LIGO Laboratory / LIGO Scientific Collaboration

LIGO-M060056-v2 *Advanced LIGO* 22 March 2011

Advanced LIGO Reference Design

Advanced LIGO Team

This is an internal working note
of the LIGO Laboratory.

California Institute of Technology
LIGO Project – MS 100-36
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

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

Advanced LIGO Reference Design

1. Overview

This document describes the technical approach for the first major upgrade to LIGO, consistent with the original LIGO design and program plan[1].

LIGO consists of conventional facilities and the interferometric detectors. The LIGO facilities (sites, buildings and building systems, masonry slabs, beam tubes and vacuum equipment) have been specified, designed and constructed to accommodate future advanced LIGO detectors. The initial LIGO detectors were designed with technologies available at the initiation of the construction project. This was done with the expectation that they would be replaced with improved systems capable of ultimately performing to the limits defined by the facilities.

In parallel with its support of the initial LIGO construction, the National Science Foundation (NSF) initiated support of a program of research and development focused on identifying the technical foundations of future LIGO detectors. At the same time, the LIGO Laboratory[2] worked with the interested scientific community to create the LIGO Scientific Collaboration (LSC) that advocates and executes the scientific program with LIGO[3].

The LSC, which includes the scientific staff of the LIGO Laboratory, has worked to define the scientific objectives of upgrades to LIGO. It has developed a reference design and carried out an R&D program plan. This development has led to this Reference Design for construction of the Advanced LIGO upgrade following the initial LIGO scientific observing period.

This document gives a summary of the principal subsystem requirements and high-level conceptual design of Advanced LIGO. The document is intended to be dynamic, and will be updated as the project advances.

---

[1] LIGO Project Management Plan, LIGO M950001 https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=40625; LIGO Lab documents can be accessed through the LIGO Document Control Center (https://dcc.ligo.org/)

[2] LIGO Laboratory Charter, LIGO LIGO-M060323-v2

[3] LSC home page, http://www.ligo.org/

2. Sensitivity and Reference Design Configuration

The Advanced LIGO interferometer design allows tuning and optimization of the sensitivity both to best search for specific astrophysical gravitational-wave signatures and to accommodate instrumental limitations. To define the goal sensitivity of Advanced LIGO, a single measure is given: a equivalent strain noise of 10^{-22} RMS, integrated over a 100 Hz bandwidth centered at the minimum noise region of the strain spectral density, a factor of 10 more sensitive than initial LIGO. This measure allows some margin with respect to our present best estimates of the possible sensitivity.

Figure 1 gives several ‘cartoon’ examples of target sensitivity curves using our prediction of the instrument performance; technically correct curves can be found in the systems documentation (LIGO-T010075). The tunings are optimized for the following sources:

Neutron-star inspiral: The greatest ‘reach’ is obtained by optimizing the sensitivity in the ~100 Hz region, at the expense of sensitivity at lower and higher frequencies. Averaged over all polarizations and angles, and for a signal-to-noise of 8 or greater, a single Advanced LIGO interferometer can see 1.4-solar-mass binaries as far as 200 Mpc, and the three interferometers if all tuned to this optimization, can see ~300 Mpc.

Black Hole inspiral: Here the best tuning is one which optimizes low-frequency sensitivity. For equal mass binaries, the frequency of the gravitational waves when the merger phase begins is estimated to be ~250 $(20M_s/M)$Hz where M is the total mass of the binary and M_s is the mass of our sun. Advanced LIGO can observe a significant part of the inspiral for up to ~50 solar mass binaries. The third interferometer, tuned to be more sensitive at higher frequencies, can study the waves generated during the merger.

Stochastic Background: Random, but correlated signals would be produced by an e.g., cosmological, cosmic string, or confusion-limited source. For a search for cosmological signals, using an interferometer at Livingston and one at Hanford (separated by 10msec time-of-flight for gravitational waves), this sensitivity would allow a detection or upper limit, for a background flat in frequency, at the level of $\Omega \geq 9\times10^{-10}$ for a 12 month observation time. Using the collocated interferometers, it is possible to search for an isotropic stochastic background around 37 kHz. This is at the first free-spectral-range (FSR) of the 4km interferometer, where its equivalent strain noise is comparable to the equivalent strain noise at low frequencies.

Unmodeled transient sources: These are sources exhibiting short transients (lasting less than one second) of gravitational radiation of unknown waveform, and thus have a fairly broad (and imprecisely known) frequency spectrum. These include burst signals from supernovae and black hole mergers for which the physics and computational implications are complex enough that make any analytical calculation of the expected waveforms extremely difficult. Advanced LIGO can detect the merger waves from BH binaries with total mass as great as 2000 $M_\odot$, to cosmological redshifts as large as z=2. Empirical evidence suggests that neutron stars in type II supernovae receive kicks of magnitude as large as ~1000 km/s. These violent recoils imply the supernova’s collapsing-core trigger may be strongly asymmetric, emitting waves that might be detectable out to the Virgo cluster of galaxies (event rate a few/yr).

In the event of a transient gravitational wave detection, the two collocated detectors at the Hanford site will provide a powerful tool. The identical – within their measurement error – signals expected to be recorded in the two collocated instruments will be independent of signal strength, direction, polarization admixture or specific data analysis selection criteria.

Pulsars: A narrow-band tuning, centered e.g., on the region of the ‘pile-up’ of anticipated gravitational-wave signals from pulsars, LMXRBs, or other continuous-wave sources. To obtain this response, mirror transmission in the instrument must be changed from the configurations discussed above. For a single interferometer, an sensitivity of 1.5×10^{-24} in a one Hz bandwidth or a RMS equivalent strain noise, unity SNR, of $\sim 8\times10^{-28}$ for a 3-month observation is possible.

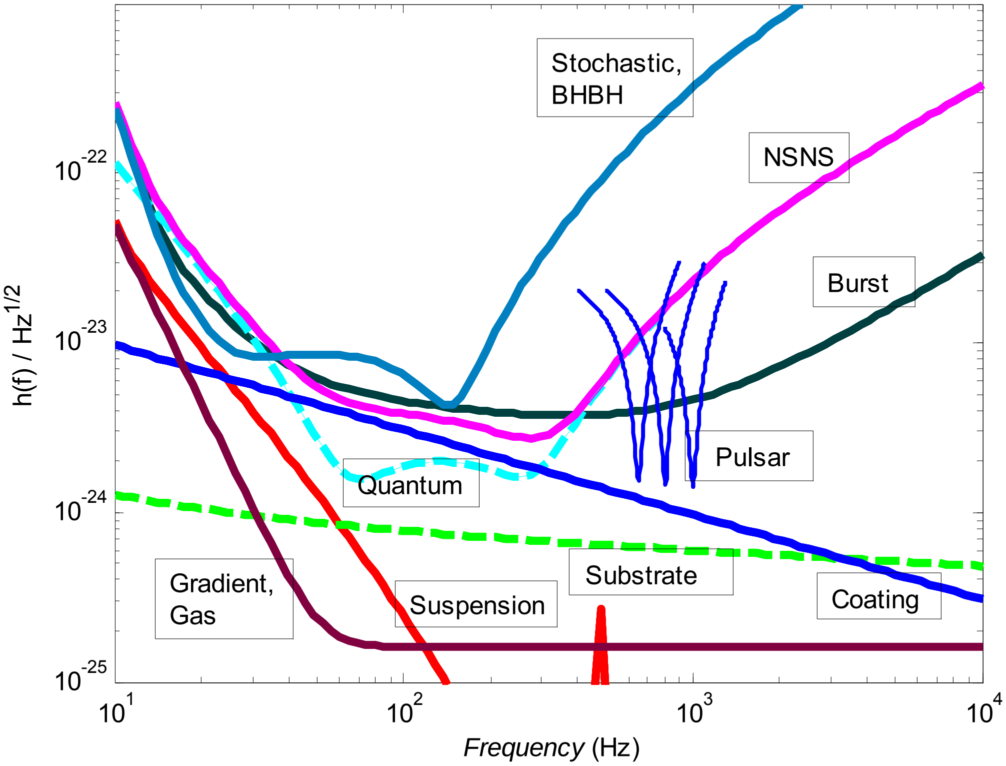

Figure 1: *Limiting noise for a variety of Advanced LIGO tunings. The equivalent strain noise, in a one-Hz bandwidth, of Advanced LIGO as limited by the thermal and quantum noise; note that small additional technical noise contributions are anticipated, and that there is margin between these simple model curves and the performance specification of* 10^{-22} RMS, integrated over a 100 Hz bandwidth centered at the minimum noise region*. Noise curves are shown for tunings optimized for a Stochastic background (flat frequency dependence) or 50 Solar Mass BH-BH inspiral, 1.4 Solar Mass NS-NS inspiral, and pulsars at 650, 800, and 1000 Hz. Also shown are expected contributions from Suspension, Substrate, and optical Coating thermal noise. The other significant limit is quantum noise (shown only for the NS-NS curve), which in quadrature sum with the thermal noise leads to the curves shown. Facility limits due to the gravitational gradients, and the fluctuations in optical path due to residual gas for the lowest achievable pressure* (10^{-9} *torr), are shown at the bottom. The design process seeks to hold technical noise sources to a fraction of the limiting noise sources shown. See LIGO-T010075 for discussion of the instrument sensitivity.*

The specific starting configuration (narrow-band vs. broad-band, tuning of the signal recycling mirror) of the three interferometers of Advanced LIGO is best determined closer to the time of implementation. The changes to the optical system are relatively small, involving fixing the transmission of one in-vacuum suspended optic; multiple substrates are planned for this signal-recycling mirror. It is likely that we will have further information from either discoveries by the first generation of gravitational-wave detectors, and/or from a better understanding of the astrophysics, which will help in making a choice.

Advanced LIGO is designed to be a flexible platform, to evolve as technologies become available and as astrophysical insights mature. Narrowband or broadband operation is one specific variation which is in the Advanced LIGO baseline. Other modifications, such as using squeezed light to improve the sensitivity without increasing the optical power, are currently being pursued by the community, and can be considered as modifications or upgrades of Advanced LIGO as appropriate.

To obtain the maximum scientific return, LIGO is also planned to be operated as an element of an international network of gravitational wave detectors involving other long baseline interferometric detectors and acoustic detectors. Long baseline interferometric detectors are expected to be operated by the Virgo Collaboration at Pisa, Italy and by the GEO600 Collaboration at Hannover, Germany. Memoranda of Understanding to cover coordination of the observations during and after the Advanced LIGO Project are currently in discussion and will be established. Plans are also underway to establish long baseline interferometric detectors in Japan and Australia, and we will strive to coordinate with these efforts as well. Simultaneous observations in several systems improve the confidence of adetection. A global network of detectors will also be able to provide full information from the gravitational waves, in particular, the polarization and the source position on the sky.

Configuration

The LIGO Scientific Collaboration, through its Working Groups, has worked with the LIGO Laboratory to identify a reference design for the Advanced LIGO detector upgrade. The reference design is planned to lead to a quantum noise limited interferometer array with considerably increased bandwidth and sensitivity.

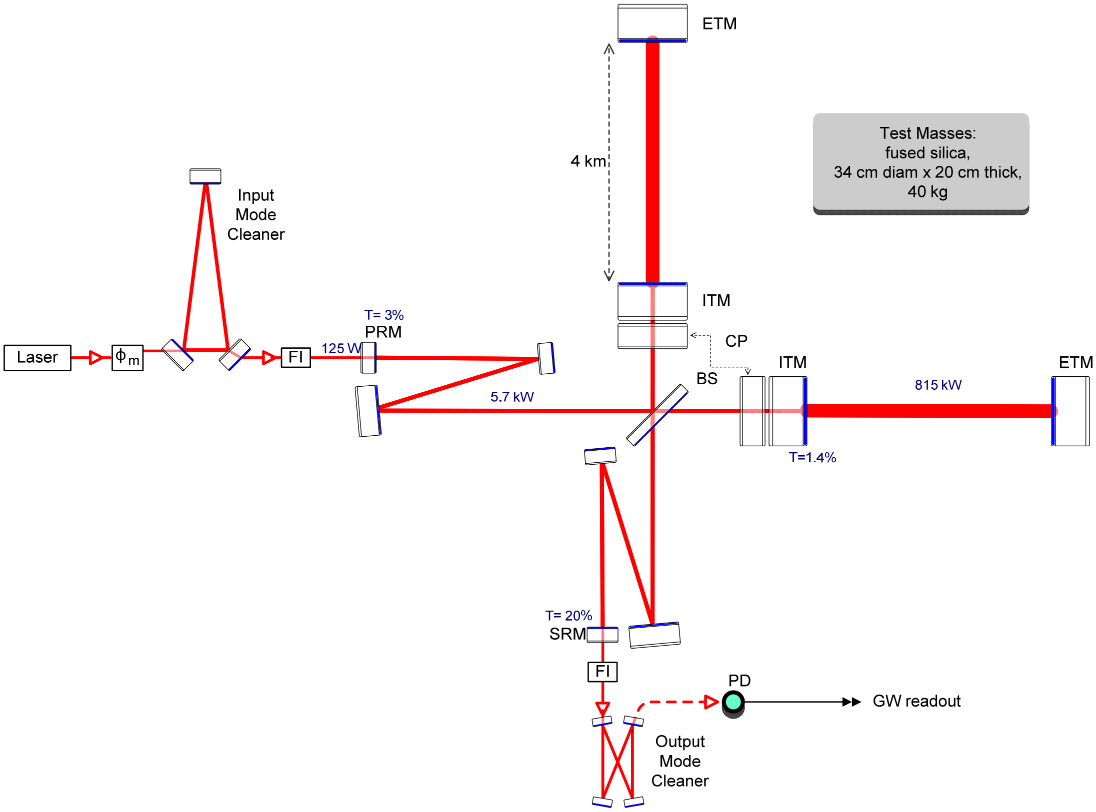

Figure 2: *Schematic of an Advanced LIGO interferometer, with representative mirror reflectivities. Several new features compared to initial LIGO are shown: more massive test masses; 20x higher input laser power; signal recycling; active correction of thermal lensing; an output mode cleaner. (ETM = end test mass; ITM = input test mass; PRM = power recycling mirror; SRM = signal recycling mirror; BS = 50/50 beam splitter; PD = photodetector; MOD = phase modulation). Seismic Isolation system, Optics Suspensions, and the mode-matching and beam-coupling telescopes not shown.*

The basic optical configuration is a power-recycled and signal-recycled Michelson interferometer with Fabry-Perot "transducers" in the arms; see Figure 2**.** Using the initial LIGO design as a point of departure, Advanced LIGO requires the addition of a signal-recycling mirror at the output "dark" port, and changes in the RF modulation and control systems. This additional mirror allows the gravitational wave induced sidebands to be stored in the arm cavities or extracted (depending upon the state of resonance of the signal recycling cavity), and allows one to tailor the interferometer response according to the character of a source (or specific frequency in the case of a fixed-frequency source). For wideband tuning, quantum noise dominates the instrument noise sensitivity at low and high frequencies and thermal noise of the test-mass-mirror coatings contributes in the mid-band. Rather than use synchronous modulation-demodulation around the interference minimum for the gravitational-wave sensing, the interferometer output port is held with servo systems slightly away from the minimum (roughly 1 picometer), leading directly to changes in output light intensity for signals (linear for the minuscule signals being detected)

The laser power is increased from 10 W to 180 W, adjustable to be optimized for the desired interferometer response, given the quantum limits and limits due to available optical materials. The resulting circulating power in the arms is roughly 850 kW, to be compared with the initial LIGO value of ~10 kW. The Nd:YAG pre-stabilized laser design resembles that of initial LIGO, but with the addition of a more powerful output stage. The conditioning of the laser light differs from initial LIGO in that both the power and recycling cavities are now stable for the fundamental optical mode. This is achieved using reflective focusing telescopes, and has the additional virtue that the recycling mirrors are smaller and easier to exchange to optimize the instrument for efficiency and astrophysical target. As in initial LIGO, an input ring-cavity mode cleaner is used, although changes to the modulators and isolators must be made to accommodate the increase in power. An output mode cleaner is added to prevent higher order spatial modes from masking the gravitational-wave signal in the fundamental mode.

Whereas initial LIGO uses 25-cm diameter, 11-kg, test masses, the fused-silica test mass optics for Advanced LIGO are larger in diameter (~32 cm) to reduce thermal noise contributions and more massive (~40 kg) to keep the radiation pressure noise to a level comparable to the suspension thermal noise. Polishing and coating are required to be somewhat better than the best results seen for initial LIGO. In particular, the coating mechanical losses must be managed to limit the thermal noise. Compensation of the thermal lensing in the test mass optics (due to absorption in the substrate and coatings) is added to handle the much-increased circulating power.

The test mass is suspended by fused silica tapered fibers attached with hydroxy-catalysis bonds, in contrast to the steel wire sling suspensions used in initial LIGO. Fused silica has much lower mechanical loss (higher Q) than steel, and the fiber geometry allows more of the energy of the pendulum to be stored in the earth's gravitational field while maintaining the required strength, thereby reducing suspension thermal noise. The resulting suspension thermal noise is anticipated to be less than the radiation pressure noise and comparable to the Newtonian background ("gravity gradient noise") at 10 Hz. The complete suspension has four pendulum stages, and is based on the suspension developed for the UK-German GEO-600 detector[4]. The mechanical control system relies on a hierarchy of actuators distributed between the seismic and suspension systems to minimize required control authority on the test masses. The test mass magnetic actuators used in the initial LIGO suspensions can thus be eliminated (to reduce thermal noise and direct magnetic field coupling from the permanent magnet attachments) in favor of electrostatic forces for locking the interferometer.

---

[4] Status of the GEO600 Detector H Lück et al (GEO600 collaboration) Class. Quantum Grav. 23, S71-S78, 2006; Damping and tuning of the fibre violin modes in monolithic silica suspensions S Gossler, G Cagnoli, D R M Crooks, H Lück, S Rowan, J R smith, K A Strin, J Hough and K Danzmann Class. Quant. Grav, 21, S923 - S933 , 2004

The much smaller forces on the test masses reduce the likelihood of compromises in the thermal noise performance and the risk of non-Gaussian noise. Local sensors and magnets/coils are used on the top suspension stage for damping, orientation, and control.

The isolation system is built on the initial LIGO piers and support tubes but otherwise is a complete replacement, required to bring the seismic cutoff frequency from ~40 Hz (initial LIGO) to ~10 Hz. RMS motions (dominated by frequencies less than 10 Hz) are reduced by active servo techniques, and control inputs complement those in the suspensions in the gravitational-wave band. The attenuation offered by the combination of the suspension and seismic isolation system eliminates the seismic noise limitation to the performance of the instrument, and for the low-frequency operation of the interferometer, the Newtonian background noise dominates.

Reference Design Parameters

Table I *Principal parameters of the Advanced LIGO reference design with initial LIGO parameters provided for comparison*

Subsystem and Parameters	**Advanced LIGO Reference Design**	**Initial LIGO Implementation**
Comparison With initial LIGO Top Level Parameters		
Observatory instrument lengths; LHO = Hanford, LLO = Livingston	LHO: 4km, 4km; LLO: 4km	LHO: 4km, 2km; LLO; 4km
Anticipated Minimum Instrument Strain Noise [rms, 100 Hz band]	$< 4\times10^{-23}$	4×10^{-22}
Displacement sensitivity at 150 Hz	$\sim1\times10^{-20}$ m/√Hz	$\sim1\times10^{-19}$ m/√Hz
Fabry-Perot Arm Length	4000 m	4000 m
Vacuum Level in Beam Tube, Vacuum Chambers	$<10^{-7}$ torr	$<10^{-7}$ torr
Laser Wavelength	1064 nm	1064 nm
Optical Power at Laser Output	180 W	10 W
Optical Power at Interferometer Input	125 W	6 W
Optical power on Test Masses	800 kW	15 kW
Input Mirror Transmission	1.4%	3%
End Mirror Transmission	5-10 ppm	5-10 ppm
Arm Cavity Beam size (1/e^2 intensity radius)	5.3 cm on ITM 6.2 cm on ETM	4 cm
Light Storage Time in Arms	1.7 ms	0.84 ms
Test Masses	Fused Silica, 40 kg	Fused Silica, 11 kg
Mirror Diameter	34 cm	25 cm
Suspension fibers	Fused Silica Fibers	Steel Wires
Seismic/Suspension Isolation System	3 stage active, 4 stage passive	Passive, 5 stage
Seismic/Suspension System Horizontal Attenuation	$\geq10^{-10}$ (10 Hz)	$\geq10^{-9}$ (100 Hz)

3. Facility Modifications and Preparation (FMP)

Overview

Advanced LIGO technical requirements will necessitate modifications and upgrades to the LIGO buildings, and vacuum equipment. In addition, the strategy for executing the Advanced LIGO construction will require some facility accommodations.

The principal impact on this WBS element is as follows:

- It is a program goal to minimize the period during which LIGO is not operating interferometers for science. For this reason, major subsystems such as the seismic isolation and suspension subsystems should be fully assembled and staged in locations on the LIGO sites ready for installation into the vacuum system as vacuum- and integration-ready units. This will require prepared assembly and staging space, materials handling equipment, and softwall clean rooms.
- Increasing the arm cavity length for the Hanford 2-kilometer interferometer to 4 kilometers will require removing and reinstalling the existing mid-station chambers and replacing them with spool pieces in the original locations.
- The larger optical beams in the input-output optics sections will necessitate changing out the input optics vacuum tube for a larger diameter tube.
- Two of the general-purpose (HAM) vacuum chambers in the vertex building will be shifted along the beam line for each interferometer to optimize the position of detection components.
- In order to support the aLIGO assembly effort, both observatories will construct a clean and bake facility to allow in-house processing of the majority of components.

Functional Requirements

Vacuum Equipment

All vacuum equipment functional requirements are the same as those in the initial LIGO design except that the vacuum level is required to be one order of magnitude lower ($<10^{-7}$ torr; the present system operates at the Advanced LIGO level). Additional equipment (chambers, spool pieces, softwall clean rooms) is needed to accommodate additional arm cavity length for one interferometer and the desire for parallel assembly and installation in more chambers and staging areas. A larger diameter spool piece for the IO Mode Cleaner beam path is required. Several of the auxiliary optics chambers in the central building will be moved several meters along the beam line to accommodate the new optical system. The seismic isolation system requirements[5] call for the Advanced LIGO subsystems to be compatible with the original LIGO vacuum envelope.
Other elements of this subsystem are the installation fixtures and hardware, equipment and materials for in-vacuum component and vacuum equipment cleaning/baking, and the installation planning (schedules, ES&H, logistics, SOP's, etc).

Beam Tube

The original end-pumped beam tube system requires no modifications or additions for Advanced LIGO. There is sufficient margin in the present vacuum performance to permit the operation of the more sensitive Advanced LIGO instrument with no changes.

---

[5] Advanced LIGO Seismic Isolation Design Requirements Document, LIGO-E990303

Conventional Facilities

Preassembly of the e.g., Advanced LIGO seismic isolation and suspension elements prior to installation in the vacuum tanks requires clean onsite staging and assembly space. At both the Hanford and Livingston Observatories there exist suitable staging buildings with appropriate height and basic configuration; improvements in air handlers, partitions, portable clean rooms, and benches are required.

Concept/Options

Vacuum Equipment

Test-mass chamber type cleanrooms will be installed in the Hanford and Livingston staging buildings. For each of the interferometers, additional clean rooms will be acquired to support parallel installation in additional chambers to facilitate reducing the duration of Advanced LIGO installation.

Four additional spool pieces will be acquired to replace the Hanford mid-station BSC chambers and to connect these chambers to the end-station BSC chambers once relocated. The chambers will be removed and reinstalled at the end stations.

The Input and Output Mode Cleaners require a larger diameter spool piece, ~15m in length, to accommodate the more complex optical layout used.

The requirement of base pressure for Adv LIGO ($<10^{-7}$ torr) is already met by the present system (which is operating at $<10^{-8}$ torr).

Beam Tube

No action needed. The original installation meets requirements for Advanced LIGO.

Conventional Facilities

The existing staging buildings at both observatories require additions of central air handlers, flow benches, fume hoods, vacuum bake ovens, and other minor equipment to support clean processing operations.

4. Seismic Isolation Subsystem (SEI)

Overview

The seismic isolation subsystem serves to attenuate ground motion in the observation band (above 10 Hz) and also to reduce the motion in the “control band” (frequencies less than 10 Hz). It also provides the capability to align and position the load. Significantly improved seismic isolation will be required for Advanced LIGO to realize the benefit from the reduction in thermal noise due to improvements in the suspension system. The isolation system will be completely replaced, and this offers the opportunity to make a coordinated design including both the controls and the isolation aspects of the interferometer.

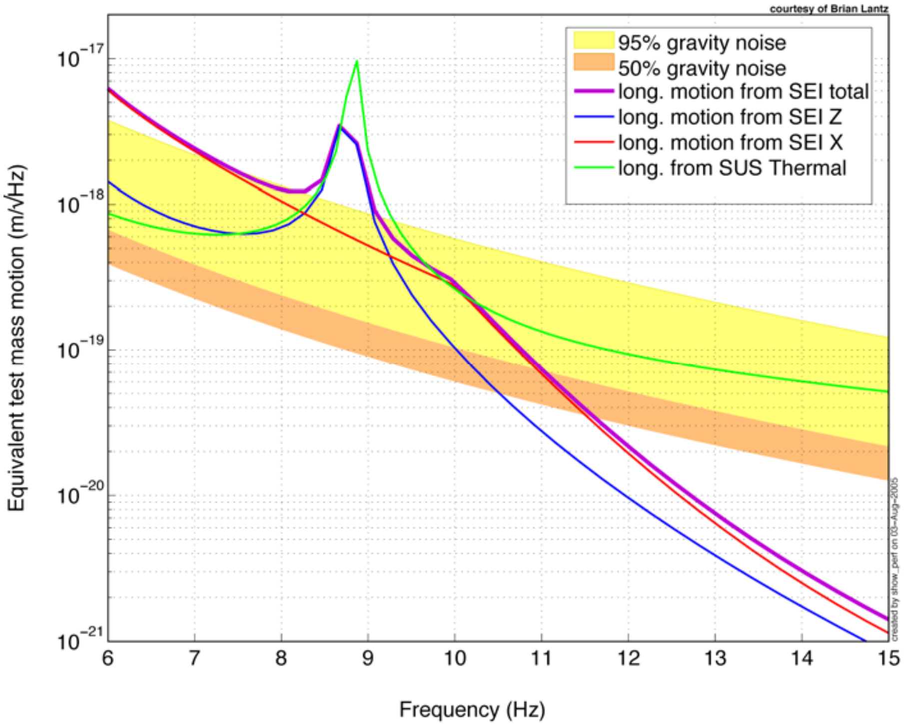

Figure 3 *Predicted test mass displacement noise. The orange and yellow shaded regions are the expected longitudinal (beam direction) motion from direct gravity coupling, at 50th and 95th percentile ground motion measured at the LIGO sites; this dominates over the seismic noise above 11 Hz or so. The red, blue and purple lines are, respectively, the contributions to test mass motion from horizontal and vertical seismic isolation system motion and the total seismic contribution at about the 90th percentile level. The green curve is the expected suspension (pendulum) thermal noise; it exceeds the seismic noise above about 10.3 Hz.*

Functional Requirements for the BSC (Test Mass Chamber) payloads

The top-level constraints on the design of the isolation system can be summarized:

Seismic attenuation: The amplitude of the seismic noise at the test mass must be equal to or less than the thermal noise of the system for the lowest frequencies where observation is planned, 10 Hz. At about that frequency and below, the competing noise sources (suspension thermal noise, radiation pressure, Newtonian background) conspire to establish a presently irreducible sensitivity level roughly a factor of 30 above the limits imposed by the LIGO facilities. **Figure 3** shows current estimates of some of these noise sources, based on 3-D dynamic models of the seismic platform and quadruple pendulum systems, 50th and 95th percentile ground motion statistics[6], and estimates of direct gravity coupling[7]. At just above 10 Hz, the expected motion from seismic coupling equals that from suspension thermal noise, at about 2–3 x 10^{-19} m/√Hz, and then falls off rapidly. The visible 'shoulder' between 10 and 20 Hz is due to a large BSC vacuum chamber resonance; recent lab results have validated a HEPI feedforward technique to reduce this band even further, should it become a problem.

The RMS differential motion of the test masses while the interferometer is locked must be held to a small value (less than 10^{-14} m) for many reasons: to limit light fluctuations at the antisymmetric port and to limit cross coupling from laser noise sources, as examples. Similarly, the RMS velocity of the test mass must be small enough and the test mass control robust enough that the interferometer can acquire lock. This establishes the requirement on the design of the seismic isolation system in the frequency band from 1 to 10 Hz of approximately 10^{-11} m/√Hz, and a reduction in the microseism band to several tenths of a μm/√Hz.

The isolation positioning system must have a large enough control range to allow the interferometer to remain locked for extended periods; our working value is 1 week.

The system must interface with the rest of the LIGO system, including LIGO vacuum equipment, the adopted suspension design, and system demands on optical layout and control.

The requirements for the **HAM (Auxiliary optics) payloads** are less stringent at 1 Hz by a factor of approximately 30 and ~100 at 10 Hz, due to the reduced optic sensitivity for these chambers. Additional information on Advanced LIGO seismic isolation requirements is available[8].

Concept

The initial LIGO seismic isolation stack will be replaced with an Hydraulic External (to the vacuum) Pre-Isolator (HEPI) stage, and an In-vacuum two-stage active Seismic Isolation (ISI) platform (**Figure 4** is a solid model of the currently under-construction prototype). The in-vacuum stages are mechanically connected with stiff springs, yielding typical passive resonances in the 2-8 Hz range. Sensing its motion in 6 degrees of freedom and applying forces in feedback loops to reduce the sensed motion attenuates vibration in each of the two-cascaded stages. Stage 1 derives its feedback signal by blending three real sensors for each degree of freedom: a long-period broadband seismometer, a short-period geophone, and a relative position sensor. The inertial sensors (seismometers and geophones) measure the platform's motion with respect to their internal suspended test masses. The position sensor measures displacement with respect to the adjacent stage. The resulting "super-sensor" has adequate signal-to-noise and a simple, resonance-free response from DC to several hundred hertz. Stage 2 uses the position sensor and high-sensitivity geophone, and some feed-forward from the outer stage 1 seismometer.

---

[6] Classical and Quantum Gravity **21**(9): 2255-2273.

[7] Phys. Rev. D **58**, 122002

[8] Advanced LIGO Seismic Isolation Design Requirements Document, LIGO-E990303

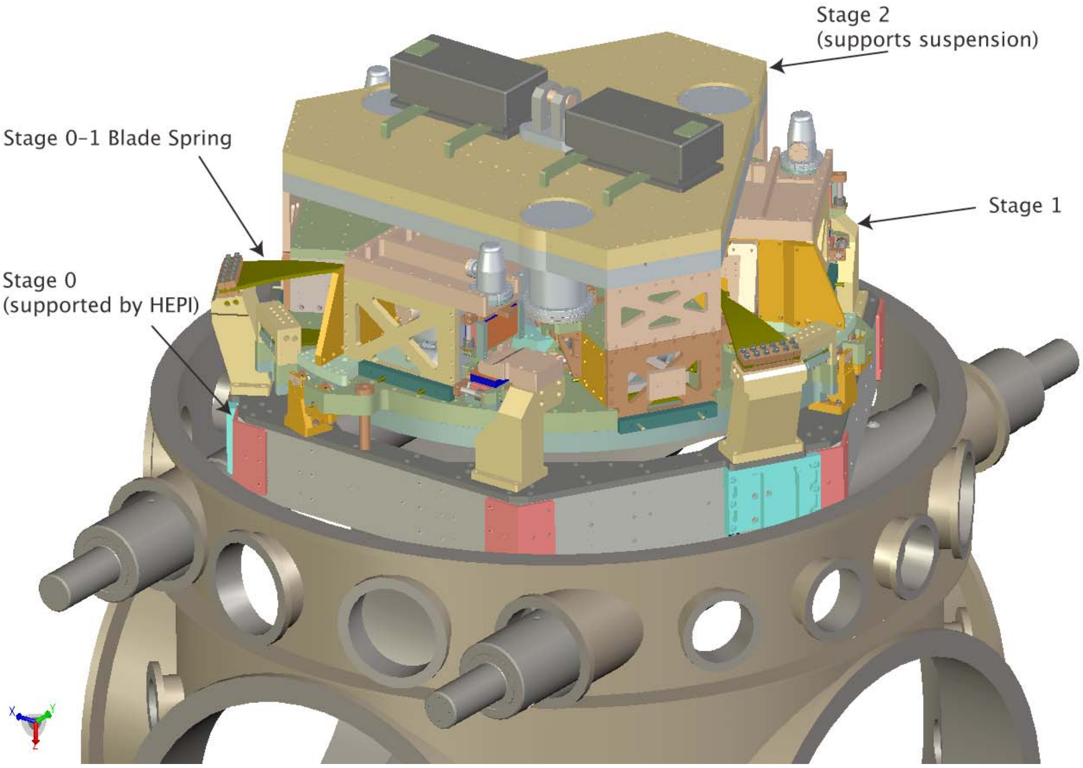

Figure 4 *Computer rendering of the prototype two-stage in-vacuum active seismic isolation system (ISI) for the test-mass (BSC) vacuum chambers, which is under construction as of this writing. The outside frame (stage 0) supports the stage 1 from three trapezoidal blade springs and vertical flexure rods. Stage 2, which supports the payload, is likewise suspended from stage 1. The bottom of stage 2 is an optics table under which the test mass suspensions are mounted.*

The outer frame of the isolation system is designed to interface to the existing in-vacuum seismic isolation support system, simplifying the effort required to exchange the present system for the new system. The outer stage is hung from the outer frame using trapezoidal leaf springs to obtain the 2-6 Hz resonances. The inner platform stage is built around a 1.5-m diameter optics table (BSC) or a larger polygonal table (HAM). The mechanical structures are carefully studied to bring the first flexible-body modes well above the ~50 Hz unity gain frequencies of the servo systems. For each suspended optic, the suspension and auxiliary optics (baffles, relay mirrors, etc.) are mounted on an optical table with a regular bolt-hole pattern for flexibility.

We will use commercial, off-the-shelf seismometers that are encapsulated in removable pods. This allows the sensors to be used as delivered, without concerns for vacuum contamination, and allows a simple exchange if difficulties arise. The actuators consist of permanent magnets and coils in a configuration that encloses the flux to reduce stray fields. These components must meet the stringent LIGO contamination requirements. The multiple-input multiple-output servo control system is realized using digital techniques; 16-bit accuracy with ~2 kHz digitization is sufficient.

The external pre-isolator is used to position the in-vacuum assembly, with a dynamic range of 1 mm, and with a bandwidth of 2 Hz or greater in all six degrees of freedom. This allows feedforward correction of low-frequency ground noise and sufficient dynamic range for Earth tides and thermal or seasonal drifts. We target approximately a factor of 10 reduction of the ~0.16 Hz microseismic motion from feedforward correction in this stage.

The performance of the ISI system is calculated with a model that includes all solid-body degrees of freedom, and measured or published sensitivity curves (noise and bandwidth) for sensors. It meets the Advanced LIGO requirements for both the test-mass (BSC) and auxiliary (HAM) chambers.

The passive isolation of the suspension system provides the final filtering. A sketch of the system as applied to the test-mass vacuum chambers (BSC) is shown in ***Figure* 5**. A similar system is designed for the auxiliary optics chambers (HAM). Further details can be found in the subsystem Design Requirements and Conceptual Design documents[9].

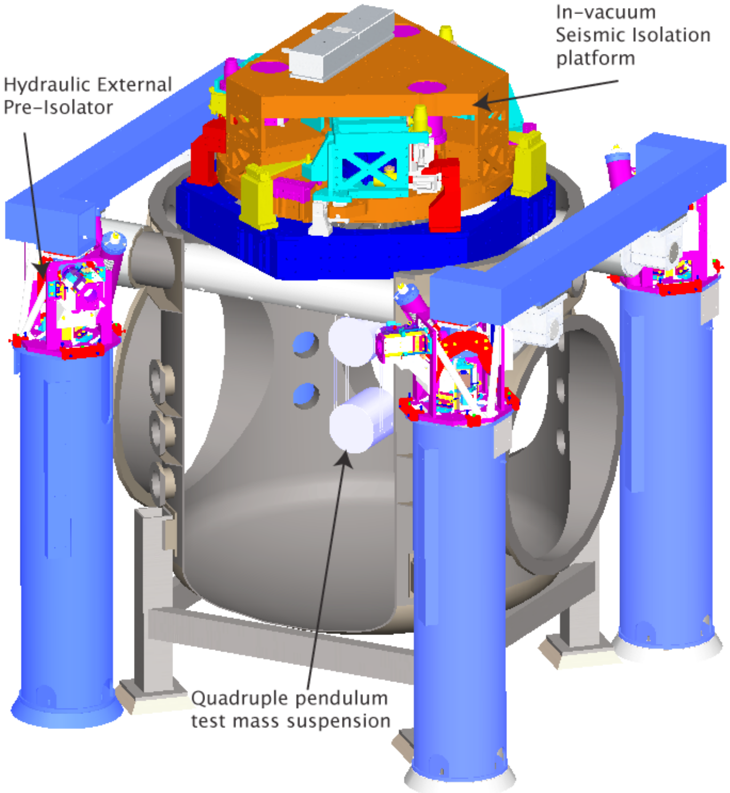

Figure 5 *Rendering of the internal isolation system (ISI) installed in the BSC (test mass chambers), with a suspension system attached below. The external pre-isolator (HEPI) provides the interface between the vertical blue piers and the green horizontal support structure.*

A similar design has been developed for the auxiliary optics HAM chambers, which uses the hydraulic external pre-isolator, and a single-stage system in the vacuum. The relaxed requirements for this chamber allow this simpler system, reducing cost and commissioning time.

---

[9] Advanced LIGO Seismic Isolation System Conceptual Design, E010016-00;
Overview for the Advanced LIGO HAM ISI Preliminary Design Review, LIGO-T080236

R&D Status/Development Issues

The HEPI system was installed in LIGO Livingston before LIGO's S4 science run, specially configured to reduce transmitted ground noise up to 2–3 Hz, in order to allow daytime operation in the presence of noise from local forestry and other human activity. It served this purpose very well. It has proven to be a reliable platform, will remain in place for Advanced LIGO; the same design is being replicated for the Hanford Observatory.

After extensive prototype testing, two units of in-vacuum seismic isolation (ISI) for the HAM Auxiliary chambers have been fabricated and installed at the Observatories as part of the enhancements to initial LIGO (eLIGO). The performance of the system meets requirements at most frequencies, and will further improve with the changes to the infrastructure planned for Advanced LIGO (addition of HEPI and feed-forward techniques). The system is in the fabrication phase for Advanced LIGO, and the two installed units will remain in place for use in Advanced LIGO.

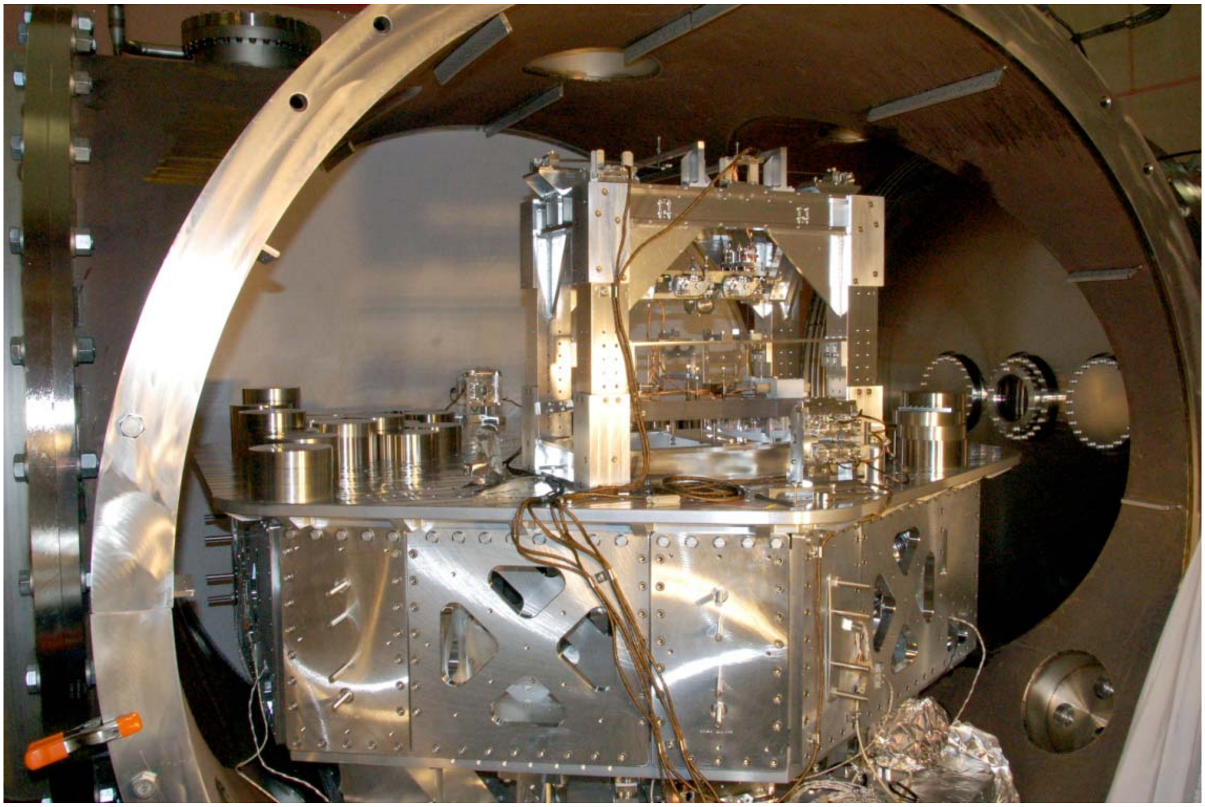

Figure 6: HAM isolator installed at the Livingston Observatory. The Output Mode Cleaner suspension is installed on top of the platform.

A full-scale prototype of the test-mass BSC chamber in-vacuum isolator has been designed and fabricated. It is installed at the MIT LASTI testbed, and has undergone characterization and integration with the quadruple stage test-mass suspension.

Figure 7: BSC Seismic Isolation prototype, being installed in the test mass vacuum chamber at the MIT LASTI testbed. The upper section of the suspension can be seen at the bottom center of the isolator.

5. Suspension Subsystem (SUS)

Overview

The test-mass suspension subsystem must preserve the low intrinsic mechanical losses (and thus the low thermal noise) in the fused silica suspension fibers and test mass. It must provide actuators for length and angular alignment, and attenuate seismic noise. The Advanced LIGO reference design suspension is an extension of the design of the GEO-600 [4] multiple pendulum suspensions, with requirements to achieve a seismic wall, in conjunction with the seismic isolation (SEI) subsystem, at ~10 Hz. A variety of suspension designs are needed for the main interferometer and input conditioning optics.

Functional Requirements

The suspension forms the interface between the seismic isolation subsystem and the suspended optics. It provides seismic isolation and the means to control the orientation and position of the optic. These functions are served while minimally compromising the thermal noise contribution from the test mass mirrors and minimizing the amount of thermal noise from the suspension elements.

The optic (which in the case of the main arm cavity mirror serves also as the test mass) is attached to the suspension fiber during the suspension assembly process and becomes part of the suspension assembly. Features on the test mass will be required for attachment. The test mass suspension system is mounted (via clamps) to the seismic isolation system by attachment to the SEI optics table.

Local signals are generated and fed to actuators to damp solid body motions of the suspension components and eddy current damping will be used to complement the active damping for some suspensions. In addition, control signals generated by the interferometer sensing/control (ISC) are received and turned into forces on the test mass and other masses in the multiple pendulums as required, to obtain and maintain the operational lengths and angular orientation. Such forces are applied by use of a reaction pendulum to reduce the reintroduction of noise through motion of the actuator. There are two variants of the test mass suspension: one for the End Test Mass (ETM) which carries potentially non-transmissive actuators behind the optic, and one for the Input Test Mass (ITM) which must leave the input beam free to couple into the Fabry-Perot arm cavity. There are also variants for the beamsplitter, folding mirror, and recycling mirrors; and for the mode cleaner, input matching telescope, and suspended steering mirrors.

Multiple simple pendulum stages improve the seismic isolation of the test mass for horizontal excitation of the pendulum support point; this is a valuable feature, but requires augmentation with vertical isolation to be effective. Vertical seismic noise can enter into the noise budget through a variety of cross-coupling mechanisms, most directly due to the curvature of the earth over the baseline of the interferometer. Simple pendulums have high natural frequencies for vertical motion. Thus, another key feature of the suspension is the presence of additional vertical compliance in the upper stages of the suspension to provide lower natural frequencies and consequently better isolation.

Further detail on requirements can be found in the Design Requirements Document.[10]

Key parameters of the test-mass suspension design are listed in **Table II**; other suspensions have requirements relaxed from these values.

---

[10] Test Mass Suspension Subsystem Design Requirements Document, T010007

Table II *Test-mass suspension parameters: quadruple pendulum*

Suspension Parameter	Value
Test mass	40 kg, silica
Penultimate mass	40 kg, silica (lower quality)
Top and upper intermediate masses	22 kg each, stainless steel
Test mass suspension fiber	Fused silica tapered fiber
Upper mass suspension fibers	Steel
Approximate suspension lengths	0.6 m test mass, 0.3, 0.3 m intermediate stages, 0.4 m top
Vertical compliance	Trapezoidal cantilever springs
Optic-axis transmission at 10 Hz	~ 2×10^{-7}
Test mass actuation	Electrostatic (acquisition and operation)
Upper stages of actuation; sensing	Magnets/coils; incoherent occultation sensors

Concept/Options

The test mass mirror is suspended as the lowest mass of a quadruple pendulum as shown in ***Figure* 8** the four stages are in series. Silica is the reference design mirror substrate material. However, the basic suspension design is such that sapphire masses could be incorporated with a modest level of redesign as a “fall-back” should further research favor its use. Both materials are amenable to low-loss bonding of the fiber to the test mass. The mass above the mirror— the penultimate mass— is made of lower-grade silica.

The top, upper intermediate and penultimate masses are each suspended from two cantilever-mounted, approximately trapezoidal, pre-curved, blade springs (inspired by and similar to the Italian-French VIRGO blade springs), and four steel wires, of which two are attached to each blade. The blade springs are stressed to about half of the elastic limit. The upper suspension wires are not vertical and their lengths and angles gives some control over the mode frequencies and coupling factors.

Fused silica pieces form the break-off points for the silica ribbons at the penultimate and test masses. These pieces or ‘ears’ are attached to the penultimate and test masses using hydroxyl-catalysis bonding, which is demonstrated to contribute negligible mechanical loss to the system. A CO_2 laser-based machine has been developed for pulling the suspension fibers and for welding them to the ears.

Tolerable noise levels at the penultimate mass are within the range of experience on prototype interferometers (10^{-17} m/√Hz at tens of Hz) and many aspects of the technology have been tested in special-purpose setups and in the application of the approach to GEO-600. At the top-mass, the main concern is to avoid acoustic emission or creep (vibration due to slipping or deforming parts).

To meet the subsystem noise performance requirements when damping the solid-body modes of the suspension, sensors with sensitivity ~10^{-10} m/√Hz at 1 Hz and 0.7 mm peak-peak working range will be used in conjunction with suitable servo control algorithms with fast roll-off in gain, complemented by eddy current damping for some degrees of freedom.

Actuation will be applied to masses in a hierarchy of lower force and higher frequency as the test mass is approached. Coils and magnets will be used on upper stages, and electrostatic actuation on the test mass itself (see *Figure* **9**) with switchable high- and low-force (and hence noise) modes for acquisition and operation respectively.

Other suspended optics will have noise requirements that are less demanding than those for the test masses, but still stricter than the initial LIGO requirements, especially in the 10-50 Hz range. Their suspensions will employ simpler suspensions than those for the test masses, such as the triple suspension design for the mode cleaner mirrors (see *Figure* **10**).

More design detail can be found in additional subsystem documentation[11].

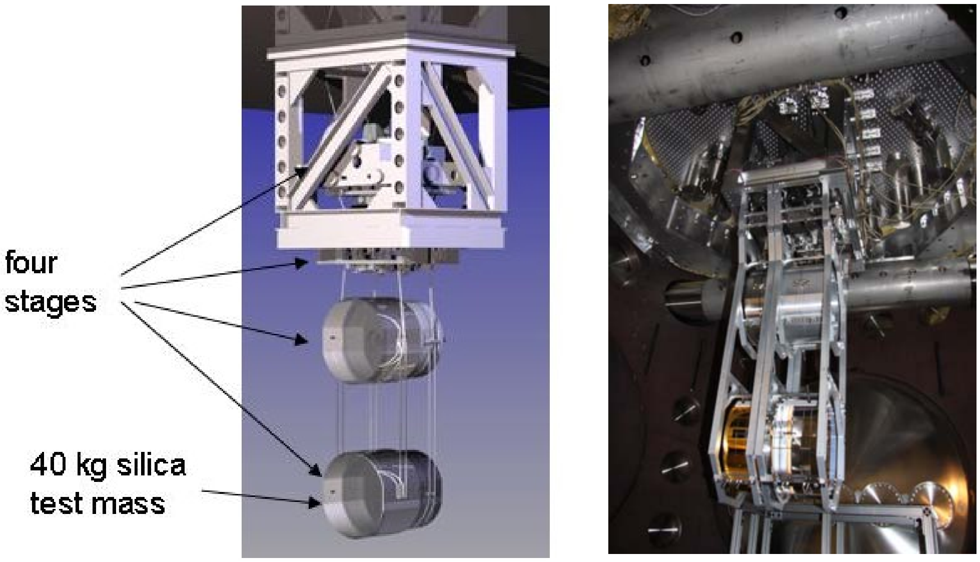

Figure 8 *Left: schematic diagram of quadruple suspension showing main chain and parallel reaction chain for interferometer control actuation, with lower support structure removed for clarity. Right: final prototype with glass masses, suspended with metal wires, installed on the seismic isolation system in LASTI*

---

[11] Advanced LIGO Suspension System Conceptual Design, T010103; Quadruple Suspension Design for Advanced LIGO, N A Robertson et al Class. Quantum Grav. Vol. 19 (2002) 4043-4058; P020001-A-R; Quad Noise prototype PDR-3 overview, T060142; Monolithic stage conceptual design for Advanced LIGO ETM/ITM C. A. Cantley et al T050215; Discussion Document for Advanced LIGO suspension (ITM, ETM, BS, FM) ECD Requirements K A Strain T050093; Advanced LIGO ITM/ETM suspension violin modes, operation and control K A Strain and G Cagnoli, T050267; Conceptual Design of a Double Pendulum for the Output Modecleaner, T060257

Figure 9 *Left: full-size silica test mass (unpolished) procured with UK funding. Right: gold coated glass plate for testing electrostatic actuation in the controls prototype quadruple suspension*

Figure 10 *Left and middle: prototype modecleaner mirror triple suspension being bench tested and being installed for further test at the LASTI facility. Right: Longitudinal transfer function top mass drive to top mass position for modecleaner -green (damping off, red (damping on), blue: MATLAB model*

R&D Status/Development Issues

The SUS effort within the LSC is spread widely over several institutions including a major contribution from the UK. A consortium of the University of Glasgow and the University of Birmingham was successful in securing UK funding of ~ $12M from the Science and Technology Facilities Council (STFC) to supply the test-mass and beamsplitter suspensions for Advanced LIGO, and funding started in 2003, with delivery of 4 test mass blanks completed (see *Figure* **9**). The GEO group at the University of Glasgow is the originator of GEO suspension design, and thus the UK team is very well positioned to carry through this effort, working in close collaboration with the US team. Other suspensions are the responsibility of the US members of SUS.

The primary role of the suspension is to realize the potential for low thermal noise, and much of the research into suspension development explores the understanding of the materials and defines processes to realize this mission. In addition, design efforts ensure that the seismic attenuation and the control properties of the suspension are optimized, and prototyping efforts ensure that the real performance is understood.

The GEO-600 suspensions utilizing the basic multiple-pendulum construction, fused-silica fibers, and hydroxy-catalysis attachments, have been in service since 2001. The systems have been reliable and the controls function essentially as modeled. Lessons learnt from the design, construction, installation and operation of the suspensions have been noted for application to the Advanced LIGO designs.

A prototype quadruple suspension for the test mass has been constructed by the UK and is installed in the MIT LASTI testbed. This prototype is designed to allow investigation of mechanical design, control aspects and installation and alignment procedures, as well as investigating the integration with the seismic isolation. This prototype will carry a glass test mass suspended from fused silica fibers as a complete test of the fabrication, installation, and controls performance of the suspension. Fabrication of metal elements of the suspension by the UK is underway.

Two all-metal triple pendulum prototypes (***Figure* 10**) for modecleaner mirrors have been constructed and assembled at Caltech for initial tests, and subsequently sent to LASTI where full characterization of its behavior including comparison with computer models has been successfully completed. The two suspensions are being used in an optical cavity to study cavity locking and controls. The adoption of optically-stable cavities at the input and output of the interferometer have led to some changes in the design requirements, and the design modifications are now underway.

The designs for the recycling cavity mirror suspensions are completed and a prototype tested in the MIT LASTI testbed in integration with the seismic isolation systems installed there.

The design for the Output Mode Cleaner suspension has been completed, and the first of two copies fabricated for use in the enhancements to Initial LIGO, as shown installed on a seismic isolation system in Figure 7. The design appears to be close to final, and elements of these ‘prototype’ suspensions will be used in Advanced LIGO.

Design details of the fiber, ‘ear’, and welding procedure, and (jointly with the US) the analog electronics design have been completed.

6. Pre-Stabilized Laser Subsystem (PSL)

Overview

The Advanced LIGO PSL will be a conceptual extension of the initial LIGO subsystem, operating at the higher power level necessary to meet the required Advanced LIGO shot noise limited sensitivity. It will incorporate a frequency and amplitude stabilized 180 W laser. The Advanced R&D program related to this subsystem has developed rod optical gain stages that are used with an injection-locked power oscillator.

The Max Planck Institute for Gravitational Wave Research/Albert Einstein Institute in Hannover, Germany is supplying the PSL systems for Advanced LIGO as a German contribution to the partnership in Advanced LIGO[12]. The Max-Planck-Gesellschaft has approved funding for both the development (which is nearing completion) and construction phase. As part of this contribution, the enhancements to initial LIGO include the implementation of the first two stages of the Advanced LIGO laser (increasing the available power from ~10W to ~30W), and yeilded considerable experience with the lasers and their interface. In addition to the lasers for the Observatories, an additional has been delivered to Caltech for characterization and as a research tool.

Functional Requirements

The main requirements of the PSL subsystem[13] are output power, and amplitude and frequency stability. lists the reference values of these requirements. Changes in the readout system allow some requirements to be less stringent with respect to initial LIGO; the higher power and extension to lower frequency provides the principal challenge.

Table III *PSL Requirements*

Requirement	Value
TEM00 Power	165 W
Non-TEM00 Power	<5 W
Frequency Noise	1 Hz/Hz$^{1/2}$ (10 Hz)
Amplitude Noise	2×10^{-9} /Hz$^{1/2}$ (10 Hz)
Beam Jitter	$\varepsilon < 9\times10^{-4}$ /Hz$^{1/2}$ (10 Hz) (fraction of beam parameters)
RF Intensity Noise	1dB above shot noise of 100mA above 9MHz

TEM$_{00}$ Power: Assuming an optical throughput of 0.72 for the input optics subsystem, the requirement of 120 W at the interferometer input gives a requirement of 165 W PSL output.
Non-TEM$_{00}$ Power: Modal contamination of the PSL output light will mimic shot noise at the mode cleaner cavity, producing excess frequency noise. A level of 5 W non-TEM$_{00}$ power is consistent with the input optics frequency-noise requirements.

---

[12] A High-Power Pre-Stabilized Laser System for the Advanced LIGO Gravitational Wave Detectors, K. Danzmann, LIGO M060061-00-M

[13] Pre-Stabilized Laser Design Requirements, T000035

Frequency Noise: Frequency noise couples to an arm cavity reflectivity mismatch to produce strain noise at the interferometer signal port. The requirement is obtained based on a model with an additional factor of 10^5 frequency noise suppression from mode cleaner and interferometer feedback, a 0.5% match in amplitude reflectivity between the arm cavities (a conservative estimate for the initial LIGO optics), and a signal recycling mirror of 10% transmissivity.

Amplitude Noise: Laser amplitude noise will mimic strain noise in two main ways. The first is through coupling to a differential cavity length offset. The second and larger coupling is through unequal radiation pressure noise in the arm cavities. Assuming a beamsplitter of reflectivity 50±1%, the requirement is established.

Beam Jitter Noise: The coupling of beam jitter noise to the strain output is through the interferometer optics misalignment. Based on a model of a jitter attenuation factor of 250 from the mode cleaner, the requirement is established on the quadratic sum ε of the fractional divergence and diameter of the beam.

RF Intensity Noise: The presence of intensity noise at the RF modulation frequency can couple via auxiliary control loops into strain noise. The noise is limited with the requirement above.

Concept/Options

The conceptual design of the Advanced LIGO PSL is similar to that developed for initial LIGO. It involves the frequency stabilization of a commercially engineered laser with respect to a reference cavity. It will include actuation paths for coupling to interferometer control signals to further stabilize the beam in frequency and in intensity.

The front end for the Advanced LIGO Laser is based on a Nd:Vanadate amplifier system. A rod-based amplifier increases the output of a monolithic non-planar ring oscillator, producing ~35 W[14]. The high-power laser is based on a ring-resonator design with four end-pumped laser heads. Each laser head is pumped by seven 45 W fiber-coupled laser diodes. Each laser diode is individually temperature stabilized to minimize the linewidth of each fiber bundle. To improve the laser diode reliability and lifetime, the output power of each laser diode is de-rated by one-third. A fused silica rod homogenizes the transverse pump light distribution due to the spatial mixing of the rays emerging from the different fibers. This minimizes changes to the pump light distribution in the event of a pump diode failure or degradation. Thus failure of a pump diode can be compensated for by increasing the operating current for the remaining pump diodes. Three lenses then image the output of the homogenizer into the laser crystal. The Advanced LIGO laser is illustrated in Figure 11

The optical layout of the PSL has four main components: the 180-W laser, a frequency stabilization path including a rigid reference cavity; an acousto-optic modulator as an actuator for the second frequency stabilization loop; a spatial filter cavity and a diagnostic path that permits investigation of the laser behavior without any disturbance to the output of the PSL. The output of the 180-W laser is spatially filtered by a small bow-tie cavity prior to being mode-matched into the suspended modecleaner.

A sample of the spatially filtered output is mode matched to the rigid reference cavity used for frequency stabilization. The scheme used is identical to that used in initial LIGO.

Two more beam samples, taken before and after the suspended modecleaner are used for the power stabilization. The baseline plan for power stabilization of the PSL is to actuate on the pump diode current to control the intensity of the laser by use of a current shunt.

---

[14] Advanced LIGO PSL Front End: Amplifiers vs Oscillator, LIGO-T060235

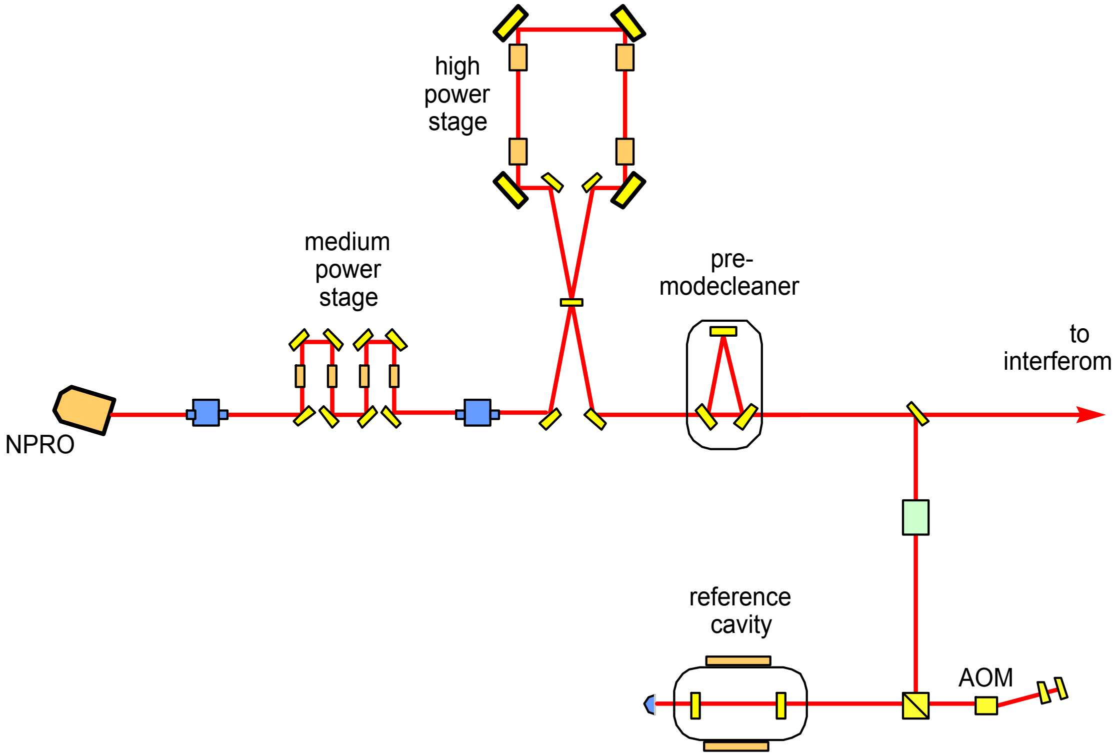

Figure 11 *Schematic of the Advanced LIGO PSL.*

R&D Status/Development Issues

Work is completed on the characterizing the design of the 180-W laser[15]. Some minor problems had been encountered relating to cleanliness issues around the laser optics but these have been resolved. The system is now undergoing long-term testing, and additional copies of the laser for testing and other uses are in construction.

Progress has been made in further understanding the noise sources that limit the performance of the intensity stabilization at low frequencies. The results achieved at the Albert Einstein Institute to date[16] are RIN=$3\text{x}10^{-9}/\sqrt{\text{Hz}}$@10Hz out-of-loop measurements, and so effectively meet the Advanced LIGO requirement of 1/10 of the strain noise at 10 Hz and easily meeting requirements at all other frequencies.

An effort with an industrial partner, the Laser Zentrum Hannover, similar to our practice in initial LIGO, has led to the engineering of a reliable unit that is designed to meet the LIGO availability goal. Tests of a complete full-power PSL are finished in Germany.

---

[15] High-Power Fundamental Mode Single-Frequency Laser, LIGO-P040053-00-R

[16] Opt. Lett. 31, 2000 (2006).

7. Input Optics Subsystem (IO)

Overview

The Advanced LIGO Input Optics (IO) subsystem is a significant evolution from the initial LIGO Input Optics design, with the higher specified power and the lower noise level required by Advanced LIGO, capability for adjustment of the matching into the interferometer, and incorporation of the optically-stable power recycling cavity. The IO consists primarily of beam conditioning optics including Faraday Isolators and phase modulators, a triangular input mode cleaner, and the interferometer mode-matching telescope.

Functional Requirements

The functions of the IO subsystem are to provide the necessary phase modulation of the input light, to filter spatially and temporally the light on transmission through the mode cleaner, to provide optical isolation as well as distribution of interferometer diagnostic signals, and to mode match the light to the interferometer with a beam-expanding telescope. *Table* **IV** lists the requirements on the output light of the Advanced LIGO IO subsystem.

Table ***IV*** *Advanced initial LIGO requirements*

Requirement	Value
Optical Throughput	0.75 (net input to TEM_{00} out)
Non-TEM_{00} Power	<5%
Frequency Noise	3×10^{-3} Hz/ $Hz^{1/2}$ (at 10 Hz)
Beam Jitter (relative to beam radius/divergence angle)	$< 10^{-8}$ / $Hz^{1/2}$ (f > 200 Hz)

The Input Optics has to deliver 120 W of conditioned power to the advanced LIGO interferometer. The optical throughput requirement ensures that the required TEM_{00} power will be delivered. The cavities of the main interferometer will accept only TEM_{00} light, so the IO mode cleaner must remove higher-order modes and its beam-expanding telescope must couple 95% of the light into the interferometer.

The IO reduces the frequency, and beam-jitter noise of the laser. The suspended mode cleaner serves as an intermediate frequency reference between the PSL and interferometer. Beam jitter (pointing fluctuation) appears as noise at the interferometer output signal through optical misalignments and imperfections. The nominal optic alignment error of 1×10^{-9} rad imposes the requirement in Table 4. Further details can be found in the IO Design Requirements document[17].

Concept/Options

The schematic layout of the IO is displayed in **Figure 12,** showing the major functional components. The development of the IO for Advanced LIGO will require a number of incremental improvements and modifications to the initial LIGO design. Among these are the needs for larger mode cleaner optics and suspensions to meet the Advanced LIGO frequency noise requirement,, increased power handling capability of the Faraday Isolator and phase modulators, and the ability to adaptively control

---

[17] Advanced LIGO Input Optics Design Requirements Document, T020020

the laser mode structure into the interferometer. The change to a stable power recycling cavity brings several interferometrically-sensed optics into the Input Optics subsystem and increases some layout complexity.

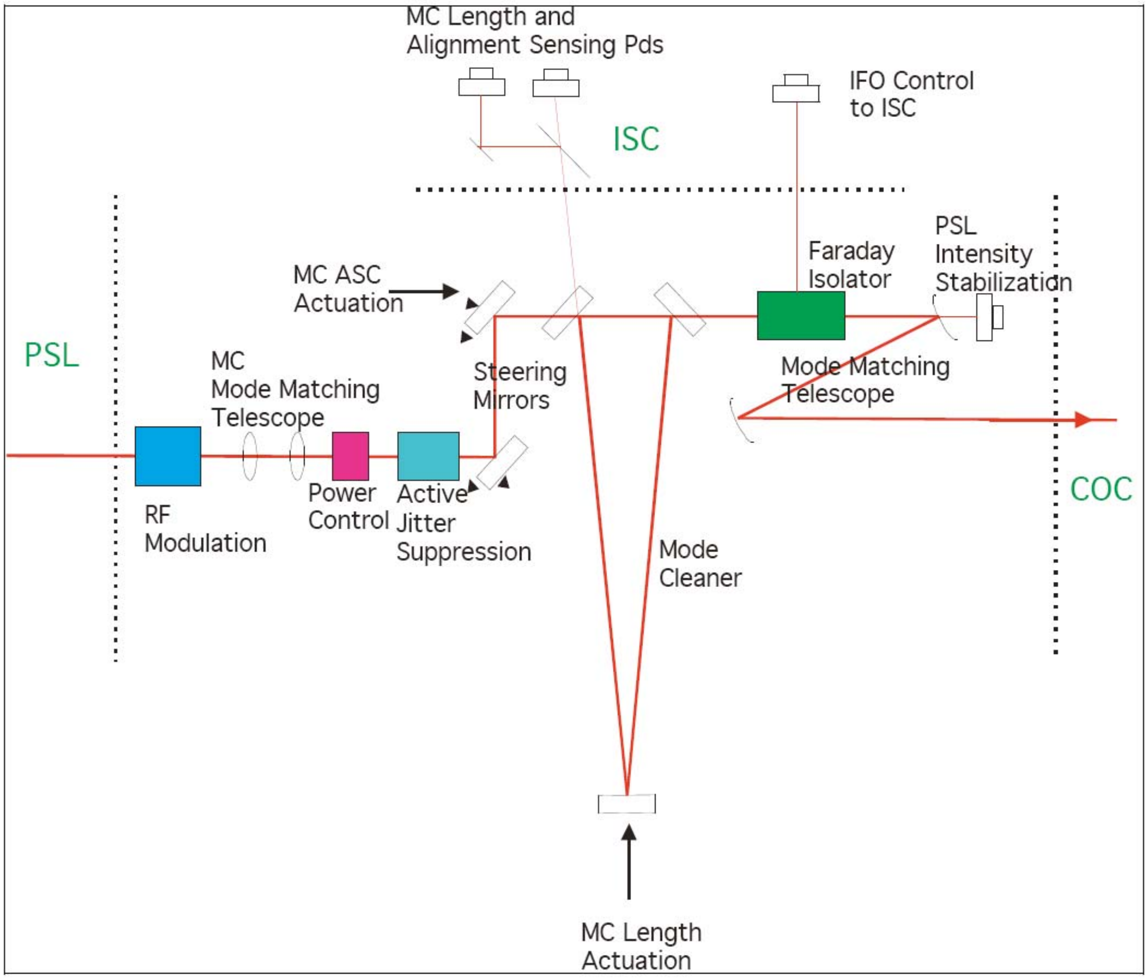

Figure 12 *Schematic diagram of the Advanced LIGO Input Optics (IO) subsystem.*

Phase modulation for use in the length and angle sensing systems is applied using electro-optic crystals. Faraday isolators are used to prevent parasitic optical interference paths to the laser and to obtain information for the sensing system.

The mode cleaner is an in-vacuum suspended triangular optical cavity. It filters the laser beam by suppressing directional and geometric fluctuations in the light entering the interferometer, and it provides frequency stabilization both passively above its pole frequency and actively through feedback to the PSL. Noise sources considered in design studies include sensor/actuator and electronic noise, thermal, photothermal, and Brownian motion in the mode cleaner mirrors, and radiation pressure noise. The mode cleaner will use 15-cm diameter, 7.5-cm thick fused silica mirrors. The cavity will be 16.7 m in length, with a finesse of 500, maintaining a stored power of ~25 kW. A triple pendulum (part of the suspensions subsystem) will suspend the mode cleaner mirrors so that seismic and sensor/actuator noise does not compromise the required frequency stability.

Finally, the mode-matching telescope, which brings the beam to the final Gaussian beam parameters necessary for interferometer resonance, will be similar to the initial LIGO design using three spherical mirrors, but will use a fused silica plate with segmented heaters on its circumference to adjustably control the mode matching without the need for vacuum excursions..

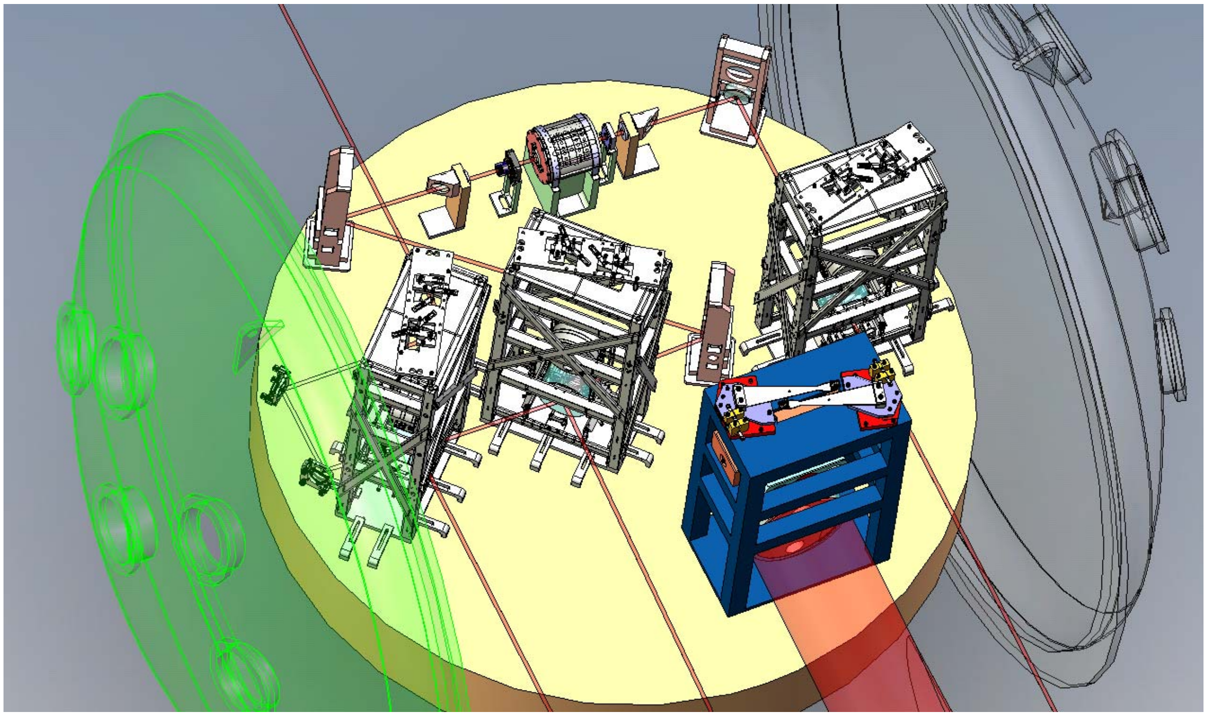

Figure 13: Rendering of IO layout for one of the HAM chambers

Further documentation of the design can be found in the Input Optics Conceptual Design Document[18] and Preliminary Design Document[19] and references therein.

R&D Status/Development Issues

The IO subsystem design is complete.

---

[18] Advanced LIGO Input Optics Subsystem Conceptual Design Document, T020027

[19] Input Optics Subsystem Preliminary Design Document, LIGO-T060269

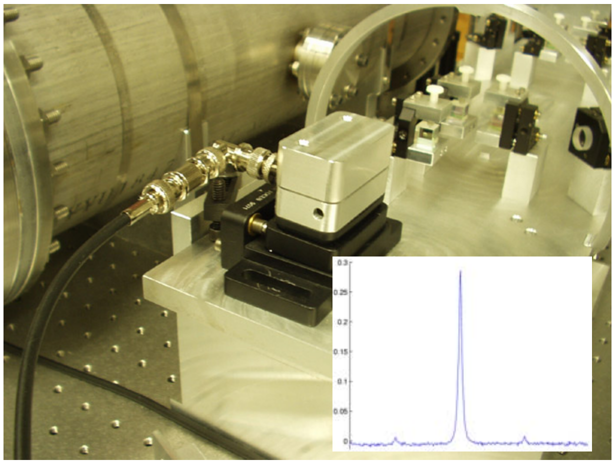

Figure 14 *The Advanced LIGO electro-optic modulators with modulated spectrum shown in the inset.*

We have developed electro-optic modulators based on rubidium titanyl arsenate (RTA) and rubidium titanyl phosphate (RTP) electro-optically active crystals. We have characterized the thermo-optic and electro-optic performance of our modulators at powers up to 175 W and power densities exceeding Advanced LIGO conditions. Negligible absorption and thermal lensing as well as high electro-optic efficiency were observed, and we have operated these modulators at high powers for over 300 hours with no change in performance.[20] Similar designs are now installed for the enhancements to initial LIGO. In addition, we are refining designs for synthesizing multiple pure sideband modulation spectra based on Mach-Zehnder modulation methods should the modulation scheme defined by ISC require it.

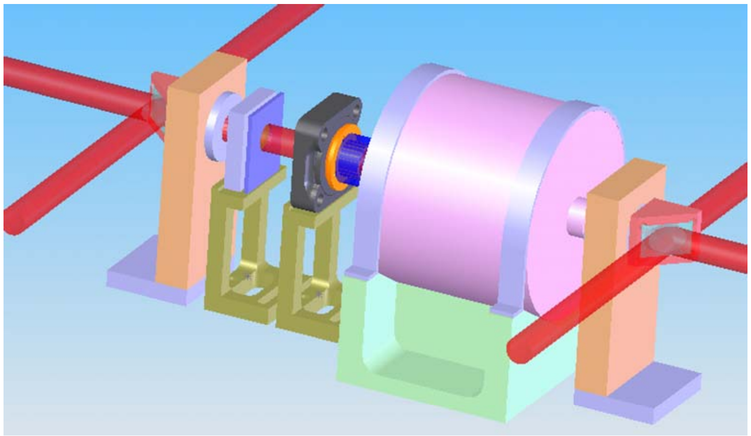

Figure 15 *Schematic drawing of the Faraday Isolator, showing from right (beam entrance) to left i) initial polarizer, ii) Faraday rotator, iii) 1/2 waveplate, iv) thermal lens compensator, and v) final polarizer.*

For the mode cleaner, we have finished the optical design and analyzed its thermal performance using Melody[21] combined with finite element modeling to better understand the effects of optical absorption on the mode quality of the interferometer. The coating absorption dominates the thermal

---

[20] "Upgrading the Input Optics for High Power Operation", LIGO-E060003

[21] R. G. Beausoleil, E. K. Gustafson, M. M. Fejer, E. D'Ambrosio, W. Kells, and J. Camp, "Model of thermal wave-front distortion in interferometric gravitational-wave detectors. I. Thermal focusing", *J. Opt. Soc. B* 20 1247-1268 (2003).

effect due to high intra-cavity powers. Absorption levels 0.5 ppm or less preserve transmitted mode quality at 165 W input powers. The relatively compact design of the mode cleaner cavity produces small spot sizes on the mirrors with average intensities of approximately 200 kW/cm^2. This is below the quoted damage threshold for tantala/silica supermirrors (approximately 1 MW/cm^2).

For the Faraday Isolator, we have addressed both wavefront distortion (thermal lensing) and depolarization through a new design[22] capable of providing compensation for polarization distortion and high isolation ratios up to the maximum test power of 160 W as shown in ***Figure* 15.** Using a negative *dn/dT* material (deuterated potassium dihydrogen phosphate) to introduce negative lensing, we achieved significant compensation of the thermal lens in the Faraday isolator, with the system focal length increasing from ~ 7 m to > 40 m at 75 W power levels.

To address control of the mode matching, we have developed and characterized an adaptive mode matching telescope for Advanced LIGO. It relies on controlled optical path deformation in a fused silica plate. Four radial heating elements allow both focus and astigmatism to be adjusted, and can be adjust the matching to the Core Optics for a range of input power to the interferometer.

The IO subsystem lead role will remain with the University of Florida group who built the IO for initial LIGO. Fabrication of prototype high power Faraday Isolators and phase modulation methods has been proceeding under the University of Florida Advanced R&D program. Advanced LIGO performance level modulators and isolators are used for the initial LIGO enhancements. The Mach-Zehnder modulation system is in test at the Caltech 40m interferometer testbed. The testing of the triple suspension for the Mode Cleaner at the MIT LASTI testbed has given confidence in that design and the controls for locking the mode-cleaner cavity.

---

[22] E. Khazanov, N. Andreev, A. Babin, A. Kiselev, O. Palashov, and D. H. Reitze, “Suppression of Self-Induced Depolarization of High-Power Laser Radiation in Glass-Based Faraday Isolators”, *J. Opt. Soc. Am B.* 17, 99-102 (2000); E. Khazanov, N. Andreev, A. Mal’shakov, O. Palashov, A. Poteomkin, A. M. Sergeev, A. Shaykin, V. Zelenogorsky, Igor Ivanov, Rupal Amin, Guido Mueller, D. B. Tanner, and D. H. Reitze, “Compensation of thermally induced modal distortions in Faraday isolators”, *IEEE J. Quant. Electron.* 40, 1500-1510 (2004).

8. Core Optics Components (COC)

Overview

The Advanced LIGO COC will involve an evolution from the initial LIGO COC to meet the higher power levels and improved shot-noise and thermal-noise limited sensitivity required of the Advanced LIGO interferometer. Many of the fabrication techniques developed for the fused silica initial LIGO COC are directly applicable to the optics production. However, a larger mass is needed to keep the radiation reaction noise to a level comparable to the suspension thermal noise, and a larger surface reduces the thermal noise. The optical coatings must also deliver the combination of low mechanical loss (for thermal noise) while maintaining low optical loss. Reduction of mechanical loss in coatings has a direct impact on the Astrophysical reach of Advanced LIGO.

Functional Requirements

The COC subsystem consists of the following optics: power recycling mirror, signal recycling mirror, beam splitter, folding mirror, compensation plate, input test mass, and end test mass (see **Figure 16**). The following general requirements are placed on the optics:

- the radius of curvature and surface figure must maintain the TEM_{00} spatial mode of the input light;
- the optics microroughness must be low enough to limit scatter to acceptable levels;
- the substrate and coating optical absorption must be low enough to limit the effects of thermal distortion on the interferometer performance;
- the optical homogeneity of the transmitting optics must be good enough to preserve the shape of the wavefront incident on the optic;
- the intrinsic mechanical losses, and the optical coating mechanical losses, must be low enough to deliver the required thermal noise performance

***Table* V** lists the COC test mass requirements.

Table V *COC test mass requirements*

Mass	**40Kg**
Dimensions	340mm x 200mm
Surface figure (deviation from sphere over central 15 cm)	< 0.7 nm RMS
Micro-roughness	< 0.2 nm RMS
Optical homogeneity (in transmission through 15 cm thick substrate, over central 8 cm)	< 2 nm RMS
Bulk absorption	< 3 ppm/cm
Bulk mechanical loss	$< 3\ 10^{-9}$
Optical coating absorption	0.5 ppm (required) 0.2 ppm (goal)
Optical coating scatter	10 ppm (required) 1 ppm (goal)
Optical coating mechanical loss	$2\ 10^{-4}$ (required) 3×10^{-5} (goal)

Requirements Documents

T000127 COC Design Requirements Document
T000128 COC Development Plan
T000098 Conceptual Design Document
C030187 Coating Development Plan

Concept

Advanced LIGO will draw on initial LIGO core optics design. Low optical absorption fused silica is the material chosen for the input and end test mass material. The initial LIGO optics far exceeded many of the specifications for Advanced LIGO; thus only incremental improvements in processes are required. The beam splitter and input test mass substrate requirements are met by the best presently available low absorption fused silica. A polishing demonstration program has successfully shown the ability to scale and improve on the LIGO1 approach to 40 kg sizes. Acceptable mechanical losses of fused silica has been seen in large substrates. The required material properties of fused silica do imply reliance on the thermal compensation system (**see 9. Auxiliary Optics Subsystem (AOS)**). Coatings with the required optical and mechanical properties have been developed and demonstrated.

The very long lead time for production of substrates, for polishing, and for coating requires early acquisition in the Advanced LIGO schedule.

R&D Status/Development Issues

The Core Optics Components subsystem has completed development. The substrates are in-house, and the polishing contract is placed and the coating request for bids is in preparation. A continuing laboratory (operations) program in coating research serves to reduce risk and pave the way to potential improvements to Advanced LIGO as first installed. Design work to ensure that the optics remain contamination-free through the installation and pumpdown is underway in the Systems group.

Figure 16 *40kg Input test mass blank, supplied by University of Glasgow.*

A very active program involving several commercial vendors to characterize and reduce the mechanical loss in the coatings has led to a coating design. The principal source of loss in conventional optical coatings has been determined by our research to be associated with the tantalum pentoxide, likely due to material. Doping of the tantala with titania is the most promising coating developed, with significantly lower thermal noise and optical properties meeting requirements.

An early test of the ability to coat full-size pieces has been completed, with a prototype test mass to be used in the integration tests of the optics, suspensions, and seismic isolation. While the polish of this mass is not to the final requirements, it has provided an opportunity to test handling, cleaning, and metrology processes at one vendor.

Studies of charging of the test mass and means to mitigate it are proceeding. Several university groups are pursuing the measurement of charge and its relaxation time on clean silica surfaces to set the scale of the problem, and others are investigating means to remove the charge through exposure to UV light, charged particles, or a very slightly conductive coating on the test mass. However, informed estimates of the effect on Advanced LIGO indicate that no changes to the test mass or coating are needed to keep this noise source at an acceptable level.

The purpose of the beamsplitter/fold mirror pathfinder is different from the polishing pathfinder. Optics of high aspect ratio are known to warp under the compressive stress of ion beam coatings. This change must be compensated in order to provide sufficiently flat optical surfaces. The compensation will be accomplished either by coating the back side of the optic with an equally stressful coating, by annealing, or by pre-figuring the optic slightly concave so that the resulting optic is flat.

9. Auxiliary Optics Subsystem (AOS)

Overview

The AOS for Advanced LIGO is an extension of this subsystem for initial LIGO, modified to accommodate the planned higher laser power and additional signal-recycling mirror. The AOS is responsible for transport of interferometer output beams and for stray light control. It includes suspended pick-off mirrors, beam reducing telescopes, and beam dumps and baffles. AOS also has responsibility for providing optical lever beams for the core optics, and for establishing the initial alignment of the interferometer. An additional element of this subsystem is active optics thermal compensation, where compensatory heating of an optic is used to cancel thermal distortion induced by absorbed laser power. It also includes the photon calibrator, which uses light pressure to apply precise calibration forces to the end test masses of the interferometer.

A Hartmann sensor developed at our LSC collaborator Adelaide University will be used to detect thermal aberrations as part of the AOS subsystem, and is being generously contributed as a component for Advanced LIGO by Australia with Australian funding.

Functional Requirements

The conventional subsystem requirements relate to control of interferometer ghost beams and scattered light, delivery of interferometer pickoff beams to the ISC subsystem, and maintenance of the surface figure of the core optics through active thermal compensation. While the requirements on these elements are somewhat more stringent than for the initial LIGO design, no significant research and development program is required to meet those requirements[23].

An additional important element is that of active thermal distortion compensation. The requirements for this component are numerically determined as part of the systems flowdown. The axisymmetric thermal lens must be corrected sufficiently to allow the interferometer to perform a “cold start”; the compensation may also be required to correct for small (cm-) scale spatial variations in the substrate absorption.

Concept/Options

The AOS conventional elements consist of low-aberration reflective telescopes that are placed in the vacuum system to reduce and relay the output interferometer beams out to the detectors, and baffles of absorptive black glass placed to catch stray and “ghost” (products of reflections from the residual reflectivity of anti-reflection coatings) beams in the vacuum system. The elements must be contamination-free and not introduce problematic mechanical resonances. Because of the increased interferometer stored power, the AOS for Advanced LIGO will involve careful attention to control of scattered light, and will require greater baffling and more beam dumps than for initial LIGO. Some of the AOS components must have mechanical isolation to keep the phase modulation of light scattered from their surfaces at a low enough level and rate, and so pendulum suspension is used for those critical elements.

The thermal compensation approach involves adding heat, which is complementary to that deposited by the laser beam, using two complementary techniques: a ring heater that deals with circularly

---

[23] AOS: Optical Lever System & Viewports Conceptual Design Requirements, T060232; AOS: PO Mirror Assembly & Telescope, and OMMT Conceptual Design Requirements, LIGO-T060360; AOS: Stray Light Control (SLC) Conceptual Design Requirements, LIGO-T060263

symmetric distortions of the high-reflectivity surface, and a directed laser that allows substrate absorption (axisymmetric or not) to be corrected. For the input test masses, a compensation plate receives the complementary heating pattern[24].

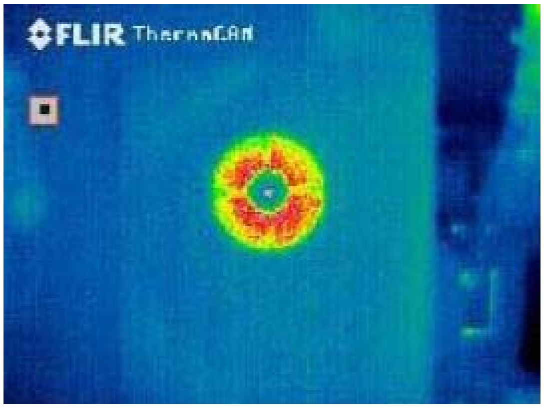

Figure 17 *An initial LIGO thermal compensation pattern.*

R&D Status/Development Issues

Development of active optic thermal compensation is proceeding under the LIGO advanced R&D program. Models of the thermal response of the interferometer in a modal basis[25] and via numerical propagation using Huygen's principle[26] are used extensively to make predictions for the deformations and of the possible compensation. A prototype has successfully demonstrated thermal compensation, in excellent agreement with the model, using both the ring heater and directed laser techniques[27]. In a transfer of technology from Advanced LIGO R&D to initial LIGO, the instruments are currently using CO_2 laser projectors on the input test masses of all three interferometers for thermal compensation both of the interferometers' self-heating and of their static mirror curvature errors. This experience taught us a great deal about servo control methods for thermal compensation and allowed us to measure compensator noise injection mechanisms (see **Figure 17 and *Figure* 18**). Further implementation of some Advanced LIGO approaches has been made in the enhancements to initial LIGO, for instance in the use of "Axicons" to efficiently convert Gaussian-profile heating beams to annular beams. The photon calibrator will employ Nd:YLF lasers, which have proven reliable in prototype and enhanced LIGO applications. .

The thermal compensation development program is in the Preliminary Design phase. A prototype of the thermal compensation system is in fabrication and will be exercised using a CO_2 beam to emulate the thermal loading from the main Nd:YAG beam.

.

---

[24] Auxiliary Optics Support System Conceptual Design Document, Vol. 1 Thermal Compensation System, T060083

[25] R.G.Beausoleil, E. D'Ambrosio, W. Kells, J. Camp, E K.Gustafson, M.M.Fejer: Model of Thermal Wavefront Distortion in Interferometric Gravitational-Wave Detectors I: Thermal Focusing, JOSA B **20** (2003)

[26] B. Bochner, Y. Hefetz, A Grid-Based Simulation Program for Gravitational Wave Interferometers with Realistically Imperfect Optics; Phys. Rev. D 68, 082001 (2003) , LIGO P030048-00.pdf

[27] Adaptive thermal compensation of test masses in Advanced LIGO, R. Lawrence, M. Zucker, P. Fritschel, P. Marfuta, D. Shoemaker, *Class. Quant. Gravity* **19** (2002)

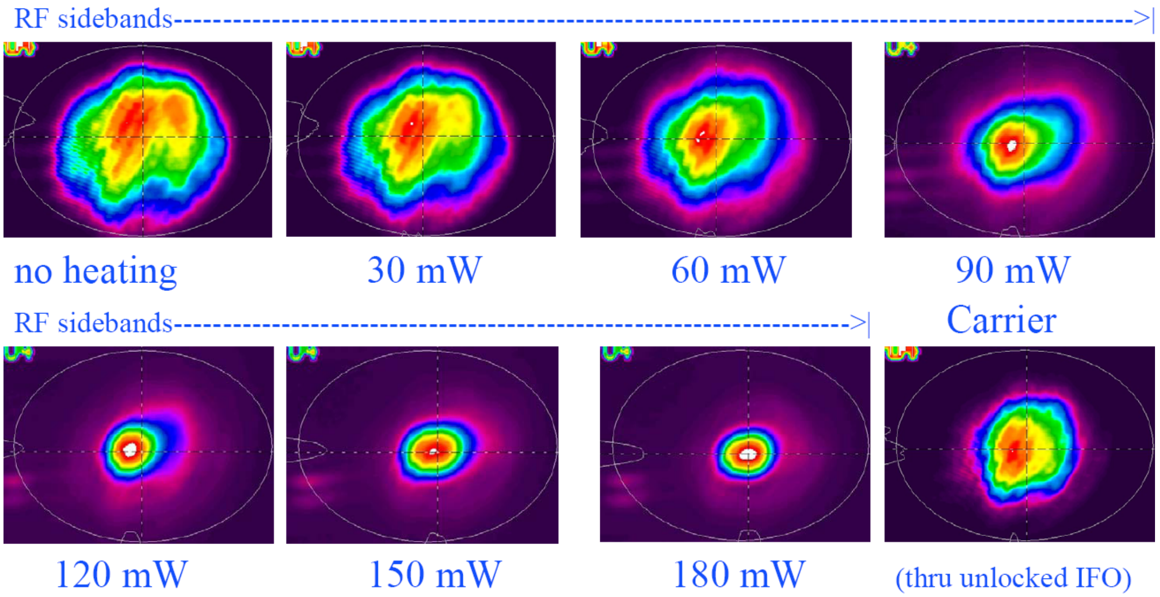

Figure 18 *RF sideband mode shape control using thermal compensation. Note the optimum overlap between RF sideband and carrier mode at 90 mW heating power.*

A reduction in the angle-sensing jitter of the present optical lever system, due to displacement/tilt cross-coupling of sensed mirror surfaces, was demonstrated with a prototype optical lever receiver telescope which was developed for Advanced LIGO. The design process for the beam dumps, baffles, reducing telescopes will resemble that for enhancements to the initial LIGO design, allowing *in-situ* tests of the approaches planned.

10. Interferometer Sensing and Controls Subsystem (ISC)

Overview

This subsystem comprises the length sensing and control, the alignment sensing and control, and the overall controls coordination for the Advanced LIGO interferometer design. The infrastructure elements will be modified to accommodate the additional control loops in the reference design. The most significant differences in the Advanced LIGO subsystem are the addition of the signal recycling mirror and the resulting requirements on its controls, the addition of an output mode cleaner in the output port, the implementation of homodyne, or DC, readout of the gravitational wave channel, and the use of stable optical cavities for the power and signal recycling cavities. In addition, a pre-lock length stabilization system is implemented to render the locking process faster and more predictable.

Australian National University (ANU) has received funding from the Australian government to contribute some key elements of the ISC subsystem to Advanced LIGO: suspended 'Tip-Tilt' pointing mirrors, and a pre-lock arm stabilization scheme.

Functional Requirements

***Table* VI** lists significant reference design parameters for the interferometer length controls.

Table VI *Significant Controls Parameters*

Configuration	**Signal and power recycled Fabry-Perot Michelson interferometer**
Controlled lengths	differential arm length (GW signal) near-mirror Michelson differential length common-mode arm length (frequency control) power recycling cavity resonance signal recycling mirror control
Controlled angles	2 per core optic, 14 in total
Main differential control requirement	10^{-15} m rms
Shot noise limited displacement sensitivity	4×10^{-21} m/√Hz
Angular alignment requirement	10^{-9} rad rms

The requirements for the readout system are in general more stringent than those for initial LIGO. The differential control requirement is a factor of 100 smaller, and the angle requirement, a factor of 10 smaller, and the additional degrees of freedom add complexity. Integration with the thermal compensation system and the gradual transition from a "cold" to a "hot" system will be needed.

In spite of the increased performance requirements for Advanced LIGO, there is a reduction in some aspects of the controls system because of the large reduction in optic residual motion afforded by the active seismic isolation and suspension systems, and the pre-lock length stabilization. Reduced core optic seismic motion can be leveraged in two ways. First, the control servo loop gain and bandwidth required to maintain a given RMS residual error can be much smaller. Second, the reduced control bandwidths permit aggressive filtering to block leakage of noisy control signals from imperfect sensor channels into the measurement band above 10 Hz. While control modeling is still underway, this latter benefit is expected to significantly relieve the signal-to-noise constraints on sensing of auxiliary length and alignment degrees of freedom.

The length sensing system requires that non-TEM_{00} and RF sideband light power at the antisymmetric output port be reduced substantially to allow a small local-oscillator level to be optimal and thus to maintain the efficiency of the overall shot-noise-limited sensing. This is the function of the output mode cleaner.

Concept/Options

The signal-recycled configuration is chosen to allow tunability in the response of the interferometer. Some examples of sensitivity curves achieved through this facility, and by varying input power, can be seen in Figure 1. For example, the broadband tuning allows control over the balance of excitation of the mirrors by the photon pressure, and the improvement in the readout resolution at 100-200 Hz. A narrow-band instrument (to search for a narrow-band source, or to complement a broad-band instrument) can also be created via a change in the signal recycling mirror transmission..

Another important advantage of the signal recycled configuration is that the power at the beamsplitter for a given peak sensitivity can be much lower; this helps to manage the thermal distortion of the beam in the beamsplitter, which is more difficult to compensate due to the elliptical form of the beam and the significant angles in the substrate.

Most length sensing degrees-of-freedom will be sensed using RF sidebands in a manner similar to that in initial LIGO. However, for the gravitational-wave output, a baseband (‘DC’) rather than synchronous modulation/demodulation (‘RF’) approach will be used. The output of the interferometer is shifted slightly away from the dark fringe and deviations from the setpoint become the measure of the strain. This approach considerably relaxes the requirements on the laser frequency; the requirement on baseband intensity fluctuations is not different from the case of RF detection. A complete quantum-mechanical analysis of the two readout schemes has been undertaken to determine which delivers the best sensitivity, and the requirements imposed on the laser and modulation sources due to coupling of technical noise have been followed through, both indicating the preference for this DC readout scheme.

Given the DC readout scheme, the output mode cleaner will be a short, rigid cavity, mounted in one of the output HAM chambers. Both the VIRGO Project and GEO-600 use output mode cleaners in their initial design. The cavity must be aligned with the nominal TEM00 axis of the interferometer, but the bulk (by several orders of magnitude) of the output power will be in higher-order modes; determining the correct alignment is thus non-trivial. The length control, in particular the lock acquisition sequence, also adds complexity.

The use of optical cavities which have a significant suppression of higher order modes (‘stable cavities’ has several advantages, the most obvious being that light is used more efficiently (being better entrained in the fundamental optical mode) for both the carrier light and for the gravitational-wave induced sidebands.

In Advanced LIGO, all of the detection will be performed in vacuum with photodetectors and auxiliary optics mounted on seismic isolation systems. This will avoid the influence of air currents and dust on the beam, and minimize the motion of the beam with respect to the photodiode.

Alignment sensing and control will be accomplished by wavefront sensing techniques similar to those employed in initial LIGO. They will play an important role in managing the potential instability in angle brought about by photon pressure if exerted away from the center of mass of the optic.

The greater demands placed by optical powers and sensitivity are complemented by the improved seismic isolation in Advanced LIGO, leading to similar demands on the control loop gains. In general, the active isolation system and the multiple actuation points for the suspension provide an opportunity to optimize actuator authority in a way not possible with initial LIGO.

To ensure rapid acquisition of the operational state of the servo control systems (‘locking’), a pre-lock arm stabilization system is in included. Frequency-doubled light at 532 nm is to be injected through the end mirrors of the 4km cavities, and the resulting cavity length detected using Pound-Drever-Hall sensing. The lower finesse of the arm cavity at the non-measurement wavelength gives a broad error signal, and one independent of the other interferometer lengths, allowing positioning of the arm lengths for a more deterministic approach to locking than was used in initial LIGO.

For more detail on the subsystem, please see the Interferometer Sensing and Control Requirements document[28]

R&D Status/Development Issues

The signal-recycled optical configuration chosen for Advanced LIGO challenges us to design a sensing and control system that includes the additional positional and angular degrees of freedom introduced by the signal-recycling mirror. A complete design for the length system has been worked through[29], and various elements of the design were tested in the enhancements to initial LIGO (in particular the DC readout and output mode cleaner), and further system tests are underway on the Caltech 40m testbed.

---

[28] http://www.ligo.caltech.edu/docs/T/T070236-00.pdf

[29] aLIGO Interferometer Sensing and Control Conceptual Design, http://www.ligo.caltech.edu/docs/T/T070247-01.pdf

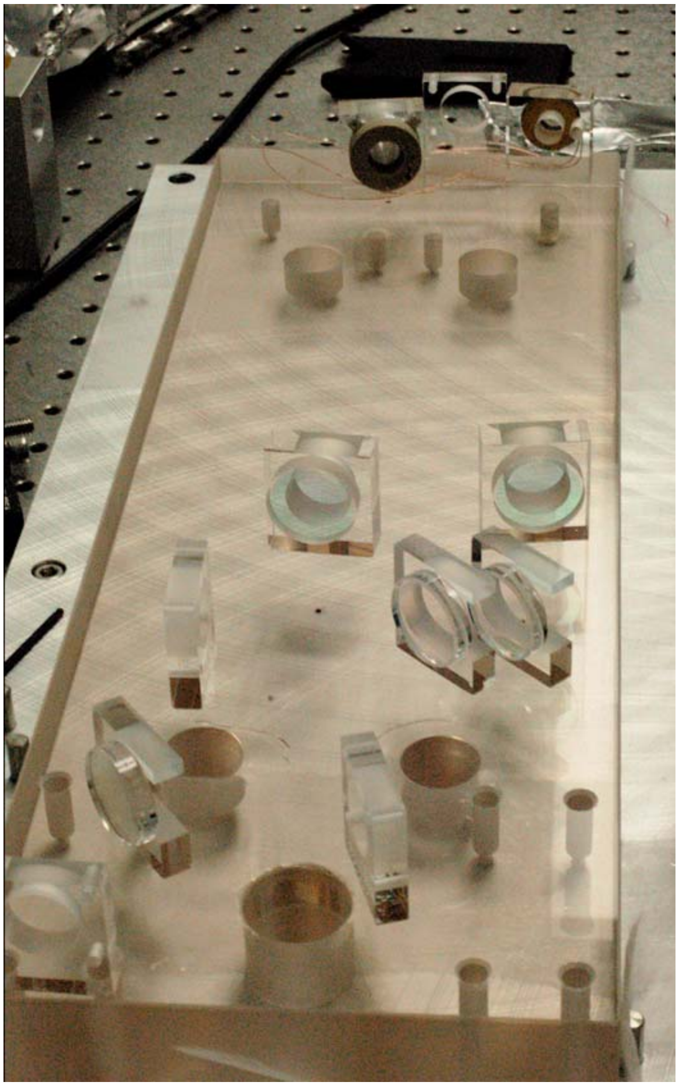

Figure 19: *The Output Mode Cleaner for the enhancements to initial LIGO; a prototype for Advanced LIGO.*

11. Data Acquisition, Diagnostics, Network & Supervisory Control (DAQ)

Overview

The differences between the initial LIGO and Advanced LIGO **Data Acquisition, Network & Supervisory Control (DAQ)** requirements derive from the increase in number of channels in the Advanced LIGO interferometers, due to the greater number of active control systems and inclusion of more of the interferometer control and status parameters into the archived frame data. For example, from initial LIGO's Hanford Observatory's two interferometers we recorded 12,733 channels, of which 1,279 were from "fast" channels (data digitized at either 2,048 Sa/sec or 16384 Sa/sec). We did not record ~50,000 "slow" channels from the EPICS control system. Advanced LIGO's DAQ is designed to record greater than 300,000 channels, of which ~3,000 will be "fast" channels.

Functional Requirements

The principal Advanced LIGO reference design parameters that drive the data acquisition subsystem requirements are summarized in the table below.

Table VII *Principal impacts of the Advanced LIGO Reference Design on Data Acquisition and Data Analysis Systems. The number of Degrees of Freedom (DOF) is indicated for one 4-km interferometer to give a sense of the scaling.*

Parameterization	**Advanced LIGO Reference Design**	**Initial LIGO Implementation**	**Comment**
Acquisition System Maximum Sample Rate [Sa/sec]	16384	16384	Effective shot noise frequency cutoff is well below $f_{Nyquist}$ (8192 Hz)
Active cavity mirrors, per interferometer	10	6	Addition of Signal Recycling Mirror and Output Mode Cleaner.
Active seismic isolation system servos – HEPI & ISI	11 chambers per interferometer; 18 DOF per chamber; total, 198 DOF	2 end chambers per interferometer, total, 12 DOF	Initial LIGO uses passive isolation with an external 6 DOF pre-isolator on end test masses; Advanced LIGO uses active multistage 6 DOF stabilization of each seismic isolation platform.
Axial and angular alignment & control, per interferometer plus beam steering	SUS DOF : 42 L DOF: 5 (θ, ϕ) DOF:12	SUS DOF: 36 L DOF: 4 (θ, ϕ) DOF: 10	Advanced LIGO has one additional cavity. Each actively controlled mirror requires 6 DOF control of suspension point plus (θ, ϕ, L) control of the bottom mirror.
Total Controlled DOFs	> 257	62	Relative comparison of servo loop number for maintaining resonance in the main cavities (PSL and IO not included)

Advanced LIGO will require monitoring and control of many more degrees of freedom (DOF) than exist in the initial LIGO design. The additional DOFs arise primarily from the active seismic isolation, with a smaller contribution from the move to multiple pendulum suspensions and the additional suspended mirror. Both the suspension and the seismic isolation systems will be realized digitally (except for the sensors and actuators) and the DAQ will need to capture a suitable number of the internal test points for diagnostics and state control (as is presently done for the initial LIGO digital suspension controllers).

Referring to Error! Reference source not found., the number of loops per interferometer that are required for Advanced LIGO is seen to be ~ 250. This is to be compared to ~ 60 for initial LIGO. The number of channels that the DAQ will accommodate from the interferometer channels for Advanced LIGO will reflect this 4X increase in “fast” channel number.

The table below presents approximate channel counts classified by sample bandwidth for Advanced LIGO and compares these to initial LIGO values. These represent the total volume of data that is generated by the data acquisition (DAQS) and the global diagnostics system (GDS); a significant fraction of these data are not permanently acquired. Nonetheless, the ability to acquire all available channels must be provided.

Table VIII *DAQ Acquisition Data Channel Count and Rates*[30]

System	Advanced LIGO Reference Design	Initial LIGO[31]	Comments
Channels, LHO + LLO Total (Total: 3 x IFO + 2 x PEM)	5464 + 3092 8556	1224 + 714 1938	Adv. LIGO will have ~4.5X greater number of channels.
Acquisition Rates, MB/s LHO + LLO Total	29.7 + 16.3 46	11.3 + 6.1 17.4	DAQS has ~3X total data acquisition.
Recorded Framed Data Rates, MB/s LHO + LLO Total	12.9 + 7.7 20.6	6.3 + 3.5 9.8	DAQS has ~2X total framed data recording rate.

Illustrations of the systems for data collection and frame creation is shown in Figure 1 and the real-time computing architecture and data flow from the sub-systems is shown in Figure 2.

Concept/Options

Driving features of the Advanced LIGO hardware design are the increase in channel count and the resulting increase in data rate, in terms of both the rate that must be available on-line, and the rate that is permanently archived.

The additional data channels required for the newer seismic isolation and compound suspension systems will require additional analog-to-digital converters distributed throughout the experimental hall Control and Data Systems (CDS) racks. Additional racks will be required and can be placed alongside the present CDS racks within the experimental halls. In those cases where there is

---

[30] These rates include are derived from subsystem interviews. Data rates quoted include a number of diagnostics channels and this rate is greater than the framed data rate which eventually is recorded for long term storage.

[31] LIGO I channel counts differ by site and interferometer; representative values are indicated.

interference with existing hardware, racks will need to be located further away, at places previously set aside for LIGO expansion. Additional cable harnesses for new channels will be accommodated within the existing cable trays.

The initial LIGO data acquisition processors do not have excess capacity sufficient to accommodate the increase in acquisition rate and will need to be upgraded. The upgrade will be a combination of updating the hardware technology from VME to modern PCI-express based ADC/DACs housed in dedicated boxes with PCI-express “mother boards” (called “I/O-Chassis”) and connected to Linux-based multicore processors via fiber-optic cables. The DAQ framebuilder and on-line mass storage systems will be upgraded to accommodate the greater data and frame size. The “framebuilder” will be separated into three computers: a collector, a network switch, and a frame writer. The Global Diagnostic System (GDS) will be upgraded to handle ~3X as much real time data as the initial LIGO GDS. Access to the data will be through a dedicated network data server, which will feed the diagnostic systems.

Further details can be found in the Subsystem Documentation.[32]

R&D Status/Development Issues

A change from VME to PCI-express was made in moving from initial to Advanced LIGO. We have moved from VxWorks to real-time Linux as the software basis. Only the legacy vacuum monitor system will remain in VME.

Acquisition systems have been designed and prototyped to determine performance of candidate hardware solutions. These systems were exercised at the 40 Meter Interferometer at Caltech, and the LASTI test bed at MIT, for both acquisition and control, and feedback going to the acquisition design team. Test systems at the observatories are being configured.

The Global Diagnostics System (GDS) hardware will be scaled for the greater processing and throughput requirements.

---

[32] Advanced LIGO Control and Data System Infrastructure Requirements, LIGO T070056; aLIGO Control and Data System Conceptual Design, T070059; and aLIGO CDS Data Acquisition System Preliminary Design, T080182

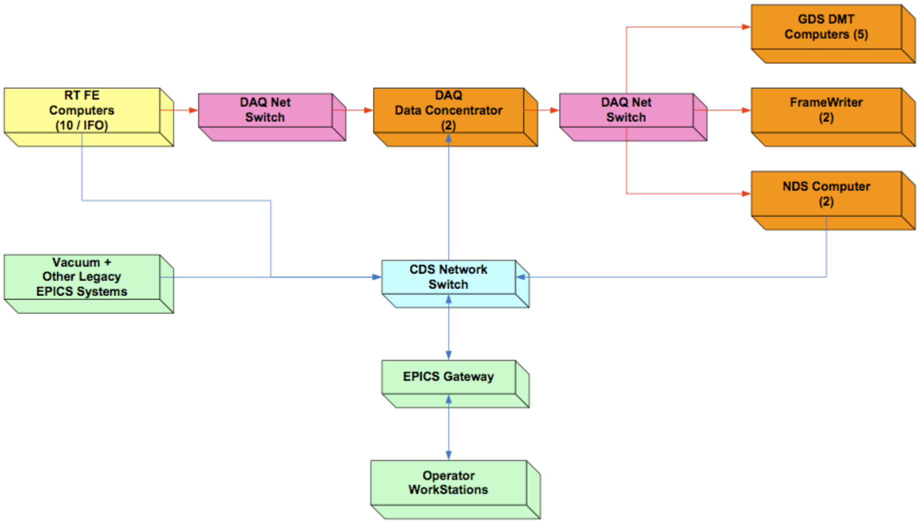

Figure 21 Data collection and frame building.

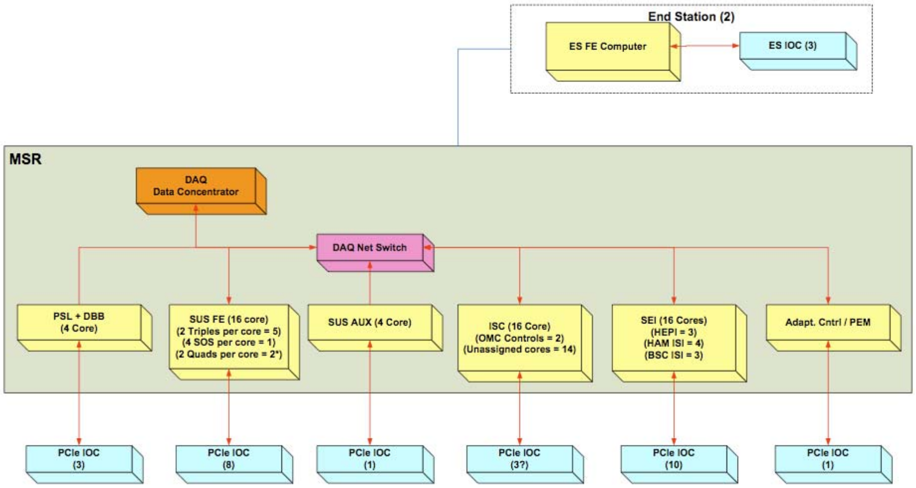

Figure 20 Real-time Computing architecture and data flow.

12. LIGO Data and Computing Subsystem (LDCS)

Overview

The computational load is increased over that for initial LIGO due to the broader frequency range of detector sensitivity. The enhanced frequency band in Advanced LIGO means that sources whose characteristic frequency of emission varies with time will be observable in the detection band for longer periods. Most of the search algorithms are based on frequency-domain matched filtering and thus the pipelines are compute-bound using the Fast Fourier Transform. Since the computational cost of the FFT grows as ~N logN with the number of data samples, longer duration waveforms require computational power that grows non-linearly with the length of the dataset. Data volume is also increased over that for initial LIGO because the interferometers are more complex and have a greater number of data acquisition channels that must be accommodated.

The impact on data analysis strategies of exploiting the increased instrumental sensitivity depends on the source type being considered and will be discussed below for those classes of search that drive the computational needs. Most presently envisioned search and analysis strategies involve spectral-domain analysis and optimal filtering using template filter banks calculated either from physics principles or parametric representations of phenomenological models. The interferometer strain output is the primary channel of interest for astrophysics. The other thousands of channels in Advanced LIGO are used to validate instrumental behavior. It is expected that relatively few channels (< 50) will also prove useful in producing improved estimates of GW strain. This would be done by removing instrumental cross-channel couplings, etc. either with linear regression techniques in the time domain (Kalman filtering) or in the spectral domain (cross-spectrum correlation). Based on Initial LIGO experience, signal conditioning is not expected to be a driver for LIGO Data and Computing System (LDCS) upgrades.

The Advanced LIGO Data and Computing Subsystem is a scaled up version of current systems with an important point of departure. By the time LDCS will be needed for Advanced LIGO science observations, disk-based mass storage technology is expected to have outpaced tape storage. Therefore, the current plan is to convert to a disk-based archival system that can grow and is sustainable throughout the period of Advanced LIGO science operations.

Functional Requirements

LIGO Laboratory and the LSC are active participants in a number of NSF-sponsored initiatives, and have already implemented a large-scale production data analysis grid, termed the LIGO Data Grid (LDG). The LDG scope includes not only LIGO Laboratory resources, but also LIGO Scientific Collaboration. Its goal has been to adopt and make widely available grid computing methods for the analysis of LIGO data. A significant portion of LIGO Laboratory's operations activities in software development has been dedicated to grid-enabling legacy software and pipelines primarily designed to run on targeted cluster resources.

The construction of Advanced LIGO offers an opportunity to start by integrating the latest grid middleware technology available at the time Advanced LIGO science operations begin. This proposal addresses the LIGO Laboratory Tier 1 components of LIGO data analysis and computing. It is assumed that these resources will be complemented by computing facilities elsewhere in the LSC (US/abroad). At appropriate times in the future, the Laboratory and the LSC will respond to opportunities for funding that will be needed in order to also enhance the Tier 2 facilities at the collaboration universities. Such enhancements will include an increase in the number of Tier 2 university centers serving the LIGO data analysis community.

For the classes of sources considered (transient "bursts", compact object inspirals, stochastic backgrounds, and continuous-wave sources), the continuous-wave and binary inspirals place the greatest demands on the computational requirements. Optimal searches for periodic sources with unknown EM counterparts (the so-called blind all-sky search) represent computational challenges that require O[10^{15} or more FLOPS] and will likely remain beyond the capacity of the collaboration to analyze using LIGO Tier 1 and Tier 2 resources[33]. Alternative techniques have been developed that lend themselves to a distributed grid-based deployment. Research in this area has been ongoing during initial LIGO and will continue. For example, during the 2005 Einstein World Year of Physics, the LIGO Scientific Collaboration, the University of California's BOINC Project, and the American Physical Society (APS) developed a project called Einstein@home[34] to develop a screensaver based on SETI@home technology to analyze LIGO data to look for continuous gravitational waves. By 1Q2006 Einstein@home had been downloaded onto over 200,000 home computers of all types. A recent posting[35] by the BOINC Project indicated that Einstein@home has some 222,000 users, and during a 24 hour period, contributed an astounding 156 TFLOPS of computational effort to the search for continuous gravitational waves.

The Tier 1 center installation for Advanced LIGO will not be specifically targeted to this class of search, since it is one that will need to be addressed on a much larger scale within the national Grid infrastructure.

Thus, the driver for establishing the computing requirements becomes the search for compact binary inspiral events. Advanced LIGO will search for compact object binary inspiral events using the same general technique that is employed in initial LIGO: a massive filter bank processing in parallel the same data stream using optimal filtering techniques in the frequency domain. The extension to lower frequencies of observation allowed by Advanced LIGO means that the duration of observation of the inspiral is significantly longer, leading to a concomitant increase in the computing power required. Counterbalancing this trend, however, are emergent theoretical improvements in techniques applying hierarchical divide-and-conquer methods to the search algorithms[36]. Improvements in search efficiency as high as 100X should be possible by optimal implementation of these techniques. While not yet demonstrated with actual data, it is reasonable to expect that algorithmic improvements will become available by the time of Advanced LIGO turn-on.

The number of distinct templates required in a search depends on many factors, but is dominated by the low-frequency cutoff of the instrument sensitivity (since compact binaries spend more orbital cycles at low frequencies) and the low-mass cutoff of the desired astrophysical search space (since low-mass systems inspiral more slowly, and hence spend more cycles in the LIGO band). Approximate scaling laws can be used, but in practice the precise number of templates depends on the specifics of the LIGO noise curve and the template-placement algorithm.

Table 9 provides a comparison between relative computational costs for inspiral searches down to $1M_\odot/1M_\odot$ binary systems between initial LIGO and Advanced LIGO. The length of the chirp sets the scale of fast-Fourier transforms (FFTs) that are required for

---

[33] c.f., Brady et al., PRD **57** (1998) 2101-2116 and PRD **61** (2000) 082001

[34] http://www.einsteinathome.org/

[35] http://www.boincstats.com/

[36] Dhurandhar et al., gr-qc/030101025, PRD **64** (2001) 042004

optimal filtering. FFT computational cost scales as ~N $\log_2 N$. On the other hand, the greater duration of the chirp provides more time to perform the longer calculation. Considered together, a ~7X increase in signal duration corresponds to a ~2X increase in computational cost. In addition, the lower frequency sensitivity of Advanced LIGO requires an additional ~2X greater number of templates. A detailed model of the computational cost indicates that ~10X greater capacity will be required to keep up with the data stream for LHO with two interferometers. If one were to go to lower mass systems, the computational costs will scale as $(M_{min})^{-8/3}$. However, current stellar evolution models predict that the minimum mass of a neutron star remnant is around $1M_\odot$. Extending the template bank below this limit may be of interest in order to cover all plausible sources, with a margin to allow for discoveries not predicted by current theories.

There is much room to improve computational methods to increase signal-to-noise for fixed computational cost. An 80% fitting factor would be enough for the first stage of a hierarchical search[37], which would go on to apply a restricted set of more accurate templates to candidate events in order to achieve a near-optimal signal-to-noise ratio. As a rough estimate, we assess a computational cost based on a flat search of a template bank twice as large as is required for the spinless case, or ~ 200,000 templates.

Table 9 *Initial LIGO and Advanced LIGO Analysis System Requirements for compact object binary inspiral detection using Wiener filtering techniques. $M=1M_\odot$ provides a reference to indicate how quantities change with M_{min}. Quantities were calculated using a spreadsheet model of the data flow for the inspiral detection analysis pipeline, and assume a 20 Hz start frequency for observation.*

Parameter	**Advanced LIGO (LHO, 2 IFOs) $1M_\odot / 1M_\odot$**	**Initial LIGO (LHO, 2 IFOs) $1M_\odot / 1M$**
Maximum template length, seconds	280 s	44 s
Maximum template length, Bytes	128 MB	16 MB
Number of templates	2.5×10^5	1.3×10^5
Calculation of templates, FLOPS	~ 4 GFLOPS	~ 2 GFLOPS
Wiener filtering analysis, FLOPS (flat search)	~ 5 TFLOPS	~ 0.4 TFLOPS

The total requirements for the Advanced LIGO Computing are given in **Table 10**. The demands are dominated by the BH-NS search type, leading to 760k templates. We assume Moore's law, a doubling of computing power for every 18 months, holds over the interval from the present (May 2007) to the time of purchase of the computing equipment (the last procurement of the Project, planned to be in FY2014).

In establishing these requirements, it is important to note that <u>we have assumed that the LIGO Laboratory via the Advanced LIGO Project will supply one-half of the computing power needed to exploit the data stream from Advanced LIGO</u>. It is assumed that the

---

[37] Phys.Rev. D67 (2003) 082004 Class.Quant.Grav. 19 (2002) 1507-1512

remaining computing resources will be supplied from the community in the US (with NSF support) and elsewhere (with other support).

***Table 10**: Projected LIGO Laboratory Computational Facilities for an early Advanced LIGO Science Run. 1AN is equal to 35LN assuming 18Month doubling.1LN is equal to 8.8GHz of Opteron-core performance.*

	Ligo Node (LN)	ALIGO Node (AN)
Inspiral	29550	845
Periodic	300	300
Burst	1000	29
Stochastic	379	11
TOTAL	31,229 (274THz CPU-core)	1185

Data Archival/Storage Upgrades

Advanced LIGO data rates are ~3X the initial LIGO rates. These are summarized in Table 11. Based on already demonstrated data compressibility, the volume of data that will be generated is ~600 TB per year. Allowing for 300% copies, Adv. LIGO archives will grow at the rate of 1.8 PB per year.

Table 11: Data volumes generated by the Advanced LIGO Reference Design

Data rate, per interferometer	10 MB/s	Annual Data Volume
Uncompressed rate for 3 interferometers	30 MB/s	947 TB
Rate for 3 interferometers, with 1.6X lossless compression[38]	19 MB/s	592 TB (single copy)
300% archive	57 MB/s	1.8 PB (3 copies)

Experience to date with LIGO I has shown that any data that are acquired are required to be archived indefinitely. We will use this same data model as a conservative estimate for Advanced LIGO requirements. In this model, all data are acquired and stored for several weeks on-line in a disk cache at the observatories that is shared with the CDS LAN to permit real-time data access from the control rooms. The data are also ingested into the RAID cluster data array capable of storing ~ 2.5 PB on the cluster disk array. This is sufficient to accommodate more than 1 year of on-site data at each observatory (for all interferometers). Data will be streamed over the WAN to the main archive at Caltech, where multiple copies will be made for backup. Reduced Data Sets (RDSs) in this tapeless model can be produced wherever it is convenient (for initial LIGO the full raw data are initially only accessible at the sites, where all RDSs are created). The experience in initial LIGO is that several stages of RDSs are desirable, each reducing the volume of data via channel selection and data downsampling by a factor ~10X. As shown in the table, accounting for a 300% backup of archived frame data, Advanced LIGO will require a ~ 1.8 PB/yr archive capacity.

---

[38] This factor represents actually achieved compressions for initial LIGO data.

Handling Greater DAQ Data Rates – Frame Data Archive Growth

The greater data rate is accommodated in the model described above.

Software Upgrades

Unified Authentication and Access

The importance of computer security and access control to computer resources is an evolving technology, continuing to provide greater protection to valuable computer resources as risk assessment dictates. Having the GLOBUS GSI infrastructure in common to all these tools assures that as the GLOBUS developers make security related changes such as bug fixes, and enhancements, they will become available to all of LIGO's data analysis environments in lock-step. The LDACS group will continue to track the evolution of access and authentication technologies, making the necessary changes and upgrades to the infrastructure to assure secure and reliable utilization of the computational resources available to the LIGO Laboratory and the LIGO Scientific Collaboration (LSC).

Reduced Data Sets (RDS) Frames

Archival RDS Frames

With Advanced LIGO, the preliminary estimates are that the number of channels will increase by more that a factor of four and that the recorded frame data rates will be ~3X relative to Initial LIGO. This implies that larger frame files will be needed if the time interval chunk size for each file is remain the same. The longer waveforms in Advanced LIGO suggests that there will be a benefit to moving to longer time intervals for the RDS frames used for analysis. To efficiently manage these larger data volumes, the underlying software used to generate the RDS frames will need to be improved upon in two areas to be able to keep up with data rates during science runs; larger processor address space in memory; better throughput from I/O through better processor speed and software efficiencies. It is also likely that the data sets associated with the raw frames and RDS will see the same gradual increase in size over time as the new Advanced LIGO interferometers are being tuned through improved understanding of their properties.

Larger, more complex frame files for Advanced LIGO will increase the importance of having thorough tools available for validating both raw and RDS frames as they are generated at the observatories and after being transferred over the internet or copied from tapes.

Custom User Frames

As user signal processing needs evolve, these and other more advanced algorithms may become important enhancements. In addition, the larger data sets typical of Advanced LIGO will require extending the address space of the processes associated with producing these custom user frames to support 64 bits to be able to work with larger files and datasets.

Data Location

Ongoing development of the data discovery, data location and data replication tools has identified these areas as candidates for integration into a more cohesive environment. To achieve this unification the extremely efficient algorithms for data discovery found in the LDAS diskCacheAPI have been made available as shared object libraries either for inclusion into existing scripts or as a basis for a new service. Grid Security Infrastructure is critical to this environment so the GLOBUS Toolkit will be an important component. With the newly wrapped GLOBUS for TCL/TK applications the option to provide this new service using TCL/TK has been proposed as a possible integration path for Advanced LIGO.

Concept/Options

The implementation of Advanced LIGO computational facilities (LDCS) is an expansion of initial LIGO LDAS. Large multi-core processor PC clusters will replace existing clusters. LAN network infrastructure in place for initial LIGO will be capable of expansion to accommodate 10 gigabit. The latest generation of Initial LIGO cluster technology supports very large volumes of hot-swappable RAID-configured disk arrays resident *within* the compute clusters, thereby providing data where they are needed – on the nodes. This has been shown to work successfully and we plan to capitalize on this paradigm, expanding it to accommodate a tapeless archive system for Advanced LIGO. The disk systems will support growth of both meta-databases and framed databases. Data servers will be upgraded to the enterprise class servers available at the time. Multiple servers may be clustered to provide greater throughput where this is required.

Existing tape libraries will be kept for large-scale backups, but will not be needed for providing deep look back production level science data access.

WAN access to LIGO data will be provided from each observatory and Caltech at 10 gigabit-over-Ethernet or greater bandwidth.

R&D Status/Development Issues

Most of the improvements in hardware performance that are discussed and identified above should become naturally available through the advance in technology that comes from market forces. LIGO will continue to meet its needs using commercial or commodity components.

Software evolution towards a grid-based paradigm will occur through continued participation by the Laboratory and the LSC in NSF-funded grid computing initiatives and in concert with the LSC Data Analysis Software Working Group.

Procurement of hardware for Advanced LIGO Data and Computing Systems will follow the model successfully implemented during the initial LIGO commissioning and science runs. Namely, procurement will be deferred until Advanced LIGO integration and test has sufficiently progressed to the point that Advanced LIGO science operations will be expected within 18 months of the start of the procurement process.

Up to this point, LIGO Laboratory will rely on its initial LIGO computing resources to support early Advanced LIGO engineering runs, integration, and test. Unlike the experience with initial LIGO, when *four* green-field computing facilities had to be implemented, for the Advanced LIGO construction phase, the Laboratory will be able to continue to provide to the collaboration the existing resources that will continue to be maintained and upgraded as needed as part of LIGO Laboratory operations.

An initial procurement plan will be developed by LIGO Laboratory in coordination with the LIGO Scientific Collaboration’s Data Analysis Working Group (DASWG) and the LSC Computing Committee which is comprised of representatives from all the Tier 1 and Tier 2 LSC computing facilities. The plan will be provided to NSF for comment and approval, typically as part of the regular Advanced LIGO Construction review cycle. Once LIGO has received approval for the plan, the procurement will proceed in a coordinated, phased manner to ensure that each LIGO Laboratory site is prepared to receive the hardware. This was executed several times during initial LIGO successfully.

The software development model has undergone a major change since the beginning of initial LIGO science operations. The creation of the collaboration-wide Data Analysis Software Working Group (DASWG) has consolidated most major software projects across the collaboration. The coordination of these activities takes place in the forum of DASWG weekly meetings. The tasks outlined above relating to upgrades to existing infrastructure in preparation for Advanced LIGO science operations will be formulated and presented for review within this working group. The activities will be organized, including as appropriate software experts from the broader collaboration. These activities will be carried out as part of the ongoing LIGO Laboratory operations program throughout the construction of Advanced LIGO.