



LIGO Laboratory / LIGO Scientific Collaboration

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Advanced LIGO

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Review Report
Interferometer Sensing and Control
Preliminary Design

*Mick Flanigan, Hartmut Grote, Eric Gustafson, David McClelland, David Nolting,
Robert Schofield, David Shoemaker, Daniel Sigg (chair)*

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LIGO Scientific Collaboration

This is an internal working note
of the LIGO Laboratory.

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 – NW22-295
185 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 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

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

1 Executive Summary

The Interferometer Sensing and Control (ISC) Preliminary Review was held during the months of May and June, 2009. The requirements are described in T070236-00, whereas the preliminary design can be found in T0900175-v1. Supporting document for the proposed change in the OMC design is T0900157, T0900095 for the arm length stabilization requirements, T0900144 for the arm length stabilization design, G0900278 for the alignment sensing and control modeling, and G0900293 for the ETM transmission monitor design.

We consider the ISC preliminary review overall a success and recommend that the ISC team go forward to working on the final design. In a few instances we feel additional work is needed. A set of action items and recommendation follows. All recommendation should be addressed by the time of the final design unless specifically mentioned otherwise.

1.1 Arm Length Stabilization

An arm length stabilization system using rear-injected green beams was selected as the seismic platform interferometer. We fully support this decision.

1.2 Modes of Operations and Commissioning Planning

The review of the conceptual design recommended a design study to investigate the trade-offs of using mode 0 as a stepping stone during commissioning. We don't believe this has been fully addressed, but we recognize that this question has to be reevaluated in the current planning of the early commissioning effort.

We fully support the effort to commission an early test of the arm locking scheme by changing the advanced LIGO installing schedule to implement an ITM and ETM seismic isolation and suspension system as early as possible. We urge the ISC team to find an implementation which also allows for the squeezing test.

Action item: Make a decision whether mode 0 will be used in the first phase of commissioning, or not. And if so, at what point would we switch over?

1.3 Alignment Sensing and Controls

The alignment sensing and controls system is complex. The present design seems to meet the requirements, but we feel that its robustness may not intrinsically be large enough to easily deal with the thermally induced lensing effects in high power operations. In initial LIGO the interdependency between angular sensing, thermal lensing and torque instabilities required significant commissioning time. Even, if it cannot fulfill the noise requirements, we feel that a truly robust sensing scheme which can decouple the arm cavities from the central interferometer and from each other has the potential to significantly reduce the time to reach design sensitivity.

Action item: Investigate the possibility of a more robust mode of operation for the alignment sensing and control, which can serve as a stepping stone to commission high power operations and shorten the overall commissioning time. We feel that the new near and far field quadrant photodetectors in the end stations, cameras looking at the ITM and ETM, as well as wavefront sensors on the green beams still have untapped potential.

1.4 Calibration

In the advent of regular detections with advanced LIGO accurate calibration will acquire a new urgency. Even so, calibration may not be the direct responsibility of the ISC group, we have to ensure that everything will be in place to extract the best science.

Action item: Engage the LSC calibration group to develop a straw man plan on how to reach a 1% amplitude and phase calibration.

1.5 Software Development and Testing

This recommendation from the conceptual review has not been addressed yet. We simply repeat our action item and expect this to be addressed by the time of the final design.

The feedback compensation network which keeps the differential arm cavity length on resonance is part of the gravitational wave readout. Having a full understanding of the corresponding computer code is crucial in a convincing detection of gravitational waves. In initial LIGO the characterization of the length sensing and controls software is not well documented. This needs significant improvements to reach the level of scrutiny which is applied to the astrophysical analysis code.

We understand that the current ISC team consists of very few software persons. We recommend that more resources be actively recruited from the detector characterization group.

Action item: More resources have to be allocated to program, test and validate crucial software pieces. In particular, the scrutiny and documentation of software paths which are part of the gravitational wave signal readout have to be on a similar level as currently practiced by the data analysis groups. Algorithms have to be analyzed for validity, performance and limitations. All testing has to be documented.

2 Technical Scope

2.1 Scope

The Interferometer Sensing and Controls system is responsible for bringing the optical resonators into a mode of operation suitable for detecting gravitational waves. This includes the longitudinal and angular degrees-of-freedom of the input mode cleaner, the main interferometer and the output mode cleaner. It includes photodetectors, demodulation electronics, analog filtering, A/D converters and the computer hardware and software. The ISC system interfaces with the Suspension (SUS) Subsystem for the actuation on the optics, and with the Pre-Stabilized Laser (PSL) for actuation on the laser frequency. The modulation scheme is implemented by Input Optics (IO), according to the requirements of the ISC system. The RF distribution system has been reviewed separately in T0900259-v4.

2.2 Charge to the Review Committee

The charge to the review committee is outlined in L080020-00.

1. With regard to requirements:

- a) Determine whether the requirements identified in the Design Requirements Document (DRD) are complete (including functional, performance and interface requirements),
- b) advise whether proposed requirement values are appropriate,
- c) if needed, recommend additional requirements to be specified, and
- d) recommend other appropriate actions.

2. With regard to the conceptual design:

- a) Evaluate the conceptual design of the ISC to determine if it is consistent with the DRD,
- b) advise on whether the recycling cavity design selection is appropriate and based upon sufficiently complete information,
- c) advise whether the design is sufficiently developed to proceed with the Preliminary Design phase,
- d) advise whether the Project cost and schedule appears appropriate, and
- e) advise whether there are any significant remaining or newly-perceived risks in meeting the requirements.

3. With regard to the preliminary design:

- f) Advise on the preliminary design work plans, in particular the prototyping and testing plans.

The committee should develop a set of actions as a result of the review, and should follow up on the completion of the actions as part of the review process.

2.3 Review Checklist

- A. System Design Requirements, especially any changes or refinements from DRR
T070236-00. No changes since DRR.
- B. Preliminary Design Document, summarizing the design and pointing to other documents
T0900175-v1
- C. Justification that the design can satisfy the functional and performance requirements
- Subsystem block and functional diagrams
Included in conceptual design (T070247-01) and ALS design (T0900144)
 - Equipment layouts
Not presented at this review.
 - Document tree and preliminary drawings (information issued)
No mechanical drawings at this stage.
 - Modeling, test, and simulation data
Included in the documents.
 - Thermal and/or mechanical stress aspects
Not relevant.
 - Vacuum aspects
Not explicitly presented.
 - Material considerations and selection
Some discussion of this with regards to the OMC construction.
 - Environmental controls and thermal design aspects
Not relevant.
 - Software and computational design aspects
See recommendations from this review.
 - Power distribution and grounding
Not presented.
 - Electromagnetic compatibility considerations
Not presented.
 - Fault Detection, Isolation, & Recovery strategy
Not presented.
- D. Resolution to action items from DRR
Done.
- E. Interface control documents
None given.
- F. Relevant RODA changes and actions completed
Not relevant.
- G. Instrumentation, control, diagnostics design approach
Included (to some degree) in the documentation.

- H. Fabrication and manufacturing considerations
Included (to some degree) in the documentation.
- I. Instrumentation, control, diagnostics design approach
Duplicate of G.
- J. Preliminary reliability/availability issues
Not addressed.
- K. Assembly procedure
Not addressed.
- L. Installation and integration plan
Not addressed.
- M. Environment, safety, and health issues
- Mitigation of personnel and equipment safety hazards; refined Hazard Analysis
N/A.
 - Reflected in equipment design and procedures for use
N/A.
- N. Human resource needs, cost and schedule
Not reviewed here.
- O. Any long-lead procurements
N/A.
- P. Technical, cost & schedule risks and planned mitigation
Schedule not reviewed here.
- Q. Test plan overview
See next item.
- R. Planned tests or identification of data to be analyzed to verify performance
- In prototyping phase
*Enhanced LIGO has proven that a DC readout is a workable solution.
The 40M continues to investigate the locking scheme.*
 - In production/installation/integration phase
A re-planning of the commissioning effort is underway with the option of an early one-arm test to verify the arm length stabilization scheme.
- S. Identification of testing resources
- The test equipment required for each test adequately identified
 - Organizations/individuals to perform each test identified
 - QA involvement
Not explicitly identified at this stage.

T. Test and evaluation schedule, prototype and production

The RF distribution system has been fast tracked and has started with production.

U. Revised Failure Modes and Effects Analysis (FMEA) (bottom-up approach based on design)

Not presented.

V. Risk Registry items discussed

Not explicitly.

W. Lessons learned documented, circulated

Done for OMC/DC readout.

X. Problems and concerns

Some discussion in documentation.

3 Answers to Design Review Action Items

The ISC conceptual design review report (T080092-A) contained six recommendations in its Executive Summary. Here is the status of those recommendations:

3.1 Stable Recycling Cavity Decision

This wasn't so much a recommendation as an approval of the decision to use stable recycling cavities. Since the ISC CDD, the note T080208-00 was written that explains this design choice.

3.2 Seismic Platform Interferometer

Action item: *Hold an independent review during the summer of 2008.*

It was decided in summer 2008 that the Arm Length Stabilization system for Advanced LIGO will use end-station injection of a 532 nm beam, and PDH cavity sensing; see M080371-v1.

3.3 Modes of Operation

Action item A: *Concentrate on developing a preliminary design for sensing and controls of mode 1b only (non-detuned broadband resonant sideband extraction).*

Action item B: *Commission a study to investigate the trade-offs of using mode 0 as a stepping stone during commissioning. This should be completed by fall 2008.*

A: We are concentrating on the non-detuned broadband mode as suggested.

B: No signal recycling mode. The length sensing and controls for this mode has been studied, and is reported here. The conclusion is that the length control of this mode can be realized without any other changes to the interferometer configuration (i.e., no modulation frequency or layout changes).

3.4 Alignment Sensing and Controls

Action item: *Allocate more resources to work on alignment sensing and controls in order to keep pace with the length sensing and controls. The controls topology needs to be worked out in full detail by the time of the preliminary design.*

See details in G0900278-v1.

3.5 Environmental Couplings

Action item: *Demonstrate by the time of the preliminary design that sufficient effort has been made to explicitly incorporate the lessons learned in initial LIGO with environmental couplings.*

The draft note of the response to the review committee comments is contained in T0900378-v1.

3.6 Software Development and Testing

Action item: *More resources have to be allocated to program, test and validate crucial software pieces. In particular, the scrutiny and documentation of software paths which are part of the gravitational wave signal readout have to be on a similar level as currently practiced by the data analysis groups. Algorithms have to be analyzed for validity, performance and limitations. All testing has to be documented.*

First we will need to adhere to good software practices: a code repository, a standard code style, comments sufficient for an experienced programmer to follow the code, user documentation, etc. Some of this is already being done well, some less well.

In addition, we should have the ability to test the Bork-Space (BS) modules generally, and the signal flow in critical sub-systems specifically (e.g., the LSC and OMC). For general module and BS compiler testing, we can use LSC and SUS-like test diagrams which use all Bork-Space (BS) modules. Each diagram should have an associated test-suite. These tests should change parameter values (gains, phases, filters, etc.) while sending in known input signals and checking for correct output signals. The diagrams used for this should not be the diagrams in use in the interferometer, as flexibility is important during commissioning and changes in the working diagrams are likely, but changes defeat the purpose of the test-suite.

Specific test suites for critical sub-system diagrams should also be developed before long-term science running, but after the majority of commissioning work (i.e., after the diagrams have stabilized).

These test suites can take any form, but as an example one could imagine running a compiled diagram on a dedicated test front-end computer and exercising it with perl scripts and standard LIGO scripting software (e.g., ezca and tds tools). As a replacement for the physical world (e.g., the IFO or mechanical system), a second dedicated FE computer could take in DAC outputs of the test FE, and send signals to its ADCs. (The replacement FE would also run a BS system which would allow for testing but needn't emulate a physical system). This would require little new software development, and it would provide a test environment very similar to that of a live system.

Furthermore, code for the BS modules, the BS “compiler” (BS to C translation), and the final critical sub-system diagrams should all be subject to review. For the BS modules and compiler, this can happen in an on-going way (e.g., as modules are added). For the diagrams, we again recommend waiting for stability.

4 Review Comments and Questions

Here is a collection of questions and answers which were investigated during the review process.

Regarding OMC: Any plan for (remote) bias control of the DC-PDs in transmission of the OMC ? If not, how do you choose the bias, also given that you can switch the load resistor value?

The bias is not as important as for RF. More testing of the DC-PDs will be done.

If OMC-CDS will run with 16 kHz, I assume you will have dedicated anti-alias filters just for this?

The rate of 16 kHz is the processing speed. The ADC will run at a higher rate.

Regarding ALS: At least in the documents I had at hand I did not see a statement on possible green light coupling either from one arm to the other, or from the vertex station back into the arms. Is it clearly no problem?

Due to the wedges in the ITM the green light will not propagate in the recycling cavities.

What is the time frame when a decision about the SRC reflectivity needs to be taken? (so it can be implemented in time)

The IO schedule shows that this batch of optics (i.e., all optics the same size as the SRM) is being coated from Oct 2009 through July 2010.

Can you actually add a non-resonant SB which is not a multiple of the main modulation frequency?

Well, no, unless it's transmitted slightly off-resonance through the MC. However, Lisa has since looked at using a non-res SB, without the MC constraint, and doesn't see any better alignment signals with them; so the question seems to be moot. She's next going to look at using a frequency-shifted sub-carrier; the idea is to make it a high enough frequency that it gets fully transmitted by the Michelson asymmetry.

I don't think that using the same modulation frequency as the main interferometer is a good idea. I think you want to make sure it is far enough away and different between the two arms.

Agreed.

I support the decision to include a rear injection arm length stabilization system based on 532 nm radiation but am not sure that using a 4 km optical fiber distribution system including fiber phase noise compensation and possibly polarization control to provide a reference frequency to phase lock a laser which is then doubled to 532 nm is worth the trouble since the coating dispersion will not allow the 532 and 1064 nm to be resonant simultaneously in any event and so some offsetting of the arm length will be required to lock to the 1064 nm. I would like to hear the arguments against using an Iodine stabilized frequency doubled NPRO at each arm end, locking each arm to the 532 light source for that arm, then slowly tuning the 532 until the 1064 nm comes into resonance and then locking the arm to the 1064 nm. Could be simpler and cheaper.

The first sentence of this comment seems to result from a misunderstanding of the ALS. In fact we don't want the 532 nm and 1064 nm beams to be simultaneously resonant in the arm; using the 532 nm beam, we want to control the arm so it is maybe a few linewidths away from resonance for the 1064 nm. The point of the fiber distribution is to tie the frequency of the ALS laser to that of the PSL. Doing absolute stabilization of each laser (ALS and PSL) using an iodine reference could be another way of doing this. We doubt, though, that iodine stabilization could give us the

frequency stability we need in the 10-100 Hz band. The fiber may not either, and we are currently looking at using another reference cavity for the ALS laser to get this level of stabilization. Then, long term synchronization could be done with either the fiber or iodine references, but since we have no experience with the latter in LIGO, we would probably favor the former, other things being equal (we will keep the iodine reference idea in mind).

I would like to better understand how the TCS actuators (ring heaters and 10 micron laser beam projectors) and TCS sensors (Hartman sensor and dual beam optical levers) fit into the overall control of advanced LIGO. The PDR Document (T0900175-v1) does not mention TCS and the CD Document (T070247-01) only says “the input mode is Gaussian (for example no clipping at the Faraday isolator) and that the mode matching between the input mode and the common arm cavity eigenmode is at least 95% w/o engaging any thermal compensation system.” Are we precluding the possibility of information flow from the Sensing and Controls System to the Thermal Compensation System or vice versa at some time in the future. It would seem a paragraph stating the case one way or the other might be a good idea and a brief discussion of the interface between the two subsystems might be useful.

You can read up on this in the TCS PDR documentation. There is a page in the Advanced LIGO wiki for this review, with links to all the documents. Regarding information flow between TCS and ISC, any slow channel info/control can be done through EPICs. Given the slow nature of TCS, this should mean that nothing is ruled out.

I am also worried about this and don't understand how software development and testing is to be accomplished. An estimate of the amount of code that needs to be written might be useful to scope out the magnitude of the problem.

See 1.5 and 3.6.