

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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**Annual Report of the
LIGO Caltech 40 Meter Prototype
Interferometer Laboratory
for FY07**

This is an internal working note
of the LIGO Laboratory.

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Major Campus Research Facilities

LIGO Laboratory maintains several research facilities on the Caltech and MIT campuses, in addition to numerous R&D labs and computing facilities. The research facilities, described below, are the 40-meter prototype interferometer on the Caltech campus, the Thermal Noise Interferometer (TNI) at Caltech, and the LIGO Advanced System Test Interferometer (LASTI) facility at MIT. These unique facilities have served multiple purposes in past years, and we plan on continuing to make effective use of them throughout the upcoming Operations period.

Broadly, these facilities are used for (a) end-to-end development, prototyping and testing of new technologies for LIGO and Advanced LIGO *before* final design decisions or installation at the observatory sites; (b) research in advanced interferometry and precision measurement science; (c) training of the next generation of gravitational-wave instrument scientists as well as outreach and K-12 learning.

These facilities are unique in the world, and in many cases are the only places where new technologies in advanced interferometry can be developed and tested. They are currently pursuing a rather long and broad range of research goals, described below, and we intend to ensure that these facilities will continue to be used effectively and productively.

40-Meter Facility

LIGO operates a 40-meter prototype interferometer (1/100th the length of the actual observatories) on the Caltech campus. The mission has been to validate new technologies and techniques later implemented in full size gravitational-wave interferometers. It is a fully instrumented interferometer with an initial LIGO pre-stabilized laser, and mirrors suspended on single pendulums forming a dual-recycled Michelson interferometer with Fabry-Perot arms (the Advanced LIGO interferometer topology).

The present and future mission of the 40-meter interferometer is for prototyping the optical configuration and controls of Advanced LIGO and enhanced LIGO, and for training students and new instrument scientists. Wherever possible, the hardware and software have been designed to be as similar as is feasible to what is planned for the observatories.



Figure 1: A view down the south arm of the LIGO Caltech 40-meter prototype interferometer.

40-Meter Accomplishments during the Current Cooperative Agreement

The 40-meter Laboratory has been rebuilt to fully develop and test the optical configuration and control scheme for Advanced LIGO. The optical configuration of the 40-meter interferometer mimics the one planned for Advanced LIGO: high finesse Fabry-Perot arms (1200, to be compared with the initial LIGO arm finesse of 200); correspondingly reduced gain in the power recycling cavity (to reduce the thermal load on the transmissive optics in the presence of higher input laser power); a mirror at the asymmetric port of the beam splitter to resonantly extract the gravitational-wave sidebands from the high-finesse arm cavities and thereby increase the detection bandwidth; and a detuning of the signal extraction cavity to enhance sensitivity at a strategically-chosen range of frequencies. This technique is often called resonant sideband extraction (RSE). The more complex optical configuration makes it significantly more difficult to control than for the initial LIGO interferometer. This makes it essential to develop a reliable scheme to bring the interferometer from an uncontrolled state into one which is optimized for gravitational-wave detection.

We completed the construction phase of the upgrade of the 40-meter Laboratory prototype in 2005. Many important contributions were made by visitors as well as the LIGO Laboratory staff.

In fall of 2005, we commissioned and tuned the many interferometric length control systems which are needed to optimize the sensitivity of the interferometer. The goal was to find signals which are robust against variations in the remaining uncontrolled length degrees of freedom, so as to bring those

degrees of freedom under control in a deterministic way. By the end of October 2005, we were able to bring the interferometer into full lock in the Advanced LIGO configuration, via multiple paths of varying complexity and robustness against environmental and technical noise. We made use of both RF and DC-derived length-sensing signals and analog and digital Common Mode servos, and exploited the power and flexibility of our digital control system. We automated and optimized the alignment and lock acquisition procedures to make them routine.

With the interferometer configured in the nominal Advanced LIGO configuration we measured the optical response of the detector. It was in excellent agreement with predictions based on the theory developed by Buonanno and Chen and with numerical simulations. The optical response is dominated by a high frequency (~ 4 kHz) RSE peak and a low frequency (~ 40 Hz) optical spring resonance, both due to the detuned signal cavity. The noise spectrum, however, was dominated by technical noise sources so that the expected quantum-limited sensing noise spectrum was not observed. These results are published in Physics Review D74, 022001 (2006).

We have continued efforts to develop robust, deterministic lock acquisition strategies, using the full power and flexibility of the digital controls. We have measured the calibrated noise spectrum (instrumental noise dominates at all interesting frequencies), and are developing a detailed noise budget to aid in identification and reduction of noise. Much effort has gone into making improvements in the following areas: RF distribution, RF photodiodes, optical levers, suspension damping systems, suspension coil drivers, and the laser frequency and amplitude stabilization. Most importantly, tuning of the mirror alignments, RF demodulation phases, and servo filters are now automated and routine, resulting in a much easier to work with system.

The main focus of work in the past year has been in the development and commissioning of a DC readout system. The Advanced LIGO optical design calls for a detuned signal cavity, RF sidebands will be unbalanced at all exit ports. This greatly increases the already serious problem of using noisy RF sidebands as the local oscillator for extracting the gravitational-wave signal. Therefore, the Advanced LIGO design will employ a DC (homodyne) detection scheme, in which a controlled amount of filtered carrier light is allowed to exit the asymmetric port of the interferometer to serve as a less noisy local oscillator for gravitational-wave detection at DC. The RF sidebands are removed by an output mode cleaner. As a bonus, the output mode cleaner prevents "junk" light in the power recycling cavity from reaching the photo detector.

In the spring and summer of 2006, the DC readout beam line was designed, built, and aligned (with the help of SURF students); it was installed in the vacuum system (at the asymmetric port of the interferometer) in September 2006. The in-vacuum beam line at the asymmetric port (after the signal recycling mirror)

consists of a pair of PZT¹-actuated tip-tilt steering mirrors, a mode-matching telescope, a monolithic output mode cleaner, and a pair of in-vacuum DC photodiodes. Length and alignment control servos and monitoring are performed by a new digital control system which is a prototype of the system envisioned for Advanced LIGO, based on PCI-X² rather than VME and using a new star network topology. The beam line was aligned, and in-air diagnostics were implemented. The new control electronics and software were merged with the old and commissioned rapidly; the beam was dither-aligned into the output mode cleaner, which was dither-locked, all with digital control signals. Experiments with the new system began in October, using the enhanced LIGO configuration (no signal recycling). The output mode cleaner clearly reduced the “junk” light and RF sidebands, and a clean DC readout signal was observed. This was then used to sense and control the differential arm length degree of freedom (used for gravitational-wave readout at the observatories). The DC readout system was observed to reduce the overall noise in the gravitational-wave channel (in comparison with RF readout), above 600 Hz; a displacement sensitivity of 2×10^{-18} m/rHz was achieved at approximately 1 kHz. We are nearing completion of a broad range of measurements of noise couplings with DC and RF readout (laser frequency noise, intensity noise, oscillator noise, etc); it appears that the expected benefits of DC readout are being realized in practice. This work will form the basis of graduate student Rob Ward's thesis.

Beginning in spring 2006, Keisuke Goda from MIT has been at the 40-meter lab, working with staff scientist Osamu Miyakawa and Prof. Shally Sharaf of RIT on the implementation of a vacuum squeezing apparatus for injection into the interferometer. They assembled an in-air beam line making use of a 2 W pick-off beam from our main laser, feeding a second-harmonic generator (SHG) and an optical parametric oscillator (OPO). The injection into the interferometer required some in-vacuum optics, which were installed along with the DC readout beam line in September 2006. By early spring 2007, they succeeded in constructing an optical system capable of delivering approximately 5 dB of noise-locked squeezed optical vacuum into the asymmetric port of the signal-recycled Michelson interferometer. A 3.1 dB or 43 percent increase in displacement sensitivity was observed in a broad band of frequencies where the interferometer output was limited by photon shot noise. Since this demonstration was carried out in a prototype interferometer with suspended mirrors, and a readout and control system similar to those used in existing gravitational-wave detectors, it is a major step toward implementing squeezing enhancements on long baseline gravitational-wave interferometers. This work will soon be submitted to the journal “Nature.”

The 40-meter team continues to work closely with the Advanced LIGO Interferometer Sensing and Control group, the enhanced LIGO group, the LIGO e2e simulation group, and LIGO Laboratory engineers and management. Graduate students, REU (Research Experience for Undergraduates) summer

¹ Lead Zirconate Titanate (PZT) - nanopositioning products.

² PCI-X (Peripheral Component Interconnect Extended) is a computer bus and expansion card standard.

students, visiting students, and visiting scientists have contributed to all aspects of the project over the last seven years. In particular, REU students have made major contributions to design and implementation of the DC readout and vacuum squeezing systems, as well as many other aspects of the interferometer. We will continue to involve students and visitors with all aspects of the project and its goals. The laboratory continues to be a popular tour site for local students, journalists, scientific visitors, and dignitaries.

40-Meter Proposed Work

The 40-meter Laboratory will continue as a valuable R&D, prototyping and training facility during the construction and commissioning of Advanced LIGO in addition to playing a major role in the development of more advanced techniques in precision interferometry well into the future.

This work will continue under the current cooperative agreement for LIGO Operations and will then continue during the period of performance for continuing operations as needed.

One of the key lessons learned at the 40-meter about the control scheme for Advanced LIGO is the difficulty in working with RF frequencies above 100 MHz. RF distribution, photodiode preamp tuning, demodulation phase stability, and the inability to work with small area segmented RF photodiodes for wavefront sensing, all make the RF sensing system needlessly problematic. It was also realized that the large Michelson length asymmetry was not necessary to couple the RF sidebands to the dark port and that an effective sensing matrix could be obtained with lower frequency sidebands. Further, one can arrange an optical configuration that allows for continuous tuning of the signal cavity over a (potentially) wide range of detunings, with no hardware modifications. Another important realization was the difficulty in achieving very low losses and thus high finesse in the long-baseline arm cavities, due to anomalous scattering. The result is lossy arm cavities and an under coupled power recycling cavity, adversely affecting the length sensing system.

It was therefore decided that the optical design for Advanced LIGO would be modified to address these issues, and that the 40-meter should be reconfigured to prototype the new design. Over the next year, we plan to settle on a new design for Advanced LIGO, incorporating the above changes. The resulting system should have no worse sensitivity to gravitational-waves. We will then design (minimal) modifications to the 40-meter to test this new configuration as faithfully as possible. This will (probably) require new (or recoated) input test mass optics, folding mirrors to form a much longer power recycling cavity, new RF electronics, phase modulators, and photodiodes, and new, higher speed digital controls. We expect that the design phase will occupy our efforts for six months, followed by six months for construction, installation, and commissioning.

During the design and commissioning phases, we will continue our efforts to develop robust and transparent lock acquisition procedures for the dual-recycled

interferometer, as well as reducing and understanding the instrumental noise. We will continue to work with the simulation group to maintain a high fidelity between the interferometer simulation programs and the 40-meter interferometer. This will increase our confidence in the detailed behavior and ultimate success of the Advanced LIGO interferometers.