LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T060183-00-R *ADVANCED LIGO* 07/25/06

LASTI Update for the Technical Advisory Committee (Aug 06)

David Ottaway (Editor),Thomas Corbitt, Richard Mittleman, Brett Shapiro and Laurent Ruet

Distribution of this document:
LIGO Science Collaboration

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
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

http://www.ligo.caltech.edu/

1 Introduction

This report summarizes the status of LASTI in August 2006 for the benefit of the LASTI Technical Advisory Committee (TAC). An update of the progress that has been made by the LASTI team for the period between March 2006 and August 2006 is included. In addition, a summary of the proposed work for the next six months will be presented. This report will summarize what has been achieved in the following projects:

1. Quadruple Pendulum Suspension Controls Prototype (LASTI lead: Brett Shapiro)
2. Internal Seismic Isolation (ISI) for BSC Chamber (LASTI lead: Richard Mittleman)
3. Triple pendulum controls testing (LASTI lead Laurent Ruet)
4. HAM SAS prototyping and testing (LASTI lead David Ottaway)
5. QND tests (LASTI leads Nergis Mavalvala and Thomas Corbitt)
6. Commercial Amplifier Tests (LASTI lead David Ottaway)

This report is meant as an internal LSC document and for this reason an exhaustive author list has not been included. The authorship of this report has been limited to those who formally wrote a section of it. The LASTI project relies on significant contributions from a large number of people and this report will not be formally reviewed by all of them before its presentation to the LASTI TAC. For this reason the author list has been confined to those people who wrote a section of this report and is by no means a representation of the total number of people who have contributed significantly to LASTI program during this period.

2 LASTI progress

2.1 Quadruple Pendulum Suspension Controls Prototype

The Quad Controls Prototype has been installed into the BSC on a stiff (no isolation) table at LASTI. Since then the system identification (sys-id) has been completed, simple damping loops constructed, the electrostatic drive installed, and eddy current damping installed onto the reaction chain. The sys-id has shown that the frequencies of the two lowest pitch modes on both chains are significantly too high (10 - 40%). Interestingly the same modes have the same frequency on both chains. Measurements taken on the quad itself indicate the wire break-off points on the tips of the blade springs are likely hanging too far under the center of mass of their respective stages. Adjusting the matlab model accordingly brings the frequencies of the predicted modes closer to the measurements, but not all the way. Thus, the cause of this disparity is not completely understood. Further, the frequencies of these modes is different from when the quad was at Caltech so something has changed between here and there, and changed the same way on both chains.

The LASTI laboratory has suffered from significant temperature fluctuations during this period, it was observed that the vertical OSEMs on the top mass went out of range when the temperature of the laboratory increased by 6 degrees Celsius. This was attributed to the relaxation of the blade springs. We are currently in the process of preparing a heat loading test for the suspension cage of the controls prototype. This will help simulate the effect of the of an additional heat load on the structure such as that provided by the thermal compensation system. This is an important consideration now as it will feed into the design of the conducted to the noise prototype and its associated thermal compensation system system.

Additional work will include further investigation of the pitch mode problem, characterization of cross coupling from the sys-id, additional testing of the eddy current damping, and improvement of the active damping loops. Tests that are less urgent but can also be conducted are the direct observation of the motion of the bottom test mass, and additional testing of the electrostatic drive. The Advanced LIGO SUS team has been involved with this research and is pursuing the consequences.

2.2 Internal Seismic Isolation Prototype

The two stage ISI is currently undergoing construction in the LASTI high-bay. The entire structure is nearly fully assembled with the exception of the sensors, actuators and springs. To date only minor problems have been encountered. The actuators and GS13 pods have been fit checked. The spring constants of the two different types of springs have been measured on the spring tester and give consistent values to within the repeatability of the tester (~1%). These measured values are consistently lower than the calculations made by ASI's using Finite Element Analysis (FEA) by about 15%, and the problem is being worked by the Advanced LIGO (AdL) SEI team..

We are currently working on installing the springs and suspending the system at a reduced weight load to compensated the softer than expected springs. At the same time we are redoing the spring FEA analysis to try and understand the spring constants and determine what the stress will be if we try these springs at the full load.

Once the system is suspended we plan to go through the balancing procedure. This involves measuring the full stiffness matrix (6 by 6) and then fine tuning the blade shims to minimize the off diagonal terms. We expect that this will be an extended learning process. Whether this happens before or after bringing the system to its full load depends on the results of the FEA analysis. In addition to this a modal analysis of the elastic body modes of stage 1 and stage 2 will be conducted. Once this is completed the ISI will be disassembled and sent out for ultra high vacuum preparation

2.3 Triple Suspension Prototype Controls Testing

The sensor noise in the current Advanced LIGO OSEMs will prevent the achievement of thermal noise limited performance of the mode cleaner if acceptable levels of solid body mode damping are applied. In the last year Laurent Ruet developed a new approach to the control of triple pendulums that could significantly enhance the rejection of sensor noise for the same level of damping. This method uses modal control associated with estimator techniques to partition the complex transfer functions of the triple pendulum into a series of second order transfer functions.

The behavior of the modal controller has been simulated using Matlab and Simulink, the results were very promising for both the damping and the sensor noise filtering. The technique relies on a good knowledge of the model, smart adjustments of the modal controllers (they control each mode one by one), and some estimator techniques that enable us to filter the sensor noise. Although the simulations are very well understood, it is necessary to confirm the model with the experiment.

Checking the loop model is not easy at high frequencies (>10Hz) because the passive attenuation from the top mass to the test mass is very high and we can't drive the top mass hard enough to have a measurable motion on the bottom mass using OSEMs. This is because the OSEMs do not have enough sensitivity and they measure motions relative to the frame.

To perform these measurements an optical cavity was formed between two triple pendulums. The second triple acted as an inertial reference, in order to measure very small displacement of the bottom mass. The light source used was a sample of the main LASTI PSL, coupled to the experiment by means of a single mode fiber. We plan to use this approach to couple the light into future LASTI experiments. This experiment also tested this approach. Unfortunately the frequency noise measured on the light emerging from the fiber was found to be higher than that going in. At present the cause of this excess frequency noise has not been identified.

The cavity was locked using the PDH technique and several improvements of the PSL have been made to reduce the frequency noise. The cavity enabled us to measure $1/f^6$ transfer functions up to 40 Hz. Some artificial sensor noise has then been injected in the top mass OSEMS and the sensor noise to test mass transmission has been plotted and compared to the loop model. Several loops have been tested and show excellent agreement with the model. This was a direct validation of the sensor noise to test mass transmission model.

Other observations have been made using the cavity. It was observed that when control forces are applied directly to the bottom mass of a suspension to lock the cavity then the dynamics of this pendulum change significantly. The locking loop acts like an inertial clamp on the bottom mass which effectively eliminates one degree of freedom and thus the expected behavior of the pendulum changes in the longitudinal direction significantly. This can cause instabilities in damping controller that rely on accurate knowledge of the pendulum behavior such as modal estimators. Hierarchical locking control has been briefly studied as a solution to this problem but more work remains to be done.

Ruet’s work is being documented in detail in his thesis, to be completed by the fall 2006.

2.4 HAM SAS at LASTI

The main progress at LASTI in this area has been in building up the infrastructure needed to host these tests and models development to guide the testing program that will be undertaken on this system for LASTI. Ottaway has been participating in the fabrication oversight in Italy to enable a quick and well-understood start to the installation and characterization. A clean room to be permanently situated over the LASTI Yend HAM has been ordered and delivered. Assembly of this cleanroom will be undertaken when technician time is freed from more pressing tasks. The additional Guralp seismometers that are required to provide a complete suite of instrumentation for the ground under the Yend HAM have been ordered. These are very long lead time items and delivery is anticipated in Aug ’06.

An undergraduate summer student (Cassandra Hunt) has been developing a Finite Element Analysis model of the HAM SAS and a triple pendulum based on the original work of Dennis Coyne. Once completed, this model will be used to guide the testing program for HAM SAS at LASTI.

2.5 Quantum Non–Demolition Experiments

The aim of these experiments is to investigate suspended cavities with high stored optical power to test mass ratios. In this regime radiation pressure effects become dominant driver of the testmass dynamics.

In the last six months we have installed a double pendulum suspension that supports a test mass of one gram. This test mass is the end mirror of a single cavity arrangement with a finesse of 8000. This set-up has produced several key results: A new locking scheme has been developed that utilizes a frequency shifted subcarrier, which allows us to lock the cavity at an arbitrary detunings. Without this we were limited to a maximum of a linewidth detuning from line center. We measured an optical rigidity of $2x10^6$ N/m, which is about a factor of 100 greater than previous experiments. This stiffness corresponds to replacing the optical beam with a rod of solid diamond. The large optical stiffness, combined with the ability to lock to any detuning, has allowed us to see Advanced LIGO/40 meter like sensitivity curves with only a single cavity. Two dips are present, one from the OS and one from the large detuning. We've also observed the optically-driven Parametric Instability effect discussed by Braginsky et al. on the drumhead mode of the ITM with an instability about 10 times stronger than the previous cavity. This has been trivially controlled for this experiment through active feedback to the OSEMs or through frequency control of the laser beam.

For the first time we have pushed the optical spring (OS) out of the control system bandwidth, allowing us to test in detail the interactions of the OS without its effect being significant impacted due to the control system. This also allows us to directly see the instability of the OS and to damp it. This last step has allowed us to confirm a key feature of the optical springs: that they do not introduce any extra thermal noise. Finally we've demonstrated optical damping of an OS (Yanbei Chen's idea). Any single optical spring is always unstable, either through a pure instability (anti-restoring force) or through an anti-damping force. We've experimentally shown that it's possible to use the carrier light to crate an optical spring with the anti-damping force, but then use the subcarrier light to provide a damping force to stabilize the OS. With this done, the control system may be cut off so that the OS is completely free. This is the first demonstration of such a scheme. These results have been documented in publication recently accepted for publication in Physical Review A (P050045-00-R) and other formal publications are in preparation.

2.6 Commercial Optical Amplifier Tests for PSL Upgrade

The aim of this project was to investigate the feasibility of using a commercially available optical amplifier to increase the available power of the Initial LIGO PSLs for use in Enhanced LIGO. This approach has become the fall-back option in case AEI/Laser Zentrum Hanover cannot deliver its 30 Watt front end to the Advanced LIGO laser on a time scale that is compatible with Enhanced LIGO.

An optical amplifier from Northrup Gruman was purchased by LSU and delivered to MIT in mid-February. It was characterized using the LASTI MOPA by David Hosken (MIT Visitor from The University of Adelaide) and Rupal Amin (LSU). At the end of David’s stay at MIT this program was transferred to LIGO Livingston for manpower reasons (LLO is Rupal Amin’s home base).

During the LASTI testing two significant achievements were demonstrated. First the output of a laser modeling code was verified which enables us to accurately predict the output power of such a system. This will enable us to design with confidence a system quickly in the future that will meet Enhanced LIGO requirements. The second major accomplishment was the verification of the utility of a birefringence compensation technique using a Faraday Rotator and double passing of a single laser rod. Unfortunately a problem was also identified in the laser amplifier, namely the introduction of a large amount of beam jitter to the transmitted optical field. This was found to be caused by poor mechanical stability of the optical amplifier gain medium. This is now the subject of further investigation by Rupal Amin at LIGO Livingston.

3 Planned Experiments for the Next Six Months

A couple of key schedule changes have altered the plan of LASTI for the proceeding six months. Firstly the ISI is taking longer to 'dirty-assemble' and test than was previously anticipated. This longer time is due to first-time troubleshooting, and identification of (to date) small design and fabrication errors. The SEI group is fully involved and integrating this information into their planning. This means that is unlikely that this system will be ready for clean installation into the LASTI vacuum before Mar 2007 based on:

Completion of Dirty Tests (Static drive test and modal tests)	1st Oct 2006
Disassembly	1st Nov 2006
Cleaning completed	1st Feb 2007
Clean assembly completed	1st Mar 2007

This, coupled with the anticipated arrival of the quadruple suspension noise prototype in March 2007, has led us after discussion with the SEI and SUS groups to abandon plans to join the ISI with the controls prototype and instead plan to join the ISI with the noise prototype. Initially this will be done with aluminum test masses to reduce the risk to the expensive and fragile LASTI glass core optics and fused silica fibers during the initial commissioning of the ISI with suspension payload. There are 2 additional major vacuum installations planned for LASTI in the next 6 months. The first is the installation of the full QND experiment currently being planned by the MIT Quantum Control group. This is currently slated for Fall 2006 and the only potential conflict is with the Quadruple suspension controls prototype testing. It is anticipated that careful staging before the vent should minimize the impact of this to 2 weeks of down time. The other anticipated major installation in LASTI is that of HAM SAS; this is a little more problematic as it has the potential to require greater vent time and it will impact both QND work and suspension controls prototype testing. It also needs to be executed in a timely manner as results from this test are needed by March 2007. This has the advantage that results from HAM SAS will be required before the major installation to install ISI/Noise prototype.

Careful planning with the Suspension group (already started) will be required to identify the additional LASTI infrastructure that will be required to enable timely merging of the seismic and suspension prototypes. Particular attention will need to be taken with regards to pre-installation external to the vacuum envelope as both systems will need to be independently assembled on different jigs and cleanrooms.

During the next 6 months Laurent Ruet will graduate. However we anticipate the arrival of a Postdoc, Fabrice Matichard from INSA, who will spend a year with us on the LIGO visitors program. The LIGO MIT group is continuing its search for an additional Postdoc who will spend some of their time working on LASTI. The LASTI lab is currently well supported by the CDS group from Caltech and we routinely get the assistance of Fred Miller from the MIT Kavli Institute when additional technical support is required. Additional scientific input has been provided by Brian O'Reily and Daniel Sigg who have both spent extended periods at MIT during the last 6 months. Discussions with the Advanced LIGO Suspension Group have confirmed that a significant presence from members of the UK suspension team is planned during the noise prototype installation. The HAM SAS effort remains understaffed; the addition of a graduate student or a postdoc would be optimal given the extremely short time frame between when results are required and installation. A post-doc search has not turned up any new hires who can (now) join us in a timely way to help with HAM-SAS. Potentially this help could be supplied by one or more visitors who would spend a couple of months at LASTI. We are pursuing this with Caltech and Columbia. With this notion, I think that our staffing profile in the near term is adequate to cover our needs particularly with continuing strong support from the aforementioned external groups. In the longer term, the currently open position for an experimental postdoc at MIT will be crucial.

The overheating situation in the LASTI laboratory has significantly improved. We have not seen a temperature excursion to 90 F in a couple of months. However, small temperature excursions are still occurring. For example a week ago the temperature spike to 80 F and this was sufficient for the Quadruple Pendulum OSEMs to go out of range. We will continue to monitor the situation and to harass the MIT Facilities department in the interest of a long-term quality solution.