LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note **LIGO-T1500022-2-D** 2015/08/06

CO2 RIN coupling to DARM for aLIGO TCS

Aidan F. Brooks, Cheryl Vorvick

Distribution of this document:

Detector Group

California Institute of Technology
LIGO Project, MS 100-36
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
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
PO Box 159
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

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

1 Introduction

The coupling of CO2 laser intensity noise to DARM is described in detail in Section 2.8.5 of Stefan Ballmer's thesis. To convert this analysis to aLIGO, we must account for the change in the TCS configuration between eLIGO and aLIGO. In eLIGO, the TCS laser actuated on the HR surface of the ITM (within the arm cavity). In aLIGO, the TCS laser actuates on an AR surface of the compensation plate (within the PRC).

The difference allows us to ignore the surface thermal expansion of the optic, equation 2.36, and simply use equation 2.37 as a measure of the total change in optic thickness. The total displacement noise is given by this modified version of equation 2.38:

$$\Delta z(x,y) = \frac{\pi}{2\,F}\left[(n-1)(1+\eta)\alpha + \frac{dn}{dT}\right]\frac{1}{2\,\pi\,i\,f\,C\,\rho}\,p(x,y)\,\mathrm{RIN}(f) \tag{1}$$

where RIN is the relative intensity noise. The mean displacement noise,$\langle\Delta z\rangle$, is given by the integral of $\Delta z(x,y)$ over the entire optic weighted by the intensity of the carrier laser beam profile.

$$\langle\Delta z\rangle = (...)\frac{\int I(x,y)\,p(x,y)\,dx\,dy}{\int I(x,y)\,dx\,dy}, \tag{2}$$

where the total power P is given by:

$$P = \int p(x,y)\,dx\,dy \tag{3}$$

2 Central heating

2.1 Central heating coupling

For central heating, the beam on the test mass is described by the following equation:

$$p_{cent}(r) = \begin{cases} P\,n_{cent}\exp\left(-2\,\frac{r^2}{w_{cent}^2}\right) & : r < a_{cent} \\ 0 & : r \geq a_{cent} \end{cases}$$

where:

$$n_{cent} = \frac{2}{\pi\,w_{cent}^2}\,\frac{1}{1-\exp\left(\frac{-2a_{cent}^2}{w_{cent}^2}\right)} \tag{4}$$

For aLIGO TCS central heating, the following values apply:

Description	**Symbol**	**Value**
CO2 central beam radius	w_{cent}	215 mm
CO2 central mask radius	a_{cent}	97 mm
Specific heat capacity of CP	C	740 J/kg/K
Density of CP	ρ	2196 kg/m^3
Refractive index of CP	n	1.45
Poisson ratio of CP	η	0.17
Finesse of arm cavity	F	450
Thermo-refractive coefficient	$\frac{dn}{dT}$	8.6E-6 K^{-1}
Coefficient of thermal expansion	α	0.55E-6 K^{-1}

For aLIGO central heating, this translates to:

$$\langle \Delta z \rangle_{cent} = 1.2 \times 10^{-15}\,\mathrm{m} \left(\frac{100\,\mathrm{Hz}}{f}\right) \left(\frac{P}{1\,\mathrm{Watt}}\right) \mathrm{RIN}(f) \tag{5}$$

2.2 Central heating alignment

Generally, the CO2 laser beam is not concentric with the IFO beam on the test mass after initial alignment.

The CO2 intensity noise coupling to DARM can be used to fine-tune the alignment of the central heating beam to the interferometer mode. This is done by injecting a large oscillation into the intensity of the AOM, observing the resulting peak in the DARM spectrum, and then adjusting the alignment of the CO2 laser beam in real-time to maximize the injected signal in DARM.

We can maximize the coupling to DARM by:

- Lowering the frequency of the injected signal. This is really only effective in frequency regimes where the DARM signal is flat. We recommend 85Hz.
- Increasing the absolute power onto the CP. We recommend using 100mW (this is small enough to inject a signal but not large enough to change the lens in the CP to such a point that the IFO becomes inoperable).
- Increasing the magnitude of the injected signal on the AOM. A RIN of 0.05 is the what we recommend.

As the CO2 central heating beam is scanned across the CP surface, the overlap integral in Equation 6 becomes:

$$\langle \Delta z \rangle = (\ldots) \frac{\int I(x,y)\, p(x + xc, y + yc)\, dx\, dy}{\int I(x,y)\, dx\, dy}, \tag{6}$$

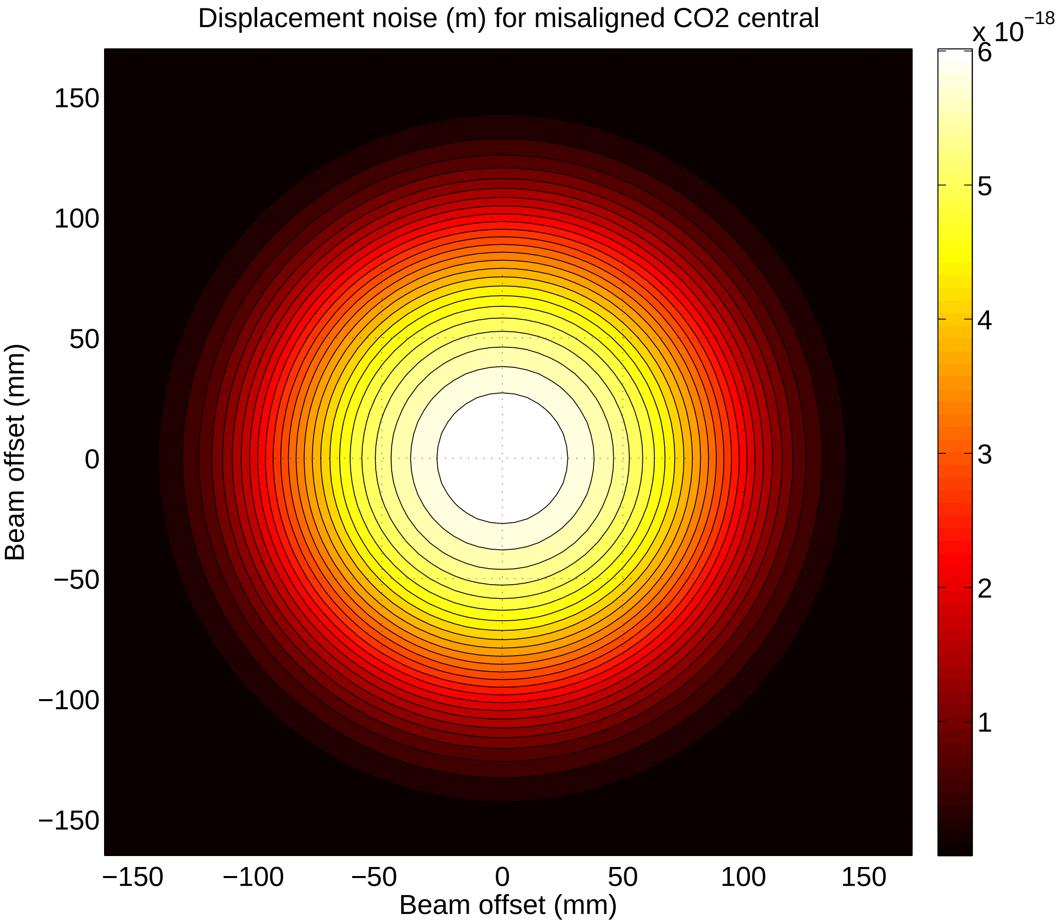

Figure 1: Model of the displacement noise amplitude in DARM for a CO2 central heating beam scanned across the ITM. Power = 100mW, frequency = 85Hz, RIN = 0.05.

3 Annular heating

3.1 Annular heating coupling

The optimum annular heat distribution, described in LIGO-T0900217-v2, is shown in the figure below. The data is at the end of this Technical Note.

The average intensity is, for 1 W of input power:

$$\begin{aligned} \langle p \rangle &= \frac{\int r\, I(r)\, p(r)\, dr}{\int r I(r)\, dr} \\ &= 11\,\mathrm{W/m^2} \end{aligned} \tag{7}$$

Therefore, the annular heating coupling is:

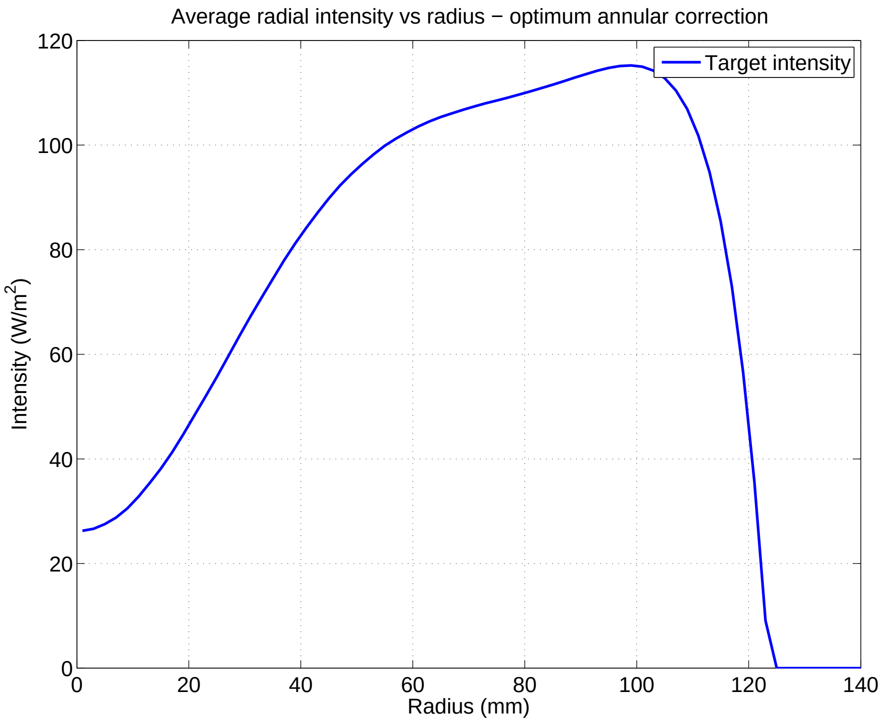

Figure 2: Optimum annular intensity to correct for residual thermal lensing from self absorption and ring heater. For 4.52W of applied power

$$\langle \Delta z \rangle_{cent} = 3.3 \times 10^{-16}\,\mathrm{m} \left(\frac{100\,\mathrm{Hz}}{f}\right) \left(\frac{P}{1\,\mathrm{Watt}}\right) \mathrm{RIN}(f) \tag{8}$$

```
Radius[mm]  p(r) [W/m^2]
   1.0000   26.2527
   5.0000   27.5310
   9.0000   30.5118
  13.0000   35.3741
  17.0000   41.2314
  21.0000   48.3141
  25.0000   55.6658
  29.0000   63.4274
  33.0000   70.8296
  37.0000   77.9145
  41.0000   84.2130
  45.0000   89.7737
  49.0000   94.4203
  53.0000   98.2165
  57.0000  101.2316
  61.0000  103.5485
  65.0000  105.3572
  69.0000  106.7516
  73.0000  107.9761
  77.0000  109.0792
  81.0000  110.2707
  85.0000  111.5475
  89.0000  112.9186
  93.0000  114.2121
  97.0000  115.1209
 101.0000  114.9799
 105.0000  112.7945
 109.0000  106.8881
 113.0000   94.8066
 117.0000   72.8475
 121.0000   35.6713
 125.0000         0
```