

# E1200797-v5

## IAS Alignment Solutions

This is an evolving notebook used for calculating/providing the positions and orientations of the IAS theodolite-total-station/autocolimator for initial alignment and positioning of the primary optics. It also calculates the pitch angles of the COC relative to the local horizontal. The alignment solutions (angles, positions/distances) calculated in this notebook are inserted into each of the IAS alignment procedures.

This notebook is released each time a particular set of alignment solutions are available. Each alignment solution, and associated notes, are given a separate DCC number. However all of the solutions to date are kept in this evolving notebook. The notebook will be posted to the parent DCC number (E1200797) as well as the subsidiary DCC number for the specific alignment solution which was the reason for the version release.

### Version History

#### E1200556-v1 D. Coyne 8/29/2011, 5/30/2012

- 1) Started with iLIGO version of this notebook
- 1) Calculation of the monument locations required for alignment of H2-FMy on LHO Mechanical Test Stand #2. (The output was released in an alignment procedure, this notebook was not released to the DCC.)
- 2) Incorporated the coordinates and orientations for all optics of H1 and L1. H2 is no longer to be deployed (H2 will become LIGO-India, I1).
- 3) Calculated the optic pitch and yaw values to be checked against values used in SolidWorks.

#### E1200556-v2 D. Coyne 6/7/2012

- 1) Released to show L1 PR3 alignment solutions (yaw, pitch, x, y, z)

#### E1200556-v3 D. Coyne 6/7/2012

- 1) Released to show L1 PRM angular alignment solution (yaw, pitch)

#### E1200556-v4 D. Coyne 6/12/2012

- 1) Updated all L1 optic positions and orientations per D0902216-x010 Zemax model. Need to update H1 as well.
- 2) Released to show LBSC2 cartridge alignment solutions -- HOWEVER THE BS ORIENTATION IS APPARENTLY OPPOSITE TO WHAT I HAVE ASSUMED -- MUST BE RE-CALCULATED

#### E1200556-v5 D. Coyne 6/14/2012

- 1) Corrected LBSC2 cartridge alignment solutions (with an orientation of the BS which reflects the actual orientation chosen at LLO)
- 2) Revised the BS AR normal vector to be consistent with BS SN002 wedge angle of 0.070 deg (rather than the average value of 0.073 deg used in Zemax D0902216-x010)
- 3) Released to show 4 BS alignment solutions for the cartridge on the test stand

#### E1200556-v6 D. Coyne 6/18/2012

- 1) LBSC2 BS AR yaw & pitch alignment: Based on measurements by Joe Hanson 6/14/2012 on the position of the LLO Test Stand #1 monuments relative to the LVEA wall (which correct D1200869-v4 and E1100374-v4), the location of the proposed monument TS1-17 in v5 of this document is in the LVEA wall. As a consequence the location of the proposed monuments to support angular alignment of the BS via the AR surface for LBSC2 are revised in this v6 version. One can (just barely) get sufficient range to separate the AR surface reflection from the HR surface reflection, when aligned normal to the HR surface. However, one cannot get sufficient range to separate the returns when aligned normal to the AR surface (in transmission through the HR surface). However, since it is possible that one can still get sufficient return signal intensity by blocking the HR reflection through the use of an iris to close down the aperture for the exiting laser autocollimator beam and, simultaneously, the return aperture, a solution is provided for alignment of the pitch & yaw of the AR surface (in transmission through the HR surface).
- 2) LBSC2 BS HR yaw & pitch alignment: I calculated that 8995 mm of distance was required between the Total Station and the BS optic in order to separate the HR and AR returns, The alignment solution for pitch & yaw alignment of the BS HR face had only 8717 mm of distance in v5. I revised the solution so that the minimum distance is achieved.

#### E1200556-v7 D. Coyne 6/26/2012

- 1) Corrected the LLO Test Stand #1 monument locations per Doug Cook's and Jason Oberling's survey and re-calculated the LBSC2 TS1 solutions.

### E1200798-v1 D. Coyne 9/4/2012

- 1) Formulated BS cartridge alignment on LHO Test Stand #2. Included "BS AR" coordinates and normal vector for H1.

### E1200797-v2 D. Coyne 9/5/2012

- 1) Formulated alignment solutions for the L1 power recycling cavity (PRC) optics: PRM, PR2 and PR3.
- 2) Calculated positional (x, y, z) alignment solution for LBSC2 BS in the chamber.

### E1200797-v3 D. Coyne 10/11/2012

- 1) Correction: had incorrect matrix indices for SR2 and SR3 in section "1.4.1, H1, corrected, calc." and in section "1.4.3, L1, corrected, calc." Since the IAS alignment solution for these optics has not yet been calculated, there are no other required changes ore updates.
- 2) Correction: Jason Oberling noted that the L1 ITMy yaw angle was incorrect in section "1.4, Optic Pitch & Yaw Angles"! Now properly calculates yaw angles.
- 3) Corrected alignment solution indexing for both H1 & L1 (did not effect previously calculated alignment solutions)
- 4) Changed notation from "BS AR" to "BS ARc" to denote the center of the AR surface of the BS optic. In the Zemax model optic location files (D0901920 and D0902216) "BS AR" denotes the in-line chief ray intersection point on the AR surface and "BS ARS" denotes the off-line chief ray intersection point on the AR surface.
- 5) Changed H1 & L1 summary tables so that empty (or "NA") entries are used for solutions not yet calculated.
- 6) Updated H1 optic locations from D0901920-v10 to D0901920-V12, which includes the Schnupp asymmetry change to 80 mm. The "BS ARc" coordinates are the average of the "BS AR" and "BS ARS" coordinates. The only H1 alignment solution provided to date (BS cartridge alignment) is not effected by this update.  
Note that the optic orientations (outward normal vector direcitons) are not given in D0901920-v12 and have not been updated/changed.  
**These optic orientations were taken from an earlier H1 Zemax model and should be updated!!**
- 7) Updated L1 optic locations per D0902216-V7 (was per Zemax model "D09002216 L1 Zemax layout.zar", PDMW vault version x010). The positional changes were all small/negligible (< 1 mm).  
**These optic orientations were taken from an earlier L1 Zemax model and should be updated!!**
- 8) Removed H2 cartridge alignment solutions for the one arm test, since H2 will no longer be installed. (Can see this solution in previous versions of this document if interested).

### E1200797-v4 D. Coyne 11/7/2012

- 0) Changed the manner of inputting the initial alignment monument labels and positions matrix for LHO to be the same as used for LLO.
- 1) Formulated alignment solutions for the H1 power recycling cavity (PRC) optics: PRM, PR2 and PR3.
- 2) **Need to incorporate separate LLO TS monuments from the overall monument list, just as done for LHO. Also need to create solution table functions specific for general monuments and each test stand, so that monument references are correct. ... Ah, this will not work for the summary table of all solutions, including test stands. Hummm ... need to consider how best to resolve.**

### E1200797-v5 D. Coyne 2/8/2013

- 0) Created a separate *Mathematica* notebook ("aLIGO recycling cavities optical layout v1.nb") to calculate the theoretically correct PRC & SRC optic positions and orientations for H1 & L1, using as-built wedge angles and thicknesses. Comparison to IO and Zemax latest layouts indicate small errors. However, fairly large differences from the dated Zemax positional information used in this workbook for the PRC alignment. This separate workbook is filed at the DCC entry for E1200797.
- 1)

## 1

# Primary Optic Positions and Orientations

## 1.1. Initialization

```
(Debug) In[2669]:=
  Off[General::"spell"]
  Off[General::"spell1"]
```

```
(Debug) In[2671]:=
  Needs["VectorAnalysis`"]
```

```
Needs["Geometry`Rotations`"]
```

is no longer needed. Use built-in `RotationTransform` and `RotationMatrix`

`RotationMatrix` uses yaw-pitch-roll angles rather than the Euler angles used by `RotationMatrix3D`

```
(Debug) In[2672]:=
  RotationMatrix3D[phi_,theta_,psi_]:=RotationMatrix[Pi - psi, {0, 0, 1}].RotationMatrix[
    theta, {1, 0, 0}].RotationMatrix[Pi - phi, {0, 0, 1}]
```

```
(Debug) In[2673]:=
  RotationMatrix3D[phi, theta, psi]
```

```
(Debug) Out[2673]=
  {{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.

```
Needs["Graphics`Shapes`"]
```

The functionality of `RotateShape`, `TranslateShape`, and `AffineShape` is provided by the newly added kernel functions `Rotate`, `Translate`, `Scale` and `GeometricTransformation`

```
(Debug) In[2674]:=
  pi = N[π, 10];
```

The function "Reflect[u,n]" takes the unit ray vector, u, and reflects it from the surface with an outward surface normal vector, n, and returns the reflected unit ray vector, v.

```
(Debug) In[2675]:=
  Clear[Reflect];
  Reflect[u_, n_] := Block[{temp, i, j}, temp = CrossProduct[u, n];
    If[temp.temp == 0, Return[-u], i =  $\frac{\text{temp}}{\sqrt{\text{temp.temp}}}$ ; j = CrossProduct[n, i]; Return[u.j j - u.n n]]];
```

The function "Refract[u,n,ni,nt]" takes the unit ray vector, u, and refracts it through the surface with an outward surface normal vector, n, and returns the refracted unit ray vector, v. The incident ray travels through a media with an index of refraction, ni, and refracts into a media with an index of refraction, nt.

```
(Debug) In[2677]:=
  Clear[Refract, ni, nt];
  Refract[u_, n_, ni_, nt_] := Block[{temp, i, j}, temp = CrossProduct[u, n]; i =  $\frac{\text{temp}}{\sqrt{\text{temp.temp}}}$ ; j = CrossProduct[n, i]; temp =  $\frac{ni u.j}{nt}$ ;
    Return[temp j -  $\sqrt{1 - \text{temp}^2}$  n]]];
```

```
(Debug) In[2679]:=
  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[2680]:=
  RAD[deg_, min_, sec_] := (deg + min / 60 + sec / 3600) Pi / 180;
```

The functions LTHR reflects the light back parallel to the input beam but translated; Lateral Transfer Hollow Retroreflector (LTHR) function. (The physical unit used in the IAS system is called a PLX retroreflector, made by the PLX Inc.)

The function LTHRangle takes the input vector, u, and returns the retroreflected ray, v.

The function LTHRpos takes an entrance aperture center point, a, translates it along the axis vector, axis, a distance, d, and returns the exit aperture center point, b, where the retroreflected and translated ray, v, emanates.

```
(Debug) In[2681]:=
  Clear[LTHRangle];
  LTHRangle[u_] := -u;
```

```
(Debug) In[2683]:=
  Clear[LTHRpos];
  LTHRpos[a_, axis_, d_] := a + d axis;
```

```
(Debug) In[2685]:=
  Clear[LTHPangle];
  LTHRangle[u_] := u;
```

```
(Debug) In[2687]:=
  Clear[LTHPpos];
  LTHRpos[a_, axis_, d_] := a + d axis;
```

```
(Debug) In[2689]:=
  LTHPlength = 15.75 × 25.4;
  LTHRlength = LTHPlength
```

```
(Debug) Out[2690]=
  400.05
```

## 1.2. 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".

### 1.2.1. Rhc -> Hanford Corner station

```
(Debug) In[2691]:=
  xangle = 619.49 × 10-6;
  yangle = 12.4832 × 10-6;
```

```
(Debug) In[2693]:=
  Rhc = RotationMatrix3D[0, yangle, 0].RotationMatrix3D[pi/2, xangle, -pi/2];
  MatrixForm[Rhc]
```

```
(Debug) Out[2694]/MatrixForm=
```

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

```
(Debug) In[2695]:=
  MatrixForm[Rhc - IdentityMatrix[3]]
```

```
(Debug) Out[2695]/MatrixForm=
```

$$\begin{pmatrix} -1.91884 \times 10^{-7} & 0. & -0.00061949 \\ 7.73322 \times 10^{-9} & -7.79151 \times 10^{-11} & 0.0000124832 \\ 0.00061949 & -0.0000124832 & -1.91962 \times 10^{-7} \end{pmatrix}$$

```
(Debug) In[2696]:=
  Rhcinv = RotationMatrix3D[Pi/2, -xangle, -Pi/2].RotationMatrix3D[0, -yangle, 0];
  MatrixForm[Rhc.Rhcinv]
```

```
(Debug) Out[2697]/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[2698]:=
```

```
MatrixForm[Rhcinv]
```

```
(Debug) Out[2698]/MatrixForm=
```

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

### 1.2.2. Rhxm -> Hanford x-mid station

```
(Debug) In[2699]:=
```

```
xangle = 305.827 × 10-6;
```

```
yangle = 12.0075 × 10-6;
```

```
(Debug) In[2701]:=
```

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

```
MatrixForm[Rhxm]
```

```
(Debug) Out[2702]/MatrixForm=
```

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

```
(Debug) In[2703]:=
```

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

```
(Debug) Out[2703]/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[2704]:=
```

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

```
MatrixForm[Rhxm.Rhxminv]
```

```
(Debug) Out[2705]/MatrixForm=
```

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

### 1.2.3. Rhxe -> Hanford x-end station

```
(Debug) In[2706]:=
```

```
xangle = -7.8389 10-6;
```

```
yangle = 11.5318 × 10-6;
```

```
(Debug) In[2708]:=
  Rhxe = RotationMatrix3D[0, yangle, 0].RotationMatrix3D[Pi / 2, xangle, -Pi / 2];
  MatrixForm[Rhxe]
```

```
(Debug) Out[2709]//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[2710]:=
```

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

```
(Debug) Out[2710]//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[2711]:=
```

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

```
(Debug) Out[2712]//MatrixForm=
```

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

#### 1.2.4. Rhym -> Hanford y-mid station

```
(Debug) In[2713]:=
```

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

```
(Debug) In[2715]:=
```

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

```
(Debug) Out[2716]//MatrixForm=
```

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

```
(Debug) In[2717]:=
```

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

```
(Debug) Out[2717]/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[2718]:=
```

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

```
(Debug) Out[2719]/MatrixForm=
```

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

### 1.2.5. Rhye -> Hanford y-end station

```
(Debug) In[2720]:=
```

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

```
(Debug) In[2722]:=
```

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

```
(Debug) Out[2723]/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[2724]:=
```

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

```
(Debug) Out[2724]/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[2725]:=
  Rhyeinv = RotationMatrix3D[Pi / 2, -xangle, -Pi / 2].RotationMatrix3D[0, -yangle, 0];
  MatrixForm[Rhye.Rhyeinv]
```

```
(Debug) Out[2726]/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[2727]:=
```

```
(180 / Pi) 619 × 10-6 // N
```

```
(Debug) Out[2727]=
```

```
0.0354661
```

### 1.2.6. Rlc -> Livingston Corner station

```
(Debug) In[2728]:=
```

```
xangle = 312.0 × 10-6;
```

```
yangle = -611.0 10-6;
```

```
(Debug) In[2730]:=
```

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

```
MatrixForm[Rlc]
```

```
(Debug) Out[2731]/MatrixForm=
```

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

```
(Debug) In[2732]:=
```

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

```
(Debug) Out[2732]/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[2733]:=
```

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

```
MatrixForm[Rlc.Rlcinv]
```

```
(Debug) Out[2734]/MatrixForm=
```

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

**1.2.7. Rlxe -> Livingston x-end station**

(Debug) In[2735]:=

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

(Debug) In[2737]:=

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

(Debug) Out[2738]/MatrixForm=

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

(Debug) In[2739]:=

```
MatrixForm[Rlxe - IdentityMatrix[3]]
```

(Debug) Out[2739]/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[2740]:=

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

(Debug) Out[2741]/MatrixForm=

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

(Debug) In[2742]:=

```
MatrixForm[Rlxeinv - Transpose[Rlxe]]
```

(Debug) Out[2742]/MatrixForm=

$$\begin{pmatrix} 0. & 0. & 0. \\ 0. & 0. & 0. \\ 0. & 0. & 0. \end{pmatrix}$$
**1.2.8. Rlye -> Livingston y-end station**

(Debug) In[2743]:=

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

(Debug) In[2745]:=

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

(Debug) Out[2746]/MatrixForm=

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

(Debug) In[2747]:=

```
MatrixForm[Rlye - IdentityMatrix[3]]
```

(Debug) Out[2747]/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[2748]:=

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

(Debug) Out[2749]/MatrixForm=

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

### 1.3. Optic surface positions & orientations and Monument Positions

-Global coordinates taken from:

H1: D0901920-v12  
 L1: D0902216-v7  
 H2: not installed

Normal vectors in global coordinates taken with Zemax from:

Zemax model "D0901920 H1 Zemax layout.zar", PDMW vault version x009 (and x010 for BS HR & AR normal vectors, with BS wedge set to 0.076 for SN06)  
 Zemax model "D090xxxx L1 Zemax layout.zar", PDMW vault version x010

by running a ray trace and exporting the normal vector components (Nx, Ny, Nz) at the location of intersection of the ray. Of course if the system is not aligned well for curved optics the normal vector will change. These values were exported 5/29-31/2012, with sign corrections as needed so that all are outward facing normal vectors; Here the outward surface normal is used in \*all cases\*.

### 1.3.1. Global Coordinates

H1

**Optics**

(Debug) In[2750]:=

```
opticLabelH1 = {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS ARC", "SRM HR", "SR2 HR", "SR3 HR", "ITMx HR", "ITMy HR", "ETMx HR", "ETMy HR"};
nOpticsH1 = Length[opticLabelH1];
```

(Debug) In[2752]:=

```
opticPosH1G = {{-20207.7, -627.3, -94.1},
{-3589.1, -530.0, -84.2},
{-19741.0, -174.4, -94.6},
{-202.6, -183.9, -82.9},
{-160.3, -226.2, -82.9},
{305.4, -19908.6, -113.2},
{-594.1, -4178.1, -104.4},
{-174.6, -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[2753]:=

```
opticOrientH1G = {{9.999826 10^-01, 5.872318 10^-03, 5.969026 x 10^-04},
{-9.999674 10^-01, 8.054606 x 10^-03, -6.194173 10^-04},
{9.999368 x 10^-01, -1.123096 10^-02, 6.194173 x 10^-04},
{-.7067506313, .7074627280, 0.000000},
{0.7058116198, -0.7083995938, 0.0000000000},
{-5.714130 10^-02, 9.983659 x 10^-01, 5.963790 x 10^-04},
{4.211194 x 10^-02, -9.991129 10^-01, 1.250005 x 10^-05},
{-1.379639 10^-02, 9.999048 x 10^-01, -1.250005 10^-05},
{1.000000 x 10^+00, 0.000000 x 10^+00, 0.000000 x 10^+00},
{0.000000 x 10^+00, 1.000000 x 10^+00, 0.000000 x 10^+00},
{-1.000000 10^+00, 0.000000 x 10^+00, 0.000000 x 10^+00},
{0.000000 x 10^+00, -1.000000 10^+00, 0.000000 x 10^+00}};
```

ensure that the normal vectors have unit length

(Debug) In[2754]:=

```

Do[
  temp = opticOrientH1G[[j]];
  i = Flatten[Position[Abs[temp], Max[Abs[temp]]]][[1]];
  If[i == 1,
    opticOrientH1G[[j]] = {Sign[temp[[1]] Sqrt[1 - temp[[2]]^2 - temp[[3]]^2], temp[[2]], temp[[3]]};,
    If[i == 2,
      opticOrientH1G[[j]] = {temp[[1]], Sign[temp[[2]] Sqrt[1 - temp[[1]]^2 - temp[[3]]^2], temp[[3]]};,
      If[i == 3, opticOrientH1G[[j]] = {temp[[1]], temp[[2]], Sign[temp[[3]] Sqrt[1 - temp[[1]]^2 - temp[[2]]^2]};,
      opticOrientH1G[[j]] = {0, 0, 0};]]],
  {j, nOpticsH1}];

```

(Debug) In[2755]:=

```

Do[
  If[Abs[opticOrientH1G[[i]].opticOrientH1G[[i]] - 1] > 10^-7, Print["error"],],
  {i, nOpticsH1}];

```

(Debug) In[2756]:=

```

tableHead = {"Xg", "Yg", "Zg", "Ug", "Vg", "Wg"};
Print[TableForm[Partition[Flatten[Transpose[{opticPosH1G, opticOrientH1G}]], 6], TableHeadings -> {opticLabelH1, tableHead}]]

```

	Xg	Yg	Zg	Ug	Vg	Wg
PRM HR	-20 207.7	-627.3	-94.1	0.999983	0.00587232	0.000596903
PR2 HR	-3589.1	-530.	-84.2	-0.999967	0.00805461	-0.000619417
PR3 HR	-19 741.	-174.4	-94.6	0.999937	-0.011231	0.000619417
BS HR	-202.6	-183.9	-82.9	-0.706751	0.707463	0.
BS ARc	-160.3	-226.2	-82.9	0.705812	-0.7084	0.
SRM HR	305.4	-19 908.6	-113.2	-0.0571413	0.998366	0.000596379
SR2 HR	-594.1	-4178.1	-104.4	0.0421119	-0.999113	0.0000125001
SR3 HR	-174.6	-19 615.9	-94.5	-0.0137964	0.999905	-0.0000125001
ITMx HR	5013.	-200.	-80.	1.	0.	0.
ITMy HR	-200.	4983.1	-80.	0.	1.	0.
ETMx HR	$3.9995 \times 10^6$	-200.	-80.	-1.	0.	0.
ETMy HR	-200.	$3.99947 \times 10^6$	-80.	0.	-1.	0.

**Tables**

(Debug) In[2758]:=

```

nTablesH1 = 11;
tableLabelH1 = {"WHAM1", "WHAM2", "WHAM3", "WHAM4", "WHAM5", "WHAM6", "WBSC1", "WBSC2", "WBSC3", "WBSC9", "WBSC10"};

```

(Debug) In[2760]:=

```

tablePosH1G = {{-22 692, 0, 0},
  {-20 122, 0, 0},
  {-3831, 0, 0},
  {0, -3831, 0},
  {0, -20 122, 0},
  {0, -22 692, 0},
  {0, 4580, 0},
  {0, 0, 0},
  {4580, 0, 0},
  {4 000 000, 0, 0},
  {0, 4 000 000, 0}};

```

(Debug) In[2761]:=

```

tableHead = {"x_global", "y_global", "z_global"};
Print[TableForm[tablePosH1G, TableHeadings -> {tableLabelH1, tableHead}]]

```

	x_global	y_global	z_global
WHAM1	-22 692	0	0
WHAM2	-20 122	0	0
WHAM3	-3831	0	0
WHAM4	0	-3831	0
WHAM5	0	-20 122	0
WHAM6	0	-22 692	0
WBSC1	0	4580	0
WBSC2	0	0	0
WBSC3	4580	0	0
WBSC9	4 000 000	0	0
WBSC10	0	4 000 000	0

**H2**

H2 will not be installed

**L1****Optics**

All of the optics positions and orientations (except for ETMs) are taken from the *Mathematica* workbook “aLIGO recycling cavities optical layout v1.nb” also filled in the DCC at the entry for E1200797-v5. This workbook calculates the positions and orientations of the optics based on as-built/assigned optics. It is in close agreement with the IO and Zemax layout.

(Debug) In[2763]:=

```

opticLabelL1 = {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS Arc", "SRM HR", "SR2 HR", "SR3 HR", "ITMx HR", "ITMy HR", "ETMx HR", "ETMy HR"};
nOpticsL1 = Length[opticLabelL1];

```

(Debug) In[2765]:=

```

opticPosL1G = {{-20 189.6, -628., -103.119}, {-3579.2, -530.4, -93.4736}, {-19 740., -176.271, -94.1727}, {-202.511, -183.961, -82.8269},
  {-160.189, -226.322, -82.8269}, {305., -19 908.6, -93.348}, {-594.1, -4178.1, -84.1985}, {-175.143, -19 615.9, -94.1005},
  {5013, -200, -80}, {-200, 4983.1, -80}, {3 999 498.0, -200.0, -80.0}, {-200.0, 3 999 468.1, -80.0}};

```

(Debug) In[2766]:=

```

opticOrientL1G = {{0.999983, 0.00587573, 0.000580694}, {-0.999968, 0.00801671, -0.000312}, {0.999938, -0.0111513, 0.000312},
  {-0.706784, 0.707429, 0.}, {0.70592, -0.708292, 0.}, {-0.0570633, 0.99837, 0.00058069}, {0.0421006, -0.999113, -0.000611},
  {-0.013788, 0.999905, 0.000611}, {1, 0, 0}, {0, 1, 0}, {-1, 0, 0}, {0, -1, 0}};

```

ensure that the normal vectors have unit length

(Debug) In[2767]:=

```

Do[
  temp = opticOrientL1G[[j]];
  i = Flatten[Position[Abs[temp], Max[Abs[temp]]]][[1]];
  If[i == 1,
    opticOrientL1G[[j]] = {Sign[temp[[1]] Sqrt[1 - temp[[2]]^2 - temp[[3]]^2], temp[[2]], temp[[3]]};,
    If[i == 2,
      opticOrientL1G[[j]] = {temp[[1]], Sign[temp[[2]] Sqrt[1 - temp[[1]]^2 - temp[[3]]^2], temp[[3]]};,
      If[i == 3, opticOrientL1G[[j]] = {temp[[1]], temp[[2]], Sign[temp[[3]] Sqrt[1 - temp[[1]]^2 - temp[[2]]^2]};,
        opticOrientL1G[[j]] = {0, 0, 0};]],
  {j, nOpticsL1}];

```

(Debug) In[2768]:=

```

Do[
  If[Abs[opticOrientL1G[[i]].opticOrientL1G[[i]] - 1] > 10^-7, Print["error"],],
  {i, nOpticsL1}];

```

(Debug) In[2769]:=

```

VectorAngle[opticOrientL1G[[4]], -opticOrientL1G[[5]]] 180 / Pi

```

(Debug) Out[2769]=

0.069934

Correct for the actual SN002 wedge angle of 0.070 deg:

(Debug) In[2770]:=

```

opticOrientL1G[[5]] = -RotationMatrix3D[.070 Pi / 180, 0, 0].opticOrientL1G[[4]]

```

(Debug) Out[2770]=

{0.705919, -0.708292, 0.}

(Debug) In[2771]:=

**tableHead = {"Xg", "Yg", "Zg", "Ug", "Vg", "Wg"};****Print[TableForm[Partition[Flatten[Transpose[{opticPosL1G, opticOrientL1G}]], 6], TableHeadings -> {opticLabelL1, tableHead}]]**

	Xg	Yg	Zg	Ug	Vg	Wg
PRM HR	-20189.6	-628.	-103.119	0.999983	0.00587573	0.000580694
PR2 HR	-3579.2	-530.4	-93.4736	-0.999968	0.00801671	-0.000312
PR3 HR	-19740.	-176.271	-94.1727	0.999938	-0.0111513	0.000312
BS HR	-202.511	-183.961	-82.8269	-0.706784	0.707429	0.
BS ARc	-160.189	-226.322	-82.8269	0.705919	-0.708292	0.
SRM HR	305.	-19908.6	-93.348	-0.0570633	0.99837	0.00058069
SR2 HR	-594.1	-4178.1	-84.1985	0.0421006	-0.999113	-0.000611
SR3 HR	-175.143	-19615.9	-94.1005	-0.013788	0.999905	0.000611
ITMx HR	5013	-200	-80	1	0	0
ITMy HR	-200	4983.1	-80	0	1	0
ETMx HR	$3.9995 \times 10^6$	-200.	-80.	-1	0	0
ETMy HR	-200.	$3.99947 \times 10^6$	-80.	0	-1	0

**Tables**

(Debug) In[2773]:=

**nTablesL1 = 11;****tableLabelL1 = {"LHAM1", "LHAM2", "LHAM3", "LHAM4", "LHAM5", "LHAM6", "LBSC1", "LBSC2", "LBSC3", "LBSC4", "LBSC5"};**

(Debug) In[2775]:=

**tablePosL1G = {{-22692, 0, 0},****{-20122, 0, 0},****{-3831, 0, 0},****{0, -3831, 0},****{0, -20122, 0},****{0, -22692, 0},****{0, 4580, 0},****{0, 0, 0},****{4580, 0, 0},****{4000000, 0, 0},****{0, 4000000, 0}};**



(Debug) In[2776]:=

```
tableHead = {"x_global", "y_global", "z_global"};
Print[TableForm[tablePosL1G, TableHeadings -> {tableLabelL1, tableHead}]]
```

	x_global	y_global	z_global
LHAM1	-22 692	0	0
LHAM2	-20 122	0	0
LHAM3	-3831	0	0
LHAM4	0	-3831	0
LHAM5	0	-20 122	0
LHAM6	0	-22 692	0
LBSC1	0	4580	0
LBSC2	0	0	0
LBSC3	4580	0	0
LBSC4	4 000 000	0	0
LBSC5	0	4 000 000	0

**Chambers**

Chamber center positions, in global coordinates, are listed in D0902216-v6

(Debug) In[2778]:=

```
chambersL1 = {"LBSC1", 0.0, 4580.0, 0.0},
{"LBSC2", 0.0, 0.0, 0.0},
{"LBSC3", 4580.0, 0.0, 0.0},
{"LBSC4", 4 000 000.0, 0.0, 0.0},
{"LBSC5", 0.0, 4 000 000.0, 0.0},
{"LHAM1", -22 692.0, 0.0, 0.0},
{"LHAM2", -20 122.0, 0.0, 0.0},
{"LHAM3", -3831.0, 0.0, 0.0},
{"LHAM4", 0.0, -3831.0, 0.0},
{"LHAM5", 0.0, -20 122.0, 0.0},
{"LHAM6", 0.0, -22 692.0, 0.0}];
nChambersL1 = Length[chambersL1];
nBSCchambersL1 = 5;
nHAMchambersL1 = 6;
```

(Debug) In[2782]:=

```

tableHead = {"x_global", "y_global", "z_global"};
Print[TableForm[chambersL1[[All, 2 ;; 4]], TableHeadings -> {chambersL1[[All, 1]], tableHead}]]

```

	x_global	y_global	z_global
LBSC1	0.	4580.	0.
LBSC2	0.	0.	0.
LBSC3	4580.	0.	0.
LBSC4	$4. \times 10^6$	0.	0.
LBSC5	0.	$4. \times 10^6$	0.
LHAM1	-22 692.	0.	0.
LHAM2	-20 122.	0.	0.
LHAM3	-3831.	0.	0.
LHAM4	0.	-3831.	0.
LHAM5	0.	-20 122.	0.
LHAM6	0.	-22 692.	0.

(Debug) In[2784]:=

```

opticPosL1G[[10, 2]] - chambersL1[[1, 3]]

```

(Debug) Out[2784]=

403.1

**H1 and L1 Differences**

(Debug) In[2785]:=

```

tableHead = {"Xg", "Yg", "Zg", "Ug", "Vg", "Wg"};
Print[TableForm[Partition[Flatten[Transpose[{{(opticPosL1G - opticPosH1G), (opticOrientL1G - opticOrientH1G)}}]], 6],
TableHeadings -> {opticLabelL1, tableHead}]]

```

	Xg	Yg	Zg	Ug	Vg	Wg
PRM HR	18.1	-0.7	-9.019	$-1.04988 \times 10^{-8}$	$3.412 \times 10^{-6}$	-0.0000162086
PR2 HR	9.9	-0.4	-9.2736	$-4.47701 \times 10^{-7}$	-0.000037896	0.000307417
PR3 HR	1.	-1.871	0.4273	$1.03472 \times 10^{-6}$	0.00007966	-0.000307417
BS HR	0.089	-0.061	0.0731	-0.0000333687	-0.0000333367	0.
BS ARc	0.111	-0.122	0.0731	0.000107565	0.000107188	0.
SRM HR	-0.4	0.	19.852	0.000078	$4.47051 \times 10^{-6}$	-0.000015689
SR2 HR	0.	0.	20.2015	-0.00001134	$-2.91161 \times 10^{-7}$	-0.0006235
SR3 HR	-0.543	0.	0.3995	$8.39 \times 10^{-6}$	$-7.08726 \times 10^{-8}$	0.0006235
ITMx HR	0.	0.	0.	0.	0.	0.
ITMy HR	0.	0.	0.	0.	0.	0.
ETMx HR	0.	0.	0.	0.	0.	0.
ETMy HR	0.	0.	0.	0.	0.	0.

Just a check; In global coordinates we expect that H1 is quite similar to L1. However since PR2, PR3, SR2 and SR3 are vertical in the local (gravity) frame, the vertical component of their surface normal vectors (Wg) should be different. Moreover the differences should be the same for PR2 & SR3, as well as for SR2 & SR3. This is the case above.

As a consequence Wg will be different for PRM and SRM as well.

The vertical positions of PRM, PR2, SRM and SR2 are also different, as a consequence of the pitch angle difference.

Yaw angles should all be very similar ... and they are. The largest difference is 11 microrad.

### 1.3.2. Local Coordinates

#### IAM @ LHO

coordinates of the Initial Alignment Monuments (IAM) for aLIGO are given in D1100291-v4

(Debug) In[2787]:=

```
IAMlho = {"BTVE-1", 0.0, 46 000.0}, {"BTVE-5", 46 000.0, 0.0}, {"IAM-1", 2362.3, -3251.2}, {"IAM-2", 11 543.0, -3251.2},
{"IAM-3", 213 360.0, -3251.2}, {"IAM-4", 2362.3, 212.9}, {"IAM-5", 11 543.1, -200.0}, {"IAM-6", -3251.2, 2362.2},
{"IAM-7", -200.0, 2362.2}, {"IAM-8", 11 543.0, 9060.0}, {"IAM-9", -3251.2, 11 428.0}, {"IAM-10", 200.0, 11 428.0},
{"IAM-11", 9163.1, 11 428.0}, {"IAM-12", -3251.2, 213 360.0}, {"PSI-1", 2362.3, 44 643.1}, {"PSI-2", 9219.6, 31 601.7},
{"PSI-3", -2362.2, 9219.6}, {"PSI-4", -22 382.7, 2362.2}, {"PSI-5", -22 382.7, 0.0}, {"PSI-6", 2362.2, 2362.2},
{"PSI-7", 0.0, -22 382.7}, {"PSI-8", 2362.1, -22 382.7}, {"PSI-9", 2362.2, -2362.2}, {"PSI-10", 9219.6, -2362.2},
{"PSI-11", 31 601.1, 9219.6}, {"PSI-12", 44 642.6, 2362.2}, {"LV1", -2132.9, 11 428.0}, {"LV2", -2133.6, 2362.2},
{"LV3", -2131.6, 38 158.1}, {"LV4", NaN, NaN}, {"LV5", -2133.6, -1930.7}, {"LV6", 11 543.0, -1930.7}, {"LV7", 38 155.0, -1930.7},
{"LV8", NaN, NaN}, {"LV9", 11 543.0, 11 428.0}, {"LV10", 27 340.1, 11 428.0}, {"LV11", 11 543.0, 27 306.3}, {"LV12", -2132.2, 25 171.9},
{"LV13", -2131.9, 31 415.1}, {"LV14", 1375.2, -1930.7}, {"LV15", 31 426.7, -1930.7}, {"LV16", 33 967.1, -1930.7},
{"LV17", 200.0, 38 158.1}, {"LV18", 0.0, 38 158.1}, {"LV19", -200.0, 38 158.1}, {"LV20", -2133.6, -3830.7}, {"LV21", -2133.6, -20 122.0},
{"LV22", -2133.6, -22 692.0}, {"LV23", -3831.0, -3050.7}, {"LV24", -20 122.0, -3050.7}, {"LV25", -22 692.0, -3050.7}, {"LV26", -2133.6, -3050.7};
```

(Debug) In[2788]:=

```
IAMLabellho = Transpose[IAMlho][[1]];
IAMPosLlho = IAMlho[[All, 2 ;; 3]];
tableHead = {"X1", "Y1"};
Print[TableForm[IAMPosLlho, TableHeadings -> {IAMLabellho, tableHead}]]
```

	X1	Y1
BTVE-1	0.	46 000.
BTVE-5	46 000.	0.
IAM-1	2362.3	-3251.2
IAM-2	11 543.	-3251.2
IAM-3	213 360.	-3251.2
IAM-4	2362.3	212.9
IAM-5	11 543.1	-200.
IAM-6	-3251.2	2362.2
IAM-7	-200.	2362.2
IAM-8	11 543.	9060.
IAM-9	-3251.2	11 428.
IAM-10	200.	11 428.
IAM-11	9163.1	11 428.
IAM-12	-3251.2	213 360.
PSI-1	2362.3	44 643.1
PSI-2	9219.6	31 601.7
PSI-3	-2362.2	9219.6

PSI-4	-22 382.7	2362.2
PSI-5	-22 382.7	0.
PSI-6	2362.2	2362.2
PSI-7	0.	-22 382.7
PSI-8	2362.1	-22 382.7
PSI-9	2362.2	-2362.2
PSI-10	9219.6	-2362.2
PSI-11	31 601.1	9219.6
PSI-12	44 642.6	2362.2
LV1	-2132.9	11 428.
LV2	-2133.6	2362.2
LV3	-2131.6	38 158.1
LV4	NaN	NaN
LV5	-2133.6	-1930.7
LV6	11 543.	-1930.7
LV7	38 155.	-1930.7
LV8	NaN	NaN
LV9	11 543.	11 428.
LV10	27 340.1	11 428.
LV11	11 543.	27 306.3
LV12	-2132.2	25 171.9
LV13	-2131.9	31 415.1
LV14	1375.2	-1930.7
LV15	31 426.7	-1930.7
LV16	33 967.1	-1930.7
LV17	200.	38 158.1
LV18	0.	38 158.1
LV19	-200.	38 158.1
LV20	-2133.6	-3830.7
LV21	-2133.6	-20 122.
LV22	-2133.6	-22 692.
LV23	-3831.	-3050.7
LV24	-20 122.	-3050.7
LV25	-22 692.	-3050.7
LV26	-2133.6	-3050.7

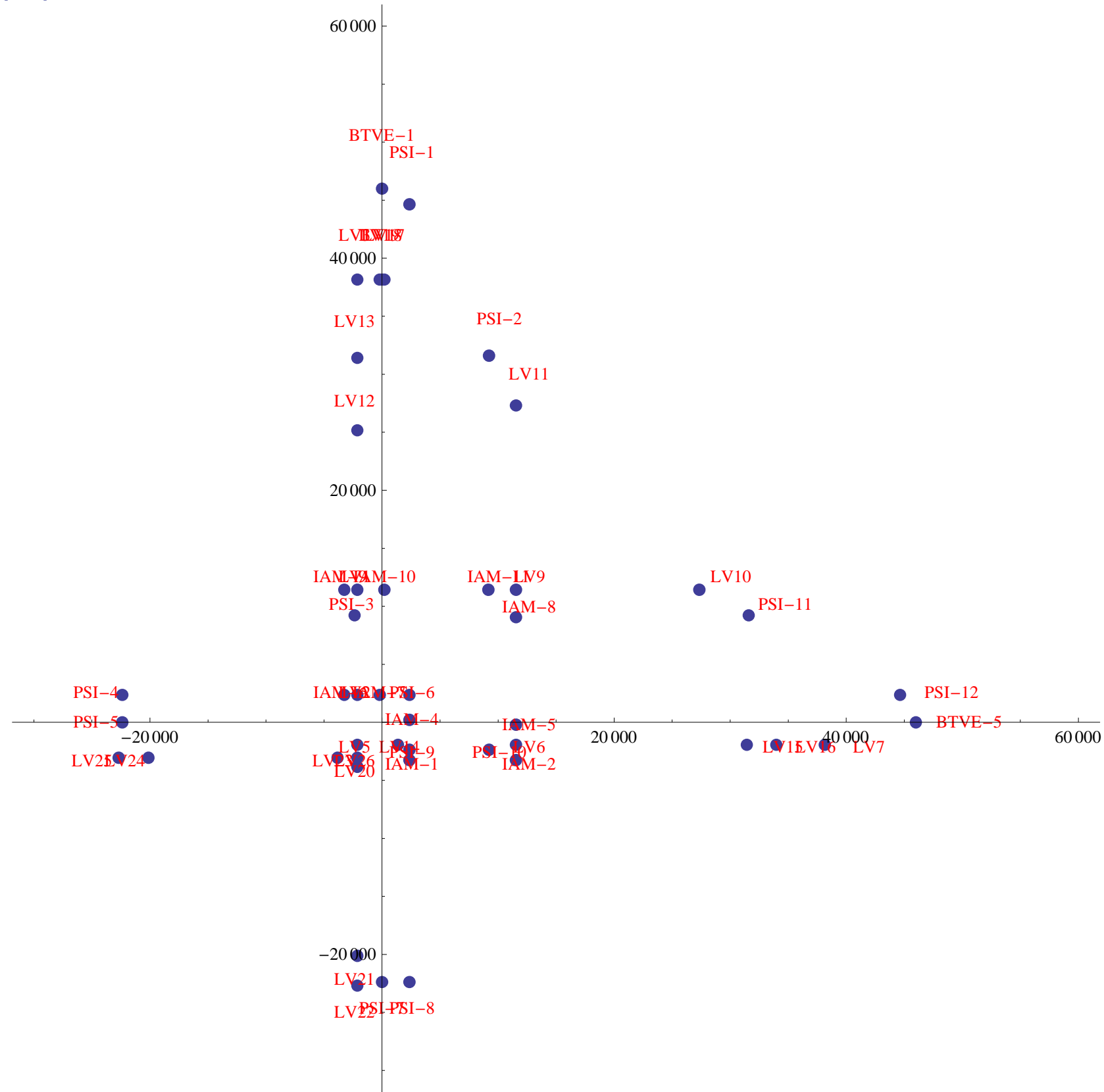
```
(Debug) In[2792]:=
```

```

labels = Text[#[[1]], 1.1 #[[{2, 3}]]] & /@Drop[IAMlho, {30, 34, 4}];
dataPlot = ListPlot[IAMPosLlho, PlotStyle → PointSize → Large];
Show[dataPlot, Graphics[{Red, labels}], PlotRange → {{-30 000, 60 000}, {-30 000, 60 000}}, AspectRatio → 1]

```

(Debug) Out[2794]=



**TS1 @ LHO**

TS#1 monuments are in local coordinates, i.e. center of TS1 is (0,0)

```
(Debug) In[2795]:=
```

```

IAMlhoTS1 = {"TS1-1", -200.0, 5133.0},
{"TS1-2", 0.0, 5133.0},
{"TS1-3", 200.0, 5133.0},
{"TS1-4", -200.0, -7570.0},
{"TS1-5", 0.0, -7570.0},
{"TS1-6", 200.0, -7570.0},
{"TS1-10", 0.0, 0.0},
{"TS1-11", -7289.0, 200.0},
{"TS1-12", -7289.0, 0.0},
{"TS1-13", -7289.0, -200.0},
{"TS1-15", 2872.0, 200.0},
{"TS1-16", 2872.0, 0.0},
{"TS1-17", 2872.0, -200.0}];

```

```
(Debug) In[2796]:=
```

```

IAMLabellhoTS1 = Transpose[IAMlhoTS1][[1]];
IAMPosLlhoTS1 = IAMlhoTS1[[All, 2 ;; 3]];

```

```
(Debug) In[2798]:=
```

```

tableHead = {"X1", "Y1"};
Print[TableForm[IAMPosLlhoTS1, TableHeadings -> {IAMLabellhoTS1, tableHead}]]

```

	X1	Y1
TS1-1	-200.	5133.
TS1-2	0.	5133.
TS1-3	200.	5133.
TS1-4	-200.	-7570.
TS1-5	0.	-7570.
TS1-6	200.	-7570.
TS1-10	0.	0.
TS1-11	-7289.	200.
TS1-12	-7289.	0.
TS1-13	-7289.	-200.
TS1-15	2872.	200.
TS1-16	2872.	0.
TS1-17	2872.	-200.

### TS2 @ LHO

TS#2 monuments are in local coordinates, i.e. center of TS2 is (0,0)

(Debug) In[2800]:=

```
IAMlhoTS2 = {"TS2-1", -200.0, 5133.0},  
{"TS2-2", 0.0, 5133.0},  
{"TS2-3", 200.0, 5133.0},  
{"TS2-4", -200.0, -7570.0},  
{"TS2-5", 0.0, -7570.0},  
{"TS2-6", 200.0, -7570.0},  
{"TS2-7", -200.0, 2800.0},  
{"TS2-8", 3327.3, 2800.0},  
{"TS2-9", 3327.3, -326.1},  
{"TS2-10", 0.0, 0.0},  
{"TS2-11", -2872.0, 200.0},  
{"TS2-12", -2872.0, 0.0},  
{"TS2-13", -2872.0, -200.0},  
{"TS2-14", 200.0, 7570.0},  
{"TS2-15", 7285.0, 200.0},  
{"TS2-16", 7285.0, 0.0},  
{"TS2-17", 7285.0, -200.0}];
```

(Debug) In[2801]:=

```
IAMLabellhoTS2 = Transpose[IAMlhoTS2][[1]];  
IAMPosLlhoTS2 = IAMlhoTS2[[All, 2 ;; 3]];
```

(Debug) In[2803]:=

```

tableHead = {"X1", "Y1"};
Print[TableForm[IAMPosLlhoTS2, TableHeadings -> {IAMLabellhoTS2, tableHead}]]

```

	X1	Y1
TS2-1	-200.	5133.
TS2-2	0.	5133.
TS2-3	200.	5133.
TS2-4	-200.	-7570.
TS2-5	0.	-7570.
TS2-6	200.	-7570.
TS2-7	-200.	2800.
TS2-8	3327.3	2800.
TS2-9	3327.3	-326.1
TS2-10	0.	0.
TS2-11	-2872.	200.
TS2-12	-2872.	0.
TS2-13	-2872.	-200.
TS2-14	200.	7570.
TS2-15	7285.	200.
TS2-16	7285.	0.
TS2-17	7285.	-200.

H1

**Optics**

(Debug) In[2805]:=

```

opticPosH1L = Table[0, {nOpticsH1}];
opticOrientH1L = opticPosH1L;

```

(Debug) In[2807]:=

```

Do[
  opticPosH1L[[i]] = opticPosH1G[[i]].Rhc // N;
  opticOrientH1L[[i]] = opticOrientH1G[[i]].Rhc // N;
  If[Abs[opticOrientH1L[[i]].opticOrientH1L[[i]] - 1] > 10^-15, Print["error"],,
  {i, nOpticsH1 - 2}];

```

(Debug) In[2808]:=

```

opticPosH1L[[nOpticsH1 - 1]] = opticPosH1G[[nOpticsH1 - 1]].Rhxe // N;
opticOrientH1L[[nOpticsH1 - 1]] = opticOrientH1G[[nOpticsH1 - 1]].Rhxe // N;
If[Abs[opticOrientH1L[[nOpticsH1 - 1]].opticOrientH1L[[nOpticsH1 - 1]] - 1] > 10^-15, Print["error"],];

```

(Debug) In[2811]:=

```

opticPosH1L[[nOpticsH1]] = opticPosH1G[[nOpticsH1]].Rhye // N;
opticOrientH1L[[nOpticsH1]] = opticOrientH1G[[nOpticsH1]].Rhye // N;
If[Abs[opticOrientH1L[[nOpticsH1]].opticOrientH1L[[nOpticsH1]] - 1] > 10^-15, Print["error"],];

```



(Debug) In[2814]:=

```

tableHead = {"X1", "Y1", "Z1", "U1", "V1", "W1"};
Print[TableForm[Partition[Flatten[Transpose[{opticPosH1L, opticOrientH1L}]], 6], TableHeadings -> {opticLabelH1, tableHead}]]

```

	X1	Y1	Z1	U1	V1	W1
PRM HR	-20 207.8	-627.299	-81.5893	0.999983	0.00587231	-0.0000225034
PR2 HR	-3589.15	-529.999	-81.9832	-0.999968	0.00805461	$1.53112 \times 10^{-7}$
PR3 HR	-19 741.1	-174.399	-82.3728	0.999937	-0.011231	$-1.73788 \times 10^{-7}$
BS HR	-202.651	-183.899	-82.7768	-0.70675	0.707463	0.000446656
BS ARC	-160.351	-226.199	-82.8035	0.705811	-0.7084	-0.000446086
SRM HR	305.33	-19 908.6	-113.638	-0.0571409	0.998366	0.00064424
SR2 HR	-594.165	-4178.1	-104.084	0.0421119	-0.999113	-0.00002606
SR3 HR	-174.659	-19 615.9	-94.6367	-0.0137964	0.999905	$8.52869 \times 10^{-6}$
ITMx HR	5012.95	-199.999	-83.108	1.	0.	-0.00061949
ITMy HR	-200.049	4983.1	-79.8139	$7.73322 \times 10^{-9}$	1.	0.0000124832
ETMx HR	$3.9995 \times 10^6$	-199.999	-48.6506	-1.	0.	$-7.8389 \times 10^{-6}$
ETMy HR	-198.463	$3.99947 \times 10^6$	2476.58	$-3.96592 \times 10^{-7}$	-1.	-0.0006392

**Tables**

Convert the global coordinates of the optics tables into the local coordinate system:

(Debug) In[2816]:=

```

tablePosH1L = Table[0, {nTablesL1}];
Do[
  tablePosH1L[[i]] = tablePosH1G[[i]].Rhc // N,
  {i, nTables}];
tableHead = {"x_local", "y_local", "z_local"};
Print[TableForm[tablePosH1L, TableHeadings -> {tableLabelH1, tableHead}]]

```

Do::iterb : Iterator {i, nTables} does not have appropriate bounds. >>

WHAM1	0
WHAM2	0
WHAM3	0
WHAM4	0
WHAM5	0
WHAM6	0
WBSC1	0
WBSC2	0
WBSC3	0
WBSC9	0
WBSC10	0

**H2**

H2 is not installed

**IAM @ LLO**

coordinates of the Initial Alignment Monuments (IAM) for aLIGO are given in D980499-C and E1100374-v4

(Debug) In[2820]:=

```
IAMllo = {{"IAM-L1", -22 382.3, -1854.2}, {"IAM-L2", -1854.2, -1854.2}, {"IAM-L3", -1854.2, -22 089.6}, {"IAM-L4", 2362.2, -1854.2},
{"IAM-L5", 38 154.0, -1854.2}, {"IAM-L6", 220 000.0, -1854.2}, {"IAM-L7", -1854.2, 2362.2}, {"IAM-L8", -1854.2, 38 154.0},
{"IAM-L9", -1854.2, 220 000.0}, {"L1 IAM 380", 0.0, NaN}, {"L1 IAM 379", -1858.0, -26 231.2}, {"L1 IAM 378", -1858.0, -2245.5},
{"L1 IAM 377", -1858.0, -1845.1}, {"L1 IAM 381", 11 591.0, -1845.1}, {"_87", 45 990.8, -1845.1}, {"L1 IAM 382", -22 283.5, -2245.5},
{"L1 IAM 376", -1858.0, 12 604.4}, {"IAM 92", -1858.0, 45 962.2}, {"AM 405", -1858.0, -22 503.2}, {"AM 404", -1858.0, -19 941.0},
{"AM 403", -1858.0, -3650.0}, {"AM 400", -3831.1, -2245.5}, {"AM 401", -20 122.1, -2245.5}, {"AM 402", -22 692.0, -2245.5},
{"IAM 333", 6526.5, 2037.4}, {"IAM 398", 6726.5, 2037.4}, {"IAM 332", 6926.5, 2037.4}, {"IAM 329", 14 019.5, 6968.4},
{"IAM 393", 14 019.5, 7168.4}, {"IAM 337", 14 019.5, 7368.4}, {"IAM 334", 6926.5, 14 739.4}, {"IAM 391", 6726.5, 14 739.4},
{"IAM 349", 6526.5, 14 739.4}, {"IAM 389", 3859.5, 7368.4}, {"IAM 397", 3859.5, 7168.4}, {"IAM 400", 3859.5, 6968.4},
{"IAM 394", 6726.5, 7168.4}, {"IAM 342", 9433.0, -1429.1}, {"IAM 396", 9633.0, -1429.1}, {"IAM 350", 9833.0, -1429.1},
{"IAM 346", 17 203.0, 3503.9}, {"IAM 392", 17 203.0, 3703.9}, {"IAM 338", 17 203.0, 3903.9}, {"IAM 327", 9833.0, 10 992.9},
{"IAM 395", 9633.0, 10 992.9}, {"IAM 385", 9433.0, 10 992.9}, {"IAM 330", 6761.0, 3903.9}, {"IAM 390", 6761.0, 3703.9},
{"IAM 326", 6761.0, 3503.9}, {"IAM 399", 9633.0, 3703.9}};
```

(Debug) In[2821]:=

```
IAMLabelllo = Transpose[IAMllo][[1]];
IAMPosLllo = IAMllo[[All, 2 ;; 3]];
tableHead = {"X1", "Y1"};
Print[TableForm[IAMPosLllo, TableHeadings -> {IAMLabelllo, tableHead}]]
```

	X1	Y1
IAM-L1	-22 382.3	-1854.2
IAM-L2	-1854.2	-1854.2
IAM-L3	-1854.2	-22 089.6
IAM-L4	2362.2	-1854.2
IAM-L5	38 154.	-1854.2
IAM-L6	220 000.	-1854.2
IAM-L7	-1854.2	2362.2
IAM-L8	-1854.2	38 154.
IAM-L9	-1854.2	220 000.
L1 IAM 380	0.	NaN
L1 IAM 379	-1858.	-26 231.2
L1 IAM 378	-1858.	-2245.5
L1 IAM 377	-1858.	-1845.1
L1 IAM 381	11 591.	-1845.1
_87	45 990.8	-1845.1
L1 IAM 382	-22 283.5	-2245.5
L1 IAM 376	-1858.	12 604.4
IAM 92	-1858.	45 962.2
AM 405	-1858.	-22 503.2
AM 404	-1858.	-19 941.

AM 403	-1858.	-3650.
AM 400	-3831.1	-2245.5
AM 401	-20122.1	-2245.5
AM 402	-22692.	-2245.5
IAM 333	6526.5	2037.4
IAM 398	6726.5	2037.4
IAM 332	6926.5	2037.4
IAM 329	14019.5	6968.4
IAM 393	14019.5	7168.4
IAM 337	14019.5	7368.4
IAM 334	6926.5	14739.4
IAM 391	6726.5	14739.4
IAM 349	6526.5	14739.4
IAM 389	3859.5	7368.4
IAM 397	3859.5	7168.4
IAM 400	3859.5	6968.4
IAM 394	6726.5	7168.4
IAM 342	9433.	-1429.1
IAM 396	9633.	-1429.1
IAM 350	9833.	-1429.1
IAM 346	17203.	3503.9
IAM 392	17203.	3703.9
IAM 338	17203.	3903.9
IAM 327	9833.	10992.9
IAM 395	9633.	10992.9
IAM 385	9433.	10992.9
IAM 330	6761.	3903.9
IAM 390	6761.	3703.9
IAM 326	6761.	3503.9
IAM 399	9633.	3703.9

(Debug) In[2825]=

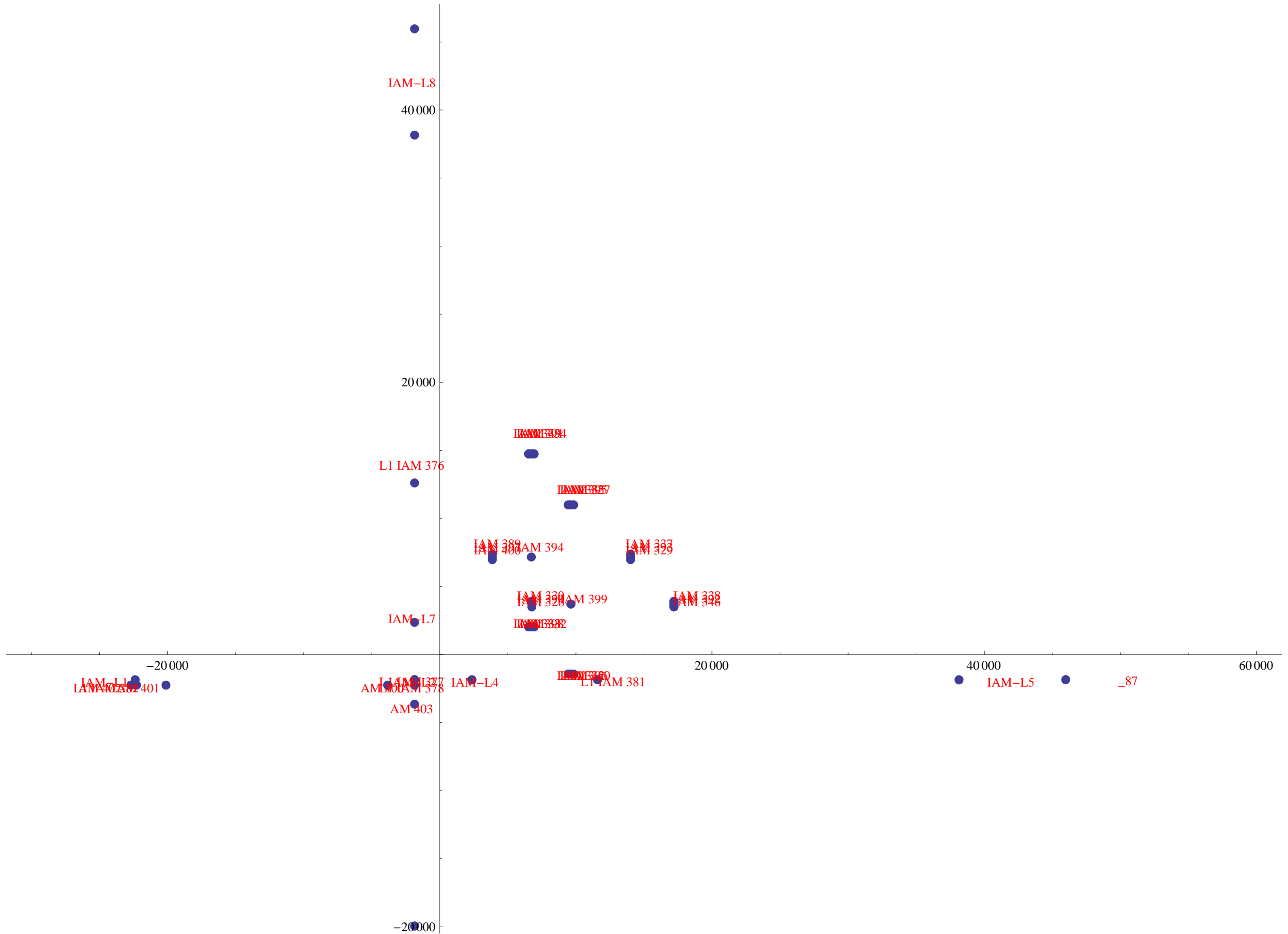
```

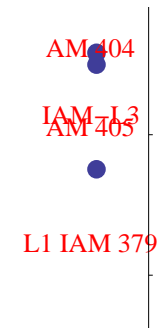
labels = Text[#[[1]], 1.1 #[[{2, 3}]]] & /@ Drop[IAMllo, {10}];
dataPlot = ListPlot[IAMPosLllo, PlotStyle → PointSize → Large];
Show[dataPlot, Graphics[{Red, labels}], PlotRange → {{-30000, 60000}, {-30000, 60000}}, AspectRatio → 1]

```

(Debug) Out[2827]=







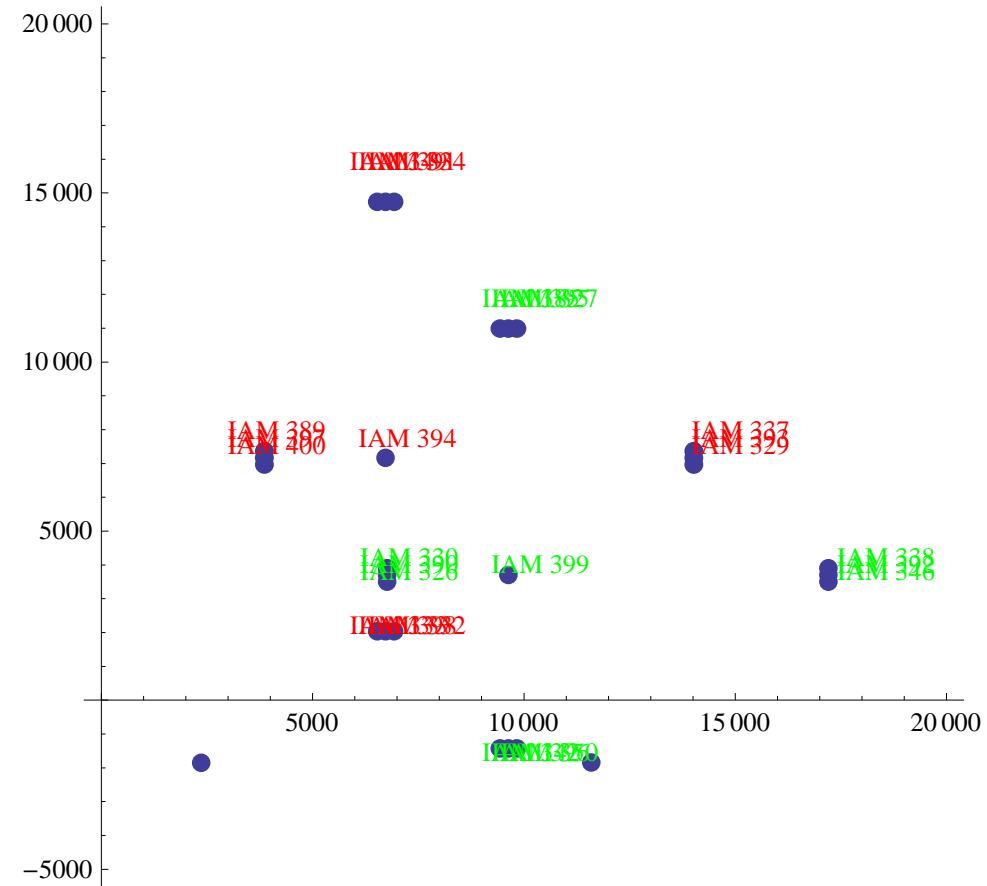
(Debug) In[2828]:=

```

labelTS1 = Text[#[[1]], 1.08 #[[{2, 3}]]] & /@ IAMllo[[25 ;; 37]];
labelTS2 = Text[#[[1]], 1.08 #[[{2, 3}]]] & /@ IAMllo[[38 ;; 50]];
dataPlot = ListPlot[IAMPosLllo, PlotStyle -> PointSize -> Large];
Show[dataPlot, Graphics[{Red, labelTS1}], Graphics[{Green, labelTS2}], PlotRange -> {{0, 20 000}, {-5000, 20 000}}, AspectRatio -> 1]

```

(Debug) Out[2831]=



Subtract center coordinates from all Test Stand #1 monuments, so that all calculations are done in TS#1 local coordinates

(Debug) In[2832]:=

```

IAMlloTS1 = Table["", {13}, {3}];
Do[IAMlloTS1[[i - 24, 1]] = IAMllo[[i, 1]]; IAMlloTS1[[i - 24, 2 ;; 3]] = IAMllo[[i, 2 ;; 3]] - IAMllo[[37, 2 ;; 3]], {i, 25, 37}];
IAMLabellloTS1 = Transpose[IAMlloTS1][[1]];
IAMPosLlloTS1 = IAMlloTS1[[All, 2 ;; 3]];
tableHead = {"X1", "Y1"};
Print[TableForm[IAMPosLlloTS1, TableHeadings -> {IAMLabellloTS1, tableHead}]]

```

	X1	Y1
IAM 333	-200.	-5131.
IAM 398	0.	-5131.
IAM 332	200.	-5131.
IAM 329	7293.	-200.
IAM 393	7293.	0.
IAM 337	7293.	200.
IAM 334	200.	7571.
IAM 391	0.	7571.
IAM 349	-200.	7571.
IAM 389	-2867.	200.
IAM 397	-2867.	0.
IAM 400	-2867.	-200.
IAM 394	0.	0.

Subtract center coordinates from all Test Stand #2 monuments, so that all calculations are done in TS#2 local coordinates

(Debug) In[2838]:=

```

IAMlloTS2 = Table["", {13}, {3}];
Do[IAMlloTS2[[i - 37, 1]] = IAMllo[[i, 1]]; IAMlloTS2[[i - 37, 2 ;; 3]] = IAMllo[[i, 2 ;; 3]] - IAMllo[[50, 2 ;; 3]], {i, 38, 50}];
IAMLabellloTS2 = Transpose[IAMlloTS2][[1]];
IAMPosLlloTS2 = IAMlloTS2[[All, 2 ;; 3]];
tableHead = {"X1", "Y1"};
Print[TableForm[IAMPosLlloTS2, TableHeadings -> {IAMLabellloTS2, tableHead}]]

```

	X1	Y1
IAM 342	-200.	-5133.
IAM 396	0.	-5133.
IAM 350	200.	-5133.
IAM 346	7570.	-200.
IAM 392	7570.	0.
IAM 338	7570.	200.
IAM 327	200.	7289.
IAM 395	0.	7289.
IAM 385	-200.	7289.
IAM 330	-2872.	200.
IAM 390	-2872.	0.
IAM 326	-2872.	-200.
IAM 399	0.	0.

L1

**Optics**

(Debug) In[2844]:=

```

opticPosL1L = Table[0, {nOpticsL1}];
opticOrientL1L = opticPosL1L;

```

(Debug) In[2846]:=

```

Do[
  opticPosL1L[[i]] = opticPosL1G[[i]].Rlc // N;
  opticOrientL1L[[i]] = opticOrientL1G[[i]].Rlc // N;
  If[Abs[opticOrientL1L[[i]].opticOrientL1L[[i]] - 1] > 10^-15, Print["error"],],
  {i, nOpticsL1 - 2}];

```

(Debug) In[2847]:=

```

opticPosL1L[[nOpticsL1 - 1]] = opticPosL1G[[nOpticsL1 - 1]].Rlxe // N;
opticOrientL1L[[nOpticsL1 - 1]] = opticOrientL1G[[nOpticsL1 - 1]].Rlxe // N;
If[Abs[opticOrientL1L[[nOpticsL1 - 1]].opticOrientL1L[[nOpticsL1 - 1]] - 1] > 10^-15, Print["error"],];

```

(Debug) In[2850]:=

```

opticPosL1L[[nOpticsL1]] = opticPosL1G[[nOpticsL1]].Rlye // N;
opticOrientL1L[[nOpticsL1]] = opticOrientL1G[[nOpticsL1]].Rlye // N;
If[Abs[opticOrientL1L[[nOpticsL1]].opticOrientL1L[[nOpticsL1]] - 1] > 10^-15, Print["error"],];

```

(Debug) In[2853]:=

```

tableHead = {"X1", "Y1", "Z1", "U1", "V1", "W1"};
Print[TableForm[Partition[Flatten[Transpose[{opticPosL1L, opticOrientL1L}]], 6], TableHeadings -> {opticLabelL1, tableHead}]]

```

	X1	Y1	Z1	U1	V1	W1
PRM HR	-20189.6	-628.063	-96.4361	0.999983	0.00587608	0.000265109
PR2 HR	-3579.23	-530.457	-92.0328	-0.999968	0.00801652	$-4.90818 \times 10^{-6}$
PR3 HR	-19740.	-176.329	-87.9061	0.999938	-0.0111511	$6.83279 \times 10^{-6}$
BS HR	-202.537	-184.012	-82.6513	-0.706784	0.707429	-0.000211723
BS ARC	-160.215	-226.373	-82.6386	0.705919	-0.708292	0.00021252
SRM HR	304.975	-19908.7	-81.279	-0.0570633	0.998371	-0.0000115106
SR2 HR	-594.125	-4178.15	-81.4603	0.0421006	-0.999113	-0.0000136772
SR3 HR	-175.169	-19616.	-82.0605	-0.013788	0.999905	$4.35997 \times 10^{-6}$
ITMx HR	5012.97	-200.049	-81.4418	1.	0.	-0.000312
ITMy HR	-200.026	4983.05	-82.9823	$-1.90632 \times 10^{-7}$	1.	-0.000611
ETMx HR	$3.9995 \times 10^6$	-200.049	1179.96	-1.	0.	-0.000315
ETMy HR	-200.001	$3.99947 \times 10^6$	-4.7478	$-5.8468 \times 10^{-9}$	-1.	-0.0000188

**Tables**

Convert the global coordinates of the optics tables into the local coordinate system:

(Debug) In[2855]:=

```

tablePosL1L = Table[0, {nTablesL1}];
Do[
  tablePosL1L[[i]] = tablePosL1G[[i]].R1c // N,
  {i, nTablesL1}];
tableHead = {"x_local", "y_local", "z_local"};
Print[TableForm[tablePosL1L, TableHeadings -> {tableLabelL1, tableHead}]]

```

	x_local	y_local	z_local
LHAM1	-22692.	0.	7.0799
LHAM2	-20122.	0.	6.27806
LHAM3	-3831.	0.	1.19527
LHAM4	0.000730311	-3831.	2.34074
LHAM5	0.0038359	-20122.	12.2945
LHAM6	0.00432582	-22692.	13.8648
LBSC1	-0.000873094	4580.	-2.79838
LBSC2	0.	0.	0.
LBSC3	4580.	0.	-1.42896
LBSC4	$4. \times 10^6$	0.	-1248.
LBSC5	-0.762528	$4. \times 10^6$	-2444.

**Chambers**



## 1.4. Optic Pitch & Yaw Angles

### 1.4.1. H1

The pitch & yaw angles are determined for the optics

Uncorrected from Zemax

(Debug) In[2859]:=

```

opticPitchRadianH1 = Table[0, {nOpticsH1}];
opticPitchDegreeH1 = opticPitchRadianH1;
opticPitchDMSH1 = opticPitchRadianH1;
opticPitchDirectionH1 = opticPitchRadianH1;
Do[
  opticPitchRadianH1[[i]] = VectorAngle[opticOrientH1L[[i]], {opticOrientH1L[[i, 1]], opticOrientH1L[[i, 2]], 0}];
  If[opticOrientH1L[[i, 3]] > 0, opticPitchDirectionH1[[i]] = "up",
    If[opticOrientH1L[[i, 3]] < 0, opticPitchDirectionH1[[i]] = "down",
      opticPitchDirectionH1[[i]] = ""];
  opticPitchDegreeH1[[i]] = opticPitchRadianH1[[i]] 180 / Pi;
  opticPitchDMSH1[[i]] = DMS[opticPitchRadianH1[[i]]],
  {i, nOpticsH1}];

```

(Debug) In[2864]:=

```

tableHead = {"U1", "V1", "W1", "Pitch", "(rad)", "(deg)", "(deg)", "(min)", "(sec)"};
Print[
  TableForm[Partition[Flatten[N[Transpose[{opticOrientH1L, opticPitchDirectionH1, opticPitchRadianH1, opticPitchDegreeH1, opticPitchDMSH1}], 3]],
    9], TableHeadings -> {opticLabelH1, tableHead}]]

```

	U1	V1	W1	Pitch	(rad)	(deg)	(deg)	(min)	(sec)
PRM HR	0.999983	0.00587231	-0.0000225034	down	0.0000225034	0.00128935	0	0	5.00
PR2 HR	-0.999968	0.00805461	$1.53112 \times 10^{-7}$	up	0.	0.	0	0	0
PR3 HR	0.999937	-0.011231	$-1.73788 \times 10^{-7}$	down	$1.73776 \times 10^{-7}$	$9.95663 \times 10^{-6}$	0	0	0
BS HR	-0.70675	0.707463	0.000446656	up	0.000446656	0.0255915	0	1.00	32.0
BS ARC	0.705811	-0.7084	-0.000446086	down	0.000446086	0.0255589	0	1.00	32.0
SRM HR	-0.0571409	0.998366	0.00064424	up	0.00064424	0.0369122	0	2.00	13.0
SR2 HR	0.0421119	-0.999113	-0.00002606	down	0.00002606	0.00149313	0	0	5.00
SR3 HR	-0.0137964	0.999905	$8.52869 \times 10^{-6}$	up	$8.52869 \times 10^{-6}$	0.000488658	0	0	2.00
ITMx HR	1.	0.	-0.00061949	down	0.00061949	0.0354942	0	2.00	8.00
ITMy HR	$7.73322 \times 10^{-9}$	1.	0.0000124832	up	0.0000124832	0.000715234	0	0	3.00
ETMx HR	-1.	0.	$-7.8389 \times 10^{-6}$	down	$7.8389 \times 10^{-6}$	0.000449136	0	0	2.00
ETMy HR	$-3.96592 \times 10^{-7}$	-1.	-0.0006392	down	0.0006392	0.0366235	0	2.00	12.0

N.B.: The local coordinate frame pitch angles of PR2 HR, PR3 HR, SR2 HR and SR3 HR should all be zero. The non-zero, local coordinate frame, pitch values for SR2 and SR3 HR reflect an error in the Zemax model; The pitch angle of these optics were set in the global coordinate system without taking into account the yaw component of the normal vector of these optics. This error is particularly acute for the SR2 optic which has the largest

yaw component. When the yaw components of the SR2 and SR3 optics are set to zero, the residual error of the pitch in local coordinates is nearly zero, as shown below.

### Corrected from Zemax

#### calc

```
(Debug) In[2866]:=
  opticOrientH1L[[2, 3]] = 0;
  opticOrientH1L[[3, 3]] = 0;
  opticOrientH1L[[7, 3]] = 0;
  opticOrientH1L[[8, 3]] = 0;
```

```
(Debug) Out[2866]=
  {{Null}, {Null3}}
```

ensure that the normal vectors have unit length

```
(Debug) In[2867]:=
  Do[
    temp = opticOrientH1L[[j]];
    i = Flatten[Position[Abs[temp], Max[Abs[temp]]]][[1]];
    If[i == 1,
      opticOrientH1L[[j]] = {Sign[temp[[1]] Sqrt[1 - temp[[2]]^2 - temp[[3]]^2], temp[[2]], temp[[3]]};,
      If[i == 2,
        opticOrientH1L[[j]] = {temp[[1]], Sign[temp[[2]] Sqrt[1 - temp[[1]]^2 - temp[[3]]^2], temp[[3]]};,
        If[i == 3, opticOrientH1L[[j]] = {temp[[1]], temp[[2]], Sign[temp[[3]] Sqrt[1 - temp[[1]]^2 - temp[[2]]^2]};,
          opticOrientH1L[[j]] = {0, 0, 0};]]],
    {j, nOpticsH1}];
  Do[
    If[Abs[opticOrientH1L[[i]].opticOrientH1L[[i]] - 1] > 10^-7, Print["error"],],
    {i, nOpticsH1}];
```

```
(Debug) In[2869]:=
  opticPitchRadianH1 = Table[0, {nOpticsH1}];
  opticPitchDegreeH1 = opticPitchRadianH1;
  opticPitchDMSH1 = opticPitchRadianH1;
  opticPitchDirectionH1 = opticPitchRadianH1;
  Do[
    opticPitchRadianH1[[i]] = VectorAngle[opticOrientH1L[[i]], {opticOrientH1L[[i, 1]], opticOrientH1L[[i, 2]], 0}];
    If[opticOrientH1L[[i, 3]] > 0, opticPitchDirectionH1[[i]] = "up",
      If[opticOrientH1L[[i, 3]] < 0, opticPitchDirectionH1[[i]] = "down",
        opticPitchDirectionH1[[i]] = ""];
    opticPitchDegreeH1[[i]] = opticPitchRadianH1[[i]] 180 / Pi;
    opticPitchDMSH1[[i]] = DMS[opticPitchRadianH1[[i]]],
    {i, nOpticsH1}];
```

(Debug) In[2874]:=

```

opticYawRadianH1 = Table[0, {nOpticsH1}];
opticYawDegreeH1 = opticPitchRadianH1;
opticYawDMSH1 = opticPitchRadianH1;
opticYawDirectionH1 = opticPitchRadianH1;
Do[
  opticYawRadianH1[[i]] = VectorAngle[{opticOrientH1L[[i, 1]], opticOrientH1L[[i, 2]], 0}, {1, 0, 0}];
  opticYawRadianH1[[i]] = Abs[opticYawRadianH1[[i]] - Round[opticYawRadianH1[[i]], Pi/2]];
  If[opticOrientH1L[[i, 1]] > 0,
    If[opticOrientH1L[[i, 2]] > 0,
      If[Abs[opticOrientH1L[[i, 1]]] > Abs[opticOrientH1L[[i, 2]]], opticYawDirectionH1[[i]] = "left", opticYawDirectionH1[[i]] = "right",
      If[Abs[opticOrientH1L[[i, 1]]] > Abs[opticOrientH1L[[i, 2]]], opticYawDirectionH1[[i]] = "right", opticYawDirectionH1[[i]] = "left"]],
    If[opticOrientH1L[[i, 2]] > 0,
      If[Abs[opticOrientH1L[[i, 1]]] > Abs[opticOrientH1L[[i, 2]]], opticYawDirectionH1[[i]] = "right", opticYawDirectionH1[[i]] = "left",
      If[Abs[opticOrientH1L[[i, 1]]] > Abs[opticOrientH1L[[i, 2]]], opticYawDirectionH1[[i]] = "left", opticYawDirectionH1[[i]] = "right"]];
  opticYawDegreeH1[[i]] = opticYawRadianH1[[i]] 180 / Pi;
  opticYawDMSH1[[i]] = DMS[opticYawRadianH1[[i]]],
  {i, nOpticsH1}];

```

**pitch table**

(Debug) In[2879]:=

```

tableHead = {"U1", "V1", "W1", "Pitch", "(rad)", "(deg)", "(deg)", "(min)", "(sec)"};
Print[
  TableForm[
    Partition[Flatten[N[Transpose[{opticOrientH1L, opticPitchDirectionH1, opticPitchRadianH1, opticPitchDegreeH1, opticPitchDMSH1}], 3]], 9],
    TableHeadings -> {opticLabelH1, tableHead}]]

```

	U1	V1	W1	Pitch	(rad)	(deg)	(deg)	(min)	(sec)
PRM HR	0.999983	0.00587231	-0.0000225034	down	0.0000225034	0.00128935	0	0	5.00
PR2 HR	-0.999968	0.00805461	0		0.	0.	0	0	0
PR3 HR	0.999937	-0.011231	0		0.	0.	0	0	0
BS HR	-0.70675	0.707463	0.000446656	up	0.000446656	0.0255915	0	1.00	32.0
BS ARC	0.705811	-0.7084	-0.000446086	down	0.000446086	0.0255589	0	1.00	32.0
SRM HR	-0.0571409	0.998366	0.00064424	up	0.00064424	0.0369122	0	2.00	13.0
SR2 HR	0.0421119	-0.999113	0		0.	0.	0	0	0
SR3 HR	-0.0137964	0.999905	0		0.	0.	0	0	0
ITMx HR	1.	0.	-0.00061949	down	0.00061949	0.0354942	0	2.00	8.00
ITMy HR	$7.73322 \times 10^{-9}$	1.	0.0000124832	up	0.0000124832	0.000715235	0	0	3.00
ETMx HR	-1.	0.	$-7.8389 \times 10^{-6}$	down	$7.8389 \times 10^{-6}$	0.000449136	0	0	2.00
ETMy HR	$-3.96592 \times 10^{-7}$	-1.	-0.0006392	down	0.0006392	0.0366235	0	2.00	12.0

**yaw table**

(Debug) In[2881]:=

```

tableHead = {"U1", "V1", "W1", "Yaw", "(rad)", "(deg)", "(deg)", "(min)", "(sec)"};
Print[TableForm[Partition[Flatten[N[Transpose[{opticOrientH1L, opticYawDirectionH1, opticYawRadianH1, opticYawDegreeH1, opticYawDMSH1}], 3]],
  9], TableHeadings -> {opticLabelH1, tableHead}]]

```

	U1	V1	W1	Yaw	(rad)	(deg)	(deg)	(min)	(sec)
PRM HR	0.999983	0.00587231	-0.0000225034	left	0.00587234	0.336461	0	20.0	11.0
PR2 HR	-0.999968	0.00805461	0	right	0.0080547	0.4615	0	27.0	41.0
PR3 HR	0.999937	-0.011231	0	right	0.0112312	0.643501	0	38.0	37.0
BS HR	-0.70675	0.707463	0.000446656	left	0.784895	44.9711	44.0	58.0	16.0
BS ARc	0.705811	-0.7084	-0.000446086	left	0.783568	44.8951	44.0	53.0	43.0
SRM HR	-0.0571409	0.998366	0.00064424	left	0.0571721	3.27572	3.00	16.0	33.0
SR2 HR	0.0421119	-0.999113	0	left	0.0421244	2.41355	2.00	24.0	49.0
SR3 HR	-0.0137964	0.999905	0	left	0.0137968	0.7905	0	47.0	26.0
ITMx HR	1.	0.	-0.00061949	right	0.	0.	0	0	0
ITMy HR	$7.73322 \times 10^{-9}$	1.	0.0000124832	right	$7.73322 \times 10^{-9}$	$4.43081 \times 10^{-7}$	0	0	0
ETMx HR	-1.	0.	$-7.8389 \times 10^{-6}$	left	0.	0.	0	0	0
ETMy HR	$-3.96592 \times 10^{-7}$	-1.	-0.0006392	right	$3.96592 \times 10^{-7}$	0.000022723	0	0	0

**1.4.2. H2**

The H@ interferometer will not be installed for aLIGO.

**1.4.3. L1**

The pitch angle is determined for hanging the optics on the bench:

**Uncorrected from Zemax**

(Debug) In[2883]:=

```

opticPitchRadianL1 = Table[0, {nOpticsL1}];
opticPitchDegreeL1 = opticPitchRadianL1;
opticPitchDMSL1 = opticPitchRadianL1;
opticPitchDirectionL1 = opticPitchRadianL1;
Do[
  opticPitchRadianL1[[i]] = VectorAngle[opticOrientL1L[[i]], {opticOrientL1L[[i, 1]], opticOrientL1L[[i, 2]], 0}];
  If[opticOrientL1L[[i, 3]] > 0, opticPitchDirectionL1[[i]] = "up",
    If[opticOrientL1L[[i, 3]] < 0, opticPitchDirectionL1[[i]] = "down",
      opticPitchDirectionL1[[i]] = ""];
  opticPitchDegreeL1[[i]] = opticPitchRadianL1[[i]] 180 / Pi;
  opticPitchDMSL1[[i]] = DMS[opticPitchRadianL1[[i]],
    {i, nOpticsL1}];

```

(Debug) In[2888]:=

```
tableHead = {"U1", "V1", "W1", "Pitch", "(rad)", "(deg)", "(deg)", "(min)", "(sec)"};
```

```
Print[
```

```
TableForm[Partition[Flatten[N[Transpose[{opticOrientL1L, opticPitchDirectionL1, opticPitchRadianL1, opticPitchDegreeL1, opticPitchDMSL1}], 3]],
  9], TableHeadings -> {opticLabelL1, tableHead}]]
```

	U1	V1	W1	Pitch	(rad)	(deg)	(deg)	(min)	(sec)
PRM HR	0.999983	0.00587608	0.000265109	up	0.000265109	0.0151896	0	0	55.0
PR2 HR	-0.999968	0.00801652	$-4.90818 \times 10^{-6}$	down	$4.90819 \times 10^{-6}$	0.000281218	0	0	1.00
PR3 HR	0.999938	-0.0111511	$6.83279 \times 10^{-6}$	up	$6.83278 \times 10^{-6}$	0.000391489	0	0	1.00
BS HR	-0.706784	0.707429	-0.000211723	down	0.000211723	0.0121308	0	0	44.0
BS Arc	0.705919	-0.708292	0.00021252	up	0.00021252	0.0121765	0	0	44.0
SRM HR	-0.0570633	0.998371	-0.0000115106	down	0.0000115106	0.00065951	0	0	2.00
SR2 HR	0.0421006	-0.999113	-0.0000136772	down	0.0000136771	0.000783643	0	0	3.00
SR3 HR	-0.013788	0.999905	$4.35997 \times 10^{-6}$	up	$4.35998 \times 10^{-6}$	0.000249809	0	0	1.00
ITMx HR	1.	0.	-0.000312	down	0.000312	0.0178763	0	1.00	4.00
ITMy HR	$-1.90632 \times 10^{-7}$	1.	-0.000611	down	0.000611	0.0350077	0	2.00	6.00
ETMx HR	-1.	0.	-0.000315	down	0.000315	0.0180482	0	1.00	5.00
ETMy HR	$-5.8468 \times 10^{-9}$	-1.	-0.0000188	down	0.0000188	0.00107716	0	0	4.00

N.B.: The local coordinate frame pitch angles of PR2 HR, PR3 HR, SR2 HR and SR3 HR should all be zero. The non-zero, local coordinate frame, pitch values for these optics reflect a slight error in the Zemax model; The pitch angle of these optics were set in the global coordinate system without taking into account the yaw component of the normal vector of these optics. So, we'll set the pitch angle for these optics to zero here -- which is an approximate correction:

Corrected from Zemax

*calc*

(Debug) In[2890]:=

```
opticOrientL1L[[2, 3]] = 0;
```

```
opticOrientL1L[[3, 3]] = 0;
```

```
opticOrientL1L[[7, 3]] = 0;
```

```
opticOrientL1L[[8, 3]] = 0;
```

(Debug) Out[2890]=

```
{{Null}, {Null3}}
```

ensure that the normal vectors have unit length

```

(Debug) In[2891]:=
Do[
  temp = opticOrientL1L[[j]];
  i = Flatten[Position[Abs[temp], Max[Abs[temp]]]][[1]];
  If[i == 1,
    opticOrientL1L[[j]] = {Sign[temp[[1]] Sqrt[1 - temp[[2]]^2 - temp[[3]]^2], temp[[2]], temp[[3]]};,
    If[i == 2,
      opticOrientL1L[[j]] = {temp[[1]], Sign[temp[[2]] Sqrt[1 - temp[[1]]^2 - temp[[3]]^2], temp[[3]]};,
      If[i == 3, opticOrientL1L[[j]] = {temp[[1]], temp[[2]], Sign[temp[[3]] Sqrt[1 - temp[[1]]^2 - temp[[2]]^2]};,
        opticOrientL1L[[j]] = {0, 0, 0};]],
    {j, nOpticsL1}];
Do[
  If[Abs[opticOrientL1L[[i]].opticOrientL1L[[i]] - 1] > 10^-7, Print["error"],],
  {i, nOpticsL1}];

(Debug) In[2893]:=
opticPitchRadianL1 = Table[0, {nOpticsL1}];
opticPitchDegreeL1 = opticPitchRadianL1;
opticPitchDMSL1 = opticPitchRadianL1;
opticPitchDirectionL1 = opticPitchRadianL1;
Do[
  opticPitchRadianL1[[i]] = VectorAngle[opticOrientL1L[[i]], {opticOrientL1L[[i, 1]], opticOrientL1L[[i, 2]], 0}];
  If[opticOrientL1L[[i, 3]] > 0, opticPitchDirectionL1[[i]] = "up",
    If[opticOrientL1L[[i, 3]] < 0, opticPitchDirectionL1[[i]] = "down",
      opticPitchDirectionL1[[i]] = ""];
  opticPitchDegreeL1[[i]] = opticPitchRadianL1[[i]] 180 / Pi;
  opticPitchDMSL1[[i]] = DMS[opticPitchRadianL1[[i]],
  {i, nOpticsL1}];

```

The convention for the yaw angle is to give a value relative to the nearest  $\text{Pi}/2$  direction. So the yaw angles are always  $\leq 45$  deg. In addition the sign is set to positive and a “left” or “right” direction is noted. The direction is stated for an ‘upright’ person (i.e. a person with their head up and feet down) looking along the nearest  $\text{Pi}/2$  cardinal direction (i.e. +X, +Y, -X or -Y direction). A “left direction means that the outward facing normal vector to the surface is then to the left of this observer.

(Debug) In[2898]:=

```

opticYawRadianL1 = Table[0, {nOpticsL1}];
opticYawDegreeL1 = opticPitchRadianL1;
opticYawDMSL1 = opticPitchRadianL1;
opticYawDirectionL1 = opticPitchRadianL1;
Do[
  opticYawRadianL1[[i]] = VectorAngle[{opticOrientL1L[[i, 1]], opticOrientL1L[[i, 2]], 0}, {1, 0, 0}];
  opticYawRadianL1[[i]] = Abs[opticYawRadianL1[[i]] - Round[opticYawRadianL1[[i]], Pi/2]];
  If[opticOrientL1L[[i, 1]] > 0,
    If[opticOrientL1L[[i, 2]] > 0,
      If[Abs[opticOrientL1L[[i, 1]]] > Abs[opticOrientL1L[[i, 2]]], opticYawDirectionL1[[i]] = "left", opticYawDirectionL1[[i]] = "right",
      If[Abs[opticOrientL1L[[i, 1]]] > Abs[opticOrientL1L[[i, 2]]], opticYawDirectionL1[[i]] = "right", opticYawDirectionL1[[i]] = "left"]],
    If[opticOrientL1L[[i, 2]] > 0,
      If[Abs[opticOrientL1L[[i, 1]]] > Abs[opticOrientL1L[[i, 2]]], opticYawDirectionL1[[i]] = "right", opticYawDirectionL1[[i]] = "left",
      If[Abs[opticOrientL1L[[i, 1]]] > Abs[opticOrientL1L[[i, 2]]], opticYawDirectionL1[[i]] = "left", opticYawDirectionL1[[i]] = "right"]];
  opticYawDegreeL1[[i]] = opticYawRadianL1[[i]] 180 / Pi;
  opticYawDMSL1[[i]] = DMS[opticYawRadianL1[[i]]],
  {i, nOpticsL1}];

```

**pitch table**

(Debug) In[2903]:=

```

tableHead = {"U1", "V1", "W1", "Pitch", "(rad)", "(deg)", "(deg)", "(min)", "(sec)"};
Print[
  TableForm[
    Partition[Flatten[N[Transpose[{opticOrientL1L, opticPitchDirectionL1, opticPitchRadianL1, opticPitchDegreeL1, opticPitchDMSL1}], 3]], 9],
    TableHeadings -> {opticLabelL1, tableHead}]]

```

	U1	V1	W1	Pitch	(rad)	(deg)	(deg)	(min)	(sec)
PRM HR	0.999983	0.00587608	0.000265109	up	0.000265109	0.0151896	0	0	55.0
PR2 HR	-0.999968	0.00801652	0		0.	0.	0	0	0
PR3 HR	0.999938	-0.0111511	0		0.	0.	0	0	0
BS HR	-0.706784	0.707429	-0.000211723	down	0.000211723	0.0121308	0	0	44.0
BS ARC	0.705919	-0.708292	0.00021252	up	0.00021252	0.0121765	0	0	44.0
SRM HR	-0.0570633	0.998371	-0.0000115106	down	0.0000115106	0.00065951	0	0	2.00
SR2 HR	0.0421006	-0.999113	0		0.	0.	0	0	0
SR3 HR	-0.013788	0.999905	0		0.	0.	0	0	0
ITMx HR	1.	0.	-0.000312	down	0.000312	0.0178763	0	1.00	4.00
ITMy HR	$-1.90632 \times 10^{-7}$	1.	-0.000611	down	0.000611	0.0350077	0	2.00	6.00
ETMx HR	-1.	0.	-0.000315	down	0.000315	0.0180482	0	1.00	5.00
ETMy HR	$-5.8468 \times 10^{-9}$	-1.	-0.0000188	down	0.0000188	0.00107716	0	0	4.00

**yaw table**

The convention for the yaw angle is to give a value relative to the nearest  $\text{Pi}/2$  direction. So the yaw angles are always  $\leq 45$  deg. In addition the sign is set to positive and a “left” or “right” direction is noted. The direction is stated for an ‘upright’ person (i.e. a person with their head up and feet down) looking along the nearest  $\text{Pi}/2$  cardinal direction (i.e. +X, +Y, -X or -Y direction). A “left direction means that the outward facing normal vector to the surface is then to the left of this observer.

(Debug) In[2905]:=

```

tableHead = {"U1", "V1", "W1", "Yaw", "(rad)", "(deg)", "(deg)", "(min)", "(sec)"};
Print[TableForm[Partition[Flatten[N[Transpose[{opticOrientL1L, opticYawDirectionL1, opticYawRadianL1, opticYawDegreeL1, opticYawDMSL1}], 3]],
9], TableHeadings -> {opticLabelL1, tableHead}]]

```

	U1	V1	W1	Yaw	(rad)	(deg)	(deg)	(min)	(sec)
PRM HR	0.999983	0.00587608	0.000265109	left	0.00587612	0.336677	0	20.0	12.0
PR2 HR	-0.999968	0.00801652	0	right	0.0080166	0.459318	0	27.0	34.0
PR3 HR	0.999938	-0.0111511	0	right	0.0111513	0.638925	0	38.0	20.0
BS HR	-0.706784	0.707429	-0.000211723	left	0.784942	44.9739	44.0	58.0	26.0
BS ARc	0.705919	-0.708292	0.00021252	left	0.78372	44.9039	44.0	54.0	14.0
SRM HR	-0.0570633	0.998371	-0.0000115106	left	0.0570943	3.27126	3.00	16.0	17.0
SR2 HR	0.0421006	-0.999113	0	left	0.042113	2.4129	2.00	24.0	46.0
SR3 HR	-0.013788	0.999905	0	left	0.0137884	0.790019	0	47.0	24.0
ITMx HR	1.	0.	-0.000312	right	0.	0.	0	0	0
ITMy HR	$-1.90632 \times 10^{-7}$	1.	-0.000611	left	$1.90632 \times 10^{-7}$	0.0000109224	0	0	0
ETMx HR	-1.	0.	-0.000315	left	0.	0.	0	0	0
ETMy HR	$-5.8468 \times 10^{-9}$	-1.	-0.0000188	right	$5.8468 \times 10^{-9}$	$3.34997 \times 10^{-7}$	0	0	0



## 2

## Theodolite/Autocolimator Alignment

### 2.1. Initialization

L1

(Debug) In[2907]:=

```
nAlignOpticsL1 = 2 * nOpticsL1;
theoYawL1 = Table[0, {nAlignOpticsL1}];
theoPitchL1 = theoYawL1;
theoDistanceL1 = theoYawL1;
theoOrientL1 = Table[0, {nAlignOpticsL1}, {3}];
theoPosL1 = theoOrientL1;
iIAMOptSql1 = Table[1, {nAlignOpticsL1}];
iIAMOptSqlRefL1 = iIAMOptSql1;
iIAMtheoL1 = iIAMOptSql1;
iIAMtheoRefL1 = iIAMOptSql1;
LTHRL1 = Table["", {nAlignOpticsL1}];
LTHPL1 = LTHRL1;
```

(Debug) In[2919]:=

```

formatLLOAlignTable[i1_, ih_] :=
Grid[
  Flatten[
    {{{"Alignment", SpanFromLeft, SpanFromLeft, SpanFromLeft, "Transit Square", SpanFromLeft, SpanFromLeft, SpanFromLeft,
      SpanFromLeft, SpanFromLeft, "Total Station", SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft,
      SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft,
      SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, "PLX", SpanFromLeft}, \
    {"Name", "Local Coordinates\n(mm)", SpanFromLeft, SpanFromLeft, "Over Monument\n(mm)", SpanFromLeft, SpanFromLeft,
      "Sights Monument\n(mm)", SpanFromLeft, SpanFromLeft, "Over Monument\n(mm)", SpanFromLeft, SpanFromLeft, SpanFromLeft,
      "Sights Monument\n(mm)", SpanFromLeft, SpanFromLeft, "Distance\n(mm)", "Yaw", SpanFromLeft, SpanFromLeft, "Pitch",
      SpanFromLeft, SpanFromLeft, "LTHR", "LTHP"}, {SpanFromAbove, "X1", "Y1", "Z1", "Name", "X1", "Y1", "Name", "X1", "Y1",
      "Name", "X1", "Y1", "Z1", "Name", "X1", "Y1", SpanFromAbove, "deg", "min", "sec", "deg", "min", "sec", SpanFromAbove, SpanFromAbove}}, \
    Table[{alignLabelL1[[i]], NumberForm[alignOpticPosL1L[[i, 1]], {10, 1}], NumberForm[alignOpticPosL1L[[i, 2]], {10, 1}],
      NumberForm[alignOpticPosL1L[[i, 3]], {10, 1}], \
      If[iIAMOptSql1[[i]] != "NA", IAMllo[[iIAMOptSql1[[i]], 1]], "NA"],
      If[iIAMOptSql1[[i]] != "NA", NumberForm[IAMllo[[iIAMOptSql1[[i]], 2]], {10, 1}], "",
      If[iIAMOptSql1[[i]] != "NA", NumberForm[IAMllo[[iIAMOptSql1[[i]], 3]], {10, 1}], "", \
      If[iIAMOptSqRefL1[[i]] != "NA", IAMllo[[iIAMOptSqRefL1[[i]], 1]], "NA"],
      If[iIAMOptSqRefL1[[i]] != "NA", NumberForm[IAMllo[[iIAMOptSqRefL1[[i]], 2]], {10, 1}], "",
      If[iIAMOptSqRefL1[[i]] != "NA", NumberForm[IAMllo[[iIAMOptSqRefL1[[i]], 3]], {10, 1}], "", \
      If[iIAMtheoL1[[i]] != "NA", IAMllo[[iIAMtheoL1[[i]], 1]], "NA"],
      If[iIAMtheoL1[[i]] != "NA", NumberForm[IAMllo[[iIAMtheoL1[[i]], 2]], {10, 1}], "",
      If[iIAMtheoL1[[i]] != "NA", NumberForm[IAMllo[[iIAMtheoL1[[i]], 3]], {10, 1}], "",
      If[iIAMtheoL1[[i]] != "NA", NumberForm[theoPosL1[[i, 3]], {10, 1}], "", \
      If[iIAMtheoRefL1[[i]] != "NA", IAMllo[[iIAMtheoRefL1[[i]], 1]], "NA"],
      If[iIAMtheoRefL1[[i]] != "NA", NumberForm[IAMllo[[iIAMtheoRefL1[[i]], 2]], {10, 1}], "",
      If[iIAMtheoRefL1[[i]] != "NA", NumberForm[IAMllo[[iIAMtheoRefL1[[i]], 3]], {10, 1}], "", \
      NumberForm[theoDistanceL1[[i]], {10, 1}], NumberForm[DMS[theoYawL1[[i]] Pi / 180][[1]], {10, 0}],
      NumberForm[DMS[theoYawL1[[i]] Pi / 180][[2]], {10, 0}], NumberForm[DMS[theoYawL1[[i]] Pi / 180][[3]], {10, 0}],
      NumberForm[DMS[theoPitchL1[[i]] Pi / 180][[1]], {10, 0}], NumberForm[DMS[theoPitchL1[[i]] Pi / 180][[2]], {10, 0}],
      NumberForm[DMS[theoPitchL1[[i]] Pi / 180][[3]], {10, 0}], \
      LTHRL1[[i]], LTHPL1[[i]], {i, i1, ih}}, 1, Frame → All];

```

**H1**

(Debug) In[2920]:=

```
nAlignOpticsH1 = 2 * nOpticsH1;
theoYawH1 = Table[0, {nAlignOpticsH1}];
theoPitchH1 = theoYawH1;
theoDistanceH1 = theoYawH1;
theoOrientH1 = Table[0, {nAlignOpticsH1}, {3}];
theoPosH1 = theoOrientH1;
iIAMOptSqH1 = Table[1, {nAlignOpticsH1}];
iIAMOptSqRefH1 = iIAMOptSqH1;
iIAMtheoH1 = iIAMOptSqH1;
iIAMtheoRefH1 = iIAMOptSqH1;
LTHR1 = Table["", {nAlignOpticsH1}];
LTHPH1 = LTHR1;
```



(Debug) In[2932]:=

```

formatLHOAlignTable[i1_, ih_] :=
  Grid[
    Flatten[
      {{"Alignment", SpanFromLeft, SpanFromLeft, SpanFromLeft, "Transit Square", SpanFromLeft, SpanFromLeft, SpanFromLeft,
        SpanFromLeft, SpanFromLeft, "Total Station", SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft,
        SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, SpanFromLeft, "PLX", SpanFromLeft}, \
      {"Name", "Local Coordinates\n(mm)", SpanFromLeft, SpanFromLeft, "Over Monument\n(mm)", SpanFromLeft, SpanFromLeft,
        "Sights Monument\n(mm)", SpanFromLeft, SpanFromLeft, "Over Monument\n(mm)", SpanFromLeft, SpanFromLeft, SpanFromLeft,
        "Sights Monument\n(mm)", SpanFromLeft, SpanFromLeft, "Distance\n(mm)", "Yaw", SpanFromLeft, SpanFromLeft, "Pitch",
        SpanFromLeft, SpanFromLeft, "LTHR", "LTHP"}, {SpanFromAbove, "X1", "Y1", "Z1", "Name", "X1", "Y1", "Name", "X1", "Y1",
        "Name", "X1", "Y1", "Z1", "Name", "X1", "Y1", SpanFromAbove, "deg", "min", "sec", "deg", "min", "sec", SpanFromAbove, SpanFromAbove}}, \
      Table[{alignLabelH1[[i]], NumberForm[alignOpticPosH1L[[i, 1]], {10, 1}], NumberForm[alignOpticPosH1L[[i, 2]], {10, 1}],
        NumberForm[alignOpticPosH1L[[i, 3]], {10, 1}], \
        If[iIAMOptSqH1[[i]] != "NA", IAMlho[[iIAMOptSqH1[[i]], 1]], "NA"],
        If[iIAMOptSqH1[[i]] != "NA", NumberForm[IAMlho[[iIAMOptSqH1[[i]], 2]], {10, 1}], ""],
        If[iIAMOptSqH1[[i]] != "NA", NumberForm[IAMlho[[iIAMOptSqH1[[i]], 3]], {10, 1}], ""], \
        If[iIAMOptSqRefH1[[i]] != "NA", IAMlho[[iIAMOptSqRefH1[[i]], 1]], "NA"],
        If[iIAMOptSqRefH1[[i]] != "NA", NumberForm[IAMlho[[iIAMOptSqRefH1[[i]], 2]], {10, 1}], ""],
        If[iIAMOptSqRefH1[[i]] != "NA", NumberForm[IAMlho[[iIAMOptSqRefH1[[i]], 3]], {10, 1}], ""], \
        If[iIAMtheoH1[[i]] != "NA", IAMlho[[iIAMtheoH1[[i]], 1]], "NA"],
        If[iIAMtheoH1[[i]] != "NA", NumberForm[IAMlho[[iIAMtheoH1[[i]], 2]], {10, 1}], ""],
        If[iIAMtheoH1[[i]] != "NA", NumberForm[IAMlho[[iIAMtheoH1[[i]], 3]], {10, 1}], ""],
        If[iIAMtheoH1[[i]] != "NA", NumberForm[theoPosH1[[i, 3]], {10, 1}], ""], \
        If[iIAMtheoRefH1[[i]] != "NA", IAMlho[[iIAMtheoRefH1[[i]], 1]], "NA"],
        If[iIAMtheoRefH1[[i]] != "NA", NumberForm[IAMlho[[iIAMtheoRefH1[[i]], 2]], {10, 1}], ""],
        If[iIAMtheoRefH1[[i]] != "NA", NumberForm[IAMlho[[iIAMtheoRefH1[[i]], 3]], {10, 1}], ""], \
        NumberForm[theoDistanceH1[[i]], {10, 1}], NumberForm[DMS[theoYawH1[[i]] Pi / 180][[1]], {10, 0}],
        NumberForm[DMS[theoYawH1[[i]] Pi / 180][[2]], {10, 0}], NumberForm[DMS[theoYawH1[[i]] Pi / 180][[3]], {10, 0}],
        NumberForm[DMS[theoPitchH1[[i]] Pi / 180][[1]], {10, 0}], NumberForm[DMS[theoPitchH1[[i]] Pi / 180][[2]], {10, 0}],
        NumberForm[DMS[theoPitchH1[[i]] Pi / 180][[3]], {10, 0}], \
        LTHRH1[[i]], LTHPH1[[i]], {i, i1, ih}}, 1, Frame -> All];

```

## 2.2. H1

### 2.2.1. Alignment Solution List

Each alignment solution is given as a single row in a table associated with an optic. Some optics require more than one alignment solution. For example, one solution for angular alignment and one for positional alignment. In order to accomplish this the optics list is augmented with additional entries. Not an elegant approach, but workable. Start by alternately listing  $\{x,y,z\}$  and  $\{\theta,\psi\}$  solutions, then tweak as needed.

```
(Debug) In[2933]:=
alignLabelH1 = Table[0, {2 * nOpticsH1}];
alignOpticPosH1L = Table[0, {2 * nOpticsH1}, {3}];
alignOpticOrientH1L = alignOpticPosH1L;
Do[
  j = Floor[(i + 1) / 2];
  alignLabelH1[[i]] = StringJoin[opticLabelH1[[j]], If[EvenQ[i], "  $\theta, \psi$ ", " x,y,z"]];
  alignOpticPosH1L[[i]] = opticPosH1L[[j]];
  alignOpticOrientH1L[[i]] = opticOrientH1L[[j]];
  , {i, 1, 2 * nOpticsH1}]
```

The BS has 4 cartridge alignment solutions and 3 chamber alignment solutions. Only one of the “BS HR  $\theta, \psi$ ” or “BS AR  $\theta, \psi$ ” solutions is needed; Both are listed just in case one return is weak.

```
(Debug) In[2937]:=
alignLabelH1[[7]] = "TS BS&AREllpBaf x,y,z";
alignLabelH1[[8]] = "TS BS HR  $\theta, \psi$ ";
alignLabelH1[[9]] = "TS BS AR  $\theta, \psi$ ";
alignLabelH1[[10]] = "TS BS HRelpBaf x,y,z";
alignOpticPosH1L[[7]] = opticPosH1L[[5]];
alignOpticPosH1L[[8]] = opticPosH1L[[4]];
alignOpticPosH1L[[9]] = opticPosH1L[[5]];
alignOpticPosH1L[[10]] = opticPosH1L[[4]];
alignOpticOrientH1L[[7]] = opticOrientH1L[[5]];
alignOpticOrientH1L[[8]] = opticOrientH1L[[4]];
alignOpticOrientH1L[[9]] = opticOrientH1L[[5]];
alignOpticOrientH1L[[10]] = opticOrientH1L[[4]];
```

Rotate the BS optic coordinates 90 deg to reflect the fact that TS#2 is rotated relative to WBSC2

```
(Debug) In[2949]:=
Do[alignOpticPosH1L[[i]] = RotationMatrix3D[Pi / 2, 0, 0].alignOpticPosH1L[[i]];
  alignOpticOrientH1L[[i]] = RotationMatrix3D[Pi / 2, 0, 0].alignOpticOrientH1L[[i]], {i, 7, 10}]
```

The BS has 3 chamber alignment solutions.

```
(Debug) In[2950]:=
alignLabelH1 = Insert[alignLabelH1, "BS HR&ITMellpBafs x,y,z", 11];
alignLabelH1 = Insert[alignLabelH1, "BS HR  $\theta, \psi$ ", 12];
alignLabelH1 = Insert[alignLabelH1, "BS AR  $\theta, \psi$ ", 13];
```

```
(Debug) In[2953]:=
alignOpticPosH1L = Join[Take[alignOpticPosH1L, 10], {opticPosH1L[[4]]}, {opticPosH1L[[4]]}, {opticPosH1L[[5]]},
  Take[alignOpticPosH1L, {11, 2 * nOpticsH1}]];
alignOpticOrientH1L = Join[Take[alignOpticOrientH1L, 10], {alignOpticOrientH1L[[4]]}, {alignOpticOrientH1L[[4]]},
  {alignOpticOrientH1L[[5]]}, Take[alignOpticOrientH1L, {11, 2 * nOpticsH1}]];
```

(Debug) In[2955]:=

```
tableHead = {"x1", "y1", "z1", "u1", "v1", "w1"};
```

```
Print[TableForm[Partition[Flatten[Transpose[{alignOpticPosH1L, alignOpticOrientH1L}]], 6], TableHeadings -> {alignLabelH1, tableHead}]]
```

	x1	y1	z1	u1	v1	w1
PRM HR x,y,z	-20 207.8	-627.299	-81.5893	0.999983	0.00587231	-0.0000225034
PRM HR $\theta,\psi$	-20 207.8	-627.299	-81.5893	0.999983	0.00587231	-0.0000225034
PR2 HR x,y,z	-3589.15	-529.999	-81.9832	-0.999968	0.00805461	0
PR2 HR $\theta,\psi$	-3589.15	-529.999	-81.9832	-0.999968	0.00805461	0
PR3 HR x,y,z	-19 741.1	-174.399	-82.3728	0.999937	-0.011231	0
PR3 HR $\theta,\psi$	-19 741.1	-174.399	-82.3728	0.999937	-0.011231	0
TS BS&AREllpBaf x,y,z	-226.199	160.351	-82.8035	-0.7084	-0.705811	-0.000446086
TS BS HR $\theta,\psi$	-183.899	202.651	-82.7768	0.707463	0.70675	0.000446656
TS BS AR $\theta,\psi$	-226.199	160.351	-82.8035	-0.7084	-0.705811	-0.000446086
TS BS HRelpBaf x,y,z	-183.899	202.651	-82.7768	0.707463	0.70675	0.000446656
BS HR&ITMellpBafs x,y,z	-202.651	-183.899	-82.7768	-0.999968	0.00805461	0
BS HR $\theta,\psi$	-202.651	-183.899	-82.7768	-0.999968	0.00805461	0
BS AR $\theta,\psi$	-160.351	-226.199	-82.8035	0.999937	-0.011231	0
SRM HR x,y,z	305.33	-19 908.6	-113.638	-0.0571409	0.998366	0.00064424
SRM HR $\theta,\psi$	305.33	-19 908.6	-113.638	-0.0571409	0.998366	0.00064424
SR2 HR x,y,z	-594.165	-4178.1	-104.084	0.0421119	-0.999113	0
SR2 HR $\theta,\psi$	-594.165	-4178.1	-104.084	0.0421119	-0.999113	0
SR3 HR x,y,z	-174.659	-19 615.9	-94.6367	-0.0137964	0.999905	0
SR3 HR $\theta,\psi$	-174.659	-19 615.9	-94.6367	-0.0137964	0.999905	0
ITMx HR x,y,z	5012.95	-199.999	-83.108	1.	0.	-0.00061949
ITMx HR $\theta,\psi$	5012.95	-199.999	-83.108	1.	0.	-0.00061949
ITMy HR x,y,z	-200.049	4983.1	-79.8139	$7.73322 \times 10^{-9}$	1.	0.0000124832
ITMy HR $\theta,\psi$	-200.049	4983.1	-79.8139	$7.73322 \times 10^{-9}$	1.	0.0000124832
ETMx HR x,y,z	$3.9995 \times 10^6$	-199.999	-48.6506	-1.	0.	$-7.8389 \times 10^{-6}$
ETMx HR $\theta,\psi$	$3.9995 \times 10^6$	-199.999	-48.6506	-1.	0.	$-7.8389 \times 10^{-6}$
ETMy HR x,y,z	-198.463	$3.99947 \times 10^6$	2476.58	$-3.96592 \times 10^{-7}$	-1.	-0.0006392
ETMy HR $\theta,\psi$	-198.463	$3.99947 \times 10^6$	2476.58	$-3.96592 \times 10^{-7}$	-1.	-0.0006392

```
(Debug) In[2957]:=
  nAlignsH1 = Length[alignLabelH1];
  nAlignOpticsH1 = 2 * nOpticsH1;
  theoYawH1 = Table[0, {nAlignsH1}];
  theoPitchH1 = theoYawH1;
  theoDistanceH1 = theoYawH1;
  theoOrientH1 = Table[0, {nAlignsH1}, {3}];
  theoPosH1 = theoOrientH1;
  iIAMOptSqH1 = Table["NA", {nAlignsH1}];
  iIAMOptSqRefH1 = iIAMOptSqH1;
  iIAMtheoH1 = iIAMOptSqH1;
  iIAMtheoRefH1 = iIAMOptSqH1;
  LTHRH1 = Table["", {nAlignsH1}];
  LTHPH1 = LTHRH1;
```

### 2.2.2. PRM Alignment

Angular Alignment ( $\theta, \psi$ )

A direct view perpendicular to the center of PRM is not possible from the region of the spool between HAM3 and BSC2, due to the PR2 suspension blocking the view. Consequently a periscope (PLX LTHP) is used

Derive yaw reference from sight line from "LV26" to "LV25" (parallel to X-axis) with Bruson Optical Square

Derive a reference line to sight/locate new monuments on the "survey pipe bridge table", in the region between HAM3 and BSC2, using "LV20" and "LV22" (parallel to the Y axis) with the Total Station.

Place Theodolite/Total Station over new monument "am 500" which is placed at same X location as "LV20" and "LV22" but along normal vector to PRM, translated by the PLX LTHP

The PLX LTHP is placed in the spool to the -X side of HAM3

#### **calculations**

```
(Debug) In[2970]:=
  ialign = 2;
  alignLabelH1[[ialign]]

(Debug) Out[2971]=
  PRM HR  $\theta, \psi$ 

(Debug) In[2972]:=
  theoOrientH1[[ialign]] = -alignOpticOrientH1L[[ialign]];

(Debug) In[2973]:=
  iIAMOptSqH1[[ialign]] = 52;
  IAMlho[[iIAMOptSqH1[[ialign]]]]

(Debug) Out[2974]=
  {LV26, -2133.6, -3050.7}
```

```
(Debug) In[2975]=
```

```
  iIAMOptSqRefH1[[ialign]] = 51;
  IAMlho[[iIAMOptSqRefH1[[ialign]]]]
```

```
(Debug) Out[2976]=
```

```
{LV25, -22 692., -3050.7}
```

Approximate position of the LTHP (in the spool to the -X side of the HAM3 chamber, but before the MC Baffle):

```
(Debug) In[2977]=
```

```
  LTHPH1[[ialign]] = "Y";
  LTHPorient = Append[LTHPLength RotationMatrix[Pi / 2].alignOpticOrientH1L[[ialign, 1 ;; 2]], 0];
  LTHPPosInX = -5550;
  s = (LTHPPosInX - alignOpticPosH1L[[ialign, 1]]) / alignOpticOrientH1L[[ialign, 1]];
  LTHPPosIn = alignOpticPosH1L[[ialign]] + s alignOpticOrientH1L[[ialign]];
  LTHPPosOut = LTHPPosIn + LTHPorient;
```

```
(Debug) In[2983]=
```

```
  d = (IAMPosLlho[[iIAMOptSqH1[[ialign]], 1]] - alignOpticPosH1L[[ialign, 1]] - LTHPorient[[1]]) / alignOpticOrientH1L[[ialign, 1]];
  theoPosH1[[ialign]] = alignOpticPosH1L[[ialign]] + d alignOpticOrientH1L[[ialign]] + LTHPorient;
  d1 = alignOpticPosH1L[[ialign]] - LTHPPosIn;
  d2 = LTHPorient;
  d3 = LTHPPosIn + LTHPorient - theoPosH1[[ialign]];
  theoDistanceH1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3];
```

```
(Debug) In[2989]=
```

```
  IAMlho = Append[IAMlho, Flatten[{"LHO AM 500", theoPosH1[[ialign, 1 ;; 2]]}]];
  iIAMtheoH1[[ialign]] = Length[IAMlho];
  Flatten[{"LHO AM 500", theoPosH1[[ialign, 1 ;; 2]]}]
```

```
(Debug) Out[2991]=
```

```
{LHO AM 500, -2133.6, -121.103}
```

```
(Debug) In[2992]=
```

```
  iIAMtheoRefH1[[ialign]] = 48;
  IAMlho[[iIAMtheoRefH1[[ialign]]]]
```

```
(Debug) Out[2993]=
```

```
{LV22, -2133.6, -22 692.}
```

```
(Debug) In[2994]=
```

```
  zeroYawReference = IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]];
  theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

```
(Debug) Out[2995]=
```

```
89.6635
```



(Debug) In[2996]:=

```
theoPitchH1[[ialign]] = ArcTan[theoOrientH1[[ialign, 3]] / theoOrientH1[[ialign, 1]]] 180 / Pi
```

(Debug) Out[2996]=

```
-0.00128937
```

(Debug) In[2997]:=

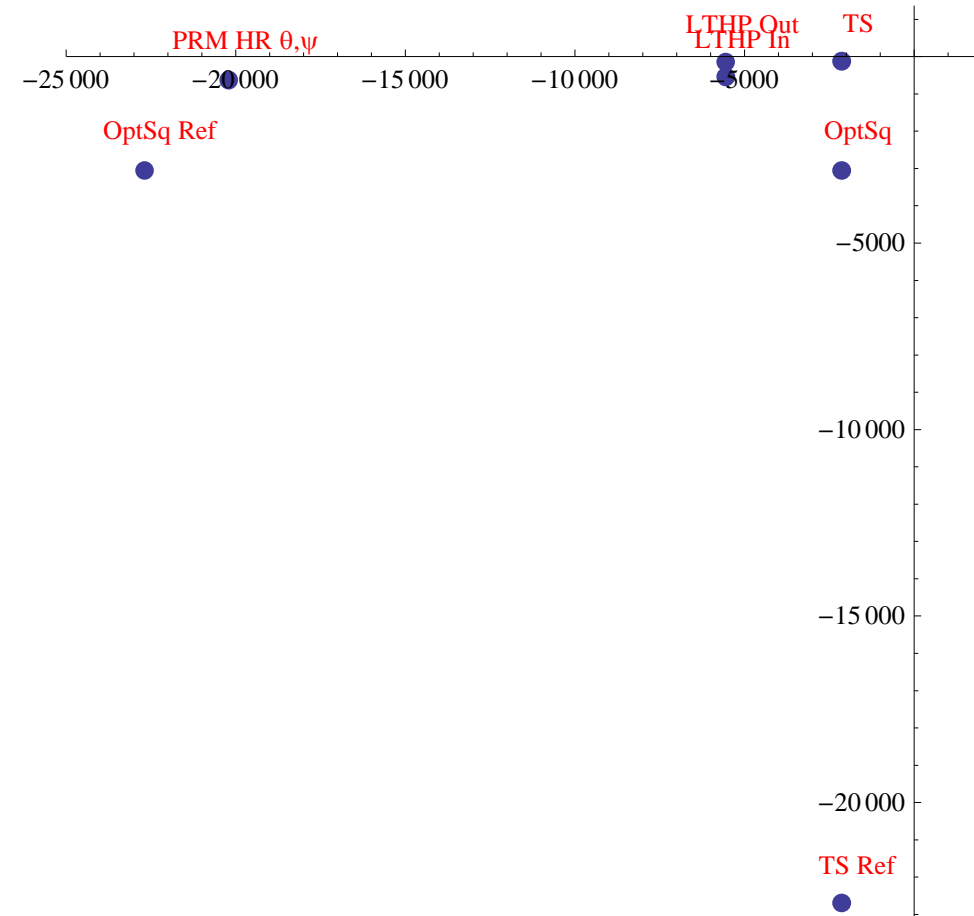
```
data = {alignOpticPosH1L[[ialign, 1 ;; 2]], IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMOptSqRefH1[[ialign]], 2 ;; 3]],
  IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMtheoRefH1[[ialign]], 2 ;; 3]], LTHPPosIn[[1 ;; 2]], LTHPPosOut[[1 ;; 2]]};
dataPlot = ListPlot[data, PlotStyle -> PointSize -> Large];
labels = {alignLabelH1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref", "LTHP In", "LTHP Out"};
PointLabels = Table[Text[labels[[i]], data[[i]] + {500, 1000}], {i, 1, Length[labels]}];
```

### results

(Debug) In[3001]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25000, 2000}, All}]
```

(Debug) Out[3001]=



```
(Debug) In[3002]:=
```

```
formatLHOAlignTable[ialign, ialign]
```

```
(Debug) Out[3002]:=
```

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl	Yl		deg	min	sec	deg	min	sec		
PRM HR 0,ψ	-20207.8	-627.3	-81.6	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 501	-2133.6	-121.1	-82.0	LV22	-2133.6	-22692.0	18476.9	89.	39.	49.	0.	0.	-5.		Y

### Position Alignment (x,y,z)

Set the Total Station/Theodolite at y = 0 for a clear sight to PRM HR center -- add this as monument "LHO AM 501"

### calculations

```
(Debug) In[3003]:=
```

```
ialign = 1;  
alignLabelH1[[ialign]]
```

```
(Debug) Out[3004]:=
```

```
PRM HR x,y,z
```

```
(Debug) In[3005]:=
```

```
iIAMOptSqH1[[ialign]] = 52;  
IAMlho[[iIAMOptSqH1[[ialign]]]]
```

```
(Debug) Out[3006]:=
```

```
{LV26, -2133.6, -3050.7}
```

```
(Debug) In[3007]:=
```

```
iIAMOptSqRefH1[[ialign]] = 51;  
IAMlho[[iIAMOptSqRefH1[[ialign]]]]
```

```
(Debug) Out[3008]:=
```

```
{LV25, -22692., -3050.7}
```

```
(Debug) In[3009]:=
```

```
theoPosH1[[ialign]] = {IAMlho[[iIAMOptSqH1[[ialign]]], 2], 0, alignOpticPosH1L[[ialign, 3]]};  
IAMlho = Append[IAMlho, Flatten[{"LHO AM 501", theoPosH1[[ialign, 1 ;; 2]]}]];  
iIAMtheoH1[[ialign]] = Length[IAMlho];  
Flatten[{"LHO AM 501", theoPosH1[[ialign, 1 ;; 2]]}]
```

```
(Debug) Out[3012]:=
```

```
{LHO AM 501, -2133.6, 0}
```

```

(Debug) In[3013]:=
  d = alignOpticPosH1L[[ialign]] - theoPosH1[[ialign]];
  theoDistanceH1[[ialign]] = Sqrt[d.d];
  theoOrientH1[[ialign]] = d / theoDistanceH1[[ialign]]

(Debug) Out[3015]=
  {-0.999398, -0.0346861, 0.}

(Debug) In[3016]:=
  iIAMtheoRefH1[[ialign]] = 48;
  IAMlho[[iIAMtheoRefH1[[ialign]]]]

(Debug) Out[3017]=
  {LV22, -2133.6, -22692.}

(Debug) In[3018]:=
  zeroYawReference = IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]];
  theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[3019]=
  88.0122

(Debug) In[3020]:=
  theoPitchH1[[ialign]] = ArcTan[theoOrientH1[[ialign, 3]] / theoOrientH1[[ialign, 1]]] 180 / Pi

(Debug) Out[3020]=
  0.

(Debug) In[3021]:=
  data = {alignOpticPosH1L[[ialign, 1 ;; 2]], IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMOptSqRefH1[[ialign]], 2 ;; 3]],
    IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMtheoRefH1[[ialign]], 2 ;; 3]]};
  dataPlot = ListPlot[data, PlotStyle -> PointSize -> Large, PlotRange -> All];
  labels = {alignLabelH1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref"};
  PointLabels = Table[Text[labels[[i]], data[[i]], {i, 1, Length[labels]}];

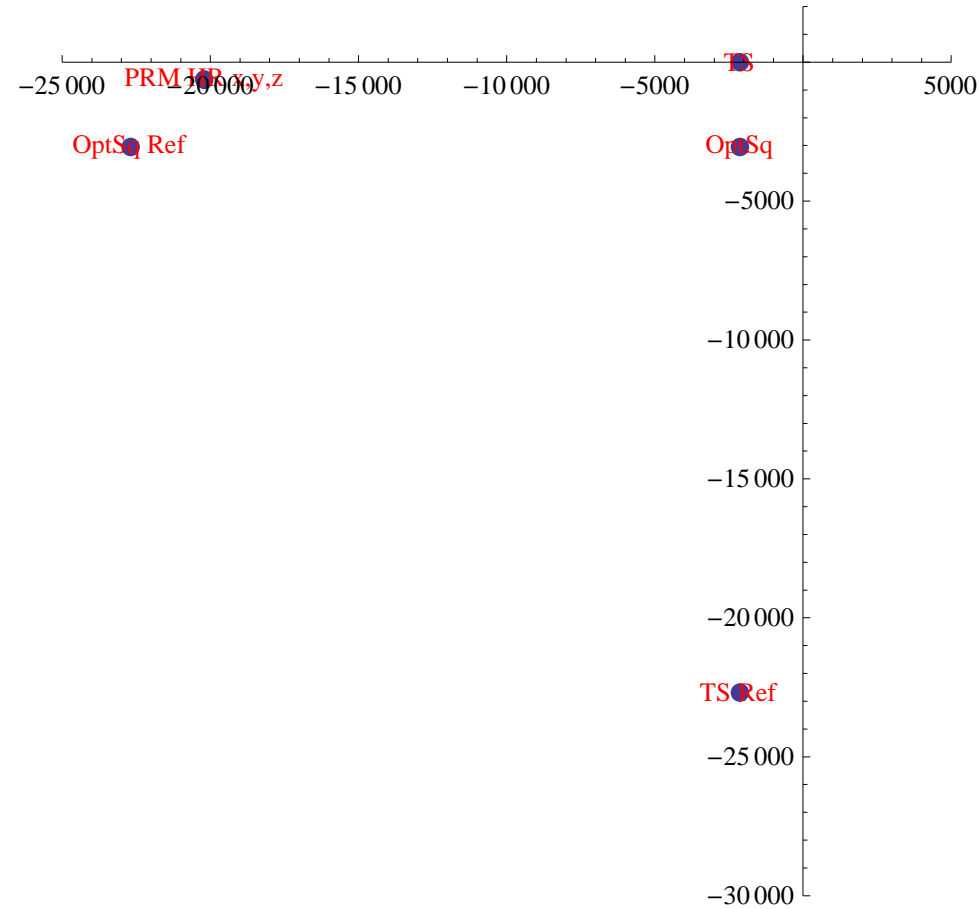
```

**results**

(Debug) In[3025]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, {-30 000, 2000}}]
```

(Debug) Out[3025]=



(Debug) In[3026]:=

```
formatLHOAlignTable[ialign, ialign]
```

(Debug) Out[3026]=

Alignment				Transit Square						Total Station						PLX									
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)		Distance (mm)	Yaw			Pitch			LTHR	LTHP	
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl		Yl	deg	min	sec	deg	min			sec
PRM HR x,y,z	-20207.8	-627.3	-81.6	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 501	-2133.6	0.0	-81.6	LV22	-2133.6	-22692.0	18085.0	88.	0.	44.	0.	0.	0.		

**2.2.3. PR2 Alignment**

**Angular Alignment ( $\theta, \psi$ )**

A direct view perpendicular to the center of PR2, from the region of the spool between HAM3 and BSC2, is possible with the use of an extended retro-reflector (PLX LTHR)

Derive yaw reference from sight line from "LV26" to "LV25" (parallel to X-axis) with Bruson Optical Square

Place Theodolite/Total Station over new monument "LHO AM 502" which is placed at same X location as "LV26" but along normal vector to PR2, translated by the PLX LTHR

The PLX LTHR is placed in the spool to the -X side of HAM3

**calculations**

```

(Debug) In[3027]:=
  ialign = 4;
  alignLabelH1[[ialign]]

(Debug) Out[3028]=
  PR2 HR  $\theta, \psi$ 

(Debug) In[3029]:=
  theoOrientH1[[ialign]] = alignOpticOrientH1L[[ialign]];

(Debug) In[3030]:=
  iIAMOptSqH1[[ialign]] = 52;
  IAMlho[[iIAMOptSqH1[[ialign]]]]

(Debug) Out[3031]=
  {LV26, -2133.6, -3050.7}

(Debug) In[3032]:=
  iIAMOptSqRefH1[[ialign]] = 51;
  IAMlho[[iIAMOptSqRefH1[[ialign]]]]

(Debug) Out[3033]=
  {LV25, -22692., -3050.7}

```

Approximate position of the LTHR (in the spool to the -X side of the HAM3 chamber, but before the MC Baffle):

```

(Debug) In[3034]:=
  LTHRH1[[ialign]] = "Y";
  LTHRorient = Append[LTHRlength RotationMatrix[-Pi/2].alignOpticOrientH1L[[ialign, 1 ;; 2]], 0]
  LTHRPosInX = -5550;
  s = (LTHRPosInX - alignOpticPosH1L[[ialign, 1]]) / alignOpticOrientH1L[[ialign, 1]];
  LTHRPosIn = alignOpticPosH1L[[ialign]] + s alignOpticOrientH1L[[ialign]]
  LTHRPosOut = LTHRPosIn + LTHRorient

(Debug) Out[3035]=
  {3.22225, 400.037, 0}

(Debug) Out[3038]=
  {-5550., -514.205, -81.9832}

(Debug) Out[3039]=
  {-5546.78, -114.168, -81.9832}

```

```

(Debug) In[3040]:=
  d = (IAMPosLlho[[iIAMOptSqH1[[ialign]], 1]] - alignOpticPosH1L[[ialign, 1]] - LTHRorient[[1]]) / alignOpticOrientH1L[[ialign, 1]];
  theoPosH1[[ialign]] = alignOpticPosH1L[[ialign]] + d alignOpticOrientH1L[[ialign]] + LTHRorient;
  d1 = alignOpticPosH1L[[ialign]] - LTHRPosIn;
  d2 = LTHRorient;
  d3 = LTHRPosIn + LTHRorient - theoPosH1[[ialign]];
  theoDistanceH1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3];

(Debug) In[3046]:=
  IAMlho = Append[IAMlho, Flatten[{"LHO AM 502", theoPosH1[[ialign, 1 ;; 2]]}]];
  iIAMtheoH1[[ialign]] = Length[IAMlho];
  Flatten[{"LHO AM 502", theoPosH1[[ialign, 1 ;; 2]]}]

(Debug) Out[3048]=
  {LHO AM 502, -2133.6, -141.66}

(Debug) In[3049]:=
  iIAMtheoRefH1[[ialign]] = 48;
  IAMlho[[iIAMtheoRefH1[[ialign]]]]

(Debug) Out[3050]=
  {LV22, -2133.6, -22692.}

(Debug) In[3051]:=
  zeroYawReference = IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]];
  theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[3052]=
  90.4615

(Debug) In[3053]:=
  theoPitchH1[[ialign]] = ArcTan[theoOrientH1[[ialign, 3]] / theoOrientH1[[ialign, 1]]] 180 / Pi

(Debug) Out[3053]=
  0.

(Debug) In[3054]:=
  data = {alignOpticPosH1L[[ialign, 1 ;; 2]], IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMOptSqRefH1[[ialign]], 2 ;; 3]],
    IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMtheoRefH1[[ialign]], 2 ;; 3]], LTHPPosIn[[1 ;; 2]], LTHPPosOut[[1 ;; 2]]};
  dataPlot = ListPlot[data, PlotStyle -> PointSize -> Large];
  labels = {alignLabelH1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref", "LTHP In", "LTHP Out"};
  PointLabels = Table[Text[labels[[i]], data[[i]] + {200, 500}], {i, 1, Length[labels]};

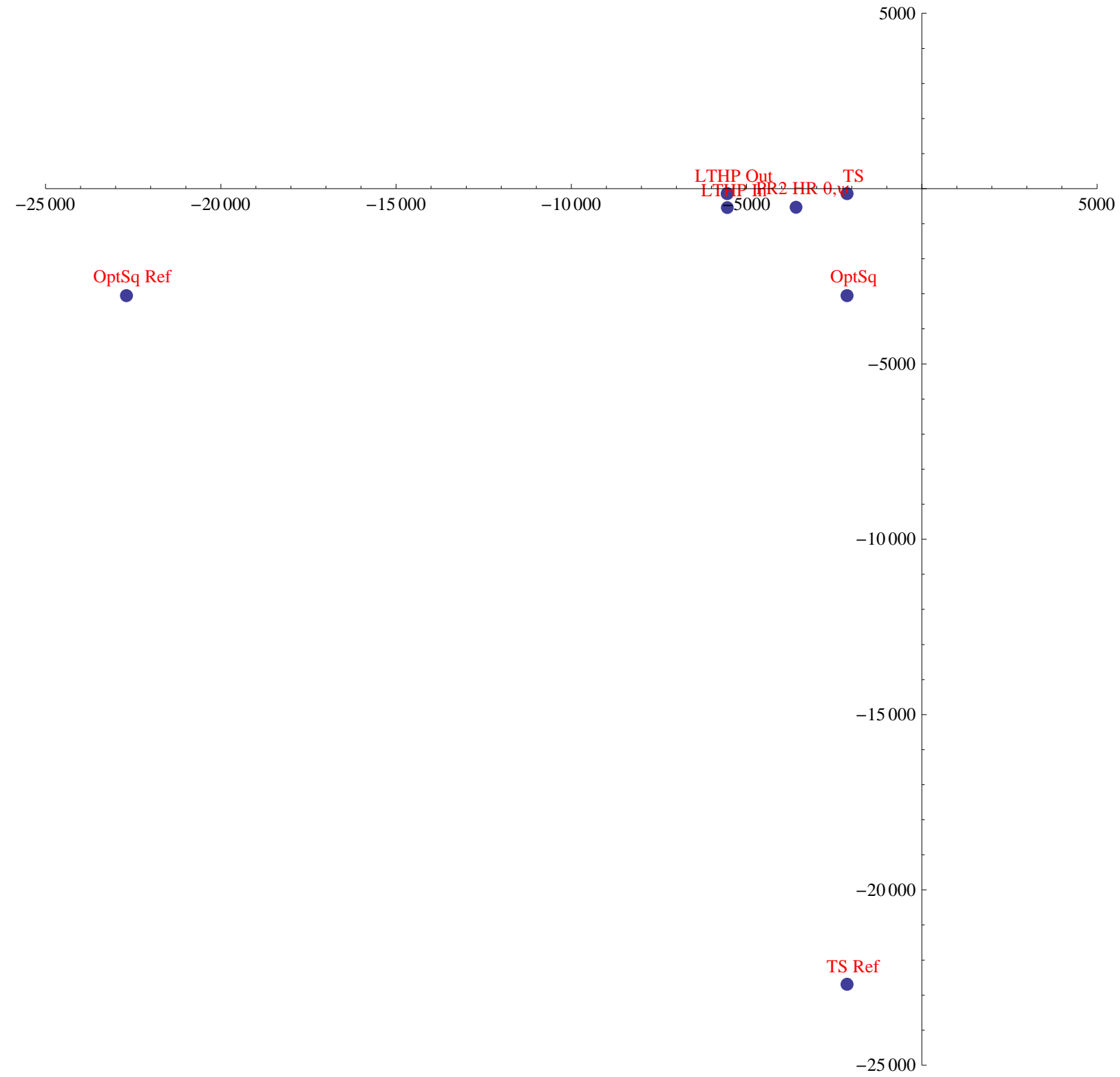
```

**results**

(Debug) In[3058]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, {-25 000, 5000}}]
```

(Debug) Out[3058]=



(Debug) In[3059]=

**formatLHOAlignTable[ialign, ialign]**

(Debug) Out[3059]=

Alignment				Transit Square						Total Station										PLX					
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PR2 HR 0,ψ	-3589.2	-530.0	-82.0	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 502	-2133.6	-141.7	-82.0	LV22	-2133.6	-22692.0	5774.3	90.	27.	41.	0.	0.	0.	Y	

**Position Alignment (x,y,z)**

Set the Total Station/Theodolite at the intersection of the PR2 HR normal vector (projected backwards) and the monument reference line x = -2133.6 mm

**calculations**

(Debug) In[3060]=

```
ialign = 3;
alignLabelH1 [[ialign]]
```

(Debug) Out[3061]=

PR2 HR x,y,z

(Debug) In[3062]=

```
iIAMOptSqH1 [[ialign]] = 52;
IAMlho [[iIAMOptSqH1 [[ialign]]]]
```

(Debug) Out[3063]=

{LV26, -2133.6, -3050.7}

(Debug) In[3064]=

```
iIAMOptSqRefH1 [[ialign]] = 51;
IAMlho [[iIAMOptSqRefH1 [[ialign]]]]
```

(Debug) Out[3065]=

{LV25, -22692., -3050.7}

(Debug) In[3066]=

```
s = (IAMlho [[iIAMOptSqH1 [[ialign]], 2]] - alignOpticPosH1L [[ialign, 1]]) / alignOpticOrientH1L [[ialign, 1]];
theoPosH1 [[ialign]] = alignOpticPosH1L [[ialign]] + s alignOpticOrientH1L [[ialign]]
```

(Debug) Out[3067]=

{-2133.6, -541.723, -81.9832}

(Debug) In[3068]=

```
IAMlho = Append [IAMlho, Flatten [{"LHO AM 503", theoPosH1 [[ialign, 1 ;; 2]]}]];
iIAMtheoH1 [[ialign]] = Length [IAMlho];
Flatten [{"LHO AM 503", theoPosH1 [[ialign, 1 ;; 2]]}]]
```

(Debug) Out[3070]=

{LHO AM 503, -2133.6, -541.723}



```

(Debug) In[3071]:=
  d = alignOpticPosH1L[[ialign]] - theoPosH1[[ialign]];
  theoDistanceH1[[ialign]] = Sqrt[d.d];
  theoOrientH1[[ialign]] = d / theoDistanceH1[[ialign]];

(Debug) In[3074]:=
  iIAMtheoRefH1[[ialign]] = 48;
  IAMlho[[iIAMtheoRefH1[[ialign]]]]

(Debug) Out[3075]=
  {LV22, -2133.6, -22692.}

(Debug) In[3076]:=
  zeroYawReference = IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]];
  theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[3077]=
  90.4615

(Debug) In[3078]:=
  theoPitchH1[[ialign]] = ArcTan[theoOrientH1[[ialign, 3]] / theoOrientH1[[ialign, 1]]] 180 / Pi

(Debug) Out[3078]=
  0.

(Debug) In[3079]:=
  data = {alignOpticPosH1L[[ialign, 1 ;; 2]], IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMOptSqRefH1[[ialign]], 2 ;; 3]],
    IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMtheoRefH1[[ialign]], 2 ;; 3]]};
  dataPlot = ListPlot[data, PlotStyle → PointSize → Large, PlotRange → All];
  labels = {alignLabelH1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref"};
  PointLabels = Table[Text[labels[[i]], data[[i]]], {i, 1, Length[labels]};

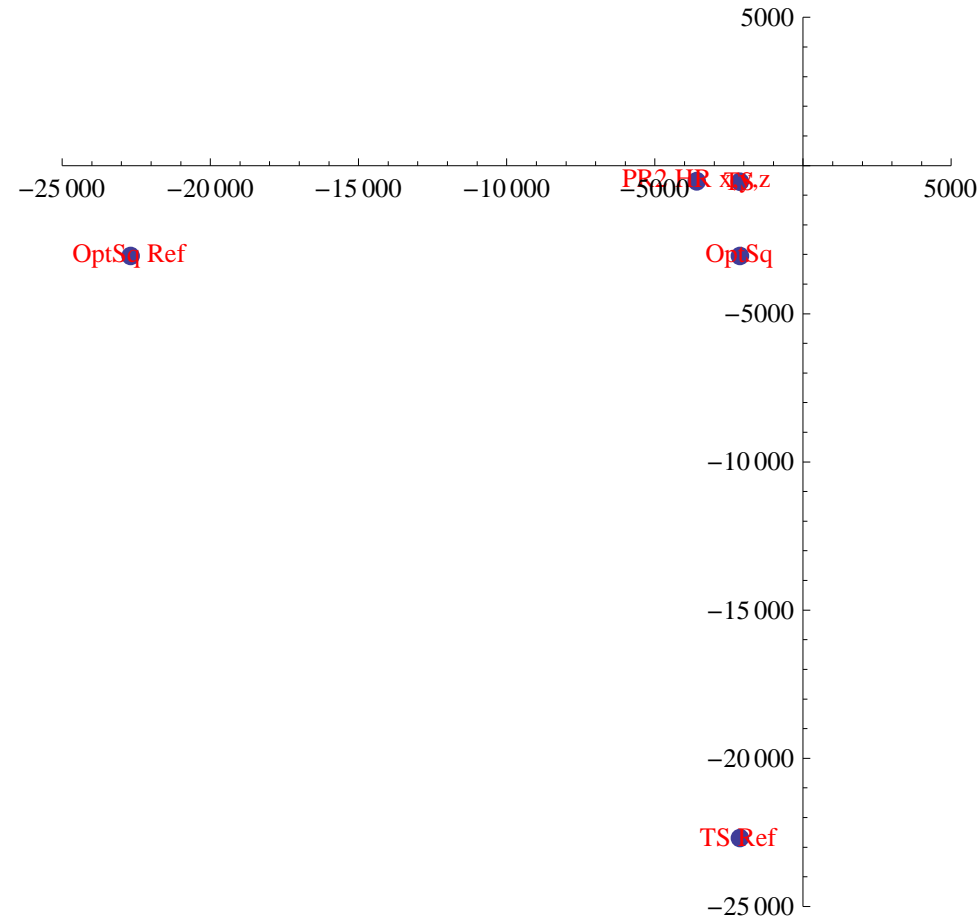
```

**results**

(Debug) In[3083]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, {-25 000, 5000}}]
```

(Debug) Out[3083]=



(Debug) In[3084]:=

```
formatLHOAlignTable[ialign, ialign]
```

(Debug) Out[3084]=

Alignment			Transit Square			Total Station						PLX													
Name	Local Coordinates (mm)			Over Monument (mm)		Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP	
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl		Yl	deg	min	sec	deg	min			sec
PR2 HR x,y,z	-3589.2	-530.0	-82.0	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 503	-2133.6	-541.7	-82.0	LV22	-2133.6	-22692.0	1455.6	90.	27.	41.	0.	0.	0.		

**2.2.4. PR3 Alignment**

**Angular Alignment ( $\theta, \psi$ )**

A direct view perpendicular to the center of PR3 is not possible from the region of the spool between HAM3 and BSC2, due to the PR2 suspension blocking the view. Consequently a periscope (PLX LTHP) is used

Derive yaw reference from sight line from "LV26" to "LV25" (parallel to X-axis) with Bruson Optical Square

Place Theodolite/Total Station over new monument "LHO AM 504" which is placed at same X location as "LV22" but along normal vector to PR3, translated by the PLX LTHP

The PLX LTHP is placed in the spool to the -X side of HAM3

**calculations**

```

(Debug) In[3085]:=
  ialign = 6;
  alignLabelH1 [[ialign]]

(Debug) Out[3086]=
  PR3 HR  $\theta, \psi$ 

(Debug) In[3087]:=
  theoOrientH1 [[ialign]] = -alignOpticOrientH1L [[ialign]];

(Debug) In[3088]:=
  iIAMOptSqH1 [[ialign]] = 52;
  IAMlho [[iIAMOptSqH1 [[ialign]]]]

(Debug) Out[3089]=
  {LV26, -2133.6, -3050.7}

(Debug) In[3090]:=
  iIAMOptSqRefH1 [[ialign]] = 51;
  IAMlho [[iIAMOptSqRefH1 [[ialign]]]]

(Debug) Out[3091]=
  {LV25, -22 692., -3050.7}

```

Approximate position of the LTHP (in the spool to the -X side of the HAM3 chamber, but before the MC Baffle):

```

(Debug) In[3092]:=
  LTHPH1 [[ialign]] = "Y";
  LTHPorient = Append[LTHPlength RotationMatrix[Pi / 2].alignOpticOrientH1L [[ialign, 1 ;; 2]], 0];
  LTHPPosInX = -5550;
  s = (LTHPPosInX - alignOpticPosH1L [[ialign, 1]]) / alignOpticOrientH1L [[ialign, 1]];
  LTHPPosIn = alignOpticPosH1L [[ialign]] + s alignOpticOrientH1L [[ialign]];
  LTHPPosOut = LTHPPosIn + LTHPorient;

(Debug) In[3098]:=
  d = (IAMPosLlho [[iIAMOptSqH1 [[ialign]], 1]] - alignOpticPosH1L [[ialign, 1]] - LTHPorient [[1]]) / alignOpticOrientH1L [[ialign, 1]];
  theoPosH1 [[ialign]] = alignOpticPosH1L [[ialign]] + d alignOpticOrientH1L [[ialign]] + LTHPorient;
  d1 = alignOpticPosH1L [[ialign]] - LTHPPosIn;
  d2 = LTHPorient;
  d3 = LTHPPosIn + LTHPorient - theoPosH1 [[ialign]];
  theoDistanceH1 [[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3];

```

(Debug) In[3104]:=

```

IAMlho = Append[IAMlho, Flatten[{"LHO AM 504", theoPosH1[[ialign, 1 ;; 2]]}]];
iIAMtheoH1[[ialign]] = Length[IAMlho];
Flatten[{"LHO AM 504", theoPosH1[[ialign, 1 ;; 2]]}]

```

(Debug) Out[3106]=

```

{LHO AM 504, -2133.6, 27.9152}

```

(Debug) In[3107]:=

```

iIAMtheoRefH1[[ialign]] = 48;
IAMlho[[iIAMtheoRefH1[[ialign]]]]

```

(Debug) Out[3108]=

```

{LV22, -2133.6, -22692.}

```

(Debug) In[3109]:=

```

zeroYawReference = IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]];
theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

```

(Debug) Out[3110]=

```

90.6435

```

(Debug) In[3111]:=

```

theoPitchH1[[ialign]] = ArcTan[theoOrientH1[[ialign, 3]] / theoOrientH1[[ialign, 1]]] 180 / Pi

```

(Debug) Out[3111]=

```

0.

```

(Debug) In[3112]:=

```

data = {alignOpticPosH1L[[ialign, 1 ;; 2]], IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMOptSqRefH1[[ialign]], 2 ;; 3]],
    IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMtheoRefH1[[ialign]], 2 ;; 3]], LTHPPosIn[[1 ;; 2]], LTHPPosOut[[1 ;; 2]]};
dataPlot = ListPlot[data, PlotStyle -> PointSize -> Large];
labels = {alignLabelH1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref", "LTHP In", "LTHP Out"};
PointLabels = Table[Text[labels[[i]], data[[i]] + {500, 1000}], {i, 1, Length[labels]};

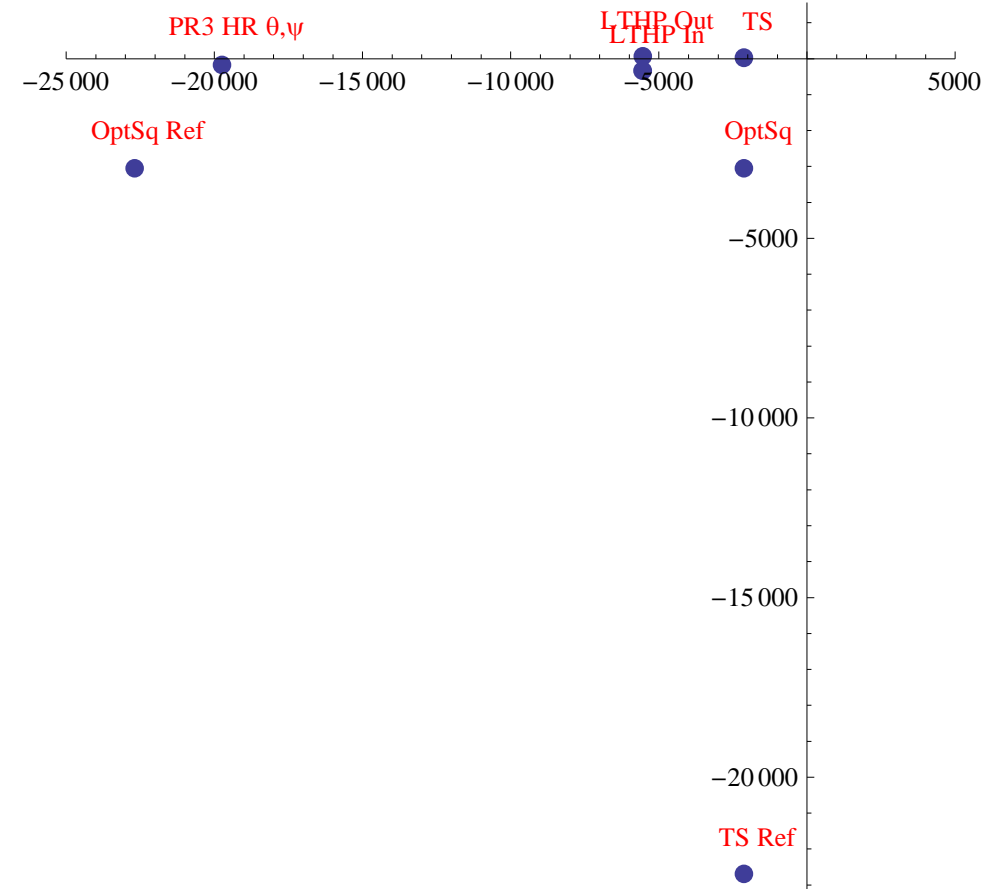
```

**results**

(Debug) In[3116]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, All}]
```

(Debug) Out[3116]=



(Debug) In[3117]:=

```
formatLHOAlignTable[ialign, ialign]
```

(Debug) Out[3117]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PR3 HR 0,ψ	-19741.1	-174.4	-82.4	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 504	-2133.6	27.9	-82.4	LV22	-2133.6	-22692.0	18004.1	90.	38.	37.	0.	0.	0.		Y

**Position Alignment (x,y,z)**

Set the Total Station/Theodolite at y = 0 for a clear sight to PR3 HR center

**calculations**

(Debug) In[3118]:=

```
ialign = 5;
alignLabelH1 [[ialign]]
```

(Debug) Out[3119]=

PR3 HR x,y,z

```

(Debug) In[3120]:=
  iIAMOptSqH1[[ialign]] = 52;
  IAMlho[[iIAMOptSqH1[[ialign]]]]

(Debug) Out[3121]=
  {LV26, -2133.6, -3050.7}

(Debug) In[3122]:=
  iIAMOptSqRefH1[[ialign]] = 51;
  IAMlho[[iIAMOptSqRefH1[[ialign]]]]

(Debug) Out[3123]=
  {LV25, -22692., -3050.7}

(Debug) In[3124]:=
  theoPosH1[[ialign]] = {IAMlho[[iIAMOptSqH1[[ialign]], 2]], 0, alignOpticPosH1L[[ialign, 3]]};
  IAMlho = Append[IAMlho, Flatten[{"LHO AM 505", theoPosH1[[ialign, 1 ;; 2]]}]];
  iIAMtheoH1[[ialign]] = Length[IAMlho];
  Flatten[{"LHO AM 505", theoPosH1[[ialign, 1 ;; 2]]}]

(Debug) Out[3127]=
  {LHO AM 505, -2133.6, 0}

(Debug) In[3128]:=
  d = alignOpticPosH1L[[ialign]] - theoPosH1[[ialign]];
  theoDistanceH1[[ialign]] = Sqrt[d.d]
  theoOrientH1[[ialign]] = d / theoDistanceH1[[ialign]]

(Debug) Out[3129]=
  17608.3

(Debug) Out[3130]=
  {-0.999951, -0.00990434, 0.}

(Debug) In[3131]:=
  iIAMtheoRefH1[[ialign]] = 48;
  IAMlho[[iIAMtheoRefH1[[ialign]]]]

(Debug) Out[3132]=
  {LV22, -2133.6, -22692.}

(Debug) In[3133]:=
  zeroYawReference = IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]];
  theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[3134]=
  89.4325

```

(Debug) In[3135]:=

```
theoPitchH1[[ialign]] = ArcTan[theoOrientH1[[ialign, 3]] / theoOrientH1[[ialign, 1]]] 180 / Pi
```

(Debug) Out[3135]=

0.

(Debug) In[3136]:=

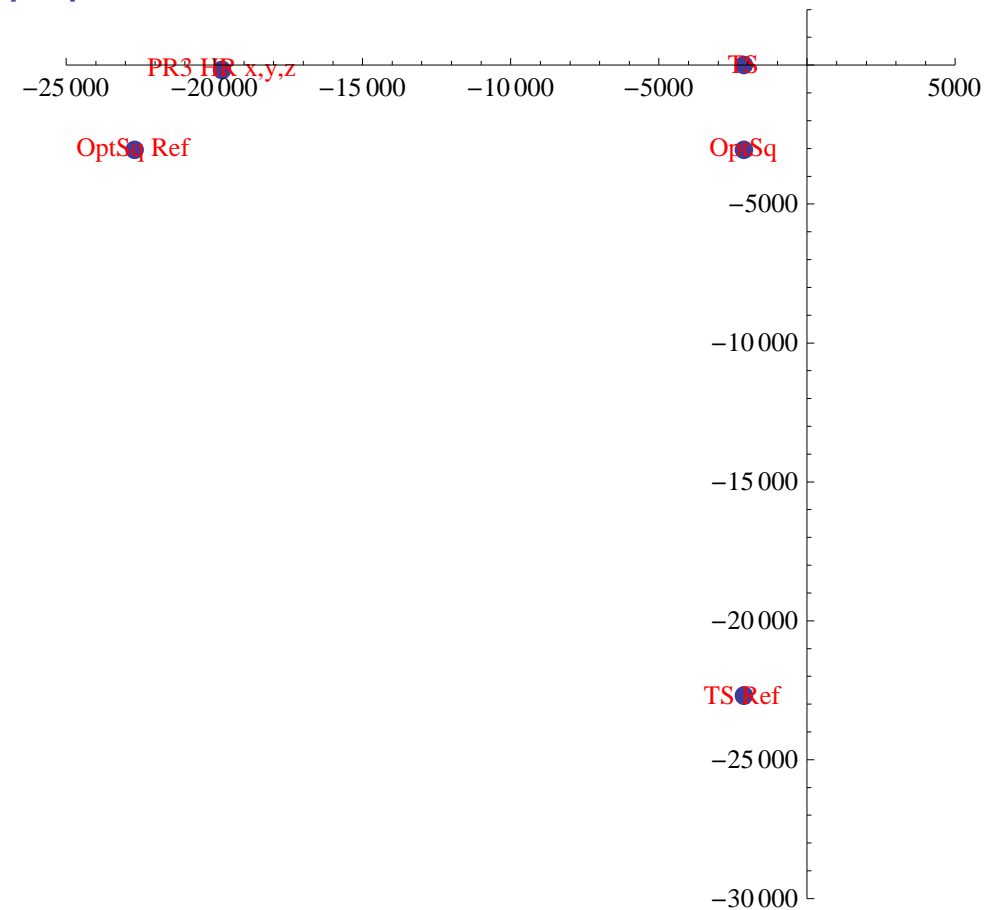
```
data = {alignOpticPosH1L[[ialign, 1 ;; 2]], IAMlho[[iIAMOptSqH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMOptSqRefH1[[ialign]], 2 ;; 3]],
  IAMlho[[iIAMtheoH1[[ialign]], 2 ;; 3]], IAMlho[[iIAMtheoRefH1[[ialign]], 2 ;; 3]]};
dataPlot = ListPlot[data, PlotStyle → PointSize → Large, PlotRange → All];
labels = {alignLabelH1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref"};
PointLabels = Table[Text[labels[[i]], data[[i]], {i, 1, Length[labels]}];
```

**results**

(Debug) In[3140]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio → 1, PlotRange → {{-25 000, 5000}, {-30 000, 2000}}]
```

(Debug) Out[3140]=



(Debug) In[3141]:=

```
formatLHOAlignTable[ialign, ialign]
```

(Debug) Out[3141]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PR3 HR x,y,z	-19741.1	-174.4	-82.4	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 505	-2133.6	0.0	-82.4	LV22	-2133.6	-22692.0	17608.3	89.	25.	57.	0.	0.	0.		

### 2.2.5. PRC Alignment Summary

Table summarizing the alignment solutions for the Power Recycling Cavity (PRC) optics: PRM, PR2 and PR3

(Debug) In[3604]:=

```
formatLHOAlignTable[1, 6]
```

(Debug) Out[3604]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Dis: t: a: n: c: e (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PRM HR x, y, z	-20.2007	-62.7006	-81.6003	LV26	-21.3005	-30.3000	LV25	-22.6009	-30.3000	LHO AM 505	-21.3003	0.0006	-81.6003	LV22	-21.3003	-22.6009	180.8005	88.	0.	44.	0.	0.	0.		
PRM HR θ, ψ	-20.2007	-62.7006	-81.6003	LV26	-21.3005	-30.3000	LV25	-22.6009	-30.3000	LHO AM 505	-21.3003	-12.1001	-82.6000	LV22	-21.3003	-22.6009	184.7006	89.	39.	49.	0.	0.	-5.		Y



PR2	-35\	-53\	-82\	LV26	-21\	-30\	LV25	-22\	-30\	LHO	-21\	-54\	-82\	LV22	-21\	-22\	145\	90.	27.	41.	0.	0.	0.		
HR	8\	0\	.\		3\	5\		6\	5\	AM	3\	1\	.\		3\	6\	5\								
x,	9\	.\	0		3\	0\		9\	0\		3\	.\	0		3\	9\	.\								
y,	.\	0			.\	.\		2\	.\	5\	.\	7			.\	2\	6								
z	2				6	7		.\	7	0\	6				6	.\									
								0		3						0									
PR2	-35\	-53\	-82\	LV26	-21\	-30\	LV25	-22\	-30\	LHO	-21\	-14\	-82\	LV22	-21\	-22\	577\	90.	27.	41.	0.	0.	0.	Y	
HR	8\	0\	.\		3\	5\		6\	5\	AM	3\	1\	.\		3\	6\	4\								
θ,	9\	.\	0		3\	0\		9\	0\		3\	.\	0		3\	9\	.\								
ψ	.\	0			.\	.\		2\	.\	5\	.\	7			.\	2\	3								
	2				6	7		.\	7	0\	6				6	.\									
								0		2						0									
PR3	-19\	-17\	-82\	LV26	-21\	-30\	LV25	-22\	-30\	LHO	-21\	0.0	-82\	LV22	-21\	-22\	176\	89.	25.	57.	0.	0.	0.		
HR	7\	4\	.\		3\	5\		6\	5\	AM	3\		.\		3\	6\	0\								
x,	4\	.\	4		3\	0\		9\	0\		3\		4		3\	9\	8\								
y,	1\	4			.\	.\		2\	.\	5\	.\				.\	2\	.\								
z	.\				6	7		.\	7	0\	6				6	.\	3								
	1							0		5						0									
PR3	-19\	-17\	-82\	LV26	-21\	-30\	LV25	-22\	-30\	LHO	-21\	27.9	-82\	LV22	-21\	-22\	180\	90.	38.	37.	0.	0.	0.		Y
HR	7\	4\	.\		3\	5\		6\	5\	AM	3\		.\		3\	6\	0\								
θ,	4\	.\	4		3\	0\		9\	0\		3\		4		3\	9\	4\								
ψ	1\	4			.\	.\		2\	.\	5\	.\				.\	2\	.\								
	.\				6	7		.\	7	0\	6				6	.\	1								
	1							0		4						0									

## 2.2.6. BS Alignment

### Cartridge

The BS is aligned on the cartridge while on Test Stand #2 at LHO.

The BS to be used for H1 is SN 06 which has a wedge angle of 0.076 deg

### solution 1

(Debug) In[3143]:=

```
ialign = 7;
alignLabelH1 [[ialign]]
```

(Debug) Out[3144]=

```
TS BS&ARellpBaf x,y,z
```

Rotate the BS optic coordinates 90 deg to reflect the fact that TS#2 is rotated relative to WBSC2

```
(Debug) In[3145]:=
```

```
    BSARPos = alignOpticPosH1L[[ialign]]
```

```
(Debug) Out[3145]=
```

```
{-226.199, 160.351, -82.8035}
```

BS wedge angle (deg) used in Zemax. Actual wedge angle for H1 BS-06 is 0.076 deg:

```
(Debug) In[3146]:=
```

```
    wedge = VectorAngle[alignOpticOrientH1L[[ialign]], -alignOpticOrientH1L[[ialign + 1]]] 180 / Pi
```

```
(Debug) Out[3146]=
```

```
0.0759981
```

```
(Debug) In[3147]:=
```

```
    BSHROrient = alignOpticOrientH1L[[ialign + 1]]
```

```
(Debug) Out[3147]=
```

```
{0.707463, 0.70675, 0.000446656}
```

```
(Debug) In[3148]:=
```

```
    BSAROrient = alignOpticOrientH1L[[ialign]]
```

```
(Debug) Out[3148]=
```

```
{-0.7084, -0.705811, -0.000446086}
```

```
(Debug) In[3149]:=
```

```
    iIAMOptSqRefH1[[ialign]] = 16;
```

```
    IAMlhoTS2[[iIAMOptSqRefH1[[ialign]]]]
```

```
(Debug) Out[3150]=
```

```
{TS2-16, 7285., 0.}
```

```
(Debug) In[3151]:=
```

```
    iIAMOptSqH1[[ialign]] = 12;
```

```
    IAMlhoTS2[[iIAMOptSqH1[[ialign]]]]
```

```
(Debug) Out[3152]=
```

```
{TS2-12, -2872., 0.}
```

```
(Debug) In[3153]:=
```

```
    IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2]]
```

```
(Debug) Out[3153]=
```

```
-2872.
```

```
(Debug) In[3154]:=
```

```
    BSARPos[[1]]
```

```
(Debug) Out[3154]=
```

```
-226.199
```

Add a monument (TS2-18) along the TS2-11 to TS2-13 line and normal to the BS AR surface:

(Debug) In[3155]:=

```
d = (IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2]] - BSARPos[[1]]) / BSAROrient[[1]];
IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-18", BSARPos + d BSAROrient}]];
iIAMtheoH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMtheoH1[[ialign]]]]
```

(Debug) Out[3158]=

```
{TS2-18, -2872., -2475.78, -84.4696}
```

(Debug) In[3159]:=

```
theoPosH1[[ialign]] = IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 4]]
```

(Debug) Out[3159]=

```
{-2872., -2475.78, -84.4696}
```

(Debug) In[3160]:=

```
theoOrientH1[[ialign]] = -BSAROrient
```

(Debug) Out[3160]=

```
{0.7084, 0.705811, 0.000446086}
```

Separation from LAC to BS AR surface (mm):

(Debug) In[3161]:=

```
theoDistanceH1[[ialign]] = Sqrt[(theoPosH1[[ialign]] - BSARPos).(theoPosH1[[ialign]] - BSARPos)]
```

(Debug) Out[3161]=

```
3734.9
```

(Debug) In[3162]:=

```
iIAMtheoRefH1[[ialign]] = "NA";
```

(Debug) In[3163]:=

```
IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2 ;; 3]]
IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 3]]
```

(Debug) Out[3163]=

```
{-2872., 0.}
```

(Debug) Out[3164]=

```
{-2872., -2475.78}
```

(Debug) In[3165]:=

```
zeroYawReference = IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 3]];
theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

(Debug) Out[3166]=

```
45.1049
```

(Debug) In[3167]:=

```
theoPitchH1[[ialign]] = Sign[theoOrientH1[[ialign, 3]]] VectorAngle[Join[theoOrientH1[[ialign, 1 ;; 2]], {0}], theoOrientH1[[ialign]]] 180 / Pi
```

(Debug) Out[3167]=

0.0255589

(Debug) In[3168]:=

```
formatLHOAlignTable[ialign, ialign]
```

(Debug) Out[3168]=

Alignment			Transit Square						Total Station									PLX							
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl	Yl		deg	min	sec	deg	min	sec		
TS BS&ARellpBaf x,y,z	-226.2	160.4	-82.8	IAM-10	200.0	11428.0	PSI-2	9219.6	31601.7	PSI-4	-22382.7	2362.2	-84.5	NA			3734.9	45.	6.	17.	0.	1.	32.		

**solution 2**

(Debug) In[3169]:=

```
ialign = 8;
alignLabelH1[[ialign]]
```

(Debug) Out[3170]=

TS BS HR  $\theta, \psi$ 

Required beam separation from HR and AR surfaces so as not to get an erroneous laser autocollimator (LAC) reading is 32 mm. The beam divergence of the Newport LDS-vector LAC is 100 urad. Given a wedge angle of 0.070 deg (minimum wedge angle for any BS) and an index of refraction at 670 nm of  $\sim 1.456$ , the separation from the LAC to the BS AR surface must be at least  $\sim 9$  m :

(Debug) In[3171]:=

```
31 / (1.456 (.070 Pi / 180) 2 - 100 * 10^-6)
```

(Debug) Out[3171]=

8965.55

(Debug) In[3172]:=

```
31.9 / (1.456 (.070 Pi / 180) 2)
```

(Debug) Out[3172]=

8966.52

So place a new TS2-19 monument along the X = 0 line (formed by TS2-10, at the center, and TS2-2):

(Debug) In[3173]:=

```
IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-19", 0, 9250 / Sqrt[2] // N}]];
iIAMOptSqH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMOptSqH1[[ialign]]]]
```

(Debug) Out[3175]=

{TS2-19, 0, 6540.74}

```
(Debug) In[3176]:=
  iIAMOptSqRefH1[[ialign]] = 10;
  IAMlhoTS2[[iIAMOptSqRefH1[[ialign]]]]
```

```
(Debug) Out[3177]=
  {TS2-10, 0., 0.}
```

```
(Debug) In[3178]:=
  alignOpticOrientH1L[[ialign]]
```

```
(Debug) Out[3178]=
  {0.707463, 0.70675, 0.000446656}
```

Add a monument (TS2-20) at the intersection of a line from TS2-19 which is normal to the line through TS2-19 and TS2-10 and a line normal to the BS HR surface, but displaced laterally by the LTHP:

```
(Debug) In[3179]:=
  LTHPH1[[ialign]] = "Y";
  LTHPorient = Append[LTHPlength RotationMatrix[Pi / 2].alignOpticOrientH1L[[ialign, 1 ;; 2]], 0];
  LTHPPosInX = 200;
  s = (LTHPPosInX - alignOpticPosH1L[[ialign, 1]]) / alignOpticOrientH1L[[ialign, 1]];
  LTHPPosIn = alignOpticPosH1L[[ialign]] + s alignOpticOrientH1L[[ialign]];
  LTHPPosOut = LTHPPosIn + LTHPorient;
```

```
(Debug) In[3185]:=
  d = (IAMlhoTS2[[iIAMOptSqH1[[ialign]], 3]] - alignOpticPosH1L[[ialign, 2]] - LTHPorient[[2]]) / alignOpticOrientH1L[[ialign, 2]];
  theoPosH1[[ialign]] = alignOpticPosH1L[[ialign]] + d alignOpticOrientH1L[[ialign]] + LTHPorient;
  d1 = alignOpticPosH1L[[ialign]] - LTHPPosIn;
  d2 = LTHPorient;
  d3 = LTHPPosIn + LTHPorient - theoPosH1[[ialign]];
  theoDistanceH1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3]
```

```
(Debug) Out[3190]=
  8967.52
```

```
(Debug) In[3191]:=
  IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-20", theoPosH1[[ialign]]}]];
  iIAMtheoH1[[ialign]] = Length[IAMlhoTS2];
  IAMlhoTS2[[iIAMtheoH1[[ialign]]]]
```

```
(Debug) Out[3193]=
  {TS2-20, 5594.53, 6540.74, -78.9501}
```

```
(Debug) In[3194]:=
  theoPosH1[[ialign]] = IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 4]]
```

```
(Debug) Out[3194]=
  {5594.53, 6540.74, -78.9501}
```

```
(Debug) In[3195]:=
  theoOrientH1[[ialign]] = -BSHROrient
```

```
(Debug) Out[3195]=
  {-0.707463, -0.70675, -0.000446656}
```

Calculate the angular separation between the beam reflected by the AR surface (after transmission through the HR surface) and the beam reflected from the HR surface:

```
(Debug) In[3196]:=
  separationAngle =
  VectorAngle[Refract[Reflect[Refract[(1 + 10^-13) theoOrientH1[[ialign]], BSHROrient, 1, 1.456], BSARorient], -BSHROrient, 1.456, 1], BSHROrient]
```

```
(Debug) Out[3196]=
  0.00386253
```

approximate calculation of this angle:

```
(Debug) In[3197]:=
  2 × 1.456 (wedge Pi / 180)
```

```
(Debug) Out[3197]=
  0.00386252
```

Calculate the separation of the beam reflected from the BS AR surface, at the location of the Total Station:

```
(Debug) In[3198]:=
  BSthickness = 59.88;
  theoDistanceH1[[ialign]] separationAngle + BSthickness 2 wedge Pi / 180
```

```
(Debug) Out[3199]=
  34.7962
```

```
(Debug) In[3200]:=
  iIAMtheoRefH1[[ialign]] = Length[IAMlhoTS2] - 1;
```

```
(Debug) In[3201]:=
  zeroYawReference = IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 3]];
  theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

```
(Debug) Out[3202]=
  44.9711
```

```
(Debug) In[3203]:=
  theoPitchH1[[ialign]] = Sign[theoOrientH1[[ialign, 3]]] VectorAngle[Join[theoOrientH1[[ialign, 1 ;; 2]], {0}], theoOrientH1[[ialign]]] 180 / Pi
```

```
(Debug) Out[3203]=
  -0.0255915
```

(Debug) In[3204]:=

**formatLHOAlignTable[ialign, ialign]**

(Debug) Out[3204]:=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
TS BS HR 0,ψ	-183.9	202.7	-82.8	PSI-5	-22382.7	0.0	IAM-8	11543.0	9060.0	PSI-6	2362.2	2362.2	-79.0	PSI-5	-22382.7	0.0	8967.5	44.	58.	16.	0.	-1.	-32.		Y

**solution 3**

In case the return beam intensity from the HR surface is too faint, add a monument (TS2-21) (near to monument (TS2-20)) at the intersection of a line at 90 deg from the line between TS2-19 and TS2-20 and a line along the retro-reflection from the BS AR surface through the BS HR surface, but displaced laterally by the LTHP:

(Debug) In[3205]:=

```
ialign = 9;
alignLabelH1[[ialign]]
```

(Debug) Out[3206]:=

TS BS AR 0,ψ

(Debug) In[3207]:=

```
iIAMOptSqRefH1[[ialign]] = 10;
IAMlhoTS2[[iIAMOptSqRefH1[[ialign]]]]
```

(Debug) Out[3208]:=

{TS2-10, 0., 0.}

Reverse the orientation of the AR surface since we are reflecting off the AR surface after transmission through the BS:

(Debug) In[3209]:=

```
theoOrientH1[[ialign]] = -Refract[-alignOpticOrientH1L[[ialign]], -BSHROrient, 1.456, 1]
```

(Debug) Out[3209]:=

{-0.708826, -0.705383, -0.000445826}

Use the optic position for the previous alignment (align-1), i.e. the HR surface:

(Debug) In[3210]:=

```
LTHPH1[[ialign]] = "Y";
LTHPorient = Append[LTHPlength RotationMatrix[Pi / 2].theoOrientH1[[ialign, 1 ;; 2]], 0];
LTHPPosInX = 200;
s = (LTHPPosInX - alignOpticPosH1L[[ialign - 1, 1]]) / theoOrientH1[[ialign, 1]];
LTHPPosIn = alignOpticPosH1L[[ialign - 1]] + s theoOrientH1[[ialign]];
LTHPPosOut = LTHPPosIn + LTHPorient;
```

```

(Debug) In[3216]:=
  d = (IAMlhoTS2[[Length[IAMlhoTS2], 2]] - alignOpticPosH1L[[ialign - 1, 1]] - LTHPorient[[1]]) / theoOrientH1[[ialign, 1]];
  theoPosH1[[ialign]] = alignOpticPosH1L[[ialign - 1]] + d theoOrientH1[[ialign]] + LTHPorient;
  d1 = alignOpticPosH1L[[ialign - 1]] - LTHPPosIn;
  d2 = LTHPorient;
  d3 = LTHPPosIn + LTHPorient - theoPosH1[[ialign]];
  theoDistanceH1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3]

(Debug) Out[3221]=
  8154.06

(Debug) In[3222]:=
  theoDistanceH1[[ialign]] separationAngle + BStickness 2 wedge Pi / 180

(Debug) Out[3222]=
  31.6541

(Debug) In[3223]:=
  IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-21", theoPosH1[[ialign]]}]];
  iIAMtheoH1[[ialign]] = Length[IAMlhoTS2];
  IAMlhoTS2[[iIAMtheoH1[[ialign]]]]

(Debug) Out[3225]=
  {TS2-21, 5594.53, 5388.63, -79.3198}

(Debug) In[3226]:=
  theoPosH1[[ialign]] = IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 4]]

(Debug) Out[3226]=
  {5594.53, 5388.63, -79.3198}

(Debug) In[3227]:=
  IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-22", 0, theoPosH1[[ialign, 2]]}]];
  iIAMtheoRefH1[[ialign]] = Length[IAMlhoTS2];
  IAMlhoTS2[[iIAMtheoRefH1[[ialign]]]]

(Debug) Out[3229]=
  {TS2-22, 0, 5388.63}

(Debug) In[3230]:=
  iIAMOptSqH1[[ialign]] = Length[IAMlhoTS2];
  IAMlhoTS2[[iIAMOptSqH1[[ialign]]]]

(Debug) Out[3231]=
  {TS2-22, 0, 5388.63}

```



```
(Debug) In[3232]:=
  zeroYawReference = IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 3]];
  theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

```
(Debug) Out[3233]=
  44.8605
```

```
(Debug) In[3234]:=
  theoPitchH1[[ialign]] = Sign[theoOrientH1[[ialign, 3]]] VectorAngle[Join[theoOrientH1[[ialign, 1 ;; 2]], {0}], theoOrientH1[[ialign]]] 180 / Pi
```

```
(Debug) Out[3234]=
  -0.025544
```

```
(Debug) In[3235]:=
  formatLHOAlignTable[ialign, ialign]
```

```
(Debug) Out[3235]=
```

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)			Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP	
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl		Yl	deg	min	sec	deg	min			sec
TS BS AR 0,ψ	-226.2	160.4	-82.8	PSI-8	2362.1	-22382.7	IAM-8	11543.0	9060.0	PSI-7	0.0	-22382.7	-79.3	PSI-8	2362.1	-22382.7	8154.1	44.	51.	38.	0.	-1.	-32.		Y

#### solution 4

```
(Debug) In[3236]:=
  ialign = 10;
  alignLabelH1[[ialign]]
```

```
(Debug) Out[3237]=
  TS BS HRel1pBaf x,y,z
```

```
(Debug) In[3238]:=
  iIAMOptSqRefH1[[ialign]] = "NA";
  iIAMOptSqH1[[ialign]] = "NA";
```

Add a monument, TS2-23, at the Y-coordinate of TS2-14, and the X-coordinate of the BS HR face:

```
(Debug) In[3240]:=
  IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-23", alignOpticPosH1L[[ialign, 1]], IAMlhoTS2[[14, 3]]}]];
  iIAMtheoH1[[ialign]] = Length[IAMlhoTS2];
  IAMlhoTS2[[iIAMtheoH1[[ialign]]]]
```

```
(Debug) Out[3242]=
  {TS2-23, -183.899, 7570.}
```

```
(Debug) In[3243]:=
  theoPosH1[[ialign]] = Append[IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 3]], alignOpticPosH1L[[ialign, 3]]]
```

```
(Debug) Out[3243]=
  {-183.899, 7570., -82.7768}
```

Add a monument, TS2-24, at the Y-coordinate of TS2-10, and the X-coordinate of the BS HR face:

(Debug) In[3244]:=

```
IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-24", alignOpticPosH1L[[ialign, 1]], IAMlhoTS2[[10, 3]]]];
iIAMtheoRefH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMtheoRefH1[[ialign]]]]
```

(Debug) Out[3246]=

```
{TS2-24, -183.899, 0.}
```

(Debug) In[3247]:=

```
theoOrientH1[[ialign]] = {0, -1, 0}
```

(Debug) Out[3247]=

```
{0, -1, 0}
```

(Debug) In[3248]:=

```
theoDistanceH1[[ialign]] = Sqrt[(theoPosH1[[ialign]] - alignOpticPosH1L[[ialign]]) . (theoPosH1[[ialign]] - alignOpticPosH1L[[ialign]])]
```

(Debug) Out[3248]=

```
7367.35
```

(Debug) In[3249]:=

```
theoYawH1[[ialign]] = 0;
theoPitchH1[[ialign]] = 0;
```

(Debug) In[3251]:=

```
formatLHOAlignTable[ialign, ialign]
```

(Debug) Out[3251]=

Alignment				Transit Square						Total Station												PLX			
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl	Yl		deg	min	sec	deg	min	sec		
TS BS HRellpBaf x,y,z	-183.9	202.7	-82.8	NA			NA			PSI-9	2362.2	-2362.2	-82.8	PSI-10	9219.6	-2362.2	7367.3	0.	0.	0.	0.	0.	0.		



2.2.7. SRM Alignment

2.2.8. SR2 Alignment

2.2.9. SR3 Alignment

2.2.10. SRC Alignment Summary

2.2.11. ITMx Alignment

2.2.12. ITMy Alignment

2.2.13. ETMx Alignment

2.2.14. ETMy Alignment

2.2.15. Summary of H1 Alignment Solutions

(Debug) In[3253]:=

```
formatLHOAlignTable[1, nAlignsH1]
```

(Debug) Out[3253]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PRM HR x,y,z	-20207.8	-627.3	-81.6	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 501	-2133.6	0.0	-81.6	LV22	-2133.6	-22692.0	18085.0	88.	0.	44.	0.	0.	0.		
PRM HR θ,ψ	-20207.8	-627.3	-81.6	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 500	-2133.6	-121.1	-82.0	LV22	-2133.6	-22692.0	18476.9	89.	39.	49.	0.	0.	-5.		Y
PR2 HR x,y,z	-3589.2	-530.0	-82.0	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 503	-2133.6	-541.7	-82.0	LV22	-2133.6	-22692.0	1455.6	90.	27.	41.	0.	0.	0.		
PR2 HR θ,ψ	-3589.2	-530.0	-82.0	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 502	-2133.6	-141.7	-82.0	LV22	-2133.6	-22692.0	5774.3	90.	27.	41.	0.	0.	0.		Y
PR3 HR x,y,z	-19741.1	-174.4	-82.4	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 505	-2133.6	0.0	-82.4	LV22	-2133.6	-22692.0	17608.3	89.	25.	57.	0.	0.	0.		
PR3 HR θ,ψ	-19741.1	-174.4	-82.4	LV26	-2133.6	-3050.7	LV25	-22692.0	-3050.7	LHO AM 504	-2133.6	27.9	-82.4	LV22	-2133.6	-22692.0	18004.1	90.	38.	37.	0.	0.	0.		Y
TS BS&ARellpBaf x,y,z	-226.2	160.4	-82.8	IAM-10	200.0	11428.0	PSI-2	9219.6	31601.7	PSI-4	-22382.7	2362.2	-84.5	NA			3734.9	45.	6.	17.	0.	1.	32.		
TS BS HR θ,ψ	-183.9	202.7	-82.8	PSI-5	-22382.7	0.0	IAM-8	11543.0	9060.0	PSI-6	2362.2	2362.2	-79.0	PSI-5	-22382.7	0.0	8967.5	44.	58.	16.	0.	-1.	-32.		Y
TS BS AR θ,ψ	-226.2	160.4	-82.8	PSI-8	2362.1	-22382.7	IAM-8	11543.0	9060.0	PSI-7	0.0	-22382.7	-79.3	PSI-8	2362.1	-22382.7	8154.1	44.	51.	38.	0.	-1.	-32.		Y
TS BS HRellpBaf x,y,z	-183.9	202.7	-82.8	NA			NA			PSI-9	2362.2	-2362.2	-82.8	PSI-10	9219.6	-2362.2	7367.3	0.	0.	0.	0.	0.	0.		
BS HR&ITMellpBafs x,y,z	-202.7	-183.9	-82.8	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
BS HR θ,ψ	-202.7	-183.9	-82.8	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
BS AR θ,ψ	-160.4	-226.2	-82.8	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SRM HR x,y,z	305.3	-19908.6	-113.6	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SRM HR θ,ψ	305.3	-19908.6	-113.6	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SR2 HR x,y,z	-594.2	-4178.1	-104.1	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SR2 HR θ,ψ	-594.2	-4178.1	-104.1	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SR3 HR x,y,z	-174.7	-19615.9	-94.6	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SR3 HR θ,ψ	-174.7	-19615.9	-94.6	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ITMx HR x,y,z	5012.9	-200.0	-83.1	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ITMx HR θ,ψ	5012.9	-200.0	-83.1	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ITMy HR x,y,z	-200.0	4983.1	-79.8	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ITMy HR θ,ψ	-200.0	4983.1	-79.8	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ETMx HR x,y,z	4.0×10 <sup>6</sup>	-200.0	-48.7	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ETMx HR θ,ψ	4.0×10 <sup>6</sup>	-200.0	-48.7	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ETMy HR x,y,z	-198.5	4.0×10 <sup>6</sup>	2476.6	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ETMy HR θ,ψ	-198.5	4.0×10 <sup>6</sup>	2476.6	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		

## 2.3. H2

H2 is not installed

## 2.4. L1

### 2.4.1. Alignment Solution List

Each alignment solution is given as a single row in a table associated with an optic. Some optics require more than one alignment solution. For example, one solution for angular alignment and one for positional alignment. In order to accomplish this the optics list is augmented with additional entries. Not an elegant approach, but workable. Start by alternately listing  $\{x,y,z\}$  and  $\{\theta,\psi\}$  solutions, then tweak as needed.

(Debug) In[3254]:=

```
alignLabelL1 = Table[0, {2 * nOpticsL1}];
alignOpticPosL1L = Table[0, {2 * nOpticsL1}, {3}];
alignOpticOrientL1L = alignOpticPosL1L;
Do[
  j = Floor[(i + 1) / 2];
  alignLabelL1[[i]] = StringJoin[opticLabelL1[[j]], If[EvenQ[i], "  $\theta,\psi$ ", " x,y,z"]];
  alignOpticPosL1L[[i]] = opticPosL1L[[j]];
  alignOpticOrientL1L[[i]] = opticOrientL1L[[j]];
  , {i, 1, 2 * nOpticsL1}]
```

The BS has 4 cartridge alignment solutions and 3 chamber alignment solutions. Only one of the “BS HR  $\theta,\psi$ ” or “BS AR  $\theta,\psi$ ” solutions is needed; Both are listed just in case one return is weak.

(Debug) In[3258]:=

```
alignLabelL1[[7]] = "TS BS&ARellpBaf x,y,z";
alignLabelL1[[8]] = "TS BS HR  $\theta,\psi$ ";
alignLabelL1[[9]] = "TS BS AR  $\theta,\psi$ ";
alignLabelL1[[10]] = "TS BS HRellpBaf x,y,z";
alignOpticPosL1L[[7]] = opticPosL1L[[5]];
alignOpticPosL1L[[8]] = opticPosL1L[[4]];
alignOpticPosL1L[[9]] = opticPosL1L[[5]];
alignOpticPosL1L[[10]] = opticPosL1L[[4]];
alignOpticOrientL1L[[7]] = opticOrientL1L[[5]];
alignOpticOrientL1L[[8]] = opticOrientL1L[[4]];
alignOpticOrientL1L[[9]] = opticOrientL1L[[5]];
alignOpticOrientL1L[[10]] = opticOrientL1L[[4]];
```

Rotate the BS optic coordinates 90 deg to reflect the fact that TS#1 is rotated relative to LBSC2

(Debug) In[3270]:=

```
Do[alignOpticPosL1L[[i]] = RotationMatrix3D[Pi / 2, 0, 0].alignOpticPosL1L[[i]];
  alignOpticOrientL1L[[i]] = RotationMatrix3D[Pi / 2, 0, 0].alignOpticOrientL1L[[i]], {i, 7, 10}]
```

The BS has 3 chamber alignment solutions.

(Debug) In[3271]:=

```
alignLabelL1 = Insert[alignLabelL1, "BS HR&ITMellpBafs x,y,z", 11];  
alignLabelL1 = Insert[alignLabelL1, "BS HR  $\theta,\psi$ ", 12];  
alignLabelL1 = Insert[alignLabelL1, "BS AR  $\theta,\psi$ ", 13];
```

(Debug) In[3274]:=

```
alignOpticPosL1L = Join[Take[alignOpticPosL1L, 10], {opticPosL1L[[4]]}, {opticPosL1L[[4]]}, {opticPosL1L[[5]]},  
  Take[alignOpticPosL1L, {11, 2*nOpticsL1}]];  
alignOpticOrientL1L = Join[Take[alignOpticOrientL1L, 10], {alignOpticOrientL1L[[4]]}, {alignOpticOrientL1L[[4]]},  
  {alignOpticOrientL1L[[5]]}, Take[alignOpticOrientL1L, {11, 2*nOpticsL1}]]];
```

(Debug) In[3276]:=

```
tableHead = {"X1", "Y1", "Z1", "U1", "V1", "W1"};
```

```
Print[TableForm[Partition[Flatten[Transpose[{alignOpticPosL1L, alignOpticOrientL1L}]], 6], TableHeadings -> {alignLabelL1, tableHead}]]
```

	X1	Y1	Z1	U1	V1	W1
PRM HR x,y,z	-20189.6	-628.063	-96.4361	0.999983	0.00587608	0.000265109
PRM HR $\theta,\psi$	-20189.6	-628.063	-96.4361	0.999983	0.00587608	0.000265109
PR2 HR x,y,z	-3579.23	-530.457	-92.0328	-0.999968	0.00801652	0
PR2 HR $\theta,\psi$	-3579.23	-530.457	-92.0328	-0.999968	0.00801652	0
PR3 HR x,y,z	-19740.	-176.329	-87.9061	0.999938	-0.0111511	0
PR3 HR $\theta,\psi$	-19740.	-176.329	-87.9061	0.999938	-0.0111511	0
TS BS&ARellpBaf x,y,z	-226.373	160.215	-82.6386	-0.708292	-0.705919	0.00021252
TS BS HR $\theta,\psi$	-184.012	202.537	-82.6513	0.707429	0.706784	-0.000211723
TS BS AR $\theta,\psi$	-226.373	160.215	-82.6386	-0.708292	-0.705919	0.00021252
TS BS HRelpBaf x,y,z	-184.012	202.537	-82.6513	0.707429	0.706784	-0.000211723
BS HR&ITMellpBafs x,y,z	-202.537	-184.012	-82.6513	-0.999968	0.00801652	0
BS HR $\theta,\psi$	-202.537	-184.012	-82.6513	-0.999968	0.00801652	0
BS AR $\theta,\psi$	-160.215	-226.373	-82.6386	0.999938	-0.0111511	0
SRM HR x,y,z	304.975	-19908.7	-81.279	-0.0570633	0.998371	-0.0000115106
SRM HR $\theta,\psi$	304.975	-19908.7	-81.279	-0.0570633	0.998371	-0.0000115106
SR2 HR x,y,z	-594.125	-4178.15	-81.4603	0.0421006	-0.999113	0
SR2 HR $\theta,\psi$	-594.125	-4178.15	-81.4603	0.0421006	-0.999113	0
SR3 HR x,y,z	-175.169	-19616.	-82.0605	-0.013788	0.999905	0
SR3 HR $\theta,\psi$	-175.169	-19616.	-82.0605	-0.013788	0.999905	0
ITMx HR x,y,z	5012.97	-200.049	-81.4418	1.	0.	-0.000312
ITMx HR $\theta,\psi$	5012.97	-200.049	-81.4418	1.	0.	-0.000312
ITMy HR x,y,z	-200.026	4983.05	-82.9823	$-1.90632 \times 10^{-7}$	1.	-0.000611
ITMy HR $\theta,\psi$	-200.026	4983.05	-82.9823	$-1.90632 \times 10^{-7}$	1.	-0.000611
ETMx HR x,y,z	$3.9995 \times 10^6$	-200.049	1179.96	-1.	0.	-0.000315
ETMx HR $\theta,\psi$	$3.9995 \times 10^6$	-200.049	1179.96	-1.	0.	-0.000315
ETMy HR x,y,z	-200.001	$3.99947 \times 10^6$	-4.7478	$-5.8468 \times 10^{-9}$	-1.	-0.0000188
ETMy HR $\theta,\psi$	-200.001	$3.99947 \times 10^6$	-4.7478	$-5.8468 \times 10^{-9}$	-1.	-0.0000188

```
(Debug) In[3278]:=
  nAlignsL1 = Length[alignLabelL1];
  nAlignOpticsL1 = 2 * nOpticsL1;
  theoYawL1 = Table[0, {nAlignsL1}];
  theoPitchL1 = theoYawL1;
  theoDistanceL1 = theoYawL1;
  theoOrientL1 = Table[0, {nAlignsL1}, {3}];
  theoPosL1 = theoOrientL1;
  iIAMOptSqL1 = Table["NA", {nAlignsL1}];
  iIAMOptSqRefL1 = iIAMOptSqL1;
  iIAMtheoL1 = iIAMOptSqL1;
  iIAMtheoRefL1 = iIAMOptSqL1;
  LTHRL1 = Table["", {nAlignsL1}];
  LTHPL1 = LTHRL1;
```

## 2.4.2. PRM Alignment

### Angular Alignment ( $\theta$ , $\psi$ )

A direct view perpendicular to the center of PRM is not possible from the region of the spool between HAM3 and BSC2, due to the PR2 suspension blocking the view. Consequently a periscope (PLX LTHP) is used

Derive yaw reference from sight line from "L1 IAM 378" to "L1 IAM 382" (parallel to X-axis) with Bruson Optical Square

Place Theodolite/Total Station over new monument "am 503" which is placed at same X location as "L1 IAM 378" but along normal vector to PRM, translated by the PLX LTHP

The PLX LTHP is placed in the spool to the -X side of HAM3

### calculations

```
(Debug) In[3291]:=
  ialign = 2;
  alignLabelL1[[ialign]]

(Debug) Out[3292]=
  PRM HR  $\theta, \psi$ 

(Debug) In[3293]:=
  theoOrientL1[[ialign]] = -alignOpticOrientL1L[[ialign]];

(Debug) In[3294]:=
  iIAMOptSqL1[[ialign]] = 12;
  IAMllo[[iIAMOptSqL1[[ialign]]]]

(Debug) Out[3295]=
  {L1 IAM 378, -1858., -2245.5}
```



```
(Debug) In[3296]:=
```

```
  iIAMOptSqRefL1[[ialign]] = 16;  
  IAMllo[[iIAMOptSqRefL1[[ialign]]]]
```

```
(Debug) Out[3297]=
```

```
{L1 IAM 382, -22 283.5, -2245.5}
```

Approximate position of the LTHP (in the spool to the -X side of the HAM3 chamber, but before the MC Baffle):

```
(Debug) In[3298]:=
```

```
  LTHPL1[[ialign]] = "Y";  
  LTHPorient = Append[LTHPlength RotationMatrix[Pi / 2].alignOpticOrientL1L[[ialign, 1 ;; 2]], 0];  
  LTHPPosInX = -5550;  
  s = (LTHPPosInX - alignOpticPosL1L[[ialign, 1]]) / alignOpticOrientL1L[[ialign, 1]];  
  LTHPPosIn = alignOpticPosL1L[[ialign]] + s alignOpticOrientL1L[[ialign]];  
  LTHPPosOut = LTHPPosIn + LTHPorient;
```

```
(Debug) In[3304]:=
```

```
  d = (IAMPosLllo[[iIAMOptSqL1[[ialign]], 1]] - alignOpticPosL1L[[ialign, 1]] - LTHPorient[[1]]) / alignOpticOrientL1L[[ialign, 1]];  
  theoPosL1[[ialign]] = alignOpticPosL1L[[ialign]] + d alignOpticOrientL1L[[ialign]] + LTHPorient;  
  d1 = alignOpticPosL1L[[ialign]] - LTHPPosIn;  
  d2 = LTHPorient;  
  d3 = LTHPPosIn + LTHPorient - theoPosL1[[ialign]];  
  theoDistanceL1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3];
```

```
(Debug) In[3310]:=
```

```
  IAMllo = Append[IAMllo, Flatten[{"am 500", theoPosL1[[ialign, 1 ;; 2]]}]];  
  iIAMtheoL1[[ialign]] = Length[IAMllo];  
  Flatten[{"am 500", theoPosL1[[ialign, 1 ;; 2]]}]
```

```
(Debug) Out[3312]=
```

```
{am 500, -1858., -120.286}
```

```
(Debug) In[3313]:=
```

```
  iIAMtheoRefL1[[ialign]] = 11;  
  IAMllo[[iIAMtheoRefL1[[ialign]]]]
```

```
(Debug) Out[3314]=
```

```
{L1 IAM 379, -1858., -26 231.2}
```

```
(Debug) In[3315]:=
```

```
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];  
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

```
(Debug) Out[3316]=
```

```
89.6633
```

(Debug) In[3317]:=

```
theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

(Debug) Out[3317]:=

0.0151899

(Debug) In[3318]:=

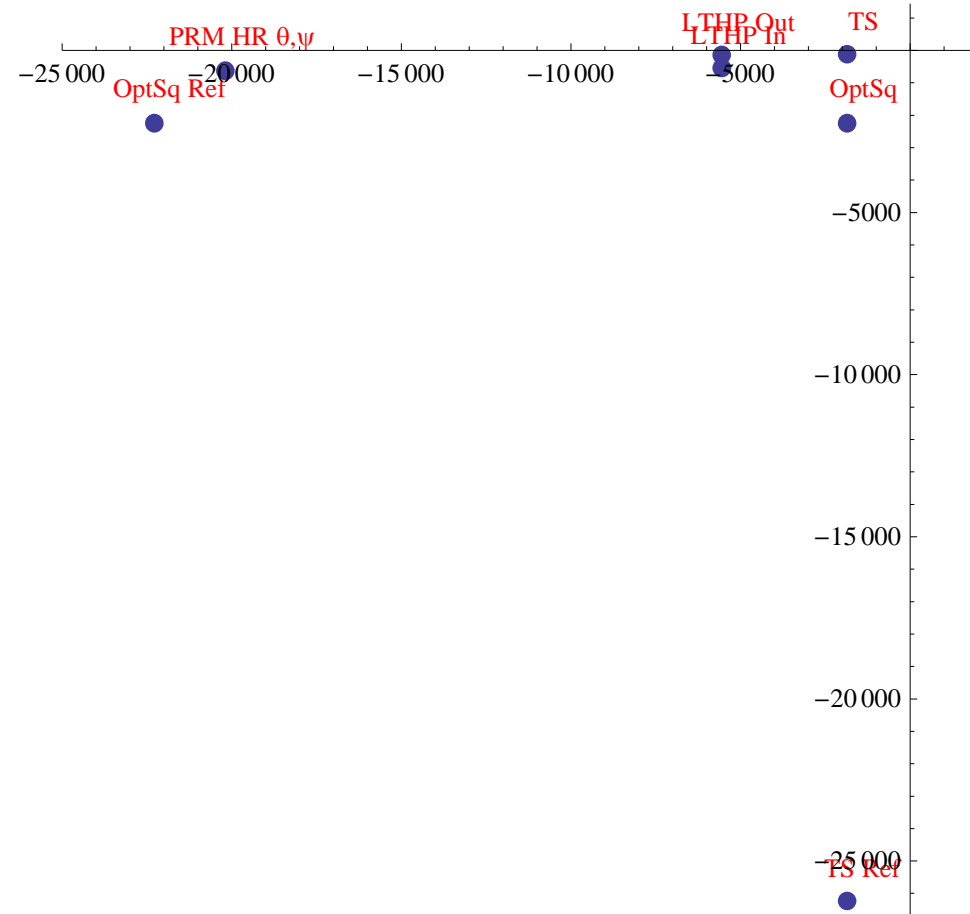
```
data = {alignOpticPosL1L[[ialign, 1 ;; 2]], IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMOptSqRefL1[[ialign]], 2 ;; 3]],
  IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMtheoRefL1[[ialign]], 2 ;; 3]], LTHPPosIn[[1 ;; 2]], LTHPPosOut[[1 ;; 2]]};
dataPlot = ListPlot[data, PlotStyle -> PointSize -> Large];
labels = {alignLabelL1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref", "LTHP In", "LTHP Out"};
PointLabels = Table[Text[labels[[i]], data[[i]] + {500, 1000}], {i, 1, Length[labels]}];
```

**results**

(Debug) In[3322]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25000, 2000}, All}]
```

(Debug) Out[3322]:=



(Debug) In[3323]=

`formatLLOAlignTable[ialign, ialign]`

(Debug) Out[3323]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl	Yl		deg	min	sec	deg	min	sec		
PRM HR 0,ψ	-20189.6	-628.1	-96.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 500	-1858.0	-120.3	-91.6	L1 IAM 379	-1858.0	-26231.2	18734.3	89.	39.	48.	0.	0.	55.		Y

**Position Alignment (x,y,z)**

Set the Total Station/Theodolite at y = 0 for a clear sight to PRM HR center

**calculations**

(Debug) In[3324]=

```
ialign = 1;
alignLabelL1[[ialign]]
```

(Debug) Out[3325]=

PRM HR x,y,z

(Debug) In[3326]=

```
iIAMOptSqL1[[ialign]] = 12;
IAMllo[[iIAMOptSqL1[[ialign]]]]
```

(Debug) Out[3327]=

{L1 IAM 378, -1858., -2245.5}

(Debug) In[3328]=

```
iIAMOptSqRefL1[[ialign]] = 16;
IAMllo[[iIAMOptSqRefL1[[ialign]]]]
```

(Debug) Out[3329]=

{L1 IAM 382, -22283.5, -2245.5}

(Debug) In[3330]=

```
theoPosL1[[ialign]] = {IAMllo[[iIAMOptSqL1[[ialign]]], 2], 0, alignOpticPosL1L[[ialign, 3]]};
IAMllo = Append[IAMllo, Flatten[{"am 501", theoPosL1[[ialign, 1 ;; 2]]}]];
iIAMtheoL1[[ialign]] = Length[IAMllo];
Flatten[{"am 501", theoPosL1[[ialign, 1 ;; 2]]}]
```

(Debug) Out[3333]=

{am 501, -1858., 0}

```
(Debug) In[3334]:=
```

```
  d = alignOpticPosL1L[[ialign]] - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d.d];
  theoOrientL1[[ialign]] = d / theoDistanceL1[[ialign]]
```

```
(Debug) Out[3336]=
```

```
{-0.999414, -0.0342411, 0.}
```

```
(Debug) In[3337]:=
```

```
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]
```

```
(Debug) Out[3338]=
```

```
{L1 IAM 379, -1858., -26231.2}
```

```
(Debug) In[3339]:=
```

```
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

```
(Debug) Out[3340]=
```

```
88.0377
```

```
(Debug) In[3341]:=
```

```
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

```
(Debug) Out[3341]=
```

```
0.
```

```
(Debug) In[3342]:=
```

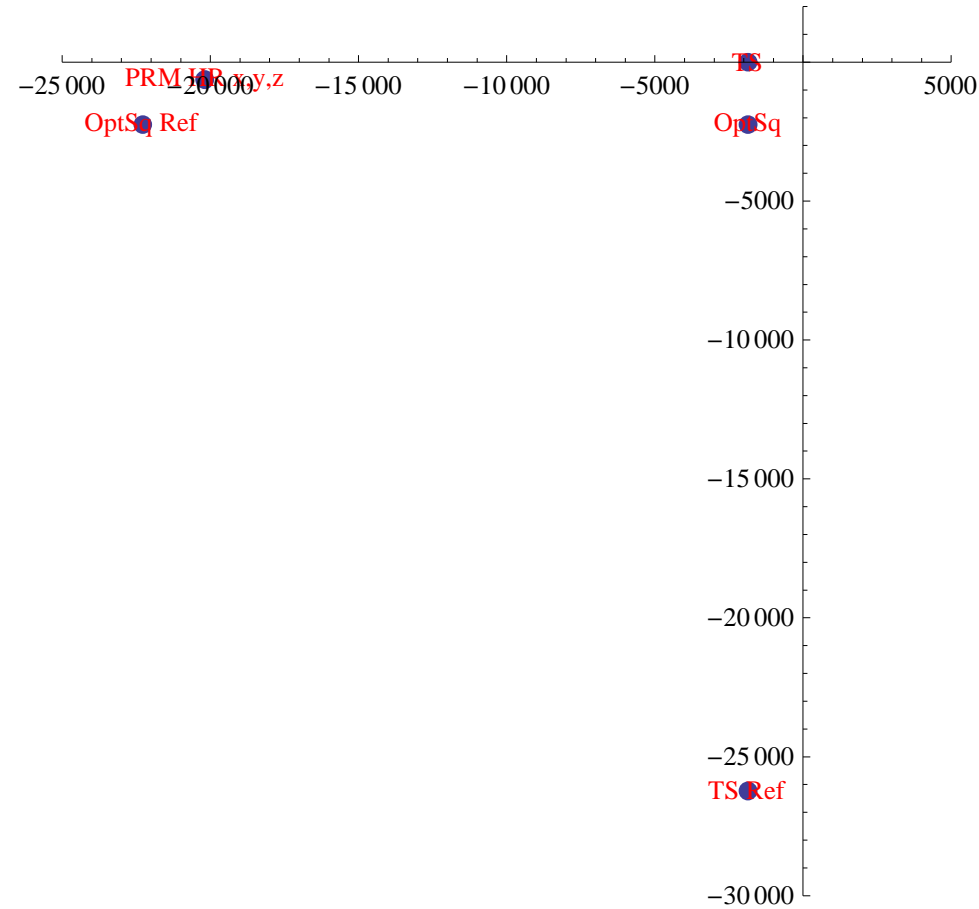
```
  data = {alignOpticPosL1L[[ialign, 1 ;; 2]], IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMOptSqRefL1[[ialign]], 2 ;; 3]],
    IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMtheoRefL1[[ialign]], 2 ;; 3]]};
  dataPlot = ListPlot[data, PlotStyle → PointSize → Large, PlotRange → All];
  labels = {alignLabelL1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref"};
  PointLabels = Table[Text[labels[[i]], data[[i]], {i, 1, Length[labels]}];
```

**results**

(Debug) In[3346]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, {-30 000, 2000}}]
```

(Debug) Out[3346]=



(Debug) In[3347]:=

```
formatLLOAlignTable[ialign, ialign]
```

(Debug) Out[3347]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl	Yl		deg	min	sec	deg	min	sec		
PRM HR x,y,z	-20189.6	-628.1	-96.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 501	-1858.0	0.0	-96.4	L1 IAM 379	-1858.0	-26231.2	18342.4	88.	2.	16.	0.	0.	0.		

**2.4.3. PR2 Alignment**

**Angular Alignment ( $\theta, \psi$ )**

A direct view perpendicular to the center of PR2, from the region of the spool between HAM3 and BSC2, is possible with the use of an extended retro-reflector (PLX LTHR)

Derive yaw reference from sight line from "L1 IAM 378" to "L1 IAM 382" (parallel to X-axis) with Bruson Optical Square

Place Theodolite/Total Station over new monument "am 500" which is placed at same X location as "L1 IAM 378" but along normal vector to PR2, translated by the PLX LTHR

The PLX LTHR is placed in the spool to the -X side of HAM3

**calculations**

```

(Debug) In[3348]:=
  ialign = 4;
  alignLabelL1[[ialign]]

(Debug) Out[3349]=
  PR2 HR  $\theta, \psi$ 

(Debug) In[3350]:=
  theoOrientL1[[ialign]] = alignOpticOrientL1L[[ialign]];

(Debug) In[3351]:=
  iIAMOptSqL1[[ialign]] = 12;
  IAMllo[[iIAMOptSqL1[[ialign]]]]

(Debug) Out[3352]=
  {L1 IAM 378, -1858., -2245.5}

(Debug) In[3353]:=
  iIAMOptSqRefL1[[ialign]] = 16;
  IAMllo[[iIAMOptSqRefL1[[ialign]]]]

(Debug) Out[3354]=
  {L1 IAM 382, -22283.5, -2245.5}

```

Approximate position of the LTHR (in the spool to the -X side of the HAM3 chamber, but before the MC Baffle):

```

(Debug) In[3355]:=
  LTHRL1[[ialign]] = "Y";
  LTHRorient = Append[LTHRlength RotationMatrix[-Pi / 2].alignOpticOrientL1L[[ialign, 1 ;; 2]], 0]
  LTHRPosInX = -5550;
  s = (LTHRPosInX - alignOpticPosL1L[[ialign, 1]]) / alignOpticOrientL1L[[ialign, 1]];
  LTHRPosIn = alignOpticPosL1L[[ialign]] + s alignOpticOrientL1L[[ialign]]
  LTHRPosOut = LTHRPosIn + LTHRorient

(Debug) Out[3356]=
  {3.20701, 400.037, 0}

(Debug) Out[3359]=
  {-5550., -514.658, -92.0328}

(Debug) Out[3360]=
  {-5546.79, -114.621, -92.0328}

```

```

(Debug) In[3361]:=
  d = (IAMPosL1lo[[iIAMOptSqL1[[ialign]], 1]] - alignOpticPosL1L[[ialign, 1]] - LTHRorient[[1]]) / alignOpticOrientL1L[[ialign, 1]];
  theoPosL1[[ialign]] = alignOpticPosL1L[[ialign]] + d alignOpticOrientL1L[[ialign]] + LTHRorient;
  d1 = alignOpticPosL1L[[ialign]] - LTHRPosIn;
  d2 = LTHRorient;
  d3 = LTHRPosIn + LTHRorient - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3];

(Debug) In[3367]:=
  IAMllo = Append[IAMllo, Flatten[{"am 502", theoPosL1[[ialign, 1 ;; 2]]}]];
  iIAMtheoL1[[ialign]] = Length[IAMllo];
  Flatten[{"am 502", theoPosL1[[ialign, 1 ;; 2]]}]

(Debug) Out[3369]=
  {am 502, -1858., -144.193}

(Debug) In[3370]:=
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]

(Debug) Out[3371]=
  {L1 IAM 379, -1858., -26 231.2}

(Debug) In[3372]:=
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[3373]=
  90.4593

(Debug) In[3374]:=
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi

(Debug) Out[3374]=
  0.

(Debug) In[3375]:=
  data = {alignOpticPosL1L[[ialign, 1 ;; 2]], IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMOptSqRefL1[[ialign]], 2 ;; 3]],
    IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMtheoRefL1[[ialign]], 2 ;; 3]], LTHPPosIn[[1 ;; 2]], LTHPPosOut[[1 ;; 2]]};
  dataPlot = ListPlot[data, PlotStyle → PointSize → Large];
  labels = {alignLabelL1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref", "LTHP In", "LTHP Out"};
  PointLabels = Table[Text[labels[[i]], data[[i]] + {200, 500}], {i, 1, Length[labels]};

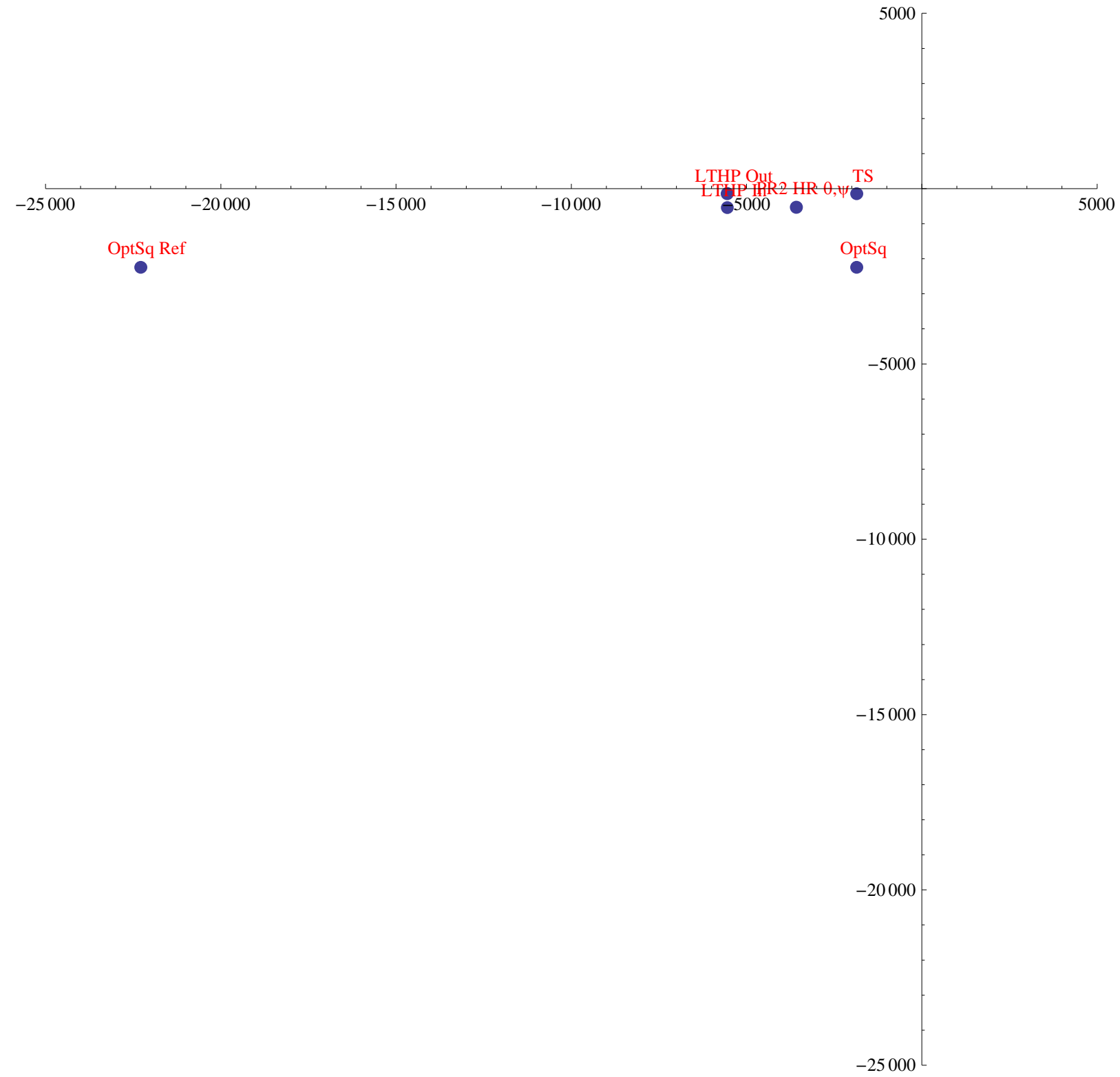
```

results

(Debug) In[3379]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, {-25 000, 5000}}]
```

(Debug) Out[3379]=





(Debug) In[3380]=

`formatLLOAlignTable[ialign, ialign]`

(Debug) Out[3380]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PR2 HR 0,ψ	-3579.2	-530.5	-92.0	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 502	-1858.0	-144.2	-92.0	L1 IAM 379	-1858.0	-26231.2	6059.8	90.	27.	34.	0.	0.	0.	Y	

**Position Alignment (x,y,z)**Set the Total Station/Theodolite at the intersection of the PR2 HR normal vector (projected backwards) and the monument reference line  $x = -1858.0$  mm**calculations**

(Debug) In[3381]=

```
ialign = 3;
alignLabelL1[[ialign]]
```

(Debug) Out[3382]=

PR2 HR x,y,z

(Debug) In[3383]=

```
iIAMOptSqL1[[ialign]] = 12;
IAMllo[[iIAMOptSqL1[[ialign]]]]
```

(Debug) Out[3384]=

{L1 IAM 378, -1858., -2245.5}

(Debug) In[3385]=

```
iIAMOptSqRefL1[[ialign]] = 16;
IAMllo[[iIAMOptSqRefL1[[ialign]]]]
```

(Debug) Out[3386]=

{L1 IAM 382, -22283.5, -2245.5}

(Debug) In[3387]=

```
s = (IAMllo[[iIAMOptSqL1[[ialign]], 2]] - alignOpticPosL1L[[ialign, 1]]) / alignOpticOrientL1L[[ialign, 1]];
theoPosL1[[ialign]] = alignOpticPosL1L[[ialign]] + s alignOpticOrientL1L[[ialign]]
```

(Debug) Out[3388]=

{-1858., -544.256, -92.0328}

(Debug) In[3389]=

```
IAMllo = Append[IAMllo, Flatten[{"am 503", theoPosL1[[ialign, 1 ;; 2]]}]];
iIAMtheoL1[[ialign]] = Length[IAMllo];
Flatten[{"am 503", theoPosL1[[ialign, 1 ;; 2]]}]
```

(Debug) Out[3391]=

{am 503, -1858., -544.256}

```
(Debug) In[3392]:=
```

```
  d = alignOpticPosL1L[[ialign]] - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d.d];
  theoOrientL1[[ialign]] = d / theoDistanceL1[[ialign]];
```

```
(Debug) In[3395]:=
```

```
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]
```

```
(Debug) Out[3396]=
```

```
{L1 IAM 379, -1858., -26 231.2}
```

```
(Debug) In[3397]:=
```

```
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

```
(Debug) Out[3398]=
```

```
90.4593
```

```
(Debug) In[3399]:=
```

```
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

```
(Debug) Out[3399]=
```

```
0.
```

```
(Debug) In[3400]:=
```

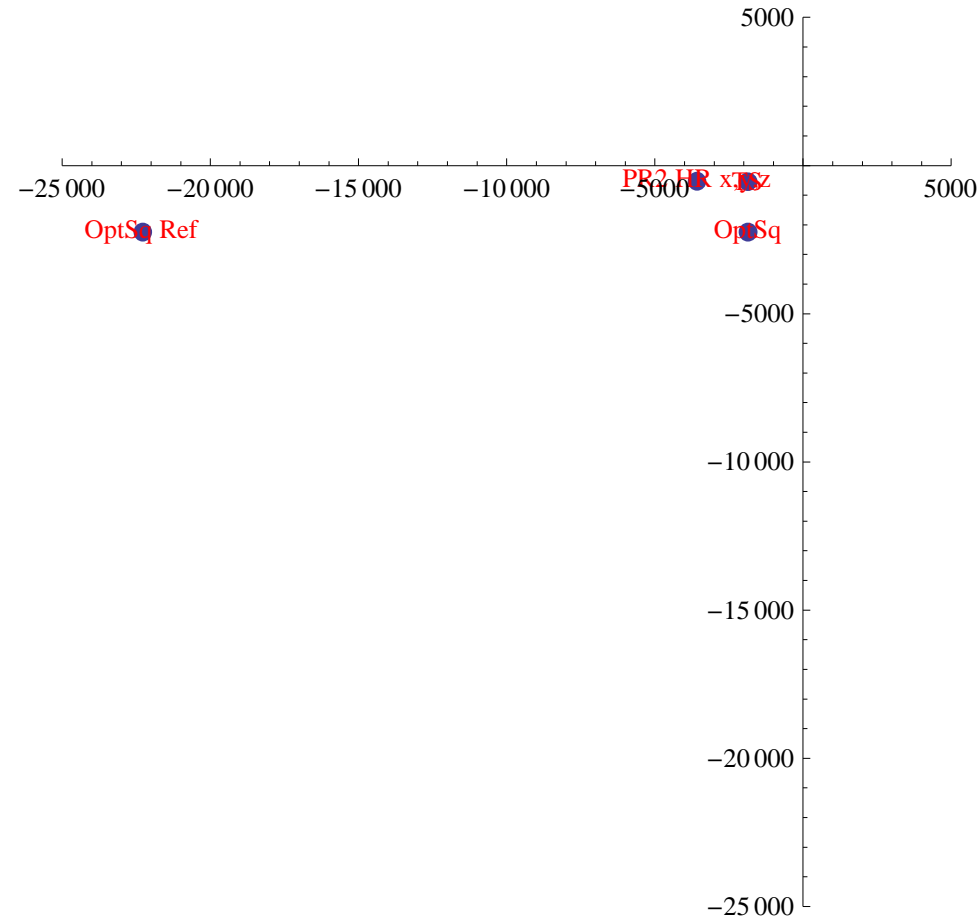
```
  data = {alignOpticPosL1L[[ialign, 1 ;; 2]], IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMOptSqRefL1[[ialign]], 2 ;; 3]],
    IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMtheoRefL1[[ialign]], 2 ;; 3]]};
  dataPlot = ListPlot[data, PlotStyle → PointSize → Large, PlotRange → All];
  labels = {alignLabelL1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref"};
  PointLabels = Table[Text[labels[[i]], data[[i]], {i, 1, Length[labels]}];
```

**results**

(Debug) In[3404]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, {-25 000, 5000}}]
```

(Debug) Out[3404]=



(Debug) In[3405]:=

```
formatLLOAlignTable[ialign, ialign]
```

(Debug) Out[3405]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PR2 HR x, y, z	-3579.2	-530.5	-92.0	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 503	-1858.0	-544.3	-92.0	L1 IAM 379	-1858.0	-26231.2	1721.3	90.	27.	34.	0.	0.	0.		

**2.4.4. PR3 Alignment**

**Angular Alignment ( $\theta, \psi$ )**

A direct view perpendicular to the center of PR3 is not possible from the region of the spool between HAM3 and BSC2, due to the PR2 suspension blocking the view. Consequently a periscope (PLX LTHP) is used

Derive yaw reference from sight line from "L1 IAM 378" to "L1 IAM 382" (parallel to X-axis) with Bruson Optical Square

Place Theodolite/Total Station over new monument "am 500" which is placed at same X location as "L1 IAM 378" but along normal vector to PR3, translated by the PLX LTHP

The PLX LTHP is placed in the spool to the -X side of HAM3

**calculations**

```

(Debug) In[3406]:=
  ialign = 6;
  alignLabelL1[[ialign]]

(Debug) Out[3407]=
  PR3 HR  $\theta, \psi$ 

(Debug) In[3408]:=
  theoOrientL1[[ialign]] = -alignOpticOrientL1L[[ialign]];

(Debug) In[3409]:=
  iIAMOptSqL1[[ialign]] = 12;
  IAMllo[[iIAMOptSqL1[[ialign]]]]

(Debug) Out[3410]=
  {L1 IAM 378, -1858., -2245.5}

(Debug) In[3411]:=
  iIAMOptSqRefL1[[ialign]] = 16;
  IAMllo[[iIAMOptSqRefL1[[ialign]]]]

(Debug) Out[3412]=
  {L1 IAM 382, -22283.5, -2245.5}

```

Approximate position of the LTHP (in the spool to the -X side of the HAM3 chamber, but before the MC Baffle):

```

(Debug) In[3413]:=
  LTHPL1[[ialign]] = "Y";
  LTHPorient = Append[LTHPlength RotationMatrix[Pi / 2].alignOpticOrientL1L[[ialign, 1 ;; 2]], 0];
  LTHPPosInX = -5550;
  s = (LTHPPosInX - alignOpticPosL1L[[ialign, 1]]) / alignOpticOrientL1L[[ialign, 1]];
  LTHPPosIn = alignOpticPosL1L[[ialign]] + s alignOpticOrientL1L[[ialign]];
  LTHPPosOut = LTHPPosIn + LTHPorient;

(Debug) In[3419]:=
  d = (IAMPosLllo[[iIAMOptSqL1[[ialign]], 1]] - alignOpticPosL1L[[ialign, 1]] - LTHPorient[[1]]) / alignOpticOrientL1L[[ialign, 1]];
  theoPosL1[[ialign]] = alignOpticPosL1L[[ialign]] + d alignOpticOrientL1L[[ialign]] + LTHPorient;
  d1 = alignOpticPosL1L[[ialign]] - LTHPPosIn;
  d2 = LTHPorient;
  d3 = LTHPPosIn + LTHPorient - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3];

```

(Debug) In[3425]:=

```

IAMllo = Append[IAMllo, Flatten[{"am 504", theoPosL1[[ialign, 1 ;; 2]]}]];
iIAMtheoL1[[ialign]] = Length[IAMllo];
Flatten[{"am 504", theoPosL1[[ialign, 1 ;; 2]]}]

```

(Debug) Out[3427]=

```
{am 504, -1858., 24.3296}
```

(Debug) In[3428]:=

```

iIAMtheoRefL1[[ialign]] = 11;
IAMllo[[iIAMtheoRefL1[[ialign]]]]

```

(Debug) Out[3429]=

```
{L1 IAM 379, -1858., -26 231.2}
```

(Debug) In[3430]:=

```

zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

```

(Debug) Out[3431]=

```
90.6389
```

(Debug) In[3432]:=

```
theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

(Debug) Out[3432]=

```
0.
```

(Debug) In[3433]:=

```

data = {alignOpticPosL1L[[ialign, 1 ;; 2]], IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMOptSqRefL1[[ialign]], 2 ;; 3]],
  IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMtheoRefL1[[ialign]], 2 ;; 3]], LTHPPosIn[[1 ;; 2]], LTHPPosOut[[1 ;; 2]]};
dataPlot = ListPlot[data, PlotStyle -> PointSize -> Large];
labels = {alignLabelL1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref", "LTHP In", "LTHP Out"};
PointLabels = Table[Text[labels[[i]], data[[i]] + {500, 1000}], {i, 1, Length[labels]};

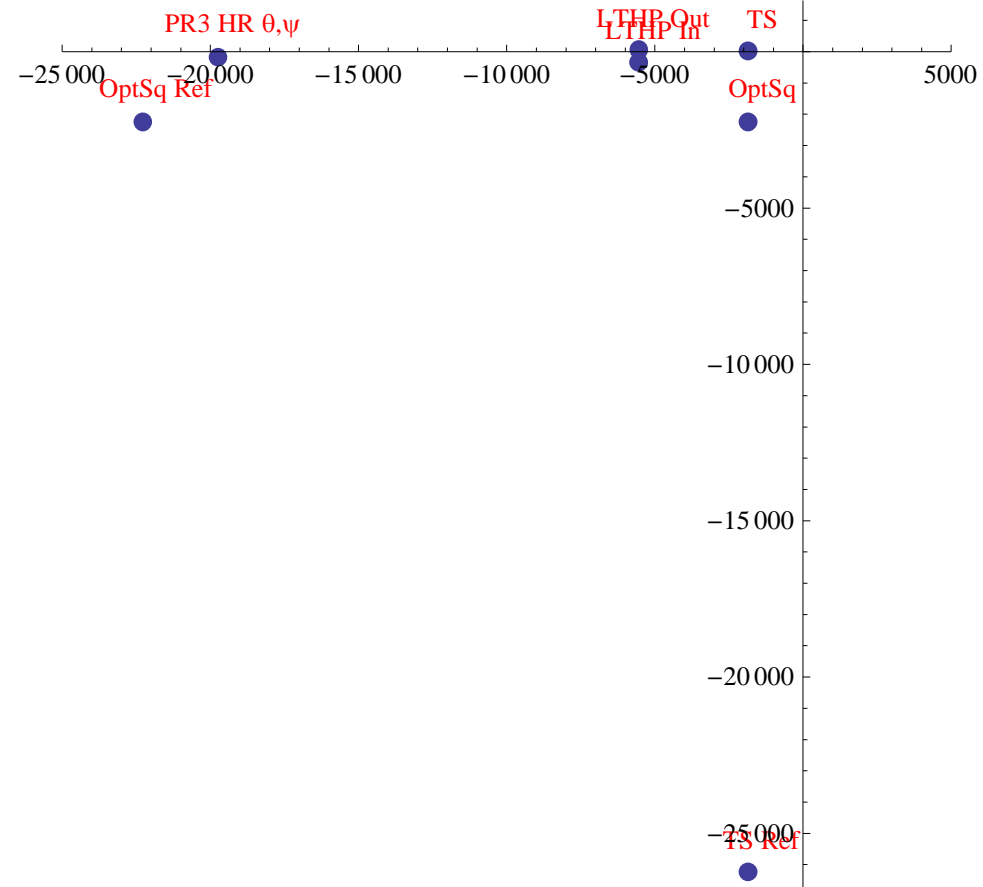
```

**results**

(Debug) In[3437]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, All}]
```

(Debug) Out[3437]=



(Debug) In[3438]:=

```
formatLLOalignTable[ialign, ialign]
```

(Debug) Out[3438]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl	Yl		deg	min	sec	deg	min	sec		
PR3 HR 0,ψ	-19740.0	-176.3	-87.9	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 504	-1858.0	24.3	-87.9	L1 IAM 379	-1858.0	-26231.2	18278.7	90.	38.	20.	0.	0.	0.		Y

**Position Alignment (x,y,z)**

Set the Total Station/Theodolite at y = 0 for a clear sight to PR3 HR center

**calculations**

(Debug) In[3439]:=

```
ialign = 5;
alignLabelL1[[ialign]]
```

(Debug) Out[3440]=

PR3 HR x,y,z

```

(Debug) In[3441]:=
  iIAMOptSqL1[[ialign]] = 12;
  IAMllo[[iIAMOptSqL1[[ialign]]]]

(Debug) Out[3442]=
  {L1 IAM 378, -1858., -2245.5}

(Debug) In[3443]:=
  iIAMOptSqRefL1[[ialign]] = 16;
  IAMllo[[iIAMOptSqRefL1[[ialign]]]]

(Debug) Out[3444]=
  {L1 IAM 382, -22 283.5, -2245.5}

(Debug) In[3445]:=
  theoPosL1[[ialign]] = {IAMllo[[iIAMOptSqL1[[ialign]], 2]], 0, alignOpticPosL1L[[ialign, 3]]};
  IAMllo = Append[IAMllo, Flatten[{"am 505", theoPosL1[[ialign, 1 ;; 2]]}]];
  iIAMtheoL1[[ialign]] = Length[IAMllo];
  Flatten[{"am 505", theoPosL1[[ialign, 1 ;; 2]]}]

(Debug) Out[3448]=
  {am 505, -1858., 0}

(Debug) In[3449]:=
  d = alignOpticPosL1L[[ialign]] - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d.d]
  theoOrientL1[[ialign]] = d / theoDistanceL1[[ialign]]

(Debug) Out[3450]=
  17 882.9

(Debug) Out[3451]=
  {-0.999951, -0.00986018, 0.}

(Debug) In[3452]:=
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]

(Debug) Out[3453]=
  {L1 IAM 379, -1858., -26 231.2}

(Debug) In[3454]:=
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[3455]=
  89.435

```

(Debug) In[3456]:=

```
theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

(Debug) Out[3456]=

0.

(Debug) In[3457]:=

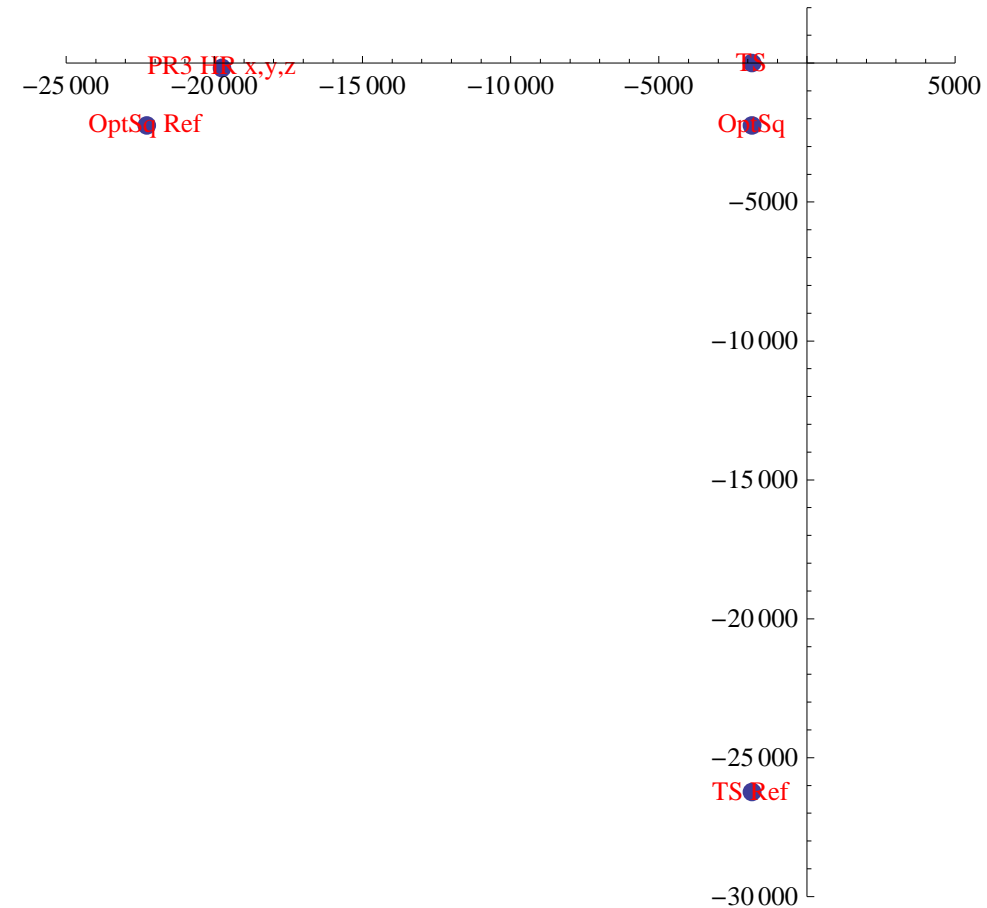
```
data = {alignOpticPosL1L[[ialign, 1 ;; 2]], IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMOptSqRefL1[[ialign]], 2 ;; 3]],
        IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMtheoRefL1[[ialign]], 2 ;; 3]]};
dataPlot = ListPlot[data, PlotStyle → PointSize → Large, PlotRange → All];
labels = {alignLabelL1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref"};
PointLabels = Table[Text[labels[[i]], data[[i]]], {i, 1, Length[labels]}];
```

**results**

(Debug) In[3461]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio → 1, PlotRange → {{-25 000, 5000}, {-30 000, 2000}}]
```

(Debug) Out[3461]=





(Debug) In[3462]:=

**formatLLOAlignTable[ialign, ialign]**

(Debug) Out[3462]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PR3 HR x,y,z	-19740.0	-176.3	-87.9	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 505	-1858.0	0.0	-87.9	L1 IAM 379	-1858.0	-26231.2	17882.9	89.	26.	6.	0.	0.	0.		

## 2.4.5. PRC Alignment Summary

Table summarizing the alignment solutions for the Power Recycling Cavity (PRC) optics: PRM, PR2 and PR3

(Debug) In[3605]:=

**formatLLOAlignTable[1, 6]**

(Debug) Out[3605]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PRM HR x,y,z	-20189.6	-628.1	-96.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 501	-1858.0	0.0	-96.4	L1 IAM 379	-1858.0	-26231.2	18342.4	88.	2.	16.	0.	0.	0.		
PRM HR $\theta, \psi$	-20189.6	-628.1	-96.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 500	-1858.0	-120.3	-91.6	L1 IAM 379	-1858.0	-26231.2	18734.3	89.	39.	48.	0.	0.	55.		Y
PR2 HR x,y,z	-3579.2	-530.5	-92.0	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 503	-1858.0	-544.3	-92.0	L1 IAM 379	-1858.0	-26231.2	1721.3	90.	27.	34.	0.	0.	0.		
PR2 HR $\theta, \psi$	-3579.2	-530.5	-92.0	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 502	-1858.0	-144.2	-92.0	L1 IAM 379	-1858.0	-26231.2	6059.8	90.	27.	34.	0.	0.	0.	Y	
PR3 HR x,y,z	-19740.0	-176.3	-87.9	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 505	-1858.0	0.0	-87.9	L1 IAM 379	-1858.0	-26231.2	17882.9	89.	26.	6.	0.	0.	0.		
PR3 HR $\theta, \psi$	-19740.0	-176.3	-87.9	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 504	-1858.0	24.3	-87.9	L1 IAM 379	-1858.0	-26231.2	18278.7	90.	38.	20.	0.	0.	0.		Y

## 2.4.6. BS Alignment

Cartridge

**solution 1**

(Debug) In[3464]:=

**ialign = 7;****alignLabelL1[[ialign]]**

(Debug) Out[3465]=

TS BS&amp;AREllpBaf x,y,z

Rotate the BS optic coordinates 90 deg to reflect the fact that TS#1 is rotated relative to LBSC2

(Debug) In[3466]:=

```
BSARPos = alignOpticPosL1L[[ialign]]
```

(Debug) Out[3466]=

```
{-226.373, 160.215, -82.6386}
```

BS wedge angle (deg):

(Debug) In[3467]:=

```
wedge = VectorAngle[alignOpticOrientL1L[[ialign]], -alignOpticOrientL1L[[ialign + 1]]] 180 / Pi
```

(Debug) Out[3467]=

```
0.07
```

(Debug) In[3468]:=

```
BSHROrient = alignOpticOrientL1L[[ialign + 1]]
```

(Debug) Out[3468]=

```
{0.707429, 0.706784, -0.000211723}
```

(Debug) In[3469]:=

```
BSAROrient = alignOpticOrientL1L[[ialign]]
```

(Debug) Out[3469]=

```
{-0.708292, -0.705919, 0.00021252}
```

(Debug) In[3470]:=

```
iIAMOptSqRefL1[[ialign]] = 5;  
IAMlloTS1[[iIAMOptSqRefL1[[ialign]]]]
```

(Debug) Out[3471]=

```
{IAM 393, 7293., 0.}
```

(Debug) In[3472]:=

```
iIAMOptSqL1[[ialign]] = 11;  
IAMlloTS1[[iIAMOptSqL1[[ialign]]]]
```

(Debug) Out[3473]=

```
{IAM 397, -2867., 0.}
```

Add a monument (TS1-14) along the IAM-389 to IAM IAM-400 line and normal to the BS AR surface:

(Debug) In[3474]:=

```
d = (IAMlloTS1[[iIAMOptSqL1[[ialign]], 2]] - BSARPos[[1]]) / BSAROrient[[1]];  
IAMlloTS1 = Append[IAMlloTS1, Flatten[{"TS1-14", BSARPos + d BSAROrient}]];  
iIAMtheoL1[[ialign]] = Length[IAMlloTS1];  
IAMlloTS1[[iIAMtheoL1[[ialign]]]]
```

(Debug) Out[3477]=

```
{TS1-14, -2867., -2471.57, -81.8463}
```

(Debug) In[3478]:= **theoPosL1[[ialign]] = IAMlloTS1[[iIAMtheoL1[[ialign]], 2 ;; 4]]**

(Debug) Out[3478]=  
{-2867., -2471.57, -81.8463}

(Debug) In[3479]:= **theoOrientL1[[ialign]] = -BSAROrient**

(Debug) Out[3479]=  
{0.708292, 0.705919, -0.00021252}

Separation from LAC to BS AR surface (mm):

(Debug) In[3480]:= **theoDistanceL1[[ialign]] = Sqrt[(theoPosL1[[ialign]] - BSARPos).(theoPosL1[[ialign]] - BSARPos)]**

(Debug) Out[3480]=  
3728.16

(Debug) In[3481]:= **iIAMtheoRefL1[[ialign]] = "NA";**

(Debug) In[3482]:= **zeroYawReference = IAMlloTS1[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMlloTS1[[iIAMtheoL1[[ialign]], 2 ;; 3]];  
theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi**

(Debug) Out[3483]=  
45.0961

(Debug) In[3484]:= **theoPitchL1[[ialign]] = Sign[theoOrientL1[[ialign, 3]]] VectorAngle[Join[theoOrientL1[[ialign, 1 ;; 2]], {0}], theoOrientL1[[ialign]]] 180 / Pi**

(Debug) Out[3484]=  
-0.0121765

(Debug) In[3485]:= **formatLLOalignTable[ialign, ialign]**

(Debug) Out[3485]=

Alignment				Transit Square						Total Station									PL					
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl	Yl		deg	min	sec	deg	min	sec	
TS BS&ARellpBaf x,y,z	-226.4	160.2	-82.6	L1 IAM 379	-1858.0	-26231.2	IAM-L5	38154.0	-1854.2	L1 IAM 381	11591.0	-1845.1	-81.8	NA			3728.2	45.	5.	46.	0.	0.	-44.	

**solution 2**

```
(Debug) In[3486]:=
  ialign = 8;
  alignLabelL1[[ialign]]
```

```
(Debug) Out[3487]=
  TS BS HR  $\theta, \psi$ 
```

Required beam separation from HR and AR surfaces so as not to get an erroneous laser autocollimator (LAC) reading is 32 mm. The beam divergence of the Newport LDS-vector LAC is 100 urad. Given a wedge angle of 0.070 deg (for BS SN002 to be used for L1) and an index of refraction at 670 nm of  $\sim 1.456$ , the separation from the LAC to the BS AR surface must be at least  $\sim 9$  m :

```
(Debug) In[3488]:=
  31 / (1.456 (.070 Pi / 180) 2 - 100  $\times 10^{-6}$ )
```

```
(Debug) Out[3488]=
  8965.55
```

```
(Debug) In[3489]:=
  31.9 / (1.456 (.070 Pi / 180) 2)
```

```
(Debug) Out[3489]=
  8966.52
```

So place a new TS1-15 monument along the X = 0 line between IAM394 and IAM391:

```
(Debug) In[3490]:=
  IAMlloTS1 = Append[IAMlloTS1, Flatten[{"TS1-15", 0, 9250 / Sqrt[2] // N}]];
  iIAMOptSqL1[[ialign]] = Length[IAMlloTS1];
  IAMlloTS1[[iIAMOptSqL1[[ialign]]]]
```

```
(Debug) Out[3492]=
  {TS1-15, 0, 6540.74}
```

```
(Debug) In[3493]:=
  iIAMOptSqRefL1[[ialign]] = 13;
  IAMlloTS1[[iIAMOptSqRefL1[[ialign]]]]
```

```
(Debug) Out[3494]=
  {IAM 394, 0., 0.}
```

```
(Debug) In[3495]:=
  alignOpticOrientL1L[[ialign]]
```

```
(Debug) Out[3495]=
  {0.707429, 0.706784, -0.000211723}
```

Add a monument (TS1-16) at the intersection of a line from TS1-15 which is normal to the line through IAM-349 and IAM-391 and a line normal to the BS HR surface, but displaced laterally by the LTHP:

(Debug) In[3496]:=

```

LTHPL1[[ialign]] = "Y";
LTHPorient = Append[LTHPLengthRotationMatrix[Pi/2].alignOpticOrientL1L[[ialign, 1 ;; 2]], 0];
LTHPPosInX = 200;
s = (LTHPPosInX - alignOpticPosL1L[[ialign, 1]]) / alignOpticOrientL1L[[ialign, 1]];
LTHPPosIn = alignOpticPosL1L[[ialign]] + s alignOpticOrientL1L[[ialign]];
LTHPPosOut = LTHPPosIn + LTHPorient;

```

(Debug) In[3502]:=

```

d = (IAMlloTS1[[iIAMOptSqL1[[ialign]], 3]] - alignOpticPosL1L[[ialign, 2]] - LTHPorient[[2]]) / alignOpticOrientL1L[[ialign, 2]];
theoPosL1[[ialign]] = alignOpticPosL1L[[ialign]] + d alignOpticOrientL1L[[ialign]] + LTHPorient;
d1 = alignOpticPosL1L[[ialign]] - LTHPPosIn;
d2 = LTHPorient;
d3 = LTHPPosIn + LTHPorient - theoPosL1[[ialign]];
theoDistanceL1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3]

```

(Debug) Out[3507]:=

8967.3

(Debug) In[3508]:=

```

IAMlloTS1 = Append[IAMlloTS1, Flatten[{"TS1-16", theoPosL1[[ialign]]}]];
iIAMtheoL1[[ialign]] = Length[IAMlloTS1];
IAMlloTS1[[iIAMtheoL1[[ialign]]]]

```

(Debug) Out[3510]:=

{TS1-16, 5593.96, 6540.74, -84.4652}

(Debug) In[3511]:=

```

theoPosL1[[ialign]] = IAMlloTS1[[iIAMtheoL1[[ialign]], 2 ;; 4]]

```

(Debug) Out[3511]:=

{5593.96, 6540.74, -84.4652}

(Debug) In[3512]:=

```

theoOrientL1[[ialign]] = -BSHROrient

```

(Debug) Out[3512]:=

{-0.707429, -0.706784, 0.000211723}

Calculate the angular separation between the beam reflected by the AR surface (after transmission through the HR surface) and the beam reflected from the HR surface:

(Debug) In[3513]=

```
separationAngle =
  VectorAngle[Refract[Reflect[Refract[(1 + 10^-13) theoOrientL1[[ialign]], BSHROrient, 1, 1.456], BSAROrient], -BSHROrient, 1.456, 1], BSHROrient]
```

Power::infy : Infinite expression  $\frac{1}{0}$  encountered. >>

Infinity::indet : Indeterminate expression 0. ComplexInfinity encountered. >>

Infinity::indet : Indeterminate expression 0. ComplexInfinity encountered. >>

Infinity::indet : Indeterminate expression 0. ComplexInfinity encountered. >>

General::stop : Further output of Infinity::indet will be suppressed during this calculation. >>

Minors::mindet : Input matrix contains an indeterminate entry. >>

Part::partw : Part 3 of {{0.707429, 0.706784, -0.000211723}, {Indeterminate, Indeterminate, Indeterminate}} does not exist. >>

Dot::rect : Nonrectangular tensor encountered. >>

Dot::rect : Nonrectangular tensor encountered. >>

(Debug) Out[3513]=

A very large output was generated. Here is a sample of it:

$$\text{ArcCos}\left[\frac{1. (\ll 1 \gg)}{\sqrt{\text{Abs}[\ll 1 \gg - 0.000211723 \sqrt{1 - \ll 1 \gg}]^2 + \text{Abs}[\ll 1 \gg]^2 + \text{Abs}[\ll 1 \gg + \ll 19 \gg \sqrt{1 - \ll 1 \gg}]^2}}\right]$$





approximate calculation of this angle:

(Debug) In[3514]=

```
2 × 1.456 (wedge Pi / 180)
```

(Debug) Out[3514]=

```
0.00355768
```

Calculate the separation of the beam reflected from the BS AR surface, at the location of the Total Station:

(Debug) In[3515]:=

```
BStickness = 59.88;
theoDistanceL1[[ialign]] separationAngle + BStickness 2 wedge Pi / 180
```

(Debug) Out[3516]=

A very large output was generated. Here is a sample of it:

$$0.146314 + 8967.3 \text{ ArcCos} \left[ \frac{1. (\ll 1 \gg)}{\sqrt{\text{Abs}[\ll 1 \gg - \ll 23 \gg \ll 1 \gg]^2 + \text{Abs}[\ll 1 \gg]^2 + \text{Abs}[\ll 1 \gg + \ll 19 \gg \sqrt{1 - \ll 1 \gg}]^2}} \right]$$

Show Less Show More Show Full Output Set Size Limit...

(Debug) In[3517]:=

```
iIAMtheoRefL1[[ialign]] = Length[IAMlloTS1] - 1;
```

(Debug) In[3518]:=

```
zeroYawReference = IAMlloTS1[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMlloTS1[[iIAMtheoL1[[ialign]], 2 ;; 3]];
theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

(Debug) Out[3519]=

44.9739

(Debug) In[3520]:=

```
theoPitchL1[[ialign]] = Sign[theoOrientL1[[ialign, 3]]] VectorAngle[Join[theoOrientL1[[ialign, 1 ;; 2]], {0}], theoOrientL1[[ialign]]] 180 / Pi
```

(Debug) Out[3520]=

0.0121308

(Debug) In[3521]:=

```
formatLLOAlignTable[ialign, ialign]
```

(Debug) Out[3521]=

Alignment				Transit Square						Total Station						PLX									
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)		Distance (mm)	Yaw			Pitch			LTHR	LTHP	
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl		Yl	deg	min	sec	deg	min			sec
TS BS HR 0,ψ	-184.0	202.5	-82.7	_87	45990.8	-1845.1	L1 IAM 377	-1858.0	-1845.1	L1 IAM 382	-22283.5	-2245.5	-84.5	_87	45990.8	-1845.1	8967.3	44.	58.	26.	0.	0.	44.		Y

**solution 3**

In case the return beam intensity from the HR surface is too faint, add a monument (TS1-17) (near to monument (TS1-16)) at the intersection of a line at 90 deg from the line between TS1-15 and TS1-16 and a line along the retro-reflection from the BS AR surface through the BS HR surface, but displaced laterally by the LTHP:

```
(Debug) In[3522]:=
  ialign = 9;
  alignLabelL1[[ialign]]
```

```
(Debug) Out[3523]=
  TS BS AR  $\theta, \psi$ 
```

```
(Debug) In[3524]:=
  iIAMOptSqRefL1[[ialign]] = 13;
  IAMlloTS1[[iIAMOptSqRefL1[[ialign]]]]
```

```
(Debug) Out[3525]=
  {IAM 394, 0., 0.}
```

Reverse the orientation of the AR surface since we are reflecting off the AR surface after transmission through the BS:

```
(Debug) In[3526]:=
  theoOrientL1[[ialign]] = -Refract[-alignOpticOrientL1L[[ialign]], -BSHROrient, 1.456, 1]
```

```
(Debug) Out[3526]=
  {-0.708685, -0.705525, 0.000212883}
```

Use the optic position for the previous alignment (align-1), i.e. the HR surface:

```
(Debug) In[3527]:=
  LTHPL1[[ialign]] = "Y";
  LTHPorient = Append[LTHPLength RotationMatrix[Pi / 2].theoOrientL1[[ialign, 1 ;; 2]], 0];
  LTHPPosInX = 200;
  s = (LTHPPosInX - alignOpticPosL1L[[ialign - 1, 1]]) / theoOrientL1[[ialign, 1]];
  LTHPPosIn = alignOpticPosL1L[[ialign - 1]] + s theoOrientL1[[ialign]];
  LTHPPosOut = LTHPPosIn + LTHPorient;
```

```
(Debug) In[3533]:=
  d = (IAMlloTS1[[16, 2]] - alignOpticPosL1L[[ialign - 1, 1]] - LTHPorient[[1]]) / theoOrientL1[[ialign, 1]];
  theoPosL1[[ialign]] = alignOpticPosL1L[[ialign - 1]] + d theoOrientL1[[ialign]] + LTHPorient;
  d1 = alignOpticPosL1L[[ialign - 1]] - LTHPPosIn;
  d2 = LTHPorient;
  d3 = LTHPPosIn + LTHPorient - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3]
```

```
(Debug) Out[3538]=
  8154.87
```



(Debug) In[3539]:=

```
theoDistanceL1[[ialign]] separationAngle + BStickness 2 wedge Pi / 180
```

(Debug) Out[3539]:=

A very large output was generated. Here is a sample of it:

$$0.146314 + 8154.87 \operatorname{ArcCos} \left[ \frac{1. (\ll 1 \gg)}{\sqrt{\operatorname{Abs}[\ll 1 \gg - \ll 23 \gg \ll 1 \gg]^2 + \operatorname{Abs}[\ll 1 \gg]^2 + \operatorname{Abs}[\ll 1 \gg + \ll 19 \gg \sqrt{1 - \ll 1 \gg}]^2}} \right]$$

Show Less Show More Show Full Output Set Size Limit...

(Debug) In[3540]:=

```
IAMlloTS1 = Append[IAMlloTS1, Flatten[{"TS1-17", theoPosL1[[ialign]]}]];
iIAMtheoL1[[ialign]] = Length[IAMlloTS1];
IAMlloTS1[[iIAMtheoL1[[ialign]]]]
```

(Debug) Out[3542]:=

```
{TS1-17, 5593.96, 5390.24, -84.3022}
```

(Debug) In[3543]:=

```
theoPosL1[[ialign]] = IAMlloTS1[[iIAMtheoL1[[ialign]], 2 ;; 4]]
```

(Debug) Out[3543]:=

```
{5593.96, 5390.24, -84.3022}
```

(Debug) In[3544]:=

```
IAMlloTS1 = Append[IAMlloTS1, Flatten[{"TS1-18", 0, theoPosL1[[ialign, 2]]}]];
iIAMtheoRefL1[[ialign]] = Length[IAMlloTS1];
IAMlloTS1[[iIAMtheoRefL1[[ialign]]]]
```

(Debug) Out[3546]:=

```
{TS1-18, 0, 5390.24}
```

(Debug) In[3547]:=

```
iIAMOptSql1[[ialign]] = 18;
IAMlloTS1[[iIAMOptSql1[[ialign]]]]
```

(Debug) Out[3548]:=

```
{TS1-18, 0, 5390.24}
```

(Debug) In[3549]:=

```
zeroYawReference = IAMlloTS1[[iIAMOptSql1[[ialign]], 2 ;; 3]] - IAMlloTS1[[iIAMtheoL1[[ialign]], 2 ;; 3]];
theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

(Debug) Out[3550]:=

```
44.8719
```

(Debug) In[3551]:=

```
theoPitchL1[[ialign]] = Sign[theoOrientL1[[ialign, 3]]] VectorAngle[Join[theoOrientL1[[ialign, 1 ;; 2]], {0}], theoOrientL1[[ialign]]] 180 / Pi
```

(Debug) Out[3551]:=

0.0121973

(Debug) In[3552]:=

```
formatLLOAlignTable[ialign, ialign]
```

(Debug) Out[3552]:=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	Xl	Yl	Zl	Name	Xl	Yl	Name	Xl	Yl	Name	Xl	Yl	Zl	Name	Xl	Yl		deg	min	sec	deg	min	sec		
TS BS AR $\theta, \psi$	-226.4	160.2	-82.6	IAM 92	-1858.0	45962.2	L1 IAM 377	-1858.0	-1845.1	L1 IAM 376	-1858.0	12604.4	-84.3	IAM 92	-1858.0	45962.2	8154.9	44.	52.	19.	0.	0.	44.		Y

**solution 4**

(Debug) In[3553]:=

```
ialign = 10;  
alignLabelL1[[ialign]]
```

(Debug) Out[3554]:=

TS BS HRel1pBaf x,y,z

(Debug) In[3555]:=

```
alignOpticPosL1L[[10, 1]]
```

(Debug) Out[3555]:=

-184.012

(Debug) In[3556]:=

```
iIAMOptSqRefL1[[ialign]] = "NA";  
iIAMOptSqL1[[ialign]] = "NA";
```

Add a monument, TS1-19, at the Y-coordinate of IAM349, and the X-coordinate of the BS HR face:

(Debug) In[3558]:=

```
IAMlloTS1 = Append[IAMlloTS1, Flatten[{"TS1-19", alignOpticPosL1L[[ialign, 1]], IAMlloTS1[[9, 3]]}];  
iIAMtheoL1[[ialign]] = Length[IAMlloTS1];  
IAMlloTS1[[iIAMtheoL1[[ialign]]]]
```

(Debug) Out[3560]:=

{TS1-19, -184.012, 7571.}

(Debug) In[3561]:=

```
theoPosL1[[ialign]] = Append[IAMlloTS1[[iIAMtheoL1[[ialign]], 2 ;; 3]], alignOpticPosL1L[[ialign, 3]]]
```

(Debug) Out[3561]:=

{-184.012, 7571., -82.6513}



**summary of BS cartridge solutions**

(Debug) In[3570]:=

```
formatLLOAlignTable[7, 10]
```

(Debug) Out[3570]=

Alignment			Transit Square						Total Station									PLX							
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
TS BS&A: Rel: lpB: af x,y,z	-226.4	160.2	-82.6	L1 IAM 379	-1858.0	-26231.2	IAM-L5	38154.0	-1854.2	L1 IAM 381	11591.0	-1845.1	-81.8	NA			3728.2	45.	5.	46.	0.	0.	-44.		
TS BS HR θ,ψ	-184.0	202.5	-82.7	_87	45990.8	-1845.1	L1 IAM 377	-1858.0	-1845.1	L1 IAM 382	-22283.5	-2245.5	-84.5	_87	45990.8	-1845.1	8967.3	44.	58.	26.	0.	0.	44.		Y
TS BS AR θ,ψ	-226.4	160.2	-82.6	IAM 92	-1858.0	45962.2	L1 IAM 377	-1858.0	-1845.1	L1 IAM 376	-1858.0	12604.4	-84.3	IAM 92	-1858.0	45962.2	8154.9	44.	52.	19.	0.	0.	44.		Y
TS BS HRel: lpB: af x,y,z	-184.0	202.5	-82.7	NA			NA			AM 405	-1858.0	-22503.2	-82.7	AM 404	-1858.0	-19941.0	7368.5	0.	0.	0.	0.	0.	0.		

**Chamber**

**solution 1**

Set the Total Station on the beam line path from the center of the BS to the center of PR3, looking at the center of the BS, in order to align the position (x, y, z) of the LBSC2 cartridge, using the HR Elliptical Baffle target (x, z) and the retro-reflector (y)

(Debug) In[3571]:=

```
ialign = 11;
alignLabelL1[[ialign]]
```

(Debug) Out[3572]=

```
BS HR&ITMellpBafs x,y,z
```

(Debug) In[3573]:=

```
iIAMOptSqL1[[ialign]] = 12;
IAMllo[[iIAMOptSqL1[[ialign]]]]
```

(Debug) Out[3574]=

```
{L1 IAM 378, -1858., -2245.5}
```

(Debug) In[3575]:=

```
iIAMOptSqRefL1[[ialign]] = 16;
IAMllo[[iIAMOptSqRefL1[[ialign]]]]
```

(Debug) Out[3576]=

```
{L1 IAM 382, -22283.5, -2245.5}
```

(Debug) In[3577]:=

```
IAMllo[[iIAMOptSqL1[[ialign]], 2]]
```

(Debug) Out[3577]=

```
-1858.
```

(Debug) In[3578]:=

```
s = (IAMllo[[iIAMOptSqL1[[ialign]], 2]] - alignOpticPosL1L[[5, 1]]) / (alignOpticPosL1L[[ialign, 1]] - alignOpticPosL1L[[5, 1]]);
theoPosL1[[ialign]] = s (alignOpticPosL1L[[ialign]] - alignOpticPosL1L[[5]]) + alignOpticPosL1L[[5]];
IAMllo = Append[IAMllo, Flatten[{"am 506", theoPosL1[[ialign, 1 ;; 2]]}]];
iIAMtheoL1[[ialign]] = Length[IAMllo];
Flatten[{"am 506", theoPosL1[[ialign, 1 ;; 2]]}]
```

(Debug) Out[3582]=

```
{am 506, -1858., -183.361}
```

(Debug) In[3583]:=

```
alignOpticPosL1L[[ialign]]
```

(Debug) Out[3583]=

```
{-202.537, -184.012, -82.6513}
```

(Debug) In[3584]:=

```
theoPosL1[[ialign]]
```

(Debug) Out[3584]=

```
{-1858., -183.361, -83.0965}
```

(Debug) In[3585]:=

```
d = alignOpticPosL1L[[ialign]] - theoPosL1[[ialign]];
theoDistanceL1[[ialign]] = Sqrt[d.d]
theoOrientL1[[ialign]] = d / theoDistanceL1[[ialign]]
```

(Debug) Out[3586]=

```
1655.46
```

(Debug) Out[3587]=

```
{1., -0.000393247, 0.00026896}
```

(Debug) In[3588]:=

```
iIAMtheoRefL1[[ialign]] = 11;
IAMllo[[iIAMtheoRefL1[[ialign]]]]
```

(Debug) Out[3589]=

```
{L1 IAM 379, -1858., -26 231.2}
```

(Debug) In[3590]:=

```
zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

(Debug) Out[3591]:=

89.9775

(Debug) In[3592]:=

```
theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

(Debug) Out[3592]:=

0.0154103

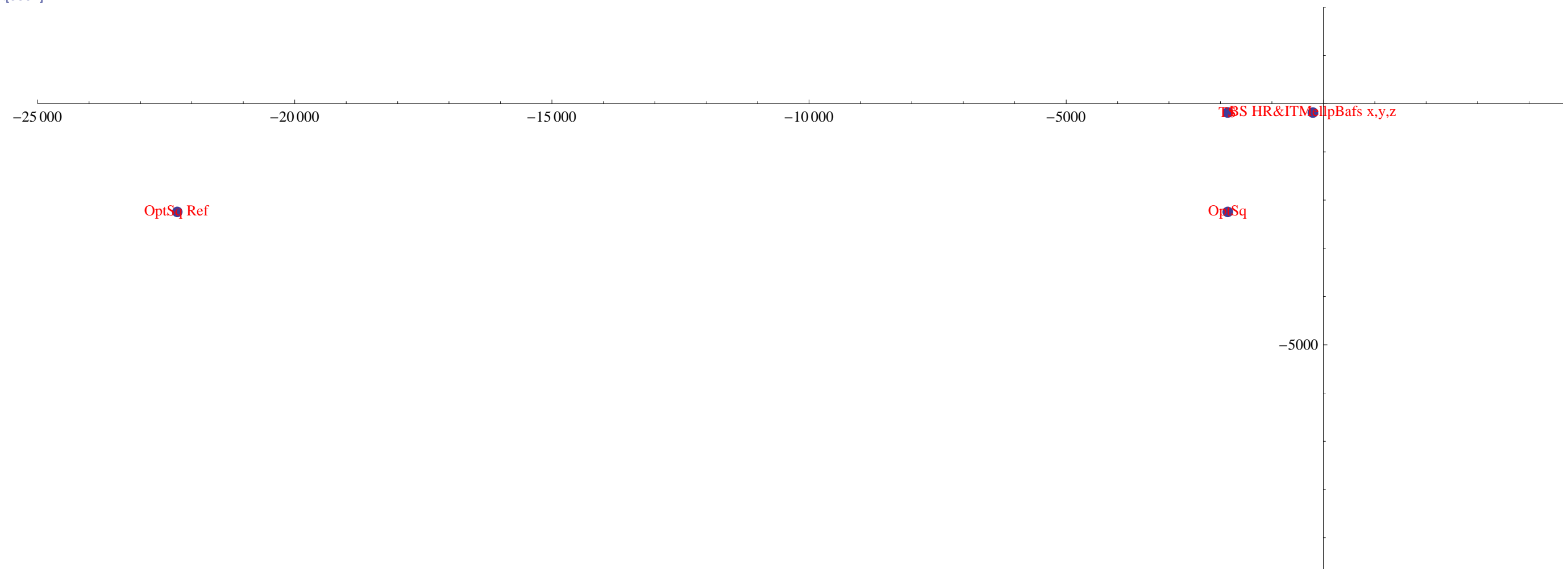
(Debug) In[3593]:=

```
data = {alignOpticPosL1L[[ialign, 1 ;; 2]], IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMOptSqRefL1[[ialign]], 2 ;; 3]],
        IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMtheoRefL1[[ialign]], 2 ;; 3]]};
dataPlot = ListPlot[data, PlotStyle -> PointSize -> Large, PlotRange -> All];
labels = {alignLabelL1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref"};
PointLabels = Table[Text[labels[[i]], data[[i]], {i, 1, Length[labels]}];
```

(Debug) In[3597]:=

```
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, {-30 000, 2000}}]
```

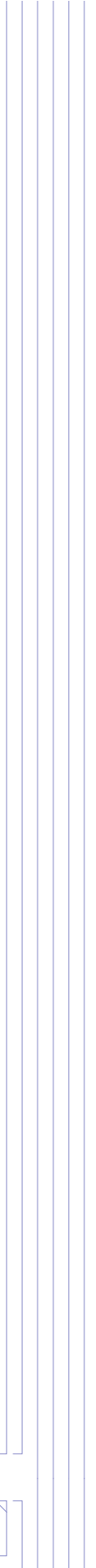
(Debug) Out[3597]:=



-10000  
-15000  
-20000  
-25000  
-30000

TSRef

(Debug) In[3598]:=  
formatLLOAlignTable[11, 11]



(Debug) Out[3598]=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
BS HR&ITMellpBafs x,y,z	-202.5	-184.0	-82.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 506	-1858.0	-183.4	-83.1	L1 IAM 379	-1858.0	-26231.2	1655.5	89.	58.	39.	0.	0.	55.		

**solution 2**

(Debug) In[3648]:=

```
ialign = 12;
alignLabelL1[[ialign]]
```

(Debug) Out[3649]=

BS HR θ,ψ

(Debug) In[3650]:=

```
iIAMOptSqL1[[ialign]] = 12;
IAMllo[[iIAMOptSqL1[[ialign]]]]
```

(Debug) Out[3651]=

{L1 IAM 378, -1858., -2245.5}

(Debug) In[3652]:=

```
iIAMOptSqRefL1[[ialign]] = 16;
IAMllo[[iIAMOptSqRefL1[[ialign]]]]
```

(Debug) Out[3653]=

{L1 IAM 382, -22283.5, -2245.5}

(Debug) In[3654]:=

```
alignOpticOrientL1L[[ialign]] = opticOrientL1L[[4]];
theoOrientL1[[ialign]] = -alignOpticOrientL1L[[ialign]];
```

(Debug) In[3656]:=

```
IAMllo[[iIAMOptSqL1[[ialign]], 2]]
```

(Debug) Out[3656]=

-1858.

(Debug) In[3657]:=

```
s = (IAMllo[[iIAMOptSqL1[[ialign]], 2]] - alignOpticPosL1L[[5, 1]]) / (alignOpticPosL1L[[ialign, 1]] - alignOpticPosL1L[[5, 1]]);
theoPosL1[[ialign]] = s (alignOpticPosL1L[[ialign]] - alignOpticPosL1L[[5]]) + alignOpticPosL1L[[5]];
IAMllo = Append[IAMllo, Flatten[{"am 506", theoPosL1[[ialign, 1 ;; 2]]}]];
iIAMtheoL1[[ialign]] = Length[IAMllo];
Flatten[{"am 506", theoPosL1[[ialign, 1 ;; 2]]}]
```

(Debug) Out[3661]=

{am 506, -1858., -183.361}



```
(Debug) In[3662]:=
  alignOpticPosL1L[[ialign]]
```

```
(Debug) Out[3662]=
  {-202.537, -184.012, -82.6513}
```

```
(Debug) In[3663]:=
  theoPosL1[[ialign]]
```

```
(Debug) Out[3663]=
  {-1858., -183.361, -83.0965}
```

```
(Debug) In[3664]:=
  alignOpticOrientL1L[[ialign]]
```

```
(Debug) Out[3664]=
  {-0.706784, 0.707429, -0.000211723}
```

Approximate position of the LTHP (in the BSC2 chamber, in the -X direction from the BS):

```
(Debug) In[3665]:=
  LTHPL1[[ialign]] = "Y";
  LTHPorient = Append[LTHPlength RotationMatrix[Pi / 2].alignOpticOrientL1L[[ialign, 1 ;; 2]], 0];
  LTHPPosInX = -1000;
  s = (LTHPPosInX - alignOpticPosL1L[[ialign, 1]]) / alignOpticOrientL1L[[ialign, 1]];
  LTHPPosIn = alignOpticPosL1L[[ialign]] + s alignOpticOrientL1L[[ialign]];
  LTHPPosOut = LTHPPosIn + LTHPorient;
```

```
(Debug) In[3671]:=
  d = (IAMPosL1lo[[iIAMOptSqL1[[ialign]], 1]] - alignOpticPosL1L[[ialign, 1]] - LTHPorient[[1]]) / alignOpticOrientL1L[[ialign, 1]];
  theoPosL1[[ialign]] = alignOpticPosL1L[[ialign]] + d alignOpticOrientL1L[[ialign]] + LTHPorient;
  d1 = alignOpticPosL1L[[ialign]] - LTHPPosIn;
  d2 = LTHPorient;
  d3 = LTHPPosIn + LTHPorient - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d1.d1] + Sqrt[d2.d2] + Sqrt[d3.d3];
```

```
(Debug) In[3677]:=
  IAMllo = Append[IAMllo, Flatten[{"am 507", theoPosL1[[ialign, 1 ;; 2]]}]];
  iIAMtheoL1[[ialign]] = Length[IAMllo];
  Flatten[{"am 507", theoPosL1[[ialign, 1 ;; 2]]}]
```

```
(Debug) Out[3679]=
  {am 507, -1858., 906.948}
```

```
(Debug) In[3680]:=
```

```
  iIAMtheoRefL1[[ialign]] = 11;  
  IAMllo[[iIAMtheoRefL1[[ialign]]]]
```

```
(Debug) Out[3681]=
```

```
{L1 IAM 379, -1858., -26 231.2}
```

```
(Debug) In[3682]:=
```

```
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];  
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

```
(Debug) Out[3683]=
```

```
44.9739
```

```
(Debug) In[3684]:=
```

```
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

```
(Debug) Out[3684]=
```

```
0.0171634
```

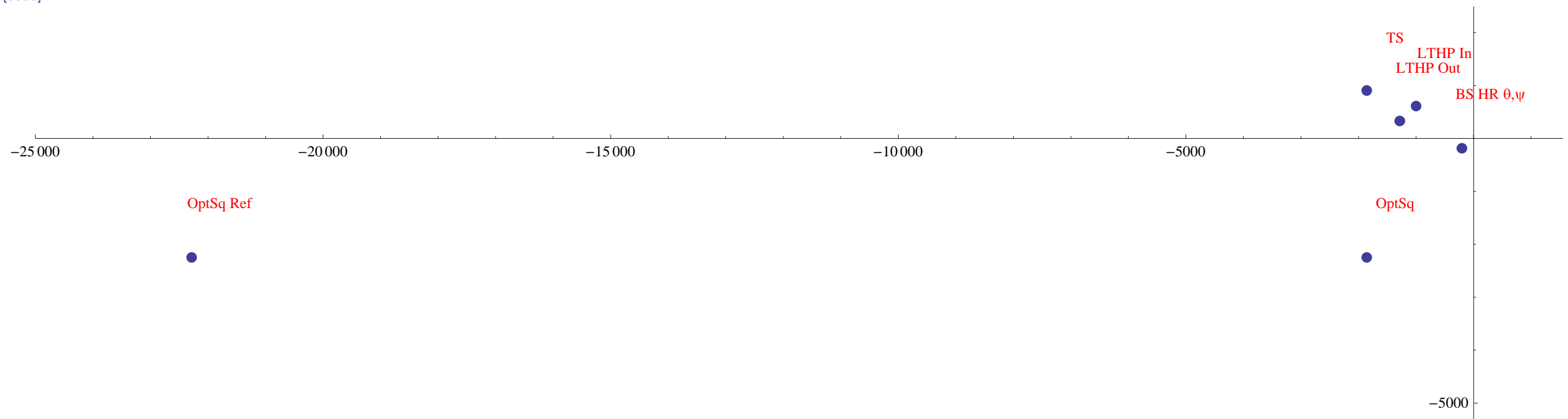
```
(Debug) In[3685]:=
```

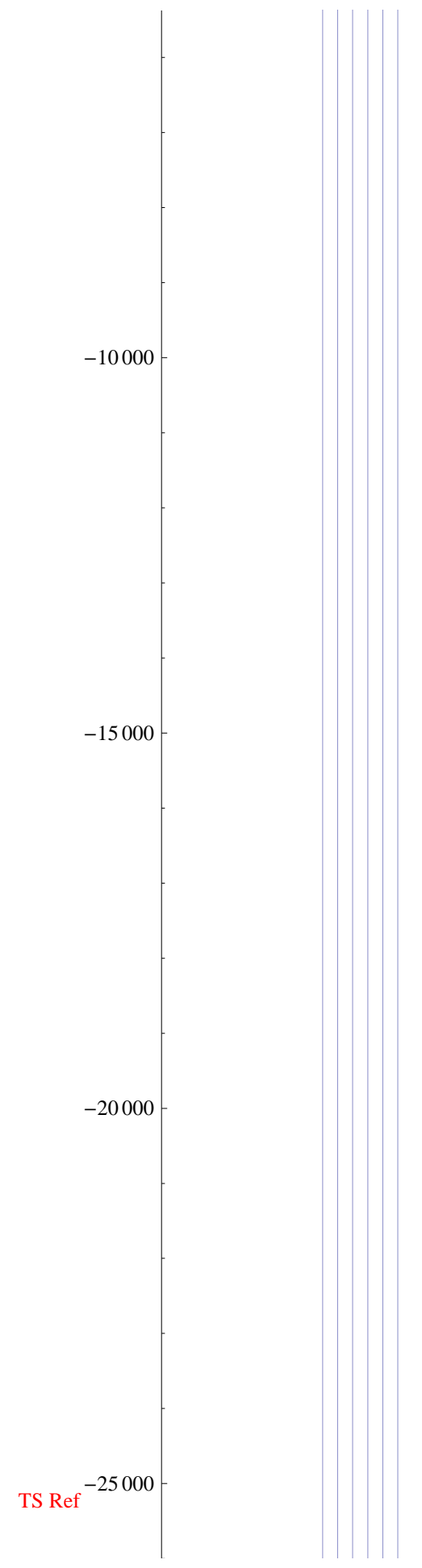
```
  data = {alignOpticPosL1L[[ialign, 1 ;; 2]], IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMOptSqRefL1[[ialign]], 2 ;; 3]],  
         IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMtheoRefL1[[ialign]], 2 ;; 3]], LTHPPosIn[[1 ;; 2]], LTHPPosOut[[1 ;; 2]]};  
  dataPlot = ListPlot[data, PlotStyle -> PointSize -> Large];  
  labels = {alignLabelL1[[ialign]], "OptSq", "OptSq Ref", "TS", "TS Ref", "LTHP In", "LTHP Out"};  
  PointLabels = Table[Text[labels[[i]], data[[i]] + {500, 1000}], {i, 1, Length[labels]}];
```

```
(Debug) In[3689]:=
```

```
  Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 2000}, All}]
```

```
(Debug) Out[3689]=
```





(Debug) In[3692]:=

```
formatLLOAlignTable[ialign - 1, ialign]
```

(Debug) Out[3692]:=

Alignment				Transit Square						Total Station									PLX						
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHE
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
BS HR&IT: Mell: pBaf: s x,y,z	-202.5	-184.0	-82.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 506	-1858.0	-183.4	-83.1	L1 IAM 379	-1858.0	-26231.2	1655.5	89.	58.	39.	0.	0.	55.		
BS HR $\theta, \psi$	-202.5	-184.0	-82.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 507	-1858.0	906.9	-83.1	L1 IAM 379	-1858.0	-26231.2	2341.9	44.	58.	26.	0.	1.	2.		Y

**solution 3**

(Debug) In[3601]:=

```
ialign = 13;  
alignLabelL1[[ialign]]
```

(Debug) Out[3602]:=

```
BS AR  $\theta, \psi$ 
```

SOLUTION NOT NEEDED -- REFLECTANCE FROM HR FACE IS SUFFICIENT

**2.4.7. SRM Alignment**

**2.4.8. SR2 Alignment**

**2.4.9. SR3 Alignment**

**2.4.10. ITMx Alignment**

Cartridge

Chamber

**2.4.11. ITMy Alignment**

Cartridge

Chamber

**2.4.12. ETMx Alignment**

Cartridge

Chamber

**2.4.13. ETMy Alignment**

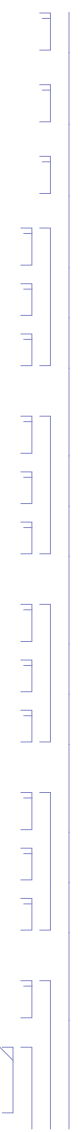
Cartridge

Chamber

**2.4.14. Summary of L1 Alignment Solutions**

(Debug) In[3691]:=

```
formatLLOAlignTable[1, nAlignsL1]
```



(Debug) Out[3691]=

Alignment				Transit Square						Total Station										PLX					
Name	Local Coordinates (mm)			Over Monument (mm)			Sights Monument (mm)			Over Monument (mm)				Sights Monument (mm)			Distance (mm)	Yaw			Pitch			LTHR	LTHP
	X1	Y1	Z1	Name	X1	Y1	Name	X1	Y1	Name	X1	Y1	Z1	Name	X1	Y1		deg	min	sec	deg	min	sec		
PRM HR x,y,z	-20189.6	-628.1	-96.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 501	-1858.0	0.0	-96.4	L1 IAM 379	-1858.0	-26231.2	18342.4	88.	2.	16.	0.	0.	0.		
PRM HR θ,ψ	-20189.6	-628.1	-96.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 500	-1858.0	-120.3	-91.6	L1 IAM 379	-1858.0	-26231.2	18734.3	89.	39.	48.	0.	0.	55.		Y
PR2 HR x,y,z	-3579.2	-530.5	-92.0	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 503	-1858.0	-544.3	-92.0	L1 IAM 379	-1858.0	-26231.2	1721.3	90.	27.	34.	0.	0.	0.		
PR2 HR θ,ψ	-3579.2	-530.5	-92.0	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 502	-1858.0	-144.2	-92.0	L1 IAM 379	-1858.0	-26231.2	6059.8	90.	27.	34.	0.	0.	0.	Y	
PR3 HR x,y,z	-19740.0	-176.3	-87.9	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 505	-1858.0	0.0	-87.9	L1 IAM 379	-1858.0	-26231.2	17882.9	89.	26.	6.	0.	0.	0.		
PR3 HR θ,ψ	-19740.0	-176.3	-87.9	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 504	-1858.0	24.3	-87.9	L1 IAM 379	-1858.0	-26231.2	18278.7	90.	38.	20.	0.	0.	0.		Y
TS BS&ARellpBaf x,y,z	-226.4	160.2	-82.6	L1 IAM 379	-1858.0	-26231.2	IAM-L5	38154.0	-1854.2	L1 IAM 381	11591.0	-1845.1	-81.8	NA			3728.2	45.	5.	46.	0.	0.	-44.		
TS BS HR θ,ψ	-184.0	202.5	-82.7	_87	45990.8	-1845.1	L1 IAM 377	-1858.0	-1845.1	L1 IAM 382	-22283.5	-2245.5	-84.5	_87	45990.8	-1845.1	8967.3	44.	58.	26.	0.	0.	44.		Y
TS BS AR θ,ψ	-226.4	160.2	-82.6	IAM 92	-1858.0	45962.2	L1 IAM 377	-1858.0	-1845.1	L1 IAM 376	-1858.0	12604.4	-84.3	IAM 92	-1858.0	45962.2	8154.9	44.	52.	19.	0.	0.	44.		Y
TS BS HRellpBaf x,y,z	-184.0	202.5	-82.7	NA			NA			AM 405	-1858.0	-22503.2	-82.7	AM 404	-1858.0	-19941.0	7368.5	0.	0.	0.	0.	0.	0.		
BS HR&ITMellpBafs x,y,z	-202.5	-184.0	-82.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 506	-1858.0	-183.4	-83.1	L1 IAM 379	-1858.0	-26231.2	1655.5	89.	58.	39.	0.	0.	55.		
BS HR θ,ψ	-202.5	-184.0	-82.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 507	-1858.0	906.9	-83.1	L1 IAM 379	-1858.0	-26231.2	2341.9	44.	58.	26.	0.	1.	2.		Y
BS AR θ,ψ	-160.2	-226.4	-82.6	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SRM HR x,y,z	305.0	-19908.7	-81.3	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SRM HR θ,ψ	305.0	-19908.7	-81.3	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SR2 HR x,y,z	-594.1	-4178.2	-81.5	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SR2 HR θ,ψ	-594.1	-4178.2	-81.5	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SR3 HR x,y,z	-175.2	-19616.0	-82.1	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
SR3 HR θ,ψ	-175.2	-19616.0	-82.1	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ITMx HR x,y,z	5013.0	-200.0	-81.4	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ITMx HR θ,ψ	5013.0	-200.0	-81.4	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ITMy HR x,y,z	-200.0	4983.1	-83.0	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ITMy HR θ,ψ	-200.0	4983.1	-83.0	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ETMx HR x,y,z	4.0 × 10 <sup>6</sup>	-200.0	1180.0	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ETMx HR θ,ψ	4.0 × 10 <sup>6</sup>	-200.0	1180.0	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ETMy HR x,y,z	-200.0	4.0 × 10 <sup>6</sup>	-4.7	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		
ETMy HR θ,ψ	-200.0	4.0 × 10 <sup>6</sup>	-4.7	NA			NA			NA				NA			0.0	0.	0.	0.	0.	0.	0.		