LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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LSC CDS Design Requirements

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1 INTRODUCTION

The LSC subsystem provides for all aspects of interferometer length control involved in maintaining the signal sensitivity required for LIGO. This includes:

- Support for the Lock Acquisition, Detection, Calibration and Diagnostics Modes of operation.
- The photodetectors and related protective hardware.
- RF source, phase shifters, mixers, cabling.
- LSC control electronics, and signal processing software used in the feedback control portion of the servo loops.
- Any hardware and/or algorithms for calibrating the gravity wave readout.

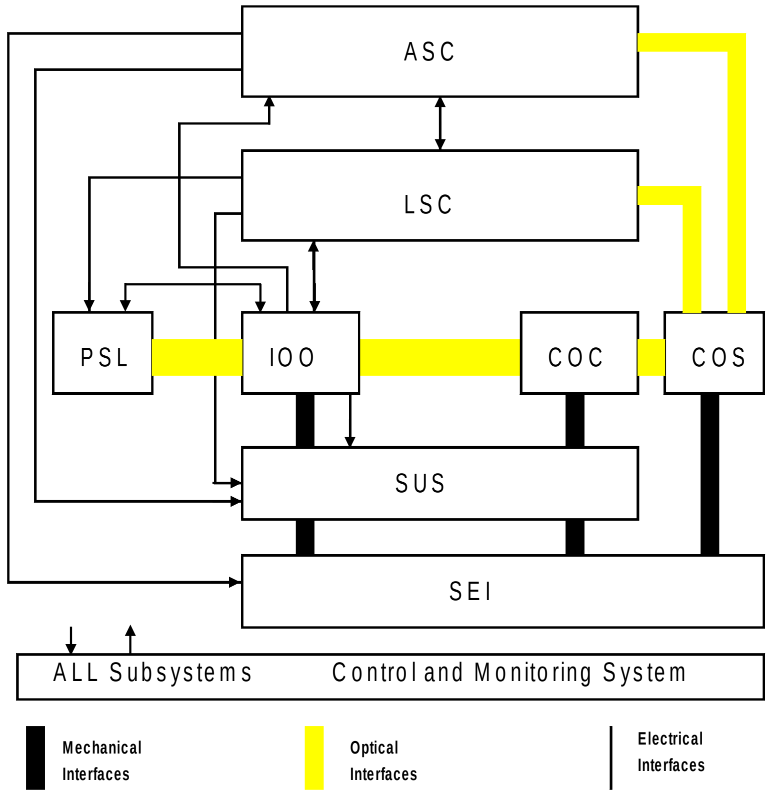
Not included in the LSC scope is any aspect of the performance of the LIGO optics, interferometer alignment, production of light or actuation of input light stabilization. It does not include the suspension or seismic isolation actuators, beam shaping optics, vacuum system viewports or hardware, or phase modulators. It also does not include the suspension control actuators in the feedback path which drive the suspended optics.

Since most of the LSC system is electronics the requirements contained in this document are essentially those of the LSC DRD (LIGO-T960058-03) and the LSC PDR (LIGO-T970122-00) at this stage of the design.

2 LSC SUBSYSTEM DESCRIPTION

The initial LIGO detector system consists of three power-recycled Michelson interferometers with Fabry-Perot cavity arms, a 2 Km and 4 Km interferometer at Hanford and a 4 Km interferometer at Livingston. The LSC subsystem provides the control to bring the interferometer lengths to resonance with the light source, sense deviations from resonance and apply the necessary corrections to the Suspension Subsystem (SUS) to cancel them. The LSC also provides a control loop correction to tune the laser frequency of the prestabilized laser (PSL) and provide the calibrated gravity wave readout to the Data Acquisition subsystem (DAQ). This document is part of an overall LIGO detector requirement specification tree. Refer to the SYS DRD for a diagram of the tree.

2.1. Subsystem Block Diagram



2.2. Modes of Operation

The LSC CDS shall be capable of supporting the operational modes described below.

2.2.1. Acquisition Mode

Acquisition Mode refers to the state in which the interferometer lengths are brought into resonance from their initial uncontrolled values. The PSL and IOO subsystems are assumed to be fully operational in this mode. The primary function of the LSC in this mode is to lock the interferometer. After lock a settling time is required. Wire and mirror resonances are permitted to settle down (or are actively damped), filters are allowed to equilibrate, control ranges are adjusted, and self tests are completed to verify that residual excitations do not exceed Detection Mode limits.

2.2.2. Detection Mode

In this mode the interferometer lengths are maintained at a level of stability which allows detection of strain signals within the LIGO sensitivity specifications. The functions in this mode are:

- sense and control the four interferometer lengths and the input laser frequency
- provide a measure of the residual deviations of the four lengths and the laser frequency
- provide a calibrated readout of the interferometer strain

2.2.3. Diagnostics & Calibration Mode

This is a mode (in fact a set of modes) that may be accessed from the preceding modes. The functions of this mode are:

- provide diagnostic capability to determine the performance of the LSC
- enable implementation of calibration procedures within the LSC
- support diagnosis and calibration of other subsystems

2.3. LIGO SRD requirements

The following requirements on the LIGO detector sensitivity and availability, as given in the Science Requirements Document, directly influence some of the requirements for the LSC CDS described in the following sections.

1. Sensitivity: The initial LIGO displacement sensitivity requirement is given in the SRD. The displacement requirement, $\mathbf{x}$, is defined such that the strain sensitivity is $h(f) = \mathbf{x}(f)/ L$, where L = 4 km; i.e., $\mathbf{x}(f)$ is the differential arm length sensitivity.
2. Availability goals: 90% for single interferometer operations; 85% for double coincidence; 75% for triple coincidence.

2.4. Assumptions and Dependencies

It is assumed that all of the other subsystems are fully operational in order for the LSC subsystem to perform its role. In addition the following assumptions (taken from the LSC DRD LIGO-T960058-03) apply to the LSC CDS and are included here for reference. A change in any of these assumptions may necessitate a change in the LSC CDS requirements.

2.4.1. PSL performance

- Fractional power fluctuations in the GW-band at the interferometer input are to be controlled to level less than or equal to *twice* the curve given in Figure 3 of this document.

2.4.2. COC parameters

- The maximum difference in the round trip loss between the two arm cavities is assumed to be 75 ppm.
- The maximum total power at the anti-symmetric port during normal operation (locked and aligned interferometer) is assumed to be 600 mW, for 6 W total input power.
- Storage time unbalance between the arms. The storage time difference can be as large as 5%, and still not affect the frequency noise requirement, which will remain dominated by the round trip loss difference quoted above.

2.4.3. Mode Cleaner – match of free-spectral-range to modulation frequency

We assume that the RF modulation frequency is within 100 Hz of the center of the mode cleaner resonance through which it passes. This involves initial setup of the mode cleaner length and the oscillator frequency, and also the long term stability of the length of the mode cleaner. Specifically, if there is no post-setup control of the oscillator frequency, the length of the mode cleaner must be stable to ~50 μm.

3 RF MODULATION AND DEMODULATION REQUIREMENTS

3.1. RF Modulation Source

To obtain the needed signals for controlling the lengths of a LIGO Interferometer operating in Detection mode, the laser light injected into the interferometer will be composed of the carrier frequency and 1 set of sidebands; the carrier resonates in both the arm cavities and the recycling cavity while the sidebands resonate only in the recycling cavity. A second set of sidebands, non-resonant in the interferometer, will be introduced so that the ASC wavefront sensing scheme will have the necessary signals for controlling the angular orientation of the test masses. The length control system will not use the non-resonant sideband for signal detection, but will provide the signal waveform source. The IO system is responsible for the electrooptic actuation system which will impose these modulation products on the incident laser beam and transmit them through the IO mode cleaner. The modulation source requirements are given in the LSC DRD (LIGO-T90058-03) and LSC PDR (LIGO-T970122-00). The baseline requires at least two and possibly three distinct modulation frequencies. The current baseline frequencies are:

1. The Resonant Sideband frequency used for all length sensing functions; 29.449 MHz for the 2 Km and 24.463 MHz for the 4 Km.
2. The Nonresonant Sideband frequency used for ASC wavefront sensing purposes; 19.62 MHz (TBR) for the 2 Km and 36.79 MHz (TBR) for the 4 Km.
3. The Mode Cleaner Length Sensing frequency which (if used) will be for the sensing and controlling of the mode cleaner cavity; 9.816 MHz for the 2 Km and 12.231 MHz for the 4 Km.

3.2. Demodulator Requirements

1. The demodulator frequency shall be (TBD) for the 4 Km interferometer and (TBD) for the 2 Km.
2. The IF bandwidth shall be (TBD).
3. The dynamic range shall be (TBD).
4. The input referred noise for the demodulators shall be (TBD).

4 RF PHOTODIODE REQUIREMENTS

One of the critical items to be developed for the LIGO interferometers are the Photodetector (PD) Assemblies, which are required to monitor continuous laser beams at various locations. The detailed requirements are given in the LSC PDR (T970122-00). Included here for reference is a subset of those requirements for the electronics.

4.1. Photodiodes

- The photodiodes require a 10 volt bias voltage.
- The bias supply must provide 200 ma of continuous DC current at 10 volts and 400 ma transients for more than 1 msec
- The bias supply must have a current interrupt for DC current 20% above the steady DC current for about 1 msec.
- Each photodiode must have an independent DC and RF amplifier and DC current limiter.

4.2. RF Amplifier

- Each channel will have an active electronic bias voltage cutoff for transient currents of more than 20% of the nominal power and durations of more than 1 msec.
- The input referred electronic noise of the RF amplifier should be less than $1.2nV\sqrt{Hz}$.
- The gain of the RF amplifier should nominally be 10.
- The gain must be linear for RF input voltages up to 100mV.
- The circuit must be tuned to resonate at 25 MHz with a Q of (TBD).
- The circuit will have a frequency trap tuned to twice the resonant frequency such that the second harmonic is attenuated more than (TBD) dB down from the modulation frequency.

4.3. DC Amplifier

- The DC amplifier should provide a linear output for up to 200 ma of continuous DC input current.

- It should have a gain of (TBD).

5 SERVO ELECTRONICS REQUIREMENTS

The LSC derives its requirements from the top level LIGO requirements for the sensitivity and availability, and from secondary requirements imposed by interactions with other IFO subsystems and the LIGO facilities. These secondary requirements are defined and allocated in conjunction with Detector Systems Engineering.

The LSC electronics noise in the gravity wave readout channel must be no greater than 10% of the signal corresponding to the LIGO SRD sensitivity, $x(f)$, in the gravity wave band of 40 Hz - 10 KHz. The suspension controller is a part of this loop but is not a part of the LSC subsystem. The noise contribution from the suspension controller is considered separately. For the purpose of assessing the LSC performance against this requirement, the suspension controller is considered to be noiseless. This requirement encompasses the electronic noise in all LSC photodetectors, mixers and servo electronics.

5.1. Acquisition Mode

The time duration of the acquisition mode must be compatible with the LIGO availability requirement. The acquisition process is a combined process of the LSC and the ASC to bring the interferometer to the proper operating point for normal detection mode operation. We require that the time duration of the acquisition process not significantly impact the Detector availability.

5.2. Detection Mode

5.2.1. Noise Requirements

The noise requirements relevant to the servo design are listed below.

1. Arm cavity differential mode loop (driven by intensity noise specification)
- $|L_1-L_2| < 10^{-13}\ \mathrm{m_{rms}}$
- Loop gain < 10^{-7} at 6.79 KHz (first test mass resonance)
- Electronic noise contributed by this loop must be at or below the LIGO strain requirement at all frequencies.

2. Recycling cavity differential mode loop (driven by specification for dark asymmetric port)
- $|l_1-l_2| < 10^{-9}\ \mathrm{m_{rms}}$
- Loop gain < 10^{-7} at 3.58 KHz (first test mass resonance)
- Electronic noise in this loop must be at least a factor of 10 below the shot noise in the L_1-L_2 loop at frequencies above 200 Hz.

3. Arm cavity common mode loop (driven by specification to maximize power in the cavity)
- $(k_l \cdot l_+) \le 9 \times 10^{-6} radians$
- Gain at 1 Hz must be at least a factor of 130 greater than the gain at 1 Hz in the Michelson interferometer common mode loop.
- Electronic noise contributed by this loop must be at least a factor 10 below the shot noise in

the L_1-L_2 loop at frequencies above 200 Hz.

4. Recycling cavity common mode loop (driven by specification to maximize power in the Michelson interferometer).

- $|l_1+l_2| < 1.25\text{x}10^{-10}\ m_{rms}$
- Loop gain < 10^{-7} at 6.79 KHz (first test mass resonance)
- Electronic noise contributed by this loop must be at least a factor 10 below the shot noise in the L_1-L_2 loop at frequencies above 200 Hz.

5.2.2. Dynamic Range

The dynamic range for each of the servo loops must be sufficient to suppress the seismic noise at the summing junction over the frequency range TBD for that loop. The dynamic range for each stage of the loop must be sufficient to keep any component from saturating more than TBD percent of the time during normal operation.

5.3. Diagnostic and Calibration Mode

This is a mode (in fact a set of modes) that may be accessed from the preceding modes.

5.3.1. Calibration

The following requirements apply to the accuracy of the calibration of the gravity wave readout channel in the band of 40 Hz - 10 KHz:

- Amplitude: better than ± 5%
- Timing: better than ± 50 µsec

The readout of the three auxiliary lengths must be accurate to within ± 10% in amplitude and ± 100 µsec in timing in the 40 Hz - 10 KHz band.

5.3.2. Diagnostics

The LSC must be able to perform diagnostics to determine the proper functioning of the LSC in Detection Mode, and to support the operation of the interferometer in a subset of alternate optical configurations (single cavity, etc.). The following functions must be provided for:

1. Determination of closed loop transfer functions of the control loops.
2. Determination of offsets in the lock-points.
3. Determination of gravity wave detection band noise produced by the LSC.
4. Monitoring of feedback forces applied to the controlled optics.

The LSC must also be able to support more global diagnostics involving other detector subsystems.

5.4. Suspension System (SUS) Interface

Each suspended optic controlled by the LSC electronics has a suspension controller between the LSC servo controller output and the suspended optic. Each of these suspension controllers will have a single input from the LSC. This interface has the following characteristics (TBD).

6 RELATED SUBSYSTEMS AND INTERFACES

6.1. Input Optics and Prestabilized Laser Interface

The LSC makes the final corrections to the laser frequency through frequency actuators in the IOO subsystem. Specifically, there are two inputs to the IOO for frequency actuation: one for control of the mode cleaner length, and a second that is a summing input to the IOO frequency stabilization loop after the mode cleaner demodulator (i.e., the additive offset). Both inputs will be used, the former at low frequencies and the latter at high frequencies. Separate inputs to the IOO are retained so that the LSC has control over the cross-over between them. This configuration and the interface are detailed in **LIGO-T970088-00-D,** *Frequency Stabilization: Servo Configuration & Subsystem Interface Specification.* The interface specification from this document is detailed in the LSC PDR (T970122-00).

6.2. Alignment Sensing and Control Interface

The LSC must provide lock status information to the ASC subsystem (TBD).

6.3. Data Acquisition Interface

The interface to the Data Acquisition system is TBD.

6.3.1. ADC Channels

7 ENGINEERING DRAWINGS & DOCUMENTATION

8 SAFETY

This item shall meet all applicable NSF and other Federal safety regulations, plus those applicable State, Local and LIGO safety requirements. A hazard/risk analysis shall be conducted in accordance with guidelines set forth in the LIGO Project System Safety Management Plan *LIGO-M950046-F, section 3.3.2.*