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The Status of LIGO

Mark W. Coles

LIGO Project
California Institute of Technology
Pasadena, CA 91125

Abstract. Construction activities at the LIGO Observatories near Hanford, Washington and Livingston, Louisiana are complete. Installation of detector components and initial commissioning of detector sub-systems is now under way. The scope of the overall project is reviewed. The current status of the commissioning effort and future plans are outlined.

INTRODUCTION

Albert Einstein predicted the existence of gravitational waves - ripples in the fabric of space and time - as part of the general theory of relativity. The Laser Interferometer Gravitational-Wave Observatory (LIGO) is one of a new generation of detectors [1-3] based on suspended mass laser interferometry which is designed to detect these waves directly, opening up a new vantage point from which to study the universe. LIGO is a national research facility designed by a team of scientists and engineers from the California Institute of Technology and the Massachusetts Institute of Technology through support from the National Science Foundation. LIGO consists of two facilities - near Livingston, Louisiana and 3000 km away near Hanford, Washington.

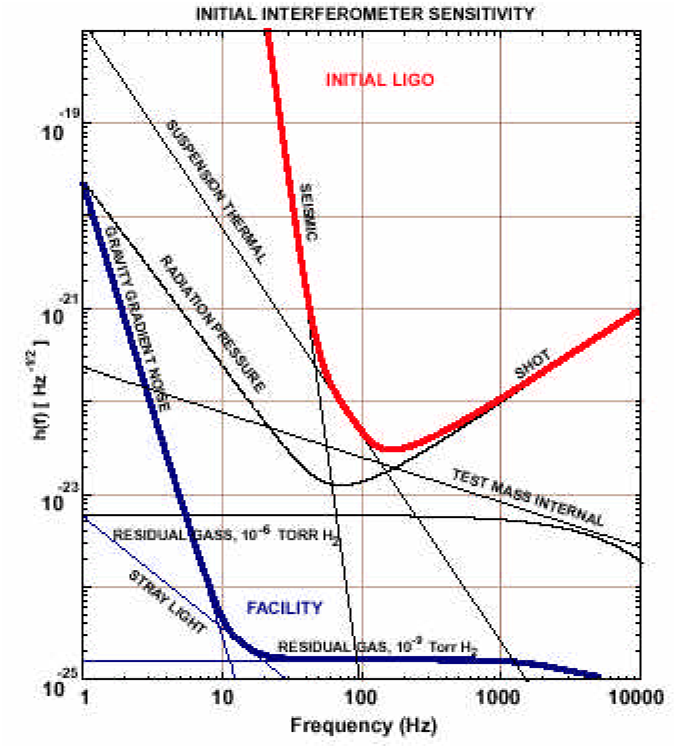
Each facility has an L-shaped laser interferometer with 4 km long arms. The two

FIGURE 1. Aerial photos of the LIGO Hanford Observatory, at left, and the LIGO Livingston Observatory, at right.

LIGO interferometers will operate in coincidence to reject noise sources that are local to a particular interferometer. To provide an additional confirmation of a genuine gravitational wave signal, a third interferometer, half as long as the other two, shares the vacuum space of the 4 km long interferometer at the Hanford site. The strain sensitivity of the interferometer increases linearly with length, consequently an important confirmation of direct detection of a gravitational wave will be the coincident observation of a half amplitude signal in the half length interferometer.

LIGO is designed to have two to three orders of magnitude improvement in detection sensitivity and band width relative to previous gravitational wave searches. The expected sensitivity of the initial LIGO interferometers is shown in figure 2. Sources of gravitational waves that can be plausibly detected with this sensitivity are: chirp signals from the coalescence of binary compact objects such as pairs of neutron stars and/or black holes, burst sources such as Type II supernova (provided that there is a sufficiently large quadrupole component to the collapse ejecta so that strong gravitational waves result), periodic signals resulting from the gravitational radiation given off by non-axisymmetric neutron stars with rotational frequencies *f* such that *2f* lies within the LIGO detection band (as is the case with many known pulsars), and stochastic signals from the early universe which can perhaps be detected by measuring the correlations in the noise background between two or more detectors.

FIGURE 2. Strain sensitivity of the LIGO interferometers. Seismic noise, thermal noise, and shot noise limit the anticipated initial LIGO sensitivity to the red line indicated.



OVERVIEW

Each LIGO interferometer is basically a Michelson interferometer whose end mirrors and beam splitter are freely suspended. The arms of the interferometer have an important modification; input test masses, together with the end test masses, form 4 km long Fabry-Perot cavities which are resonant at the laser frequency, effectively increasing the number of round trips that the light makes back in forth in each arm by the quality factor of the cavity, which is around 50. A second enhancement to the optical topology of the interferometer is the inclusion of a “recycling mirror”. In an ideal equal arm length Michelson interferometer, all of the light in the interferometer would destructively interfere in the direction of the interferometer output and would instead return from the beam splitter in the direction of the laser. The recycling mirror creates an optically resonant cavity between it and the two input test masses, causing the light reflecting towards the laser to remain in the interferometer and further boosting the total circulating laser power by about a factor of about 30. Principal parameters which characterize the overall design of LIGO are listed in Table 1.

TABLE 1. LIGO Design Parameters.

Arm length	4000 meters
Light source	Nd3+:YAG, λ=1.06μ
Input optical power to mode cleaner	6 watts
Power recycling factor	30
Fabry-Perot arm quality factor	50
Mass of suspended input and end mirrors	10.7 kg
Mirror diameter	25 cm
Mirror material	Fused silica
Mirror internal Q per mode	$>10^6$
Mirror internal adsorption at 1.06μ	~5 ppm
Mirror scattering loss (transmission + scattering)	50 ppm
Pendulum material	Steel wire, Q=200,000
Pendulum frequency	1 Hz
Seismic isolation at 100 Hz	> 110 dB

Each observatory site is laid out with a major building at the vertex of the interferometer and additional smaller buildings at the location of the end test masses 4 km away. At LHO, two additional buildings exist which surround the end test masses of the 2 km interferometer which shares vacuum space with the 4 km interferometer. Additional structures provide support infrastructure to the site such as storage, heating and cooling, fire protection, etc. The control room, support labs and shops, and meeting room space are located within the major building at the vertex. The high bay areas of the vertex and end stations at each observatory site have been constructed to accommodate the installation of an additional interferometer which could be added later without necessitating further civil construction.

The laser beam propagates in an evacuated beam tube running between the vertex and the mid and end stations. It is located above ground on a straight concrete slab. The beam tube is fabricated from 304L stainless steel having a wall thickness of only 3 mm. Prior to fabrication, the steel was specially processed to reduce the outgassing rate of hydrogen from the material to a level of less than 10^{-13} torr-liter/sec/cm^2. The tube is jacketed in thermal insulation so that it can be electrically heated for bake out to remove residual water from the clean inner surface of the tube. Bellows located every 130 feet accommodate thermal expansion of the tube. The beam tube is protected under pre-cast concrete arches placed in ten foot long segments over the entire length of the tube. Roughing pumps, turbo pumps, and liquid nitrogen cryo-pumps located at the mid and end stations (at LLO at the ends only) are used to maintain the vacuum within the beam tube. Additional pump-out ports located at 250 meter intervals along the beam tube provide additional access for diagnostic testing or the installation of additional capacity should it be required at some future point.

Large vacuum vessels house the suspended test masses of the interferometer, along with their associated vibration isolation suspension assemblies, as well as support optics for length and alignment sensing of the interferometer. Large gate valves are located between the vacuum vessels and the beam tube and between various chambers to allow them to be independently evacuated or vented without disturbing the beam tube vacuum. The vessels rest on thirty inches thick concrete floors which are isolated from the building footings to reduce ambient vibration levels in this area.

STATUS

Major construction activities, which began in 1995, are now complete at both observatory sites. At each location, laboratories and shops for support of site activities have been set up and are now functioning. Office space for resident staff and visitors and meeting areas also exist. High bay areas have been commissioned as "clean" work spaces. Control rooms have also been set up and are evolving as the detector installation and commissioning work progresses.

All vacuum vessels and beam tubes have been installed and accepted at both sites, along with associated pumps, vacuum measurement apparatus, and purge air systems. Bake out of the beam tube is complete at LHO and in progress at LLO. During bake out, an evacuated 2 km section of the beam tube is raised in temperature to 168 C for approximately 3 weeks by ohmic heating, as 2000 amps DC flows through the tube wall. Following cool down to ambient, internal pressures of approximately 1 nano-torr are obtained within the beam tube. The residual gas is dominated by hydrogen, while the partial pressure of water is approximately 10^{-13} torr, a million-fold reduction relative to the partial pressure of water observed prior to baking. It is expected that the bake out activity at LLO will be complete in May 2000.

The light source used by LIGO is a nominally 10 Watt single mode Nd:YAG laser, built by Light Wave Electronics. It is stabilized in frequency, intensity, and angle on an optical table before insertion into the interferometer vacuum. Collectively, the light source and associated optics and servo systems are called the "pre-stabilized laser" or PSL. Initial frequency stabilization is accomplished by locking the laser frequency to a thermally stabilized reference cavity. A triangular "pre-mode cleaner" located on the optical table acts as a spatial filter to reduce the frequency and angular noise of the light by about two orders of magnitude before it enters the mode cleaner. The pre-mode cleaner optical path length can be servo controlled via a PZT which displaces one of the three mirrors to allow locking of the pre-mode cleaner to the thermally stabilized frequency reference cavity. Before leaving the PSL table, the light is mode matched to the in-vacuum 15 meter triangular mode cleaner and modulated at three different frequencies used to lock the various interferometer cavities.

Initial construction and testing of the PSL was used to demonstrate the laser performance and to validate the design of the frequency and intensity stabilization servos and the pre-mode cleaner servo. At LHO, the PSL has been installed and operating for approximately one year. Frequency stabilization and intensity control have been demonstrated to be extremely reliable over this initial operating period, with locking periods of many hundreds of hours. At LLO, the PSL has been installed only recently. Similar acceptance and commissioning tests are now underway.

In-vacuum mirrors are each supported from a single loop wire pendulum clamped to a suspension "tower" (see figure 3). The wire contacts the mirror around its circumference at just above its mid-point, giving overall stability to the assembly. The optic is initially balanced and aligned normal to the design beam orientation within the vacuum chamber. Small magnets glued at four points around the circumference of the mirror and at one point on the circumferential surface can be independently pushed or pulled by small electromagnet coils mounted on the suspension tower adjacent to the optic, allowing the angular orientation and the displacement of the mirror to be externally controlled. Position sensing for control and damping is supplied by LED's and shadow sensors within the electromagnet coil assembly. Additional feedback from length and alignment sensing servos can be used to introduce frequency dependent actuation of the mirror.

FIGURE 3. Installation of a suspension tower assembly within the interferometer vacuum.

The mirrors are "super polished" fused silica with multi-layer dielectric coatings. LIGO optics are fabricated from specially selected glass to minimize absorption at 1.06 microns in order to reduce thermal distortions. The glass also exhibits high Q values (greater than one million) for body resonances in order to limit thermal noise contributions to the interferometer's performance. Precision measurements made at CSIRO and in LIGO's own metrology lab confirm that the surfaces of the mirrors are figured to an RMS tolerance of less than $\lambda/800$. LIGO's large optics have a approximately 10.7 kg mass, with the multi-layer dielectric coating extending over the entire 25 mm diameter surface. Large optics comprise the recycling mirror, end and input test masses, one of the mode matching mirrors used to match the recycling cavity to the output of the mode cleaner, and the beam splitter. Smaller optics used for guiding the input and output beams have approximately 130 mm diameters.

Mirror substrates for all three interferometers have been polished and coated. Procedures for vacuum preparation and assembly into suspension towers have been developed and are now being used to build up the suspension assemblies at each site. Installation of optics towers into the interferometer vacuum is underway at LHO. The mode cleaner components, recycling mirror, and end mirrors are now installed, with additional installation underway. At LLO, installation of suspended optics will begin in Fall, 1999.

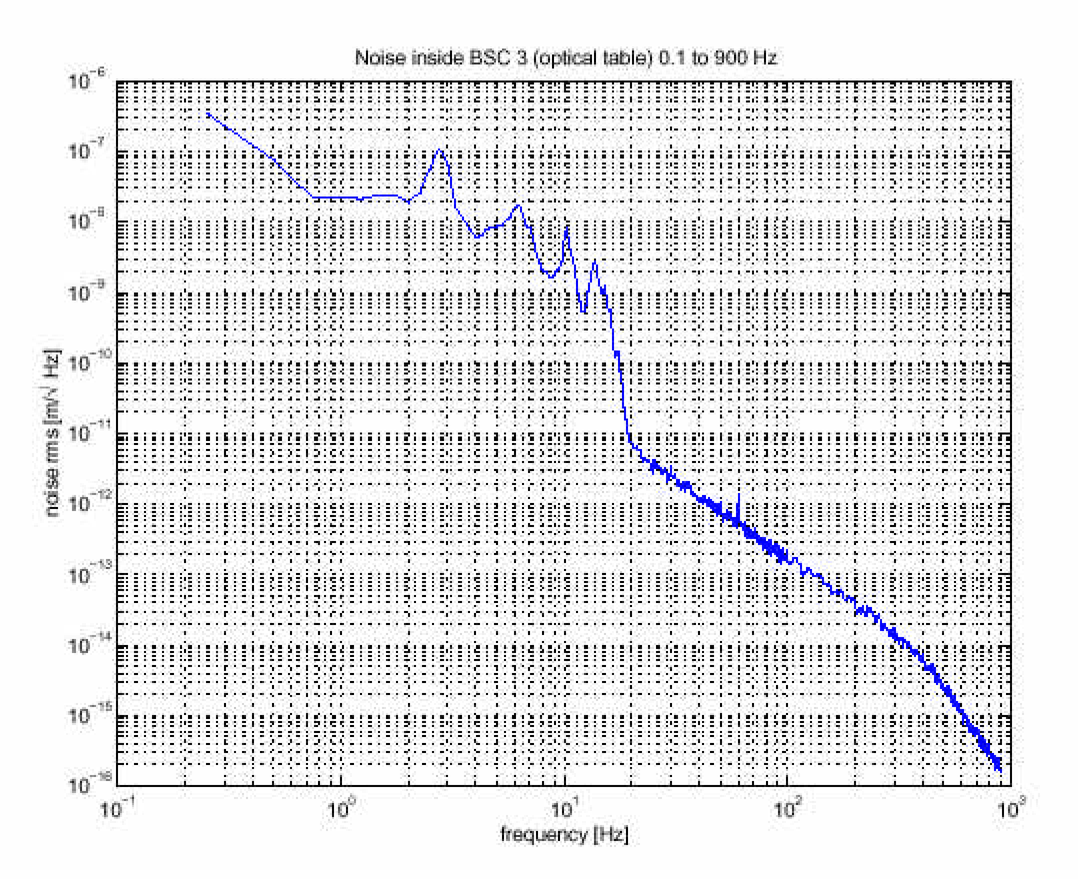
The suspension towers are attached to seismic isolation platforms which passively isolate the suspended optics from ambient vibration present in the concrete slab supporting the vacuum chambers. The seismic support structures consist of three layers (for support optics) or four layers (for the test masses, beam splitter, and recycling mirror) of steel interleaved with layers of helical damped springs . The spring design utilizes an internal viscous layer, constrained between the the helical spring housing and a row of metal slugs along each spring’s axis, to damp the spring’s resonances. This limits the magnitude of the ambient vibration within the seismic isolation platform in the 1-10 Hz band (the frequency region over which the lowest order structural resonances occur) while still providing good attenuation above 10 Hz.

Seismic installation work is underway at both sites and should complete for all three interferometers in 2000. Measurements of the in-vacuum vibration transfer functions of the installed large optic seismic assemblies have been made and agree well with engineering predictions of performance (see figure 4).

Input optics have been installed on the seismic isolation assemblies at LHO and commissioning of the 15 meter mode cleaner is now underway there. This is the first step in commissioning the interferometer which integrates the PSL controls with the suspension servo controls and the length and alignment sensing. Initial alignment and preliminary locking of the cavity were achieved in air, followed by more detailed studies that are now being conducted in vacuum.

Precision sensing of the alignment is accomplished using wave front sensing. Tilts of the mirrors cause a slight admixture of (0,1) or (1,0) modes to propagate in the mode cleaner along with the TEM00 mode. The amplitudes of these modes are used as error signals to control the orientation of the mirrors and maintain angular alignment. The commissioning of the mode cleaner is providing the opportunity to evaluate this system and validate that it is functioning properly. Similar work will be undertaken at LLO early in 2000.

FIGURE 4. In-vacuum measurement of the vertical displacement noise measured on a four layer seismic isolation system at LLO. The data above about 20 Hz is limited by the noise floor of the measurement instrumentation.



Following completion of the mode cleaner studies, a "long arm" test is planned that will optically couple the mode cleaner to each of the 2 km arms independently. This provides an additional level of system integration of the control system and provides an extremely sensitive test of the angular alignment control system over a 2 km baseline. This work will take place during the latter half of 1999.

In parallel with the installation of the optics and seismic systems, the data acquisition and control system installation work is also well under way. Local computing networks to handle interferometer data acquisition and control, general computing, on-site on-line data analysis, and global diagnostic monitoring have been designed. The hardware to implement these systems is now being installed at each site. The software which monitors and controls the vacuum system and PSL has been installed at both sites and environmental monitoring (of ground vibration, acoustics, the electromagnetic spectrum, and weather parameters) has also been installed. The suspension control hardware and software have been completely installed at LHO in preparation for the 2 km arm tests while installation work is now underway at LLO. Installation of the length and alignment sensing and control system for the mode cleaner and the end test mass suspensions is also complete for the 2 km interferometer at LHO. Installation activity is just beginning at LLO.

The LIGO Data Analysis System (LDAS) will provide the capability to perform initial analysis of interferometer data on-site. The design of the software and hardware configuration for this system is now complete. It makes use of a layered modular design that can easily accommodate extensions and revisions to the analysis flow based on operating experience. The system, when installed, will include the capability to distribute data to local and remote users for further analysis and will include an off-line system dedicated to archiving data and distributing it for computationally intensive re-analysis of the gravitational wave channel. The raw data (as much as 6 MBytes/sec, which includes all of the interferometer diagnostic data and environmental monitoring data as well as the gravitational wave channel) is ordered into “frames”. These are a unified data structure which groups extensible sets of time series data into one second chunks for random access. The frame format will provide a standardized mechanism for communicating data within the LIGO scientific collaboration and between gravitational wave groups that adopt this format.

A major effort to construct a simulation and modelling software program is also underway. So far, an overall "end-to-end" model structure has been completed and released so that individual model elements can be built up and linked to the program. At present, a time domain model of the PSL has been completed and validation of the model using the installed PSL hardware at LHO is in progress. A simple model of the mechanical suspension system for the optics has also been developed and implemented. Detailed models of the seismic isolation system performance using the measured transfer functions and characterizations of the ambient seismic background are now being developed and will be available shortly. The servo control models which digitally represent the various LIGO control loops are now being documented and implemented. The long arm tests planned for this fall will provide a means to test and validate these models.

SCHEDULE

Tests of the LHO PSL and mode cleaner will continue through the fall of 1999 with "first light" down the interferometer arms planned for late in the year. Additional installation and commissioning activities at both sites will continue through 2000. Because of the limited staff available, many installation and commissioning tasks are performed sequentially from one interferometer to the next, making use of many of the same staff to repeat the installation and commissioning process. Thus the LHO 2km interferometer will be completed first, followed by the LLO 4km interferometer, and then the LHO 4km interferometer. On-going engineering studies of increasing complexity are planned as the installation, integration, and commissioning activities at LHO and LLO continue. The 2 km is being used to test essential features of the interferometer design while the LLO 4 km interferometer will follow these initial studies with detailed characterizations of the interferometer system. The LHO 4 km interferometer commissioning is expected to benefit significantly from this prior work.

Operation for engineering studies and evaluation will involve first one operating interferometer and then the simultaneous operation of two and then three interferometers for detailed studies of their individual and correlated performance.

The first scientific data runs involving all three interferometers operating in coincidence are planned in 2002.

ACKNOWLEDGMENTS

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