this very detailed model is around 300 times slower (i.e., to simulate 1 second of reality, it takes 300 seconds) in a Xeon 3GHz Linux box when all noises and alignment degrees of freedom (with spatial modes upto order 2) are included. Speed improvement considerations (code improvements, compilers, more extensive use of thread, faster machines, etc) are now under investigation.

Figure 4 shows the comparison of the noise spectrum generated by SimLIGO for the Hanford 4 km (H1) interferometer with the current actual noise curve and the design sensitivity curve as described below:

- **H1** : A representative noise curve from the LIGO Science run 2.
- **SimLIGO H1** : This noise curve is generated by SimLIGO including most of the known non-fundamental noise sources in order to understand the gap between SRD and H1.
- **SRD** : The design sensitivity spectrum is referred to as the SRD (Scientific Requirement Document) curve. It takes into account only the fundamental noise sources, namely seismic, thermal and shot.

The details behind the differences found among SRD, H1 and SimLIGO-H1 curves are described in a LIGO technical note [17]. The aim behind generating the SimLIGO-H1 curve was to explain the current noise curve and so efforts were made to make the simulation settings as close as possible to the known reality. So, most of the electronic noise sources were enabled and the nominal level seismic noise value was used. However, the following points are worth noting: (i) It is known that the seismic noise level used for generating SRD was less than the measured

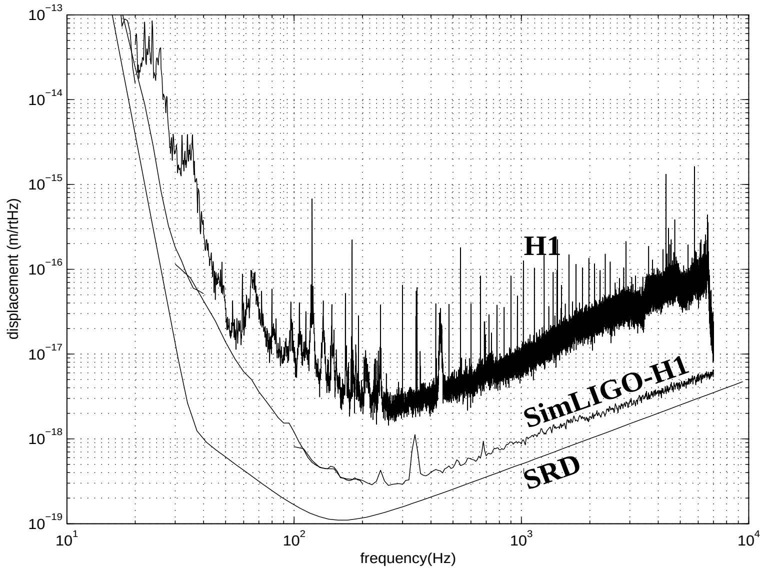

Figure 4: Simulated and actual noise curves of LIGO

value at Hanford. So, it is not surprising to find the seismic noise level in H1 or SimLIGO-H1 is higher than that in SRD. (ii) The input light to the interferometer is set to 5W (close to the design best value) in SimLIGO run, whereas during the Science 2 run of LIGO (when H1 spectrum was generated), the input power was about 0.8 Watt. This accounts for a contribution of about a factor of 2.2 in the existing larger difference between H1 and SimLIGO H1 at high frequency shot noise limit. It should be noted that, with input power that is much less than the design value, the mode matching was not very good during Science 2 run. As a result sideband power in the recycling cavity could not reach its maximum attainable level and that contributed to the higher level of shot noise in H1. SimLIGO run did not take this effect into account. (iii) In SimLIGO run only 25% of light was used at the dark port (because only one of the 4 photodetectors of the LIGO design was used when the H1 noise curve was generated) and most of the electronic noise sources were enabled and the nominal level seismic noise value was used. (iv) The broad peak at $\sim$ 330 in SimLIGO-H1 is actually the fundamental violin mode. The broadening of the width is an artifact due to the frequency resolution imposed by the limited simulation time.

We are currently investigating the reasons that give rise to the gap that exists between H1 and SimLIGO-H1. This work is still at a preliminary and unfinished level and so we donot elaborate much on these issues here. However, this exercise shows how a time-domain simulation model like E2E can be effectively used to study the noise sources of the interferometer and their individual or coupling effects.

5 Concluding remarks

As stated earlier, the end-to-end package provides tools for studying a wide range of planar optical configurations. So, besides the above two main models of the full LIGO system, many other simpler models for testing subsystems or some specific effects were built up and studied. On a number of occasions we could provide important feedbacks or insight to the LIGO commissioning team to resolve Physics-related issues or solve problems encountered.

More details and documents describing E2E software package and its design, models based on the package and physics behind E2E's simulation modules can be accessed from the website: http://www.ligo.caltech.edu/∼e2e

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