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Overview of the 40m End-to-End Model

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1 Scope

This proposal gives a brief outline of the 40m End-to-End model and suggests the experiments to validate the model within Recycling experiment.

2 Definition of the Model

The 40m End-to-End model (40m model, for short) is a part of the LIGO End-to-End model. Unlike the LIGO End-to-End model the 40m model does not include astrophysics or data analisys aspects of the gravitational waves detection.

The 40m model is a time domain model of the 40m power recycling interferometer with electronics and main noise sources. The program is written in C++ and uses a single time step digital filter paradigm.

The initial state of the model includes only longitudinal degrees of freedom of all the optics. It is limited by the cavity fundamental mode. Transverse modes of the cavities and therefore angular degrees of freedom for the suspended optics are not included. The imperfections of mirror coatings are not included.

This model will be used as a basis of the LIGO end-to-end model.

3 Structure of the Model

3.1 Modeled 40m Subsystems

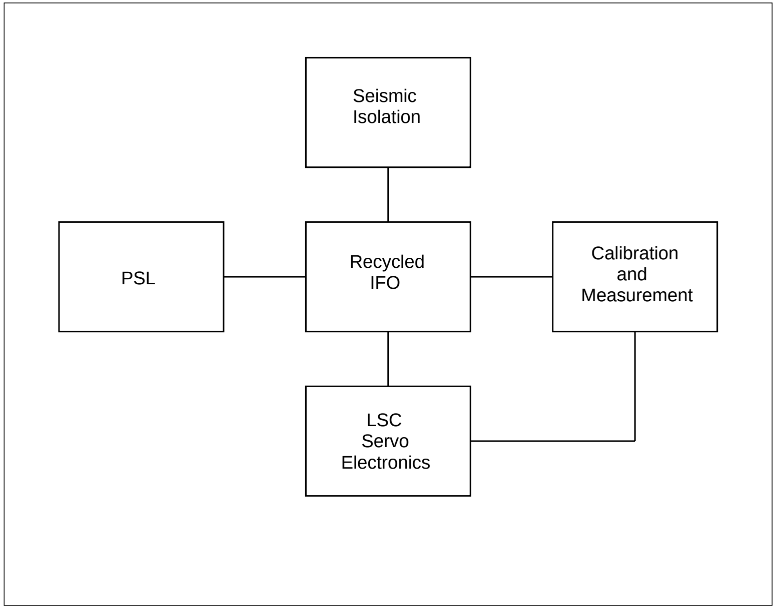
The structure of the 40m model is similar to the structure of the 40m interferometer. The model is naturally divided into several subsystems. The subsystem is a collection of of modules, connections, parameters, as well as input and output data files. Often model subsystem corresponds to a real 40m subsystem with the same name.

The 40m model consists of the following subsystems:

1. Seismic Isolation
2. Pre-Stabilized Laser (PSL)
3. Power Recycling Interferometer
4. Length Sensing Servo Electronics
5. Calibration and Measurement Electronics

The diagram of the subsystems and schematic connections is shown on Fig.1.

Figure 1: 40m Model Subsystems



3.2 Modeled Noise Sources

The model includes the following noise sources

- *Seismic noise.* The seismic motion of the ground enters the model after it is filtered through the seismic isolation stack.
- *Thermal noise.* The thermal noise includes resonances of the Test Masses, Suspension Wires and the Mode Cleaner.
- *Shot noise.* The shot noise is the non-stationary Poisson pulses created at the photo-detectors.
- *Laser frequency and amplitude noise.* The Laser source is characterized in the model by the time domain amplitude and frequency noise with given spectra.
- *Oscillator phase and amplitude noise.* Although we do not directly model RF electronics due to computation speed limitations, we can incorporate low frequency ($\leq$ 10 kHz) amplitude and phase noise of the RF Oscillator.
- *Magnetic field fluctuations.* External magnetic fields at the test mass coils affect displacement of the test masses. These effects can be easily modeled if the measurements of the magnetic field fluctuations are available.
- *Electronics noise.* All electronics modules introduces noise in the system. Due to model scope limitations we model only few major electronics noise sources.

4 Description of the Subsystems

4.1 Suspension and Seismic Noise

The model generates time domain seismic motion of the top plate, which serves as a support for the suspension. The motion of the top plate is ground motion filtered through the seismic isolation stack. Only longitudinal motion (along the beam) is included in the current version of the model. The next stage of the model will include transverse laser modes and the mirror orientation controls.

The suspension model takes motion of the top plate as an input and provides position of test masses as an output. The output of the suspension subsystem serves as one of the inputs for the IFO subsystem of the model.

4.2 PSL

PSL subsystem model consists of modeled laser frequency and amplitude noise, the Mode Cleaner cavity with its resonances and other elements.

The output of PSL is the frequency and amplitude of the laser with noise suppressed to the specified levels. The frequency and amplitude of the laser serves as an input for the interferometer subsystem.

4.3 Power Recycling Interferometer

The Recycling IFO consists of two 40m arm cavities combined into Michelson interferometer and the Recycling cavity.

In addition to optical cavities the IFO part includes phase and quadrature demodulation signals. The resonances of the Test Masses, the Suspension Wires are also included into the model.

4.4 Length Sensing Servo Electronics

Four input - four output length sensing servo. The four loops consist of various electronics modules. All of them are modeled by digital filters. The following are few main modules of the servo electronics

1. Differential Mode Servo
    - 5-pole 8 kHz Butterworth filter
    - DM Coil Driver
    - Recomb Coil Driver
2. Common Mode Servo
    - CM Servo Preamp
    - MC Piezo Drive Filter
    - Insertion Amp

  - CM Coil Driver

3. Beam Splitter Servo
   - Recomb BS Servo Amp
   - SR-560

The Recycling Mirror Servo is similar to the Beam Splitter servo. Its components will be soon installed at the 40m.

4.5 Measurement and Calibration Electronics

The model incorporates few measurements electronics devices used to perform standard measurements at the 40m. These are

- Fourier transforms and Spectra of various signals
- MC and Arm cavity Ringdowns
- Displacement Calibration
- Calibrated Power spectrum (sensitivity measurements)

The power spectra are necessary to characterize the noise performance of the interferometer. This is done by HP3563A spectrum analyzer. In the model this device will be mimicked by the FFT-module. The FFT-module will provide Fourier transform of various signals. Few additional features as power spectrum, Fourier domain filtering will be built into the model.

In the ringdowns measurements provide the cavity storage time.

The calibration is necessary for defining the scale for the sensitivity plots. The 40m model will include the read-out chain and feedback loops to simulate such measurements.

The power spectrum together with the calibration result in the sensitivity of the interferometer.

5 Requirements for Agreement between the Model and 40m

5.1 Limitations of the Model

Comparison between the model and the 40m depends on range to which the model is valid. The model being a simplified description of the real physical system is inherently limited in its predictions.

The limitations of the model comes from

1. *Unmodelled effects.* A number of effects are not modeled.
2. *Approximate values of the parameters input into the model.* This happens when precise values of the parameters are not available.

3. *Approximations made in the model*. The algorithms in the model are based on analytical expressions that have a limited range and inevitably introduce errors into the model.

4. *Numerical (round-off) errors in the model*. These errors reduced to minimal by running self-consistency checks on the model.

5.2 Qualitative and Quantitative Agreement

The criteria for agreement between modeled and experimental performance of the 40m are not known at the present. In the process of validation these criteria will be worked out.

In situations when the model is limited only qualitative agreement will be required. Otherwise, quantitative agreement will be necessary to achieve. The degree of the discrepancy between the model and experiment needs to be explained based on the above limitations of the model.

However, in certain cases the agreement may not be achieved because of the imperfections of the real system. The real 40m interferometer deviates from the designed performance in many ways. Some of them are not well understood and difficult to measure. The following are just a few examples of these deviations:

- slow temperature variations associated with a daily cycle,
- fast temperature variations due to laser heating of the optics,
- fast temperature variations due to heating of the electronics,
- electrostatic charges on suspended optics and accidental discharge,
- RF pick-ups in the electronics,
- ground loops,
- drift of the settings and offsets in electronics,
- mechanical imperfections in the electronics gain verniers.

The slow variations will not affect the agreement drastically. However, those imperfections that have characteristic times comparable to experiment and model run time will affect the agreement between the model and the experiment.

6 Experiments at the 40m

The scope of experimental work can be divided into two main parts

- Subsystems Construction
- Model Performance tests

6.1 Subsystems Construction

In the process of construction of the model we need to

- identify various optics and electronics elements to be modeled,
- get relevant parameters for these elements (cavity lengths, amplifier gains, transfer functions of servos and etc.)
- specify features to be present in the model (monitoring ports, gain adjustments, switches and etc.)

6.2 Model Performance Tests

The performance evaluation tests are various experiments to provide comparison between the model and the 40m. The tests will be performed on the level of the individual modules, subsystems and the entire interferometer.

Checking the performance of the modeled elements and subsystems will be done against

- design specifications (those parameters are easily available),
- real performance of the 40m devices.

Checking against performance of the real 40m subsystems includes experiments and measurements of parameters within the range of interest. Often to show the agreement we will need to vary the parameters of the model and the 40m over a largest possible range.

7 Proposed Measurements

7.1 Characterization of Fabry-Perot Cavities

7.1.1 Arm Cavity Parameters

1. Repeat the measurement of the Arm cavity length (coating-to-coating).
2. Infer input and end test mass transmission and losses through ringdown measurements.
3. Calibrate Symmetric, Antisymmetric and two Arm cavities transmission photodiodes for absolute DC light power. This will allow accurate measurements of the cavity optical power gain and visibility.

7.1.2 Cavity Dynamics with Open Loop

1. Study the characteristic high frequency oscillating signal in the demod-out during fast motion of the test masses through successive resonances.
2. Measure relative velocity of the test masses. Measure threshold velocity.
3. Study saturation characteristics of electronics with loop open (no feedback applied to the arms). Develop limiters for the model.

7.1.3 Cavity Dynamics with Closed Loop

The following transfer functions of the Fabry-Perot cavity will be measured and compared with the modeled results:

1. End Mirror → Demod-out
2. Laser phase modulation → Demod-out
3. Laser amplitude modulation → Demod-out
4. Oscillator phase and amplitude modulation → Demod-out

7.1.4 Characterization of Mode Cleaner

The Mode Cleaner is Fabry-Perot cavity with mirrors glued onto the Quartz Spacer. Since the range of motion of the Mode Cleaner mirrors is limited slightly different tests are needed for the Mode Cleaner:

1. Obtain transmissions and losses of the Mode Cleaner mirrors.
2. Measure efficiency of the PZT
3. Measure the range of the mirror motion
4. Measure Mode Cleaner visibility and transmitted power.

7.2 Interferometer Characterization

7.2.1 Recombined Interferometer

A set of experiments to validate the model of recombined interferometer will be performed before we do tests of the model with the recycling interferometer.

In the following experiments we compare the modeled and real performance for recombined interferometer:

1. *Simple Michelson interferometer*. In this experiment both End Test Masses are misaligned and the Beam Splitter is at the dark fringe.

2. *Michelson and Common Mode*. In this experiment one Arm Cavity is in lock and the Beam Splitter is at the dark fringe.

3. *Full Recombined Interferometer*. Both Arm cavities are in lock and the Beam Splitter is at the dark fringe.

7.2.2 Power Recycling Interferometer

The following are various configurations of recycling interferometer. Some of them may not be feasible. Both the model and real interferometer should similar behavior in these configurations.

1. *Recycling cavity*. In this experiment both end test masses are misaligned and either in-line or perpendicular recycling cavity is locked.

2. *In-line Double Cavity*. Arm 1 (East Arm) is aligned and SV is blocked. BS has no effect in this setup.

3. *Perpendicular Double Cavity*. Same as (1) but with Arm 2 (South Arm) aligned and EV blocked. This is slightly more complicated setup than in (1) because Beam Splitter needs to be controlled.

4. *Recycling Michelson Interferometer*. In this experiment both End Test masses are missalgned, the Vertex Test Masses form Michelson interferometer and Beam Splitter is at the dark fringe.

5. *Recycling Michelson and Common Mode*. In this experiment one Arm cavity is in lock and Beam Splitter is at the dark fringe.

6. *Power Recycling Interferometer*. Both Arms are in lock and Beam Splitter is at the dark fringe and Recycling mirror is at resonance.

7.3 PSL Characterization

7.3.1 Ar^+-Laser Characterization

1. Measure various parameters of PSL.

2. Measure Laser frequency and amplitude noise with Laser loop open.

3. Measure MC resonance frequencies and Q’s.

4. Measure Laser frequency noise with Laser loop closed (PSL locked, Arm CM loop open)

5. Measure intensity noise with power stabilization on (may require additional AOM)

7.4 Calibration and Measurement Subsystem Building

Calibration and Measurement is a subsystem of the model that allows to perform measurements within the model. It includes the module that performs Fourier transformations on various signals and calculates Power Spectra of these signals in the model. The subsystem can perform displacement calibration of the model similar to the one done at the 40m interferometer.

The ringdown measurements are also done within the model. The subsystem turns on the modulation of the input light intensity and measures the light transmitted through the arm cavities. The measured trace then can be processed by the LabView ringdown program.

7.5 Suspension Characterization

1. Measure seismic noise at the 40m. The seismic motion of the ground is filtered through the Seismic Isolation Stack. The residual motion excites the Top Plate that supports the Suspension. The stack is not modeled at the present. The Suspension is modeled. The model takes motion of the Top Plate as an input for the suspension subsystem.
2. Measure or obtain parameters of the Suspension: Suspension Wire lengths, the Wire resonant frequencies and their Q's, PZT efficiency and etc.
3. Characterize velocity-proportional damping servo and other electronics filters in the loop.
4. Generate time domain motion of the Test Mass in the model under the influence of the seismic noise with the damping ON and OFF.
5. Measure the relaxation times and compare them with the model.
6. Compare response of the model and the real system to step function, pulse function etc.
7. Compare the modeled and real traces of the motion of the top plate, Test Mass and the Suspension Wire in time domain. Obtain spectra of the motion. Compare the modeled and real spectra.

7.6 Servo Electronics Characterization

The characterization of electronics for the model can be done in two ways. For existing electronics modules we need

1. measure the transfer function of the 40m electronics modules.
2. measure the overload characteristics of the electronics.

For recycling mirror servo we input the transfer functions into the model from the design specifications and later measure them at the 40m.

8 Noise Spectrum Measurements

After the model showed agreement with the 40m interferometer in all the above tests and the interferometer locking sequence is understood the noise performance becomes important. The sensitivity of the 40m Power Recycling Interferometer should be limited by shot noise within the bandwidth of interest. In general the model and the real interferometer should have the same contributions for the following noise sources:

1. Shot noise
2. Thermal noise
3. Seismic noise

9 Future Development

The following are possible extensions of the model in future:

- *Seismic isolation stack.* The seismic isolation stack is not included in the present stage of the model. In future we can obtain the transfer function of the stack and measure the seismic motion of the ground. This will be more realistic model but more complicated model.
- *Transverse cavity modes and angular degrees of freedom.* In the next stage model will include the transverse modes of the optical cavities, angular degrees of freedom of suspended optics and phase front sensing electronics. The imperfection of mirror coatings will also be included.