LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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LLO BS Prism Gluing Issue and Resolution

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1   Introduction

1.1   Purpose and Scope

When the LLO BS was hung, it had a large pitch offset, possibly due to prisms glued in the wrong position. This document describes the efforts to understand the problem and the eventual decision to correct it using trim mass at the IM.

1.2   References

LIGO-E1000753: Preparation of a beamsplitter or folding mirror (BS/FM) (Gluing primary and secondary wire break-off prisms)

LIGO-E1000829: BS/FM Prism Gluing Jig Settings Calculation Spreadsheet

LIGO-D0901076: adLIGO SYS ASSEMBLY OF BS OPTIC with PRISMs

LIGO-D080660: D080660_ALIGO COC_BS_SUBSTRATE

LIGO-D080765: aLIGO Beam Splitter Wire Breakoff Prism

LIGO-Q1000008: Inspection document for the primary wire break-off prisms for the beamsplitter/folding mirror

LIGO-D0902368: Adv LIGO SUS FM / BS 2nd Prism Metal

LIGO-D1002147: aLIGO BS/FM Prism bonding jig

LIGO-E1000752: Preparation of a thermal compensation plate (TCP) or end reaction mass (ERM) (Gluing wire break-off prisms and earthquake stops)

LIGO-E1100601: aLIGO SUS BSFM Tooling

https://redoubt.ligo-wa.caltech.edu/svn/sus/trunk/Common/MathematicaModels/TripleLite2/mark.barton/bsimbalance
(location in SUS SVN repository of Mathematica triple suspension models prepared for this report)

1.3   Version history

8/8/12: Pre-rev-v1 draft.

8/16/12: Pre-rev-v1 draft circulated for discussion.

8/17/12: -v1 incorporating feedback but still preliminary.

2   Background

BS and FM optics have prisms glued to the sides to locate the wires that support them (Figure 1). On each side there is a double-notched primary prism (D080765) of sapphire which sets the breakoff positions of the two wires and below it a similar secondary prism of metal (D0902368) which helps constrain the angles of the wires as they pass through the primary prism notches.

Figure 1: View of BS (or FM) with prisms
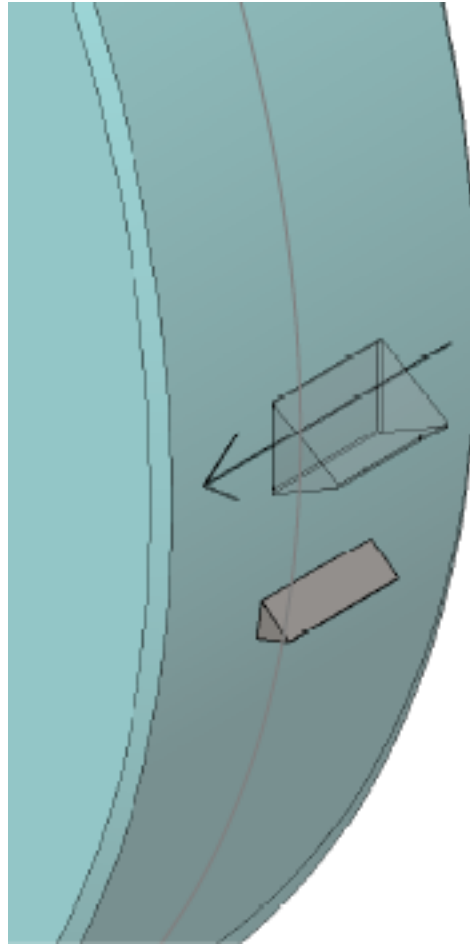
The prisms are attached with EP30 glue using the jig D1002147 according to the procedure E1000753 in conjunction with the jig setting calculation spreadsheet E1000829.

The optic has an arrow reference mark (ARM) scribed by the vendor on the barrel (Figure 1). The body of the arrow indicates the thinnest point of the wedge, and the arrowhead points to the "HR" (i.e. beamsplitting) surface, which is defined to be the front. When viewed from the front in the install orientation, the ARM is at the 3 o'clock position, i.e., the wedge is horizontal. There are also non-arrowed fiducial marks at the 12, 6 and 9 o'clock positions. Prisms are glued at the ARM position and diametrically opposite - the "180ARM" position.

The equilibrium position and dynamics of the pendulum are affected by the position of the primary prisms. The vertical position sets the parameter d4 (see e.g., T080188) which has little effect on anything but the fundamental pitch frequency, and then only a modest one, so the requirement is very loose (±1 mm). The procedure calls for the prisms to be located directly on top of the ARM and 180ARM lines, and the jig is designed with this assumption. In fact the vendor did a very sloppy job of placing the fiducials but since there is no provision in the jig for aiming off, it was decided to place the prisms over the fiducials regardless even though this used up a good fraction of the tolerance in some cases.

Conversely, front-back prism position errors move the COM relative to the supporting wires, and because the pendulum is very soft against pitch torques, there is a very tight requirement: ±0.1 mm, or better if possible.

For the optic not to create a pitch torque, the COM must lie on the line between the prism centres as viewed from above. To allow for the horizontal wedge, the procedure uses the front surface as a reference for both prisms, and sets them both back relative to this surface by a common amount equal to the average thickness of the mass. This choice has the advantage that the front surface will not be yawed relative to the plane of the wires or the upper masses - all the yaw will be in the back face. (An obvious alternative would be to put each prism halfway back on its respective face, splitting the yaw between front and back faces.) A common-mode error (both prisms too far or too close to the front surface) is much more problematic (because it produces large pitches), than a differential-mode error (which produces only a small yaw).

The front-back position is set by adjusting a pair of micrometers (see Figure 2), which protrude sideways from the underside of the jig and keep it a precisely settable distance from the front surface. The same jig is used for both the left and right sides of the optic, and to facilitate using the front surface as a reference in each case, the jig has two independent pairs of micrometers. The appropriate settings for the micrometers, D_{screw1} and D_{screw2}, are calculated using the spreadsheet E1000829. D_{screw1} is applied to the left micrometers when gluing to the ARM side of the optic with and D_{screw2} is applied to the right micrometers when bonding on the 180ARM side. The inputs to the calculation are

1. x_{j1} and x_{j2}: The distances on the jig from the surfaces where the micrometers emerge to the surface which locates the prism holder. These have nominal values of 16 and 50 mm but the actual values including any machining error are measured for each jig (see Figure 2).
2. x_{ph}: the distance on the prism holder from the surface that references the jig to the surface that references the prism (see Figure 3).
3. w_p: the distance on the prism from the surface that references the prism holder to the midpoint between the notches (see Figure 4)
4. w_M: the thickness of the mass measured at the barrel axis, equal to $(w_{max} + w_{min})/2$ (see Figure 5).

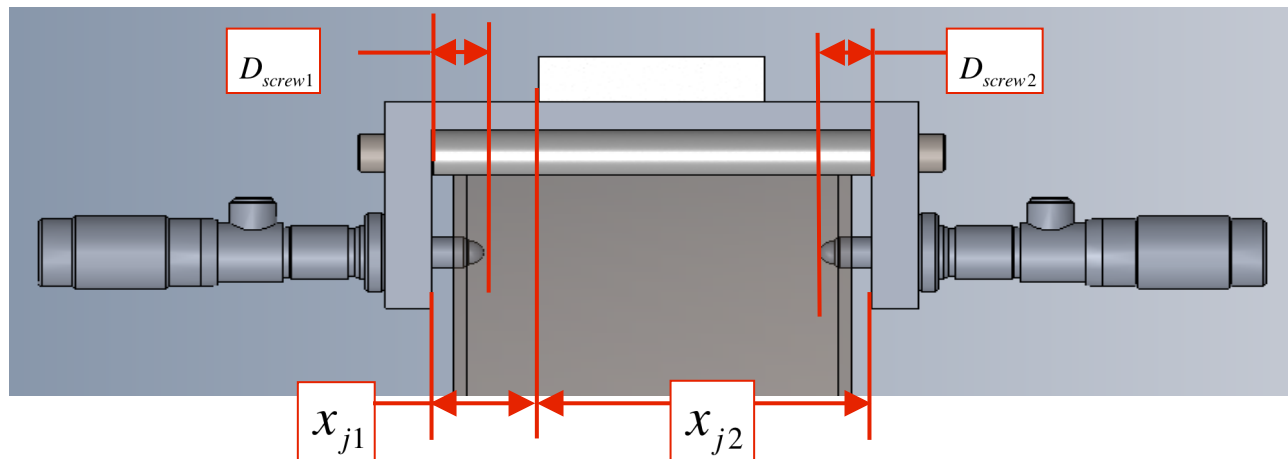**Figure 2: Jig parameters**

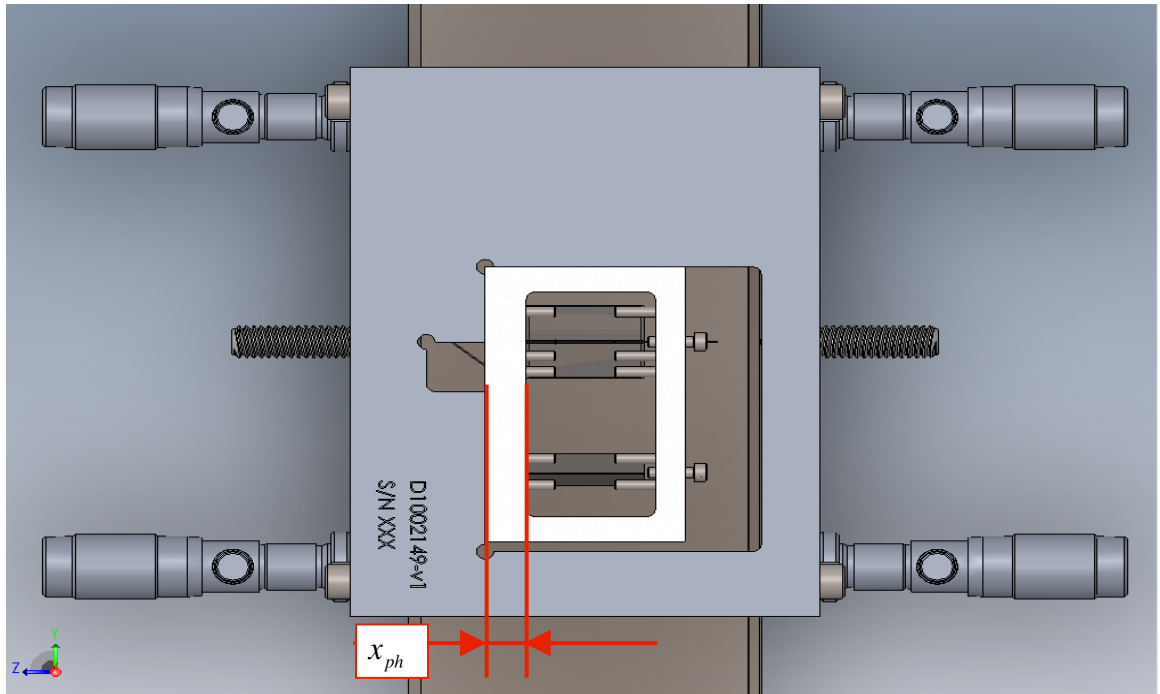**Figure 3: Prism holder parameters**
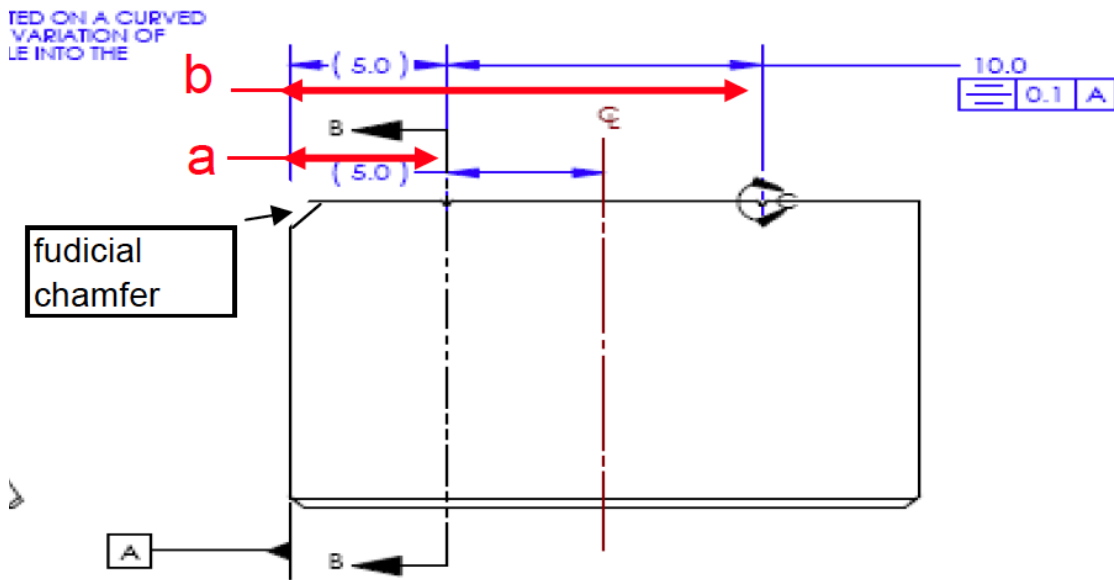

Figure 4: Prism parameters

Figure 5: Mass parameters

[add diagram here]

In terms of these parameters,

$$D_{screw1} = x_{j1} + x_{ph} + \frac{w_{p1}}{2} - \frac{w_M}{2}$$

$$D_{screw2} = x_{j2} - x_{ph} - \frac{w_{p2}}{2} - \frac{w_M}{2}$$

3   Issue

When the BS was hung, following gluing, it had a large pitch imbalance of some -1° 9' (-20.1 mrad) with the upper masses free. (Negative pitch has the "HR" face tilted up.)

4   Diagnosis

To eliminate the possibility that this was due to the front wire loop being shorter than the rear one, the optic was reinserted back-to-front. It again hung with the HR face up, suggesting rather a misalignment between the prisms and the COM.

To rule out an error in the spreadsheet, the formulae and data were audited. Version E1000829-v5 of the spreadsheet had been used, with values as follows:

Parameter	Value (mm)	Note
jig	BSFM01	LLO jig
x_{j1}	16.00	measured by Danny Sellers
x_{j2}	50.02	measured by Danny Sellers
prism holder	1	LLO prism holder
x_{ph}	6.93	measured by Danny Sellers
optic	BS02	assigned by COC group
$w_M / 2$	60.13	half average of max and min measurements from E1200464-v1
ARM prism	#43	chosen by Danny Sellers
180ARM prism	#44	chosen by Danny Sellers
$w_{p1} / 2$	9.96	average of a and b for prism #43 in Q1000008
$w_{p2} / 2$	10.00	average of a and b for prism #44 in Q1000008
D_{screw1}	2.8235	formula
D_{screw2}	3.032	formula

All of these values were found to have been correctly transcribed from the source documents and/or correctly calculated.

To rule out entirely wrong prisms having been used, the empty storage packets were recovered, and they were indeed #43 and #44 as called out in E1000829-v5. See below for more on the correct side assignment and orientation.

A deficiency in the procedure was noticed: the values $w_{p1} / 2$ and $w_{p2} / 2$ for the prisms are measured from the end with the "fiducial chamfer" (visible as a flattened corner on the left in

Figure 4). The formulae assume that this chamfer is also on the left (from the technician's point of view) during bonding, both when gluing to the ARM side and when gluing to the 180ARM side. That is, the chamfer is nearer the HR surface for the ARM side and farther from it for the 180ARM side. However this is not specified in the procedure, and for definiteness Danny had decided to put both chamfers nearer the front surface. Fortunately the prisms are very nearly symmetrical so this was a small error (see below).

Dimensions along the sides of the optic (including to key points on the prisms) were remeasured with a travelling microscope, using the front surface as a reference. The measurements were done three times and an average was taken for each position. As a check, the prism lengths were also remeasured with calipers. See Table 1. The dimensions of the prism on the 180ARM side (supposedly #44) are a good fit to those of #43 from Q1000008, suggesting that the prism was bonded on the wrong side (as well as back-to-front). However some doubt is thrown on this conclusion by the fact that the ARM-side prism is not a good fit to #44 - the length and b dimensions are off. Nor is it a good fit to any other prism in the database.

Table 1: Length measurements on BS after gluing

Note: the prism dimensions in the "Inferred" column have been calculated allowing for the fact that the 180ARM prism had the fiducial notch nearer the HR surface (so "first end"="end with fiducial notch" in both cases), but no other corrections (prisms #43 and #44 on originally called-out sides).

Distance	Measured	Inferred	E1000829/ Q1000008
ARM (thin) side, from HR surface			
Prism			#43
To first end	20.13		16.00+6.93-2.8235=20.11
To first notch	25.17		
To second notch	35.10		
To second end	40.12		
To back face	59.92		59.92
a		25.17-20.13=5.04	4.94
b		35.10-20.13=14.97	14.98
b-a		35.10-25.17=9.93	10.04
c (length)	19.99	40.12-20.13=19.99	19.90
$w_p/2$		(5.04+14.97)/2=10.005	9.96
180ARM (thick) side, from HR surface			
Prism			#44

To first end	19.97		50.02-6.93-3.032-19.99=20.068
To first notch	24.90		
To second notch	34.86		
To second end	unrecorded		
To back face	60.33		60.33
a		24.90-19.97=4.93	5.02
b		34.86-19.97=14.89	14.97
b-a		34.86-24.90=9.96	9.94
c (length)	20.03	??	19.99
$w_p/2$		(14.89+4.93)/2=9.91	10.00

In any case, the distances from the HR face to the suspension points (the midpoints of the pairs of notches) are as in Table 2.

Table 2 - positions of suspension points

Side	Nominal		Actual	Delta	Net
ARM	$w_M/2$	=	(35.10+25.17)/2=30.135	0.07	-0.115
180ARM	60.13/2=30.065		(34.86+ 24.90)/2=29.88	-0.185	

The upshot is that the prism on the ARM side is too far from the HR face and the prism on the 180ARM side is too close, so that there is some cancellation for the purposes of pitch imbalance and the overall support point is 0.115 mm too close to the HR surface. This is of the right sign to explain the HR pitching up. To check whether the magnitude is plausible, a case `{"mark.barton", "20120712bsglass"}` of the `TripleLite2` Mathematica model in the SVN was prepared, based on the production wire-hang model with corrections for glass. For this case, the pitch compliance at the optic is 0.639 rad/(N.m). The torque produced by the COM error is $mg\Delta x$ = 14.211*9.81*0.000115=0.0160 N.m, which implies a pitch of 0.0102 rad or 10.2 mrad, a factor 2 short of the observed 1° 9' = 20.1 mrad. However the measurements are tricky and this is at least in the ballpark.

5   Resolution

While it would probably have been possible to unglue the prisms (using the standard technique of wicking with a water/detergent mix to soften the glue per E1000753 Section 5.1) and reglue them, this would have been time consuming and not without risk. Also, while mistakes in the procedure were identified, the net effect seems to have been small, and there was a risk of creating similar

offsets just through accumulation of tolerances. Therefore it was decided to try rebalancing by moving around trim mass at the IM in the first instance.

To check for possible deleterious effects of this fix on the dynamics, a modified version of the Mathematica model was prepared, {"mark.barton", "bsimbalance", "20120712bsglassfix1"}, with an offset of `prismerrorfb` to the attachment points of the wires at the optic, and an amount of mass `trimmass` moved from {I2trimposold2x, I2trimposold2y, I2trimposold2z} to {I2trimposnew2x, I2trimposnew2y, I2trimposnew2z}.

A value of `prismerrorfb` of 0.25 mm was chosen to give a pitch offset of 22 mrad (i.e., going with the larger and more accurately measured pitch offset rather than the estimated prism offset). This was offset at the optic by a movement of 305 g of trim mass from a position 15 mm to the rear of the IM to one 15 mm to the front. (Ballpark numbers were picked considering the amount of trim mass available and the approximate dimensions of the IM, and then fine-tuned to zero the pitch at the optic, but were not intended to correspond to any detailed accounting of the many trim weights that would be involved. Trim mass can only be moved - the total amount needs to stay the same to maintain vertical height given the compliance of the blades.)

In a variant, {"mark.barton", "bsimbalance", "20120712bsglassfix2"}, the trim mass was also moved up from -50 mm to +50 mm in vertical to reflect likely constraints due to the diagonally offset trim mass recesses in the IM (see Figure 6). This variant took only 95% as much mass (290 g) because raising the COM reduces `d2` and `d3` and makes the system more compliant, thus increasing the effect of the horizontal trim.

The resulting equilibrium positions are given in Figure 7. In both versions of the fix there is a residual pitch of the UM of ≈7.5 mrad and a residual pitch of the IM of ≈16.7 mrad. This is a significant change to the flag positions for the OSEMs but should be within the adjustment range.

Figure 6: Diagonally offset trim mass recesses in the IM (one visible at bottom, one hidden at top)
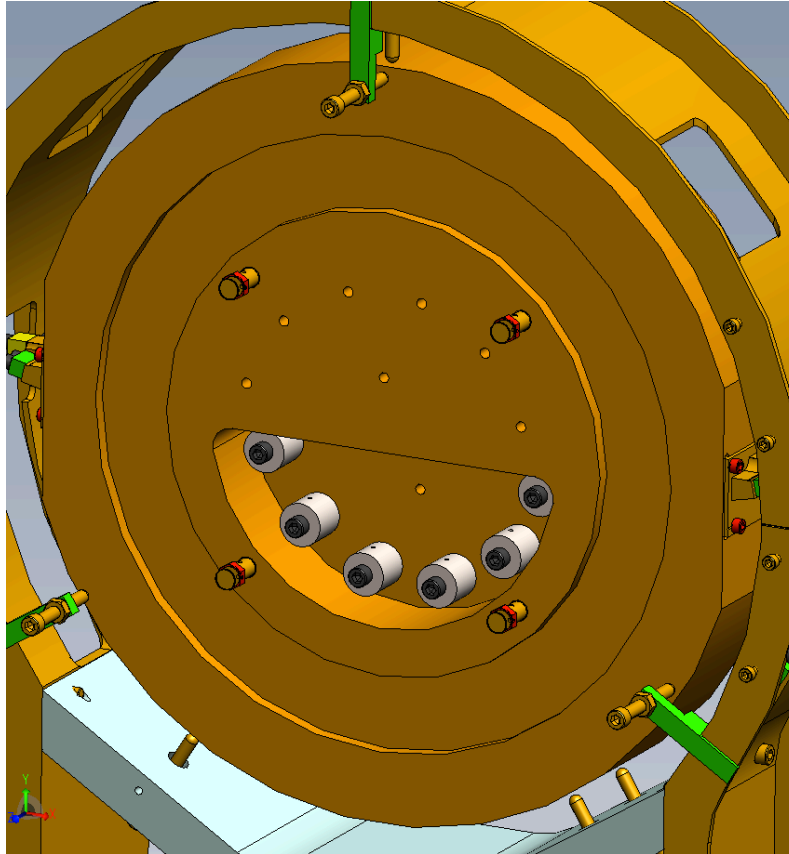
Frequencies for the base model and the two variants are given in `20120712bsglass`

	x	y	z	yaw	pitch	roll
Mass U	8.11039×10^{-17}	2.85402×10^{-7}	-0.607887	8.42902×10^{-13}	-8.10504×10^{-13}	6.37844×10^{-6}
Mass I	-3.28281×10^{-17}	3.34796×10^{-6}	-1.19703	-9.28809×10^{-13}	8.10707×10^{-13}	0.0000143284
optic	1.07033×10^{-7}	3.40676×10^{-6}	-1.69795	-2.78663×10^{-13}	-1.55445×10^{-16}	0.000021702

`20120712bsglassfix1`

	x	y	z	yaw	pitch	roll
Mass U	-7.5806×10^{-6}	2.85305×10^{-7}	-0.607887	5.02716×10^{-8}	0.00758045	6.37371×10^{-6}
Mass I	-0.000189966	3.34799×10^{-6}	-1.19703	5.23796×10^{-8}	0.0167248	0.0000143291
optic	-0.000455482	3.40719×10^{-6}	-1.69795	-1.06867×10^{-7}	5.9884×10^{-6}	0.0000217007

`20120712bsglassfix2`

	x	y	z	yaw	pitch	roll
Mass U	-7.61763×10^{-6}	2.86157×10^{-7}	-0.607887	2.9503×10^{-8}	0.00761747	6.3968×10^{-6}
Mass I	-0.000190893	3.36018×10^{-6}	-1.19703	4.565×10^{-8}	0.0168065	0.0000143825
optic	-0.000456639	3.41959×10^{-6}	-1.69795	-1.01164×10^{-7}	0.0000776307	0.000021754

Figure 8. Moving the trim mass horizontally produces essentially no effect on the modes, whereas moving it diagonally upward slightly decreases the fundamental pitch frequency.

Figure 7: Equilibrium position comparison - base model and two versions of proposed fix.

x=longitudinal, y=tranverse, z=vertical, distances in m, angles in rad.

```
20120712bsglass
```

	x	y	z	yaw	pitch	roll
Mass U	8.11039×10^{-17}	2.85402×10^{-7}	-0.607887	8.42902×10^{-13}	-8.10504×10^{-13}	6.37844×10^{-6}
Mass I	-3.28281×10^{-17}	3.34796×10^{-6}	-1.19703	-9.28809×10^{-13}	8.10707×10^{-13}	0.0000143284
optic	1.07033×10^{-7}	3.40676×10^{-6}	-1.69795	-2.78663×10^{-13}	-1.55445×10^{-16}	0.000021702

```
20120712bsglassfix1
```

	x	y	z	yaw	pitch	roll
Mass U	-7.5806×10^{-6}	2.85305×10^{-7}	-0.607887	5.02716×10^{-8}	0.00758045	6.37371×10^{-6}
Mass I	-0.000189966	3.34799×10^{-6}	-1.19703	5.23796×10^{-8}	0.0167248	0.0000143291
optic	-0.000455482	3.40719×10^{-6}	-1.69795	-1.06867×10^{-7}	5.9884×10^{-6}	0.0000217007

```
20120712bsglassfix2
```

	x	y	z	yaw	pitch	roll
Mass U	-7.61763×10^{-6}	2.86157×10^{-7}	-0.607887	2.9503×10^{-8}	0.00761747	6.3968×10^{-6}
Mass I	-0.000190893	3.36018×10^{-6}	-1.19703	4.565×10^{-8}	0.0168065	0.0000143825
optic	-0.000456639	3.41959×10^{-6}	-1.69795	-1.01164×10^{-7}	0.0000776307	0.000021754

Figure 8: Mode frequency comparison - base model and two versions of proposed fix.

```
20120712bsglass
```

```
N    f          type
1    0.42095    pitch3    pitch2
2    0.4234     y3        y2          roll3
3    0.492723   yaw3      yaw2
4    0.513635   pitch3
5    1.05029    pitch1    pitch2
6    1.05108    y2        y3          y1        roll1
7    1.08197    pitch1    pitch2
8    1.08387    z3        z2
9    1.39175    pitch1
10   1.39596    yaw1
11   1.55495    roll3     roll2
12   1.69866    x1        pitch2
13   2.19008    roll1     roll3
14   2.25223    yaw2      yaw3
15   3.2069     roll1     roll3
16   3.76044    z1
17   17.5219    z2        z3
18   25.9721    roll3     roll2
```

```
20120712bsglassfix1

N     f          type
1     0.42095    pitch3    pitch2
2     0.423398   y3        y2        roll3
3     0.492694   yaw3      yaw2
4     0.513642   pitch3
5     1.05022    pitch1    pitch2
6     1.05108    y2        y3        y1        roll1
7     1.08003    pitch1    pitch2
8     1.08546    pitch1    pitch2
9     1.3914     pitch1
10    1.39594    yaw1
11    1.55496    roll3     roll2
12    1.69867    x1        pitch2
13    2.18953    roll1     roll3
14    2.25269    yaw2      yaw3
15    3.20718    roll1     roll3
16    3.76066    z1
17    17.5222    z2        z3
18    25.9737    roll3     roll2

20120712bsglassfix2

N     f          type
1     0.420535   pitch3    pitch2
2     0.423483   y3        y2        roll3
3     0.492693   yaw3      yaw2
4     0.501651   pitch3
5     1.05155    y2        y3        y1        roll1
6     1.0521     pitch1    pitch2
7     1.06477    pitch1    pitch2
8     1.08396    pitch2    pitch1    pitch3    z3
9     1.38813    pitch1
10    1.39594    yaw1
11    1.55746    roll3     roll2
12    1.69737    x1        x2
13    2.18411    roll1     roll3
14    2.25263    yaw2      yaw3
15    3.20228    roll1     roll3
16    3.76066    z1
17    17.5222    z2        z3
18    25.9743    roll3     roll2
```

To check for untoward effects on the dynamics, all 36 transfer functions from structure coordinates to optic coordinates were plotted for the base model and the two modified models described above (Figure 9 - final section of this document, best printed on 11"x17" paper). As expected, the error and fix introduced cross-couplings between pairs of coordinates that had been independent, for example structure longitudinal (x00) to optic vertical (z3). However there are no new couplings that are obviously problematic. Also it turns out that it is the horizontal component of the trim mass

adjustment that drives the effect - adding the vertical component doesn't significantly increase any of the couplings further.

6   Implementation of fix

The above proposal (305 g moved 30 mm to the front of the IM) was put to the LLO team, with the guidance that it was the product of the two values that actually mattered, and that the detailed implementation in terms of individual trim masses was at their discretion. The amount of mass moved and the distance it was moved were in the ballpark of the estimate required, but a detailed accounting has not yet been done. [Need info of exactly what was done in practice, including new COM and MOI estimates from Janeen and estimate of UM and IM residual pitches from Jason.]

7   Post-fix dynamics

Need some test data and a new model incorporating the exact new trim mass configuration.

8   Conclusion

Need a conclusion.

Figure 9: TFs from structure coordinates (x00 etc) to those of the optic (x0 etc)

Key: black = no error or fix, blue = error and fix with horizontal movement of trim, red = error and fix with diagonal movement of trim)