



*LIGO Laboratory / LIGO Scientific Collaboration*

LIGO-T1300495-v3

*Advanced LIGO*

Date: January 28, 2014

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TCS Testing for the DRMI Test at LLO  
(Summer 2013)

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Distribution of this document:  
LIGO Scientific Collaboration

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## 1 Introduction

The purpose of this document is to describe the proposed testing of TCS during the Dual-Recycled Michelson (DRMI) Test at LLO during Summer of 2013.

## 2 References

## 3 Available components

All corner station TCS components will be available during the DRMI. These are:

- ITMX and ITMY Hartmann Wavefront Sensors
- ITMX and ITMY Ring Heaters
- ITMX and ITMY CO<sub>2</sub> laser projectors

## 4 Scientific test

There are three main scientific aims to TCS testing

- 1) Characterize the precise and accuracy of the vertex Hartmann sensors
- 2) Verify that the spatial profile of the thermal lens is as expected (accounting for time)
- 3) Characterize the noise coupling to the interferometer beam

## 4.1 Precision and accuracy of Hartmann sensors

### 4.1.1 Precision

- Leave the HWS running for 24 hours or longer with the IFO with the ITMs and BS controlled or at least damped.
  - Plot the noise spectrum for the Zernikes (PRISM, SPHERICAL POWER, ASTIGMATISM) versus the expected Gaussian noise floor?
  - Plot RMS (with PRISM removed) spectrum vs Gaussian noise floor
- Repeat this measurement on HWS with the HEPA filters – over a 1 hour time period (this is a low priority measurement simply for reference)

Measure RMS wavefront distortion with prism removed. This will test [LIGO-T1100517-v7](#), Section 3.1: **Wavefront sensitivity  $\leq 1.36\text{nm}$  at the HWS**

- Plot the noise spectrum of the Zernikes corresponding to PITCH and YAW?
  - Determine the motion of the HWS beam from ISI and suspended optic motion. Plot on the same plot as HWS measured Zernikes.
- Plot the coherence between Zernikes.

### 4.1.2 Temperature coupling

- Leave the HWS running for 4 days or longer with the IFO with the ITMs and BS controlled or at least damped.
  - Plot the PRISM and (time-averaged) DEFOCUS signals vs in-chamber and in-air temperature
    - Is there any evidence of diurnal fluctuations in the HWS tilt and defocus signals?
    - Plot the temperature-induced defocus from known couplings (HWS, in-air table, in-chamber table).
    - Include a plot of the maximum acceptable defocus over time.

This will test [LIGO-T1100517-v7](#), Section 3.2.2:

**$\Delta S \leq 7.4\text{E-4 m}^{-1}$  at the HWS**

### 4.1.3 Accuracy

- Induce a thermal lens in one ITM (either CO2 laser or Ring Heater).
  - Measure with the HWS.
  - Use the OMC to scan the HOM present in a beam from the relevant optic.
    - E.g. look for astigmatism from the RH.
  - Operate the IFO only as a Michelson.
    - Use it as a phase-scanning interferometer by modulating the position of one of the ITMs. Measure the interference pattern intensity distribution on OMC REFL camera of the interferometer.

- Extract wavefront map at the output of the IFO. Compare to the HWS. Account for the difference in position of the HWS and AS camera optical planes.

The target accuracy of the HWS is not well defined as a requirement as the system is designed to operate at a null point – which makes the precision more important.

#### 4.1.4 Characterize the imaging

- Imaging – confirm we can get the HWS positioned at the image plane of the ITM.
  - Modulate the ITM YAW at 100mHz.
  - Remove the HWS Hartmann plate.
  - Measure the return beam centroid vs time. Determine the amplitude of the 100mHz position modulation.
  - Move the HWS along the optical axis and repeat. Plot the amplitude of the 100mHz beam position vs position on the optical axis.
  - Move the HWS to the point on the optical axis of zero amplitude.
  - Move the HWS 11mm back along the optical axis to account for the HWS lever arm

This will demonstrate [LIGO-T1000179-v17](#), Section 1.1, Item 1: **HWS conjugate plane no further than 1500mm from ITM.**

- Measure the magnification by inducing a known YAW into the ITM and measuring the YAW at the HWS.
  - Compare PRISM measured at the HWS with PRISM predicted by the injection into ITM YAW versus PRISM measured by optical lever.
  - Magnification =  $OL\_PRISM/HWS\_PRISM$

This will test [LIGO-T1000179-v17](#), Section 1.1, Item 2: **ITM to HWS magnification should be 1/17.5x**

#### 4.1.5 Determine the cross-coupling of ITMX and ITMY signals

- After the imaging test, measure the power returned from each test mass by measuring all permutations of ITMX and ITMY being aligned and then misaligned.

#### 4.2 Verify spatial profile of thermal lens

- Induce a thermal lens in the ITM with the CO2 laser.
- Characterize how well it matches the predicted thermal lens versus time.
  - Plot the RMS difference between predicted distortion and measured distortion (HWS or MICH) versus time. A simple scaling the predicted wavefront distortion model to minimize RMS is acceptable as this simply accounts for errors in power applied.

This will test [LIGO-T1100570-v3](#), Section 3.2: **Requirements for the optical design: an annular pattern that produces a thermal lens that results in a residual optical path distortion that scatters less than 0.1%.** Test this using models and data from this measurement.

- Calibrate the power required to produce a given thermal lens. Compare to the predicted value.
  - Make a note if the difference is greater than 10%.

- Quantify the difference in RH-induced TL from the expected value.
- Measure the non-axi-symmetric component of the thermal lens from the ring heater
  - Compare the astigmatic component of the RH thermal lens to the models produced by UF. Plot astigmatism versus time measured with HWS and AS port camera

### 4.3 Characterize displacement noise coupling to IFO

- Measure the transfer function between laser intensity noise and displacement noise on the interferometer.
  - A 1W annular beam modulated around 150Hz with 0.01 modulation depth should produce a displacement noise of around 1E-15m. The DRMI is expecting a displacement sensitivity of around 1E-17m.
  - Repeat transfer function measurement with central heating beam
  - Is the CO2 coupling to displacement noise as expected? Determine if this can be used to align the CO2 laser beam to the interferometer.

This will test the RIN-DN coupling calculations made for [LIGO-T1100570-v3](#), Section 3.1.1: **Amplitude noise requirement.**

- What is the RIN measured by the ISS photodiodes?
- Is there any evidence that there is excess noise coupled to displacement noise?
  - Measure the noise coupled to the IFO.
    - Can we integrate for a long time to determine the coherence?
  - Is there any excess CO2 laser noise? Modulate CO2 laser at  $< 1$  Hz and integrate displacement noise spectrum.<sup>1</sup>
  - Demodulate the DN spectrum at the CO2 modulation frequency and look for CO2 laser noise coupling. Plot the expected coupling from the known ISS laser noise and RIN-DN transfer function.

This will test [LIGO-T1100570-v3](#), Section 3.1.1: **Amplitude noise requirement.**

- Measure the long term intensity noise and monitor for variations. Plot in-band RMS (20-2000Hz) versus time.
- Can we produce displacement noise with the HWS?
  - Put a chopper in HWS beam. Measure the DN spectrum at the chopping frequency. Determine noise coupling and compare to the expected value.

This will test [LIGO-T1100517-v7](#), Section 3.2.3: **Requirements to prevent degradation of aLIGO performance.**

- Question for commissioners: what is the displacement noise in DRMI test?

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<sup>1</sup> The purpose of this is to try to measure the actual intensity noise coupled into the IFO from TCS. By modulating the power at a low frequency, we can double demodulate (demodulate the IFO noise spectrum at the low frequency modulation). Additionally, the low frequency modulation allows us to coherently integrate for some time to improve the sensitivity of this measurement. Those frequencies in the noise curve that are coherently modulated with the low frequency TCS modulation tell us about the noise that TCS is coupling in. In particular, we want to see if the injected noise spectrum from TCS contains any features (e.g. beam jitter?) that are not present in the measured intensity noise spectrum (measured on the TCS table).

The lower modulation frequency has to be carefully chosen: too high and we'll just see it and harmonics of it in the IFO noise spectrum; too low and everything about the IFO will increasingly vary at that frequency.

## 4.4 Minor science objectives

### 4.4.1 Characterize the internal temperature spectrum of the HAM chambers?

- Retrieve data from the 4 HAM chamber temperature sensors and plot spectra of internal temperature fluctuations.
- What is the coupling/transfer function from the exterior temperature on the chambers?

### 4.4.2 What is the coupling of ISI motion to HWS measurements?

- Measure the motion of the HWS return beam on the HWS when actuating on the HAM4 and HAM5 ISIs.
- Determine the coupling to 1<sup>st</sup> and 2<sup>nd</sup> order Zernike's.
- Produce a plot of the noise coupling to HWS measurements based on nominal motion of HAM ISIs.

Measure RMS wavefront distortion with prism removed. This will test [LIGO-T1100517-v7](#), Section 3.1: **Wavefront sensitivity  $\leq 1.36\text{nm}$  at the HWS**

### 4.4.3 Self heating from the interferometer

It is an interesting investigation to see if we can see any evidence of self-induced thermal lensing from the interferometer. If the HWS functions at or close to its nominal performance and is limited by Gaussian noise, it may be possible to measure the thermal lensing from self-heating of the interferometer.

- Self heating thermal lens (assuming  $\sim 350\text{W}$  of stored power in the PRC, and  $0.3\text{ppm}$  absorption)
  - Magnitude:  $50\text{pm}$
  - Time constant:  $\sim 20$  minutes
- HWS nominal sensitivity
  - $\sim 100\text{pm}$  across the Gaussian beam size
  - Measurement time:  $\sim 5$  seconds
  - Measurements per self heating time:  $\sim 240$
  - Gaussian limited sensitivity over 20 minutes:  $6.5\text{pm}$
- Leave HWS running and turn PSL laser power up and down over 40 minute periods for a 12 hour period.

## 5 Engineering aims

Additionally, a selection of engineering testing must be performed.

### 5.1 EtherCAT chassis

- Check that the EtherCAT system functions as expected
  - Confirm all channels can be accessed when EtherCAT chassis is integrated into site EtherCAT system
  - Confirm all channels are saved to frames.

This will test [LIGO-T1100517-v7](#), Section 6.3: **EtherCAT control**

- Confirm all inputs and outputs control all TCS electronics

This will test [LIGO-E1100892](#), **TCS Electronics block diagram**

- Monitor long-term performance of EtherCAT for glitches. These should be present across multiple channels.

## 5.2 Hartmann sensor

- What is the total return optical power level from the ITM?
  - How does that vary versus the predicted level predicted in [Table 1 in T1000682](#)
  - What is the resulting acquisition speed of the HWS? Confirm that it is greater than 1 measurement per 5s.

This will test [LIGO-T1100517-v7](#), Section 3.2.1:

**Minimum measurement speed = 200mHz (1 measurement per 5s).**

- How much does the HWS beam move around as the IFO is aligned? Quantify the RMS motion of the HWS prism as the IFO alignment takes place.
- How much diffraction is there on the HWS beam? Remove the HWS plate. Compare the image of the HWS beam to that predicted from ZEMAX. If the difference is noticeably bad, make a note of this and, possibly, adjust the alignment.

This will test [LIGO-T1100517-v7](#), Section 5.1.3: **Diffraction in the ITM optical layout**

- Verify the display and acquisition of HWS phase-maps on CSS and in frames, respectively.
- Confirm that all HWS code functions as expected.
  - Confirm HWS code produces sensible data in EPICS channels.
  - Confirm launching and exiting functions as detailed in User Manual
  - Make note of any crashes that occur.

This will test [LIGO-T1100517-v7](#), Section 7: **HWS software**

- Confirm all HWS hardware/electronics works as expected. Measure long-term HWS SLED power level.
  - Verify functionality of each of the electronics chassis when it is built in-situ. This can be done, for most of them, simply by demonstrating the EtherCAT channels work as expected.

This will test [LIGO-T1100517-v7](#), Section 6: **HWS Electronics**

- What is the leakage field from of 1064nm into the HWS table? Set the IFO to dark/bright fringe?
- Measure backscatter into the interferometer – reflect light and modulate it with chopper or PZT (Too little displacement noise sensitivity?)

This will test [LIGO-T1100445-v5](#), Section 4.1.10: **H1 & L1 Hartmann Beam Scatter**

## 5.3 CO2 laser projector

- Verify the real-time CO2 laser control model functions as expected
  - Inspect all channels in the model to determine if they are accessible as expected and pass data as required.

This will test [LIGO-T1100570-v3](#), Section 8.1: **Realtime code**

- Characterize long-term CO2 laser performance
  - Measure the power on all PDs and QPDs.
  - Plot these channels versus time on spectrum
  - Quantify the rate of glitches over the summer (excluding those that occur during and shortly after CO2 laser maintenance)

This will test [LIGO-T1100570-v3](#), Section 3.2.2.1: **Reliability** and Section 3.2.2.3: **Glitches/mode-hops**

- Characterize long-term CO2 laser performance
  - Measure the position of the beam on the 2 QPDs
  - Plot the beam axis position and angle versus time.
    - Also use the HWS and IFO ASC signals<sup>2</sup> to determine the variation in pointing drift of the CO2 laser on the ITM.
  - Plot the RMS beam motion over summer on a scatter plot

This will test [LIGO-T1100570-v3](#), Section 3.2.2.2: **Beam pointing**

- Measure the CO2 laser temperature spectrum over summer
- Confirm all CO2 laser hardware/electronics works as expected
  - Verify functionality of each of the electronics chassis when it is built in-situ. This can be done, for many of them, simply by demonstrating the EtherCAT channels work as expected. The earlier verification of all real-time channels will complete this verification.
- What is the maximum that is deliverable from the CO2 laser table?
  - Measure the CO2 laser power delivered from the table.
  - Determine the ratio of the power leaving the table to the power level measured with the on-table power meter.

This will test [LIGO-T1100570-v3](#), Section 3.2: **Requirement for optic design: 15W must be available.**

- Test CO2 thermal imaging camera
  - Confirm images can be accessed and stored for analysis

This will test [LIGO-T1100570-v3](#), Section 8.2: **GigE beam imaging cameras**

## 5.4 Miscellaneous tests

Run tests on TCS predictor (based on work with SURF)

- what are the aims of this?
- Monitor thermal lens vs time and compare to model predictions

Evaluate coupling of TCS to IFO alignment

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<sup>2</sup> Aside from using the HWS, maybe we could derive something from the alignment signals from the IFO. Assuming we inject an axially symmetric beam onto the ITM and place it co-axially with the IFO beam, then the alignment signals shouldn't change (not 100% true as the Gouy phases will change due to lensing). This is actually a topic for investigation from the commissioning meeting back in January.



Cavity scan with RHs running in DRMI – how much does astigmatism show up?