

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T0900239-v1

ADVANCED LIGO

xxx

**AOS: Optical Lever and Viewport
Conceptual Design**

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Table of Contents

| | | |
|----------|--|-------------------------------------|
| 1 | INTRODUCTION | ERROR! BOOKMARK NOT DEFINED. |
| 1.1 | PURPOSE | 5 |
| 1.2 | SCOPE | 5 |
| 1.3 | DEFINITIONS | 5 |
| 1.4 | ACRONYMS | 5 |
| 1.5 | APPLICABLE DOCUMENTS | 6 |
| 1.5.1 | <i>LIGO Documents</i> | 6 |
| 1.5.2 | <i>Non-LIGO Documents</i> | 6 |
| 2 | CATALOG OF XXXXX DESIGN REQUIREMENTS..... | 7 |
| 3 | CONCEPTUAL DESIGN..... | 8 |
| 3.1.1 | <i>xxx Characteristics</i> | 15 |
| 3.1.1.1 | <i>xxx Performance Characteristics</i> | 15 |
| 3.1.1.2 | <i>Interface Definitions</i> | 15 |
| 3.1.1.3 | <i>Reliability</i> | 15 |
| 3.1.1.4 | <i>Transportability</i> | 16 |
| 3.2 | DESIGN AND CONSTRUCTION..... | 17 |
| 3.2.1 | <i>Materials and Processes</i> | 17 |
| 3.2.1.1 | <i>Materials</i> | 17 |
| 3.2.1.2 | <i>Processes</i> | Error! Bookmark not defined. |
| 3.2.1.3 | <i>Component Naming</i> | 17 |
| 3.2.2 | <i>Workmanship</i> | 17 |
| 3.2.3 | <i>Interchangeability</i> | 17 |
| 3.2.4 | <i>Safety</i> | 17 |
| 3.2.5 | <i>Human Engineering</i> | 17 |
| 3.3 | ASSEMBLY AND MAINTENANCE | 17 |
| 3.4 | DOCUMENTATION | 17 |
| 3.4.1 | <i>Specifications</i> | 18 |
| 3.4.2 | <i>Design Documents</i> | 18 |
| 3.4.3 | <i>Engineering Drawings and Associated Lists</i> | 18 |
| 3.4.4 | <i>Technical Manuals and Procedures</i> | 18 |
| 3.4.4.1 | <i>Procedures</i> | 18 |
| 3.4.4.2 | <i>Manuals</i> | 18 |
| 3.4.5 | <i>Documentation Numbering</i> | 18 |
| 3.4.6 | <i>Test Plans and Procedures</i> | 18 |
| 3.5 | LOGISTICS..... | 18 |
| 3.6 | PRECEDENCE..... | ERROR! BOOKMARK NOT DEFINED. |
| 3.7 | QUALIFICATION | ERROR! BOOKMARK NOT DEFINED. |
| 4 | QUALITY ASSURANCE PROVISIONS..... | 19 |
| 4.1 | GENERAL | 19 |
| 4.1.1 | <i>Responsibility for Tests</i> | 19 |
| 4.1.2 | <i>Special Tests</i> | 19 |
| 4.1.2.1 | <i>Engineering Tests</i> | 19 |
| 4.1.2.2 | <i>Reliability Testing</i> | 19 |
| 4.1.3 | <i>Configuration Management</i> | 19 |
| 4.2 | QUALITY CONFORMANCE INSPECTIONS | 19 |
| 4.2.1 | <i>Inspections</i> | 19 |
| 4.2.2 | <i>Demonstration</i> | 20 |
| 4.2.3 | <i>Test</i> | 20 |
| 5 | PREPARATION FOR DELIVERY | 21 |
| 5.1 | PREPARATION | 21 |

5.2 PACKAGING21
 5.3 MARKING.....21
 6 NOTES.....22

Appendices

Appendix A Quality Conformance Inspections 23

Table of Tables

Table 2 Environmental Performance Characteristics 16
Table 4 Quality Conformance Inspections 23

Table of Figures

Figure 1: ETM Telescope, ray model **Error! Bookmark not defined.**
Figure 2: TRANSMON QPD spot, x-cross section..... **Error! Bookmark not defined.**
Figure 3: TRANSMON QPD spot, y-cross section..... **Error! Bookmark not defined.**

Abstract

This document will present the conceptual designs for the Advanced LIGO optical levers used to restore mirror alignment for lock re-acquisition.

When interferometer lock is lost, the angular feedback signals that keep the interferometer aligned at low noise are lost. The mirrors swing back to their suspension's equilibrium position.

The optical levers maintain the memory of the angular alignment that will allow the interferometer to acquire lock. The alignment requirements for this task are detailed in T09....

The optical lever signals will be used to pre-align the interferometer and to keep it aligned during lock acquisition, until the interferometric feedback signals can take over. It is assumed that the multiple pendula supporting the mirrors will have been ring down properly, to the end of reducing the pitch and yaw hysteresis to less than 100 μ radian in order to fall within the optical lever dynamic range. It is also supposed that the oscillation of the mirror is internally damped in the multiple pendula.

1.1 Purpose

The purpose of this document is to present a conceptual design that meets the requirements derived in [T0900174 requirements doc](#).

1.2 Scope

This document will present a conceptual design for the Advanced LIGO optical levers to be used to restore mirror alignment for lock re-acquisition.

1.3 Definitions

1.4 Acronyms

AOS - Auxiliary Optics Support

BS - Beam Splitter

BSC - Beam Splitter Chamber

ETM_x, ETM_y - End Test Mass in the interferometer 'X' or 'Y' arm

HAM - Horizontal Access Module

ITM_x, ITM_y - Input Test Mass in the interferometer 'X' or 'Y' arm

LIGO - Laser Interferometer Gravity Wave Observatory

LVEA-vacuum equipment area

mrad – milliradian

MTBF – mean time before failure

NA – not applicable

OPTLEV- optical lever

p-p, peak to peak

ppm - parts per million

PRM – Power Recycling Mirror

p-v, peak to valley

QPD – quadrant photo diode

rms - root-mean-square

SRM – Signal Recycling Mirror

TBD - To Be Determined

1.5 Applicable Documents

1.5.1 LIGO Documents

1. T0900174 Advanced-LIGO Optical Levers Design Requirements
2. T010076-01 Optical Layout for Advanced LIGO
3. E950111-A LIGO Naming Convention
4. M950046-F LIGO Project System Safety Management Plan
5. E960022-B LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures
- 6.

1.5.2 Non-LIGO Documents

2 Catalog of Optical lever Design Requirements

The requirements for the Optical lever subsystem are derived in T0xxx Design Requirements.

The alignment resolution requirements of the Ad-LIGO optical lever is less than a microradian (for a detailed requirement see table TBD). The present LIGO optical levers measured angular resolution was of the order of 5 microradian depending on the lever in object. The requirement is almost an order of magnitude tighter than in present LIGO and require more stable supports and optics.

Table 1: Required angular sensitivity for individual mirrors, physical and physical parameters of individual Optical levers. The arm length given is the one between the monitored mirror and the detection diode, the beam travels twice that distance from the launcher telescope to the detection diode.

| Optics element | Requirement Straight/ /Folded interferometer [μ radian] | (Half) Arm-length (straight/ folded) [m] | Required spatial resolution [μ m] | Required Spotsizes (2w) [mm] | Launching Telescope diameter [mm] | Launching / Detection height [m] | Dynamic range [mm] / [μ radian] | Expected sensitivity / stability [nrad] / [μ rad] |
|----------------|--|--|---|------------------------------------|--------------------------------------|----------------------------------|--------------------------------------|---|
| ITM | 2.56/2.54 | 35 | 89 | 4 | 40 | | $\pm 7/200$ | 1.3/ ? |
| ETM | 2.3/2.28 | 6/3 | 14/7 | 2 | 12 | | $\pm 5/330$ | 3.5/ ? |
| PR3 | 2.74/2.81 | 14/13.7 | 27 | 2 | 25 | | $\pm 5/140$ | 1.2/ ? |
| SR3 | 1.9/2.02 | 14/13.7 | 26 | 2 | 25 | | $\pm 5/140$ | 1.2/ ? |
| BS | 2.78/2.85 | 1.9/2 | 5.2 | 1 | 10 | | $\pm 4/500$ | 5/ ? |
| FMX | Na/2.85 | 2 | 5.2 | 1 | 10 | | $\pm 4/500$ | 5/ ? |
| FMY | Na/2.85 | 3 | 5.2 | 1 | 10 | | $\pm 4/330$ | 3.3/ ? |

Note that for safety margin the adopted pointing accuracy requirement ($\pm 0.7 \mu$ radian) is chosen tighter than all of the above numbers.

Launching-wise the most requiring is the Input Test Mass telescope (70 m roundtrip), detection-wise the most requiring telescope is the Beam Splitter telescope (5 μ m resolution).

Sufficient dynamic range with coarse resolution is necessary to find the mirror alignment after a lost lock and “drag” it back to its nominal position (center of the Quad Photo Diode).

3 Conceptual Design

Bench tests show that with properly designed and mechanically stable launching telescopes, the optical stability and sensitivity (nradian) of even a short (2m) Optical Lever are more than sufficient to satisfy the requirements ($0.7 \mu\text{radian}$). Much more noise was detected on the actual optical levers (using polarization maintaining fiber on a non polarized laser).

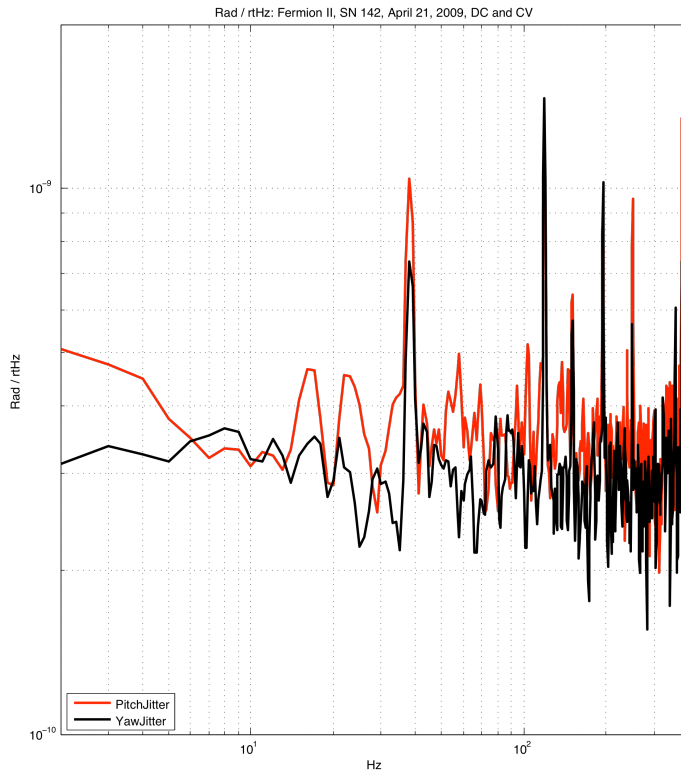


Figure Angular sensitivity measured in a 2 m optical bench straight optical lever.

Add strip chart recording and data on long term drift (larger effect)

Robert Schofield found the following causes for the angular noise: seismic noise amplified by the pylons, possible differential expansion in the optics mount screws, and differential thermal expansion warping of the launching optics benches.

Other identified sources of noise are air turbulence between the launching telescope and the vacuum optical port and stray ambient light on the detection diodes.

The seismic noise on top of the pylon was found to be 10 times worse than on ground.

The benches' warping was probably originating by differential expansion between the steel bench and its aluminum shroud on the top side, and between parts of the pylon attachments on the bottom. The optical bench warping was reduced by loosening the thermal and air current shroud screws.

About the excess seismic problem, a close inspection showed that the problem arises from too heavy pylons sitting on the weak footing of the kinematic tunable mount, which is made of threaded rods. These screws are weak when compared with the almost 2 m long, thick-wall steel tube pylon they support. The pylons are unnecessarily heavy. The problem appears to be present, in different amounts, in all the optical levers that we inspected.

It was also found that air currents affect the beam spot stability and that pipes around the air sections of the beam reduce this effect.

The pylon excitation problem will be treated by lighter and more rigid pyramidal pylons, directly bolted and grouted to ground, eliminating the weak kinematic mounts. The BSC pier experience also showed that much lighter pylons than the present ones are required to avoid to be limited by the concrete floor stiffness.

Note, the beam splitter Optical Lever is constrained behind and supported by the existing blue piers, which are known to be seismic amplifier. The problem may be exacerbated by the forced actuated on it by the hydraulic external seismic isolators, which may include low frequency forces like tidal corrections. It is difficult to build a rigid independent support for the optical lever in the restrained space. A possible solution could be to drill a couple of 30 mm diameter holes in the steel pier and shoot the optical levers through the pier. TBD

The optical bench warping problem will be treated by eliminating the optical benches, and by building a thermal and air current shield completely separated from the pylon (The pylon needs to be inside a thermal shield to reduce differential heating and thermal expansion effects, to match the requirements. Less than one microradian long term angular stability requires better than a tenth of a degree thermal stability on opposite sides of the launching pylon, which can be guaranteed only inside a thermal shield).

Additionally, all thermal sources will be located well outside the thermal shield (laser or readout electronics) or be kept normally OFF (the beam spot alignment stepper motors, if present, will need to be physically off, no quiescent current, when not in use).

To reach the required angular stability it is important to build an optical system and its support all with the same material, or built with a high level of thermal expansion compensation. This includes the materials used inside the launching telescope.

When an optical lever has a slope, the launching will be done from the lower pier, and the detection on the higher one, to minimize angular noise.

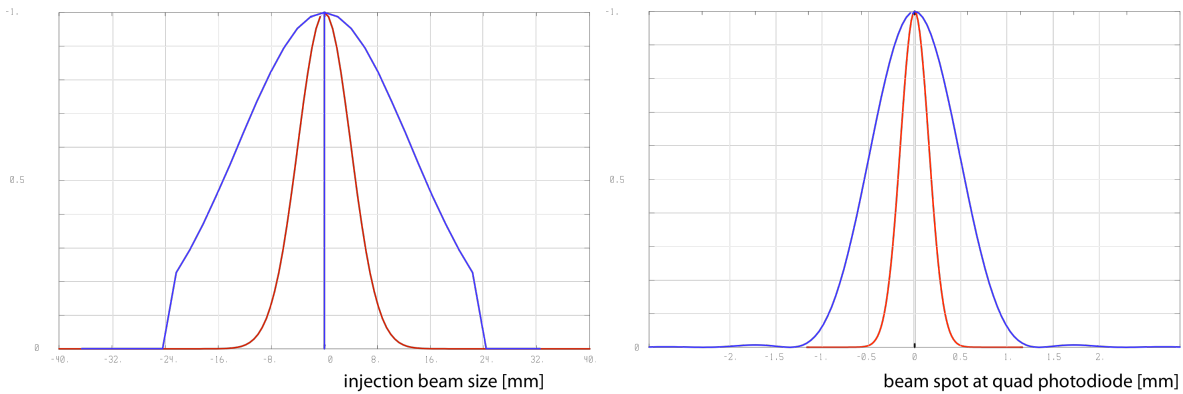
The structure holding the launching optics needs to be more rigid than the present one. The optical bench will be suppressed, replaced by a spherical washer solidly clamped on the top of the pylon. The spherical washer will allow pointing of the laser beam to the detection quadrant diode.

The laser beam launching will be achieved with a single rigid, ~20 to 30 cm long, fiber fed, Galilean telescope beam-expander collimator mountable on a lockable spherical washer. Manual micrometric screws allow the alignment before locking.

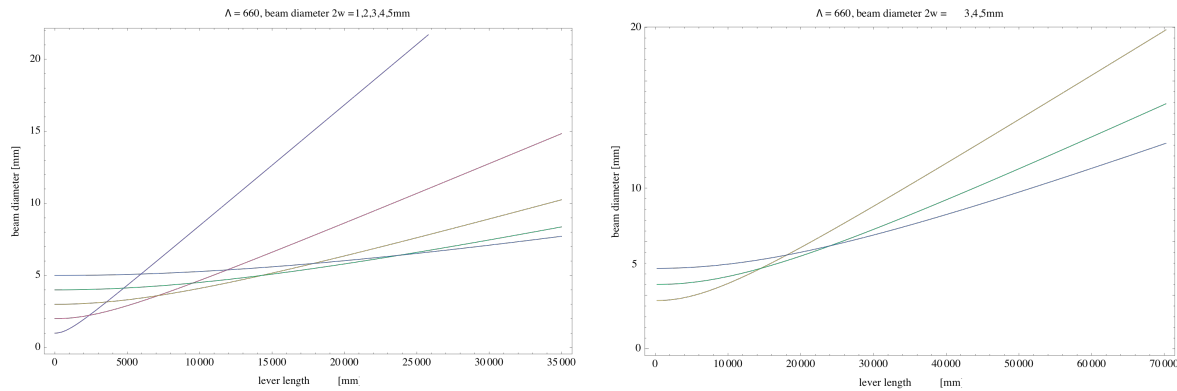
Different telescope expansion ratios and laser beam diameters will be used to match the necessity of levers of different length to produce the required beam spot diameter ($1/e^2$) on the quadrant diode.

The light will be directly coupled to the launching telescope from a monomode (not polarization maintaining) fiber.

Although the injection filling ration in the telescope is not critical (see figure), sufficiently large diameter telescope (~40 mm for the long levers) will be used to avoid rings in the light spot on the detection diode.



Injected beam profile in the launching telescope and beam profile at the quadrant diode. Overfilling of the launching telescope produce rings around the spot on the detection diode.



Evaluation of the beam spot diameter as function of the beam waist on the quadrant photo diode and distance from the waist. The required launching telescope diameter is evaluated as the beam diameter at the launching distance (twice the optical lever length).

Micrometric screws acting on the spherical washer tilts will allow coarse (tens of microradian) alignment of the telescope to the detection diode before clamping. Finer and remote telescope alignment will not be available because they would not allow sufficient long-term stability.

The required periodic nulling of the quad diode signal will be achieved by micrometrically translating the quad diode itself at the receiving end, which is much less sensitive (by the ratio of the telescope over the optical lever lengths). Besides the photodiode is much easier to move. Commercial, remote control, linear movement stages with fifty mm range will be adequate to position the photo diodes and null their Right/Left and Up/Down signals.

Pylon structure.

The triangular pyramidal pylon will be made of laser cut, 2 mm thick stainless steel sheet panels, windowed to eliminate drum mode excitations. In each panel, all internal cross beams will be provided with a full-length, 30 mm wide lip folded at 90° for stiffening. Each panel will have a 20 mm folded stiffening lip at the two edges connecting to the mating panel. The mating folded lips will be fist clamped and then welded together.

The bottom of the pyramid will be welded to a 20 mm thick stainless steel plate. The rigidity of the mounting to ground will be achieved by grouting the base plate to ground with expansive concrete. Three holes for anchoring bolts and three threaded holes for tuning screws, positioned at the three corners of the plate, will allow leveling of the pylon before grouting. Large diameter holes in the plate will allow injection of the grout, and provide the bulk of the rigidity.

A 10 mm thick platform will be welded at the top of the pylon, with a shallow housing for a 10 cm diameter spherical washer.

The pylon will have the height, and will be leaning or bent, to satisfy the spatial requirements of individual Optical Levers.

The telescope mount (or quad diode translation stage) mounts directly on the washer.

A single central screw, with ergo-nut operated from inside the pylon, locks the movement of the spherical washer.

The telescope size will be adapted to provided the required beam spot of individual levers.

The telescope focusing mechanism must have internal locking screws as well to guarantee sufficient aiming stability.

The thermal and air current shield will be made of 50 mm thick, aluminum foil sheated insulating foam panels, separated at least 25 mm from the pylon and optical structure. The top part of the shield must be removable to allow manual tuning and servicing.

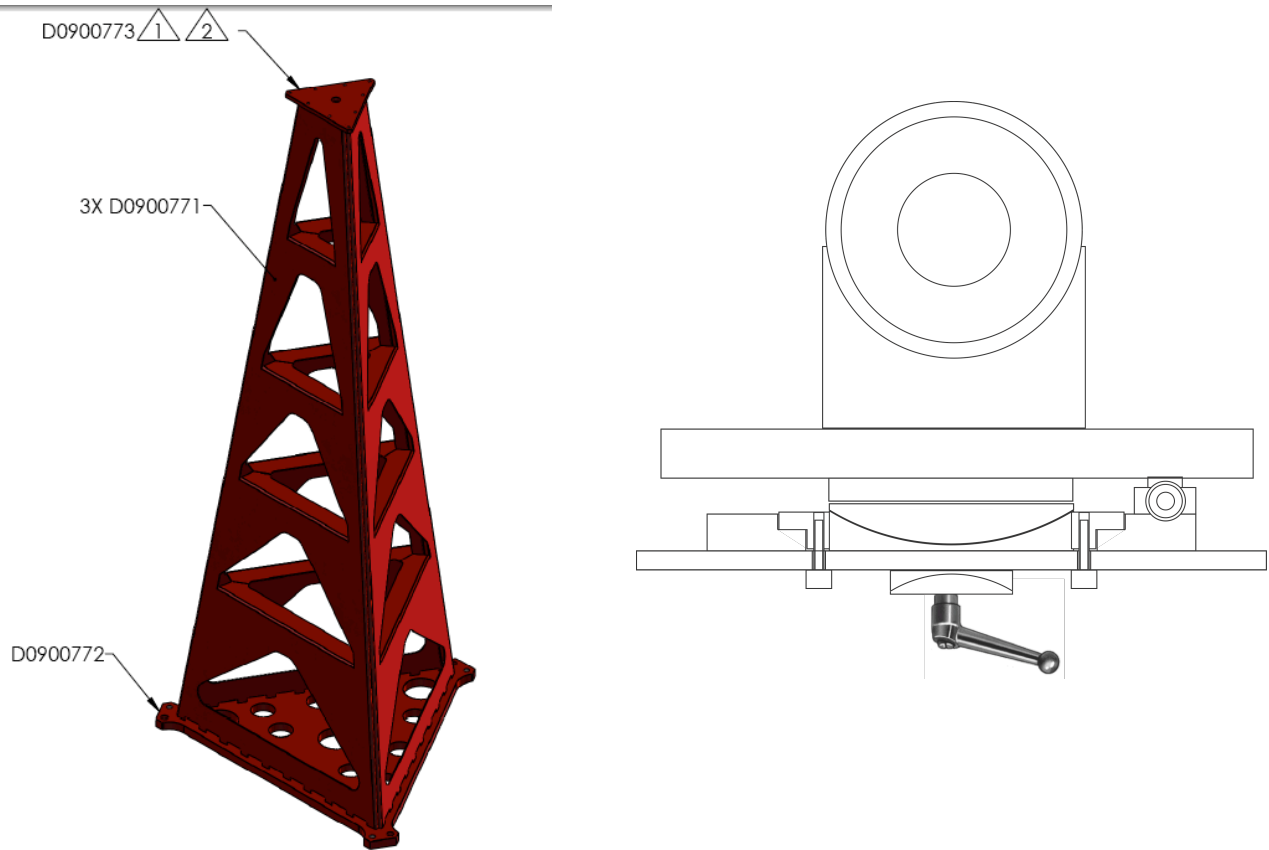


Figure 1; Schematic design of a light pylon to carry the optical lever launching and receiving optics and of a launching telescope to be mounted on top of the pylon. The pylon is made with sheet metal laser cut, bent and stitch welded. The thicker base plate would be bolted and grouted to ground for maximal stiffness; it is provided with large holes to allow the grout to mushroom through, expand and lock the structure to ground.

The telescope, will be mounted on a spherical washer, lockable with an handle nut inside the pylon structure. Micrometric screws allow precision alignment before locking. The manual alignment precision is sufficient to aim the beam within the 50 mm range of the receiving Quad Photo Diode.

As in present LIGO the light will be fed in the launching optics by means of a monomode fiber:
to wash out any possible laser angular jitter
to remove the laser from the pylon vicinities
to allow laser replacement (in case of failure) without losing the alignment.

The monomode (non polarization conserving) fiber will be at least 5 m long to fully scramble the laser polarization and any possible injection mis-alignment.

The fibers will be of the angle-cut type, to avoid light reflections back to the laser diode.

The laser must be replaceable without touching the fiber attachment to the launcher optics to avoid altering the launcher alignment. If needed, a separate fiber will be connected to the launcher telescope, with an intermediate connection far from the pylon.

The laser will be of similar kind of those presently used in LIGO.

Lasers of different colors may be used to match the reflectivity of the main optics if needed.

The detection Quadrant Photo Diode will be the same 6 mm Quadrant Dode. It provides precision positioning only when the beam is within half a width from its center as illustrated in the figure. The figure is calculated for a 2 mm 2w beam spot, using measured Quadrant Photo Diode noise levels.

A remote control, 50 mm X-Y movement mounted on the detection Pylon will be used to null the Quadrant Diode signal, thus guaranteeing its best sensitivity.

Position sensitivity can be extracted, with substantially less sensitivity from the single ended R or L quadrants when the more precise R-L signal tapers off.

This trick allows to extend the effective dynamic range of the Quadrant Photo Diodes to ± 5 mm with the 2 mm beam size.

In the ITM, with 4 mm beam size, the positioning dynamic range will be ~ 8 mm for a corresponding angular dynamic range of 230 μ radian.

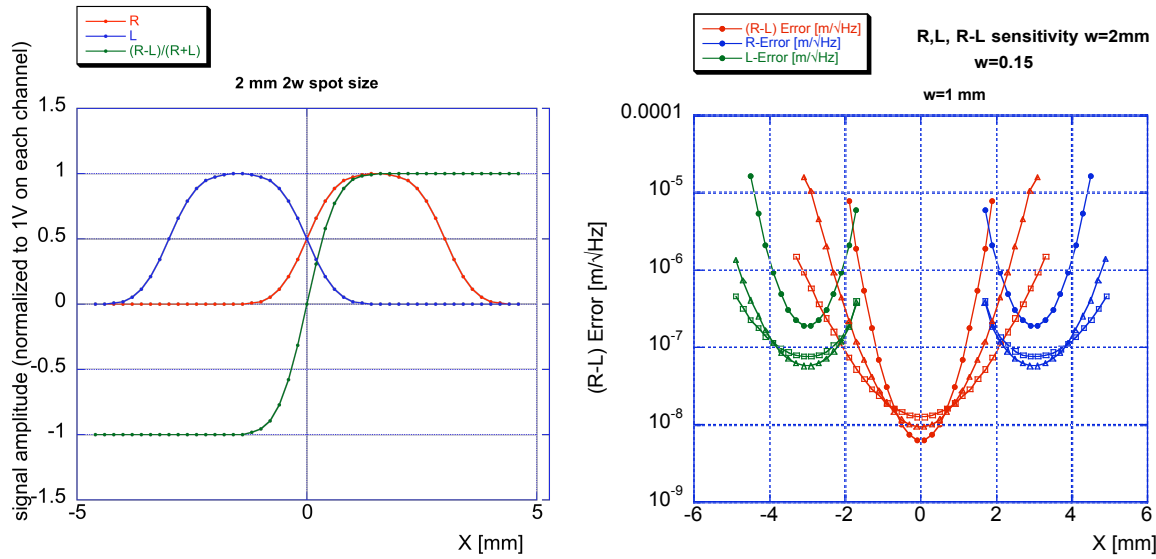


Figure: Power deposited on the Quadrant Photo diode as a 2 mm beam is scanned transversally (left panel), and estimated position resolution using measured noise levels (right panel). The sensitivity estimation is repeated for different spot sizes.

The R-L position resolution increases linearly with smaller spot sizes, it is optimal only when the spot centered on the quadrant photo diode within half spot width.

The position dynamic range, evaluated as the displacement for which either the R or the L signal fade, diminishes with smaller spot size.

The angular resolution is obtained dividing by the lever arm length.

Viewports will be provided for the injection and collection of the Optical Lever laser beams.

Optionals.

Wherever possible the laser spot size on the quad photodiode will be set by the focusing of the launching lens or telescope and we will rely on the physical length of the lever to reach the required angular resolution.

A compact telescope at the receiving end can be used to extend the effective optical lever length if the actual lever length proved not sufficient.

Similarly, if the spot was too large on the detection diode, a beam reducer telescope can be used.

The quad photodiode can be replaced with a CCD target and an image processor, in case of higher angular resolution and/or larger range requirements. This option is not studied.

To reduce low frequency electronics noise the laser can be modulated so that the quad diode signal can be detected with a lock in amplifier.

3.1.1 xxx Characteristics

3.1.1.1 xxx Performance Characteristics

3.1.1.1.1 Electrical characteristics

3.1.1.2 Interface Definitions

3.1.1.2.1 Interfaces to other LIGO detector subsystems

3.1.1.2.2 Interfaces external to LIGO detector subsystems

3.1.1.2.2.1 Mechanical Interfaces

3.1.1.2.2.2 Electrical Interfaces

3.1.1.2.2.3 Stay Clear Zones

3.1.1.3 Reliability

3.1.1.3.1 Mean Time Before Failure

Lasers with more than 8000 hours of MTBF will be used.

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3.1.1.3.2 Maintainability

In case of failure the lasers will be replaceable without getting close to the launching pylons

3.1.1.3.3 Environmental Conditions

3.1.1.3.3.1 Natural Environment

3.1.1.3.3.1.1 Temperature and Humidity

The optical levers are designed to operate in the humidity and temperature controlled environment of the enclosed LIGO LVEA.

Table 1 Environmental Performance Characteristics

| Operating | Non-operating (storage) | Transport |
|--|---|--|
| +20C to +25C, 20-70% RH, non- condensing | 0C to +60C, 10-90% RH, non-condensing | 0C to +60C, 10-90% RH, non- condensing |

3.1.1.3.3.1.2 Atmospheric Pressure

The optical levers will function under normal atmospheric pressure conditions

3.1.1.3.3.1.3 Seismic Disturbance

To maintain the best alignment wit respect to the ground, the optical levers will be mounted on the lightest and most rigid pylons so that they will be subjected to, as closely as possible all ground seismic disturbances.

3.1.1.3.3.2 Induced Environment

3.1.1.3.3.2.1 Acoustic

An external sound/thermal shield will reduce the acoustic impact on the optical lever performance.

3.1.1.3.3.2.2 Mechanical Vibration

Reduced with pylon internal dampers if necessary.

3.1.1.4 Transportability

All items will be transportable by commercial carrier without degradation in performance. As necessary, provisions will 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 will be utilized to prevent damage. The mounting pedestals and arbors will be movable by forklift, and will have appropriate lifting eyes and mechanical strength to be lifted by cranes.

3.2 Design and Construction

3.2.1 Materials and Processes

The in-vacuum materials and processes used in the fabrication of the viewports will be compatible with the LIGO approved materials list.

3.2.1.1 Materials

A list of currently approved materials for use inside the LIGO vacuum envelope can be found in E960022-B LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures. All materials used inside the vacuum chamber will comply with LIGO-E960022-00-D.

3.2.1.1.1 Cleaning

All materials used inside the vacuum chambers will be cleaned in accordance with Specification **Error! Reference source not found.**

3.2.1.2 Component Naming

All components will be identified using the E950111-A LIGO Naming Convention. This will include identification (part or drawing number, revision number, serial number) physically stamped on all components, in all drawings and in all related documentation.

3.2.2 Workmanship

All components will be manufactured according to good commercial practice.

3.2.3 Interchangeability

Common elements with ordinary dimensional tolerances will be interchangeable.

3.2.4 Safety

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

3.2.5 Human Engineering

NA

3.3 Assembly and Maintenance

Assembly procedures will be developed in conjunction with the hardware design.

3.4 Documentation

The documentation will consist of working drawings, assembly drawings, alignment procedures, and manufacturer's data sheets wherever applicable.

3.4.1 Specifications

The manufacturer's specifications for the purchased components will apply.

3.4.2 Design Documents

Revised drawings and calibration documents will be produced as necessary.

3.4.3 Engineering Drawings and Associated Lists

A complete set of drawings suitable for fabrication will be provided along with Bill of Material (BOM) and drawing tree lists. The drawings will comply with LIGO standard formats and shall be provided in electronic format. All documents shall use the LIGO drawing numbering system, be drawn using LIGO Drawing Preparation Standards.

3.4.4 Technical Manuals and Procedures

3.4.4.1 Procedures

Procedures will be provided for, at minimum,

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

3.4.4.2 Manuals

All manufacturers' operating and installation manuals will be supplied in addition to LIGO calibration procedures.

3.4.5 Documentation Numbering

All documents will 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 will be developed in accordance with the LIGO Test Plan Guidelines, LIGO document. **TBD**.

3.5 Logistics

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

4 Quality Assurance Provisions

This section includes all of the examinations and tests to be performed in order to ascertain the product, material or process to be developed or offered for acceptance conforms to the requirements in section 3.

4.1 General

4.1.1 Responsibility for Tests

AOS will conduct tests to verify the as-delivered performance specifications of the sub-system.

4.1.2 Special Tests

4.1.2.1 Engineering Tests

TBD

4.1.2.2 Reliability Testing

No reliability testing is anticipated.

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

Manufactured parts with LIGO identification numbers or marks will be inspected to determine conformity with the procurement specification.

Witness samples will be acceptable proof of the properties of HR and AR coatings applied to the optical surfaces.

4.2.2 Demonstration

A demonstration of the visual quality of the autocollimator alignment pattern retro-reflected through the telescope will be accepted as verification of acceptable wavefront deformation of the focused telescope.

4.2.3 Test

Appropriate tests will be implemented to verify the specifications of the purchased components.

TBD

5 Preparation for Delivery

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

5.1 Preparation

- Vacuum preparation procedures as outlined in E960022-B LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures will be followed for all components intended for use in vacuum. After wrapping vacuum parts as specified in this document, an additional, protective outer wrapping and provisions for lifting shall be provided.
- Electronic components will be wrapped according to standard procedures for such parts.

5.2 Packaging

Procedures for packaging will ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection will be provided for shipping loads and environmental stress during transportation, hauling and storage. The shipping crates used for large items will use for guidance military specification **Error! Reference source not found.**, Crates, Wood; Lumber and Plywood Sheathed, Nailed and Bolted. Passive shock witness gauges will accompany the crates during all transits.

For the viewports, the shipping preparation will include double bagging with Ameristat 1.5TM plastic film (heat sealed seams as practical, with the exception of the inner bag, or tied off, or taped with care taken to insure that the tape does not touch the cleaned part). The bag will be purged with dry nitrogen before sealing.

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 will be provided.

Identification of the material will be maintained through all manufacturing processes. Each component will be uniquely identified. The identification will enable the complete history of each component to be maintained (in association with Documentation “travelers”). A record for the optical lever support structures will indicate all weld repairs and fabrication abnormalities.

The specification for marking the viewports will state that marking fluids, die stamps and/or electro-etching is not permitted. A vibratory tool with a minimum tip radius of 0.005" is acceptable for marking on surfaces that are not hidden from view. Engraving and stamping are also permitted.

6 Notes

Appendix A Quality Conformance Inspections

Appendix A contains a table that lists the requirements and the method of testing requirements.
TBD

Table 2 Quality Conformance Inspections

| Paragraph | Title | I | A | D | S | T |
|-----------|---------------------------------|---|---|---|---|---|
| | Performance Characteristics | | | | | |
| | Controls Performance | | | | | |
| | Timing Performance ^c | | | | | |
| | | | | | | |
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