SimLIGO 020704: System Structure

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1 Introduction

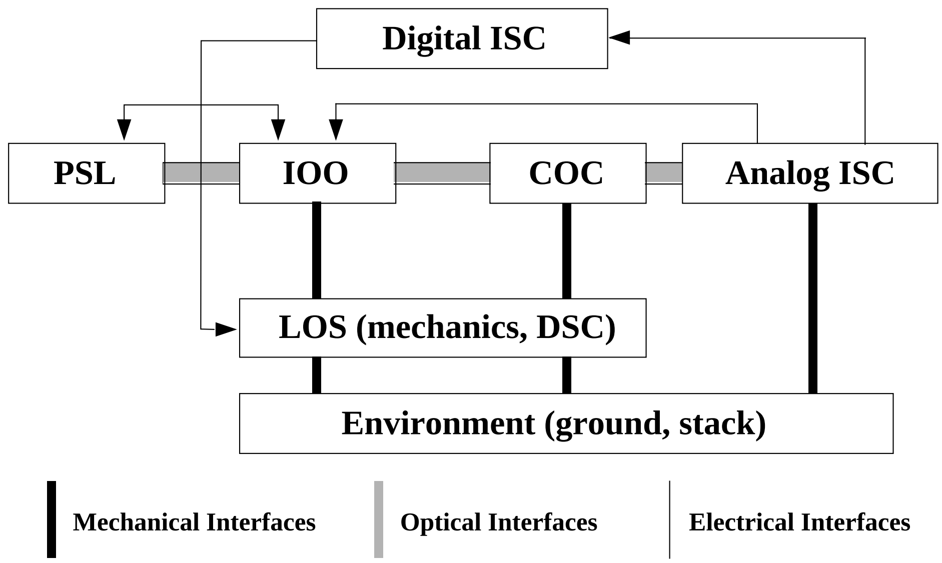
The LIGO End to End simulation package (E2E) has been developed to simulate the LIGO detector. E2E is a generic calculation environment, like matlab, which has many useful tools built in, including the time domain modal model for the field evolution calculation. Since E2E is a time domain simulation, it is not limited to linear response functions, making it an excellent tool for understanding bi-linear and non-linear systems. Because of it's modular design, it can be used to simulate a wide variety of detector configurations.

SimLIGO is a model of the first generation of LIGO detectors constructed in the E2E environment. Its primary objective is to assist in the understanding and reduction of noise in the LIGO detectors. Ultimately SimLIGO will help bring the detectors to their highest achievable gravitational-wave sensitivity.

2 Overview: The Detector

The SimLIGO detector simulation is made up of several separate subsystems. At the heart of the detector is an optical interferometer that acts as a spacio-optical transducer, converting gravitational distortions in space-time to phase modulations of optical beams. Built around this interferometer, the pieces of which are known as the "Core Optics Components" (COC), are several supporting subsystem. The input laser beam in provided by the "Pre-Stabilized Laser" (PSL) and arrives at the COC via a chain of "Input

Optics" (IOO). All of the core optics and many of the input optics are suspended by sophisticated suspension systems. The "Large Optics Suspension" (LOS) described below is one such system.



Detecting the state of the fields in the interferometer is important both as a mechanism for sensing the effects of gravitational waves and for holding the core optics at their operating points. The sensing subsystems feed their output into a filtering chain that leads eventually to a digital controller which exerts forces on the optics via their suspension systems. "Interferometer Sensing and Control" (ISC) is thus made up of two parts, the sensing electronics and the digital control system (the actuators are part of the suspension subsystem). These subsystems, along with the COC itself, are simulated in SimLIGO and are described below.

3 PSL-IOO

The PSL subsystem includes the laser source and the RF phase modulators. At present, this system is represented in very little detail since its noise spectra and input responses are wrapped in with those of the IOO.

The IOO subsystem, which includes the input optics and the modecleaner, is represented simply by a transfer function and two noise spectra.

The transfer function takes a voltage at the frequency correction input to the resulting phase shift imparted on the beam incident on the recycling mirror. The noise spectra represent the frequency and intensity noises seen at the recycling mirror in the absence of feedback from the COC.

4 COC

4.1 Optics

This subsystem represents the 6 core optics and simulates their interaction with the input field. The Power-Recycled-Michelson (PRM) is simulated by a "summation cavity" that allows the simulation to analytically compute internal field evolution over many round-trips in the cavity in a single time-step. The interferometer arms, which happen to serve the purpose of gravitational-wave transduction, are represented by a pair of propagators and an end mirror and interface with the PRM at the input test masses. The length of the propagators in the arms set the time scale for the simulation to a one-way-trip time in an arm (about 13 micro-seconds for the 4km interferometers).

4.2 Sensing: Analog ISC

The analog ISC electronics included in this subsystem are the photo-detectors (PD), mixers, filters, and analog-to-digital converters (ADC). The ISC system is divided into two disctinct components "Length Sensing and Control" (LSC) and "Angular Sensing and Control" (ASC).

There are three primary LSC PDs, one at each of the anti-symmetric, reflection and pick-off ports. Each of these sensors produces two demodulated signals (in-phase and quad-phase) which are passed through whitening and anti-aliasing filters and then digitized for use in the digital LSC system. Each filter in the chain is represented by a transfer function and noise level, both of which may depend on the state of the component's "knobs."

The ASC sensor array is comprised of 5 demodulated quadrant detectors each of which produces 8 signals. This system is considerably larger than the LSC system and is not included in this release of SimLIGO.

In addition to the ISC sensors, a collection of diagnostic sensors sense the properties of the beams exiting the COC. These sensors can, in principal, be anything, but in the present version of SimLIGO the diagnostic sensors are similar to the optical spectrum analyzers present in the physical detectors.

4.3 Suspensions

Each of the core optics, as well as MMT3, are suspended (see LOS below). The suspension point motion of each optic is computed from the environmental suspension point data for each stack and the orientation of the optic (see Environment below).

5 Digital ISC

The digital part of the Interferometer Sensing and Control (ISC) system consists primarily of two parts: the Length Sensing and Control (LSC) and the Alignment Sensing and Control (ASC). Each of these sub-systems, described in more detail below, is made up of an input matrix which translates the sensor signals into some convenient control basis, a set of filters for turning error signals into control signals, and an output matrix which translates the control signals into actuator signals.

5.1 LSC

The first step in producing control signals from demodulated signals is mixing them to make error signals for the canonical degrees of freedom (DARM, CARM, MICH, PRC). This mixing is done by the "Input Matrix." The input matrix can be thought of as a basis-rotation from the interferometers demodulation signal basis (AS_Q, REFL_I, REFL_Q, POB_I) to the degree-of-freedom (DOF) basis.

The second step is to filter the error signals for each DOf to produce control signals. The filters used in this step are similar to those used in the physical detectors and produce stable control servos for each DOF.

The final step is to convert the DOF control signals into control signals for each optic. There are many ways in which this mapping can be done, the one chosen in this version of SimLIGO applies the CARM and DARM signals to the ETMs, the MICH and PRC signals to the recycling mirror and beam-splitter, and leaves the ITMs uncontrolled by the LSC system.

5.2 ASC

The digital ASC system is not implemented in this version of SimLIGO.

6 LOS

The LOS subsystem is composed of two primary parts: 1) the mechanical system that supports, senses and actuates on the suspended optic and 2) the analog and digital electronics that connect that process the sensor signals to produce actuation signals and allow for input from the ISC.

6.1 Mechanics

The heart of the mechanical system is a model of the suspended optic. While this is, at first glance, a simple pendulum, a complete description of the system that includes all of its degrees of freedom is somewhat more complicated. The E2E implementation of this system includes all of the dynamics of suspension viewed as a collection of rigid bodies (e.g., the pitch-position coupling) as well as the bounce mode of the optic.

The position of the optic relative to its suspension cage is sensed by five shadow sensors (four on the back and one on the side, though the side sensor is not present in this version of SimLIGO). An optical lever also provides information about the angular position of the optic, in this case relative to the beam-tube/ground. Five coil-magnet actuators, co-located with the shadow sensors, are used to apply forces to the optic.

6.2 Digital Suspension Controller

Signals from the shadow sensors and optical lever are filtered (whiten and anti-alias) and digitized at 2048 Hz. Further filtering, both for stability and noise suppression, is applied in the 16384 Hz digital front-end. Signals from the ISC are added to the damping signals in the digital controller before they undergo a final stage of filtering necessary to to decouple the pitch and position drives. Finally, the control signals are broken into signal for each actuator, converted to analog, filtered (anti-image and dewhiten), and sent to coil-drivers.

7 Environment

In principle the environment "subsystem" includes all of the inputs to the system over which no real-time control is exerted (ground motion, acoustic excitation, electrical line noise, outside temperature and humidity, etc.), but in practice only the environmental effects which impact the detector most directly are included. The only environmental effect currently included is ground motion, which results in "seismic noise," discussed in the following section.

7.1 Seismic Noise

In order to simulate the seismic noise component of the detector noise spectrum, the motion of the suspension points of each optic, in all six degrees of freedom, must be generated with power and coherence spectra that are representative of those at the site. The ground motion at the base of each stack is generated in accordance with the measured ground motion at LHO and is transferred to the suspension point via a 6x6 set of transfer functions. There are different transfer matrices for each type of stack (BSC and HAM), based on the state space models provided by the stack designer (HyTech).