LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Annual Report of the LIGO Caltech 40 Meter Prototype Interferometer Laboratory for FY06

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LIGO operates a 40-Meter prototype (1/100th the length of the actual observatories) on the Caltech campus. To prototype the Advanced LIGO optical configuration and controls and study its performance, a fully instrumented suspended-mass interferometer is needed. The 40-Meter facility fulfills this function. However, it is not possible to install full-size seismic isolation, suspensions, and optical components into the 40-Meter facility vacuum.

The 40-Meter Laboratory has been rebuilt in order 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 (1235, 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 beamsplitter to resonantly extract the GW 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. The more complex optical configuration makes it significantly more difficult to acquire full lock than for Initial LIGO, so it is essential to establish a well-defined, reliable, robust and automated procedure for lock acquisition with a full prototype such as the 40-Meter interferometer well in advance of Advanced LIGO construction.

The upgrade of the 40 Meter Laboratory prototype of the Advanced LIGO optical configuration and controls has completed its construction phase. Active participants presently are Ben Abbott, Rana Adhikari, Rolf Bork, Dan Busby, Keisuke Goda, Jay Heefner, Alex Ivanov, Osamu Miyakawa, Bob Taylor, Monica Varvella, Steve Vass, Sam Waldman, Rob Ward, and Alan Weinstein, with many important contributions from visitors and the LIGO Laboratory staff.

Visitors include: Seiji Kawamura and Fumkio Kawazoe from NAOJ, Noriyasu Nakagawa from TAMA, David Blair and Ju Li from UWA Perth, Shally Sharaf from University of Rochester, Matt Evans and Valera Frolov from LIGO, Kentaro Somiya from AEI.
Summer 2005 SURF students: Marcus Ng (Caltech) and Ryan Kinney (U Missouri).
Summer 2006 SURF students: Jenne Driggers (U Washington), David Malling (Syracuse U), Darcy Barron (U Illinois), Royal Reinecke (Caltech).

This annual report is for FY06. The report for FY05 is LIGO-M050290.

Accomplishments in FY 2006

In fall of 2005, we fully commissioned and tuned the many length sensing signals that are available for lock acquisition and control. 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 AdLIGO 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, so that they became routine.

With full lock, we have measured the optical response to differential and common-mode arm motion at a variety of laser power levels and arm cavity offsets. The optical responses are in excellent agreement with predictions based on the theory developed by Buonanno and Chen and with detailed numerical calculations. 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 resonant signal extraction 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 now published in Phys. Rev. D74, 022001 (2006).

The control scheme that we have employed makes use of signals derived from two RF sidebands, at 33 MHz and 166 MHz, in order to cleanly separate the signals that sense the arm length changes from those that sense the Michelson and recycling cavity length changes. In order for this to work, we must avoid the generation of sidebands-on-sidebands; so the RF sidebands must be applied using electro-optic modulators arranged in parallel, in a Mach-Zehnder interferometer configuration. A paper describing this issue and our solution for it has been submitted for publication in the journal Classical and Quantum Gravity.

Immediately after making these measurements (at the start of S5), our 10 watt laser was shipped to LIGO Livingston Observatory to replace their dying laser. We received a replacement laser from Hanford (operating at less than 5 watts) two months later. A variety of laser- and equipment-related issues then arose, requiring constant and careful monitoring of the laser performance, and re-optimization of all related servos and controls. As a net result, our lock acquisition development work has suffered a ~ 6 month delay. However, our infrastructure, electronics, and diagnostics systems are now in much better shape than they were in fall 2005. Continued development, optimization and automation of the lock acquisition and control, calibration and characterization of the response, and noise reduction are now proceeding rapidly. With the interferometer in various locked configurations, we can measure fully calibrated displacement noise spectra and are developing a comprehensive noise budget analysis, to guide the noise reduction efforts.

To ensure that these procedures are directly relevant for Advanced LIGO, we continue to pursue detailed simulations of the dynamics of both the 40-Meter and Advanced LIGO interferometers. We are collaborating with the LIGO *e2e* group and the VIRGO Orsay group to develop a detailed time-domain model simulation of Advanced LIGO and 40-Meter interferometers, as well as of Advanced VIRGO.

Because 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 GW 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 to serve as a less noisy local oscillator for GW detection at DC. A major effort during calendar 2006 has been the implementation of a DC detection system at the asymmetric port of the interferometer. The in-vacuum beamline at the asymmetric port (after the signal mirror) consists of a pair of PZT-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 will be performed by a new digital control system which is a prototype of the system envisioned for AdLIGO, based on PCIX rather than VME and using a new star network fabric. We expect to install the in-vacuum hardware by the end of summer 2006, implement and commission the new control electronics at that time, and begin experiments with the new system. The primary goal is to learn how to operate the optics and electronics; the observation of noise reduction is a secondary goal which requires us to achieve quantum-limited sensitivity. In other words, this is a controls prototype, not a noise prototype.

Beginning in Spring 2006, Keisuke Goda from MIT has been at the 40m lab, implementing a vacuum squeezing apparatus for injection into the asymmetric port of the interferometer. The goal is to observe a reduction in the quantum-limited displacement noise in some carefully-selected frequency range. As of this summer, the in-air beamline has been assembled. This includes a 2W pickoff beam from our main laser, feeding a second-harmonic generator (SHG) and an optical parametric oscillator (OPO). The injection into the asymmetric port will require one fixed and one movable in-vacuum mirror, to be installed along with the DC readout beamline at the end of the summer.

The 40-Meter team continues to work closely with the LIGO Controls group, the Advanced LIGO Interferometer Sensing and Control group, the Intermediate LIGO group, the LIGO *e2e* simulation group, and LIGO Laboratory engineers and management. Graduate students, REU (Research Experiences for Undergraduates) summer 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 of the main interferometer optical plant and the length and alignment control systems, to the configuration and commissioning of the pre-stabilized laser, digital suspension controllers, suspended-mass input mode cleaner, and optical lever alignment sensing systems, the simulation of lock acquisition and dynamics of the dual-recycled interferometers with e2e, and the development of a displacement noise budget. 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.

Near-term plans

During FY 2007 in the Caltech 40-Meter Interferometer Laboratory we plan to:

- continue the development and optimization of a variety of robust and automated procedures for acquiring lock and controlling our prototype power- and signal-recycled Fabry-Perot Michelson interferometer;
- ensure through simulation that the procedures will work effectively for Advanced LIGO;
- study the noise spectrum and the various contributions to the noise, and implement methods to reduce the technical noise so as to expose the quantum-limited noise;
- install, commission, and fully test a prototype homodyne detection system, including in-vacuum output mode cleaner, DC photodetector, and new-generation PCIX-based controls;
- explore length sensing schemes which avoid the use of high-frequency RF sidebands (since RF electronics at frequencies much above 100 MHz present a variety of technical difficulties), and develop tests for these schemes using the 40m interferometer;
- inject squeezed vacuum into the asymmetric port of the interferometer and measure its effect on the interferometer response;
- use our input mode cleaner to study the angular instabilities that may be important for AdLIGO;
- prepare the interferometer for additional prototyping tasks, including advanced interferometer sensing and control technologies and architectures, suspension point interferometers.