

**LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
-LIGO-**

California Institute of Technology
Massachusetts Institute of Technology

Document Number: **LIGO-M030003-00-R** Date: 1/9/03

Authors: Alan Weinstein for the 40 Meter Group

**LIGO Annual Report for FY02
Campus based research activities
At the 40 Meter Interferometer Facility**

*This is an internal working note
of the LIGO Laboratory.*

**California Institute of Technology
LIGO Laboratory, MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-3064
Fax (626) 304-9834**

**Massachusetts Institute of Technology
LIGO Laboratory, NW17-161
175 Albany St.
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014**

**LIGO Hanford Observatory
P.O. Box 159
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**

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January 9, 2003

Project Description:

LIGO operates a 40 Meter prototype gravitational wave interferometer on the Caltech campus. This facility has been in continual operation and development for the past 15 years. Many of the key technologies used in the present LIGO detectors were developed and/or first prototyped at the 40 Meter, including the vacuum envelope and controls, passive seismic isolation stacks, optics suspensions, the Fabry-Perot Michelson optical configuration, power recycling, and most importantly, the interferometer sensing and length control system. A generation of gravitational wave interferometer physicists has been trained on this facility, and many of these are key players in the construction and commissioning of LIGO. The 40 Meter facility established that such a suspended mass interferometer could be locked and controlled, and that a displacement sensitivity on the order of 10^{-18} m/ $\sqrt{\text{Hz}}$ could be achieved at frequencies around several hundred Hz (Fig. 2). It achieved the best broad-band strain sensitivity of any fully instrumented gravitational wave detector, until the turn-on of TAMA and LIGO.

In order 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 is well suited to this task. (The LIGO observatory sites would be an even better place to do this prototyping, but they will be in the midst of the LIGO science run and must be left undisturbed while Advanced LIGO is being developed). The 40 Meter facility is being upgraded in order to perform these critical prototyping tasks in the years before the installation of Advanced LIGO at the observatory sites.

Several key elements of the proposed optical configuration for Advanced LIGO are novel, and therefore require careful prototyping. In addition to the Initial LIGO configuration (consisting of a pre-stabilized laser, 12 meter input mode cleaner, input optics system, the core suspended-mass power-recycled Michelson interferometer with Fabry-Perot arms, and Pound-Drever style MIMO length- and angular misalignment sensing and control plants), the scheme calls for:

- the addition of a seventh mirror for signal recycling with a detuned signal cavity;
- a pair of phase-modulated RF sidebands with frequencies made as low and as high as is practically possible (so that little of the low-frequency RF sidebands see the signal mirror, while one of the high-frequency RF sidebands has maximal sensitivity to that mirror position), and the use of double demodulation to produce the error signals;
- a short output mode cleaner to filter out all RF sidebands and higher-order transverse modes (allowing only the carrier and signal sidebands to pass);

- DC readout of the gravitational wave signal; and
- offset-locked arms to permit a controlled amount of arm-filtered carrier light to exit the dark port of the beam splitter.

These elements have been chosen in summer 2000 by the Advanced Interferometer Configurations working group of the LSC, after the successful tests of several different table-top interferometers, but no one interferometer has employed them all, with any degree of fidelity to the proposed configuration. As is now well appreciated, all elements of a complex optical configuration such as the one proposed for Advanced LIGO interact with one another in non-trivial, often non-intuitive ways. Thus, a full-scale systems test of all features of the configuration, in a suspended-mass interferometer, is essential. The Caltech 40 Meter interferometer facility is a natural place to perform such a test, because of its well-developed and appropriate infrastructure, and its proximity to the Advanced LIGO controls engineering team.

The primary role of the upgraded 40 Meter interferometer facility will be perform a full systems prototype of all aspects of the Advanced LIGO optical configuration, the interferometer sensing and control, and gravitational wave signal extraction. Special attention will be paid to minimizing any extrapolation of the prototyped system to the LIGO facilities, by maximizing the fidelity of the tests. Cavity finesses, as determined by mirror transmittances, will be exactly as planned for Advanced LIGO. The full interferometer length and angular misalignment sensing scheme, including all control topologies, RF frequencies, electronics, *etc.*, will be as close as possible to what will be employed at the sites.

It is expected that the currently proposed Advanced LIGO optical configuration and controls scheme will evolve as more thought, effort, modeling, and prototyping continues over the next few years. In particular, a test of many of the features of the configuration will be prototyped at the Glasgow 10 meter suspended mass interferometer in 2003. The 40 Meter team will closely follow this progress. If required, any changes to the planned configuration and control scheme will be implemented in the 40 Meter prototype. The highest priority will be placed on the highest fidelity of the prototyping to the actual scheme to be implemented at the sites. After the 40 Meter interferometer is fully working, commissioning and testing will undoubtedly uncover a variety of problems or poor optimization in the implementation. We expect that at least one iteration of the prototyping will be required before the final scheme is installed at the sites. This is reflected in the schedule.

The following milestones were presented at the NSF review on 1/29/01, and at subsequent 40 Meter Technical Advisory Committee meetings:

- 4Q 2001: Infrastructure complete
 - PSL, 12m MC envelope, vacuum controls, DAQS, PEM
 - Conceptual design review. Begin procurement of CDS, ISC, etc
- 2Q 2002:
 - 12m input MC optics and suspensions, and suspension controllers.

- Begin installation and commissioning of 12m input mode cleaner
- 4Q 2002:
 - Core optics (early) and suspensions ready. Suspension controllers. Some ISC.
 - Glasgow 10m experiment informs 40m program
 - Control system finalized
- 2Q 2003:
 - Core optics (late) and suspensions ready. Suspension controllers.
 - auxiliary optics, IFO sensing and control systems assembled
- 3Q 2003: Core subsystems commissioned, begin experiments
 - Lock acquisition with all 5 length dof's, 2x6 angular dof's
 - Measure transfer functions, noise
 - Inform CDS of required modifications
- 3Q 2004: Next round of experiments.
 - DC readout. Multiple pendulum suspensions?
 - Final report to LIGO Lab.

Progress in FY2002:

An internal Conceptual Design Review for the 40m Dual Recycling project was held on October 18, 2001. At that time, detailed conceptual designs were presented (with accompanying documentation) for the overall project, the tentative optical configuration and control scheme, the optical layout, all sensing table instrumentation, core suspended optics, mechanical suspensions, digital suspension controllers, and auxiliary optics (stray light control, initial alignment system, optical levers, video monitoring, etc), laboratory infrastructure and vacuum systems, environmental monitoring, data acquisition, computing and networking. Progress on key components was reviewed. The schedule of milestones (above) was again presented and discussed. The review committee was satisfied with the design and the progress, and a few specific concerns were addressed.

As of January 2003, we are on schedule. In particular, the following components and subsystems are implemented:

- The laboratory building has been expanded and upgraded, providing room for electronics racks, optical tables, controls consoles, etc.
- Power conditioners have been installed for all electronics. New cable trays have been installed. All electronics racks needed for the full interferometer controls have been installed. All optical tables and optical enclosures have been installed. A new control room, with display consoles, has been installed.
- Vacuum equipment (pumps, gauges, RGAs) have been upgraded. An Initial-LIGO-like vacuum control system has been built and commissioned. The system is fully operational and in continual use.
- The existing vacuum envelope has been augmented with a new output optic chamber with seismic stack, a 13 meter mode cleaner beam tube, a small chamber and seismic stack for the end mode cleaner suspended optic (MC2). New IR-

coated optical ports, new flexible in-vacuum cables, new welded vacuum electrical feedthroughs, and new cameras and mounts for viewing the beam on the in-vacuum suspended optics have been installed.

- In early 2001 a commercial active seismic pre-isolation system (STACIS) was installed on all four test mass chambers and is now in continuous use.
- An Initial-LIGO pre-stabilized laser (PSL) was installed in spring 2001. It has been fully commissioned and characterized, and is in continual use.
- An Initial-LIGO data acquisition system (DAQS) was installed in spring 2001, and has been in continual use.
- EPICS slow control system, networking, and computer displays are all installed and in continual use.
- A small number of environmental monitoring devices (dust counter, weather station, accelerometers, magnetometers) have been installed and are fully integrated into the EPICS slow control and DAQS systems.
- The optics for the 13-meter mode cleaner were produced, polished, and coated. The polishing and coating quality was measured by LIGO optical engineers in March 2002.
- The suspensions for the 13-meter mode cleaner were fabricated, cleaned and baked, and assembled, by March 2002.
- During April 2002, the three suspended optics for the 13-meter mode cleaner were hung, tested, and installed into the vacuum envelope.
- Digital suspension controllers for the mode cleaner suspensions were designed, fabricated, and finally installed into the laboratory by May 2002. The full digital suspension control system for all 8 vertex-area suspended optics required for dual recycling was installed in December 2002. Digital suspension controllers for the two ends are designed and partially fabricated.
- Mode cleaner length and frequency control servo electronics, and optical sensing trains and beam tubes, were installed into the laboratory by late May 2002.
- The mode cleaner was aligned, and first fringes seen, in June 2002.
- Mode cleaner lock acquisition was debugged and tuned throughout the summer, and by September 2002, lock acquisition was routine and robust.
- Three 2002 SURF students made major contributions to the characterization of the mode cleaner optics' suspension controllers, and mode cleaner control servos.
- One 2002 SURF student made major contributions to the re-configuration of the pre-stabilized laser optical train, as part of the mode cleaner commissioning.
- The characterization of the mode cleaner performance, and its interaction with the pre-stabilized laser system, occupied much of fall 2002. By the end of December 2002, the noise performance of the system met specifications.
- The intensity stabilization system (ISS) for the pre-stabilized laser was developed and installed by the end of 2002.
- During 2002, five new temperature-controlled vacuum bake ovens were commissioned in the South Annex of the laboratory, and many bake jobs were completed and qualified.
- The Global Diagnostics System (GDS), including DTT, AWG, and DMT have been installed, and DTT/AWG is in use.

- All of the core optics for the main dual recycled interferometer (including spares) were produced, polished, and coated, and their optical properties measured by LIGO engineers, by August 2002.
- All of the mechanical suspensions for the core optics for the main dual recycled interferometer were designed, fabricated, cleaned and baked, by August 2002.
- Sensor/actuators (OSEMs) for the all the suspended optics were assembled, cleaned and baked, tested, and prepared for installation.
- Three core optics (the beamsplitter, ITMx, and ITMy) were suspended and damped in September 2002. Four remain to be suspended.
- We plan to suspend the remaining four optics (power recycling mirror, signal recycling mirror, ETMx and ETMy), and install them into the vacuum envelope by spring 2003.
- The interferometer sensing optical trains were designed in 2001. Almost all of the optical and electro-optical components were procured by the end of 2002.
- Several key auxiliary systems (the in-vacuum Faraday isolator, the in-vacuum mode matching telescope with off-axis parabolic mirrors, the in-vacuum PZT steering mirror system, and the optical lever zoom telescope system) were designed, and components procured, by the end of 2002.
- A summer 2002 SURF student analyzed the alignment sensing (WFS) signals expected from the full dual-recycled interferometer, and proposed a workable sensing scheme.
- In the second half of 2002, we resumed work on the detailed simulation of the full dual-recycled interferometer dynamics and lock acquisition, with the E2E software.

Thus, there has been considerable progress in the fabrication and commissioning of a full dual-recycled interferometer with LIGO-engineered controls. The work that remains to complete the fabrication and begin the experiments in dual recycling configuration response, lock acquisition, and control, is described in a later section.

Plans for FY2003

The fabrication of an Advanced LIGO-design dual-recycled Fabry-Perot Michelson interferometer at the 40 Meter laboratory is planned to be completed in FY03. The activities required to complete the fabrication are listed below.

- The digital suspension controllers for the remaining 2 (of 10) suspended optics should be complete by 1Q 2003.
- The remaining 4 (of 10) suspended optics (PRM, SRM, ETMx, ETMy) will be assembled, damped, and installed in the vacuum envelope by 2Q 2003.
- Fabricate and install all remaining optical sensing equipment on the existing enclosed optical tables, by 2Q 2003.

- Begin commissioning of the interferometer in stages, with 1 degree-of-freedom systems (short Michelson, Fabry-Perot arms) by 2Q 2003, even before a digital length control system is installed.
- Fabricate and install auxiliary optics systems: scattered light control, initial alignment system, optical levers, video monitoring.
- Fabricate and install the length sensing and control system.
- Fabricate and install the alignment sensing and control system.
- Begin commissioning the full dual-recycled Michelson with Fabry-Perot arms, by 3Q 2003.
- Data handling: fiber link to CACR? (Currently, we only save all trend frames, backed-up to AIT occasionally).
- There may be some necessary augmentation of the DAQS, computing, networking, and environmental monitoring systems.

The plan is to have all these systems installed, and the process of commissioning them begun, by summer 2003. First experiments in dual recycled configuration response, lock acquisition, and control are planned for 3Q 2003, and are expected to take at least a year. We expect that LSC members, as well as students, will participate in this most interesting phase of the project.

We will delay until FY04 the implementation of some elements of the interferometer which have not yet been designed in any detail: the output mode cleaner and associated sensing system, and the DC demodulation scheme. We also continue to consider the possibility of implementing multiple pendulum suspensions, at a later stage in the project.