

LIGO-E1300128-v1

aLIGO Interferometer Optics Positions and Orientations for Initial Alignment

■ Revision History

■ Version -v1

■ Version -v2

2/12/2013, D. Coyne

- 1) Fixed error in calculation to insure that the PR2, PR3, SR2, SR3 optics are oriented vertically with respect to the local gravity vector (i.e. in local coordinates). Previous calculation had a small pitch error (due to yaw rotation in the global coordinate frame instead of local frame).
- 2) completed calculations of the locations and orientations of all of the H1 PRC and SRC optics (was partial for -v1)
- 3) Made nicely formatted tables for the summary tables

■ Notes and Notation

Both Zemax and Optica (a TM package for optical design in Mathematica) can be used to ray trace through an existing placement of optics, but it is cumbersome to use for determining the aligned positions of a number of wedged optics (as is

the case with the recycling cavity). This notebook determines the positions and orientations of the optics given the following information/assumptions:

1) the X- and Y-arms are assumed to exactly 90 degrees apart. (T960176-C indicates that the deviation from 90 degrees is 1.2 microradian).

2) the x and y axes are aligned parallel to the Fabry-Perot arm cavity axes, with the origin defined at the intersection of the recycling cavity beams and the splitting surface of the BS

(Note that this is later converted to the LIGO global coordinate system; The LIGO coordinate system has its origin at the projected intersection of the BT cavity axes.)

3) the notation is as follows:

u_i = ray unit vector for the beam incident upon surface i

v_i = ray unit vector for the beam reflected from surface i

w_i = ray unit vector for the beam refracted through surface i

n_i = unit normal vector for surface i

- | | |
|-----|------------------------------------|
| i | surface |
| 0 | BS (AR surface) |
| 1 | ITMy (HR surface) |
| 2 | ITMy (AR surface) |
| 3 | CPy (surface adjacent to ITM) |
| 4 | CPy (other surface) |
| 5 | BS (50/50 surface) |
| 6 | PR3 (HR surface) |
| 7 | BS (AR surface, y-transmitted ray) |
| 8 | SR3 (HR surface) |
| 9 | ITMx (HR surface) |
| 10 | ITMx (AR surface) |
| 11 | CPx (surface adjacent to ITM) |

- 12 CPx (other surface)
- 13 BS (AR surface, x-transmitted ray)
- 14 PR2 (HR surface)
- 15 PRM (HR surface)
- 16 SR2 (HR surface)
- 17 SRM (HR surface)

ar = anti-reflectance surface

hr = high reflectance surface

bs = beamsplitting surface

d12 = ITMy thickness at center, mm

d23 = ITMy to CPy gap distance, mm

d34 = CPy thickness at center, mm

d45 = CPy to BS(hr) distance, mm

d56 = BS(hr) to PR3 distance, mm

dBS = BS thickness at center, mm

d57 = BS(hr) to BS(ar) for y-beam, mm

d78 = BS(ar), at y-beam intercept, to SR3, mm

d513 = BS(hr) to BS(ar) for x-beam, mm

d910 = ITMx thickness at center, mm

d1011 = ITMx to CPx gap distance, mm

d1112 = CPx thickness at center, mm

d1213 = CPx to BS(ar) distance, mm

d614 = PR3 to PR2 distance, mm

d1415 = PR2 to PRM distance, mm

The “given” parameters (from Zemax layout, etc.) are as follows:

- ITM (hr) center positions from Zemax
- ITM thickness

- ITM to CP gaps
- CP thickness
- BS thickness

ITM_x = vertical, thick side down

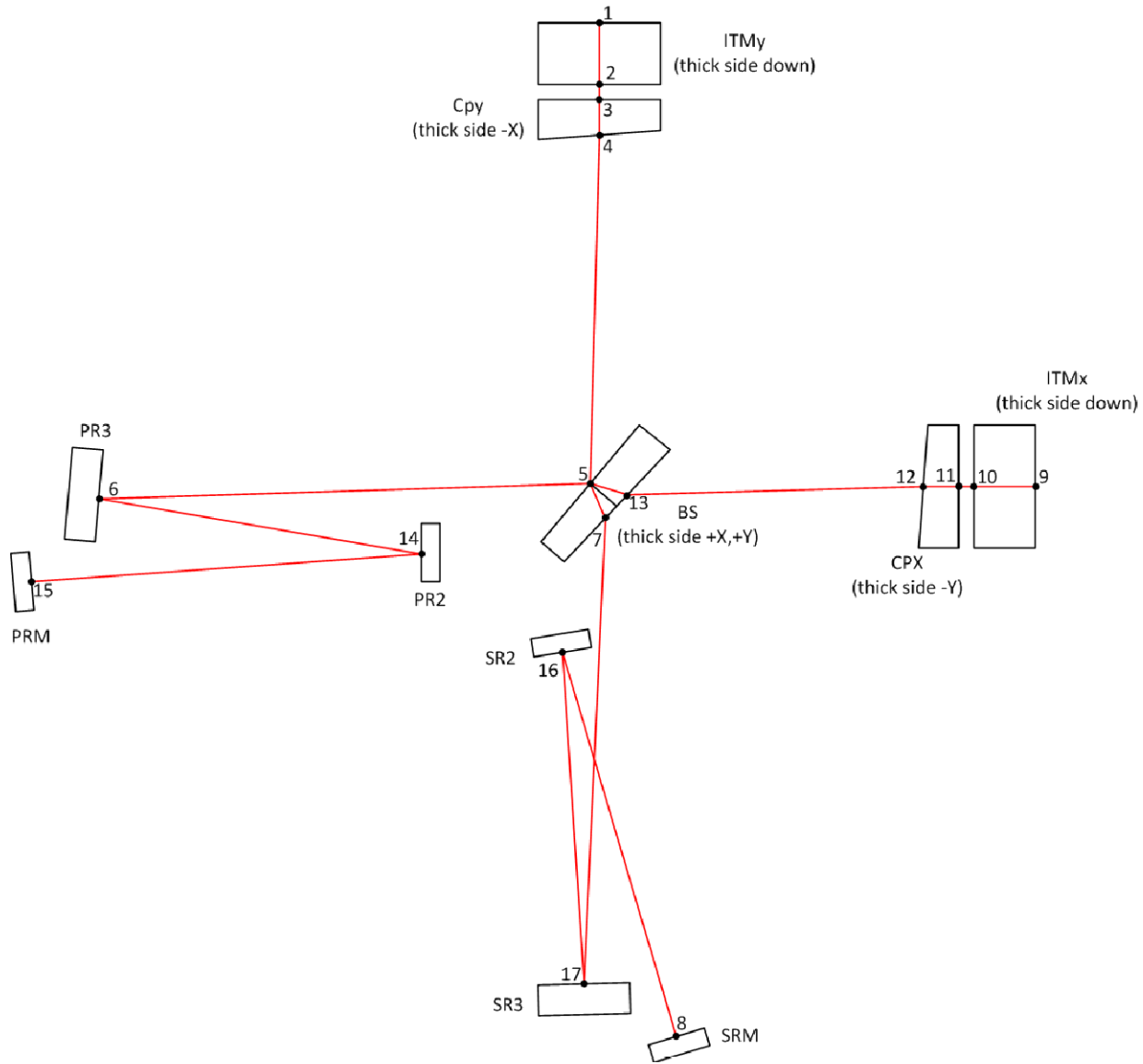
ITM_y = vertical, thick side down

CP_x = horizontal, thick side - Y

CP_y = horizontal, thick side - X

BS = horizontal, thick side + X/+Y



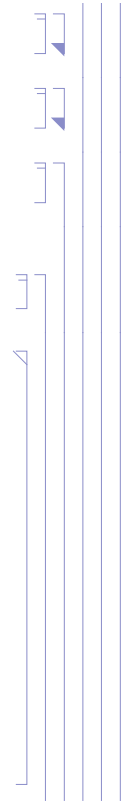


- SRM position determination
- PRC, SRC & Schnupp Assymetry Lengths
- Summary

- Optic Parameters

(Debug) In[3801]:=

```
opticLabel = {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS ARs",  
             "SRM HR", "SR2 HR", "SR3 HR", "CPx", "ITMx", "CPy", "ITMy"};  
nOptics = Length[opticLabel];  
opticWedge = {"NA", "NA", "NA", wedgeBS, "NA",  
             "NA", "NA", "NA", wedgeCPx, wedgeITMx, wedgeCPy, wedgeITMy};  
opticThick = {"NA", "NA", "NA", BSthick, "NA", "NA", "NA",  
             "NA", CPxThick, ITMxThick, CPyThick, ITMyThick};  
opticDiameter = {"NA", "NA", "NA", BSDiameter, "NA", "NA", "NA",  
                "NA", CPxDiameter, ITMxDiameter, CPyDiameter, ITMyDiameter};
```



(Debug) In[3806]:=

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(Debug) Out[3806]=

Optic	wedge		Thickness	Diameter
	rad	deg		
PRM HR	NA	NA	NA	NA
PR2 HR	NA	NA	NA	NA
PR3 HR	NA	NA	NA	NA
BS HR	0.001326	0.076000	60.410000	369.850000
BS ARs	NA	NA	NA	NA
SRM HR	NA	NA	NA	NA
SR2 HR	NA	NA	NA	NA
SR3 HR	NA	NA	NA	NA
CPx	0.001204	0.069000	99.820000	340.130000
ITMx	0.001344	0.077000	200.220000	340.130000
CPy	0.001204	0.069000	99.910000	340.220000
ITMy	0.001361	0.078000	199.640000	340.060000

■ Results

(Debug) In[3807]:=

```

opticPositionG = {p15, p14, p6, p5, p7, p17, p16, p8, p11, p9, p3, p1};
opticPositionL = opticPositionG.Rhc;
opticNormalG = {n15, n14, n6, n5y, n13, n17, n16, n8, n11, n9, n3, n1};
opticNormalL = opticNormalG.Rhc;
opticYaw =
  {PRMyaw, PR2yaw, PR3yaw, BSyaw, 0, SRMyaw, SR2yaw, SR3yaw, 0, 0, 0, 0};

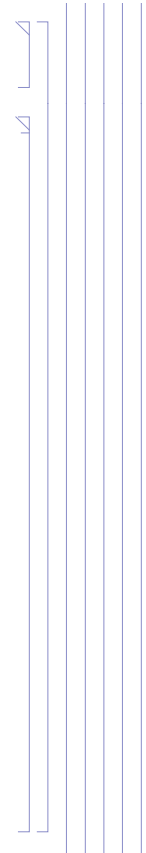
```


(Debug) In[3812]:=

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(Debug) Out[3812]=

Optic	Global Coordinates (mm)			Local Coordinates (mm)		
	Xg	Yg	Zg	Xl	Yl	Zl
PRM HR	-20189.6	-628.0	-95.0	-20189.7	-628.0	-82.5
PR2 HR	-3581.3	-530.4	-84.8	-3581.4	-530.4	-82.6
PR3 HR	-19740.0	-173.9	-94.9	-19740.1	-173.9	-82.7
BS HR	-202.6	-183.8	-83.0	-202.7	-183.8	-82.9
BS ARs	-183.9	-250.1	-83.0	-183.9	-250.1	-82.9
SRM HR	305.4	-19908.6	-114.1	305.3	-19908.6	-114.5
SR2 HR	-594.1	-4178.1	-105.0	-594.2	-4178.1	-104.7
SR3 HR	-174.1	-19615.9	-94.9	-174.2	-19615.9	-95.0
CPx	4792.9	-200.0	-80.0	4792.9	-200.0	-83.0
ITMx	5013.0	-200.0	-80.0	5012.9	-200.0	-83.1
CPy	-200.0	4763.7	-80.0	-200.0	4763.7	-79.8
ITMy	-200.0	4983.1	-80.0	-200.0	4983.1	-79.8

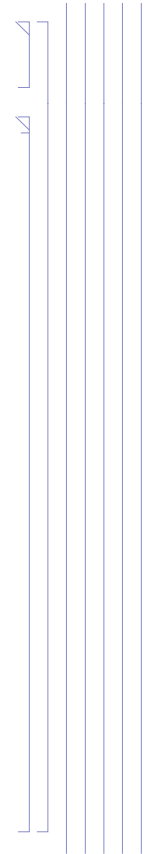


(Debug) In[3813]:=

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(Debug) Out[3813]=

Optic	Normal Unit Vector (global) (mm)			Normal Unit Vector (local) (mm)		
	Ug	Vg	Wg	Ul	Vl	Wl
PRM HR	0.999983	0.005876	0.000612	0.999983	0.005876	-0.000007
PR2 HR	-0.999967	0.008092	-0.000620	-0.999967	0.008092	-0.000000
PR3 HR	0.999936	-0.011284	0.000620	0.999936	-0.011284	0.000000
BS HR	-0.706736	0.707478	0.000000	-0.706736	0.707478	0.000447
BS ARs	0.705797	-0.708415	0.000000	0.705796	-0.708415	-0.000446
SRM HR	-0.057089	0.998369	0.000577	-0.057088	0.998369	0.000625
SR2 HR	0.042146	-0.999111	0.000039	0.042146	-0.999111	0.000000
SR3 HR	-0.013850	0.999904	-0.000021	-0.013850	0.999904	0.000000
CPx	0.999999	0.000000	-0.001344	0.999998	0.000000	-0.001963
ITMx	1.000000	0.000000	0.000000	1.000000	0.000000	-0.000619
CPy	0.000000	0.999999	-0.001361	-0.000001	0.999999	-0.001349
ITMy	0.000000	1.000000	0.000000	0.000000	1.000000	0.000012



(Debug) In[3814]:=

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(Debug) Out[3814]=

Optic	Yaw	Yaw		
	rad	deg	min	sec
PRM HR	0.005877	0.	20.	12.
PR2 HR	-0.008092	0.	-27.	-49.
PR3 HR	-0.011284	0.	-38.	-47.
BS HR	-0.784873	-44.	-58.	-12.
BS ARs	0.000000	0.	0.	0.
SRM HR	0.057120	3.	16.	22.
SR2 HR	0.042159	2.	24.	56.
SR3 HR	0.013851	0.	47.	37.
CPx	0.000000	0.	0.	0.
ITMx	0.000000	0.	0.	0.
CPy	0.000000	0.	0.	0.
ITMy	0.000000	0.	0.	0.

■ Zemax results

Zemax results are from D0901920-v13

The wedge angle magnitudes (but not orientations/signs) reported in the Zemax optical layout, D0901920-v13 differ, as follows:

ITMx = ITM10? = 0.077 deg (same value but serial number designation is wrong)

ITMy = ITM11? = 0.076 deg (value and serial number incorrect)

CPx = CP01 = 0.070 deg (serial number correct, used “final” wedge angle instead of C1107164-v1 value)

CPy = CP02 = 0.069 deg (serial number is incorrect)

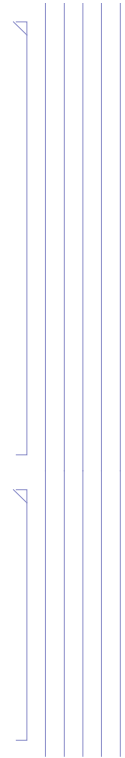
BS = BS06 = 0.076 deg (same)

(Debug) In[3815]:=

```
opticLabelZemax = {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS ARs",  
  "SRM HR", "SR2 HR", "SR3 HR", "ITMx", "ITMy", "ETMx", "ETMy"};  
nOpticsZemax = Length[opticLabelZemax];  
opticPosGZemax = {{-20194.3, -628.0, -95.8}, {-3581.7, -530.4, -84.5},  
  {-19740.5, -174.0, -94.8}, {-202.6, -183.9, -82.9},  
  {-184.0, -249.8, -82.9}, {305.4, -19908.6, -113.2},  
  {-594.1, -4178.1, -104.4}, {-174.2, -19615.9, -94.5},  
  {5013.0, -200.0, -80.0}, {-200.0, 4983.1, -80.0},  
  {3999498.0, -200.0, -80.0}, {-200.0, 3999468.1, -80.0}};
```

(Debug) In[3818]:=

```
compareOpticLabel = opticLabelZemax[[1 ;; 10]];  
nCompareOptics = 10;  
comparePositionG =  
  Drop[opticPositionG, {9, 11, 2}] - opticPosGZemax[[1 ;; 10]];
```



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(Debug) In[3821]:=
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```

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(Debug) Out[3821]=
```

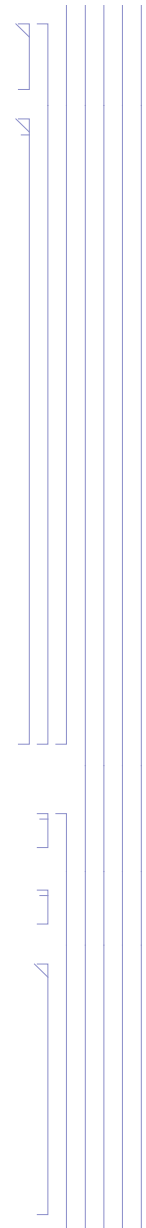
Optic	Global Coordinate Difference (mm)		
	ΔX_g	ΔY_g	ΔZ_g
PRM HR	4.7	-0.0	0.8
PR2 HR	0.4	-0.0	-0.3
PR3 HR	0.5	0.1	-0.1
BS HR	-0.0	0.1	-0.1
BS ARs	0.1	-0.3	-0.1
SRM HR	0.0	0.0	-0.9
SR2 HR	0.0	-0.0	-0.6
SR3 HR	0.1	0.0	-0.4
ITMx	0.0	0.0	0.0
ITMy	0.0	0.0	0.0

■ IO results

IO Layout results for PRM, PR2 and PR3 are from E1100494-v3, E1100495-v4

```
(Debug) In[3822]:=
```

```
opticLabelIO = {"PRM HR", "PR2 HR", "PR3 HR"};
nOpticsIO = Length[opticLabelIO];
opticPosGIO = {{-20189.6, -628, -94.2},
               {-3581.3, -530.4, -84.3}, {-19740, -177.4, -94.6}};
```



(Debug) In[3825]:=

```
compareOpticLabel = opticLabelIO[[1 ;; 3]];
nCompareOptics = Length[compareOpticLabel];
comparePositionG = opticPositionG[[1 ;; 3]] - opticPosGIO;
```

(Debug) In[3828]:=

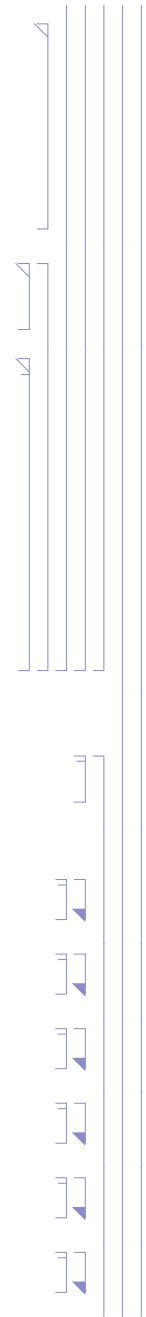
```
formattedTableComparePositions
```

(Debug) Out[3828]=

Optic	Global Coordinate Difference (mm)		
	ΔX_g	ΔY_g	ΔZ_g
PRM HR	0.0	-0.0	-0.8
PR2 HR	0.0	-0.0	-0.5
PR3 HR	-0.0	3.5	-0.3

■ L1

- Notes
- L1 Unique Parameters
- optic surface orientation determination
- BS position determination
- PR3 position determination
- PR2 position determination



- **PRM position determination**
- **SR3 position determination**
- **SR2 position determination**
- **SRM position determination**
- **PRC, SRC & Schnupp Assymetry Lengths**
- **Summary**

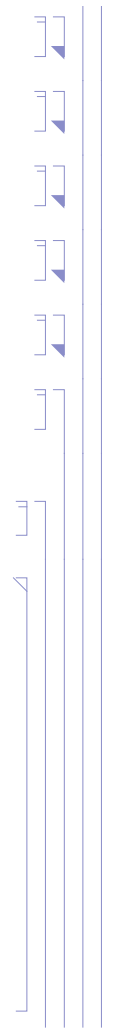
- **Optic Parameters**

(Debug) In[3968]:=

```

opticLabel = {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS ARs",
              "SRM HR", "SR2 HR", "SR3 HR", "CPx", "ITMx", "CPy", "ITMy"};
nOptics = Length[opticLabel];
opticWedge = {"NA", "NA", "NA", wedgeBS, "NA",
              "NA", "NA", "NA", wedgeCPx, wedgeITMx, wedgeCPy, wedgeITMy};
opticThick = {"NA", "NA", "NA", BSthick, "NA", "NA", "NA",
              "NA", CPxThick, ITMxThick, CPyThick, ITMyThick};
opticDiameter = {"NA", "NA", "NA", BSDiameter, "NA", "NA", "NA",
                 "NA", CPxDiameter, ITMxDiameter, CPyDiameter, ITMyDiameter};

```

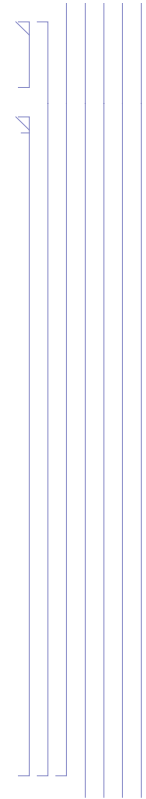


(Debug) In[3973]:=

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(Debug) Out[3973]=

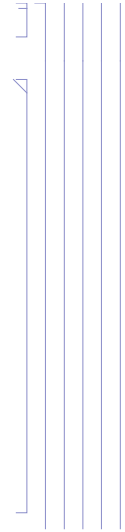
Optic	wedge		Thickness	Diameter
	rad	deg		
PRM HR	NA	NA	NA	NA
PR2 HR	NA	NA	NA	NA
PR3 HR	NA	NA	NA	NA
BS HR	0.001222	0.070000	59.880000	369.980000
BS ARs	NA	NA	NA	NA
SRM HR	NA	NA	NA	NA
SR2 HR	NA	NA	NA	NA
SR3 HR	NA	NA	NA	NA
CPx	0.001274	0.073000	100.310000	339.940000
ITMx	0.001265	0.072500	200.270000	340.000000
CPy	0.001152	0.066000	100.320000	340.110000
ITMy	0.001292	0.074000	199.610000	339.920000



■ Results

(Debug) In[3974]:=

```
opticLabel = {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS ARs",
              "SRM HR", "SR2 HR", "SR3 HR", "CPx", "ITMx", "CPy", "ITMy"};
nOptics = Length[opticLabel];
opticPositionG = {p15, p14, p6, p5, p7, p17, p16, p8, p11, p9, p3, p1};
opticPositionL = opticPositionG.Rlc;
opticNormalG = {n15, n14, n6, n5y, n13, n17, n16, n8, n11, n9, n3, n1};
opticNormalL = opticNormalG.Rlc;
opticYaw =
  {PRMyaw, PR2yaw, PR3yaw, BSyaw, 0, SRMyaw, SR2yaw, SR3yaw, 0, 0, 0, 0};
```

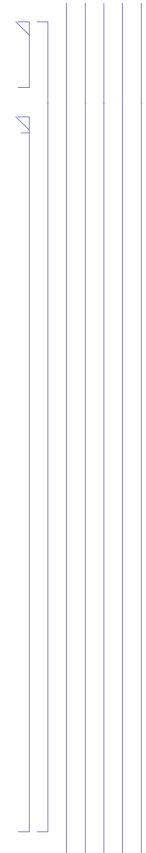


(Debug) In[3981]:=

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(Debug) Out[3981]=

Optic	Global Coordinates (mm)			Local Coordinates (mm)		
	Xg	Yg	Zg	Xl	Yl	Zl
PRM HR	-20189.6	-628.0	-103.4	-20189.6	-628.1	-96.7
PR2 HR	-3579.2	-530.4	-93.7	-3579.2	-530.5	-92.3
PR3 HR	-19740.0	-176.4	-94.2	-19740.0	-176.5	-87.9
BS HR	-202.5	-184.1	-82.8	-202.5	-184.2	-82.7
BS ARs	-183.9	-249.9	-82.9	-184.0	-249.9	-82.6
SRM HR	305.0	-19908.6	-93.2	305.0	-19908.7	-81.1
SR2 HR	-594.1	-4178.1	-84.3	-594.1	-4178.2	-81.6
SR3 HR	-175.3	-19615.9	-94.1	-175.3	-19616.0	-82.1
CPx	4792.9	-200.0	-80.0	4792.8	-200.0	-81.4
ITMx	5013.0	-200.0	-80.0	5013.0	-200.0	-81.4
CPy	-200.0	4763.7	-80.0	-200.0	4763.7	-82.9
ITMy	-200.0	4983.1	-80.0	-200.0	4983.1	-83.0

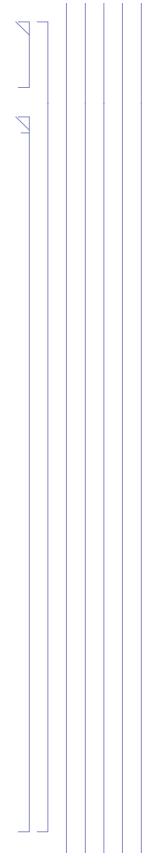


(Debug) In[3982]:=

formattedTableNormals

(Debug) Out[3982]=

Optic	Normal Unit Vector (global) (mm)			Normal Unit Vector (local) (mm)		
	Ug	Vg	Wg	Ul	Vl	Wl
PRM HR	0.999983	0.005876	0.000585	0.999983	0.005876	0.000269
PR2 HR	-0.999968	0.008012	-0.000307	-0.999968	0.008011	0.000000
PR3 HR	0.999938	-0.011146	0.000305	0.999938	-0.011146	0.000000
BS HR	-0.706784	0.707429	0.000000	-0.706785	0.707429	-0.000212
BS ARs	0.705920	-0.708292	0.000000	0.705920	-0.708292	0.000213
SRM HR	-0.057063	0.998370	0.000562	-0.057063	0.998371	-0.000030
SR2 HR	0.042095	-0.999113	-0.000597	0.042095	-0.999114	-0.000000
SR3 HR	-0.013783	0.999905	0.000607	-0.013783	0.999905	-0.000000
CPx	0.999999	0.000000	-0.001265	0.999999	-0.000001	-0.001577
ITMx	1.000000	0.000000	0.000000	1.000000	0.000000	-0.000312
CPy	0.000000	0.999999	-0.001292	-0.000001	0.999998	-0.001903
ITMy	0.000000	1.000000	0.000000	-0.000000	1.000000	-0.000611



(Debug) In[3983]:=

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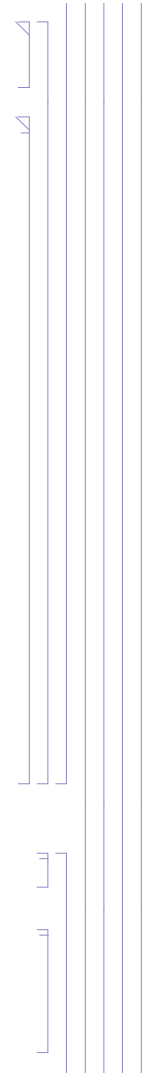
(Debug) Out[3983]=

Optic	Yaw	Yaw		
	rad	deg	min	sec
PRM HR	0.005876	0.	20.	12.
PR2 HR	-0.008011	0.	-27.	-32.
PR3 HR	-0.011146	0.	-38.	-19.
BS HR	-0.784942	-44.	-58.	-26.
BS ARs	0.000000	0.	0.	0.
SRM HR	0.057094	3.	16.	17.
SR2 HR	0.042108	2.	24.	45.
SR3 HR	0.013783	0.	47.	23.
CPx	0.000000	0.	0.	0.
ITMx	0.000000	0.	0.	0.
CPy	0.000000	0.	0.	0.
ITMy	0.000000	0.	0.	0.

■ Zemax results

Zemax results are from D0902216 - v8

The wedge angle magnitudes (but not orientations/signs) reported in the Zemax optical layout, D0902216-v8 match the serial numbers and wedge angle values given above.



(Debug) In[3984]:=

```
opticLabelZemax = {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS ARs",  
  "SRM HR", "SR2 HR", "SR3 HR", "ITMx", "ITMy", "ETMx", "ETMy"};  
nOpticsZemax = Length[opticLabelZemax];  
opticPosGZemax = {{-20190.0, -628.0, -102.8}, {-3579.6, -530.4, -93.3},  
  {-19740.5, -176.3, -93.9}, {-202.5, -184.0, -82.8},  
  {-183.9, -250.0, -82.9}, {305.0, -19908.6, -93.2},  
  {-594.1, -4178.1, -84.4}, {-175.2, -19615.9, -94.1},  
  {5013.0, -200.0, -80.0}, {-200.0, 4983.1, -80.0},  
  {3999498.0, -200.0, -80.0}, {-200.0, 3999468.1, -80.0}};
```

(Debug) In[3987]:=

```
compareOpticLabel = opticLabelZemax[[1 ;; 10]];  
nCompareOptics = 10;  
comparePositionG =  
  Drop[opticPositionG, {9, 11, 2}] - opticPosGZemax[[1 ;; 10]];
```

```
(Debug) In[3990]:=
```

```
formattedTableComparePositions
```

```
(Debug) Out[3990]=
```

Optic	Global Coordinate Difference (mm)		
	ΔX_g	ΔY_g	ΔZ_g
PRM HR	0.4	-0.0	-0.6
PR2 HR	0.4	-0.0	-0.4
PR3 HR	0.5	-0.1	-0.3
BS HR	-0.0	-0.1	-0.0
BS ARs	-0.0	0.1	0.0
SRM HR	-0.0	0.0	0.0
SR2 HR	0.0	0.0	0.1
SR3 HR	-0.1	0.0	-0.0
ITMx	0.0	0.0	0.0
ITMy	0.0	0.0	0.0

■ IO results

IO Layout results for PRM, PR2 and PR3 are from E1100492-v11, E1100493-v9

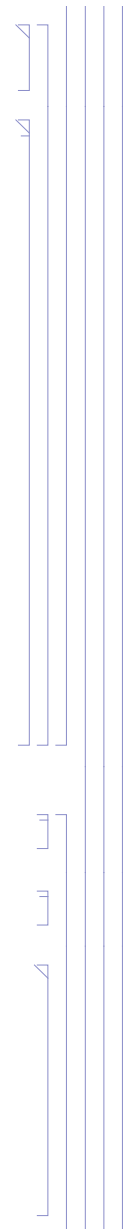
```
(Debug) In[3991]:=
```

```
opticLabelIO = {"PRM HR", "PR2 HR", "PR3 HR"};
```

```
nOpticsIO = Length[opticLabelIO];
```

```
opticPosGIO = {{-20189.6, -628, -104.1},
```

```
          {-3579.2, -530.4, -94.1}, {-19740, -177.4, -94.5}};
```



(Debug) In[3994]:=

```
compareOpticLabel = opticLabelIO[[1 ;; 3]];
nCompareOptics = Length[compareOpticLabel];
comparePositionG = opticPositionG[[1 ;; 3]] - opticPosGIO;
```

(Debug) In[3997]:=

```
formattedTableComparePositions
```

(Debug) Out[3997]=

Optic	Global Coordinate Difference (mm)		
	ΔX_g	ΔY_g	ΔZ_g
PRM HR	-0.0	-0.0	0.7
PR2 HR	-0.0	-0.0	0.4
PR3 HR	-0.0	1.0	0.3

