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- LIGO -
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ASC CDS Design Requirements Document

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Abstract

This technical note is being generated to outline the design requirements for the ASC CDS. It covers all electronics hardware and software, cabling, and control and monitoring requirements for the system.

1 INTRODUCTION

1.1. Purpose

This specification establishes the performance, design, development and test requirements for the ASC CDS of the Laser Interferometer Gravitational Wave Observatory (LIGO).

1.2. Scope

The specific items to be designed and implemented through use of this requirement specification include:

- All electronics and cabling required to control and monitor the ASC.
- All control and monitoring hardware and software required.

1.3. Definitions

ASC CDS: All electronics hardware and software provided by the LIGO CDS group for use in controlling and monitoring the LIGO ASC system.

1.4. Acronyms

- ASC- Alignment Sensing and Control
- CDS- Control and Data System
- ETM- End Test Mass
- ICD- Interface Control Document
- IFO- Interferometer
- IOO- Input/Output Optics
- ISCC- Interferometer Sensing and Control Computer
- ITM- Input Test Mass
- LIGO- Laser Interferometer Gravitational Wave Observatory
- LSC- Length Sensing and Control
- LVEA- Laser and Vacuum Equipment Area
- MTBF- Mean Time Between Failure
- MTTR- Mean Time To Repair
- PSL- Pre-Stabilized Laser
- QMPD- Quadrant Monitor Photodiode
- QMPU- Quadrant Monitor Processing Unit
- SUS- Suspension System
- TBD- To Be Determined
- WFS- Wavefront Sensor
- WPU- Wavefront Processing Unit

1.5. Applicable Documents

1.5.1. LIGO Documents

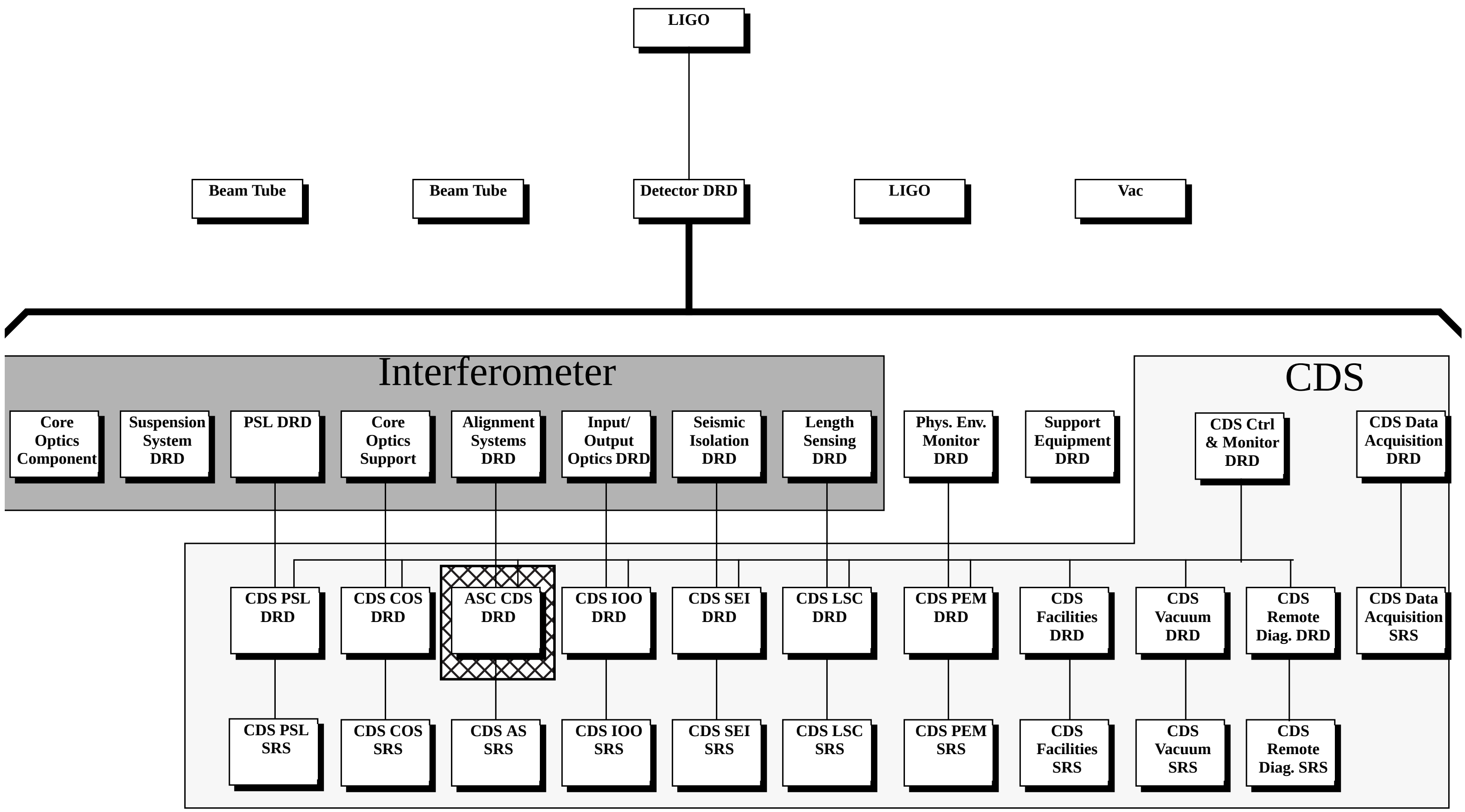
- **LIGO-T9520070-03-I** Alignment Sensing/Control Design Requirements Document
- **LIGO-T960134-00-D** Alignment Sensing/Control Conceptual Design
- **LIGO-T970060-00-D** Alignment Sensing/Control Preliminary Design
- **LIGO-T960111-00-D** Wavefront Sensor
- **LIGO-G960183-00-D** ASC Design Requirements Review Viewgraphs

1.5.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

2.1. Specification Tree

This document is part of an overall LIGO detector requirement specification tree. This particular document is highlighted by a cross hatched background in the following figure.


LIGO
Beam Tube
Beam Tube
Detector DRD
LIGO
Vac
Interferometer
CDS
Core Optics Component
Suspension System DRD
PSL DRD
Core Optics Support
Alignment Systems DRD
Input/ Output Optics DRD
Seismic Isolation DRD
Length Sensing DRD
Phys. Env. Monitor DRD
Support Equipment DRD
CDS Ctrl & Monitor DRD
CDS Data Acquisition DRD
CDS PSL DRD
CDS COS DRD
ASC CDS DRD
CDS IOO DRD
CDS SEI DRD
CDS LSC DRD
CDS PEM DRD
CDS Facilities DRD
CDS Vacuum DRD
CDS Remote Diag. DRD
CDS Data Acquisition SRS
CDS PSL SRS
CDS COS SRS
CDS AS SRS
CDS IOO SRS
CDS SEI SRS
CDS LSC SRS
CDS PEM SRS
CDS Facilities SRS
CDS Vacuum SRS
CDS Remote Diag. SRS

2.2. Product Perspective

The ASC CDS portion of the LIGO detector provides all electronics hardware and software necessary to control and monitor each of the ASC systems. The ASC systems are:

- Optical Levers
- Wavefront Sensors (WFS)
- Quadrant Monitor Photodiodes (QMPD)
- Cameras

The figure below shows the ASC CDS in relation to each of these systems and other interferometer systems.

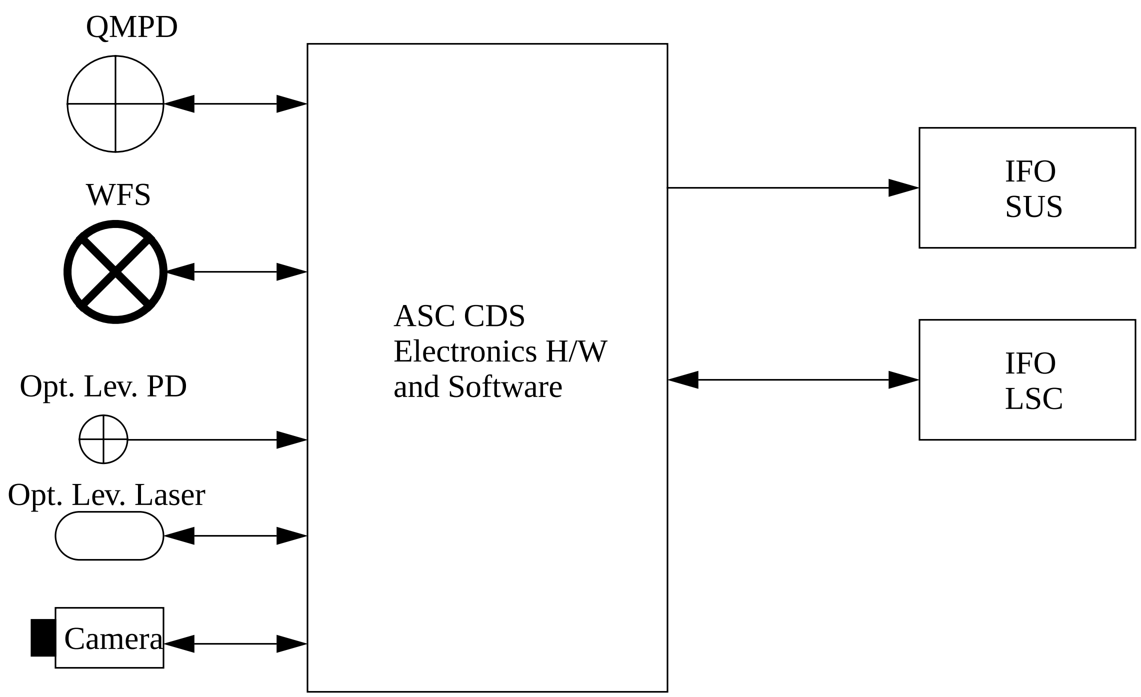


Figure 1: ASC CDS Product Perspective

2.3. Product Functions

The ASC CDS provides all electronics hardware and software for the ASC optical levers, wavefront sensors, cameras, and quadrant monitor photodiodes. The function of each of these systems is:

- ASC Optical Levers- The optical levers provide for the monitoring of the pitch and yaw degrees of freedom for each suspended optical component, but are also designed to have the capability of providing the local pitch and yaw signals for orientation damping.
- ASC Wavefront Sensors- The wavefront sensing system provides for control of the pitch and yaw degrees of freedom for each of the core optics in the interferometer. The wavefront sen-

sors use modal information in the detected wavefronts at various positions in the interferometer to produce correction signals for the optics.

- ASC Cameras- The cameras are used to provide “live” displays to the operator of the beam position on each optic, views of the chamber interiors and images of the beam at selected ports in the interferometer.
- ASC Quadrant Monitor Photodiodes- The quadrant monitor photodiodes are used to detect and correct beam centering on each optic.

2.4. General Constraints

2.5. Assumptions and Dependencies

2.5.1. Input Optics Alignment Requirements

It has been assumed that the input optics (IOO) system puts no new requirements on the ASC CDS, i.e. the standard WFS, QMPD, optical levers and camera systems described in this document can be used to build alignment systems for the IOO.

Details of the control requirements for IOO will be covered in the LIGO IOO CDS DRD.

3 REQUIREMENTS

3.1. Introduction

The placement of the ASC sensors with respect to the LIGO optical layout is shown in the figure below. The functional components for each ASC CDS system are also shown in the figure. The function and requirements for each of these components are described in the sections that follow.

Note: All connections to the ASC CDS are not depicted the figure, for example the optical lever control and monitoring points. The figure is meant to be illustrative of the functional connections.

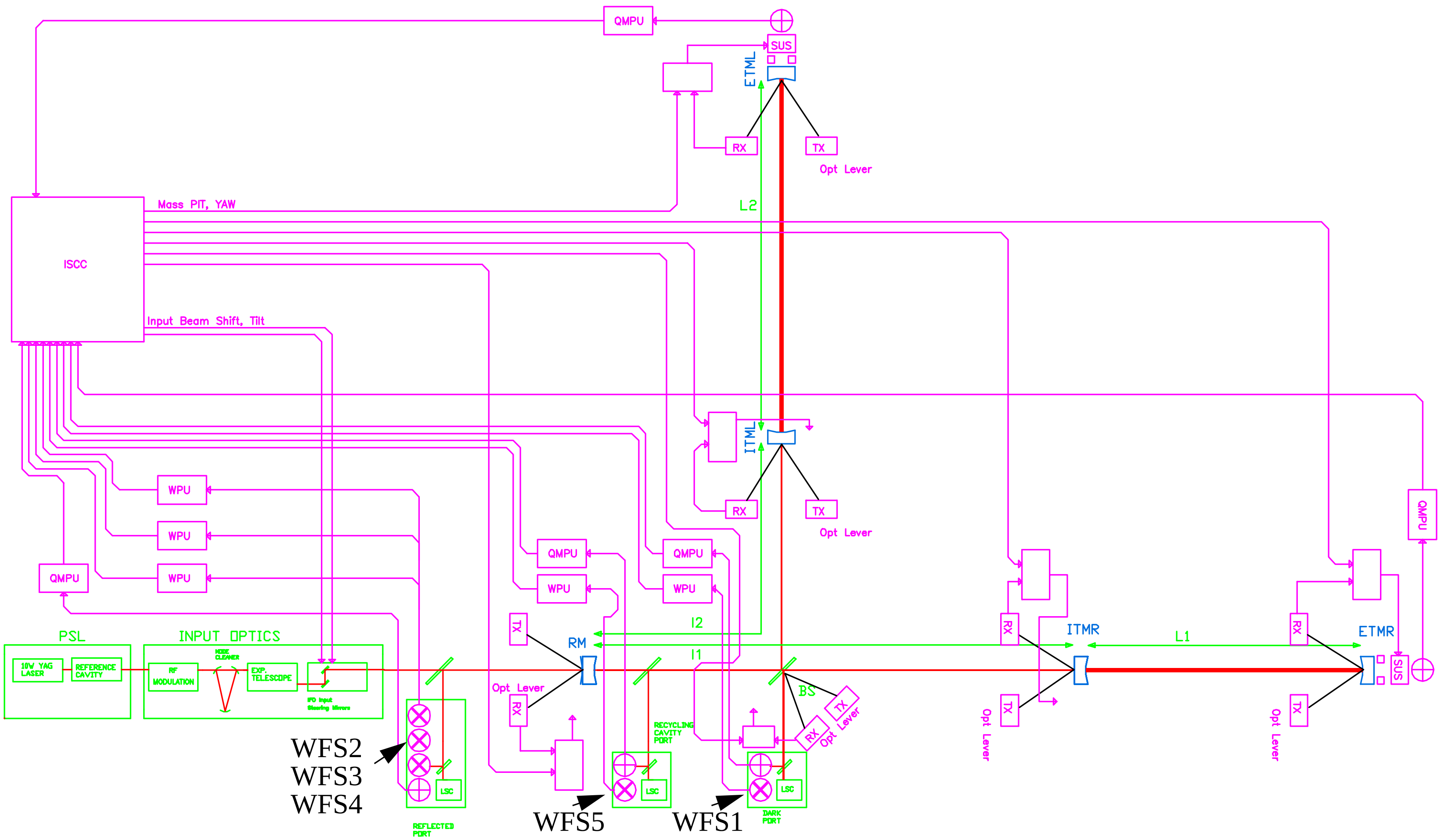


Figure 2: ASC CDS Functional Layout

3.2. Characteristics

3.2.1. Performance Characteristics

The performance requirements for ASC CDS are broken into the following sections:

- System Level Requirements (3.2.1.1 System Level Requirements)
- Wavefront Processing Requirements (3.2.1.2 Wavefront Processing Unit (WPU) Requirements)
- Quadrant Monitor Photodiodes (3.2.1.3 Quadrant Monitor Processing Unit (QMPU) Requirements)
- Optical Levers (3.2.1.4 Optical Lever Requirements)
- Cameras (3.2.1.5 Camera Requirements)

System level requirements are those requirements that pertain to more than one of the ASC subsystems. In general, the system level requirements will be handled by the functional block labelled ISCC in Figure 2: ASC CDS Functional Layout. The requirements that pertain to individual subsystems are described in the appropriate sections below.

3.2.1.1 System Level Requirements

The ASC CDS system level requirements are broken into the following sections:

- Operational Modes (3.2.1.1.1 Operational Modes)
- Supervisory Controls(3.2.1.1.2 Supervisory Control)
- Data Acquisition and Diagnostics (3.2.1.1.3 Data Acquisition and Diagnostics)

The requirements for each are described in the following paragraphs.

3.2.1.1.1 Operational Modes

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

3.2.1.1.1.1 Initial Alignment Mode

The initial alignment mode and ASC support of optic installation is described in section 2.1 of the ASC Conceptual Design (LIGO T960134).

3.2.1.1.1.1.1 Optical Lever zero setting (sec 2.1.3 ASC conceptual design)

ASC CDS shall provide the following to support optical lever zero setting during the initial alignment mode.

- The ability to “locally” control and monitor each optical lever. This includes read back of optical lever X and Y positions and control of all motorized mirrors. In this context locally refers to locations within the VEAs near the VE chambers as opposed to the LIGO main control room.
- The ability to incorporate a “one button” alignment nulling algorithm. This algorithm will allow the ASC control and monitor system to automatically null each of the optical lever systems without manual operator intervention. Note that the initial requirement is to allow for the addition of this feature at some time in the future.

3.2.1.1.1.1.2 Initial beam direction zero (sec. 2.1.4 ASC conceptual design)

ASC CDS shall provide the following to support initial beam direction zero as described in section 2.1.4 of the ASC Conceptual Design (LIGO T960134).

- The ability for the operator to monitor all Quad PD outputs, CCD cameras and WFS DC outputs.
- The ability to control motorized mirrors on the ASC/LSC optical table used to center the beams on the each ASC/LSC detectors.
- The ability to monitor an additional camera looking at the retro-reflection from the Recycling Mirror. The camera will be looking at a TBD optic in the IOO.

3.2.1.1.1.2 Transition to Acquisition Alignment (Acquisition Alignment Mode)

The transition to acquisition alignment mode is described in section 4.3 of the ASC Preliminary Design (LIGO T970060). Once each of the procedures is successfully completed, the interferometer is aligned. This aligned state is referred to as the Acquisition Alignment Mode. The Acquisition Alignment state is held until the LSC system locks.

ASC CDS shall provide all controls and monitors necessary to support each of the operating modes. It should be noted that the Transition to Acquisition Alignment Mode and the Acquisition Alignment Mode require the PSL, IOO, to be operational.

3.2.1.1.1.2.1 Unlocked Recycled Michelson- Manual Alignment

The ASC CDS shall be designed such that the system will support the manual alignment of the unlocked recycled Michelson. Some of the controls that are required for this operation are:

- Adjustment of recycling mirror, ITM and ETM angles.
- Monitoring of spot pattern on recycling mirror and on line ITM using cameras.
- Monitoring of cavity power using the DC readout from the WFS.
- Monitoring of anti-symmetric spot pattern using cameras.

3.2.1.1.1.2.2 Resonating Short Michelson (State 2)

The ASC CDS shall be designed such that the system will support operation of the interferometer as a short michelson. Some of the controls that are required for this operation are:

- manual adjustment of input mirrors (IOO)
- manual adjustment of beam splitter angles.
- Use of WFS 2a and WFS 2b to control alignment once the LSC is locked.
- Use of cameras to view ETM surfaces and BSC interior walls.
- Use of QMPUs to center on and off line beams on ETMs.

3.2.1.1.1.2.3 Recycled Michelson and One Arm Locked (State 3)

The ASC CDS shall be designed such that the system will support this mode (state 3) of operation. Some of the controls that are required for this operation are:

- Manual alignment of each ETM.
- Use of optical levers to bring each ETM to the orientation determined during initial alignment.
- Use of cameras to view ITM and BSC interior walls.

3.2.1.1.1.3 Detection Mode (sec. 3.0 ASC Conceptual Design)

The Detection mode is described by the following procedures and in section 3.0 of the ASC Conceptual Design (LIGO T960134). ASC CDS shall provide all controls and monitors necessary to support each of the procedures described below.

3.2.1.1.1.3.1 Establish Center of Rotation for Masses (sec. 3.2.2.2 ASC Conceptual Design)

The ASC CDS shall be designed such that the system will support the operations required to establish the center of rotation for each of the masses (recycling mirror, beam splitter, ITMs, ETMs). Some of the controls that are required are:

- Full operation of the wavefront servo systems
- Full operation of the beam centering servo systems.
- A flowchart of the procedure used to establish the center of rotation for each mass is shown in figure 8 of the ASC Conceptual Design. Some of the operations required are:
  - Use of IFO Diag. system to dither the pitch and yaw of the masses. The LSC length readout is then monitored to measure pitch and yaw coupling to length changes.
  - New angles are computed for masses and the process repeated until coupling is below an operator defined threshold. It should be noted that this procedure is a combined ISC (LSC & ASC) function. The requirements on ASC are to hold the IFO in detection mode using the WFS and QMPD (centering) and to accept new pitch and yaw angles for masses from LSC.

3.2.1.1.1.3.2 Detection Mode Hold

The ASC CDS shall be designed such that the system will support the detection mode hold. In this mode of operation the WFS servo and beam centering servo systems are used to control the 10 mirror alignment degrees of freedom and beam centering.

3.2.1.1.1.4 Diagnostic/Calibration Mode

TBD

3.2.1.1.1.4.1 Alternate ASC Control and Sensing

In this mode of operation, individual wavefront sensor control loops will be turned off and the respective optics held under local suspension sensor damping for the angles. ASC CDS shall provide all electronics hardware and software required to support this mode of operation. (See section 5.1 of ASC Conceptual Design)

3.2.1.1.1.4.2 Support for Non-Standard Optical Configurations

TBD

3.2.1.1.1.4.3 Mode matching

ASC CDS shall provide all controls and monitors necessary for the operator to “manually” adjust the mode matching of the input beam to the interferometer. During this procedure the operator will monitor beam position and shape using 4 CCDs on the ASC optical tables and adjust the mode matching telescope in the IOO. The operator will also monitor power levels in the interferometer as measured by ASC and LSC photodiodes.

3.2.1.1.1.4.4 WFS Calibration (pg 45 of ASC Conceptual Design)

Wavefront sensor calibration is used to determine the transfer function of optical angles of each mass to wavefront sensor output. The procedure for determining these transfer functions are similar to the dithering routines described for establishing the center of rotation for each mass. The ASC CDS shall be designed such that the system will support all operations required to calibrate the WFS. Some of the controls required include:

- Operation of the WFS servo system
- Injection of dither signals into each optic pitch and yaw test input.
- Use of the ASC optical lever read out system to measure the magnitude of the dither for each optic.

The ASC CDS shall also support the calibration of the WFS sensor head. This calibration requires that the head be illuminated with a light source. The controls required are TBD.

3.2.1.1.2 Supervisory Control

3.2.1.1.2.1 Transfer of Control from Suspension to WFS

The ASC CDS shall provide a means to transfer angular control of each controlled optic from the local suspension damping to wavefront sensor control. The control of this transfer is TBD. In this mode of operation the operator shall be able to select between velocity damping and the DC gain mode of the SUS suspension controller.

3.2.1.1.2.2 Use of Optical Levers for Local Suspension Damping

The design of the ASC CDS system shall be such as to allow for the use of the optical levers in place of the local suspension damping system. Selection of the local damping mode, i.e. optical level or suspension shall be under operator control.

It should be noted that the initial requirement is not that the ASC CDS system provide for optical lever control of the optic, but that the system be designed such that optical lever control can be added at a future date.

3.2.1.1.2.3 ASC Detection Mode Supervisory Control

In Detection Mode it is the responsibility of the ISCC (see Figure 2: ASC CDS Functional Layout) to collect information from the WPU and QMPU (described below), filter the data, perform the appropriate basis transformation and output pitch and yaw information for each optical element being controlled. The block diagram below and the sections that follow detail the requirements.

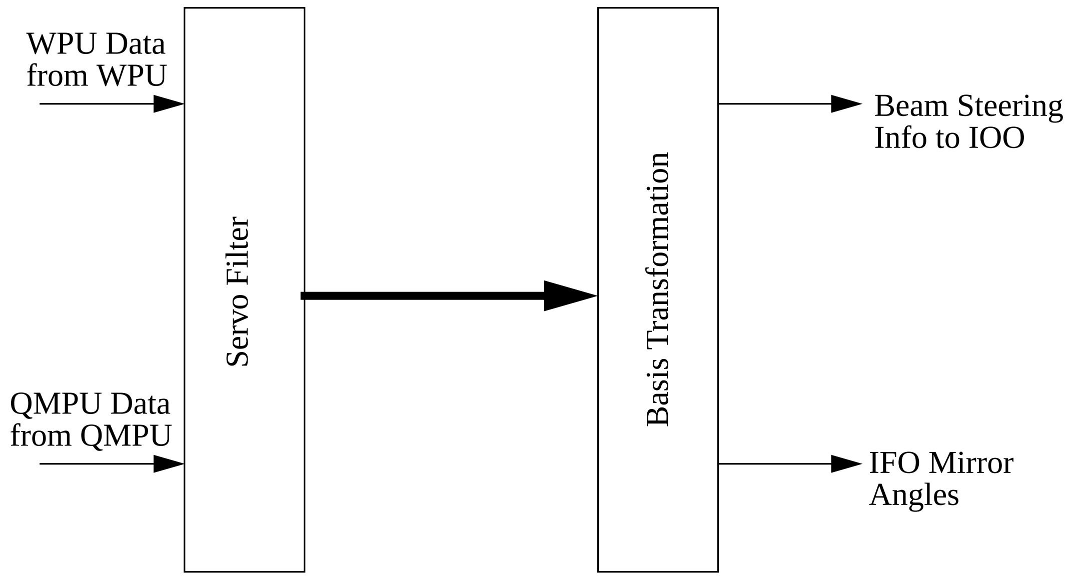


Figure 3: ASC Detection Mode Supervisory Control

3.2.1.1.2.3.1 Servo loop filter detection mode

In the detection mode, the IFO mirror angles passed to the suspension controller will be filtered as shown in the diagram below. Note that the initial filtering prior to the basis transformation is pro-

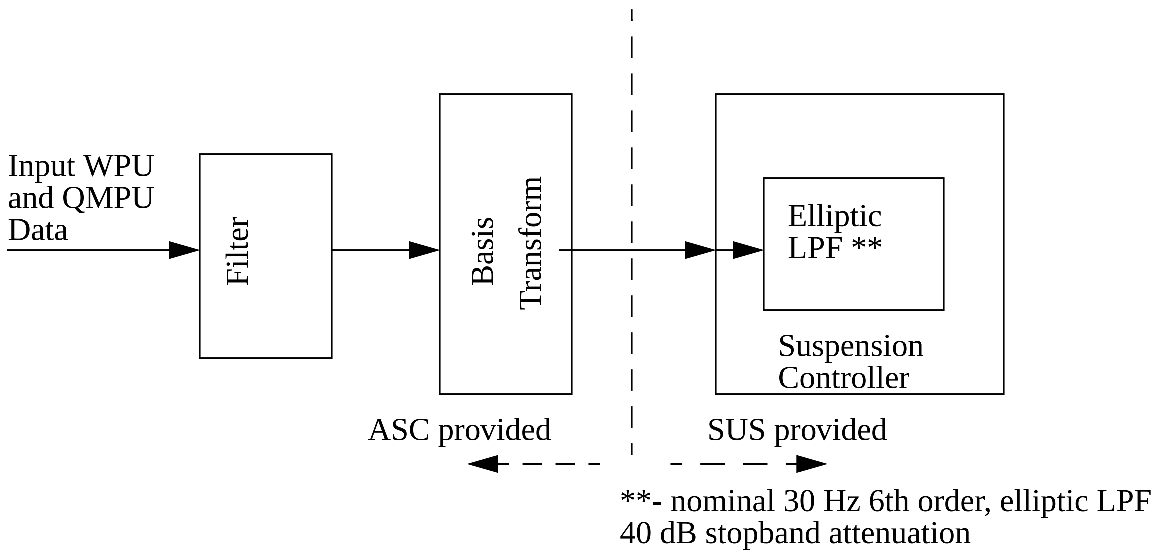
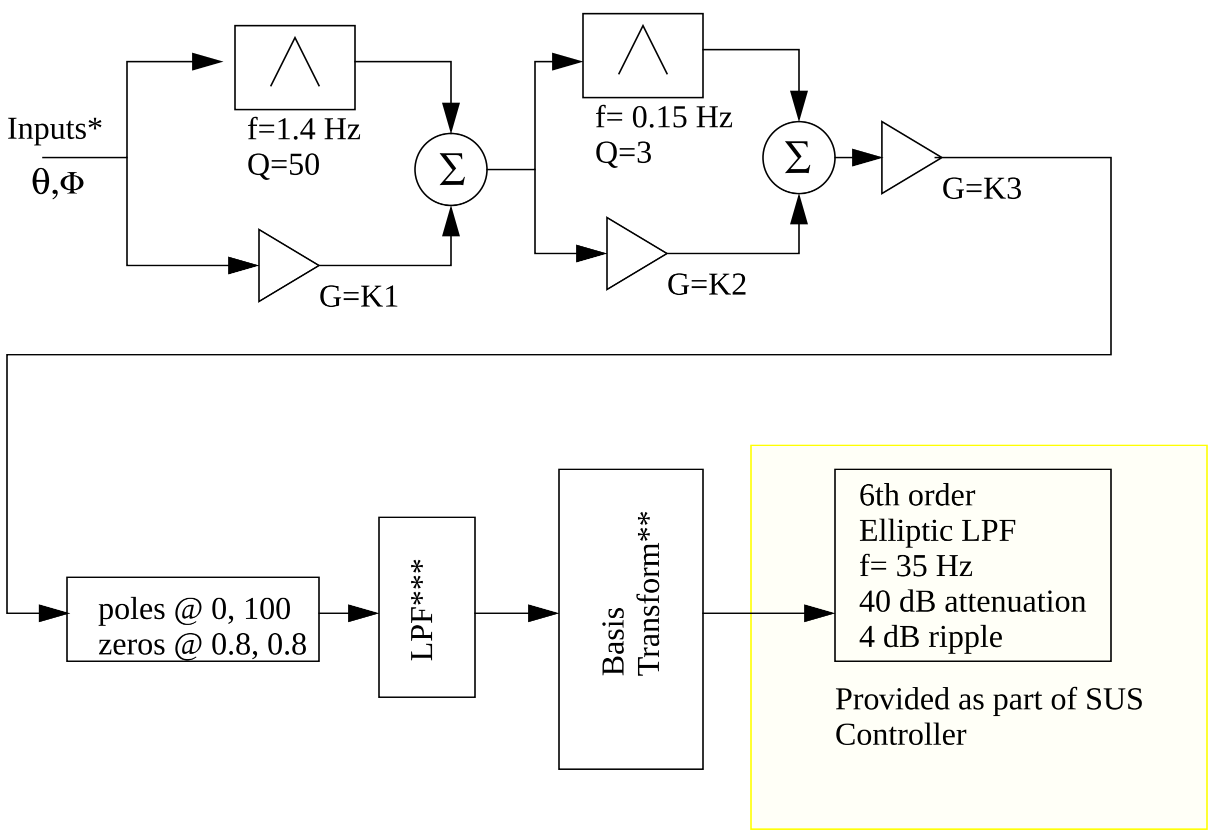


Figure 4: Detection Mode Filtering

vided as part of the ASC controls and the output elliptic filters are provided by the suspension controller provided by SUS. The output filter shown in the diagram is a nominal 6th order elliptic, but may be optimized for ASC and SUS performance as long as the provided filter attenuates signals above 30 Hz by at least 60 dB and does not produce a phase shift greater than the nominal elliptic filter by more than 10 degrees at 4.5 Hz. For the purposes of discussing the filtering function, the basis transformation can be considered as unity.

The block diagram below details the expected filter function shown in the preceding figure. The actual filter function required is TBD. The additional low pass filter required by WFS 2, 3 and 4 is TBD. Therefore the design of the ASC CDS system shall be such as to allow for changes to the filter function with a minimum of system redesign and reconfiguration.



*Note 1- Each WFU and QMPU input is filtered with this filter (7 total θ, 7 total Φ).
**Note 2- The basis transform is described in the next section
***Note 3- This is an additional low pass filter required by WFS2, 3, and 4.

Figure 5: Detection Mode Servo Controller

The input referred noise of the servo filter, basis transformation and elliptic low pass filter combination (the controller) shall be less than 100 uV/rtHz for frequencies less than 35 Hz. The input referred noise shall be less than $(50nV)/(\sqrt{Hz})$ for frequencies greater than 40 Hz.

The dynamic range of the controller shall be greater than 80 dB for frequencies less than 35 Hz.

3.2.1.1.2.3.2 Basis transformation of WPU and QMPU information

Pitch and Yaw information from the WPU and QMPU undergoes a TBD basis transformation.

The basis transformation for WFS is inverse of alignment matrix shown in the ASC DRD and Concept design. It is multiplied by the transform matrix in the ASC DRD to get control signals for each mirror. See sect. 2.4 of ASC DRD.

The QMPU data is used to control the beamsplitter and input beam angles.

The output of the ASC supervisory control unit shall be transformed such that the information passed to each controlled optic in the IOO and the interferometer is in units of Pitch and Yaw for the respective optic. The nominal transformation is a multiplication of the 5 WFS inputs plus the 2 QMPU inputs by a 7x7 matrix to obtain the pitch and yaw correction signals. The transformation is depicted in the following equations,

$$\begin{bmatrix}\Theta_{WFS1}\\ \Theta_{WFS2}\\ \Theta_{WFS3}\\ \Theta_{WFS4}\\ \Theta_{WFS5}\\ \Theta_{QMPU1}\\ \Theta_{QMPU2}\end{bmatrix} \times \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17}\\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} & a_{27}\\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} & a_{37}\\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} & a_{47}\\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} & a_{57}\\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} & a_{67}\\ a_{71} & a_{72} & a_{73} & a_{74} & a_{75} & a_{76} & a_{77}\end{bmatrix} = \begin{bmatrix}\Theta_{ITM1}\\ \Theta_{ETM1}\\ \Theta_{ITM2}\\ \Theta_{ETM2}\\ \Theta_{RM}\\ \Theta_{BS}\\ \Theta_{IB}\end{bmatrix}$$

$$\begin{bmatrix}\Phi_{WFS1}\\ \Phi_{WFS2}\\ \Phi_{WFS3}\\ \Phi_{WFS4}\\ \Phi_{WFS5}\\ \Phi_{QMPU1}\\ \Phi_{QMPU2}\end{bmatrix} \times \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} & b_{16} & b_{17}\\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} & b_{26} & b_{27}\\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} & b_{36} & b_{37}\\ b_{41} & b_{42} & b_{43} & b_{44} & b_{45} & b_{46} & b_{47}\\ b_{51} & b_{52} & b_{53} & b_{54} & b_{55} & b_{56} & b_{57}\\ b_{61} & b_{62} & b_{63} & b_{64} & b_{65} & b_{66} & b_{67}\\ b_{71} & b_{72} & b_{73} & b_{74} & b_{75} & b_{76} & b_{77}\end{bmatrix} = \begin{bmatrix}\Phi_{ITM1}\\ \Phi_{ETM1}\\ \Phi_{ITM2}\\ \Phi_{ETM2}\\ \Phi_{RM}\\ \Phi_{BS}\\ \Phi_{IB}\end{bmatrix}$$

where ITM= input test mass, ETM= end test mass, RM= recycling mirror, BS= beam splitter, and IB= input beam.

3.2.1.1.3 Data Acquisition and Diagnostics

3.2.1.1.3.1 Data Acquisition Channels

Table 10 of the ASC Conceptual Design Document contains a preliminary list of channels to monitored by the DAQ system.

3.2.1.1.4 IFO Diagnostics

Table 9: Diagnostics tests. in Appendix 2 ASC Diagnostics Tests contains a preliminary list of diagnostic tests the ASC CDS system and the IFO Diagnostics system must be designed to support.

3.2.1.2 Wavefront Processing Unit (WPU) Requirements

3.2.1.2.1 Placement of sensors

Wavefront sensor photodiodes are located on common ASC/LSC optical tables in the LVEA. The rough placement of the optical tables is depicted in Figure 2: ASC CDS Functional Layout. The table below lists the location of each sensor.

Table 1: WFS Number vs. Location

WFS Number	*Location*
1	ASC/LSC Dark Port Optical Table
2	ASC/LSC Reflected Port Optical Table
3	ASC/LSC Reflected Port Optical Table
4	ASC/LSC Reflected Port Optical Table
5	ASC/LSC Recycling Cavity Pick-Off Optical Table

3.2.1.2.2 Motorized Mirror Controls

The design shall provide for operator control of pitch and yaw of motorized mirrors located on ASC/LSC table. The type, number and detailed requirements are TBD.

3.2.1.2.3 Sensor Head Electronics

3.2.1.2.3.1 Photodiode Tuning Circuit Q

The tuning circuit used to tune the PD response to the modulation frequency shall have a Q of TBD. Traps for twice modulation frequency terms shall be incorporated into the design. The traps shall attenuate the twice frequency term such that the twice frequency term is more than 50 dB down from the modulation frequency.

3.2.1.2.3.2 Transimpedance Gain

The nominal gain of the photodiode electronics shall be 10K ohms. The design shall incorporate the ability to switch in a 20 dB attenuator. The switch shall be under operator control.

The design shall include a DC output for monitoring the power on the photodiode. The nominal gain of the readout shall be 1K ohms (V/A) with operator selectable x10 and x100 options.

3.2.1.2.3.3 Input/Output Referred Noise

The input referred noise of the sensor head electronics shall be less than $7.0((nV)/(\sqrt{Hz}))$, including the thermal noise of the tuned circuit.

3.2.1.2.3.4 RF Phase Matching

The physical length of the cables used to connect the sensor head electronics to the wavefront demodulator boards shall be matched to better than 10 mm within one wavefront detector system.

3.2.1.2.4 Demodulator Electronics

3.2.1.2.4.1 Demodulation Frequencies

The demodulation frequencies shall be 29.42 MHz (TBR), and 19.62 MHz (TBR) for 2 Km resonant and non-resonant sidebands, respectively and 24.53 MHz (TBR) and 36.79 MHz (TBR) for the 4 Km resonant and non-resonant side bands, respectively.

Wavefront Sensors 1, 2 and 5 are tuned to the resonant sideband. Wavefront Sensors 3 and 4 are tuned to the non-resonant sideband.

3.2.1.2.4.2 Gain/Frequency Response/Input RF Dynamic Range

Gain: 20 dB, TBD adjustment

IF bandwidth: 10 KHz

Dynamic Range: > 80 dB

3.2.1.2.4.3 Channel to Channel Isolation

The channel to channel isolation for the entire wavefront system shall be better than 50 dB.

3.2.1.2.4.4 Input/Output Referred Noise

The input referred noise of the wavefront demodulation electronics shall be less than $(20nV)/(\sqrt{Hz})$.

3.2.1.2.5 WPU Transfer Function and Processing Requirements

The following is a block diagram of the Wavefront Processing Unit.

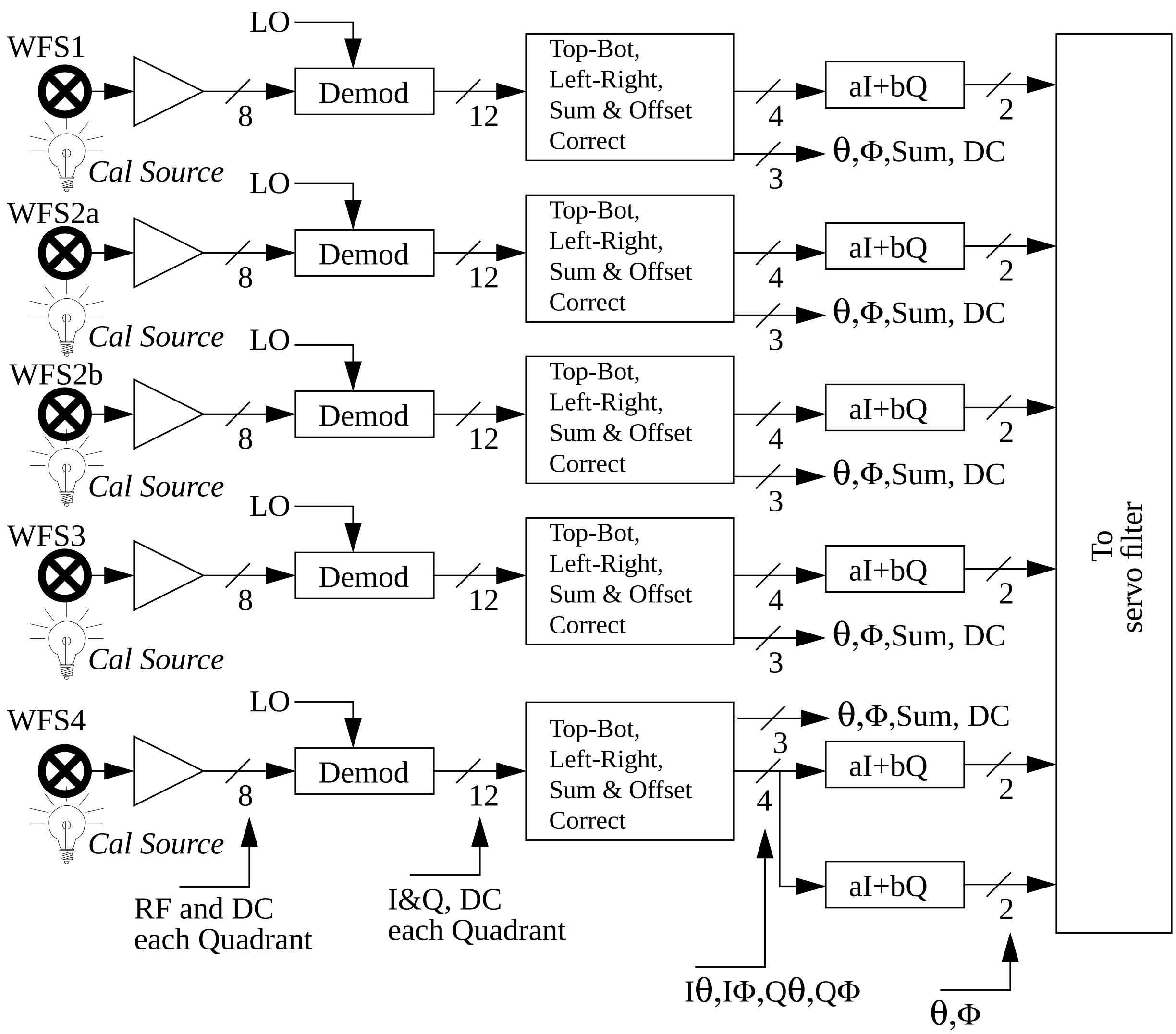


Figure 6: Wavefront Processing Unit Block Diagram

As can be seen from the figure, calculated pitch and yaw angles for each of the 5 wavefront sensors are passed to the servo filter block of the supervisory control unit. A sixth pitch and yaw signal is derived from the last wavefront sensor. This signal is also made available to the servo filter, but is redundant and not necessary for the servo calculations. The actual calculations represented by aI+bQ in the figure are TBD.

The Top-Bot, Left-Right, and Sum calculations shall incorporate the ability to adjust the offset and gain for each variable used in the calculation. This adjustment shall be controllable by the operator while the system is operational.

The WPU shall calculate θ,Φ, and Sum for the DC signals as shown in the figure.

3.2.1.2.6 On-Line and Off-Line Calibration

The design of the WPU shall incorporate the ability to illuminate the sensor head with a light source as shown in the figure. The calibration procedure is TBD.

3.2.1.3 Quadrant Monitor Processing Unit (QMPU) Requirements

3.2.1.3.1 Placement of sensors

Quadrant monitor sensor photodiodes are located on optical tables in the LVEA and VEAs. The rough placement of the optical tables is depicted in Figure 2: ASC CDS Functional Layout. Photodiodes in the LVEA are located on the same optical tables as the LSC and wavefront photodiodes.

3.2.1.3.2 Photodiode Electronics

3.2.1.3.2.1 Transimpedance Gain/Frequency Response

The nominal transimpedance for each quad photodiode segment shall be 500 ohm and the frequency response shall be greater than 1 KHz during the detection mode of operation. Other modes of operation require the transimpedance to range from 250 kohm to 10 Mohms. During these mode of operation the frequency response shall be greater than 100 Hz and the output referred noise is not important. The table below outlines the required gain, frequency response and noise for each mode of operation.

Table 2: QMPD Requirements vs. Operational Modes

IFO State	*Transimpedance gain (each element)*	*Output Noise Density (f>30 Hz)*	*Bandwidth (3 dB)*
2. Recycled Michelson	10 Mohm	N/A	>100 Hz
3. Recycled Michelson + one arm	10 Mohm/250 Kohm	N/A	>100 Hz
4. Detection Mode	500 ohm	$(20nV)/(\sqrt{Hz})$	> 1 KHz

The design shall incorporate operator selectable transimpedances ranging from the nominal 500 ohm used in detection mode to the 10 Mohm required during the recycled michelson state. Gain selections are in nominal 6 and 20 dB steps.

3.2.1.3.2.2 Input/Output Referred Noise

The output referred noise for the nominal 500 ohm transimpedance shall be less than $(20nV)/(\sqrt{Hz})$.

3.2.1.3.3 Transfer Function and Processing Requirements

3.2.1.3.3.1 Position Calculation

The QMPU shall calculate the position of the beam on the quad using the following equations:

$$Y_{Position} = \frac{K_{Top}(Top - Top_{offset}) - K_{Bottom}(Bot - Bot_{offset})}{Sum}$$

$$X_{Position} = \frac{K_{Left}(Left - Left_{offset}) - K_{Right}(Right - Right_{offset})}{Sum}$$

$$Sum = (K_{Top}Top) + (K_{Bot}Bot) + (K_{Left}Left) + (K_{Right}Right) - \sum_{Top}^{Right} offsets$$

where the offsets for each channel are obtained during a calibration procedure in which the beam to quad photodiode is blocked and the offset voltage for each channel is measured and stored for use in the calculations listed above. The gain constants are obtained during a calibration procedure in which the quad photodiode is uniformly illuminated and the output of each channel is measured. The relative gain for each channel is then calculated once the offsets are subtracted.

3.2.1.3.4 On-Line and Off-Line Calibration

TBD

3.2.1.4 Optical Lever Requirements

A block diagram of a nominal optical lever configuration is shown in the figure below.

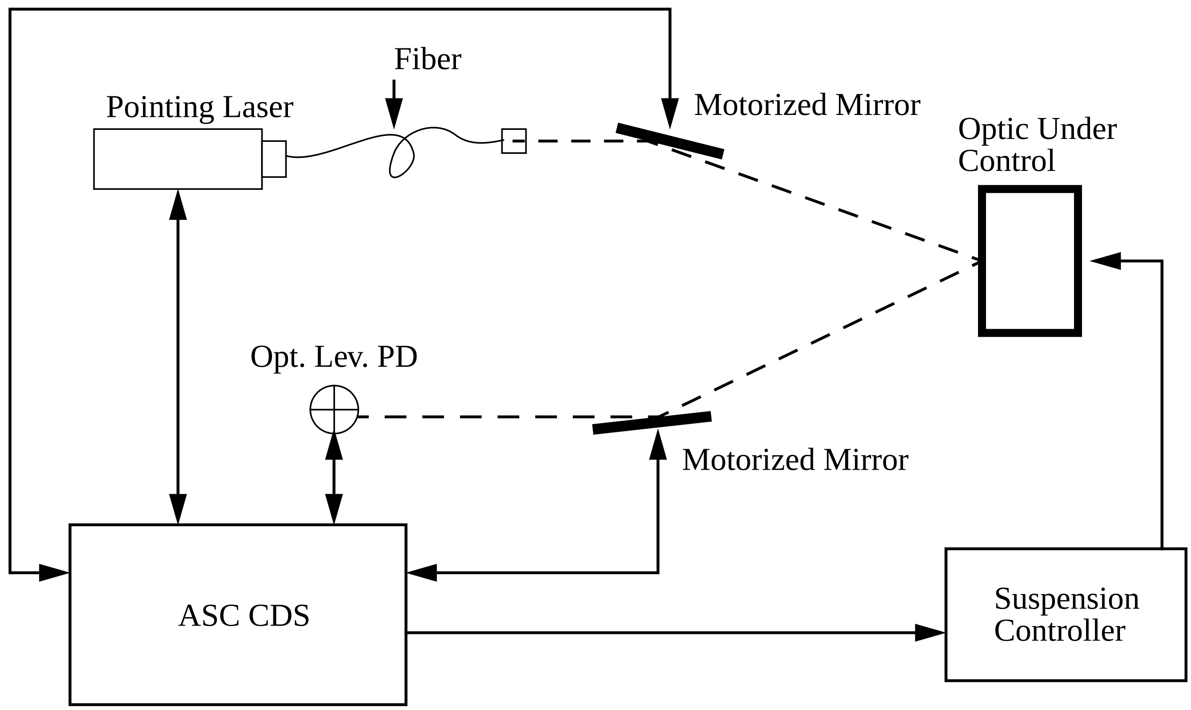


Figure 7: Optical Lever Block Diagram

3.2.1.4.1 Placement of sensors

Optical levers are located on the following optics:

- Recycling Mirror
- Beam Splitter
- X Arm ITM
- Y Arm ITM
- X Arm ETM
- Y Arm ETM
- 2 Folding Mirrors for 2 Km IFO

The locations of the optical levers (with the exception of the folding mirrors) are depicted in Figure 2: ASC CDS Functional Layout.

3.2.1.4.2 Pointing Laser Controls

3.2.1.4.2.1 Intensity stabilization

Nominal intensity stabilization is provided by the laser vendor, and there is no requirement for further stabilization.

3.2.1.4.2.2 Laser Control and Monitoring

ASC CDS shall provide all electronics hardware and software required to control and monitor the pointing laser, typically including monitoring of ON/OFF status, power, diode current, TEC current and temperature, depending on the features provided on the laser unit.

3.2.1.4.3 Motorized Mirror Controls

ASC CDS shall provide all electronics hardware and software necessary to control the kinematic steering mirrors used to direct the output beam into the vacuum port to the optic and from the vacuum port to the optical lever quadrant photodiode.

3.2.1.4.4 Receiver Electronics and Processing Requirements

A block diagram of the optical lever electronics and processing is shown in the figure below.

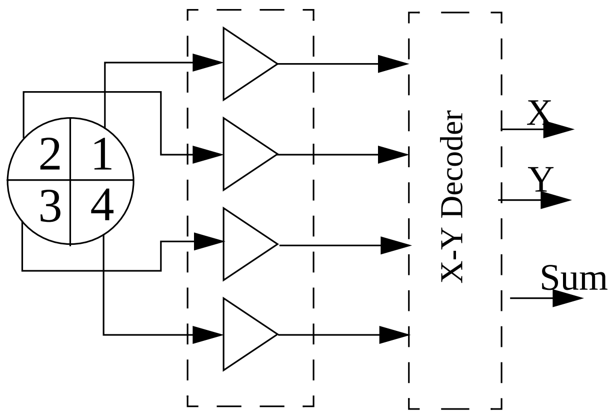


Figure 8: Optical Lever Receiver Electronics Block Diagram

3.2.1.4.4.1 Photodiode Electronics

3.2.1.4.4.1.1 Transimpedance Gain/Frequency Response

The nominal transimpedance of each channel of the quad photodiode amplifier shall be 1000 ohms. The frequency response shall be greater than 1 KHz. The design shall include a provision for operator selection of alternate gains. The selection shall be 1K ohm, 10 K ohms, and 100 Kohms.

3.2.1.4.4.1.2 Input/Output Referred Noise

The input referred noise of the amplifier shall be less than $6\times10^{-12}\frac{\mathrm{A}}{\sqrt{\mathrm{Hz}}}$ for frequencies greater than 40 Hz.

3.2.1.4.4.1.3 Offset Drift

The offset drift shall be less than one part in 10K over the operating temperature range.

3.2.1.4.4.2 Transfer Function and Processing Requirements

3.2.1.4.4.2.1 X and Y Position Calculation

The Optical Lever Electronics shall calculate the position of the beam on the quad using the following equations:

$$Y_{Position} = \frac{K_{Top}(Top - Top_{offset}) - K_{Bottom}(Bot - Bot_{offset})}{Sum}$$

$$X_{Position} = \frac{K_{Left}(Left - Left_{offset}) - K_{Right}(Right - Right_{offset})}{Sum}$$

$$Sum = (K_{Top}Top) + (K_{Bot}Bot) + (K_{Left}Left) + (K_{Right}Right) - \sum_{Top}^{Right} offsets$$

where the offsets for each channel are obtained during a calibration procedure in which the beam to quad photodiode is blocked and the offset voltage for each channel is measured and stored for use in the calculations listed above. The gain constants are obtained during a calibration procedure in which the quad photdiode is uniformly illuminated and the output of each channel is measured. The relative gain for each channel is then calculated once the offsets are subtracted.

3.2.1.4.4.2.2 Frequency Response of Position Calculation

The position calculation shall be updated at a rate greater than TBD times per second.

3.2.1.5 Camera Requirements

3.2.1.5.1 Placement of Cameras

The nominal placement of cameras for one interferometer at the Washington site is shown in the table below.

Table 3: Nominal Camera Locations for One WA IFO

Location	*Number of Cameras*	*Nominal Viewing*
LVEA; at BSC1	2-4	interior of BSC1
LVEA; at BSC2	2-4	interior of BSC2
LVEA; at BSC3	2-4	interior of BSC3
End Station; X Arm/Y Arm	2-4/2-4	interior of BSC9/BSC10
LVEA; at BSC1	1	surface of Y-arm ITM
LVEA; at BSC2	1	surface of beamsplitter
LVEA; at BSC3	1	surface of X-arm ITM
End Station; X Arm/Y Arm	1/1	surface of X-arm/Y-arm ETM
LVEA; at HAM3	1	surface of recycling mirror
LVEA; at HAM2	1	surface of MC mirror
LVEA; at HAM1	1	surface of MC mirror
ISC Table; Rec Cav sample	1	recycling cavity beam
ISC Table; Anti-symmetric port	1	Anti-symmetric beam
ISC Table; Reflected port	1	Reflected beam
ISC Table; ETM transmission, X/Y Arm	1/1	X/Y Arm ETM transmitted beam
ISC Mode Cleaner Table	1	MC transmitted beam

3.2.1.5.2 Camera Controls

3.2.1.5.2.1 Panning, Zooming, Moving of Cameras

The design shall accommodate the movement of cameras at least TBD meters from their nominal locations. This capability will be used to move the cameras to port locations where the inside walls of vacuum equipment chambers can be viewed during the initial and acquisition alignment modes.

ASC CDS shall provide all hardware and software necessary to control panning and zoom functions for the cameras.

ASC CDS will provide all electronics hardware and software for control of camera filter wheels.

3.2.1.5.2.2 Illuminators

The design of the camera system shall incorporate the ability to illuminate the optic being viewed. This capability will be used to find the edges of the optic during beam centering calibration.

3.2.1.5.2.3 Calibration

TBD

3.2.1.5.3 Image Processing Requirements

The are no on-line image processing requirements. CDS shall provide a means for the operator to view the output of each CCD in real time (30 frames per second). In addition the operator will be able to snapshot the image and store the snapshot for future display or analysis.

The maximum number of cameras to be viewed simultaneously shall be TBD.

3.2.2. Interface Definitions

3.2.2.1 Interfaces to other LIGO detector subsystems

3.2.2.1.1 Mechanical Interfaces

Table 4: ASC CDS Detector Mechanical Interfaces

ASC CDS Component	*Other System or Subsystem*	*Characteristics*
TBD		

3.2.2.1.2 Electrical Interfaces

Table 5: ASC CDS Detector Electrical Interfaces

ASC CDS Component	*Other System or Subsystem*	*Characteristics*
ASC Controller	IFO Core Optics Suspension Controller	Pitch and Yaw referenced to local optic Sensitivity = TBD nrad/Volt @ Unity gain frequency (~5 Hz)
ASC Controller	IOO Beam Steering Optics	Pitch and Yaw referenced to local optic Sensitivity = TBD nrad/Volt @ Unity gain frequency (~5 Hz)

3.2.2.1.3 Optical Interfaces

Table 6: ASC CDS Detector Optical Interfaces

ASC CDS Component	*Other System or Subsystem*	*Characteristics*
N/A		

3.2.2.1.4 Stay Clear Zones

TBD

3.2.2.2 Interfaces external to LIGO detector subsystems

3.2.2.2.1 Mechanical Interfaces

N/A

3.2.2.2.2 Electrical Interfaces

N/A

3.2.2.2.3 Stay Clear Zones

N/A

3.2.3. Reliability

Mean Time Between Failures (MTBF), Availability: TBD

3.2.4. Maintainability

Mean Time To Repair (MTTR); Qualitative requirements for accessibility, modular construction, test points, etc.: TBD

3.2.5. Environmental Conditions

3.2.5.1 Natural Environment

3.2.5.1.1 Temperature and Humidity

Table 7: Environmental Performance Characteristics

Operating	*Non-operating (storage)*	*Transport*
+0 C to +50 C, 0-90%RH	-40 C to +70 C, 0-90% RH	-40 C to +70 C, 0-90% RH

3.2.5.1.2 Atmospheric Pressure

The ASC CDS design must accommodate atmospheric pressure change from a maximum of 15.2 psia to a minimum of 14.2 psia.

3.2.5.1.3 Seismic Disturbance

N/A

3.2.5.2 Induced Environment

3.2.5.2.1 Electromagnetic Radiation

The ASC CDS shall not degrade due to electromagnetic emissions as specified by IEEE C95.1-1991.

The ASC electronics shall not produce electromagnetic emissions beyond those specified in TBD.

3.2.5.2.2 Acoustic

ASC electronics shall be designed to produce the lowest levels of acoustic noise as possible and practical. In any event, ASC electronic components shall not produce acoustic noise levels greater than those specified in TBD.

3.2.5.2.3 Mechanical Vibration

ASC electronics shall not produce mechanical vibrations greater than those specified in TBD.

3.2.6. Transportability

All items shall be transportable by commercial carrier without degradation in performance. As necessary, provisions shall be made for measuring and controlling environmental conditions (temperature and accelerations) during transport and handling. Special shipping containers, shipping and handling mechanical restraints, and shock isolation shall be utilized to prevent damage. All containers shall be movable for forklift. All items over 100 lbs. which must be moved into place within LIGO buildings shall have appropriate lifting eyes and mechanical strength to be lifted by cranes.

3.3. Design and Construction

3.3.1. Materials and Processes

3.3.1.1 Finishes

- Ambient Environment: Surface-to-surface contact between dissimilar metals shall be controlled in accordance with the best available practices for corrosion prevention and control.
- *External surfaces: External surfaces requiring protection shall be painted purple or otherwise protected in a manner to be approved.*

3.3.1.2 Materials

TBD

3.3.1.3 Processes

TBD

3.3.2. Component Naming

All components shall identified using the LIGO Detector Naming Convention (document TBD). This shall include identification physically on components, in all drawings and in all related documentation.

3.3.3. Workmanship

All details of workmanship shall be of the highest grade appropriate to the methods and level of fabrication and consistent with the requirements specified herein. There shall be no evidence of poor workmanship that would make the components unsuitable for the purpose intended. All electronic circuits and wiring shall be consistent with good engineering practice and fabricated to best commercial standards.

3.3.4. Interchangeability

The ASC electronics shall be designed to maximize interchangeability and replaceability of mating components. Using the Line Replaceable Unit (LRU) concept, the designs shall be such that mating assemblies may be exchanged without selection for fit or performance and without modification to the section, the unit being replaced or adjacent equipment. Mature performance proven, standard, commercially available equipment shall not be modified unless it impacts safety.

3.3.5. 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 <u>*LIGO Project System Safety Management Plan*</u> *LIGO-M950046-F, section 3.3.2.*

3.3.6. Human Engineering

N/A

3.4. Documentation

3.4.1. Specifications

TBD

3.4.2. Design Documents

TBD

3.4.3. Engineering Drawings and Associated Lists

Any drawings to be provided and any standard formats that they must comply with, such as shall use LIGO drawing numbering system, be drawn using LIGO Drawing Preparation Standards, etc.

3.4.4. Technical Manuals and Procedures

3.4.4.1 Procedures

Procedures shall be provided for, at minimum,

- *Initial installation and setup of equipment*
- *Normal operation of equipment*
- *Normal and/or preventative maintenance*
- *Troubleshooting guide for any anticipated potential malfunctions*

3.4.4.2 Manuals

TBD

3.4.5. Documentation Numbering

All documents shall be numbered and identified in accordance with the LIGO documentation control numbering system LIGO document TBD

3.4.6. Test Plans and Procedures

All test plans and procedures shall be developed in accordance with the LIGO Test Plan Guidelines, LIGO document TBD.

3.5. Logistics

The design shall include a list of all recommended spare parts and special test equipment required.

3.6. Precedence

TBD

3.7. Qualification

TBD

4 QUALITY ASSURANCE PROVISIONS

4.1. General

4.1.1. Responsibility for Tests

TBD

4.1.2. Special Tests

4.1.2.1 Engineering Tests

TBD.

4.1.2.2 Reliability Testing

Reliability evaluation/development tests shall be conducted on items with limited reliability history that will have a significant impact upon the operational availability of the system.

4.1.3. Configuration Management

Configuration control of specifications and designs shall be in accordance with the LIGO Detector Implementation Plan.

4.2. Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications shall be verified by inspection, analysis, demonstration, similarity, test or a combination thereof per the Verification Matrix, Appendix 1 (See example in Appendix). Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures. Verification of compliance to the requirements of this and subsequent specifications may be accomplished by the following methods or combination of methods:

4.2.1. Inspections

Inspection shall be used to determine conformity with requirements that are neither functional nor qualitative; for example, identification marks.

4.2.2. Analysis

Analysis may be used for determination of qualitative and quantitative properties and performance of an item by study, calculation and modeling.

4.2.3. Demonstration

Demonstration may be used for determination of qualitative properties and performance of an item and is accomplished by observation. Verification of an item by this method would be accomplished by using the item for the designated design purpose and would require no special test for final proof of performance.

4.2.4. Similarity

Similarity analysis may be used in lieu of tests when a determination can be made that an item is similar or identical in design to another item that has been previously certified to equivalent or more stringent criteria. Qualification by similarity is subject to Detector management approval.

4.2.5. Test

Test may be used for the determination of quantitative properties and performance of an item by technical means, such as, the use of external resources, such as voltmeters, recorders, and any test equipment necessary for measuring performance. Test equipment used shall be calibrated to the manufacture's specifications and shall have a calibration sticker showing the current calibration status.

5 PREPARATION FOR DELIVERY

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

5.1. Preparation

Equipment shall be appropriately prepared. For example, vacuum components shall be prepared to prevent contamination.

5.2. Packaging

Procedures for packaging shall ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection shall be provided for shipping loads and environmental stress during transportation, hauling and storage.

5.3. Marking

Appropriate identification of the product, both on packages and shipping containers; all markings necessary for delivery and for storage, if applicable; all markings required by regulations, statutes, and common carriers; and all markings necessary for safety and safe delivery shall be provided.

6 NOTES

APPENDIX 1 QUALITY CONFORMANCE VERIFICATION MATRIX

Table 8: Quality Conformance Inspections

Paragraph	*Title*	*I*	*A*	*D*	*S*	*T*

APPENDIX 2 ASC DIAGNOSTICS TESTS

Table 9: Diagnostics tests.

Diagnostics	*Type*	*Condition*	*Drive*	*Measurement*	*Monitor*	*Analysis*	*Action*
Sensitivity Matrix	external	detection mode	ifo mirror angles sine: 50–200 Hz 10^{-13} to 10^{-12} rad	WFS	SUS sensors opt. lev.	Fourier	update ASC servo matrix & rf phases
Centering	external	detection mode	bs & ib direction sine: <1 Hz 10^{-7} to 10^{-6} rad	QMPU bs & ib control	WFS SUS sensors opt. lev.	Fourier	update ASC servo matrix
Angle-length coupling	external	detection mode	ifo mirror angles sine: 50–200 Hz 10^{-13} to 10^{-12} rad	LSC signals	WFS SUS sensors opt. lev.	Fourier	adjust transverse mirror positions
Input beam jitter coupling	external	detection mode	ib direction sine: 50–200 Hz 10^{-13} to 10^{-12} rad ifo mirror angles static: ~10^{-7} rad	LSC signals (dark port)	WFS SUS sensors opt. lev.	Fourier	update ASC servo offsets
Maximum GW sensitivity	external	detection mode	ifo mirror angles static: grid diff. length, e.g. 150 Hz, 10^{-17} m	power LSC signals	WFS SUS sensors opt. lev.	Average Fourier	update ASC servo offsets
Mode matching	external	detection mode	mode matching telescope	power	cameras	Average	adjust telescope
Frequency response	external	detection mode	ifo mirror angles ib direction step: 1–10 s	WFS angle controls	WFS SUS sensors opt. lev.	Average	update ASC servo bandwidth
Transient	external	acquisition mode	seismic	WFS, power LSC signals	SUS sensors opt. lev.	Time series	get smart
Photodiode calibration	internal	setup mode	light bulb	WFS (dc & rf)		Fourier	adjust ASC calibration corrections