

The Status of LIGO Installation and Commissioning (LIGO-000026-00-W)

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Abstract

LIGO is engaged in installation and commissioning of three suspended-mass interferometers at observatory sites in Hanford and Livingston. We are commissioning the first instance of any subsystem installed, prior to completion of the entire detector, so we may apply lessons learned to later installations. We have installed all seismic-isolation stacks, installed lasers and input optics at both observatories and we have operated both of the 2-km Fabry-Perot cavities at Hanford, with lock times up to 10 hrs.

General Description

The LIGO observatories in Hanford, Washington and Livingston, Louisiana comprise the US effort to detect gravitational waves in the frequency band from a few hertz to several kilohertz[1]. LIGO is funded by the U.S. National Science Foundation (NSF) through cooperative agreement PHY-9210038. The LIGO Laboratory has constructed and now operates the observatories and supporting facilities on the Caltech and MIT campuses. The LIGO Science Collaboration (LSC) conducts the scientific program for LIGO in coordination with the LIGO Laboratory. Currently the LSC consists of more than three hundred scientists and engineers worldwide. This review describes the work of my many colleagues within the Laboratory and the Collaboration.

The observatory facilities for LIGO have been completed and these are shown in Figure 1. The Hanford Observatory is located on the U.S. Department of Energy Hanford Site, in arid, shrub-steppe habitat approximately 25-30 km from the cities of Richland, Kennewick and Pasco. The Livingston Observatory is located in forested land a similar distance from Baton Rouge. Each observatory has two perpendicular arms, 4 km long, spanned by 1.2-m diameter stainless steel vacuum tubing. Vacuum chambers, containing the vibration-isolation stacks and suspended mirrors for the 4-km interferometers, are

within buildings at the corner and ends of the arms. At Hanford, an additional 2-km interferometer shares the same vacuum tubing, with its end mirrors in buildings at the midpoints of the arms. The observatories were oriented relative to each other to optimize detection of a common wave polarization. The facilities were designed to accommodate the most sensitive future detectors imaginable, allowing for burst detectors operating well below 10^{-24} in strain.

The initial interferometer[1] evolved from design principles successfully demonstrated with respect to minimizing displacement noise[2] and phase noise[3], and techniques for controlling laser frequency[4,5], length[6,7] and alignment[8,9] in interferometer test beds. It uses a power-recycled, Fabry-Perot-Michelson configuration[6], shown schematically in Figure 2. A beam splitter divides laser light equally between the two arms. A 4-km Fabry-Perot cavity is formed in each arm by a mirror in the corner station and a mirror in the end- (or mid-) station. These mirrors are suspended from a modular cage using a single loop of fine wire, allowing the mirrors to respond freely to gravitational waves. Magnets glued to the mirrors and coils attached to the cage are used for fine actuation of the mirrors. The suspension structures are attached to passive seismic isolation stacks[10] inside the vacuum. Load forces are brought out of the vacuum systems through support rods and bellows to an actuation system for coarse positioning and alignment. The interferometer is operated in a balanced state, with light resonating in the arms and then returning toward the laser source after recombining at the beam splitter, so the other port is in relative darkness. A photodetector in this “dark port” detects any imbalance of the interferometer. Feedback holds the interferometer in balance at all times and provides a measure of gravitational waves and perturbations to the interferometer. The light returning toward the laser is recycled[11] by a recycling mirror to increase light in the interferometer. The interferometer sensitivity[12] will be limited by the seismic background below 35 Hz and by a thermal noise background[13] from 35 Hz to 150 Hz. Above 150 Hz the noise is expected to increase linearly with frequency due to shot noise[14]. The noise equivalent strain at 150 Hz is approximately 3×10^{-22} .

Results

The LIGO vacuum system is capable of providing vacuum to 10^{-9} Torr in the beam tubes, principally due to hydrogen outgassing, with much lower partial pressures of gases with higher polarizabilities. This required an extended bake-out of the completed vacuum and certification that leaks in the 50 km of weld seams at each site were negligible. Each 2-km-long tube segment was wrapped in a 15-cm thick layer of fiberglass insulation and baked at temperatures of 150-160 C for 3-4 weeks. Large magnet power supplies, on loan from Fermi National Accelerator Laboratory, fed approximately 1800 amps of current through the length of the tubing to provide heat, while cryopumps along the length of the tubing removed evolved gases. Post-bake accumulation measurements certified that H_2 outgassing was below 10^{-13} torr-liters/cm²/s, while water vapor and other species outgassed at rates between 10^{-17} and 10^{-20} torr-liters/cm²/s.

As of July 2000 installation was ongoing on all three interferometers and commissioning was well under way. We have adopted the strategy of pushing for the earliest possible date for installation of at least one example of each subsystem and then immediately beginning to commission that subsystem, so lessons learned could be more readily incorporated into later installations. We began this process with the 2-km interferometer at Hanford, then continued with installation of the 4-km Livingston interferometer, followed by the Hanford 4-km interferometer. Resident staff at the observatories worked alongside the developers of the subsystems to optimize the technology transfer.

A pre-stabilized laser system (PSL) and the input optics (IOO) supply conditioned laser light to the interferometer. The PSL (Figure 3) incorporates a 10-W, diode-pumped, Nd:YAG laser[15], developed for LIGO by Lightwave Electronics. A sample of light from this laser is frequency shifted and locked to a reference cavity using the standard RF reflection locking technique [4]. The main light beam is passed through a small mode cleaning cavity (pre-mode cleaner) to improve its power stability and beam shape and then enters the input optics for further filtering and beam conditioning. The laser system has inputs for active power stabilization and frequency correction. At very low frequencies, the temperature of the reference cavity may be adjusted for common-mode compensation of the Earth tide. PSL is phase modulated for locking to subsequent

cavities and then injected into the main vacuum system. A triangular mode-cleaning cavity[16], formed by suspended mirrors on vibration-isolated tables, is used in transmission to further stabilize the frequency, amplitude and mode quality of the light. This mode cleaner has a length of 12-15 m, tuned to the RF modulation sidebands that are transmitted with the carrier light. The PSL and IOO systems have been completed for the 2-km interferometer at Hanford and the 4-km interferometer at Livingston. By June 2000 a PSL frequency stability of $0.02 \text{ Hz}/(\text{Hz})^{1/2}$ had been achieved at frequencies above 1 kHz. Acoustic excitation of the PSL has been observed at lower frequencies and efforts to minimize acoustic coupling are in progress.

The seismic isolation stacks for LIGO are comprised of several layers of massive leg elements separated by layers of coil springs with internal, constrained layers of damping material. The optical table supporting the suspension structures uses an internal space-frame structure to maintain high stiffness with low mass. Transfer function measurements in air have verified good agreement with engineering models describing the stack resonances and more recent in-vacuo measurements have verified isolation factors of 10^6 near 35 Hz. All in-vacuo components of the isolation stacks and the accompanying coarse actuation systems have been installed. Additionally the fine actuators, to be used for removing differential Earth tides and the microseism, have been installed and characterized on the Hanford 2-km system.

The first laser light was sent down one of the evacuated arms for the Hanford 2-km interferometer in late November 1999. The initial shots down each arm landed within 25 cm of the mirror center, verifying the accuracy of the alignment procedures, from initial site survey through final optical alignment. Residual voice coil actuation of the mirrors was sufficient to bring the arms into full alignment.

Each of the 2-km Fabry-Perot arms at Hanford were locked using a single, temporary, analog servo and measurements were made to characterize environmental influences and to verify the optical performance predicted from laboratory measurements. A 20-hr engineering data run was taken during the first week of April 2000. The environmental influences are illustrated in Figure 4 by data from this “one-arm” configuration. The

figure shows one-second averages of the correction signal holding the arm in resonance with the input light from the IOO system. At very low frequencies, one can see the effects of Earth tide and some residual temperature drift of the laser frequency. Tidal effects were unusually small in this data. On more typical days, the tide drives the system out of lock in approximately one hour with no tidal compensation. The higher frequency modulation, with a period of approximately 8 seconds, is the microseism, which is relatively stable in frequency but varies in amplitude as storms cross the ocean.

Our experience installing and commissioning the 2-km interferometer has verified that many of our designs and procedures were well matched to our task. The alignment procedures worked and the actuators had sufficient range to deal with environmental disturbances, which were within expectations. The optics performed as expected in their first long-baseline tests and we were able to fine tune our methods for aligning and mode-matching. We were able to tune up the controls for the PSL and IOO systems and we observed an improvement in alignment stability for the 2-km cavity using wave-front sensors. Mechanical Q's of mirrors have typically been measured to be within the expected range of 10^6 to 10^7 , although some low Q values were obtained which require further attention. We have identified two areas where more work is needed. The problem of acoustic sensitivity of the PSL was mentioned above. The shadow-sensors, used for local damping of pendulum, pitch and yaw modes of suspended mirrors, proved to be more susceptible to interference from scattered light than anticipated. These issues are being addressed by changes incorporated into subsequent interferometers.

We were preparing to lock the power recycled Michelson interferometer comprised of the mirrors in the corner station at Hanford by summer 2000, using the fully-digital length control system developed for the complete interferometer. At Livingston, the PSL and IOO systems were in place and the main interferometer optics were being installed by this time. Attempts to lock the entire Hanford 2-km interferometer were planned for autumn of 2000. Joint engineering runs using the Hanford 2-km and Livingston 4-km interferometers are scheduled for 2001 as installation of the Hanford 4-km machine is completed. Science runs are expected to commence in 2002.

Note Added in Proof

The Hanford 2-km, power-recycled, Fabry-Perot Michelson interferometer was locked for the first time by October, 2000 and characterization of lock acquisition and robustness were begun. Five days of data were taken in a recombined mode, with no power recycling, during a one-week engineering run in November. The duty cycle for data obtained in this configuration was approximately 95%, and 2 terabytes of interferometer, system and environmental data were recorded. Loss of lock was principally due to the Earth tide, in good agreement with a standard tidal model.

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Figure Captions:

Figure 1. Photos of the Hanford (left) and Livingston (right) observatories, with map indicating locations.

Figure 2: A schematic of the initial LIGO interferometer.

Figure 3: A schematic of the pre-stabilized laser source.

Figure 4: Data from a single 2-km Fabry-Perot arm.







