LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T1400053-v2 February 10, 2014

Integration testing report for the L1 DRMI

P Fritschel, V Frolov

This is an internal working note
of the LIGO Laboratory

California Institute of Technology
Massachusetts Institute of Technology
LIGO Hanford Observatory
LIGO Livingston Observatory

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

1 Overview

This integration test report covers the DRMI testing on L1. This testing has been carried out in 3 phases, separated by 2 vents of the vertex vacuum volume for various installation tasks.

1. July – mid-Sept 2013. The input power (to the IMC) was limited during this period due to the risk of damaging the IMC mirror coatings, as these mirrors had not been FC-cleaned prior to pumpdown. This phase focused on getting the DRMI locking on the carrier, which required work on the BS actuation and thermally-induced alignment fluctuations.

Mid-Sept vent: Baffle installation; optic cleaning.

2. End-Sept – mid-Nov 2013. This phase focused on locking on the RF sidebands using the 3-f error signals.

Mid-Nov vent: New PR3 baffle; modified PR2 baffle.

3. End-Nov 2013 – end-Jan 2104. This phase focused on noise investigations.

The main goal of the DRMI testing was to achieve robust locking on the RF sidebands using the 3-f error signals, as this is an early step in the planned full lock acquisition scheme. This was accomplished, with plenty of lesson learned as described in this report. A draft locking procedure document has been written: LIGO-T1300991, *PRMI Locking Procedure.*

2 DRMI testing results: checklist review

The list of measurements planned for the DRMI phase was given in T1300558; their status and results are summarized here.

2.1 PRC cavity length

This was measured using the technique described in T1300009 (measuring phase difference between PRMI carrier lock and PRMI RF sideband lock). The result indicated an offset of the PRC length (one-way) of -0.5mm (shorter than nominal); this is relative to the length appropriate to the modulation frequency at the time: 9,099,055 Hz (about 400 Hz lower than the design value). The inferred PRC length is 57.658 m. Design PRC length is 57.656 m, and the length tolerance is a few millimeters. See LLO log entries 8204 and 8562.

More recently the PRC length has been measured with a separate probe beam; see log 10694. The result is a length of 57.6628 m (+/- 2.4 mm), corresponding to a matching modulation frequency of 9,098,584 Hz.

2.2 SRC cavity length

The SRC length was measured with the signal-recycled Michelson (SRMI) configuration, by looking at the REFL 45 I&Q signals for different Michelson offsets; see LLO log entry 8566. Comparison with a model indicates the SRC length is offset from the nominal by about 3 mm (no sign reported); this is relative to the modulation frequency for the measurement: 45,495,275 Hz.

2.3 Schnupp asymmetry

The Schnupp asymmetry was found to be 80 mm, which is the design value. This was measured using the RF phase difference between PRX and PRY configurations; see log entry 8562.

2.4 Michelson contrast defect

The contrast defect was found to be relatively large due to effective curvature differences between the ITM substrates. This could be minimized using the TCS ring heater (RH) on ITMX:

State	Michelson P_{min}/P_{max}	Log entry
Nominal	6 x 10^{-3}	8243
ITMX RH optimized	2 x 10^{-4}	8629

Simulations of L1 (FFT) are found in LIGO-T1301001 and LIGO-G1400092. The current versions give simulation results for the contrast defect (P_{min}/P_{max}) of: 8x10^{-3} (nominal) and 1.3x10^{-3} (minimum with RoC tuning). Why the simulation predicts a significantly higher minimum contrast defect than is actually observed is a mystery at this point.

2.5 Power recycling gain

The power recycling gain is measured to be 35-40 when the ITMX RHs are optimized, and 25-30 with no RH correction; see log entry 9733. The recycling gain is significantly lower than would be expected purely from optic reflectivities (50-55). This was first pointed out by the University of Birmingham group to be caused by a larger than expected beam size, and resultant beam clipping loss at the beamsplitter. The large beam size is a result of the effective radii-of-curvature of the ITMs, including the substrate effects; see LIGO-T1300954 for a write-up of the effect, and a comparison of modeled and measured gain and contrast. (The beam size increase will not occur for the carrier light when we have the full interferometer, as the arm cavities will determine the mode size.)

2.6 Signal recycling gain

The SRC signal gain was measured by comparing the response in ASQ (45 MHz) to a MICH excitation, for the DRMI and PRMI configurations. The latest measurement shows a ratio of 7.5-8 (entry 10769), compared to a calculated ratio of 12.

2.7 Suspension violin mode Qs

The Qs of the fundamental modes of the ITMY fibers were measured in Sept 2103 and found to all lie in the range 113—130 million; see log entry 8628. There was some speculation that these Qs could have been limited by residual gas damping (not likely), or residual adsorbed water on the fiber surface (more plausible). The expected Q in the absence of these effects is about 600 million. More measurements should be taken, for both ITMs. No violin mode Q measurements for any of the recycling cavity triple suspensions have been made to date.

Related mystery: In October 2013 it was noted that the fundamental modes of the ITMY suspension fibers (around 510 Hz) were excited at a level about 1000x higher than the thermal noise level. The high excitation persisted for at least a week (?); in February 2014 they were no longer excited. See log entries 9439, 9470, and 10386.

2.8 Magnetic field coupling to the ITMs

Coupling measurements were made in Nov 2013 using the PRMI to read out the response. See LIGO-G1301268 for the latest summary (and log references therein); more measurements were made in Dec 2013, and should be reported on in the near future. This will be an ongoing investigation as we realize more sensitive interferometer configurations. Currently the measured coupling of magnetic field injections appears to be to electronics (not pin pointed), or possibly to the BS suspension at the lowest frequencies; neither of these couplings should be a concern for full interferometer sensitivity.

2.9 Mode matching to the PRC and OMC

The measured mode mismatch to the PRMI is 10-12% (entry 9733). The mismatch is believed to be mostly due to the ITM substrate lensing (or lack thereof) in the cold state: the PRC mode matching was designed assuming a 35 km thermal lens in each ITM; and the inherent substrate lens term, which is on average negative. See LIGO-G1301122 (the file 'Mode_Matching_CM.pdf').

The measured mode matching to the OMC is 74%, using a bright Michelson beam. This significant mismatch is understood as due to a combination of the ITM substrate lens terms (or absence of, in the case of the assumed thermal lens) and small errors in the radii-of-curvature of the PR3/PR2/SR3/SR2 optics and/or their physical separations. See LIGO-G1300909 and LIGO-G1400107 for details.

2.10 Length fluctuation spectra (control band)

Calibrated length fluctuation spectra in the band 1mHz—10 Hz were made for the IMC length, PRCL, and MICH; see log entry 9852. The rms length fluctuations, down to 1 mHz, are: IMC length, 300 nm; MICH, 2 microns; PRCL, 1 micron. These are dependent on the ISI control filters, as described in the referenced log entry.

2.11 Alignment fluctuation spectra (control band)

Angular motion spectra for the BS, ITMY, PR3, and SR3 were measured using their optical levers. See log entry 10587 for results.

2.12 LSC sensing matrix

Measurements were made for both the PRMI and DRMI; see logs 8434 and 8232, respectively. The results are not simple to summarize—it is still a work in progress. Latest result: the Michelson optical gain at the AS port does agree fairly well with expectations: 10799.

2.13 ASC sensing matrix

The most recent ASC sensing matrix is reported in entry 9669. Verification and comparison with models is still in progress.

2.14 Michelson noise spectrum and noise budget

The most recent Michelson noise spectrum is from Jan 14, 2014, log entry 10414. This was in the PRMI configuration, with 10 W input to the IMC, and reading out the Michelson using DC readout with the OMC. The Michelson noise is limited by laser intensity noise at all frequencies above 20Hz (roughly 1×10^{-16} $\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz).

2.15 TCS testing

The basic functionality of the ITM ring heaters was confirmed as they were used to balance the substrate lensing between the two arms. The Hartmann wavefront sensors (HWS) were successfully aligned to both X and Y arms. The CO_2 laser projectors were not installed at the time of this writing.

The performance of the HWS was characterized in terms of the stability over time of the wavefront curvature measurement. The stability is essentially at the required level (of 2.5×10^{-6} m^{-1} curvature at the ITM).

The TCS testing performed up to early January 2014 is presented in LIGO-G1400018.

3 Actions resulting from DRMI testing

3.1 Engineering change requests

ECR	Title	Comment
E1300789	ECR for 135 MHz chain (REFLAIR-B on ISCT6)	The signal from this detector is used for 3-f locking of the DRMI. The signal strength was found to be too small, so this ECR is for adding amplification as well as RF filtering to this signal chain. An RF diplexer amplifier was designed for the job: LIGO-E1300852
E1300788	ECR: add baffle to PR3 suspensions to prevent wire heating	PR3 was observed to drift in pitch when there was significant power buildup in the PRC. It was suspected that some of the cavity beam was being absorbed by the PR3 lower suspension wires, making them heat up and expand. Baffles to shield the wires were designed and installed on both L1 and H1. Subsequent L1 testing showed that the PR3 drift problem was fixed.
Bug 474	PR2 scraper baffle modification (no ECR)	Suspicious of the PR2 scraper baffle as a cause of the low recycling gain, it was discovered that the hole in this baffle for the PRC beam was made smaller than intended. New baffles were made and installed in both L1 and H1: LIGO-D1000328. It was later established that the original baffle was not the cause of the low gain (see section 2.5).

3.2 Lessons learned & Open issues

3.2.1 Beam Splitter pitch drift

The BS drifts in pitch when there is significant power buildup in the PRC; log entry 9920 reports 5 micro-radian of pitch with 60 W in the cavity. The suspected cause is suspension wire heating from absorbed cavity beam light (as with PR3). The effect is presumably made worse by the enlarged beam size in this configuration, and may not be so significant in the long term. Nonetheless, designs for shielding the BS suspension wires are being pursued. This issue is in the Integration Issue Tracker, as bug #505.

3.2.2 Recycling cavity mode & mode-matching

It was always planned that the positions of the recycling cavity mirrors may need to be iterated to optimize the mode-matching (measurements of the radii-of-curvature are not accurate enough). For L1, we may need to adjust the PR3-PR2 & SR3-SR2 separations in the future. Prompted by the L1 mode-matching results, a plan for measuring the PRC mode-matching parameters was developed, and is being tried first on H1; see LIGO-T1400013. The latest summary of the mode-matching situation, including options for addressing it, is in LIGO-G1400107; see also log entry 10762 on the PRC probe beam measurements.

Even though the large beam size at the BS and the resulting low recycling gain should not be an issue for the carrier when the arms are resonant, the effect will remain for the RF sidebands. This will affect the sensing gain for all the RF error signals. The real impact of this is not yet known, but modeling work is in progress.

3.2.3 Alignment control & Wavefront sensors (WFS)

Alignment control was found to be necessary to deal with the thermally induced misalignments of PR3 and the BS. At first the in-air WFS were used for alignment sensing, then the in-vacuum WFS were used after they were installed and checked out. Lessons learned from implementing alignment control:

- Beam parameters for a WFS chain need to be measured in-situ and the Gouy phase telescopes iterated for the measured parameters (design values are not good enough). In retrospect, measurements of the ISC telescope lenses might have been useful.
- First use of in-vacuum WFS. Though cabling up the in-vac WFS can be tricky, once done they worked just as well as the in-air WFS. We may be able to bypass the in-air WFS, and start directly with the in-vac WFS in the future.
- Beam centering control on the WFS is needed for robust operation (low bandwidth), to deal with drifts or other changes in alignment from day to day. With the in-vac WFS, centering using the HTTS optics works as planned.
- WFS beam size. There was some concern that the design value for the beam size on the WFS diodes was too small. This is still a bit of an open issue, but we have kept the design beam size for further evaluation.
- Offsets to the WFS error points are required to maximize power buildup in the PRMI. The offsets appear to be optical in origin (not electronic), and exist both for the in-air and in-vac WFS. The cause is an open issue.

3.2.4 BSC ISI CPS noise

Two issues involving the capacitive position sensors (CPS) in the BSC ISI platforms would cause excess noise and sometimes prevent DRMI locking: broadband noise from grounding problems; discrete frequency combs due to beating between CPS oscillators. Both of these issues are being addressed with hardware modifications, and are tracked in the Integration Issue Tracker in bugs #629 and 630.

3.2.5 Beam Splitter actuation

Actuating on the BS to control the Michelson proved to be trickier than expected. One problem was that the acquisition forces applied to the BS penultimate stage would trip the ISI watchdogs (there is no reaction chain for the BS suspension). This was avoided by disabling ISI stage 2 isolation loops for acquisition (they can be engaged after acquisition). More work was devoted to reducing angular fluctuations of the BS. This was accomplished with a combination of implementing optical lever damping of the BS, and careful force-to-angle decoupling at the actuated (penultimate) stage of the BS. This work is described in log entries:

- 7723 & 7726: first designs of force-to-pitch (F2P) and pitch-to-pitch decoupling filters
- 7835: final result after implementing optical lever loops to reduce suspension mode Qs; demonstrated factor of 30 reduction of pitch motion due to force feedback with designed F2P filters

Note: need to document a more detailed procedure for this.

3.2.6 RF Modulation depth

The design modulation depth of 0.1 radians was found to be too small for 3-f locking. Most of the DRMI locking was done with a modulation depth of 0.3 radians. Tests are still being done to see if this can be reduced to 0.15-0.2 radians.

3.2.7 Vertex cavity lengths

It is not yet clear how well we need to match the IMC length and the PRC length (ideally, L_PRC = 3.5*L_IMC). Currently, the modulation frequency that matches the IMC length is a 400 Hz to 800 Hz higher than the frequency that matches the PRC length (depending on which PRC length measurement is used). In log entry 10354, it was found that the frequency needed to be matched to the PRC length in order to transition DRMI control to the 3-f error signals. The IMC and PRC lengths may need to be matched in the future by repositioning the HAM3 ISI platform.

3.2.8 Laser intensity noise

As noted, the Michelson noise is limited by laser intensity noise above 20 Hz; this is even with the ISS outer loop engaged. Scattered light and/or beam clipping is probably at least part of the problem; engaging the ISS outer loop actually impresses extra noise on the laser intensity over much of the band. See log entry 10032.

3.2.9 OMC length noise

The length noise of the OCS has been measured by locking it at half-fringe to the beam from the IMC (beam from single ITM). Many noise peaks are observed around 1 kHz, and the highest of these are about 100x higher amplitude than the safe OMC length noise level estimated in T1000276. See log entry10554 and the other entries reference therein. This is an ongoing investigation.

3.2.10 Input power for locking

We would like to lock at a relatively high IMC input power, so as to minimize the amount of power ramping that is needed later for science mode operation. For most of the DRMI testing the locking power was 3 W (into the IMC), but they are attempting to increase it to 10 W.

3.2.11 Automated initial alignment procedure

An outstanding issue is to develop an automated (or least partially automated) procedure for achieving initial alignment of the DRMI. Currently, the initial alignment is manually tuned by the commissioners before locking. Creating a procedure that can be performed by operators will be a challenge.