**LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY**

*LIGO Laboratory / LIGO Scientific Collaboration*

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# Initial Alignment System (IAS)
# Design Requirements Document

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# Table of Contents

# 1 Introduction

## 1.1 Purpose

The purpose of this document is to specify the requirements for the Initial Alignment System (IAS) for Advanced LIGO, which is a component of the Auxiliary Optics System (AOS).

## 1.2 Scope

The Initial Alignment System (IAS) comprises the necessary metrology equipment and procedures for setting the initial positions and the angular alignment of all primary optics[1]. This task includes preliminary alignment support for optical payloads as they are integrated onto the seismically isolated tables. It also includes alignment of beam dumps and baffles associated with the primary optics.

In addition to this principal role, IAS is responsible for enabling alignment of all other optical systems to the primary optics. This task involves providing targets or pre-aligned optics which allows the non-primary optics to be aligned to the primary optics.

All tooling, alignment instruments and alignment procedures are the responsibility of the IAS subsystem. All alignment activities are performed under the direction of the Installation team.

The following alignment tasks are not part of the IAS scope:

1) Pre-Stabilized Laser (PSL) alignment: The PSL group is responsible for alignment of its optical elements and for optical alignment to its interface with the Input Optics (IO) group.
2) Input Optics (IO) alignment: The IO subsystem defines their alignment procedures and tooling to enable the IO elements to direct the PSL beam into the Mode Cleaner and to deliver the beam from the Mode Cleaner to the power recycling cavity.
3) IO optics table alignment: The IO group is responsible for alignment to, and within, its diagnostic beam optics table(s).
4) Interferometer Sensing and Control (ISC) alignment: The ISC subsystem has optical elements and detectors within the HAM1 and HAM6 chambers (HAM7 and HAM12 for the H2 interferometer), the Transmission Monitor (TransMon) and the Arm Length Stabilization (ALS) systems. The procedures and tooling for alignment of these optical elements are ISC's responsibility.
5) Optical Levers (OptLev): Optical levers monitor the core optics and the optical tables of HAM chambers 2, 3, 4 and 5 (8, 9, 10 and 11 for H2). The procedures and tooling for the alignment of the optical levers are the responsibility of the OptLev group.
6) Thermal Compensation System (TCS) Laser: the procedures and tooling for the alignment of the CO2 laser used for the TCS system is a TCS responsibility.

[1] Primary are those optics which form the basic interferometer configuration (a dual recycled, Michelson interferometer with Fabry-Pérot arm cavities). All other optics, as well as the laser beams injected into the system, are aligned, by others, to the primary optics. The primary optics consists of the following: ETMs, ITMs, BS, FM, PR3, PR2, PRM, SR3, SR2 and SRM. To draw a distinction, core optics are a subset of the "primary optics" that are the responsibility of the Core Optics subsystem; generally those optics which are both large and have demanding performance requirements. The core optics set is the primary optics less the PR2, PRM, SR2 and SRM.

7) Hartmann Wavefront Sensor (HWS): the procedures and tooling for the alignment of the $CO_2$ laser used for the TCS system is a TCS responsibility.

## 1.3 Referenced Documents

T952007-04, (iLIGO) Alignment Sensing/Control Design Requirements Document

T970060-00, (iLIGO) Alignment Sensing/Control (ASC) Preliminary Design

T0900435-v2, HAM Small Triple Suspension (HSTS) Final Design Document

T1000012-v1, HAM Large Triple Suspension (HLTS) Final Design Document

T1000268-v1, Pitch and Yaw Ranges for Test Mass Suspensions

T1000273-v1, Pitch and Yaw Ranges for Beamsplitter/Folding Mirror Suspensions

T1000230-v1, Initial Alignment System, Final Design Document

# 2 Input to the Design Requirements

## 2.1 SUS Suspension Actuator Dynamic Range

The following tables give dynamic ranges for key suspensions used to establish IAS angular alignment accuracy requirements.

**Table 1: Triple Suspension Range**

| Suspension | DOF | Angle Bias Range | Reference |
|---|---|---|---|
| HSTS | Pitch | ± 2.6 mrad | T0900435-v2 |
| | Yaw | ± 4.1 mrad | T0900435-v2 |
| HLTS | Pitch | ± 2.8 mrad | T1000012-v1 |
| | Yaw | ± 1.0 mrad | T1000012-v1 |

**Table 2: Quadruple Suspension Range**

| Suspension | DOF | Angle Bias Range | Reference |
|---|---|---|---|
| Quad | Pitch | ± 1.6 mrad | T1000268-v1 |
| | Yaw | ± 1.6 mrad | T1000268-v1 |

**Table 3: BS/FM Suspension Range**

| Suspension | DOF | Angle Bias Range | Reference |
|---|---|---|---|
| BS/FM | Pitch | ± 1.1 mrad | T1000273-v1 |
| | Yaw | ± 3.8 mrad | T1000273-v1 |

# 3 Requirements

## 3.1 Transverse Positioning of suspended Mirrors

The transverse positioning of the center of the HR face of the ITM and ETM mirrors shall be within ± 1 mm of the ideal optical axis (ref T952007-04, Alignment Sensing/Control Design Requirements Document).

For initial LIGO the requirement on the transverse position accuracy of the center of the HR face of the small triple suspended optics, including the input mode cleaner cavity was ± 3 mm of the ideal optical axis (ref T952007-04, Alignment Sensing/Control Design Requirements Document). Also for initial LIGO, the requirement on the transverse position accuracy of the center of the HR face of the BS, large power recycling cavity optic (MMT3), and FM mirrors was ± 5 mm of the ideal optical axis (ref T952007-04, Alignment Sensing/Control Design Requirements Document). However for aLIGO the radius of curvature of the power and signal recycling cavity optics is so short that the decentering error causes an apparent angular error[2], which must be small relative to the OSEM range, ay 10%. The decentering which corresponds to 10% of the OSEM range for the power and signal recycling optics is given in Table 4. These requirements can be roughly (and safely) summarized as ± 1 mm vertically and ± 2 mm horizontally for HSTS optics and ± 3 mm for HLTS optics.

[2] Since the PR3, SR3, PR2 and SR2 optics should remain vertical (to minimize residual vertical motion from coupling into length noise), one might think that pitching the optic to compensate for the decentering error is not an acceptable approach. However this simply corrects for the optical pitch resulting from the decenter and thus minimizes the coupling.

**Table 4: Decentering tolerance for recycling cavity optics**

| Optic | ROC (mm) | 10% OSEM range (microrad) | | Vertical ± mm | Horizontal ± mm |
|---|---|---|---|---|---|
| | | pitch | Yaw | | |
| PRM | 11000 | 260 | 410 | 2.9 | 4.5 |
| F-PRM | 9970 | 260 | 410 | 2.6 | 4.1 |
| PR2 | 4560 | 260 | 410 | 1.2 | 1.9 |
| F-PR2 | 4410 | 260 | 410 | 1.1 | 1.8 |
| PR3 | 36000 | 280 | 100 | 10.1 | 3.6 |
| F-PR3 | 34000 | 280 | 100 | 9.5 | 3.4 |
| SRM | 5690 | 260 | 410 | 1.5 | 2.3 |
| F-SRM | 11400 | 260 | 410 | 3.0 | 4.7 |
| SR2 | 6430 | 260 | 410 | 1.7 | 2.6 |
| F-SR2 | 4890 | 260 | 410 | 1.3 | 2.0 |
| SR3 | 36000 | 280 | 100 | 10.1 | 3.8 |

## 3.2 Axial Positioning of Suspended Mirrors

The axial position of the HR surfaces for all suspended optics shall be within ± 3 mm of the ideal axial position (ref T970060-00, Alignment Sensing/Control (ASC) Preliminary Design).

## 3.3 Angular Pointing of Suspended Mirrors

The fundamental pointing accuracy requirement is to align the optics well enough that the beam can be detected coming out the other end of the beam tube. For initial LIGO, this meant that the beam had to make it through the 1meter diameter tube. For advanced LIGO, we have baffles that narrow the target to 0.34 meters. To mitigate this extra accuracy requirement, there will be photo detectors (0.4 m dia.) that can sense the beam outside of this target. Depending on the sensitivity of the photo detectors we will need a pointing accuracy of about 100 microradians. There is an additional requirement that IAS shall set the angular alignment of the HR surfaces of the suspended optics to within 10% of the SUS actuator angular dynamic range. An angular alignment within 100 micro radians of the ideal optical axis meets this requirement for all optics. However the specific angular alignment requirements by optic are defined in Table 4.

**Table 5: Angular Pointing Accuracy Requirements by Primary Optic**

| Optic | Pitch (microrad) | Yaw (microrad) |
|---|---|---|
| ITM, ETM | ± 160 | ± 160 |
| BS/FM | ± 110 | ± 380 |
| PR3, SR3 | ± 280 | ± 100 |
| PR2, PRM, SR2, SRM | ± 260 | ± 410 |

The goal for the initial angular alignment of PR3, SR3 and the test mass surface normals will be within ± 50 micro radians of the ideal optical axis (ref T970060-00, Alignment Sensing/Control (ASC) Preliminary Design).

## 3.4 Cleanliness of Optics

Initial alignment fixtures and alignment procedures shall not compromise the cleanliness of the primary optics. In particular:

a) FirstContact™ shall be maintained on the optic surfaces at all times when not aligning. If FirstContact™ is removed for alignment purposes, it must be replaced and be removed only just prior to closing up a chamber.

b) Human activity in the vicinity of the optics should be minimized especially when no, or low, air flow conditions are invoked to support alignment of suspended optics.

c) The number and duration of spool removals should be minimized.

## 3.5 Support the Installation Sequence

The IAS must be able to the planned installation sequence, or reasonable deviaitions from this sequence. In particular on the H2 interferometer the installation will start with the y-arm (ETM and ITM chambers) whereas for the L1 interferometer the installation will start in the input optics section (HAM2 and HAM3). Ideally any arbitrary installation sequence should be supported by the IAS, so as to allow for flexibility in installation re-planning.

## 3.6 Support the "Cartridge" Installation for BSC Chambers

It is intended that the payload for each BSC chamber be integrated onto the optics table for the chamber while positioned on a test stand adjacent to the chamber. Then this integrated "cartridge" is installed into the BSC chamber. All of the payload elements in the cartridge are to be aligned relative to each other whiel on the test stand by IAS. Once in the chamber the entire cartridge is then aligned, as a rigid body, by IAS.