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ASC Optical Lever

Specification and Design Document

David H. Shoemaker, John H. Tappan

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California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

Abstract

This is the Specification and Conceptual Design Requirements Document for the ASC (Alignment Sensing and Control) Optical Lever.

1 INTRODUCTION

1.1. Purpose

The purpose of this document is to define the specifications and the conceptual design for the Optical Lever. It is a working document to aid in the detailed design.

1.2. Scope

- These specifications and conceptual design are for the Optical Lever (or Optlev), a subsystem of the Alignment Sensing and Control.
- The specifications and conceptual design are for all applications of the Optical lever: both for operational use (where the Optlev is required to maintain operational alignment for short periods of time) and in any role in the Initial Alignment (where it may be part of a search for the beam tube aperture etc.). There will be small differences in the specifications for different specific applications, e.g., different focal lengths for different baselines.
- It does not describe the other subsystems of the ASC with which the Optlev may have a complicated and deep interface.

1.3. Definitions

The basic naming convention for the Optlev is given in T950070-00-D. Additional definitions are given below.

Sensed Optic The optic, of which the angle is sensed by the optical lever. In general, the optics are suspended; and some of the objects whose angle is stabilized may not be simple mirrors but instead Faraday isolators, lenses, etc.

Optlev Baseline The distance from the measurement photodiode to the sensed optic.

Pitch Angle of motion around a horizontal axis; also called ‘θ’

Yaw Angle of motion around the vertical axis; also called ‘ϕ’

1.4. Acronyms

ASC Alignment Sensing and Control

CDS Control and Data System

OptLev Optical Lever Alignment System

SUS Suspension System, here used to refer to both the Suspension itself and the control systems which make angular motions in response to input control signals.

1.5. Applicable Documents

1.5.1. LIGO Documents

LIGO-T952007-00-D ASC DRD, or Alignment Sensing and Control Overall Design Requirements Document

LIGO-T950070-00-D Naming Convention and Interface Definition for Optical Lever

LIGO-T950106-00-D ASC Optical Lever DRD (Design Requirement Document

1.5.2. Non-LIGO Documents

None.

2 CONCEPTUAL DESIGN

2.1. Product Functions

The Optical Lever system will maintain the externally determined angle of a sensed optic (normally, a suspended optic) for an intermediate duration. It will be the primary control system once the initial alignment has brought the optics to within range of the Optical Lever, and until the Wavefront Sensing system starts to function. It has a stability and a noise performance which allows operation of the interferometers at their design sensitivity for short times (order of 1-10 minutes) to allow diagnostic tests.

2.2. General Constraints

There will be one OptLev per suspended component. Failure of a single OptLev would in general make the interferometer inoperational. LIGO must operate with high availability, and so this subsystem must be designed with high reliability and low mean time to repair.

It is preferred that the OptLev beam be visible for ease of initial alignment and troubleshooting.

2.3. Assumptions and Dependencies

It is assumed that the Sensed Optics will have a transparency and a reflectivity that are both greater than 1% at the OptLev beam wavelength.

The performance of the Optlev is to some extent dependent on the stability of the Facility foundation slab, and also on the ground noise (ambient and Facility-dependent). We assume (hard data is not presently available) that these external environmental conditions limit the useful duration over which Optlev can maintain operational performance to 500 seconds.

2.4. Description

The Optical lever (Optlev) uses an optical lever to produce a position change on a quadrant photodetector (quaddiode) due to angular motion of a suspended component. The resulting signal is used as an ‘error signal' in a servo loop to apply corrective forces to the mirror (via the suspended component actuators, presently magnets and coils). See Figure 4 on page 21 for a sketch.

The Optlev serves to reduce the angular motion of the test mass to operational levels. The excitation comes from seismic motion as transmitted by the seismic isolation system and suspension system; resonances, notably that of the suspension system, can bring the level of motion well above the initial level of excitation. The closed-loop Optlev control system actively damps the motion due to the suspension resonance (around 0.5 Hz for the angular motions), thus changing the transfer function of the suspension near the suspension resonances. Stack resonances are not reduced in their Q, but gain in the Optlev control loop can reduce the net angular motion of the optic due to these resonances.

The reference quadrant photodiode is used in a closed-loop servo system to stabilize the position of the light source as it falls on the suspended optic; this reduces first order sensitivity to beam motion of the Optlev laser beam. A fiber-pigtailed diode laser is used to reduce high-frequency beam jitter and allow rapid replacement of the laser without need for a re-alignment.

A large range mode, using either auxiliary lenses or photodiodes, may be required by the Initial Alignment subsystem (up to planned port sizes).

While in operation, the Wavefront sensor continually updates the null point of the Optlev system such that if the Wavefront system ceases to operate (e.g., loss of longitudinal lock), the Optlev can seamlessly take over control of the optic. Similarly, if a failure of an Optlev unit takes place (e.g., failure of a Optlev laser), the output control signals will be held at their last good value to maintain a nominally correct alignment for a short interim period.

There are two aspects to the design: the Sensing System and the Optical Layout.

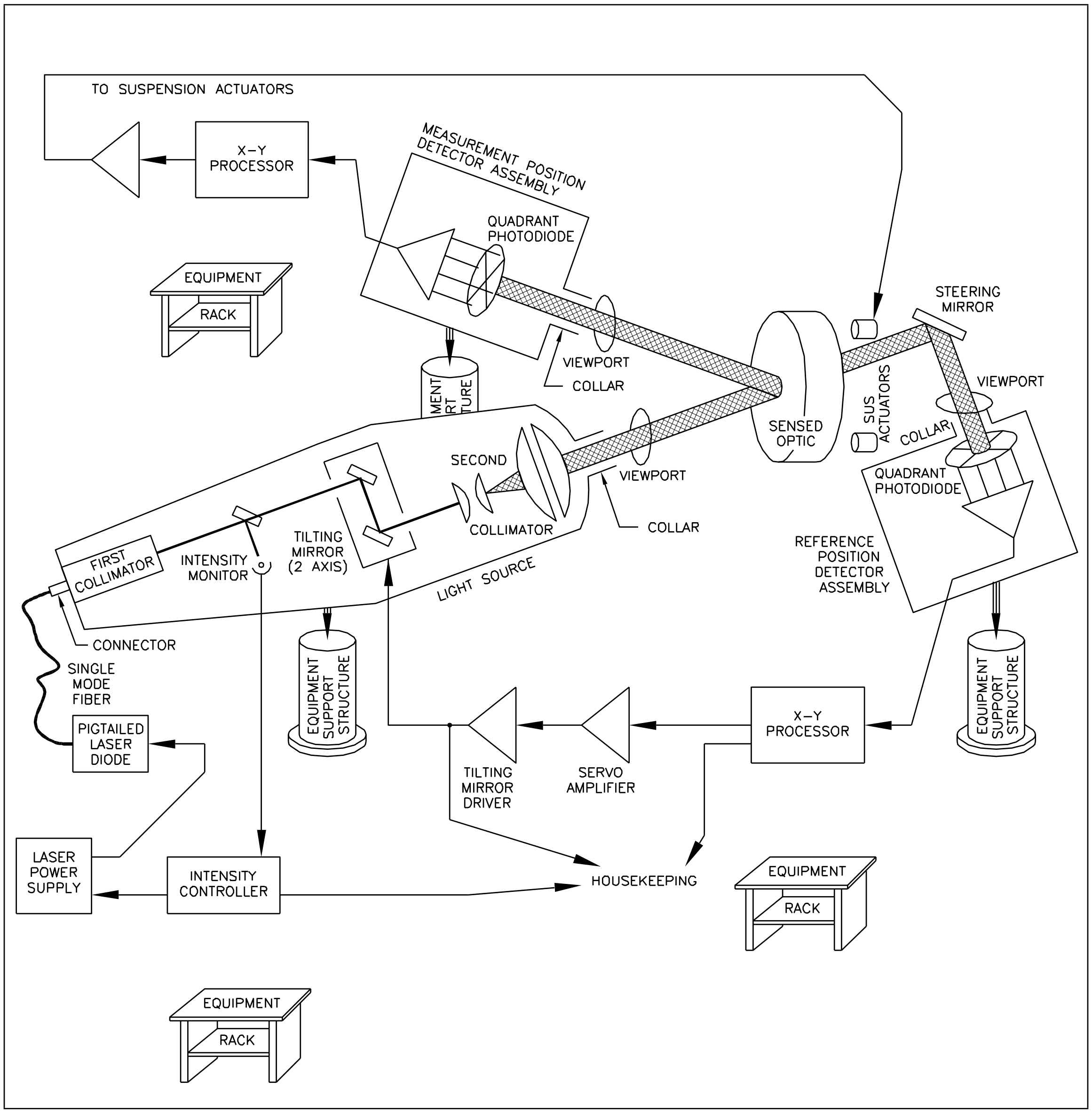

Figure 1: Conceptual design of an optical lever

2.4.1. Sensing System Conceptual Design

The Optlev Sensing System consists of a collimated laser source and active beam steering system (the Light Source), a position sensitive monitor of the light transmitted through the suspended optic (the Reference Position Detector Assembly or Ref Pos Det), and a position sensitive detector of the reflected light (the Measurement Position Detector Assembly or Meas Pos Det). In addition, there are support structures and electronics and optics equipment to feed and read the elements named above.

2.4.1.1 Light Source

The Light Source takes light form the laser diode and processes it into a stable, matched light beam which then can be used for the measurement. It is a self-contained closed unit (possibly hermetic), with connectors for the light input and electronics I/O. There are several elements inside the light source:

2.4.1.1.1 Fiber connector

The light input is made via a single-mode polarization-holding fiber, using a commercial kinematic connector. The objective is to make the optical path and beam parameters inside the light source independent of the fiber to allow interchangeability and quick repair.

2.4.1.1.2 First collimator

The light from the connector is brought to roughly collimated beam, with a diameter of roughly 1 mm. This beam is a convenient size for the subsequent processing. This collimator must be sufficiently stable against temperature changes and temperature gradients to meet long-term alignment and sensitivity specifications.

2.4.1.1.3 Intensity monitor

The light intensity from the First Collimator is monitored using a beamsplitter and photodiode. The resulting signal voltage is used in a closed-loop intensity control (see Intensity Controller and Laser Power Supply) to maintain constant intensity over short (measurement) and long (calibration) time scales.

2.4.1.1.4 Tilting mirror

The light beam transmitted through the Intensity Monitor beamsplitter is reflected from one or several mirrors which have remote (voltage) control of the angle of the mirror. There is both coarse remote alignment (e.g., Picomotor 2-angle mount) which is used during alignment but not operation, and fine continuous control (e.g., PI PZT actuators) which is part of a closed-loop control over the output angle of the light source (see Ref Pos Det Assembly, Servo Amplifier, and Tilting Mirror Driver). The bandwidth of the control will be sufficient to meet performance specifications.

2.4.1.1.5 Second collimator

The light beam from the Tilting Mirror is optically matched to the Optlev Baseline light path (order of 5 meters) with a second collimator assembly. This beam will be several mm to 1 cm in diameter. The collimator has some adjustment of the lens separation, and the possibility to exchange lenses, to make the beam appropriate for the specific baseline.

2.4.1.2 Pigtailed laser diode and Laser Power Supply

The light for the Optlev is produced by a laser diode. The Laser Diode is permanently connected to a single-mode polarization-maintaining optical fiber with a connector at the output end. The output wavelength is in the visible (e.g., 670 nm) and the output power is 10-100 mW as needed per specifications. The Laser Power Supply delivers a tightly regulated current, and contains a closed-loop temperature controller to eliminate longitudinal mode-hops. It has a modulation input which allows fast (e.g., 10 kHz Unity Gain Frequency) control of the laser intensity.

2.4.1.3 Single Mode Fiber

The light from the Pigtailed Laser Diode is carried to the Light Source via a single-mode polarization-maintaining Optical Fiber. Both ends carry connectors and a variety of lengths are used according to convenience of equipment mounting.

2.4.1.4 Intensity Controller

The output of the Intensity Monitor is processed in the Intensity Controller to form a closed-loop control of the light intensity at the output of the Light Source. This is where the servo transfer function, set point, and diagnostics are realized.

2.4.1.5 Tilting Mirror Driver and Servo Amplifier

The output of the Ref Pos Det Assembly is processed by the X-Y processor to develop signals (voltages) proportional to the perceived angular motion of the light beam at the Ref Pos Det. This signal is processed (gain, transfer function, set point, diagnostics) in the Servo Amplifier, and converted to a suitable lever (e.g., high voltage amplifiers) in the Servo Amplifier.

2.4.1.6 Position Detector Assemblies

The Measurement Position Detector Assembly and Reference Position Detector Assemblies are nominally identical units (with possible gain differences). The Detector Assembly consists of a quadrant photodiode and current-to-voltage amplifiers, line drivers, any required diagnostic and signal processing electronics, and an enclosure with connectors.

2.4.1.7 X-Y Processors

The X-Y processors for the Measurement and Reference channels are nominally identical (with possible gain differences). The X-Y Processor converts the signals from the Detector Assemblies into X and Y components of motion on the Detector photodiode surface and provides total intensity and diagnostic signals.

2.4.1.8 Equipment Support Structures

The Equipment Support Structures support the elements of the OptLev on the Facility floor. They are in general optical tables with a possibility of kinematically demounting and remounting from a base fixed to the Facility Floor. The thermal stability will be such that the performance requirements can be met.

2.4.2. Optical Layout Conceptual Design

In the baseline design, there is one sensing system per sensed optic; the optical path forms a ‘V’ with a baseline of 5-50 meters between the sensed optic and the light source/measurement photodiode. All three components are mounted on monuments (in task) and to the floor of the facility. An alternative to reduce sensitivity to foundation slab distortion is to mount the laser and the measurement diodes on a low-thermal-expansion optical table somewhat decoupled from the slab. A conceptual layout of Optical Levers has been made[1] for the purposes of testing the Vacuum Equipment conceptual design for flexibility; this is for reference only, but shows the basic feasibility of the baseline Optical Lever approach. The vacuum viewports are also part of the task.

And alternative is to establish a reference beam which runs the length of the facility along each arm; this light is picked off by beamsplitters for each sensed optic, sent to the sensed optic, and the return sent back parallel to the arm to the measurement photodiode. Each optical table within the vacuum is also sensed to allow a regression to remove the motion of the optical table. The advantage is the ability to determine the paths for each sensed optic beam, making clear paths easy to find; the disadvantage is the complexity of the in-vacuum optics. A choice between these two will be made by the time of the DRR.

3 SPECIFICATIONS

3.1. Introduction

The Specifications will be complete by the time of the PDR. At present, placeholders for the principal specifications are given with rough values to show the range being considered.

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[1] Abramovici and Zucker, Vacuum Equipment TIGER Team documentation, March 1993

3.2. Specifications

Table 1: Physical and Environmental specifications for the Optlev subsystem

Specification	*Value*
noise performance of Detectors	TBD $\mathrm{m}/\sqrt{\mathrm{Hz}}$ for TBD beam dia. (~$10^{-8}\mathrm{m}/\sqrt{\mathrm{Hz}}$ for 3 mm beam)
diameter of Detectors	TBD (~1.5 cm)
power of Optlev laser	1-10 mW minimum
frequency stability of Optlev laser	TBD
wavelength of Optlev laser	400nm - 700 nm
Optlev laser 1/f intensity noise servo performance	$dI/I < 2\times10^{-4}$ from 0.1 to 10 Hz
Optlev beam sizes	$w_0 \approx 3\pm1$ mm.
Optlev intrinsic long-term laser beam stability	$<1\times10^{-4}$ rad for 100 secs
Optlev pointing servo system performance	TBD; 1×10^{-8} rad
collimator adjustment range, resolution	TBD
Mechanical outlines	TBD
attachment points	TBD
specific input/output signals, levels, signs	
connectors	TBD

3.3. Discussion of selected specifications

3.3.1. power of Optlev laser

There are constraints from the low-frequency control regime, and the high-frequency GW band performance requirement. All power levels are at each photodiode, after the optics of the system have been encountered. It will be necessary to calculate back to the laser source strength once the reflectivity/transmission of the sensed optics at the Optlev wavelength is known, and once the optical layout is chosen. For the ‘V’ configuration, an estimate is that the power must be 10x the per-photodiode power, leading to a minimum of 1 mW; for the pick-off configuration, an estimate is for 100x the per-photodiode power, or a minimum of 10 mW.

3.3.1.1 control frequencies (10 Hz-0.002 Hz)

Shot Noise: For a l=50m arm and a d=3mm diameter beam, the rate of change of intensity I for a total intensity of I_0 with position x is approximately $dI/dx \approx I_0/d$ and the shot noise is

$i = \sqrt{2eI}\mathrm{amp}/\sqrt{\mathrm{Hz}}$. The resulting position noise is $x = d\sqrt{2(e/I)}$ (to within factors of 2). With a typical quaddiode efficiency of η =1/4 amp/watt, we find that to meet our requirement of $\theta = 10^{-8}$ rad with a bandwidth of BW=0.1 to 10 Hz, we need

$$P = \frac{1}{\eta}\frac{2ed^2}{(l\theta)^2 BW} = 4\times\frac{2(1.6\times10^{-19})(3\times10^{-3})^2}{(50\times1\times10^{-8})^2\times10.1} = 5\times10^{-12}\mathrm{W}$$

- Photodetector/amplifier noise: At the low frequencies of intended operation, a typical current amplifier for this application would have 10 $\mathrm{pA}/\sqrt{\mathrm{Hz}}$; this corresponds to 1.2×10^{-10} W of needed power for the signal to be comparable to this noise source; this places a stronger requirement than does the shot noise.

3.3.1.2 GW frequencies (10 Hz-3 kHz)

- Beam motion at GW frequencies must be such that the product of (the signal from this motion) and (the forward transfer function from the quaddiode to the suspensions's actuator) cause angular motions of the mass which have a negligible effect on the GW sensitivity. The simplest way to guarantee this is to require that the motions be smaller than the angular seismic noise. Using the DHS RMS Noise memo as a reference, the angular motion (in attitude) of the mass at 70 Hz is roughly $5\times10^{-19}\mathrm{rad}/\sqrt{\mathrm{Hz}}$. The forward gain will be of the order of 2×10^{-9} for roughly unity gain at 1 Hz (damping, from S. Kawamura's suspension calculations). This dictates a sensing noise of $2.5\times10^{-10}\mathrm{rad}/\sqrt{\mathrm{Hz}}$, or a light power of 8×10^{-8} W. TBD; this must be calculated more carefully.
- Amplifier noise: we want to be dominated by the shot noise in the light. This, with the practical amplifier designs, leads to a specification of 0.1 mW.
- Ease of alignment (finding the beam with the eye or CCD camera, etc.) leads to a power specification of minimum 0.1 mW. This is in the range of commercially available products at a variety of wavelengths with reasonable lifetimes.

3.3.2. frequency stability of Optlev laser

Frequency fluctuations in the Optlev laser can lead to excess noise due to parasitic interferometers. To limit this, the Optlev laser shall be single longitudinal mode and have a temperature controller to maintain operation without any mode hops after the warm-up time. If necessary, a monitor to temporarily (for an msec or so) suspend closed loop control during a rare mode hop will be developed. This would be a software test of the difference from sample to sample of the intensity, with an abrupt change indicating a time to ignore input.

3.3.3. wavelength of Optlev laser

The wavelength has only weak constraints.

- We require that the wavelength be visible with the human eye. This is an aid in alignment and debugging.
- The transmission through the designed coatings for the GW-sensing laser should be not less than 0.01 and not greater than 0.99 (to allow both beams to be used)
- The availability of laser diodes adds more wavelength constraints. 670 nm is a popular wavelength, which makes other components readily available.

We specify that the wavelength be between 400 nm and 700 nm, TBR.

3.3.4. Optlev laser 1/f intensity noise

Variations in the intensity of the Optlev laser can mimic motions of the beam, and thus constitutes a competing noise source. Using formulæ and values above, we see that $dI/I = dx/d = (l/d)\,d\theta$ or that a fractional intensity noise of $dI/I < 2\times10^{-4}$ would be just equivalent to our required sensitivity. The sensitivity to this his noise is reduceable by normalizing the difference of quaddiode elements (left/right or top/bottom) to the total current, and thus is reduced in its coupling by a factor which is of the order of 10. Including a safety factor of 10 gives a requirement of $dI/I < 2\times10^{-4}$ over the bandwidth from 0.002 to 10 Hz. This requirement, with the performance specification for available lasers/power supplies and observed fluctuations given the single-mode fiber coupling, will determine the specification for the loop gain in the intensity stabilization servo.

3.3.5. Optlev beam sizes and quality

Constraints on the beams sizes come from the

- viewport diameter (15 cm free aperture)
- stay-free zones (desire to minimize beam diameter, with roughly 10 mm the point of diminishing returns)
- collimator design (less expensive to use smaller optics)
- quaddiode sizes (integrated quadrant photodiodes are available up to 1.5 cm diameter)
- sensing sensitivity (smaller spots make larger $dI/d\theta$)
- diffraction limit for the length and distance traveled. For a beam which grows by $\sqrt{2}$ from waist to maximum over the nominal distance and with a nominal wavelength, this leads to $w_0 \approx 3$ mm, or a maximum $1/e^2$ diameter of 12 mm.

The beam is thus specified to have a $w_0 \approx 3\pm1$ mm.

The beam quality must meet requirements (put in reqs doc!) for the power in the wings of the gaussian to limit accidental beam overlap and thus interference.

3.3.6. quaddiode and amplifier

Top-level specifications for the photodiode and for the amplifier performance are given here.

quaddiode size (TBD, about 1.5 cm diameter)

quaddiode quadrant separation (TBD; <1/100 quadrant size)

quaddiode maximum current (TBD; 10 mW)

amplifiers (TBD; gain, bandwidth, noise, range): See Optlev Electrical Specifications Document

3.3.7. Optlev intrinsic long-term laser beam stability

The laser beam from the collimator must be sufficiently stable in position (before any active control) to align the beam and place it on the reference quaddiode. This leads to a requirement of beam wander integrated for 100 secs of less than an angle corresponding to the quaddiode radius (order of 5 mm) viewed from a distance of the Optical lever baseline (order of 50 m), or $<1\times10^{-4}$ rad for 100 secs. This drift could be due to either thermal distortions of the collimator or motions of the Optlev collimator support.

3.3.8. Optlev pointing servo system performance

There is an active stabilization of the Optlev beam position where the reference diode signal is the servo error signal held to a minimum, and mirrors mounted on a $\theta - \phi$ PZT mount are the actuators. The maximum bandwidth of the servo system will be limited by the mechanical characteristics of the galvanometer actuators. The performance requirement is that the integrated residual angle motion of the Optlev beam be less than 1×10^{-8} rad over time periods up to TBR 500 secs. If the primary source of Optlev beam jitter is the LIGO translational seismic noise acting over a baseline of 1m (a worst-case scenario for the angular seismic noise), then the integrated input spectrum is of the order of 4×10^{-7} rad (ref DHS RMS), with most of the contribution coming from the 0.1-0.3 Hz region. Foundation slab distortions and resonances, collimator acoustic excitation, and unshielded air paths are some of the additional input noise with which this servo system must deal. Using the seismic estimate above, a unity-gain frequency of some 20 Hz will be sufficient and easily achievable. As a safety margin, we specify a unity-gain frequency of 100 Hz.

A more detailed study will lead to specifications for:

- servo gain as a function of frequency (probably a simple pole at 0.1 Hz)
- actuator first resonance and Q
- dynamic range

- gain required to deal with stack resonances
- gain required to deal with microseismic peak (in attitude; altitude no problem)

3.4. Physical and Environmental specifications for the Optlev

3.4.1. Dimensions

3.4.1.1 Light Source

TBD; order of 15cm X 15 cm X 50 cm

3.4.1.2 Ref and Meas Pos Det Assemblies

TBD; order of 2.5 cm X 2.5 cm X 10 cm

3.4.1.3 Support Structures

TBD; as needed to support the above equipment. In some cases, larger surfaces are needed to provide a common base for the Light Source and Meas Pos Det.

3.4.1.4 Auxiliary equipment

TBD; as needed, in racks. All signals are electrical except for the Single Mode Fiber, which is jacketed and can be treated as an electrical cable EXCEPT that it should not be subjected to excessive vibration.

3.4.2. Environment

No special requirements beyond the LVEA specifications are made. Over the environmental temperature and humidity range, the Optlev shall function within its specifications and without introducing noise from mode hops, PZT arcing in the humid atmosphere, or differential thermal expansion (‘creaking’).

3.5. Design and Construction

3.5.1. Materials and Processes

3.5.1.1 Finishes

- *External surfaces: External surfaces requiring protection shall be painted purple or otherwise protected in a manner to be approved.*

3.5.1.2 Materials

The relay mirrors in the vacuum must be prepared with only approved vacuum-compatible materials and manufactured, cleaned, and handled according to procedures approved for in-vacuum equipment.

All of the remaining parts of the Optlev are in the LVEA, and have minimal additional special material requirements.

3.5.1.3 Processes

None identified as of this date.

3.5.2. 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.

3.5.3. Workmanship

Standard of workmanship desired, uniformity, freedom from defects and general appearance of the finished product shall be of the standard adopted for the Detector hardware. No special considerations have been identified.

3.5.4. Interchangeability

All components will be fully interchangeable, with the following restrictions:

- The second collimators may be different in lens curvatures and lens placement, but will all fit into a standard mounting system in the standard light source.
- The Collars which adapt from the second collimator to the viewport may differ in length, but will interface in a standard way with the light source
- The gain resistors in the Quadrant Photodiodes may differ, but the circuit boards will be standard so that retrofitting can bring them all to an identical state.

3.5.5. Human Engineering

Remote control of the coarse alignment of the Optical Levers would be facilitated by a simple handheld device with a joystick-like control.

3.6. Documentation