LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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ASC Initial Alignment Subsystem Final Design

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IAS FDR Committee

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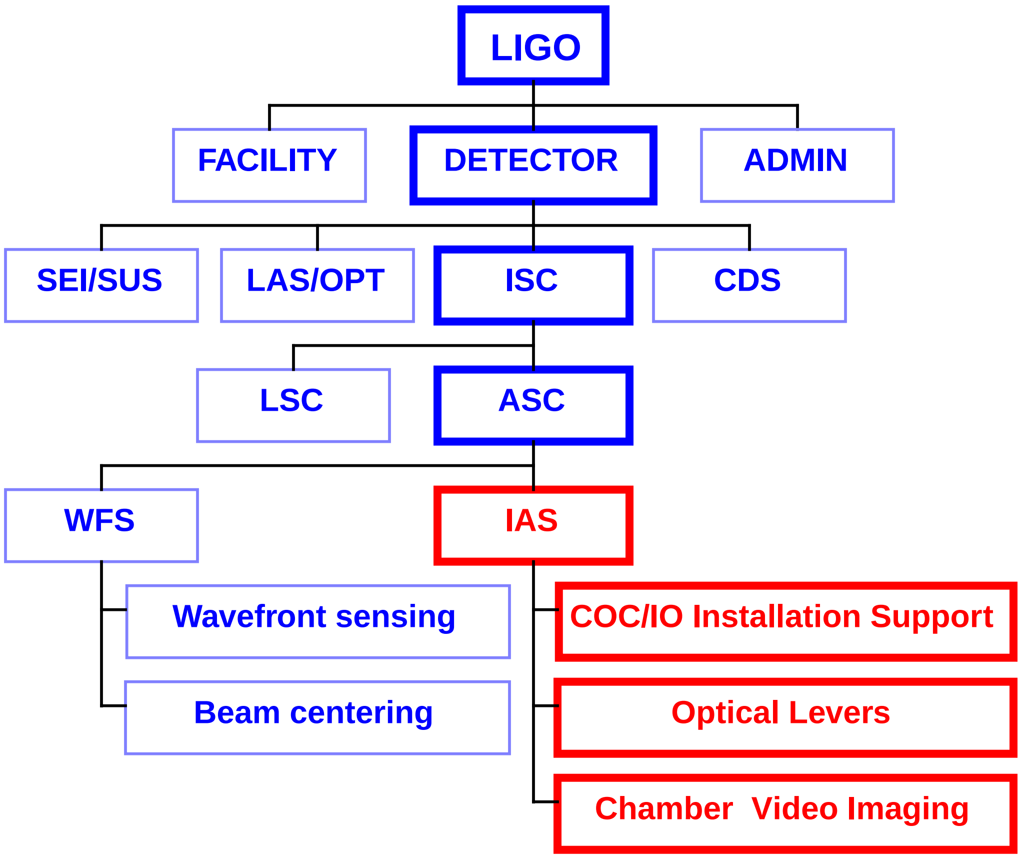
1. INITIAL ALIGNMENT: SCOPE AND INTERFACES

This document and associated drawings describe the design for the LIGO Detector Initial Alignment Subsystem (IAS), a component of the LIGO Detector Alignment Sensing and Control (ASC) system (Figure 1). The complete ASC system function is described in *ASC Preliminary Design* [5]; the complementary WFS component of ASC (including detection-mode wavefront sensing alignment and beam centering) will be specified in a separate final design document.

Figure 1: Initial Alignment Subsystem context



The optical lever and chamber video imaging components of the IAS include associated vacuum viewports, some of which are antireflection coated. No other IAS components (or other ASC/LSC components) are exposed to the LIGO vacuum environment.

1.1. COC and IO installation alignment support

IAS provides optical tooling, reference monuments and procedures for positioning the axial and transverse positions and pitch and yaw angles of suspended core optics components (COC) and certain input optics (IO) within the LIGO vacuum envelope. Tooling and fixtures for handling, installing and adjusting these optics are provided by SUS or IO. Placement of cleanrooms, backfill, purge and opening of vacuum envelope components is also supported by others (VE and site operations staff). As such the installation of each optic will be a cooperative team effort involving IAS and other task groups.

1.2. Optical levers

Suspended core optics and MMT3 (part of IO) will each be monitored during and after installation by an optical lever system. This system provides an angular readout of the pitch and yaw angles of the optic with respect to the local facility foundation. A fiber-coupled collimated diode laser source and a quadrant position-sensing photodiode receiver are mounted adjacent to viewports on the vacuum envelope. Optical levers primarily serve in a range of diagnostic capacities, including monitoring of atmospheric pressure-induced misalignments due to pumpdown, drift in seismic isolation stack equilibria, or misalignments due to strain relaxation in suspension components. They also permit rapid replacement or adjustment of damaged or displaced core optics without reverting to invasive primary-reference surveys. In addition they can augment or temporarily replace wavefront sensor-based alignment error signals for closed-loop ASC operation (at reduced performance).

Remote control adjustable mirrors are provided on both the light source and receiver platforms to adjust the incident beam and null the receiver after acceptable alignment has been established. Platforms for light source and receiver components are either mounted to the floor, or (where adjacent to BSC-type chambers) are bolted to an adapter provided by SEI on each BSC seismic isolation support pier. Each optical lever source and receiver beam travels in a fully enclosed dust- and air-current shield joined to its housing and to the viewport periphery. This shield also fully contains any stray laser beams generated within the vacuum envelope (e.g., due to a failure or error condition) for safety.

Optical lever lasers are selected according to the incidence angle and expected reflectivity of the COC or IO surface being sensed (in some cases this is the “back” , or antireflection-coated, surface). The wavelength options are 635 nm and 950 nm.

Seven optical levers are provided for each 4 km interferometer, one for each ITM (2), ETM (2), BS (1), RM (1) and MMT3 (1). Two more (total of 9) are provided for the Hanford 2km interferometer to monitor the two folding mirrors (FM).

1.3. Chamber video imaging and Illumination

IAS will provide AR-coated viewports and monochrome video cameras to observe scattered light from the surfaces of core optics and critical input optics. These cameras will be sensitive to 1.06 micron IR as well as a normal visible light spectrum; the viewport AR coating will be optimized for IR, to reduce ghost reflections and improve visual discrimination of internal laser field scatter patterns. In normal operation, this will provide a visual indication of the centroid of the resonant cavity mode. The cameras are also used to find beams and guide them to mirror centers during startup. Each camera will be placed on a locking adjustable mount which grips the perimeter of a viewport flange. No remote pan/tilt or filter controls are required. The mount and camera are entirely enclosed for stray beam containment. 8 fixed cameras are provided for each interferometer, one per ‘active’ chamber (3 input HAM chambers, 1 BS BSC chamber, 2 ITM BSC chambers, and 2 ETM BSC chambers). Views in the output-end HAM are effectively occluded by the COS output telescopes, so no cameras or illuminators are planned for that chamber. Ten additional camera/viewport sets (6 for Hanford, 4 for Livingston) are provided for temporary mounting on the valved 10” turbomolecular pump ports in the 72” beam tube manifolds at each station. These image the inner manifold wall, to pick up transmitted beam tube light reflected off the Brewster-angle COS baffle, to aid initial beam finding.

IAS will also provide halogen illuminators to flood chamber interiors with light. This will allow imaging of internal component landmarks, for startup alignment, and of the optic edge bevel as a fiducial for beam centering. Illuminators are mounted on fixed mounts which grip the perimeter of the viewport flange. Uncoated viewports are used here for economy. The lamp and mount cover the viewport aperture fully for stray beam containment. 9 illuminators are provided for each interferometer, one per active chamber (3 input HAM chambers, 1 output HAM, 1 BS BSC chamber, 2 ITM BSC chambers, and 2 ETM BSC chambers).

1.4. IAS subsystem principal interfaces

1.4.1. Vacuum Equipment

- **Viewports:** all viewports are standard 10” nominal OD Conflat^{TM} or equivalent metal-sealedports. All viewports are to be cleaned, vacuum-baked and packaged for shipping and pre-integration storage per [21].
- **Nozzle positions:** Optical lever beams pass very close to viewport nozzle edges in some cases. Nozzles at extreme limits of positioning tolerances, combined with allowed variation of chamber and internal optic locations, could conspire to obstruct optical lever beam paths. Fully accommodating all possible variability in a worst-case sense would significantly increase system cost and compromise performance. Nonetheless, as-built nozzle positions have generally been much closer to plan than the allowed tolerances. We propose to accept this risk and mitigate interferences (if any arise) by maintaining sufficient spares and infrastructure to implement workarounds.
- **Stayclears:** VE/IAS interferences are regulated by the Integrated Layout Drawings [16].

1.4.2. COC

- **Dimensions & wedge angles:** IAS relies on COC diameters as specified in COC Design Requirements, .
- **Nominal position and orientation:** IAS assumes nominal first-surface center positions and normal vectors (direction cosines in LIGO global coordinates) specified in [14].

- **Coating reflectance:** For design purposes, reflectances of COC coatings at optical lever and autocollimator wavelengths and incidence angles have been assumed to conform with references [25] and [26]. These are informational only, not binding specifications. Until actual coating test data are available there exists a risk that insufficient reflectivity or high polarization sensitivity will impair optical lever or autocollimator performance. Additional wavelength, source power and procedural options are being considered in parallel to handle this contingency.

1.4.3. COS

- **Internal baffles:** Internal COS chamber and tube baffles must be arranged (or perforated) to transmit optical lever incident and reflected beams, and to afford adequate direct view factors for video camera imaging and illumination.
- **Beam finding:** Large Brewster-angle beam tube manifold baffles (placed in sections WA-7B and similar) should be arranged to project their reflection of light emanating from the beam tube onto an unbroken section of manifold wall. This section will be imaged by a video camera mounted on a valved 10” pumpout port opposite.

1.4.4. SUS

- **SUS installation fixturing:** The SUS installation fixtures will carry a threaded socket to accept a cube-corner reflector . This reflector is needed to determine the axial position using the distance-measuring rangefinder feature of the theodolite (see Section 2).

1.4.5. SEI

- **SEI pier optical lever supports:** Optical lever transmitters and receivers adjacent to BSC chambers will be attached to SEI seismic isolation support piers. A bracket with tapped mounting holes is welded to the pier. Interface dimensions are shown in [23]; installation orientation is depicted in D970220-00-D, WA corner LVEA 4k IAS equipment layout.

1.4.6. IOO

- **Equipment:** IAS will provide optical levers (MMT3 only), video cameras (all active HAM chambers) and illuminators (all active HAM chambers) to support IO optics. IAS will also provide the corresponding viewports. Additional “spare” viewports will be provided for temporary installation in place of optical-quality, low scatter viewports for laser I/O should these be unavailable for timely installation.
- **Installation support:** IAS will support installation alignment of MMT3 in the same manner as COC/SUS.
- **Alignment of IO to COC:** IO will install their equipment using locally-derived alignment information. Alignment of the IO output beam to the COC will be accommodated by adjustment to MMT1-3 [9] with reference to the recycling mirror surface normal.

2. COC/IO INSTALLATION SUPPORT DESIGN

Installation alignment equipment and procedures are detailed in reference [4], which is the primary design document for this portion of the IAS subsystem. Below we will summarize some generic design features and methods.

2.1. Changes from the preliminary design

- A distance-measuring theodolite is used to both position and dial in correct angles for each core optic. The theodolite will be modified to accept and boresight the autocollimator; its built-in autocollimation function is inadequate for the distance, reflectance range and angular accuracy required.
- A transit square is used in concert with a precision theodolite to step off accurate right angles for establishing parallels.
- The beam tubes are scheduled to be inaccessible (due to bakeout), essentially for the duration of optics installation. Long-distance parallels will instead be established by sighting through a port in the LVEA/VEA wall to a point 250m down the beamtube, in order to establish an axis parallel to the beamtube centerline.
- Elevations of the view from the HAM1 or HAM7 endcap, with suspensions and other internal components in their final (3-D) positions, reveal that the aperture is fully occluded. The installation alignment procedure was revised to involve removal of access connector sections from the vacuum envelope, obtaining a frontal view of each core optic for installation. This method is logistically more complex and more time consuming, but also carries somewhat lower potential for cumulative errors.

2.2. Installation support functions & requirements

Suspended core optics (COC) will have restricted ranges of angular adjustment after installation. For example, the COC suspension will permit no more than +/- 0.8 milliradians of pitch or yaw adjustment. In addition, RF sideband resonance conditions constrain the ratio between the mode cleaner and recycling cavity length (LIGO-T960122), and alignment thermal noise requires accurate centering of the resonant mode on the physical center of each core optic [3]. It is therefore necessary to establish accurate fiducial positions and equilibrium angles for these optics, referred to the site coordinate system, at the time of their installation. IAS will provide the procedures and tooling to measure and verify these translations and angles, and the means to evaluate or recover them after disturbances.

Transverse position settings must be +/- 1 mm or better for input test masses, +/- 5 mm or better for beamsplitters, recycling mirrors and folding mirrors, and +/- 3 mm or better for mode cleaner mirrors [3]. Requirements on the axial position setting accuracy (for all optics) and on the transverse position accuracy of the IO beam expander components remain TBD at this time; for the purposes of this preliminary design, they are assumed to be no more stringent than +/- 3 mm for each.

For all core optics and the final IO steering mirror, the goal for initial setting of the surface normal will be within +/- 80 microradians of the ideal optical axis (note that a beam reflected from such an optic will thus be within +/- 160 microradians of the ideal direction) [3]. This alignment corresponds to an error of +/- 32 cm at 4 km, in principle allowing us to get the interferometer beam through the beam tube by dead reckoning.

2.3. Facility monuments, initialization and errors

Each LVEA/VEA station is provided with alignment monuments ("brass plugs") bonded to the facility technical foundation, originally installed to aid vacuum equipment installation. These will be augmented by additional reference monuments as shown in "D970210-00-D, WA corner LVEA 2k & 4k IAS survey monuments". These monuments are placed to permit convenient sighting and measurement of core optics as described in "T970151-00-D, IAS SUS installation alignment procedure." Briefly, the layout provides convenient axial and transverse position references which are referred to the fundamental station coordinate references (i.e., LIGO global coordinate system origin and the beam tube termination gate valve centerlines). However, unlike these fundamental references, the chosen monuments are visible from key positions on each core optic's normal vector, placed near removable spools of the vacuum envelope.

The other primary function of the monuments is to permit precision alignment (primarily in azimuth) of this station coordinate system to the global coordinates set by the beam tube axes. Successive surveys by CB&I and Rogers Surveying [27] indicate probable azimuthal errors in setting of beam tube alignment of approximately +/- 3 mm (note that, due to atmospheric effects, vertical errors are generally greater; IAS will use precision levels for altitude, with calibrated correction for the curvature of the earth [15]). A special window is provided through the LVEA/VEA wall which permits direct line-of-sight approximately 200 m down one side of the beam tube enclosure. There a monument is laid outside with reference to the previously surveyed beam tube alignment marks. By spreading the +/- 6 mm total error of two monuments over a baseline of 200 m, we expect to parallel the true beam tube axis to an accuracy of +/- 15 microradian. As detailed in T970151, accumulation of errors from instrumentation and from intermediate transfer and reading steps is expected to yield a total error budget within the +/- 80 microradian goal.

2.4. Installation Support Tooling

Much of the instrumentation used for installation alignment is relatively standard in the surveying and millwright trades. Brief descriptions of the chosen equipment are given below to help the reader understand the methodology and error budget.

2.4.1. Optical transit square

We will use a Brunson 75-H optical transit square (or equivalent) to establish an axis parallel to the beam tube centerline. This instrument has a 30x telescope (1 degree field of view) and is equipped with a micrometer (for accurate parallel translation) and a coincidence vial level (for sub-arcsecond leveling). An integral precision optical flat is mounted with its surface parallel to the telescope axis, such that a beam retroreflected from this mirror is precisely normal to the transit sight. The plunge axle is hollow (and the mirror has parallel front and back surfaces) such that this mirror is visible from both sides of the instrument.

The transit square is also equipped with an optical plummet, which permits lateral placement of the transit axes directly over a predetermined floor mark.

2.4.2. Distance-measuring theodolite

The Sokkia Set2BII electronic total station theodolite (or equivalent) is used to preset pitch and yaw angles of suspended optics and to determine their lateral and axial positions. It incorporates a 30x telescope (1.5 degree field of view). The distance measuring feature uses a laser rangefinder and is accurate to +/- 2 mm (transverse positions, which need greater accuracy, will be determined by a steel reference tape). Since the optic will not be aligned normal to the theodolite beam until alignment has been completed, a corner cube retroreflector is mounted to the LOS suspension cage to enable precise axial range determination.

2.4.3. Electronic autocollimator

The theodolite is modified by retrofitting a laser autocollimator and boresighting it to coincide with the theodolite axis. Autocollimator selection is TBD pending trials of sample units. Specifications include accuracy (1 arcsecond or better), range (15 m or greater with expected optic reflectivity of 10%) and weight (< 2.5 kg, to enable adaptation to the theodolite). Among these specifications, the most difficult appears to be the combination of range and optic reflectivity, which is atypical for standard autocollimator applications. As a result, most autocollimator shots called out in “T970151-00-D, IAS SUS installation alignment procedure” are deliberately chosen to be as short as possible. However, after testing autocollimators the required accuracy may prove achievable over longer distances. This could permit significantly less invasive opening of the vacuum envelope (and selection of simpler sections to remove) during installation.

The autocollimator provides an electronic readout indicating the degree to which a mirror in its view is misaligned to its axis. It is made normal to the transit square axis (and thus perpendicular to the beam tube axis) by adjusting the theodolite; the theodolite scale is zeroed, establishing a baseline normal to the beam tube, and then the assembly is rotated to the specified core optic azimuth and declination. Aligning the core optic to achieve autocollimation then replicates this angle.

2.4.4. Reference flat

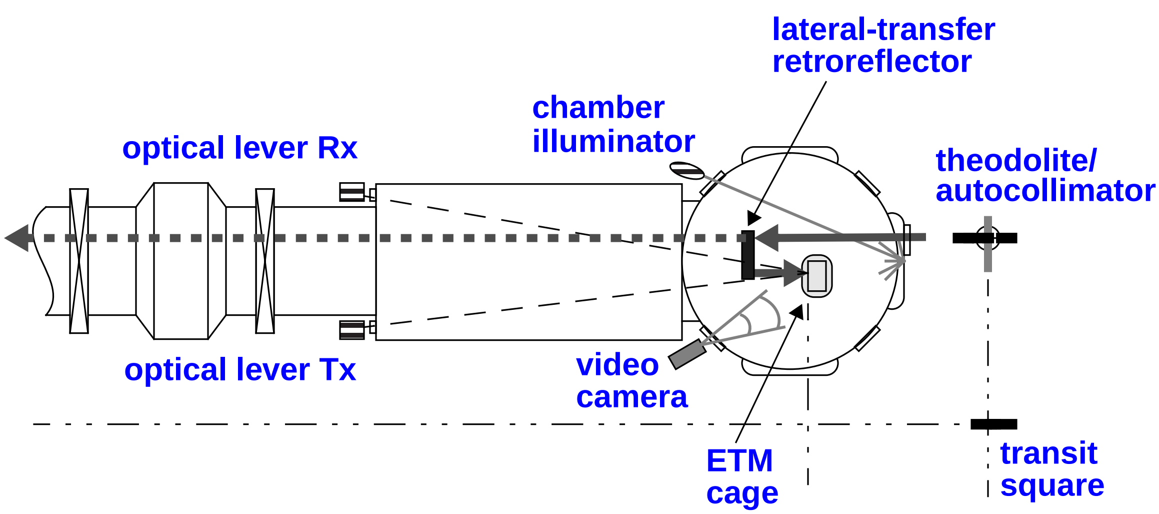
In some cases (folding mirrors and beamsplitters) it is necessary to align an optic with reference to BOTH beam tube axes. This is achieved by temporarily installing adjustable reference flats within the vacuum system. The reference flat is adjusted by following the above procedure with the transit square and theodolite on one arm. The core optic is then adjusted from the other arm, by sighting this flat in reflection.

2.4.5. Lateral transfer retroreflector

In some cases the vacuum equipment spool facing the "front" surface of the mirror is relatively difficult to access. In these conditions, a 400 mm offset PLX Lateral Transfer Retroreflector (or equivalent) is used to reflect and translate the line of sight around the core optic toward the back of the optic. This retroreflector is specified to maintain parallelism of 2 arcseconds between input and output beams.

Use of the retroreflector and other installation tooling is illustrated in Figure 2. For more complete description of the installation alignment methodology, see "T970151-00-D, IAS SUS installation alignment procedure."

Figure 2: End station core optic installation tooling arrangement



3. CHAMBER VIDEO IMAGING DESIGN

3.1. Changes from the preliminary design

- Fewer cameras: Completion of the optical layouts for both IO and COC showed that a limited subset of the proposed camera locations (previously held as options) would obtain a usable view. The aim of imaging scatter off the back interior surface of each chamber (for beam finding) conflicted with the COS requirement to control scattered light. As a result we now have only one camera per chamber. We will use temporary manifold-mounted cameras for beam finding.

3.2. Imaging requirements & design overview

Video cameras are used to view the vacuum chamber interiors during Initial Alignment, and to monitor the position of the beam on the COC and IO optics; in both cases scattered 1.06 µm light is collected by the camera's lens. The edge outline of the optic and other geometric fiducial features may be highlighted by illumination from a floodlamp mounted to a chamber port. Video cameras are monochrome only and are sensitive to both visible and IR light. Lenses are selected for each camera to image the appropriate field of view. Each camera has provision for lens-mounted filters (as a future option) to select or reject specific wavelengths. Camera viewports will be AR coated for transmission of infrared light, to minimize confusion due to ghost reflections when imaging beam scatter. Illuminator viewports will be uncoated.

Camera resolution for ITM and ETM monitoring must be adequate to permit measurement of the beam centroid with respect to the rim of the mirror to a precision better than 1 mm. Choosing a lens which fills the field of view of the camera, a distance measurement between two individual pixels will be accurate to a fractional accuracy of the number of TV lines, so we would need 250 lines of effective resolution. The beam and rim images contain many pixels, so in fact the individual pixel resolution can be significantly poorer. For simplicity we set the minimum resolution to 250 lines vertical and horizontal.

Camera flux sensitivity is set by the brightness of expected scattered light images. At present we anticipate adequate flux from ITM and ETM scatter. We are planning to test the selected camera system at the lower incident flux levels corresponding to MMT3, the beamsplitter and recycling mirror; if necessary, higher sensitivity cameras may be substituted in these locations.

Note that additional video cameras are carried on each ISC table for imaging output beam profiles. These have somewhat different requirements and are not included here.

3.2.1. Video camera, lens & mount design

Video cameras will be Sony XC-73 or equivalent. This camera is special-ordered without its standard internal IR-blocking filter. It is a high-resolution machine vision monochrome camera, using a 1/3" CCD with 768 X 494 pixels (effective resolution 570 h X 485 v lines). NTSC-compatible output is provided on a standard 75 ohm BNC coaxial connector. It requires +12 VDC @ 1.4 W power, supplied to a connector on its case.

The cameras take standard C-mount lenses, which are available in a wide variety of focal lengths and apertures. Lens selection remains TBD at this time pending review of view factors; most applications will use a moderate telephoto, 50 mm focal length. Lenses are provided with screw threads for future fitting of external optical filters if required.

The camera mount utilizes an aluminum tube structure which slips over the 10” OD viewport flange and grips the flange with radial set screws. A flat mounting plate with tapped holes, welded inside this tube, supports a commercial swivel tripod mount which in turn supports the camera. After positioning and locking the camera angle, focus and other controls, a flat cover plate is installed over the open end of the tube to exclude dust and stray light and to block unintended laser emission.

3.2.2. Illuminator lamp selection and mount design

The illuminator lamp is an industrial 70W industrial halogen flood unit, Waldmann HGKW-70-24V or equivalent. It includes a rugged extruded aluminum reflector housing which mounts directly to a flat viewport cover plate. This plate is screwed to a 10” ID ring which houses radial set screws to grip the viewport flange (see D970211-00-D, port mounted video camera assembly). The lamp requires 24V AC or DC @ 70 W (approximately 3 A). Each lamp may be turned on or off remotely.

Close coupling of the lamp to the viewport is required for adequate illumination field of view through the nozzle neck. This raises the possibility of excess heat deposition. A lamp and viewport were assembled and the lamp run at rated output to test this. After equilibration the viewport (in air, unmounted) rose by 25C above ambient, as measured by a thermocouple mounted to the glass. Since viewports are rated for 200C vacuum bakeout (see below) we conclude there is negligible risk to the glass or seal integrity. However, we have not modeled possible effects of the illuminator’s radiated heat on internal detector components.

3.2.3. Viewport specifications

Cameras are mounted to standard MDC VP-800 or equivalent 5.38” clear diameter zero-length kovar-sealed viewports, made of Corning 7056 glass (see L980086-00-D, Viewport specification). The mounting interface is a standard 10” nominal OD Conflat-compatible metal seal flange, for direct mounting to vacuum equipment nozzles. Ports are antireflection coated for minimum reflectance (specified $R < 0.25\%$ per surface) at 1064 nm, normal incidence. The viewports will withstand extended vacuum bakeout at 200C. Coated flanges are edge-engraved with the nominal transmission wavelength to aid field identification.

Viewports for illuminators are identical, but uncoated.

3.3. Camera and illuminator locations

The following locations have been selected for mounting chamber illuminators and video imaging cameras. Refer to “D970220-00-D, WA corner LVEA 4k IAS equipment layout” and similar for equipment layout plan views and [2] for port nozzle naming convention (note that this preliminary naming convention is unreleased, so equipment layouts should take precedence).

Table 1 : Chamber imaging video camera/illuminator locations and views (WA 2k).

Chamber	*Nozzle*	*Coating*	*Lens*	*Function*
WH7	A1F3	IR	*TBD*	MMT3 & MC input coupler
WH7	A1F5	-	-	illuminator
WH8	A2F3	IR	*TBD*	MC end mirror, MMT2
WH8	A2F4	-	-	illuminator
WH9	A2F3	IR	*TBD*	recycling mirror (thru AR surface)
WH9	A2F4	-	-	illuminator
WB4	G9	IR	*TBD*	beamsplitter face (thru AR surface)
WB4	G6	-	-	illuminator
WB7	G12	IR	*TBD*	ITM_x and fold mirror
WB7	G3	-	-	illuminator
WB8	G9	IR	*TBD*	ITM_y and fold mirror
WB8	G6	-	-	illuminator
WB5	G6	IR	*TBD*	ETM_x
WB5	G9	-	-	illuminator
WB6	G3	IR	*TBD*	ETM_y
WB6	G12	-	-	illuminator
WBE-5	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)
WBE-6	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)
WA-7B1	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)
WA-7B2	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)

Table 2 : Chamber imaging video camera/illuminator locations and views (WA 4k).

Chamber	*Nozzle*	*Coating*	*Lens*	*Function*
WH1	A1F3	IR	*TBD*	MMT3 & MC input coupler
WH1	A1F5	-	-	illuminator
WH2	A2F3	IR	*TBD*	MC end mirror, MMT2
WH2	A2F4	-	-	illuminator
WH3	A2F3	IR	*TBD*	recycling mirror (front surface)
WH3	A2F4	-	-	illuminator
WH4	A2F1	IR	*TBD*	main output telescope
WH4	A2F2	-	-	illuminator
WB2	G9	IR	*TBD*	beamsplitter face (thru AR surface)
WB2	G6	-	-	illuminator
WB3	G12	IR	*TBD*	ITM_x
WB3	G9	-	-	illuminator
WB1	G3	IR	*TBD*	ITM_y
WB1	G6	-	-	illuminator
WB9	G6	IR	*TBD*	ETM_x
WB9	G9	-	-	illuminator
WB10	G3	IR	*TBD*	ETM_y
WB10	G12	-	-	illuminator
WA-7B1	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)
WA-7B2	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)

Table 3 : Chamber imaging video camera/illuminator locations and views (LA 4k).

Chamber	*Nozzle*	*Coating*	*Lens*	*Function*
LH1	A1F3	IR	*TBD*	MMT3 & MC input coupler
LH1	A1F5	-	-	illuminator
LH2	A2F3	IR	*TBD*	MC end mirror, MMT2
LH2	A2F4	-	-	illuminator
LH3	A2F3	IR	*TBD*	recycling mirror (front surface)
LH3	A2F4	-	-	illuminator
LH4	A2F1	IR	*TBD*	main output telescope
LH4	A2F2	-	-	illuminator
LB2	G9	IR	*TBD*	beamsplitter face (thru AR surface)
LB2	G6	-	-	illuminator
LB3	G12	IR	*TBD*	ITM_x
LB3	G9	-	-	illuminator
LB1	G3	IR	*TBD*	ITM_y
LB1	G6	-	-	illuminator
LB9	G6	IR	*TBD*	ETM_x
LB9	G9	-	-	illuminator
LB10	G3	IR	*TBD*	ETM_y
LB10	G12	-	-	illuminator
LBE-5	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)
LBE-6	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)
LA-7B1	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)
LA-7B2	(TBD)	IR	*TBD*	beam find (temp. mt. on 10” turbo gate)

4. OPTICAL LEVER DESIGN

Optical levers are required for each core optic, plus the final IO output telescope/steering mirror designated MMT3. The optical lever system for each optic consists of a collimated laser light source assembly and a quadrant photodetector receiver assembly, which are common to all instances, mated to a kinematic support structure which is customized to each particular application.

4.1. Changes from the preliminary design

- **Fiberoptic connectors:** Originally we planned to connectorize the beam delivery fiber to allow line replacement of the laser without disturbing the alignment. The connectors proved so unreliable, however, that this doesn't make sense. We are now using a ruggedized unit assembly with a short singlemode fiber and mount the laser diode near the light source (although outside the housing, to minimize thermal gradients).
- **IR wavelength option for ITM/ETM:** The reflectivity of the COC high-reflectance coatings was inadequate to guarantee rated performance near normal incidence. For test masses we switched to a 950 nm laser which otherwise has substantially the same specs. The photodetector is compatible with this wavelength as well. Viewports coated for IR (nominally 1064 nm) are also reasonably compatible.
- **Back surface for most optics:** For other optics we are now using the back (AR-coated) surface for the optical lever.
- **SEI column support:** In the congested area between the BSC SEI support column and the BSC "G" nozzles (where several COC optical lever light sources and receivers must be located) it was very difficult to place a floor-mounted kinematic platform. SEI will now provide an interface plate on the SEI support piers for attachment of optical lever components. This saves considerable cost, complexity and access space.

4.2. Requirements & design overview

The optical lever is intended primarily as a "flywheel" reference for core optic alignment to maintain continuity between installation and operation. Its ultimate performance is limited by motions of the facility foundations; for example, pumpdown of a vacuum equipment section is likely to induce local floor tilts of order 100 microradian, and diurnal flexures of order tens of microradians are expected due to cycling temperature gradients. However these effects are in principle predictable. As a result we take a long-term stability requirement that enables an optical lever, once set, to recover core optic alignment such that a reflected beam will rethread the beam tube. This translates into a design goal of +/- 50 microradian peak over extended time periods (weeks). No requirement has been set for shorter-term stability, but we expect significantly smaller excursions over hour timescales.

4.2.1. Light source assembly

The optical lever light source uses a commercial, fiber-coupled OEM diode laser module, Blue Sky Research “FiberBrite” FBC019 (6 mW, 635 nm) or FBC0xy (6mW, 950 nm) or equivalent. This module includes an integral regulated power supply and intensity control. The laser requires 5 VDC @ TBD mA; no other controls or readouts are required. It is coupled to the projection optics assembly with an armored singlemode polarization-preserving optical fiber, terminating in an integral GRIN output collimator.

Each collimator is mounted in precision alignment with a commercial 10X or 30X beam expander [Melles Griot 09 LBM 013 (10X) or 09 LBM 107 (30X), or equivalent]. The beam expander magnification is selected to give an appropriate focal spot diameter at the receiver quadrant detector, given the length of the optical path for each instance.

The collimator output is steered by a 2” motorized mirror (New Focus 8853 with Picomotor drives), which directs the beam through the viewport onto the suspended mirror inside the chamber. The entire assembly is shrouded by a removable aluminum thermal/dust housing. The short air path from this housing to the viewport is sealed against dust and air currents by a telescoping shroud. Although optical lever lasers will be ANSI Class IIIb, the shroud and case are fully enclosed for containment of Class IV laser radiation in the unlikely event an errant high-power Nd:YAG beam were to reach the viewport.

Approximately 5 milliwatts of optical power will be delivered to the suspended optic, which is not optimized for reflectivity at the diode laser wavelength or angle of incidence. Expected reflectances for each instance range from nearly 90% to as little as 5%. The receiver electronics are therefore specified to operate at the required SNR with as little as 250 microwatts of detected power (see [6]).

4.2.2. Receiver assembly

The optical lever receiver comprises another motorized beam steering mirror (similar) and a quadrant photodetector electronics package, in a housing similar to the light source assembly. The motorized mirror steers the reflected beam exiting the viewport onto a silicon quadrant photodiode (Centro Vision QD100-0, 100 mm^2 Si PIN quadrant diode) mounted in a shielded electronics enclosure with its readout and bias electronics. The motorized mirror is used to optically null the quadrant sensor when the desired fiducial alignment has been achieved. By counting steps to the picomotors, it also may be used for coarse calibration of the quadrant detector readouts. A holder is provided for future addition of a fixed optical bandpass and/or neutral density filter in front of the photodiode (not required for initial operation). As on the light source, the air path between viewport and housing is enclosed by a telescoping shield tube.

4.2.3. Viewport selection

Viewports for most optical lever incident and reflected beams are standard MDC VP-800 or equivalent 5.38” clear diameter, zero-length kovar-sealed viewports, made of Corning 7056 glass. They are rated for extended vacuum bakeout at 200 C. The mounting interface is a standard 10” nominal OD Conflat-compatible metal seal flange, for direct mounting to vacuum equipment nozzles. Ports are antireflection coated for minimum reflectance (specified R < 0.25% per surface) at either 635 nm or 1064 nm, normal incidence. While 1064 nm does not match the 950 nm optical lever wavelength option, this coating is already used for video cameras and offers acceptable transmission at 950 nm. In some cases, the only viable optical lever beam paths pass close to the edge of a vacuum chamber nozzle. In these instances, AR-coated fused quartz viewports (Insulator Seal part no. 9722012 or equivalent) with 7.78” clear aperture are used. Finally, in one instance a 4.5” nominal OD port is used; this will have a special custom viewport (specification TBD). All coated flanges are edge-engraved with the nominal center wavelength to aid field identification.

4.2.4. Support frame and mounting

Both transmitter and receiver are supported by pedestals bolted to the facility floor. In 6 instances, these pedestals are actually BSC SEI support columns (by others) which have been provided with a tapped ISC interface plate. For all other optical levers, a custom pedestal mounted directly to the facility floor is provided by ISC. In some instances both transmitter and receiver may be carried by the same pedestal.

Optical lever support pedestals are mounted to the floor through a kinematic interface plate. A fixed lower plate is semi-permanently attached to the floor using expansion anchors. It may also be grouted in place to minimize contact distortion (TBD). The pedestal base is attached to this plate using a 6 degree-of-freedom system of tungsten carbide kinematic contact points (ball, groove and plane) preloaded by Belleville spring washers. This allows removal and replacement of the pedestal (for example, to access blocked nozzles for chamber entry) without losing alignment references. The expected angular repeatability for removal and replacement of the pedestal is approximately +/- 50 microradians.

4.3. Optical lever locations

The following tables list chamber and port locations, laser (thus viewport coating) wavelength, viewport size options, and COC/IO component for each optical lever light source and receiver. Mounting provision (SEI support column near BSC or custom floor mount) is also indicated.

Table 4 : Optical lever port locations, wavelength, beam expanders, and functions (WA 2k).

Chamber	*Nozzle*	λ	*VP Dia*	*BX*	*mount*	*Function*
WH7	B2F1	635	5	10x	floor	MMT3 Tx
WH7	B2F2	635	5	-	floor	MMT3 Rx
WB4	G11	635	8	10x	SEI	RM Tx
WB4	G2	635	8	-	SEI	RM Rx
WB4	G1	635	5	10x	SEI	BS Tx
WB4	G3	635	5	-	SEI	BS Rx
WB7	G4	635	5	10x	SEI	FM_x Tx
WB7	G5	635	5	-	SEI	FM_x Rx
#ecap	#	950	5	30x	floor	ITM_x Tx
#ecap	#	950	5	-	floor	ITM_x Rx
WB8	G3	635	8	10x	SEI	FM_y Tx
#60x48	#	635	5	-	SEI	FM_y Rx
#ecap	#	950	5	30x	floor	ITM_y Tx
#ecap	#	950	5	-	floor	ITM_y Rx
#ecap	#	950	5	30x	floor	ETM_x Tx
#ecap	#	950	5	-	floor	ETM_x Rx
#ecap	#	950	5	30x	floor	ETM_y Tx
#ecap	#	950	5	-	floor	ETM_y Rx

Table 5 : Optical lever port locations, wavelength, beam expanders, and functions (WA 4k).

Chamber	*Nozzle*	*λ*	*VP Dia*	*BX*	*mount*	*Function*
WH1	B2F1	635	5	10x	floor	MMT3 Tx
WH1	B2F2	635	5	-	floor	MMT3 Rx
WH2	AF41	635	8	10x	floor	RM Tx
WH2	A2F3	635	8	-	floor	RM Rx
WB2	G1	635	5	10x	SEI	BS Tx
WB2	G3	635	5	-	SEI	BS Rx
#ecap	#	950	5	30x	floor	ITM_x Tx
#ecap	#	950	5	-	floor	ITM_x Rx
#ecap	#	950	5	30x	floor	ITM_y Tx
#ecap	#	950	5	-	floor	ITM_y Rx
#ecap	#	950	5	30x	floor	ETM_x Tx
#ecap	#	950	5	-	floor	ETM_x Rx
#ecap	#	950	5	30x	floor	ETM_y Tx
#ecap	#	950	5	-	floor	ETM_y Rx

Table 6 : Optical lever port locations, wavelength, beam expanders, and functions (LA 4k).

Chamber	*Nozzle*	*λ*	*VP Dia*	*BX*	*mount*	*Function*
LH1	B2F1	635	5	10x	floor	MMT3 Tx
LH1	B2F2	635	5	-	floor	MMT3 Rx
LH2	AF41	635	8	10x	floor	RM Tx
LH2	A2F3	635	8	-	floor	RM Rx
LB2	G1	635	5	10x	SEI	BS Tx
LB2	G3	635	5	-	SEI	BS Rx
#ecap	#	950	5	30x	floor	ITM_x Tx
#ecap	#	950	5	-	floor	ITM_x Rx
#ecap	#	950	5	30x	floor	ITM_y Tx
#ecap	#	950	5	-	floor	ITM_y Rx
#ecap	#	950	5	30x	floor	ETM_x Tx
#ecap	#	950	5	-	floor	ETM_x Rx
#ecap	#	950	5	30x	floor	ETM_y Tx
#ecap	#	950	5	-	floor	ETM_y Rx

APPENDIX 1 OPTICAL LEVER PROTOTYPE TESTS

Under construction.

APPENDIX 2 CHAMBER VIDEO CAMERA SENSITIVITY

Under construction.

APPENDIX 3 REFERENCES

LIGO Documents:

[1] LIGO-T960112-05-D, *Detector Subsystems Requirements*

[2] LIGO-E950111-c1-E, *LIGO Naming Conventions*

[3] LIGO-T952007-04-I, *Alignment Sensing and Control Design Requirements*

[4] LIGO-T970151-04-D, *IAS SUS installation alignment procedure*

[5] LIGO-T970060-00-D, *Alignment Sensing and Control Preliminary Design*

[6] LIGO-T970061-00-C, *ASC/CDS Design Requirements*

[7] LIGO-T970062-00-D, *ASC/CDS Conceptual Design*

[8] LIGO-T960093-02-D, *Input optics design requirements*

[9] LIGO-T970009-00-D, *Input Optics Final Design*

[10] LIGO-T960103-00-D, *ASC: Environmental Input to Alignment Noise*

[11] LIGO-T960065-02-D, *Seismic Isolation Design Requirements*

[12] LIGO-E950099-04-D, *Core Optics Components Design Requirements*

[13] LIGO-E970167-00-D, *LOS Alignment Fixture Design Specification*

[14] LIGO-T970091-00-D, *Determination of the Wedge Angles for the Core Optics Components*.

[15] LIGO-T960176-00-E, *Hanford beam tube slab survey*

[16] LIGO-D970310-02-E, *Equipment arrangement, Hanford site LVEA, plan view*

[17] LIGO-D960128-01-E, *Mid-station (X-arm) Integrated Layout (Hanford)*

[18] LIGO-D961252-00-E, *End-Station (X-arm) Integrated Layout (Hanford)*

[19] LIGO-D970301-01-E, *Interferometer optomechanical layout, Hanford site-elevation view*

[20] LIGO-D970308-01-E, *Interferometer optomechanical layout, Hanford site-plan view*

[21] LIGO-E960022-A-E, *LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures*

[22] LIGO-D980001-00-D, *Retroreflector assembly*

[23] LIGO-D972128-00-D, *BSC Seismic Isolation Support Pier*

Non-LIGO Documents:

[24] ANSI Z136.1-1986, *American National Standard for the Safe Use of Lasers.* American National Standards Institute, NY (1986).

[25] Facsimile transmission of 10 February 1998 from Dale Ness (Research Electro-Optics, Inc.) to Garilynn Billingsley (LIGO), Re: spectral performance of draft designs for LIGO core optics coating designs (0 degree AR and HR).

[26] Facsimile transmission of 18 February 1998 from Dale Ness (Research Electro-Optics, Inc.) to Garilynn Billingsley (LIGO), Re: spectral performance of draft designs for LIGO core optics coating designs (0 degree 3% transmission).

[27] Gary P. Wagner, "Precision Survey of Beam Tube/ Vacuum Equipment Interface", Rogers Surveying, October 1,1996.

APPENDIX 4 IAS DRAWING LIST

ASC Initial Alignment drawing/specification list

(To level III, detail levels not shown)

1.0 IAS SUS INSTALLATION SUPPORT:

1.1 T970151-00-D, IAS SUS installation alignment procedure
1.2 D98____-__-_, LA right end VEA IAS survey monuments **
1.3 D98____-__-_ , LA left end VEA IAS survey monuments **
1.4 D98____-__-_ , LA corner LVEA IAS survey monuments **
1.5 D970210-00-D SHT.1, WA corner LVEA 2k & 4k IAS survey monuments
1.6 D970210-00-D SHT.2, WA right mid VEA 2k IAS survey monuments
1.7 D970210-00-D SHT.4, WA left mid VEA 2k IAS survey monuments
1.8 D970210-00-D SHT.3, WA right end VEA 4k IAS survey monuments
1.9 D970210-00-D SHT.5, WA left end VEA 4k IAS survey monuments

2.0 IAS FIXED EQUIPMENT:

2.1 D98____-__-_, LA right end VEA IAS equipment layout **
2.2 D98____-__-_, LA left end VEA IAS equipment layout **
2.3 D98____-__-_, LA corner LVEA IAS equipment layout **
2.4 D980221-00-D, WA right mid VEA IAS equipment layout
2.5 D980223-00-D, WA left mid VEA IAS equipment layout
2.6 D980222-00-D, WA right end VEA IAS equipment layout
2.7 D980224-00-D, WA left end VEA IAS equipment layout
2.8 D970220-00-D, WA corner LVEA 4k IAS equipment layout
2.9 D970220-00-D, WA corner LVEA 2k IAS equipment layout
    2.9.1 D98____-__-_, optical lever assembly, ITM *
        2.9.1.1 L980086-00-D, Viewport specification
        2.9.1.2 D970161-00-D, Light Source subassembly (950 nm)
        2.9.1.3 D970156-00-D, Position Detector subassembly
    2.9.2 D98____-__-_ , optical lever assembly, FM*
    2.9.3 D98____-__-_ , optical lever assembly, BS *
    2.9.4 D970190-00-D, optical lever assembly, MMT3
        2.9.4.1 L980086-00-D, viewport specification
        2.9.4.2 D970102-00-D, light source subassembly (635nm)
        2.9.4.3 D970156-00-D, position detector subassembly
    2.9.5 D970211-00-D, port mounted video camera assembly

2.9.6 D970212-00-D, port mounted chamber illuminator