

## LIGO-E1300128-v3

# aLIGO Interferometer Optics Positions and Orientations for Initial Alignment

### ■ Revision History

#### ■ Version -v1

2/7/2013, D. Coyne: initial release to support update to the L1 PRC and BS alignment solutions

#### ■ 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

(note the version of this notebook which is posted to the DCC under E1300128-v1 includes the changes noted above for -v2)

8/30/2013. D. Coyne

4) added notes on the distances between the PRC & SRC optics noted in T0900043-v11, and compared them to the distances calculated herein

- 5) Changed from Rotate3D (obsolete) to RotationTransform
  - 6) Changed from CrossProduct (obsolete) to Cross
  - 7) Added a comparison to the global coordinates reported by IO for the PRC & SRC in E1200616 (H1) and E1200274-v3 (L1)
- 9/6/2013 D. Coyne posted to DCC for discussion with commissioners regarding apparent error in SR3 optic positioning resulting in poor modal overlap with PRC cavity

### ■ Version -v3

9/6/2013, D. Coyne

- 1) Changed length/distance comparisons to T0900043-v11 from the cold case to the nominal design case for 12.5 W of PSL input power.
- 2) Changed the global positions of the H1 SRM and SR2 HR centers to be consistent with IO's (Luke William's) H1 master coordinate list E1200616-v7. The positions of these optics changed based on the as-built radii of curvature (ROC).
- 3) N.B. : According to the IO H1 Master Coordinates List, the center of the HR fface of PRM is at  $\{-20193.8, -628.0, -94.2\}$ , or 4.2 mm different in x compared to E1100494-v3! Leaving as is for now.

### ■ 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 parrallel 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

d717 = BS(ar), at SRC-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<sub>x</sub> = vertical, thick side down

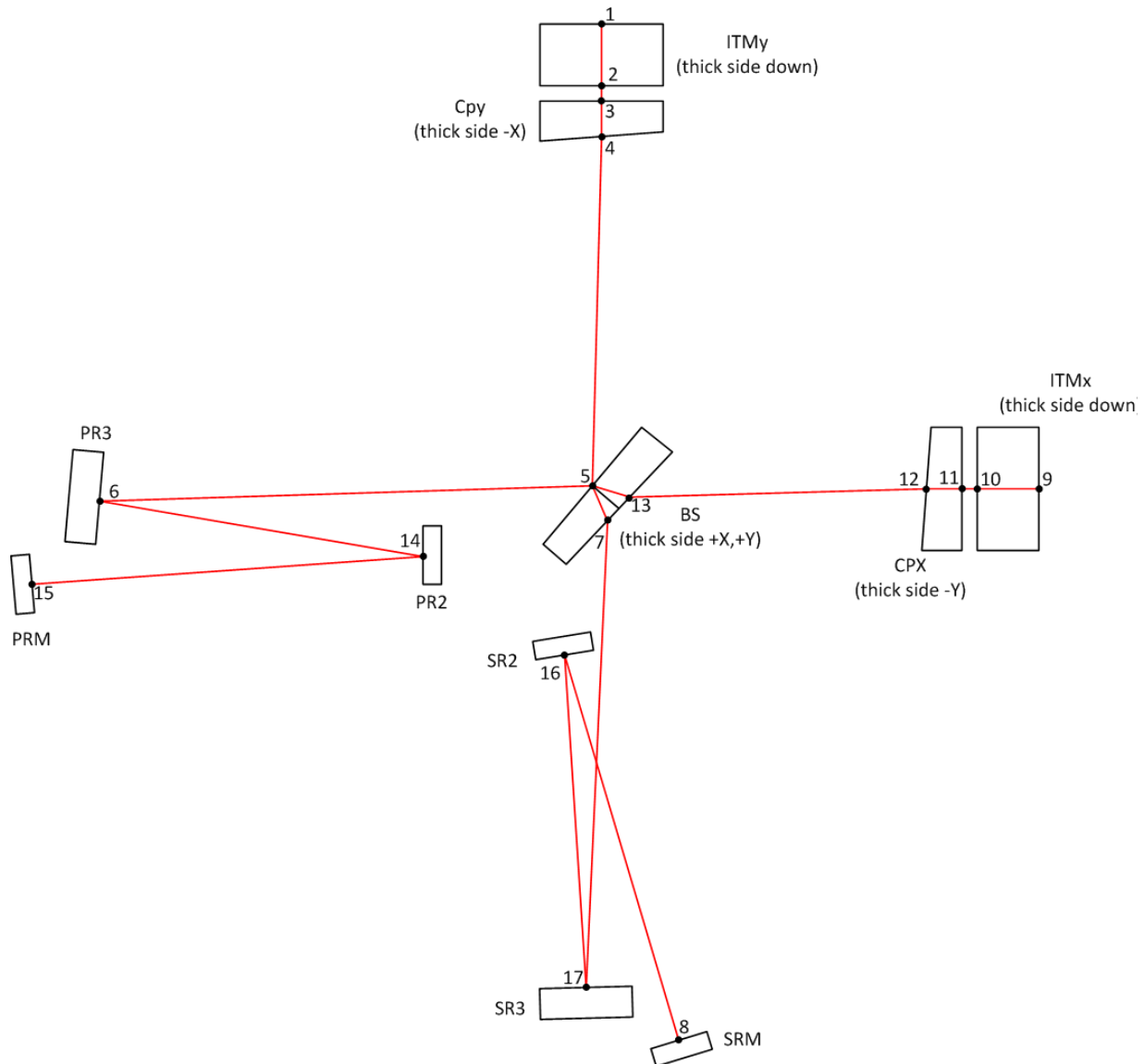
ITM<sub>y</sub> = vertical, thick side down

CP<sub>x</sub> = horizontal, thick side - Y

CP<sub>y</sub> = horizontal, thick side - X

BS = horizontal, thick side + X/+Y





## ■ Intialization

(Debug) In[1]:=

```
Off[General::"spell"]
Off[General::"spell1"]
```

(Debug) In[3]:=

```
RotationMatrix3D[phi_, theta_, psi_] :=
  RotationMatrix[Pi - psi, {0, 0, 1}].RotationMatrix[
  theta, {1, 0, 0}].RotationMatrix[Pi - phi, {0, 0, 1}]
```

```
(Debug) In[4]:=
  RotationMatrix3D[phi, theta, psi]
(Debug) Out[4]=
  {{Cos[phi] Cos[psi] - Cos[theta] Sin[phi] Sin[psi],
    Cos[psi] Sin[phi] + Cos[phi] Cos[theta] Sin[psi],
    Sin[psi] Sin[theta]},
  {-Cos[psi] Cos[theta] Sin[phi] - Cos[phi] Sin[psi],
    Cos[phi] Cos[psi] Cos[theta] - Sin[phi] Sin[psi],
    Cos[psi] Sin[theta]},
  {Sin[phi] Sin[theta], -Cos[phi] Sin[theta], Cos[theta]}}
```

Note: Per J. Wertz, "Spacecraft Attitude Determination and Control", D. Reidel Pub., 1985, pp.763-764, This is a Type 2 Euler Angle representation with a z-x-z rotation sequence.

```
(Debug) In[5]:=
  pi = N[π, 10];
(Debug) In[6]:=
  Clear[Reflect];
  Reflect[u_, n_] := Block[{temp, i, j}, temp = Cross[u, n];
    i =  $\frac{\text{temp}}{\sqrt{\text{temp} \cdot \text{temp}}}$ ; j = Cross[n, i]; Return[u.j j - u.n n];
```

```
(Debug) In[8]:=
  Clear[Refract, ni, nt];
  Refract[u_, n_, ni_, nt_] := Block[{temp, i, j},
    temp = Cross[u, n]; i =  $\frac{\text{temp}}{\sqrt{\text{temp} \cdot \text{temp}}}$ ; j = Cross[n, i];
    temp =  $\frac{\text{ni} \cdot \text{u} \cdot \text{j}}{\text{nt}}$ ; Return[temp j -  $\sqrt{1 - \text{temp}^2}$  n];
```

```
(Debug) In[10]:=
  DMS[rad_] := {IntegerPart[rad 180 / Pi], IntegerPart[
    FractionalPart[rad 180 / Pi] 60 + Sign[rad] 10^-18],
    Round[FractionalPart[(rad 180 / Pi) 60] 60]};
```

```
(Debug) In[11]:=
  RAD[deg_, min_, sec_] := (deg + min / 60 + sec / 3600) Pi / 180;
```

`(Debug) In[12]:=`

```

formattedTablePositions := Grid[Flatten[{{
  {"Optic", "Global Coordinates\n(mm)", SpanFromLeft,
  SpanFromLeft, "Local Coordinates\n(mm)",
  SpanFromLeft, SpanFromLeft},
  {SpanFromAbove, "Xg", "Yg", "Zg", "Xl", "Yl", "Zl"}},
Table[{opticLabel[[i]],
  NumberForm[opticPositionG[[i, 1]], {10, 1}},
  NumberForm[opticPositionG[[i, 2]], {10, 1}},
  NumberForm[opticPositionG[[i, 3]], {10, 1}}, \
  NumberForm[opticPositionL[[i, 1]], {10, 1}},
  NumberForm[opticPositionL[[i, 2]], {10, 1}},
  NumberForm[opticPositionL[[i, 3]], {10, 1}]]},
{i, 1, nOptics}]]}, 1], Frame → All];

```

`(Debug) In[13]:=`

```

formattedTableNormals := Grid[Flatten[{{
  {"Optic", "Normal Unit Vector (global)\n(mm)",
  SpanFromLeft, SpanFromLeft,
  "Normal Unit Vector (local)\n(mm)",
  SpanFromLeft, SpanFromLeft},
  {SpanFromAbove, "Ug", "Vg", "Wg", "Ul", "Vl", "Wl"}},
Table[{opticLabel[[i]],
  NumberForm[opticNormalG[[i, 1]], {10, 6}},
  NumberForm[opticNormalG[[i, 2]], {10, 6}},
  NumberForm[opticNormalG[[i, 3]], {10, 6}}, \
  NumberForm[opticNormalL[[i, 1]], {10, 6},
  ExponentFunction -> (If[-30 < # < 30, Null, #] &)],
  NumberForm[opticNormalL[[i, 2]], {10, 6},
  ExponentFunction -> (If[-30 < # < 30, Null, #] &)],
  NumberForm[opticNormalL[[i, 3]], {10, 6},
  ExponentFunction -> (If[-30 < # < 30, Null, #] &)]},
{i, 1, nOptics}]]}, 1], Frame → All];

```

`(Debug) In[14]:=`

```

formattedTableAngles := Grid[Flatten[{{
  {"Optic", "Yaw", "Yaw", SpanFromLeft, SpanFromLeft},
  {SpanFromAbove, "rad", "deg", "min", "sec"}}, Table[
  {opticLabel[[i]], NumberForm[opticYaw[[i]], {10, 6},
    ExponentFunction -> (If[-10 < # < 10, Null, #] &)],
    NumberForm[DMS[opticYaw[[i]]][[1]], {10, 0}},
    NumberForm[DMS[opticYaw[[i]]][[2]], {10, 0}},
    NumberForm[DMS[opticYaw[[i]]][[3]], {10, 0}}],
  {i, 1, nOptics}}], 1], Frame -> All];

```

`(Debug) In[15]:=`

```

formattedTableComparePositions := Grid[Flatten[{{
  {"Optic", "Global Coordinate\n Difference (mm)",
    SpanFromLeft, SpanFromLeft},
  {SpanFromAbove, "DXg", "DYg", "DZg"}},
  Table[{compareOpticLabel[[i]],
    NumberForm[comparePositionG[[i, 1]], {10, 1},
      ExponentFunction -> (If[-30 < # < 30, Null, #] &)],
    NumberForm[comparePositionG[[i, 2]], {10, 1},
      ExponentFunction -> (If[-30 < # < 30, Null, #] &)],
    NumberForm[comparePositionG[[i, 3]], {10, 1},
      ExponentFunction -> (If[-30 < # < 30, Null, #] &)]},
  {i, 1, nCompareOptics}}], 1], Frame -> All];

```

`(Debug) In[16]:=`

```

formattedTableCompareLengths := Grid[Flatten[{{
  {"Length", "Length (mm)", SpanFromLeft, SpanFromLeft},
  {SpanFromAbove, "T0900043-v11", "Calculated",
    "Difference"}}, Table[{RCLengthsLabel[[i]],
    NumberForm[compareRCLengths[[i, 1]], {10, 1},
      ExponentFunction -> (If[-30 < # < 30, Null, #] &)],
    NumberForm[compareRCLengths[[i, 2]], {10, 1},
      ExponentFunction -> (If[-30 < # < 30, Null, #] &)],
    NumberForm[compareRCLengths[[i, 3]], {10, 1},
      ExponentFunction -> (If[-30 < # < 30, Null, #] &)]},
  {i, 1, nRCLengths}}], 1], Frame -> All];

```



```
(Debug) In[17]:=
  formattedTableParameters := Grid[Flatten[{{
    {"Optic", "wedge",
     SpanFromLeft, "Thickness", "Diameter"},
    {SpanFromAbove, "rad", "deg", "mm", "mm"}},
  Table[{opticLabel[[i]], NumberForm[opticWedge[[i]],
    {10, 6}], NumberForm[If[opticWedge[[i]] != "NA",
     opticWedge[[i]] * 180 / pi, "NA"], {10, 6}],
    NumberForm[opticThick[[i]], {10, 6}],
    NumberForm[opticDiameter[[i]], {10, 6}]}],
  {i, 1, nOptics}]], 1], Frame → All];
```

## ■ Global to Local Coordinate Transformation Matrices

See Tables 10-14 and Tables 25-27 of T980044-v1(aka -10), "Determination of Local and Global Coordinate Axes for the LIGO Sites".

### ■ Rhc → Hanford Corner station

```
(Debug) In[18]:=
  xangle = 619.49 × 10-6;
  yangle = 12.4832 × 10-6;
```

```
(Debug) In[20]:=
  Rhc = RotationMatrix3D[0, yangle, 0].
        RotationMatrix3D[pi / 2, xangle, -pi / 2];
  MatrixForm[Rhc]
```

```
(Debug) Out[21]//MatrixForm=
  (
    1.          0.          -0.00061949
    7.73322 × 10-9  1.          0.0000124832
    0.00061949  -0.0000124832  1.
  )
```

```
(Debug) In[22]:=
  MatrixForm[Rhc - IdentityMatrix[3]]
```

```
(Debug) Out[22]//MatrixForm=
  (
    -1.91884 × 10-7  0.          -0.00061949
    7.73322 × 10-9  -7.79151 × 10-11  0.0000124832
    0.00061949      -0.0000124832  -1.91962 × 10-7
  )
```

```
(Debug) In[23]:=
```

```

Rhcinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhc.Rhcinv]

```

```
(Debug) Out[24]//MatrixForm=
```

$$\begin{pmatrix} 1. & 1.65436 \times 10^{-24} & 1.0842 \times 10^{-19} \\ 1.65436 \times 10^{-24} & 1. & 0. \\ 1.0842 \times 10^{-19} & 0. & 1. \end{pmatrix}$$

```
(Debug) In[25]:=
```

```
MatrixForm[Rhcinv]
```

```
(Debug) Out[25]//MatrixForm=
```

$$\begin{pmatrix} 1. & 7.73322 \times 10^{-9} & 0.00061949 \\ 0. & 1. & -0.0000124832 \\ -0.00061949 & 0.0000124832 & 1. \end{pmatrix}$$

## ■ Rhxm -> Hanford x-mid station

```
(Debug) In[26]:=
```

```

xangle = 305.827 × 10-6;
yangle = 12.0075 × 10-6;

```

```
(Debug) In[28]:=
```

```

Rhxm = RotationMatrix3D[0, yangle, 0].
RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rhxm]

```

```
(Debug) Out[29]//MatrixForm=
```

$$\begin{pmatrix} 1. & 0. & -0.000305827 \\ 3.67222 \times 10^{-9} & 1. & 0.0000120075 \\ 0.000305827 & -0.0000120075 & 1. \end{pmatrix}$$

```
(Debug) In[30]:=
```

```
MatrixForm[Rhxm - IdentityMatrix[3]]
```

```
(Debug) Out[30]//MatrixForm=
```

$$\begin{pmatrix} -4.67651 \times 10^{-8} & 0. & -0.000305827 \\ 3.67222 \times 10^{-9} & -7.209 \times 10^{-11} & 0.0000120075 \\ 0.000305827 & -0.0000120075 & -4.68372 \times 10^{-8} \end{pmatrix}$$

(Debug) In[31]:=

```
Rhxminv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
          RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhxm.Rhxminv]
```

(Debug) Out[32]//MatrixForm=

$$\begin{pmatrix} 1. & 4.1359 \times 10^{-25} & 0. \\ 4.1359 \times 10^{-25} & 1. & 0. \\ 0. & 0. & 1. \end{pmatrix}$$

## ■ Rhxe -> Hanford x-end station

(Debug) In[33]:=

```
xangle = -7.8389 10^-6;
yangle = 11.5318 x 10^-6;
```

(Debug) In[35]:=

```
Rhxe = RotationMatrix3D[0, yangle, 0].
        RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rhxe]
```

(Debug) Out[36]//MatrixForm=

$$\begin{pmatrix} 1. & 0. & 7.8389 \times 10^{-6} \\ -9.03966 \times 10^{-11} & 1. & 0.0000115318 \\ -7.8389 \times 10^{-6} & -0.0000115318 & 1. \end{pmatrix}$$

(Debug) In[37]:=

```
MatrixForm[Rhxe - IdentityMatrix[3]]
```

(Debug) Out[37]//MatrixForm=

$$\begin{pmatrix} -3.07242 \times 10^{-11} & 0. & 7.8389 \times 10^{-6} \\ -9.03966 \times 10^{-11} & -6.64913 \times 10^{-11} & 0.0000115318 \\ -7.8389 \times 10^{-6} & -0.0000115318 & -9.72155 \times 10^{-11} \end{pmatrix}$$

```
(Debug) In[38]:=
```

```

Rhxeinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
          RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhxe.Rhxeinv]

```

```
(Debug) Out[39]//MatrixForm=
```

$$\begin{pmatrix} 1. & 0. & 0. \\ 0. & 1. & 1.69407 \times 10^{-21} \\ 0. & 1.69407 \times 10^{-21} & 1. \end{pmatrix}$$

## ■ Rhym -> Hanford y-mid station

```
(Debug) In[40]:=
```

```

xangle = 619.97 × 10-6;
yangle = 325.84 × 10-6;

```

```
(Debug) In[42]:=
```

```

Rhym = RotationMatrix3D[0, yangle, 0].
        RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rhym]

```

```
(Debug) Out[43]//MatrixForm=
```

$$\begin{pmatrix} 1. & 0. & -0.00061997 \\ 2.02011 \times 10^{-7} & 1. & 0.00032584 \\ 0.00061997 & -0.00032584 & 1. \end{pmatrix}$$

```
(Debug) In[44]:=
```

```
MatrixForm[Rhym - IdentityMatrix[3]]
```

```
(Debug) Out[44]//MatrixForm=
```

$$\begin{pmatrix} -1.92181 \times 10^{-7} & 0. & -0.00061997 \\ 2.02011 \times 10^{-7} & -5.30859 \times 10^{-8} & 0.00032584 \\ 0.00061997 & -0.00032584 & -2.45267 \times 10^{-7} \end{pmatrix}$$

```
(Debug) In[45]:=
```

```

Rhyminv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
           RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhym.Rhyminv]

```

```
(Debug) Out[46]//MatrixForm=
```

$$\begin{pmatrix} 1. & 2.64698 \times 10^{-23} & 0. \\ 2.64698 \times 10^{-23} & 1. & 0. \\ 0. & 0. & 1. \end{pmatrix}$$

## ■ Rhye -> Hanford y-end station

(Debug) In[47]:=

```
xangle = 620.45 × 10-6;
yangle = 639.20 × 10-6;
```

(Debug) In[49]:=

```
Rhye = RotationMatrix3D[0, yangle, 0].
      RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rhxe]
```

(Debug) Out[50]//MatrixForm=

$$\begin{pmatrix} 1. & 0. & 7.8389 \times 10^{-6} \\ -9.03966 \times 10^{-11} & 1. & 0.0000115318 \\ -7.8389 \times 10^{-6} & -0.0000115318 & 1. \end{pmatrix}$$

(Debug) In[51]:=

```
MatrixForm[Rhye - IdentityMatrix[3]]
```

(Debug) Out[51]//MatrixForm=

$$\begin{pmatrix} -1.92479 \times 10^{-7} & 0. & -0.00062045 \\ 3.96592 \times 10^{-7} & -2.04288 \times 10^{-7} & 0.0006392 \\ 0.00062045 & -0.0006392 & -3.96767 \times 10^{-7} \end{pmatrix}$$

(Debug) In[52]:=

```
Rhyeinvs = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
           RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rhye.Rhyeinvs]
```

(Debug) Out[53]//MatrixForm=

$$\begin{pmatrix} 1. & -5.29396 \times 10^{-23} & 0. \\ -5.29396 \times 10^{-23} & 1. & -1.0842 \times 10^{-19} \\ 0. & -1.0842 \times 10^{-19} & 1. \end{pmatrix}$$

(Debug) In[54]:=

```
(180 / Pi) 619 × 10-6 // N
```

(Debug) Out[54]=

```
0.0354661
```

## ■ Rlc -> Livingston Corner station

(Debug) In[55]:=

```
xangle = 312.0 × 10-6;
yangle = -611.0 10-6;
```

(Debug) In[57]:=

```
Rlc = RotationMatrix3D[0, yangle, 0].
      RotationMatrix3D[Pi/2, xangle, -Pi/2];
MatrixForm[Rlc]
```

(Debug) Out[58]//MatrixForm=

$$\begin{pmatrix} 1. & 0. & -0.000312 \\ -1.90632 \times 10^{-7} & 1. & -0.000611 \\ 0.000312 & 0.000611 & 1. \end{pmatrix}$$

(Debug) In[59]:=

```
MatrixForm[Rlc - IdentityMatrix[3]]
```

(Debug) Out[59]//MatrixForm=

$$\begin{pmatrix} -4.8672 \times 10^{-8} & 0. & -0.000312 \\ -1.90632 \times 10^{-7} & -1.8666 \times 10^{-7} & -0.000611 \\ 0.000312 & 0.000611 & -2.35332 \times 10^{-7} \end{pmatrix}$$

(Debug) In[60]:=

```
Rlcinv = RotationMatrix3D[Pi/2, -xangle, -Pi/2].
          RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rlc.Rlcinv]
```

(Debug) Out[61]//MatrixForm=

$$\begin{pmatrix} 1. & 0. & 0. \\ 0. & 1. & 1.0842 \times 10^{-19} \\ 0. & 1.0842 \times 10^{-19} & 1. \end{pmatrix}$$

## ■ Rlxe -> Livingston x-end station

(Debug) In[62]:=

```
xangle = -315.0 10-6;
yangle = -610.0 10-6;
```

```
(Debug) In[64]:=
```

```

Rlxe = RotationMatrix3D[0, yangle, 0].
RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rlxe]

```

```
(Debug) Out[65]//MatrixForm=
```

$$\begin{pmatrix} 1. & 0. & 0.000315 \\ 1.9215 \times 10^{-7} & 1. & -0.00061 \\ -0.000315 & 0.00061 & 1. \end{pmatrix}$$

```
(Debug) In[66]:=
```

```

MatrixForm[Rlxe - IdentityMatrix[3]]

```

```
(Debug) Out[66]//MatrixForm=
```

$$\begin{pmatrix} -4.96125 \times 10^{-8} & 0. & 0.000315 \\ 1.9215 \times 10^{-7} & -1.8605 \times 10^{-7} & -0.00061 \\ -0.000315 & 0.00061 & -2.35662 \times 10^{-7} \end{pmatrix}$$

```
(Debug) In[67]:=
```

```

Rlxeinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rlxe.Rlxeinv]

```

```
(Debug) Out[68]//MatrixForm=
```

$$\begin{pmatrix} 1. & 0. & 0. \\ 0. & 1. & 0. \\ 0. & 0. & 1. \end{pmatrix}$$

```
(Debug) In[69]:=
```

```

MatrixForm[Rlxeinv - Transpose[Rlxe]]

```

```
(Debug) Out[69]//MatrixForm=
```

$$\begin{pmatrix} 0. & 0. & 0. \\ 0. & 0. & 0. \\ 0. & 0. & 0. \end{pmatrix}$$

## ■ Rlye -> Livingston y-end station

```
(Debug) In[70]:=
```

```

xangle = 311.0 × 10-6;
yangle = 18.8 × 10-6;

```

```
(Debug) In[72]:=
```

```

Rlye = RotationMatrix3D[0, yangle, 0].
RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
MatrixForm[Rlye]

```

```
(Debug) Out[73]//MatrixForm=
```

$$\begin{pmatrix} 1. & 0. & -0.000311 \\ 5.8468 \times 10^{-9} & 1. & 0.0000188 \\ 0.000311 & -0.0000188 & 1. \end{pmatrix}$$

```
(Debug) In[74]:=
```

```

MatrixForm[Rlye - IdentityMatrix[3]]

```

```
(Debug) Out[74]//MatrixForm=
```

$$\begin{pmatrix} -4.83605 \times 10^{-8} & 0. & -0.000311 \\ 5.8468 \times 10^{-9} & -1.7672 \times 10^{-10} & 0.0000188 \\ 0.000311 & -0.0000188 & -4.85372 \times 10^{-8} \end{pmatrix}$$

```
(Debug) In[75]:=
```

```

Rlyein v = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].
RotationMatrix3D[0, -yangle, 0];
MatrixForm[Rlye.Rlyein v]

```

```
(Debug) Out[76]//MatrixForm=
```

$$\begin{pmatrix} 1. & 0. & 0. \\ 0. & 1. & 0. \\ 0. & 0. & 1. \end{pmatrix}$$

## Vector Analysis for Wedge Position & Orientation Determination

### ■ Parameters

```
wl = 1.064;
```

```
nOptic = ModelRefractiveIndex[FusedSilica][WaveLength -> wl]
```

```
nAir = ModelRefractiveIndex[Air][WaveLength -> wl]
```

```
nVacuum = ModelRefractiveIndex[Vacuum][WaveLength -> wl]
```



(Debug) In[77]:=

```
nOptic = 1.44963;  
nAir = 1.0;  
nVacuum = 1.0;
```

Note : D0901920-v12 &-v13 pdf file reports nOptic = 1.44963. In fact Zemax uses Suprasil-Ext index for 20C, zero pressure at 1064 nm which is 1.4500310

According to

- I. H. Malitson. Interspecimen Comparison of the Refractive Index of Fused Silica, J. Opt. Soc. Am. 55, 1205-1208 (1965) doi:10.1364/JOSA.55.001205

- Handbook of Optics, 3rd edition, Vol. 4. McGraw-Hill 2009

as calculated at this URL:

http://refractiveindex.info/wiki/Citing\_RefractiveIndex.INFO

the index at 1064 nm is 1.44963

## ■ H1

### ■ Notes

1) The ITM optic assignments of specific serial numbered optics is given in T1200324-v2. The assignments of the CP and BS optics, and the parameters of each COC optic is given by serial number at <https://nebula.ligo.caltech.edu/optics/>, with the exception of CPy. GariLynn states that CP09 must be replaced (currently part of H2-ITMy destined to become H1-ITMy) and has chosen CP02 for its replacement.

ITMx is ITM09

ITMy is ITM06

CPx is CP01

CPy is CP02

BS is BS06

2) The magnitude and orientation of the wedge angles are as follows::

ITMx = 0.077 deg, vertical, thick side down

ITMy = 0.078 deg, vertical, thick side down

CPx = 0.069 deg, horizontal, thick side -Y

CPy = 0.069 deg, horizontal, thick side -X

BS = 0.076 deg, horizontal, thick side +X/+Y

The wedge angle values given in <https://nebula.ligo.caltech.edu/optics/> are the "final" values reported by the polishing contractor. However there is some round-off/approx. in

this data. GariLynn Billingsley suggests using the values reported in C1107164-v1.

## ■ H1 Unique Parameters

(Debug) ln[80]:=

```
wedgeITMx = 0.077*pi/180;
wedgeITMy = 0.078*pi/180;
wedgeCPx = 0.069*pi/180;
wedgeCPy = 0.069*pi/180;
wedgeBS = 0.076*pi/180;
```

(Debug) ln[85]:=

```
ITMxThick = 200.22;
ITMxDiameter = 340.13;
ITMyThick = 199.64;
ITMyDiameter = 340.06;
CPxThick = 99.82;
CPxDiameter = 340.13;
CPyThick = 99.91;
CPyDiameter = 340.22;
BSThick = 60.41;
BSDiameter = 369.85;
```

(Debug) ln[95]:=

```
p1 = {-200, 4983.1, -80};
p9 = {5013, -200, -80};
d12 = ITMyThick - (ITMyDiameter / 2) Tan[wedgeITMy];
d910 = ITMxThick - (ITMxDiameter / 3) Tan[wedgeITMx];
d23 = 20;
d1011 = 20;
d34 = CPyThick - (CPyDiameter / 2) Tan[wedgeCPy];
d1112 = CPxThick - (CPxDiameter / 2) Tan[wedgeCPx];
dBS = BSThick - (BSDiameter / 2) Tan[wedgeBS];
```

Note that the distances d513 and d57 are approximate -- they do not take into account the wedge angle of the BS

## ■ optic surface orientation determination

### ■ normal vectors for ITMs and CPs

(Debug) In[104]:=

```
n1 = {0, 1, 0};
n2=RotationMatrix3D[0,wedgeITMy,0].n1
```

(Debug) Out[105]=

```
{0., 0.999999, -0.00136136}
```

(Debug) In[106]:=

```
n3 = n2;
n4 = RotationMatrix3D[0, 0, -wedgeCPy].n3
```

(Debug) Out[107]=

```
{-0.00120428, 0.999998, -0.00136136}
```

(Debug) In[108]:=

```
n9 = {1, 0, 0};
n10 = RotationMatrix3D[pi/2, -wedgeITMx, -(pi/2)].n9
```

(Debug) Out[109]=

```
{0.999999, 0., -0.0013439}
```

(Debug) In[110]:=

```
n11 = n10;
n12 = RotationMatrix3D[0, 0, wedgeCPx].n11
```

(Debug) Out[111]=

```
{0.999998, -0.00120428, -0.0013439}
```

### ■ ITMy path to BS

(Debug) In[112]:=

```
u1 = -n1;
w1 = u1;
u2 = w1;
w2 = Refract[u2, n2, nOptic, nVacuum]
```

(Debug) Out[115]=

```
{0., -1., -0.000612107}
```

```
(Debug) In[116]:=  
  u3 = w2;  
  w3 = Refract[u3, n3, nVacuum, nOptic]
```

```
(Debug) Out[117]=  
  {0., -1., 2.1684 × 10-19}
```

```
(Debug) In[118]:=  
  u4 = w3;  
  w4 = Refract[u4, n4, nOptic, nVacuum]
```

```
(Debug) Out[119]=  
  {-0.00054148, -1., -0.000612108}
```

```
(Debug) In[120]:=  
  u5y = w4;
```

#### ■ ITMx path to BS

```
(Debug) In[121]:=  
  u9 = -n9;  
  w9 = u9;  
  u10 = w9;  
  w10 = Refract[u10, n10, nOptic, nVacuum]
```

```
(Debug) Out[124]=  
  {-1., 0., -0.00060426}
```

```
(Debug) In[125]:=  
  u11 = w10;  
  w11 = Refract[u11, n11, nVacuum, nOptic]
```

```
(Debug) Out[126]=  
  {-1., 0., 2.1684 × 10-19}
```

```
(Debug) In[127]:=  
  u12 = w11;  
  w12 = Refract[u12, n12, nOptic, nVacuum]
```

```
(Debug) Out[128]=  
  {-1., -0.00054148, -0.000604261}
```

```
(Debug) In[129]:=  
  u13 = w12;
```

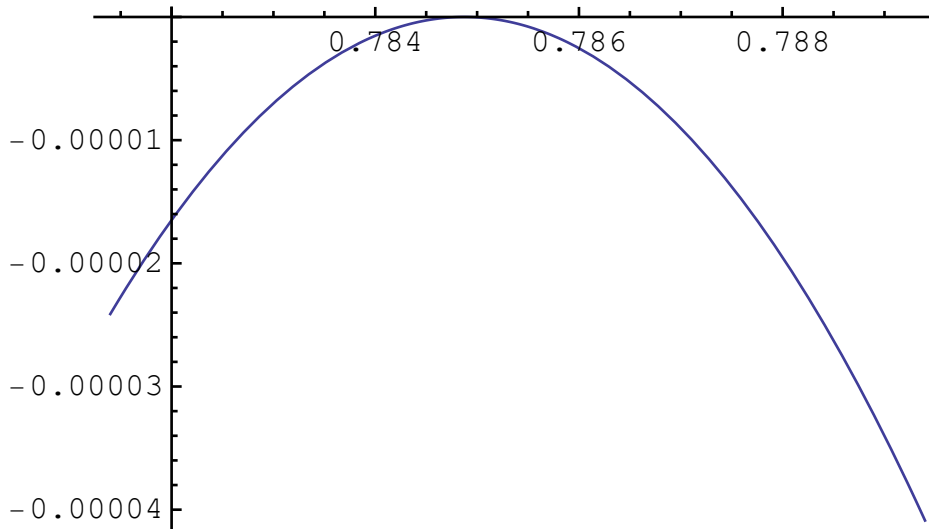
(Debug) In[130]:=

```

Plot[Reflect[u5y, RotationTransform[yaw, {0, 0, 1}][
  {0, 1, 0}]].Refract[Refract[u13,
  -RotationTransform[yaw - wedgeBS, {0, 0, 1}][
  {0, 1, 0}], nVacuum, nOptic],
  -RotationTransform[yaw, {0, 0, 1}][{0, 1, 0}],
  nOptic, nVacuum] - 1,
  {yaw, Pi / 4 - .004, Pi / 4 + .004}]

```

(Debug) Out[130]=



(Debug) In[131]:=

```

Clear[yaw];
soln = Maximize[
  Reflect[u5y, RotationTransform[yaw, {0, 0, 1}][
  {0, 1, 0}]].Refract[Refract[u13,
  -RotationTransform[yaw - wedgeBS, {0, 0, 1}][
  {0, 1, 0}], nVacuum, nOptic],
  -RotationTransform[yaw, {0, 0, 1}][{0, 1, 0}],
  nOptic, nVacuum], yaw]

```

(Debug) Out[132]=

```
{1., {yaw -> 0.784873}}
```

```
(Debug) In[133]:=
  BSyaw = -yaw /. soln[[2]];
  BSyawDeg = BSyaw 180 / pi

(Debug) Out[134]=
  -44.9699

(Debug) In[135]:=
  n5y = RotationMatrix3D[BSyaw, 0, 0].{0, 1, 0}
  n5x = -n5y;

(Debug) Out[135]=
  {-0.706736, 0.707478, 0.}

(Debug) In[137]:=
  RotationTransform[BSyaw, {0, 0, 1}][{0, 1, 0}]

(Debug) Out[137]=
  {0.706736, 0.707478, 0.}

(Debug) In[138]:=
  v5 = Reflect[u5y, n5y]

(Debug) Out[138]=
  {-1., 0.000507921, -0.000612108}

(Debug) In[139]:=
  w5y = Refract[u5y, n5y, nVacuum, nOptic]

(Debug) Out[139]=
  {0.271849, -0.96234, -0.000422251}

(Debug) In[140]:=
  n13 = RotationMatrix3D[wedgeBS, 0, 0].n5x;
  n7 = -n13

(Debug) Out[141]=
  {-0.705797, 0.708415, 0.}

(Debug) In[142]:=
  u7 = w5y;
  w7 = Refract[u7, n7, nOptic, nVacuum]

(Debug) Out[143]=
  {0.00050405, -1., -0.000612108}
```

```
(Debug) In[144]:=
  w13 = Refract[u13, n13, nVacuum, nOptic];
  u5x = w13;
  w5x = Refract[u5x, n5x, nOptic, nVacuum]

(Debug) Out[146]=
  {-1., 0.000507926, -0.000604261}
```

## ■ BS position determination

```
(Debug) In[147]:=
  d513 = dBS / (-w13.n5x)

(Debug) Out[147]=
  68.9204

(Debug) In[148]:=
  d57 = dBS / (w5y.n5x)

(Debug) Out[148]=
  68.9204

(Debug) In[149]:=
  p2 = p1 + d12 w1

(Debug) Out[149]=
  {-200., 4783.69, -80.}

(Debug) In[150]:=
  p3 = p2 + d23 w2

(Debug) Out[150]=
  {-200., 4763.69, -80.0122}

(Debug) In[151]:=
  p4 = p3 + d34 w3

(Debug) Out[151]=
  {-200., 4663.99, -80.0122}

(Debug) In[152]:=
  p10 = p9 + d910 w9

(Debug) Out[152]=
  {4812.93, -200., -80.}
```

```

(Debug) In[153]:=
  p11 = p10 + d1011 w10
(Debug) Out[153]=
  {4792.93, -200., -80.0121}
(Debug) In[154]:=
  p12 = p11 + d1112 w11
(Debug) Out[154]=
  {4693.32, -200., -80.0121}
(Debug) In[155]:=
  Clear[dBSy, dBSx]
  soln = Minimize[EuclideanDistance[p4 + dBSy w4,
    p12 + dBSx w12 + d513 w13], {dBSy, dBSx}]
(Debug) Out[156]=
  {0.0204444, {dBSy → 4847.8, dBSx → 4829.64}}
(Debug) In[157]:=
  d45 = dBSy /. soln[[2]];
  d1213 = dBSx /. soln[[2]];
(Debug) In[159]:=
  p5 = p4 + d45 w4
  p13 = p12 + d1213 w12
  p13 + d513 w13
(Debug) Out[159]=
  {-202.625, -183.81, -82.9796}
(Debug) Out[160]=
  {-136.32, -202.615, -82.9304}
(Debug) Out[161]=
  {-202.625, -183.81, -82.9592}
(Debug) In[162]:=
  p7 = p5 + d57 u7
(Debug) Out[162]=
  {-183.889, -250.134, -83.0087}

```

### ■ PR3 position determination

Take as a given the global x - coordinate of the PR3 from the IO layout (E1100494-v3) and



in the H1 Master Coordinates List (E1200616-v7):

(Debug) In[163]:=

```
pPR3 = {-19 740, -177.4, -94.6};
```

(Debug) In[164]:=

```
xPR3 = pPR3[[1]];
```

(Debug) In[165]:=

```
d56 = (xPR3 - p5[[1]]) / v5[[1]]
```

(Debug) Out[165]=

```
19 537.4
```

(Debug) In[166]:=

```
p6 = p5 + d56 v5
```

(Debug) Out[166]=

```
{-19 740., -173.886, -94.9386}
```

## ■ PR2 position determination

PR3 is constrained to be vertical (zero pitch angle) in local coordinates (to minimize vertical bounce mode-to-length coupling). Consequently the normal vector for this optic must be pitched in global coordinates.

Take as a given the global x and y coordinates of the PR2 from the IO layout (because the IO layout position is used in the SolidWorks layouts used to physically place the suspensions

pPR2 from IO layout (E1100495-v4, and E1200616-v7) should equal p14

(Debug) In[167]:=

```
pPR2io = {-3581.3, -530.4, -84.3};
```

(Debug) In[168]:=

```
u6 = v5;
```

Clear[s, yaw]

```
soln = Minimize[EuclideanDistance[p6 + s Reflect[u6, Rhc.Rotate3D[{1, 0, 0}], -yaw, 0, 0]], pPR2io], {s, yaw}]
```

```

(Debug) In[169]:=
  Clear[s, yaw]
  soln = Minimize[EuclideanDistance[
    p6 + s Reflect[u6, Rhc.RotationTransform[yaw,
      {0, 0, 1}][{1, 0, 0}]], pPR2io], {s, yaw}]

(Debug) Out[170]=
  {0.504593, {s → 16162.6, yaw → -0.0112838}}

(Debug) In[171]:=
  PR3yaw = yaw /. soln[[2]];
  d614 = s /. soln[[2]];
  n6 = Rhc.RotationTransform[PR3yaw, {0, 0, 1}][{1, 0, 0}]
  v6 = Reflect[u6, n6];
  p14 = p6 + d614 v6

(Debug) Out[173]=
  {0.999936, -0.0112836, 0.000619591}

(Debug) Out[175]=
  {-3581.3, -530.4, -84.8046}

```

## ■ PRM position determination

PR2 is constrained to be vertical (zero pitch angle) in local coordinates (to minimize vertical bounce mode-to-length coupling). Consequently the normal vector for this optic must be pitched in global coordinates.

Take as a given the global x and y coordinates of the PRM from the IO layout (because the IO layout position is used in the SolidWorks layouts used to physically place the suspensions

pPRM from IO layout (E1100494-v3) should equal p15

```

(Debug) In[176]:=
  pPRMio = {-20189.6, -628.0, -94.2};

```

**N.B. :** According to the IO H1 Master Coordinates List, the center of the HR face of PRM is at  $\{-20193.8, -628.0, -94.2\}$ , or 4.2 mm different in x compared to E1100494-v3!

Leaving as is for now.

```

(Debug) In[177]:=
  u14 = v6;

```

```

(Debug) In[178]:=
  Clear[s, yaw]
  soln = Minimize[EuclideanDistance[
    p14 + s Reflect[u14, Rhc.RotationTransform[-yaw,
      {0, 0, 1}][{-1, 0, 0}]], pPRMio], {s, yaw}]

(Debug) Out[179]=
  {0.769346, {s → 16 608.6, yaw → 0.0080916}}

(Debug) In[180]:=
  PR2yaw = yaw /. soln[[2]];
  d1415 = s /. soln[[2]];
  n14 =
    Rhc.RotationTransform[-PR2yaw, {0, 0, 1}][{-1, 0, 0}]
  v14 = Reflect[u14, n14];
  p15 = p14 + d1415 v14

(Debug) Out[182]=
  {-0.999967, 0.0080915, -0.000619571}

(Debug) Out[184]=
  {-20 189.6, -628., -94.9693}

(Debug) In[185]:=
  u15 = v14;
  n15 = -v14;
  Clear[yaw]
  soln = Maximize[
    n15.RotationTransform[-yaw, {0, 0, 1}][{1, 0, 0}],
    {yaw}];
  PRMyaw = yaw /. soln[[2]]

(Debug) Out[189]=
  -0.00587651

```

### ■ SR3 position determination

Take as a given the global y - coordinate of the SR3 from Zemax layout (D0901920-v13).  
pSR3 from Zemax should equal p8

```

(Debug) In[190]:=
  pSR3 = {-174.2, -19 615.9, -94.5};
  ySR3 = pSR3[[2]];

```

Note : This is close to the position given in the IO H1 Master Coordinates List (E1200616-v7):  $\{-174.1, -19615.9, -94.9\}$

(Debug) In[192]:=

```
d717 = (ySR3 - p7[[2]]) / w7[[2]]
```

(Debug) Out[192]=

```
19 365.8
```

(Debug) In[193]:=

```
p8 = p7 + d717 w7
```

(Debug) Out[193]=

```
 $\{-174.128, -19615.9, -94.8627\}$ 
```

(Debug) In[194]:=

```
n15 = -v14;
```

## ■ SR2 position determination

SR3 is constrained to be vertical (zero pitch angle) in local coordinates (to minimize vertical bounce mode-to-length coupling). Consequently the normal vector for this optic must be pitched in global coordinates.

Originally the global coordinates of the SRC optics in the SolidWorks layouts were taken from the Zemax layout (D0902216-v8) to locate the suspensions in the CAD model.

However, as-built ROC changes caused the locations of the SR2 and SRM to be changed.

The latest coordinates are given in the H1 Master Coordinates List E1200616-v7 and were used to revise the SolidWorks layout. Take as a given the global x and y coordinates of the PR2 from the Master Coordinate List

pSR2 should equal p16

(Debug) In[195]:=

```
pSR2zemax = {-594.1, -4178.1, -104.4};  
pSR2master = {-594.1, -4161.5, -105.0};
```

(Debug) In[197]:=

```
u8 = w7;
```

```
(Debug) In[198]:=
```

```
Clear[s, yaw]
soln = Minimize[EuclideanDistance[p8 + s Reflect[u8,
    Rhc.RotationTransform[yaw, {0, 0, 1}][{0, 1, 0}]],
    pSR2master], {s, yaw}]
```

```
(Debug) Out[199]=
```

```
{0.0231668, {s → 15 460.1, yaw → 0.0138362}}
```

```
(Debug) In[200]:=
```

```
SR3yaw = yaw /. soln[[2]];
d816 = s /. soln[[2]];
n8 = Rhc.RotationTransform[SR3yaw, {0, 0, 1}][{0, 1, 0}]
v8 = Reflect[u8, n8];
p16 = p8 + d816 v8
```

```
(Debug) Out[202]=
```

```
{-0.0138357, 0.999904, -0.0000210531}
```

```
(Debug) Out[204]=
```

```
{-594.1, -4161.5, -104.977}
```

## ■ SRM position determination

SR2 is constrained to be vertical (zero pitch angle) in local coordinates (to minimize vertical bounce mode-to-length coupling). Consequently the normal vector for this optic must be pitched in global coordinates.

Originally the global coordinates of the SRC optics in the SolidWorks layouts were taken from the Zemax layout (D0902216-v8) to locate the suspensions in the CAD model.

However, as-built ROC changes caused the locations of the SR2 and SRM to be changed.

The latest coordinates are given in the H1 Master Coordinates List E1200616-v7 and were used to revise the SolidWorks layout. Take as a given the global x and y coordinates of the PRM from the Master Coordinate List

pSRM should equal p17

```
(Debug) In[205]:=
```

```
pSRMzemax = {305.4, -19 908.6, -113.2};
pSRMmaster = {305.4, -19 875.8, -114.1};
```

```
(Debug) In[207]:=
```

```
u16 = v8;
```

```
(Debug) In[208]:=
Clear[s, yaw]
soln =
  Minimize[EuclideanDistance[p16 + s Reflect[u16, Rhc.
    RotationTransform[-yaw, {0, 0, 1}][{0, -1, 0}]],
    pSRMmaster], {s, yaw}]
```

```
(Debug) Out[209]=
{0.0405644, {s → 15 740., yaw → -0.0421734}}
```

```
(Debug) In[210]:=
SR2yaw = yaw /. soln[[2]];
d1617 = s /. soln[[2]];
n16 =
  Rhc.RotationTransform[-SR2yaw, {0, 0, 1}][{0, -1, 0}]
v16 = Reflect[u16, n16];
p17 = p16 + d1617 v16
```

```
(Debug) Out[212]=
{0.0421609, -0.999111, 0.0000385903}
```

```
(Debug) Out[214]=
{305.4, -19 875.8, -114.059}
```

```
(Debug) In[215]:=
u17 = v16;
n17 = -v16;
Clear[yaw]
soln = Maximize[
  n17.RotationTransform[-yaw, {0, 0, 1}][{0, 1, 0}],
  {yaw}];
SRMyaw = yaw /. soln[[2]]
```

```
(Debug) Out[219]=
-0.0571785
```

## ■ Schnupp Assymetry

According to T0900043-v11, the Schnupp Assymetry length is supposed to be 50 mm lengths.

However, the Schnupp Assymetry is supposed to be 80 mm, according to RODA M1200276-v1

```
(Debug) In[220]:=
  schnuppAssy =
    Abs [ (nOptic d12 + d23 + nOptic d34 + d45) - (nOptic d910 +
      d1011 + nOptic d1112 + d1213 + nOptic d513) ]
```

```
(Debug) Out[220]=
  82.5752
```

## ■ PRC Lengths

According to T0900043-v11, the power recycling cavity (PRC) lengths are supposed to be:

Distance b/w PRM and PR<sub>2</sub> 16603.7

Distance b/w PR<sub>2</sub> and PR<sub>3</sub> 16155.8

Distance b/w PR<sub>3</sub> and BS 19538.4

Distance b/w BS and CPy 4849.7

Distance b/w CPy and ITMy 5

PRC length = 57656.0 mm

```
(Debug) In[221]:=
  dPRMtoPR2 = 16 603.7 ;
  d1415
  d1415 - dPRMtoPR2
```

```
(Debug) Out[222]=
  16 608.6
```

```
(Debug) Out[223]=
  4.88972
```

```
(Debug) In[224]:=
  dPR2toPR3 = 16 155.8 ;
  d614
  d614 - dPR2toPR3
```

```
(Debug) Out[225]=
  16 162.6
```

```
(Debug) Out[226]=
  6.83594
```

```

(Debug) In[227]:=
  dPR3toBS = 19 538.4 ;
  d56
  d56 - dPR3toBS

(Debug) Out[228]=
  19 537.4

(Debug) Out[229]=
  -1.0188

(Debug) In[230]:=
  dBStoCPy = 4849.7 ;
  d45
  d45 - dBStoCPy

(Debug) Out[231]=
  4847.8

(Debug) Out[232]=
  -1.90247

(Debug) In[233]:=
  dPRCIO = 57 656.0 ;
  dPRC = d1415 + d614 + d56 +
    ( (nOptic d12 + d23 + nOptic d34 + d45) + (nOptic d910 +
      d1011 + nOptic d1112 + d1213 + nOptic d513) ) / 2
  dPRC -
  dPRCIO

(Debug) Out[234]=
  57 651.3

(Debug) Out[235]=
  -4.70384

```

## ■ SRC Lengths

According to T0900043-v11, the signal recycling cavity (SRC) lengths are supposed to be:

Distance b/w SRM and SR<sub>2</sub> 15726.0  
 Distance b/w SR<sub>2</sub> and SR<sub>3</sub> 15460.7  
 Distance b/w SR<sub>3</sub> and BS 19368.0  
 Distance b/w BS and CP 4804.6



BS Effective thickness 131.5

Distance b/w CPx and ITMx 5

SRC length = 56008.0 mm

(Debug) In[236]:=

**dSRMtoSR2 = 15 726.0;**

**d816**

**d816 - dSRMtoSR2**

(Debug) Out[237]=

15 460.1

(Debug) Out[238]=

-265.891

(Debug) In[239]:=

**dSR2toSR3 = 15 460.7;**

**d1617**

**d1617 - dSR2toSR3**

(Debug) Out[240]=

15 740.

(Debug) Out[241]=

279.326

(Debug) In[242]:=

**dSR3toBS = 19 368.0;**

**d717**

**d717 - dSR3toBS**

(Debug) Out[243]=

19 365.8

(Debug) Out[244]=

-2.22831

(Debug) In[245]:=

**dBStoCPx = 4804.6;**

**d1213**

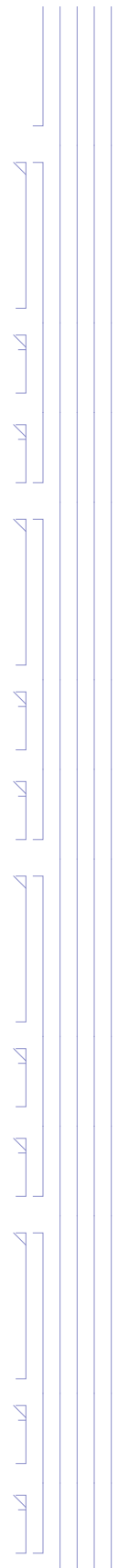
**d1213 - dBStoSPx**

(Debug) Out[246]=

4829.64

(Debug) Out[247]=

4829.64 - dBStoSPx



(Debug) In[248]:=

**dBSe = 131.5;**

**d57 + d513**

**d57 + d513 - dBSe**

(Debug) Out[249]=

137.841

(Debug) Out[250]=

6.34076

(Debug) In[251]:=

**dSRCIO = 56 008.0;**

**dSRC = d1617 + d816 + d717 + nOptic d57 +**

**((nOptic d12 + d23 + nOptic d34 + d45) + (nOptic d910 +  
d1011 + nOptic d1112 + d1213 + nOptic d513)) / 2**

**dSRC -**

**dSRCIO**

(Debug) Out[252]=

56 008.5

(Debug) Out[253]=

0.504407



## ■ Summary

### ■ Optic Parameters

(Debug) In[254]:=

```

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[259]:=

```
formattedTableParameters
```

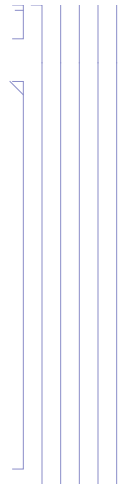
(Debug) Out[259]=

Optic	wedge		Thickness mm	Diameter mm
	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[260]:=

```
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[265]=

**formattedTablePositions**

(Debug) Out[265]=

Optic	Global Coordinates (mm)			Local Coordinates (mm)		
	Xg	Yg	Zg	Xl	Yl	Zl
PRM HR	-2018- 9.- 6	-628.0	-95.0	-2018- 9.- 7	-628.0	-82.5
PR2 HR	-3581- .3	-530.4	-84.8	-3581- .4	-530.4	-82.6
PR3 HR	-1974- 0.- 0	-173.9	-94.9	-1974- 0.- 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	-1987- 5.- 8	-114.1	305.3	-1987- 5.- 8	-114.5
SR2 HR	-594.1	-4161- .5	-105.0	-594.2	-4161- .5	-104.7
SR3 HR	-174.1	-1961- 5.- 9	-94.9	-174.2	-1961- 5.- 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[266]=

**formattedTableNormals**

(Debug) Out[266]=

Optic	Normal Unit Vector (global) (mm)			Normal Unit Vector (local) (mm)		
	Ug	Vg	Wg	Ul	Vl	Wl

PRM HR	0.999- 98- 3	0.005- 87- 6	0.000- 61- 2	0.999- 98- 3	0.005- 87- 6	-0.00- 00- 07
PR2 HR	-0.99- 99- 67	0.008- 09- 2	-0.00- 06- 20	-0.99- 99- 67	0.008- 09- 2	-0.00- 00- 00
PR3 HR	0.999- 93- 6	-0.01- 12- 84	0.000- 62- 0	0.999- 93- 6	-0.01- 12- 84	0.000- 00- 0
BS HR	-0.70- 67- 36	0.707- 47- 8	0.000- 00- 0	-0.70- 67- 36	0.707- 47- 8	0.000- 44- 7
BS ARs	0.705- 79- 7	-0.70- 84- 15	0.000- 00- 0	0.705- 79- 6	-0.70- 84- 15	-0.00- 04- 46
SRM HR	-0.05- 71- 47	0.998- 36- 6	0.000- 57- 7	-0.05- 71- 47	0.998- 36- 6	0.000- 62- 5
SR2 HR	0.042- 16- 1	-0.99- 91- 11	0.000- 03- 9	0.042- 16- 1	-0.99- 91- 11	0.000- 00- 0
SR3 HR	-0.01- 38- 36	0.999- 90- 4	-0.00- 00- 21	-0.01- 38- 36	0.999- 90- 4	-0.00- 00- 00
CPx	0.999- 99- 9	0.000- 00- 0	-0.00- 13- 44	0.999- 99- 8	0.000- 00- 0	-0.00- 19- 63
ITMx	1.000- 00- 0	0.000- 00- 0	0.000- 00- 0	1.000- 00- 0	0.000- 00- 0	-0.00- 06- 19
CPy	0.000- 00- 0	0.999- 99- 9	-0.00- 13- 61	-0.00- 00- 01	0.999- 99- 9	-0.00- 13- 49
ITMy	0.000- 00- 0	1.000- 00- 0	0.000- 00- 0	0.000- 00- 0	1.000- 00- 0	0.000- 01- 2

(Debug) In[267]:=

**formattedTableAngles**

(Debug) Out[267]=

Optic	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	-0.057178	-3.	-16.	-34.
SR2 HR	-0.042173	-2.	-24.	-59.
SR3 HR	0.013836	0.	47.	34.
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[268]:=

```

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[271]:=

```

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

```

(Debug) In[274]:=

```

formattedTableComparePositions

```

(Debug) Out[274]=

Optic	Global Coordinate Difference (mm)		
	DXg	DYg	DZg
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	32.8	-0.9
SR2 HR	-0.0	16.6	-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:

```

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}};
```

IO Layout results for PRM, PR2, PR3, SRM, SR2 and SR3 are from E1200616-v7 for H1 in global coordinates

(Debug) In[275]:=

```
opticLabelIO =  
  {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS ARs",  
   "SRM", "SR2", "SR3", "CPx", "ITMx", "CPy", "ITMy"};  
nOpticsIO = Length[opticLabelIO];  
opticPosGIO =  
  {{-20193.8, -628, -94.2}, {-3581.3, -530.4, -84.3},  
   {-19740, -177.4, -94.6}, {-201.9, -183.9, -82.9},  
   {-183.3, -249.8, -82.9}, {305.4, -19875.8, -114.1},  
   {-594.1, -4161.5, -105.0}, {-174.1, -19615.9, -94.9},  
   {4793.0, -200.0, -80.0}, {5013.0, -200.0, -80.0},  
   {-200.0, 4763.1, -80.0}, {-200.0, 4983.1, -80.0}};
```

(Debug) In[278]:=

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

`(Debug) In[281]:=``formattedTableComparePositions``(Debug) Out[281]=`

Optic	Global Coordinate Difference (mm)		
	DXg	DYg	DZg
PRM HR	4.2	-0.0	-0.8
PR2 HR	0.0	-0.0	-0.5
PR3 HR	0.0	3.5	-0.3
BS HR	-0.7	0.1	-0.1
BS ARs	-0.6	-0.3	-0.1
SRM	-0.0	-0.0	0.0
SR2	-0.0	0.0	0.0
SR3	-0.0	0.0	0.0
CPx	-0.1	0.0	-0.0
ITMx	0.0	0.0	0.0
CPy	0.0	0.6	-0.0
ITMy	0.0	0.0	0.0

## ■ RC Length Results

`(Debug) In[282]:=`

```

RClengthsLabel =
  {"PRM to PR2", "PR2 to PR3", "PR3 to BS", "BS to CPy",
   "PRC", "SRM to SR2", "SR2 to SR3", "SR3 to BS",
   "BS effective thickness", "BS to CPx", "SRC"};
nRClengths = Length[RClengthsLabel];
RClengthsIO = {dPRMtoPR2, dPR2toPR3,
  dPR3toBS, dBStoCPy, dPRCIO, dSRMtoSR2,
  dSR2toSR3, dSR3toBS, dBSe, dBStoCPx, dSRCIO};
RClengths = {d1415, d614, d56, d45, dPRC, d816,
  d1617, d717, d57 + d513, d1213, dSRC};
compareRClengths = Transpose[
  {RClengthsIO, RClengths, RClengths - RClengthsIO}];

```

`(Debug) In[287]:=``formattedTableCompareLengths``(Debug) Out[287]=`

Length	Length (mm)		
	T0900043-v11	Calculated	Difference
PRM to PR2	16603.7	16608.6	4.9
PR2 to PR3	16155.8	16162.6	6.8
PR3 to BS	19538.4	19537.4	-1.0
BS to CPy	4849.7	4847.8	-1.9
PRC	57656.0	57651.3	-4.7
SRM to SR2	15726.0	15460.1	-265.9
SR2 to SR3	15460.7	15740.0	279.3
SR3 to BS	19368.0	19365.8	-2.2
BS effective thickness	131.5	137.8	6.3
BS to CPx	4804.6	4829.6	25.0
SRC	56008.0	56008.5	0.5

## ■ L1

### ■ Notes

1) The ITM optic assignments of specific serial numbered optics is given in T1200324-v2. The assignments of the CP and BS optics, and the parameters of each COC optic is given by serial number at <https://nebula.ligo.caltech.edu/optics/>, with the exception of CPy. GariLynn states that CP09 must be replaced (currently part of H2-ITMy destined to become H1-ITMy) and has chosen CP02 for its replacement.

ITMx is ITM04

ITMy is ITM08

CPx is CP06

CPy is CP08

BS is BS02

2) The magnitude and orientation of the wedge angles are as follows::

ITMx = 0.0725 deg, vertical, thick side down

ITMy = 0.074 deg, vertical, thick side down

CPx = 0.073 deg, horizontal, thick side -Y  
 CPy = 0.066 deg, horizontal, thick side -X  
 BS = 0.070 deg, horizontal, thick side +X/+Y

The wedge angle values given in <https://nebula.ligo.caltech.edu/optics/> are the "final" values reported by the polishing contractor. However there is some round-off/approx. in this data. GariLynn Billingsley suggests using the values reported in C1107164-v1.

## ■ L1 Unique Parameters

optic thicknesses are the as-built values reported in C1107164-v1 for the assigned optics

(Debug) In[288]:=

```
wedgeITMx = 0.0725*pi/180;
wedgeITMy = 0.074*pi/180;
wedgeCPx = 0.073*pi/180;
wedgeCPy = 0.066*pi/180;
wedgeBS = 0.070*pi/180;
```

(Debug) In[293]:=

```
ITMxThick = 200.27;
ITMxDiameter = 340.0;
ITMyThick = 199.61;
ITMyDiameter = 339.92;
CPxThick = 100.31;
CPxDiameter = 339.94;
CPyThick = 100.32;
CPyDiameter = 340.11;
BSThick = 59.88;
BSDiameter = 369.98;
```

(Debug) In[303]:=

```
p1 = {-200, 4983.1, -80};
p9 = {5013, -200, -80};
d12 = ITMyThick - (ITMyDiameter / 2) Tan[wedgeITMy];
d910 = ITMxThick - (ITMxDiameter / 3) Tan[wedgeITMx];
d23 = 20;
d1011 = 20;
d34 = CPyThick - (CPyDiameter / 2) Tan[wedgeCPy];
d1112 = CPxThick - (CPxDiameter / 2) Tan[wedgeCPx];
dBS = BSThick - (BSDiameter / 2) Tan[wedgeBS];
```

Note that the distances d513 and d57 are approximate -- they do not take into account the wedge angle of the BS

## ■ optic surface orientation determination

### ■ normal vectors for ITMs and CPs

(Debug) In[312]:=

```
n1 = {0, 1, 0};
n2=RotationMatrix3D[0,wedgeITMy,0].n1
```

(Debug) Out[313]=

```
{0., 0.999999, -0.00129154}
```

(Debug) In[314]:=

```
n3 = n2;
n4 = RotationMatrix3D[0, 0, -wedgeCPy].n3
```

(Debug) Out[315]=

```
{-0.00115192, 0.999999, -0.00129154}
```

(Debug) In[316]:=

```
n9 = {1, 0, 0};
n10 = RotationMatrix3D[pi/2, -wedgeITMx, -(pi/2)].n9
```

(Debug) Out[317]=

```
{0.999999, 0., -0.00126536}
```

(Debug) In[318]:=

```
n11 = n10;
n12 = RotationMatrix3D[0, 0, wedgeCPx].n11
```

(Debug) Out[319]=

```
{0.999998, -0.00127409, -0.00126536}
```



(Debug) In[335]:=

```
u12 = w11;
```

```
w12 = Refract[u12, n12, nOptic, nVacuum]
```

(Debug) Out[336]=

```
{-1., -0.00057287, -0.000568947}
```

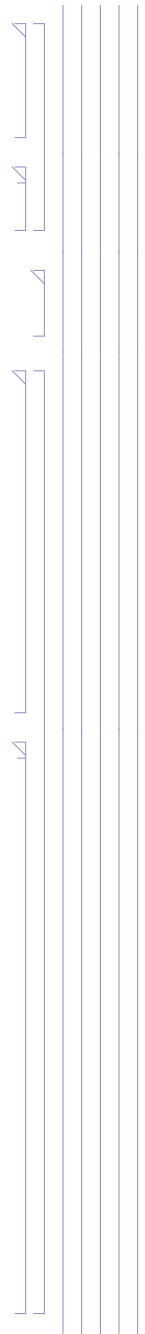
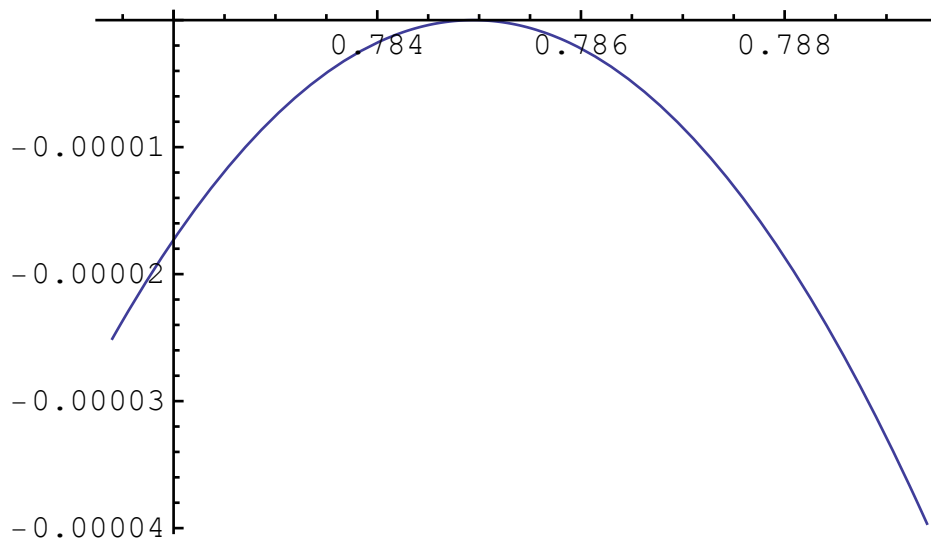
(Debug) In[337]:=

```
u13 = w12;
```

(Debug) In[338]:=

```
Plot[Reflect[u5y, RotationTransform[yaw, {0, 0, 1}][
  {0, 1, 0}]] . Refract[Refract[u13,
  -RotationTransform[yaw - wedgeBS, {0, 0, 1}][
  {0, 1, 0}], nVacuum, nOptic],
  -RotationTransform[yaw, {0, 0, 1}][{0, 1, 0}],
  nOptic, nVacuum] - 1,
  {yaw, Pi/4 - .004, Pi/4 + .004}]
```

(Debug) Out[338]=



```

(Debug) In[339]:=
  Clear[yaw];
  soln = Maximize[
    Reflect[u5y, RotationTransform[yaw, {0, 0, 1}][
      {0, 1, 0}]] . Refract[Refract[u13,
      -RotationTransform[yaw - wedgeBS, {0, 0, 1}][
        {0, 1, 0}], nVacuum, nOptic],
      -RotationTransform[yaw, {0, 0, 1}][{0, 1, 0}],
      nOptic, nVacuum], yaw]

(Debug) Out[340]=
  {1., {yaw → 0.784942}}

(Debug) In[341]:=
  BSyaw = -yaw /. soln[[2]];
  BSyawDeg = BSyaw 180 / pi

(Debug) Out[342]=
  -44.9739

(Debug) In[343]:=
  n5y = RotationMatrix3D[BSyaw, 0, 0].{0, 1, 0}
  n5x = -n5y;

(Debug) Out[343]=
  {-0.706784, 0.707429, 0.}

(Debug) In[345]:=
  RotationTransform[BSyaw, {0, 0, 1}][{0, 1, 0}]

(Debug) Out[345]=
  {0.706784, 0.707429, 0.}

(Debug) In[346]:=
  v5 = Reflect[u5y, n5y]

(Debug) Out[346]=
  {-1., 0.000393619, -0.000580718}

(Debug) In[347]:=
  w5y = Refract[u5y, n5y, nVacuum, nOptic]

(Debug) Out[347]=
  {0.271891, -0.962328, -0.000400597}

```



```
(Debug) In[348]:=
  n13 = RotationMatrix3D[wedgeBS, 0, 0].n5x;
  n7 = -n13
```

```
(Debug) Out[349]=
  {-0.70592, 0.708292, 0.}
```

```
(Debug) In[350]:=
  u7 = w5y;
  w7 = Refract[u7, n7, nOptic, nVacuum]
```

```
(Debug) Out[351]=
  {0.000445259, -1., -0.000580718}
```

```
(Debug) In[352]:=
  w13 = Refract[u13, n13, nVacuum, nOptic];
  u5x = w13;
  w5x = Refract[u5x, n5x, nOptic, nVacuum]
```

```
(Debug) Out[354]=
  {-1., 0.000393615, -0.000568947}
```

## ■ BS position determination

```
(Debug) In[355]:=
  d513 = dBS / (-w13.n5x)
```

```
(Debug) Out[355]=
  68.3363
```

```
(Debug) In[356]:=
  d57 = dBS / (w5y.n5x)
```

```
(Debug) Out[356]=
  68.3363
```

```
(Debug) In[357]:=
  p2 = p1 + d12 w1
```

```
(Debug) Out[357]=
  {-200., 4783.71, -80.}
```

```
(Debug) In[358]:=
  p3 = p2 + d23 w2
```

```
(Debug) Out[358]=
  {-200., 4763.71, -80.0116}
```

```

(Debug) In[359]:=
  p4 = p3 + d34 w3

(Debug) Out[359]=
  {-200., 4663.59, -80.0116}

(Debug) In[360]:=
  p10 = p9 + d910 w9

(Debug) Out[360]=
  {4812.87, -200., -80.}

(Debug) In[361]:=
  p11 = p10 + d1011 w10

(Debug) Out[361]=
  {4792.87, -200., -80.0114}

(Debug) In[362]:=
  p12 = p11 + d1112 w11

(Debug) Out[362]=
  {4692.78, -200., -80.0114}

(Debug) In[363]:=
  Clear[dBSy, dBSx]
  soln = Minimize[EuclideanDistance[p4 + dBSy w4,
    p12 + dBSx w12 + d513 w13], {dBSy, dBSx}]

(Debug) Out[364]=
  {0.040814, {dBSy → 4847.71, dBSx → 4829.55}}

(Debug) In[365]:=
  d45 = dBSy /. soln[[2]];
  d1213 = dBSx /. soln[[2]];

(Debug) In[367]:=
  p5 = p4 + d45 w4
  p13 = p12 + d1213 w12
  p13 + d513 w13

(Debug) Out[367]=
  {-202.511, -184.127, -82.8268}

(Debug) Out[368]=
  {-136.766, -202.767, -82.7591}

(Debug) Out[369]=
  {-202.511, -184.127, -82.786}

```

```
(Debug) In[370]:=
```

$$\mathbf{p7} = \mathbf{p5} + \mathbf{d57} \mathbf{u7}$$

```
(Debug) Out[370]=
```

```
{-183.931, -249.889, -82.8541}
```

## ■ PR3 position determination

Take as a given the global x - coordinate of the PR3 from the IO layout (because the IO layout position is used in the SolidWorks layouts used to physically place the suspensions pPR3 from the IO layout (E1100492-v11, E1100493-v9) should equal p6

```
(Debug) In[371]:=
```

$$\mathbf{pPR3} = \{-19740.0, -177.4, -94.5\};$$

$$\mathbf{xPR3} = \mathbf{pPR3}[[1]];$$

```
(Debug) In[373]:=
```

$$\mathbf{d56} = (\mathbf{xPR3} - \mathbf{p5}[[1]]) / \mathbf{v5}[[1]]$$

```
(Debug) Out[373]=
```

```
19537.5
```

```
(Debug) In[374]:=
```

$$\mathbf{p6} = \mathbf{p5} + \mathbf{d56} \mathbf{v5}$$

```
(Debug) Out[374]=
```

```
{-19740., -176.436, -94.1725}
```

## ■ PR2 position determination

PR3 is constrained to be vertical (zero pitch angle) in local coordinates (to minimize vertical bounce mode-to-length coupling). Consequently the normal vector for this optic must be pitched in global coordinates.

Take as a given the global x and y coordinates of the PR2 from the IO layout (because the IO layout position is used in the SolidWorks layouts used to physically place the suspensions

pPR2 from the IO layout (E1200274-v3) should equal p14

```
(Debug) In[375]:=
```

$$\mathbf{pPR2io} = \{-3579.2, -530.4, -94.2\};$$

```
(Debug) In[376]:=
```

$$\mathbf{u6} = \mathbf{v5};$$

```

(Debug) In[377]:=
  Clear[s, yaw]
  soln = Minimize[EuclideanDistance[
    p6 + s Reflect[u6, Rlc.RotationTransform[yaw,
      {0, 0, 1}][{1, 0, 0}]], pPR2io], {s, yaw}]

(Debug) Out[378]=
  {0.505734, {s → 16164.7, yaw → -0.0111462}}

(Debug) In[379]:=
  PR3yaw = yaw /. soln[[2]];
  d614 = s /. soln[[2]];
  n6 = Rlc.RotationTransform[PR3yaw, {0, 0, 1}][{1, 0, 0}]
  v6 = Reflect[u6, n6];
  p14 = p6 + d614 v6

(Debug) Out[381]=
  {0.999938, -0.0111461, 0.00030517}

(Debug) Out[383]=
  {-3579.2, -530.4, -93.6943}

```

## ■ PRM position determination

PR2 is constrained to be vertical (zero pitch angle) in local coordinates (to minimize vertical bounce mode-to-length coupling). Consequently the normal vector for this optic must be pitched in global coordinates.

Take as a given the global x and y coordinates of the PRM from the IO layout (because the IO layout position is used in the SolidWorks layouts used to physically place the suspensions

pPRM from the IO layout (E1200274-v3) should equal p15

```

(Debug) In[384]:=
  pPRMio = {-20189.6, -628.0, -104.1};

(Debug) In[385]:=
  u14 = v6;

```

```

(Debug) In[386]:=
  Clear[s, yaw]
  soln = Minimize[EuclideanDistance[
    p14 + s Reflect[u14, Rlc.RotationTransform[-yaw,
      {0, 0, 1}][{-1, 0, 0}]], pPRMio], {s, yaw}]

(Debug) Out[387]=
  {0.69607, {s → 16 610.7, yaw → 0.00801149}}

(Debug) In[388]:=
  PR2yaw = yaw /. soln[[2]];
  d1415 = s /. soln[[2]];
  n14 =
    Rlc.RotationTransform[-PR2yaw, {0, 0, 1}][{-1, 0, 0}]
  v14 = Reflect[u14, n14];
  p15 = p14 + d1415 v14

(Debug) Out[390]=
  {-0.999968, 0.00801159, -0.000307095}

(Debug) Out[392]=
  {-20 189.6, -628., -103.404}

(Debug) In[393]:=
  u15 = v14;
  n15 = -v14;
  Clear[yaw]
  soln = Maximize[
    n15.RotationTransform[-yaw, {0, 0, 1}][{1, 0, 0}],
    {yaw}];
  PRMyaw = yaw /. soln[[2]]

(Debug) Out[397]=
  -0.00587578

```

### ■ SR3 position determination

Take as a given the global y - coordinate of the SR3 from Zemax.  
 pSR3 from Zemax should equal p8

```

(Debug) In[398]:=
  pSR3 = {-175.2, -19 615.9, -94.1};
  ySR3 = pSR3[[2]];

```

```
(Debug) In[400]:=
  d717 = (ySR3 - p7[[2]]) / w7[[2]]
```

```
(Debug) Out[400]=
  19 366.
```

```
(Debug) In[401]:=
  p8 = p7 + d717 w7
```

```
(Debug) Out[401]=
  {-175.308, -19 615.9, -94.1003}
```

```
(Debug) In[402]:=
  n15 = -v14;
```

## ■ SR2 position determination

SR3 is constrained to be vertical (zero pitch angle) in local coordinates (to minimize vertical bounce mode-to-length coupling). Consequently the normal vector for this optic must be pitched in global coordinates.

Take as a given the global x and y coordinates of the SR2 from the Zemax layout (because the Zemax layout positions for the SRC are used in the SolidWorks layouts used to physically place the suspensions

pSR2 from Zemax (D0902216-v8) should equal p16

```
(Debug) In[403]:=
  pSR2zemax = {-594.1, -4178.1, -84.4};
```

```
(Debug) In[404]:=
  u8 = w7;
```

```
(Debug) In[405]:=
  Clear[s, yaw]
  soln = Minimize[EuclideanDistance[p8 + s Reflect[u8,
    Rlc.RotationTransform[yaw, {0, 0, 1}][{0, 1, 0}]]],
    pSR2zemax], {s, yaw}]
```

NMinimize::cvmit : Failed to converge to the  
requested accuracy or precision within 100 iterations. >>

```
(Debug) Out[406]=
  {0.0670134, {s → 15 443.5, yaw → 0.0137832}}
```

```
(Debug) In[407]:=
  SR3yaw = yaw /. soln[[2]];
  d816 = s /. soln[[2]];
  n8 = Rlc.RotationTransform[SR3yaw, {0, 0, 1}][{0, 1, 0}]
  v8 = Reflect[u8, n8];
  p16 = p8 + d816 v8
```

```
(Debug) Out[409]=
  {-0.0137827, 0.999905, 0.000606642}
```

```
(Debug) Out[411]=
  {-594.1, -4178.1, -84.333}
```

## ■ SRM position determination

SR2 is constrained to be vertical (zero pitch angle) in local coordinates (to minimize vertical bounce mode-to-length coupling). Consequently the normal vector for this optic must be pitched in global coordinates.

Take as a given the global x and y coordinates of the PRM from the Zemax layout (because the Zemax SRC layout positions are used in the SolidWorks layouts used to physically place the suspensions

pSRM from Zemax (D0902216-v8) should equal p17

```
(Debug) In[412]:=
  pSRMzemax = {305.0, -19908.6, -93.2};
```

```
(Debug) In[413]:=
  u16 = v8;
```

```
(Debug) In[414]:=
  Clear[s, yaw]
  soln =
  Minimize[EuclideanDistance[p16 + s Reflect[u16, Rlc.
    RotationTransform[-yaw, {0, 0, 1}][{0, -1, 0}]],
    pSRMzemax], {s, yaw}]
```

```
(Debug) Out[415]=
  {0.0111367, {s → 15756.2, yaw → -0.0421077}}
```

```
(Debug) In[416]:=
  SR2yaw = yaw /. soln[[2]];
  d1617 = s /. soln[[2]];
  n16 =
    Rlc.RotationTransform[-SR2yaw, {0, 0, 1}][{0, -1, 0}]
  v16 = Reflect[u16, n16];
  p17 = p16 + d1617 v16
```

```
(Debug) Out[418]=
  {0.0420953, -0.999113, -0.000597325}
```

```
(Debug) Out[420]=
  {305., -19 908.6, -93.1889}
```

```
(Debug) In[421]:=
  u17 = v16;
  n17 = -v16;
  Clear[yaw]
  soln = Maximize[
    n17.RotationTransform[-yaw, {0, 0, 1}][{0, 1, 0}],
    {yaw}];
  SRMyaw = yaw /. soln[[2]]
```

```
(Debug) Out[425]=
  -0.0570944
```

## ■ Schnupp Assymmetry

According to T0900043-v11, the Schnupp Assymmetry length is supposed to be 50 mm lengths.

However, the Schnupp Assymmetry is supposed to be 80 mm, according to RODA M1200276-v1

```
(Debug) In[426]:=
  schnuppAssy =
    Abs [(nOptic d12 + d23 + nOptic d34 + d45) - (nOptic d910 +
      d1011 + nOptic d1112 + d1213 + nOptic d513)]
```

```
(Debug) Out[426]=
  81.9188
```



## ■ PRC Lengths

According to T0900043-v11, the power recycling cavity (PRC) lengths, for the 12.5W input power case, are supposed to be:

Distance b/w PRM and PR<sub>2</sub> 16610.7

Distance b/w PR<sub>2</sub> and PR<sub>3</sub> 16164.7

Distance b/w PR<sub>3</sub> and BS 19538.1

Distance b/w BS and CPy 4862.0

Distance b/w CPy and ITMy 5

PRC length = 57656.0 mm

(Debug) In[427]:=

```
dPRMtoPR2 = 16 610 .7 ;
```

```
d1415
```

```
d1415 - dPRMtoPR2
```

(Debug) Out[428]=

```
16 610 .7
```

(Debug) Out[429]=

```
-0.0100448
```

(Debug) In[430]:=

```
dPR2toPR3 = 16 164 .7 ;
```

```
d614
```

```
d614 - dPR2toPR3
```

(Debug) Out[431]=

```
16 164 .7
```

(Debug) Out[432]=

```
-0.0241063
```

(Debug) In[433]:=

```
dPR3toBS = 19 538 .1 ;
```

```
d56
```

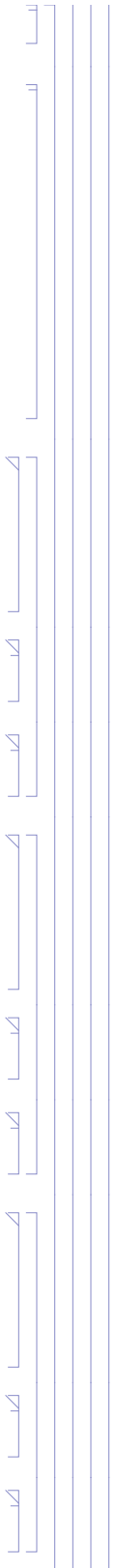
```
d56 - dPR3toBS
```

(Debug) Out[434]=

```
19 537 .5
```

(Debug) Out[435]=

```
-0.606003
```



(Debug) In[436]:=

**dBStoCPy = 4862.0;**

**d45**

**d45 - dBStoCPy**

(Debug) Out[437]=

4847.71

(Debug) Out[438]=

-14.2864

(Debug) In[439]:=

**dPRCIO = 57 656.0;**

**dPRC = d1415 + d614 + d56 +**

**((nOptic d12 + d23 + nOptic d34 + d45) + (nOptic d910 +  
d1011 + nOptic d1112 + d1213 + nOptic d513)) / 2**

**dPRC -**

**dPRCIO**

(Debug) Out[440]=

57 655.7

(Debug) Out[441]=

-0.28183

## ■ SRC Lengths

According to T0900043-v11, the signal recycling cavity (SRC) lengths for the 12.5W case are supposed to be:

Distance b/w SRM and SR<sub>2</sub> 15758.6

Distance b/w SR<sub>2</sub> and SR<sub>3</sub> 15443.5

Distance b/w SR<sub>3</sub> and BS 19366.1

Distance b/w BS and CP 4804.6

BS Effective thickness 131.5

Distance b/w CP<sub>x</sub> and ITM<sub>x</sub> 5

SRC length = 56008.0 mm

```
(Debug) In[442]:=  
  dSRMtoSR2 = 15 758.6;  
  d816  
  d816 - dSRMtoSR2
```

```
(Debug) Out[443]=  
  15 443.5
```

```
(Debug) Out[444]=  
  -315.117
```

```
(Debug) In[445]:=  
  dSR2toSR3 = 15 443.5;  
  d1617  
  d1617 - dSR2toSR3
```

```
(Debug) Out[446]=  
  15 756.2
```

```
(Debug) Out[447]=  
  312.676
```

```
(Debug) In[448]:=  
  dSR3toBS = 19 366.1;  
  d717  
  d717 - dSR3toBS
```

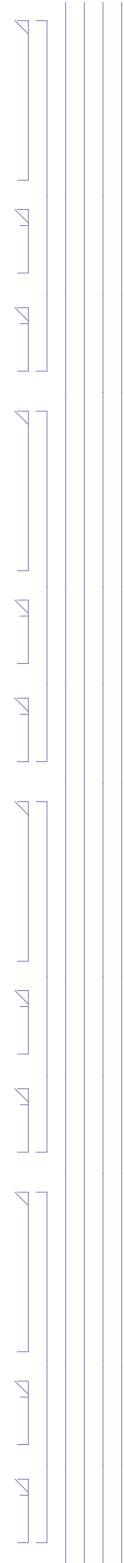
```
(Debug) Out[449]=  
  19 366.
```

```
(Debug) Out[450]=  
  -0.0834483
```

```
(Debug) In[451]:=  
  dBStoCPx = 4804.6;  
  d1213  
  d1213 - dBStoSPx
```

```
(Debug) Out[452]=  
  4829.55
```

```
(Debug) Out[453]=  
  4829.55 - dBStoSPx
```



(Debug) In[454]:=

**dBSe = 131.5;**

**d57 + d513**

**d57 + d513 - dBSe**

(Debug) Out[455]=

136.673

(Debug) Out[456]=

5.17262

(Debug) In[457]:=

**dSRCIO = 56008.0;**

**dSRC = d1617 + d816 + d717 + nOptic d57 +**

**((nOptic d12 + d23 + nOptic d34 + d45) + (nOptic d910 +  
d1011 + nOptic d1112 + d1213 + nOptic d513)) / 2**

**dSRC -**

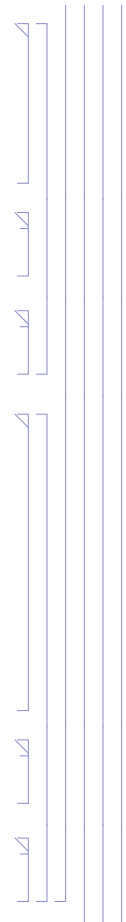
**dSRCIO**

(Debug) Out[458]=

56007.6

(Debug) Out[459]=

-0.404112



## ■ Summary

### ■ Optic Parameters

(Debug) In[460]:=

```

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[465]:=

**formattedTableParameters**

(Debug) Out[465]=

Optic	wedge		Thickness	Diameter
	rad	deg	mm	mm
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[466]:=

```
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,  
           BScyaw, 0, SRMyaw, SR2yaw, SR3yaw, 0, 0, 0, 0};
```

`(Debug) In[473]:=``formattedTablePositions``(Debug) Out[473]=`

Optic	Global Coordinates (mm)			Local Coordinates (mm)		
	Xg	Yg	Zg	Xl	Yl	Zl
PRM HR	-2018- 9.- 6	-628.0	-103.4	-2018- 9.- 6	-628.1	-96.7
PR2 HR	-3579- .2	-530.4	-93.7	-3579- .2	-530.5	-92.3
PR3 HR	-1974- 0.- 0	-176.4	-94.2	-1974- 0.- 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	-1990- 8.- 6	-93.2	305.0	-1990- 8.- 7	-81.1
SR2 HR	-594.1	-4178- .1	-84.3	-594.1	-4178- .2	-81.6
SR3 HR	-175.3	-1961- 5.- 9	-94.1	-175.3	-1961- 6.- 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[474]:=``formattedTableNormals``(Debug) Out[474]=`

Optic	Normal Unit Vector (global) (mm)			Normal Unit Vector (local) (mm)		
	Ug	Vg	Wg	Ul	Vl	Wl

PRM HR	0.999- 98- 3	0.005- 87- 6	0.000- 58- 5	0.999- 98- 3	0.005- 87- 6	0.000- 26- 9
PR2 HR	-0.99- 99- 68	0.008- 01- 2	-0.00- 03- 07	-0.99- 99- 68	0.008- 01- 1	-0.00- 00- 00
PR3 HR	0.999- 93- 8	-0.01- 11- 46	0.000- 30- 5	0.999- 93- 8	-0.01- 11- 46	0.000- 00- 0
BS HR	-0.70- 67- 84	0.707- 42- 9	0.000- 00- 0	-0.70- 67- 85	0.707- 42- 9	-0.00- 02- 12
BS ARs	0.705- 92- 0	-0.70- 82- 92	0.000- 00- 0	0.705- 92- 0	-0.70- 82- 92	0.000- 21- 3
SRM HR	-0.05- 70- 63	0.998- 37- 0	0.000- 56- 2	-0.05- 70- 63	0.998- 37- 1	-0.00- 00- 30
SR2 HR	0.042- 09- 5	-0.99- 91- 13	-0.00- 05- 97	0.042- 09- 5	-0.99- 91- 14	0.000- 00- 0
SR3 HR	-0.01- 37- 83	0.999- 90- 5	0.000- 60- 7	-0.01- 37- 83	0.999- 90- 5	0.000- 00- 0
CPx	0.999- 99- 9	0.000- 00- 0	-0.00- 12- 65	0.999- 99- 9	-0.00- 00- 01	-0.00- 15- 77
ITMx	1.000- 00- 0	0.000- 00- 0	0.000- 00- 0	1.000- 00- 0	0.000- 00- 0	-0.00- 03- 12
CPy	0.000- 00- 0	0.999- 99- 9	-0.00- 12- 92	-0.00- 00- 01	0.999- 99- 8	-0.00- 19- 03
ITMy	0.000- 00- 0	1.000- 00- 0	0.000- 00- 0	-0.00- 00- 00	1.000- 00- 0	-0.00- 06- 11



`(Debug) In[475]:=``formattedTableAngles``(Debug) Out[475]=`

Optic	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[476]:=`

```

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[479]:=

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

(Debug) In[482]:=

```
formattedTableComparePositions
```

(Debug) Out[482]=

Optic	Global Coordinate Difference (mm)		
	D <sub>Xg</sub>	D <sub>Yg</sub>	D <sub>Zg</sub>
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
ITM <sub>x</sub>	0.0	0.0	0.0
ITM <sub>y</sub>	0.0	0.0	0.0

## ■ IO results

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

```
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}};
```

IO Layout results for PRM, PR2, PR3, SRM, SR2 and SR3 are from E1200274-v3 for L1 in global coordinates

(Debug) In[483]:=

```

opticLabelIO =
  {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS ARs",
   "SRM", "SR2", "SR3", "CPx", "ITMx", "CPy", "ITMy"};
nOpticsIO = Length[opticLabelIO];
opticPosGIO =
  {{-20189.6, -628, -104.1}, {-3579.2, -530.4, -94.2},
   {-19740.0, -177.4, -94.4}, {-201.9, -183.9, -82.9},
   {-183.3, -249.8, -83.2}, {305.2, -19909.0, -94.3},
   {-594.3, -4178.1, -84.8}, {-175.5, -19615.9, -94.5},
   {4793.0, -200.0, -80.0}, {5013.0, -200.0, -80.0},
   {-200.0, 4763.1, -80.2}, {-200.0, 4983.1, -80.0}};

```

(Debug) In[486]:=

```

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

```

(Debug) In[489]:=

```

formattedTableComparePositions

```

(Debug) Out[489]=

Optic	Global Coordinate Difference (mm)		
	DXg	DYg	DZg
PRM HR	-0.0	-0.0	0.7
PR2 HR	-0.0	-0.0	0.5
PR3 HR	0.0	1.0	0.2
BS HR	-0.6	-0.2	0.1
BS ARs	-0.6	-0.1	0.3
SRM	-0.2	0.4	1.1
SR2	0.2	0.0	0.5
SR3	0.2	0.0	0.4
CPx	-0.1	0.0	-0.0
ITMx	0.0	0.0	0.0
CPy	0.0	0.6	0.2
ITMy	0.0	0.0	0.0

## ■ RC Length Results

(Debug) In[490]:=

```

RClengthsLabel =
  {"PRM to PR2", "PR2 to PR3", "PR3 to BS", "BS to CPy",
   "PRC", "SRM to SR2", "SR2 to SR3", "SR3 to BS",
   "BS effective thickness", "BS to CPx", "SRC"};
nRClengths = Length[RClengthsLabel];
RClengthsIO = {dPRMtoPR2, dPR2toPR3,
  dPR3toBS, dBStoCPy, dPRCIO, dSRMtoSR2,
  dSR2toSR3, dSR3toBS, dBSe, dBStoCPx, dSRCIO};
RClengths = {d1415, d614, d56, d45, dPRC, d816,
  d1617, d717, d57 + d513, d1213, dSRC};
compareRClengths = Transpose[
  {RClengthsIO, RClengths, RClengths - RClengthsIO}];

```

(Debug) In[495]:=

```
formattedTableCompareLengths
```

(Debug) Out[495]=

Length	Length (mm)		
	T0900043-v11	Calculated	Difference
PRM to PR2	16610.7	16610.7	-0.0
PR2 to PR3	16164.7	16164.7	-0.0
PR3 to BS	19538.1	19537.5	-0.6
BS to CPy	4862.0	4847.7	-14.3
PRC	57656.0	57655.7	-0.3
SRM to SR2	15758.6	15443.5	-315.1
SR2 to SR3	15443.5	15756.2	312.7
SR3 to BS	19366.1	19366.0	-0.1
BS effective thickness	131.5	136.7	5.2
BS to CPx	4804.6	4829.5	24.9
SRC	56008.0	56007.6	-0.4

## ■ SRC alignment per IAS procedure E1100784-v6

Check that positions set per the Initial Alignment Subsystem (IAS) procedure are consistent with the positions given above

For SR2, monument “TS-2” is used for positioning

(Debug) In[496]:=

```
pTS2 = {367.43, -27 000.0, -81.60};
pitch = 0;
yaw = RAD[87, 35, 15] // N;
distanceAlignSR2HR = 22 842.04;
uAlignSR2HR =
  RotationTransform[-yaw, {0, 0, 1}][{-1, 0, 0}]
```

(Debug) Out[500]=

```
{-0.0420936, 0.999114, 0.}
```

(Debug) In[501]:=

```
pSR2IAS = pTS2 + distanceAlignSR2HR uAlignSR2HR
opticPositionL[[7]]
pSR2IAS - opticPositionL[[7]]
```

(Debug) Out[501]=

```
{-594.074, -4178.21, -81.6}
```

(Debug) Out[502]=

```
{-594.125, -4178.15, -81.5948}
```

(Debug) Out[503]=

```
{0.0510217, -0.054854, -0.00521101}
```

Check that positions set per the Initial Alignment Subsystem (IAS) procedure are consistent with the positions given above

For SR3, monument “TS-1” is used

(Debug) In[504]:=

```
pTS1 = {-73.43, -27 000.0, -8.987};
pitch = Pi / 2 - RAD[90, 34, 30];
yaw = RAD[89, 12, 37] // N;
distanceAlignSR3HR = 7283.2;
uAlignSR3HR = RotationTransform[pitch, {1, 0, 0}][
  RotationTransform[-yaw, {0, 0, 1}][{-1, 0, 0}]
```

(Debug) Out[508]=

```
{-0.0137828, 0.999855, -0.0100345}
```

```
(Debug) In[509]:=  
  pSR3IAS = pTS1 + distanceAlignSR3HR uAlignSR3HR  
  opticPositionL[[8]]  
  pSR3IAS - opticPositionL[[8]]
```

```
(Debug) Out[509]=  
  {-173.813, -19717.9, -82.0704}
```

```
(Debug) Out[510]=  
  {-175.333, -19616., -82.0603}
```

```
(Debug) Out[511]=  
  {1.52048, -101.905, -0.0101233}
```

The distance used in the IAS procedure already has the thickness of the SR3 optic taken into account. This is OK is the remaining offset taken into account was to the AR surface. HOWEVER, the procedure says to account for an offset to the HR face!

