

# E1200797-v2

## 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**

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

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

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

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

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

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

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

**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.



# Primary Optic Positions and Orientations

## 1.1. Intialization

## 1.2. Global to Local Coordinate Transformation Matrices

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

-Global coordinates taken from:

H1: D0901920-v10 ( was E1101147-v2, "H1\_recycling cavity length .076wedge")

L1: Zemax model "D090xxxx L1 Zemax layout.zar", PDMW vault version x010

H2: D0902345-v8 (was E1101148-v2, "H2\_recycling-cavity-length-0.076wedge")

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

Zemax model "D090xxxx H2 Zemax layout.zar", PDMW vault version x009

by running a ray trace and exporting the normal vector components ( $N_x$ ,  $N_y$ ,  $N_z$ ) 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\*.

Note that H2 will not be deployed (H2 components will become LIGO-India, I1). However the alignment solutions for ITMy (WBSC8) and ETMy (WBSC6) are given in this notebook (these two ITMs are used for the One Arm Test)

### 1.3.1. Global Coordinates

### 1.3.2. Local Coordinates

IAM @ LHO

TS1 @ LHO

TS2 @ LHO

H1

*Optics*

*Tables*

H2

IAM @ LLO

L1

*Optics*

*Tables*

*Chambers*



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## 1.4. Optic Pitch & Yaw Angles

## 2

# Theodolite/Autocolimator Alignment

## 2.1. Initialization

L1

(Debug) In[274]:=

```
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[286]:=

```

formatAlignTable[il_, 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[{alignLabelL1[[i]], NumberForm[alignOpticPosL1L[[i, 1]], {10, 1}], NumberForm[alignOpticPosL1L[[i, 2]], {10, 1}],
      NumberForm[alignOpticPosL1L[[i, 3]], {10, 1}], \
      If[iIAMOptSqL1[[i]] != "NA", IAMlloTS1[[iIAMOptSqL1[[i]], 1]], "NA"},
    If[iIAMOptSqL1[[i]] != "NA", NumberForm[IAMlloTS1[[iIAMOptSqL1[[i]], 2]], {10, 1}], "",
    If[iIAMOptSqL1[[i]] != "NA", NumberForm[IAMlloTS1[[iIAMOptSqL1[[i]], 3]], {10, 1}], "", \
      If[iIAMOptSqRefL1[[i]] != "NA", IAMlloTS1[[iIAMOptSqRefL1[[i]], 1]], "NA"},
    If[iIAMOptSqRefL1[[i]] != "NA", NumberForm[IAMlloTS1[[iIAMOptSqRefL1[[i]], 2]], {10, 1}], "",
    If[iIAMOptSqRefL1[[i]] != "NA", NumberForm[IAMlloTS1[[iIAMOptSqRefL1[[i]], 3]], {10, 1}], "", \
      IAMlloTS1[[iIAMtheoL1[[i]], 1]], NumberForm[IAMlloTS1[[iIAMtheoL1[[i]], 2]], {10, 1}],
    NumberForm[IAMlloTS1[[iIAMtheoL1[[i]], 3]], {10, 1}], NumberForm[theoPosL1[[i, 3]], {10, 1}], \
      If[iIAMtheoRefL1[[i]] != "NA", IAMlloTS1[[iIAMtheoRefL1[[i]], 1]], "NA"},
    If[iIAMtheoRefL1[[i]] != "NA", NumberForm[IAMlloTS1[[iIAMtheoRefL1[[i]], 2]], {10, 1}], "",
    If[iIAMtheoRefL1[[i]] != "NA", NumberForm[IAMlloTS1[[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, il, ih}}, 1, Frame -> All];

```

```
(Debug) In[287]:=
formatIAMAlignTable[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[{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}], "", \
      IAMllo[[iIAMtheoL1[[i]], 1]], NumberForm[IAMllo[[iIAMtheoL1[[i]], 2]], {10, 1}], NumberForm[IAMllo[[iIAMtheoL1[[i]], 3]], {10, 1}],
    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

2.2. H1

2.3. H2

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[461]:=
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 2 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[465]:=
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 HRelpBaf 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[477]:=
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[478]:=

```
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];
alignOpticPosL1L[[11]] = opticPosL1L[[4]];
alignOpticPosL1L[[12]] = opticPosL1L[[4]];
alignOpticPosL1L[[13]] = opticPosL1L[[5]];
alignOpticOrientL1L[[11]] = opticOrientL1L[[4]];
alignOpticOrientL1L[[12]] = opticOrientL1L[[4]];
alignOpticOrientL1L[[13]] = opticOrientL1L[[5]];
```

(Debug) In[487]:=

```
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	-20 207.7	-627.563	-97.3818	0.999983	0.00584648	0.000281441
PRM HR $\theta,\psi$	-20 207.7	-627.563	-97.3818	0.999983	0.00584648	0.000281441
PR2 HR x,y,z	-3589.13	-530.437	-92.6961	-0.999967	0.00808431	0
PR2 HR $\theta,\psi$	-3589.13	-530.437	-92.6961	-0.999967	0.00808431	0
PR3 HR x,y,z	-19 741.	-174.828	-88.324	0.999937	-0.0112396	0
PR3 HR $\theta,\psi$	-19 741.	-174.828	-88.324	0.999937	-0.0112396	0
TS BS&AREllpBaf x,y,z	-226.281	160.346	-82.7217	-0.708326	-0.705886	0.000212551
TS BS HR $\theta,\psi$	-183.941	202.656	-82.7344	0.707463	0.706751	-0.000211754
TS BS AR $\theta,\psi$	-226.281	160.346	-82.7217	-0.708326	-0.705886	0.000212551
TS BS HRelpBaf x,y,z	-183.941	202.656	-82.7344	0.707463	0.706751	-0.000211754
BS HR&ITMellpBafs x,y,z	-202.656	-183.941	-82.7344	-0.706751	0.707463	-0.000211754
BS HR $\theta,\psi$	-202.656	-183.941	-82.7344	-0.706751	0.707463	-0.000211754
BS AR $\theta,\psi$	-160.346	-226.281	-82.7217	0.705886	-0.708326	0.000212551
SRM HR x,y,z	-594.216	-4178.15	-82.1118	0.0421198	-0.999113	0
SRM HR $\theta,\psi$	-175.046	-19 616.	-82.4501	-0.013804	0.999905	$4.06389 \times 10^{-6}$
SR2 HR x,y,z	-175.046	-19 616.	-82.4501	-0.013804	0.999905	$4.06389 \times 10^{-6}$
SR2 HR $\theta,\psi$	5012.97	-200.049	-81.4418	1.	0.	-0.000312
SR3 HR x,y,z	5012.97	-200.049	-81.4418	1.	0.	-0.000312
SR3 HR $\theta,\psi$	-200.026	4983.05	-82.9823	$-1.90632 \times 10^{-7}$	1.	-0.000611
ITMx HR x,y,z	-200.026	4983.05	-82.9823	$-1.90632 \times 10^{-7}$	1.	-0.000611
ITMx HR $\theta,\psi$	$3.9995 \times 10^6$	-200.049	1179.96	-1.	0.	-0.000315
ITMy HR x,y,z	$3.9995 \times 10^6$	-200.049	1179.96	-1.	0.	-0.000315
ITMy HR $\theta,\psi$	-200.001	$3.99947 \times 10^6$	-4.7478	$-5.8468 \times 10^{-9}$	-1.	-0.0000188
ETMx HR x,y,z	-200.001	$3.99947 \times 10^6$	-4.7478	$-5.8468 \times 10^{-9}$	-1.	-0.0000188

(Debug) In[489]:=

```
nAlignsL1 = Length[alignLabelL1];
```



## 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[490]:=

```
ialign = 2;
alignLabelL1[[ialign]]
```

(Debug) Out[491]=

```
PRM HR  $\theta$ ,  $\psi$ 
```

(Debug) In[492]:=

```
theoOrientL1[[ialign]] = -alignOpticOrientL1L[[ialign]];
```

(Debug) In[493]:=

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

(Debug) Out[494]=

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

(Debug) In[495]:=

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

(Debug) Out[496]=

```
{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[497]:=

```
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[503]:=
  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[509]:=
  IAMllo = Append[IAMllo, Flatten[{"am 500", theoPosL1[[ialign, 1 ;; 2]]}]];
  iIAMtheoL1[[ialign]] = Length[IAMllo];
  Flatten[{"am 500", theoPosL1[[ialign, 1 ;; 2]]}]

(Debug) Out[511]=
  {am 500, -1858., -120.223}

(Debug) In[512]:=
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]

(Debug) Out[513]=
  {L1 IAM 379, -1858., -26 231.2}

(Debug) In[514]:=
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[515]=
  89.665

(Debug) In[516]:=
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi

(Debug) Out[516]=
  0.0161256

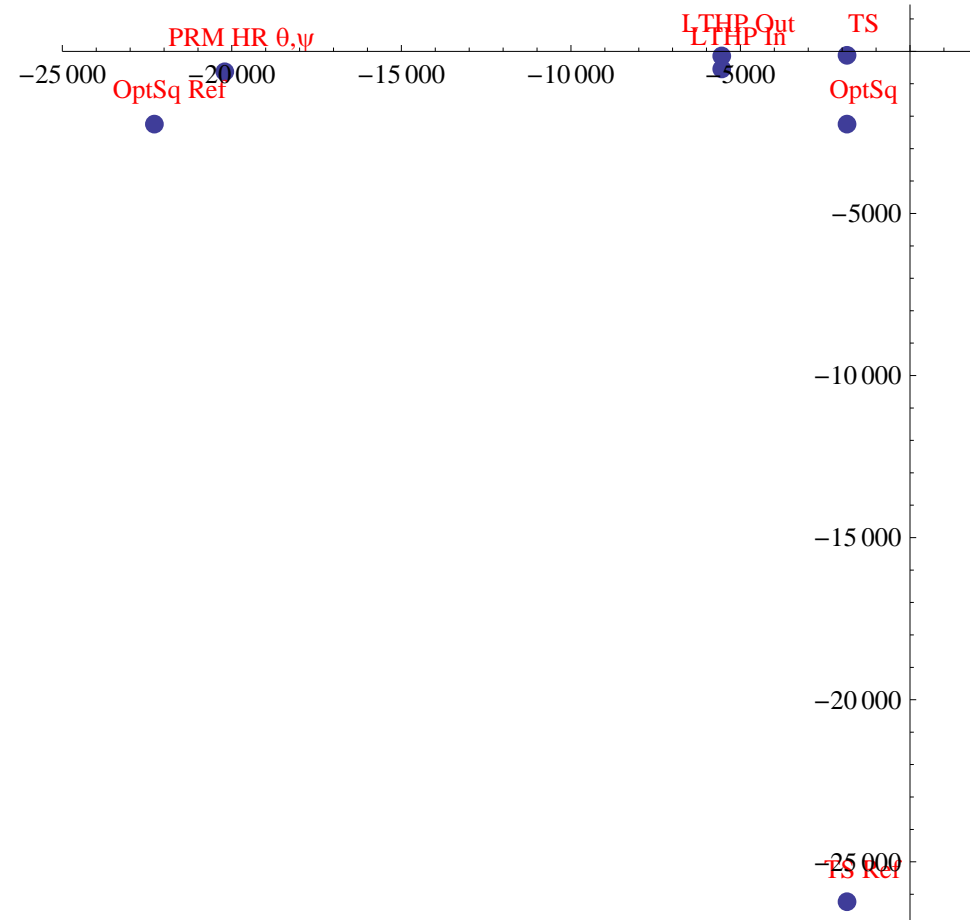
(Debug) In[517]:=
  data = {alignOpticPosL1L[[ialign, 1 ;; 2]], IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMOptSqRefL1[[ialign]], 2 ;; 3]],
    IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]], IAMllo[[iIAMtheoRefL1[[ialign]], 2 ;; 3]], LTHPPosIn[[1 ;; 2]], LTHPPosOut[[1 ;; 2]]};
  dataPlot = ListPlot[data, 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[521]:= Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 2000}, All}]
```

(Debug) Out[521]=



```
(Debug) In[522]:= formatIAMAlignTable[ialign, ialign]
```

(Debug) Out[522]=

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	-20207.7	-627.6	-97.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 500	-1858.0	-120.2	-92.2	L1 IAM 379	-1858.0	-26231.2	18752.4	89.	39.	54.	0.	0.	58.		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[523]:= ialign = 1;
alignLabelL1[[ialign]]
```

(Debug) Out[524]=  
PRM HR x, y, z

```

(Debug) In[525]:=
  iIAMOptSqL1[[ialign]] = 12;
  IAMllo[[iIAMOptSqL1[[ialign]]]]

(Debug) Out[526]=
  {L1 IAM 378, -1858., -2245.5}

(Debug) In[527]:=
  iIAMOptSqRefL1[[ialign]] = 16;
  IAMllo[[iIAMOptSqRefL1[[ialign]]]]

(Debug) Out[528]=
  {L1 IAM 382, -22 283.5, -2245.5}

(Debug) In[529]:=
  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[532]=
  {am 501, -1858., 0}

(Debug) In[533]:=
  d = alignOpticPosL1L[[ialign]] - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d.d];
  theoOrientL1[[ialign]] = d / theoDistanceL1[[ialign]]

(Debug) Out[535]=
  {-0.999416, -0.0341802, 0.}

(Debug) In[536]:=
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]

(Debug) Out[537]=
  {L1 IAM 379, -1858., -26 231.2}

(Debug) In[538]:=
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[539]=
  88.0412

```

```
(Debug) In[540]:=
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

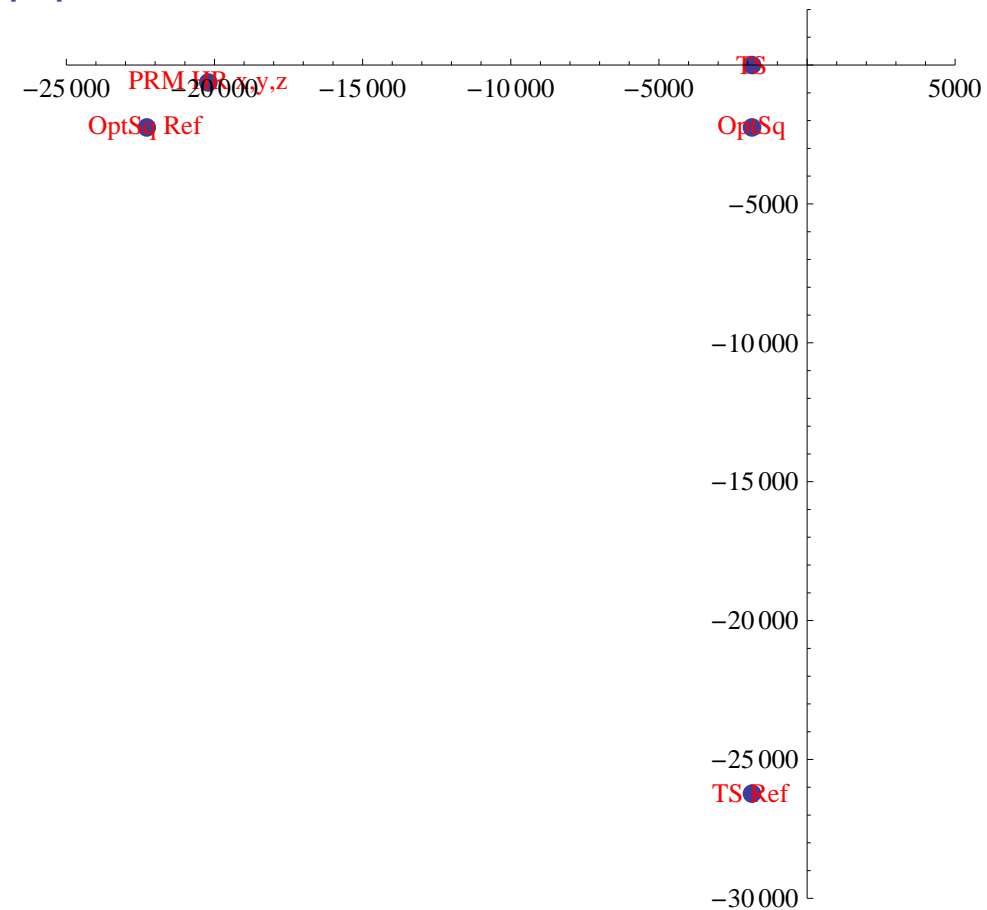
```
(Debug) Out[540]=
  0.
```

```
(Debug) In[541]:=
  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[545]:=
  Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio → 1, PlotRange → {{-25 000, 5000}, {-30 000, 2000}}]
```

```
(Debug) Out[545]=
```



```
(Debug) In[546]:=
formatIAMAlignTable[ialign, ialign]
```

```
(Debug) Out[546]=
```

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	-20207.7	-627.6	-97.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 501	-1858.0	0.0	-97.4	L1 IAM 379	-1858.0	-26231.2	18360.5	88.	2.	28.	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" (parrallel 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[547]:=
ialign = 4;
alignLabelL1[[ialign]]
```

```
(Debug) Out[548]=
PR2 HR  $\theta, \psi$ 
```

```
(Debug) In[549]:=
theoOrientL1[[ialign]] = alignOpticOrientL1L[[ialign]];
```

```
(Debug) In[550]:=
iIAMOptSqL1[[ialign]] = 12;
IAMllo[[iIAMOptSqL1[[ialign]]]]
```

```
(Debug) Out[551]=
{L1 IAM 378, -1858., -2245.5}
```

```
(Debug) In[552]:=
iIAMOptSqRefL1[[ialign]] = 16;
IAMllo[[iIAMOptSqRefL1[[ialign]]]]
```

```
(Debug) Out[553]=
{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[554]:=
  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[555]=
  {3.23413, 400.037, 0}

(Debug) Out[558]=
  {-5550., -514.585, -92.6961}

(Debug) Out[559]=
  {-5546.77, -114.548, -92.6961}

(Debug) In[560]:=
  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[566]:=
  IAMllo = Append[IAMllo, Flatten[{"am 502", theoPosL1[[ialign, 1 ;; 2]]}]];
  iIAMtheoL1[[ialign]] = Length[IAMllo];
  Flatten[{"am 502", theoPosL1[[ialign, 1 ;; 2]]}]

(Debug) Out[568]=
  {am 502, -1858., -144.37}

(Debug) In[569]:=
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]

(Debug) Out[570]=
  {L1 IAM 379, -1858., -26 231.2}

(Debug) In[571]:=
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

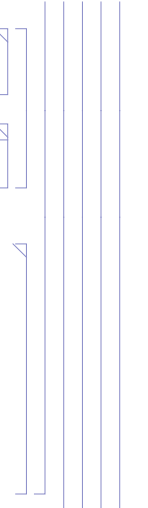
(Debug) Out[572]=
  90.4632

```

```
(Debug) In[573]:=
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

```
(Debug) Out[573]=
  0.
```

```
(Debug) In[574]:=
  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]}];
```



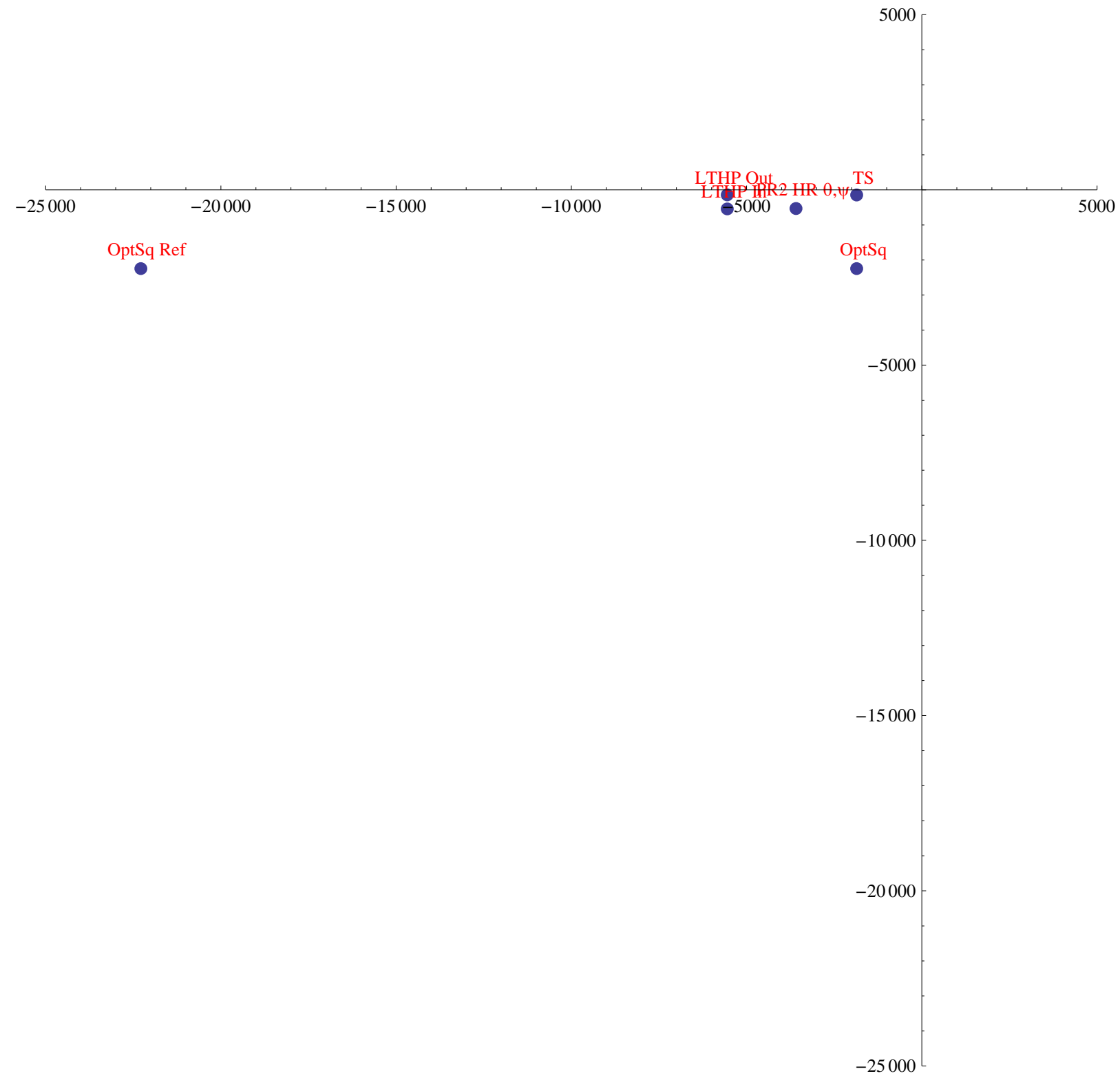


**results**

(Debug) In[578]:=

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

(Debug) Out[578]=



```
(Debug) In[579]:=
```

```
formatIAMAlignTable[ialign, ialign]
```

```
(Debug) Out[579]=
```

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 0,ψ	-3589.1	-530.4	-92.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 502	-1858.0	-144.4	-92.7	L1 IAM 379	-1858.0	-26231.2	6049.9	90.	27.	48.	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[580]:=
```

```
ialign = 3;
```

```
alignLabelL1[[ialign]]
```

```
(Debug) Out[581]=
```

```
PR2 HR x,y,z
```

```
(Debug) In[582]:=
```

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

```
IAMllo[[iIAMOptSqL1[[ialign]]]]
```

```
(Debug) Out[583]=
```

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

```
(Debug) In[584]:=
```

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

```
IAMllo[[iIAMOptSqRefL1[[ialign]]]]
```

```
(Debug) Out[585]=
```

```
{L1 IAM 382, -22283.5, -2245.5}
```

```
(Debug) In[586]:=
```

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

```
(Debug) Out[587]=
```

```
{-1858., -544.433, -92.6961}
```

```
(Debug) In[588]:=
```

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

```
iIAMtheoL1[[ialign]] = Length[IAMllo];
```

```
Flatten[{"am 503", theoPosL1[[ialign, 1 ;; 2]]}]
```

```
(Debug) Out[590]=
```

```
{am 503, -1858., -544.433}
```

```

(Debug) In[591]:=
  d = alignOpticPosL1L[[ialign]] - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d.d];
  theoOrientL1[[ialign]] = d / theoDistanceL1[[ialign]];

(Debug) In[594]:=
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]

(Debug) Out[595]=
  {L1 IAM 379, -1858., -26 231.2}

(Debug) In[596]:=
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[597]=
  90.4632

(Debug) In[598]:=
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi

(Debug) Out[598]=
  0.

(Debug) In[599]:=
  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]};

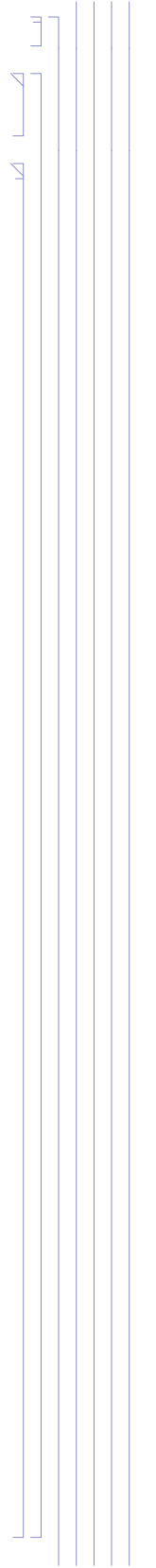
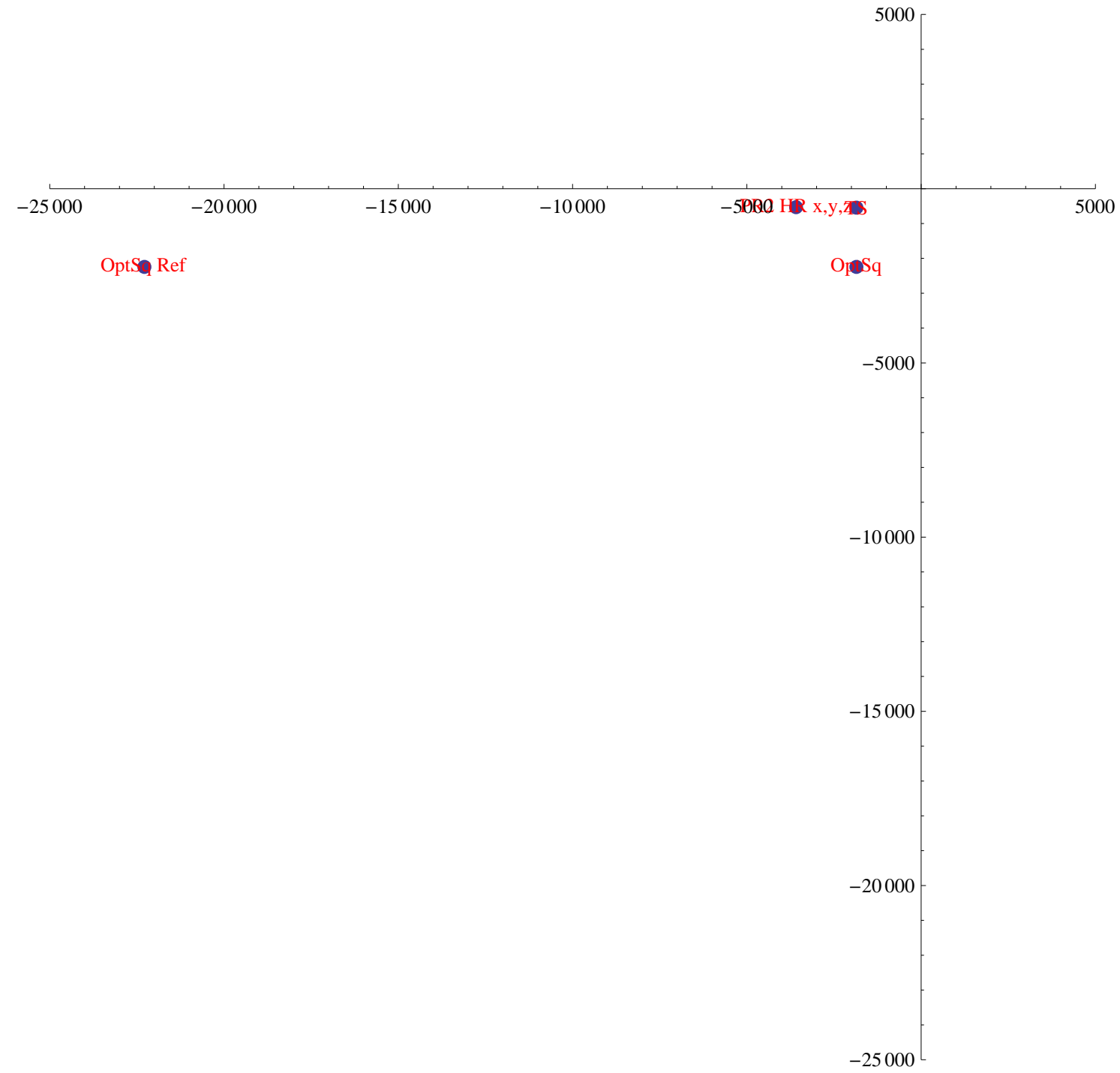
```

results

(Debug) In[603]:=

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

(Debug) Out[603]=



```
(Debug) In[604]:=
```

```
formatIAMAlignTable[ialign, ialign]
```

```
(Debug) Out[604]=
```

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	-3589.1	-530.4	-92.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 503	-1858.0	-544.4	-92.7	L1 IAM 379	-1858.0	-26231.2	1731.2	90.	27.	48.	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[605]:=
```

```
ialign = 6;  
alignLabelL1[[ialign]]
```

```
(Debug) Out[606]=
```

```
PR3 HR  $\theta$ ,  $\psi$ 
```

```
(Debug) In[607]:=
```

```
theoOrientL1[[ialign]] = -alignOpticOrientL1L[[ialign]];
```

```
(Debug) In[608]:=
```

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

```
(Debug) Out[609]=
```

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

```
(Debug) In[610]:=
```

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

```
(Debug) Out[611]=
```

```
{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[612]:=
```

```

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[618]:=
```

```

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[624]:=
```

```

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

```

```
(Debug) Out[626]=
```

```
{am 504, -1858., 24.2371}
```

```
(Debug) In[627]:=
```

```

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

```

```
(Debug) Out[628]=
```

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

```
(Debug) In[629]:=
```

```

zeroYawReference = IAMllo[[iIAMOptSql1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

```

```
(Debug) Out[630]=
```

```
90.644
```

```
(Debug) In[631]:=
```

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

```
(Debug) Out[631]=
```

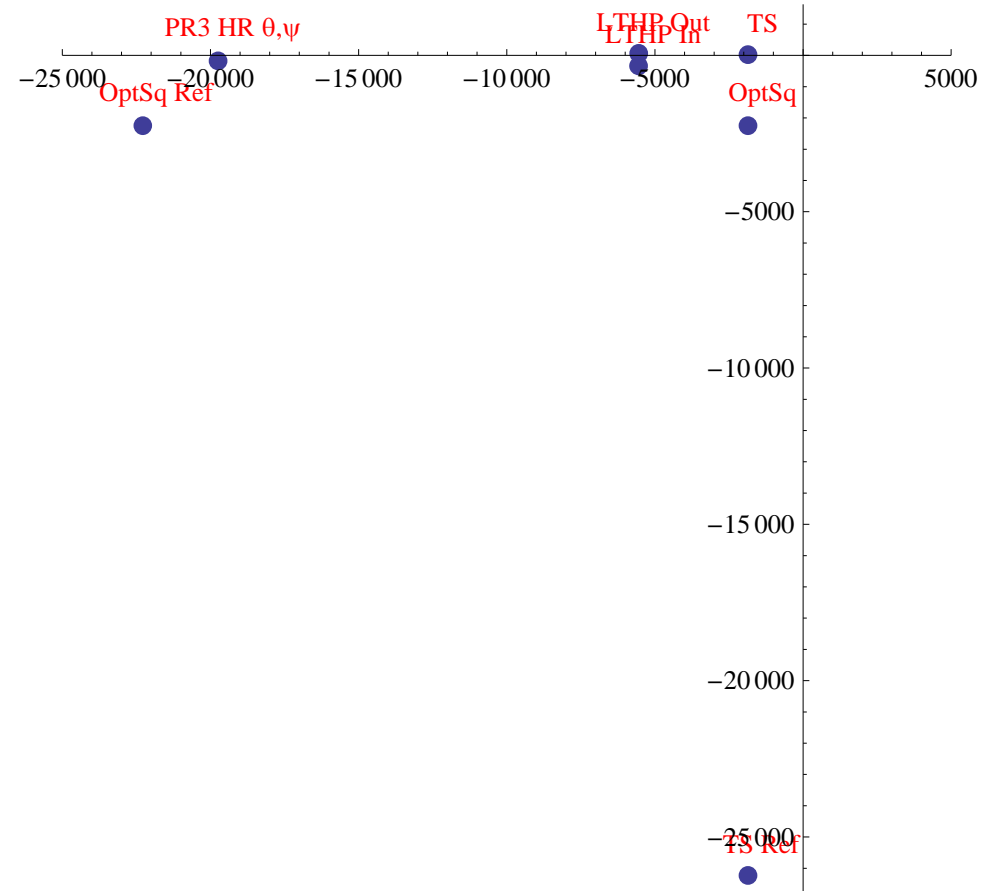
```
0.
```

```
(Debug) In[632]:=
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[636]:=
Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, All}]
```

(Debug) Out[636]=



```
(Debug) In[637]:=
formatIAMAlignTable[ialign, ialign]
```

(Debug) Out[637]=

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	-19741.0	-174.8	-88.3	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 504	-1858.0	24.2	-88.3	L1 IAM 379	-1858.0	-26231.2	18279.7	90.	38.	38.	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[638]:=
  ialign = 5;
  alignLabelL1[[ialign]]

(Debug) Out[639]=
  PR3 HR x,y,z

(Debug) In[640]:=
  iIAMOptSqL1[[ialign]] = 12;
  IAMllo[[iIAMOptSqL1[[ialign]]]]

(Debug) Out[641]=
  {L1 IAM 378, -1858., -2245.5}

(Debug) In[642]:=
  iIAMOptSqRefL1[[ialign]] = 16;
  IAMllo[[iIAMOptSqRefL1[[ialign]]]]

(Debug) Out[643]=
  {L1 IAM 382, -22283.5, -2245.5}

(Debug) In[644]:=
  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[647]=
  {am 505, -1858., 0}

(Debug) In[648]:=
  d = alignOpticPosL1L[[ialign]] - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d.d]
  theoOrientL1[[ialign]] = d / theoDistanceL1[[ialign]]

(Debug) Out[649]=
  17883.9

(Debug) Out[650]=
  {-0.999952, -0.00977572, 0.}

(Debug) In[651]:=
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]

(Debug) Out[652]=
  {L1 IAM 379, -1858., -26231.2}

```



```
(Debug) In[653]:=
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

```
(Debug) Out[654]=
  89.4399
```

```
(Debug) In[655]:=
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi
```

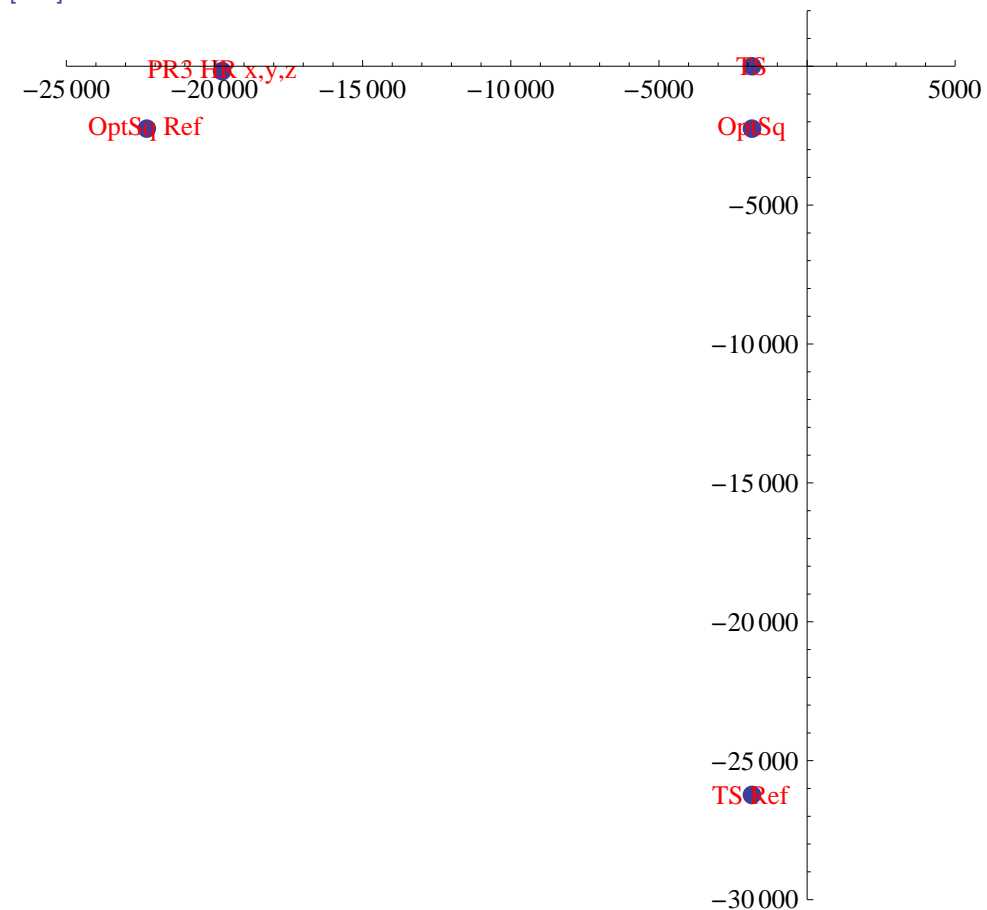
```
(Debug) Out[655]=
  0.
```

```
(Debug) In[656]:=
  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[660]:=
  Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, {-30 000, 2000}}]
```

```
(Debug) Out[660]=
```



(Debug) In[661]:=

**formatIAMAlignTable[ialign, ialign]**

(Debug) Out[661]=

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 x,y,z	-19741.0	-174.8	-88.3	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 505	-1858.0	0.0	-88.3	L1 IAM 379	-1858.0	-26231.2	17883.9	89.	26.	24.	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[662]:=

**formatIAMAlignTable[1, 6]**

(Debug) Out[662]=

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	-20207.7	-627.6	-97.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 501	-1858.0	0.0	-97.4	L1 IAM 379	-1858.0	-26231.2	18360.5	88.	2.	28.	0.	0.	0.		
PRM HR θ,ψ	-20207.7	-627.6	-97.4	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 500	-1858.0	-120.2	-92.2	L1 IAM 379	-1858.0	-26231.2	18752.4	89.	39.	54.	0.	0.	58.		Y
PR2 HR x,y,z	-3589.1	-530.4	-92.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 503	-1858.0	-544.4	-92.7	L1 IAM 379	-1858.0	-26231.2	1731.2	90.	27.	48.	0.	0.	0.		
PR2 HR θ,ψ	-3589.1	-530.4	-92.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 502	-1858.0	-144.4	-92.7	L1 IAM 379	-1858.0	-26231.2	6049.9	90.	27.	48.	0.	0.	0.	Y	
PR3 HR x,y,z	-19741.0	-174.8	-88.3	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 505	-1858.0	0.0	-88.3	L1 IAM 379	-1858.0	-26231.2	17883.9	89.	26.	24.	0.	0.	0.		
PR3 HR θ,ψ	-19741.0	-174.8	-88.3	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 504	-1858.0	24.2	-88.3	L1 IAM 379	-1858.0	-26231.2	18279.7	90.	38.	38.	0.	0.	0.		Y

(Debug) In[663]:=

**TableForm[IAMllo]**

(Debug) Out[663]/TableForm=

```

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	-20 122.1	-2245.5
AM 402	-22 692.	-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.	-1429.1
IAM 396	9633.	-1429.1
IAM 350	9833.	-1429.1
IAM 346	17 203.	3503.9
IAM 392	17 203.	3703.9
IAM 338	17 203.	3903.9
IAM 327	9833.	10 992.9
IAM 395	9633.	10 992.9
IAM 385	9433.	10 992.9
IAM 330	6761.	3903.9
IAM 390	6761.	3703.9
IAM 326	6761.	3503.9
IAM 399	9633.	3703.9
am 500	-1858.	-120.223
am 501	-1858.	0
am 502	-1858.	-144.37
am 503	-1858.	-544.433
am 504	-1858.	24.2371
am 505	-1858.	0

## 2.4.6. BS Alignment

### Cartridge

### 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[771]:=

```
ialign = 11;
alignLabelL1[[ialign]]
```

(Debug) Out[772]=

```
BS HR&ITMellpBafs x,y,z
```

(Debug) In[773]:=

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

(Debug) Out[774]=

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

(Debug) In[775]:=

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

(Debug) Out[776]=

```
{L1 IAM 382, -22283.5, -2245.5}
```

(Debug) In[777]:=

```
IAMllo[[iIAMOptSqL1[[ialign]], 2]]
```

(Debug) Out[777]=

```
-1858.
```

(Debug) In[778]:=

```
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[782]=

```
{am 506, -1858., -183.169}
```

(Debug) In[783]:=

```
alignOpticPosL1L[[ialign]]
```

(Debug) Out[783]=

```
{-202.656, -183.941, -82.7344}
```

(Debug) In[784]:=

```
theoPosL1[[ialign]]
```

(Debug) Out[784]=

```
{-1858., -183.169, -83.208}
```

```

(Debug) In[785]:=
  d = alignOpticPosL1L[[ialign]] - theoPosL1[[ialign]];
  theoDistanceL1[[ialign]] = Sqrt[d.d]
  theoOrientL1[[ialign]] = d / theoDistanceL1[[ialign]]

(Debug) Out[786]=
  1655.34

(Debug) Out[787]=
  {1., -0.000466408, 0.000286083}

(Debug) In[788]:=
  iIAMtheoRefL1[[ialign]] = 11;
  IAMllo[[iIAMtheoRefL1[[ialign]]]]

(Debug) Out[789]=
  {L1 IAM 379, -1858., -26 231.2}

(Debug) In[790]:=
  zeroYawReference = IAMllo[[iIAMOptSqL1[[ialign]], 2 ;; 3]] - IAMllo[[iIAMtheoL1[[ialign]], 2 ;; 3]];
  theoYawL1[[ialign]] = VectorAngle[theoOrientL1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi

(Debug) Out[791]=
  89.9733

(Debug) In[792]:=
  theoPitchL1[[ialign]] = ArcTan[theoOrientL1[[ialign, 3]] / theoOrientL1[[ialign, 1]]] 180 / Pi

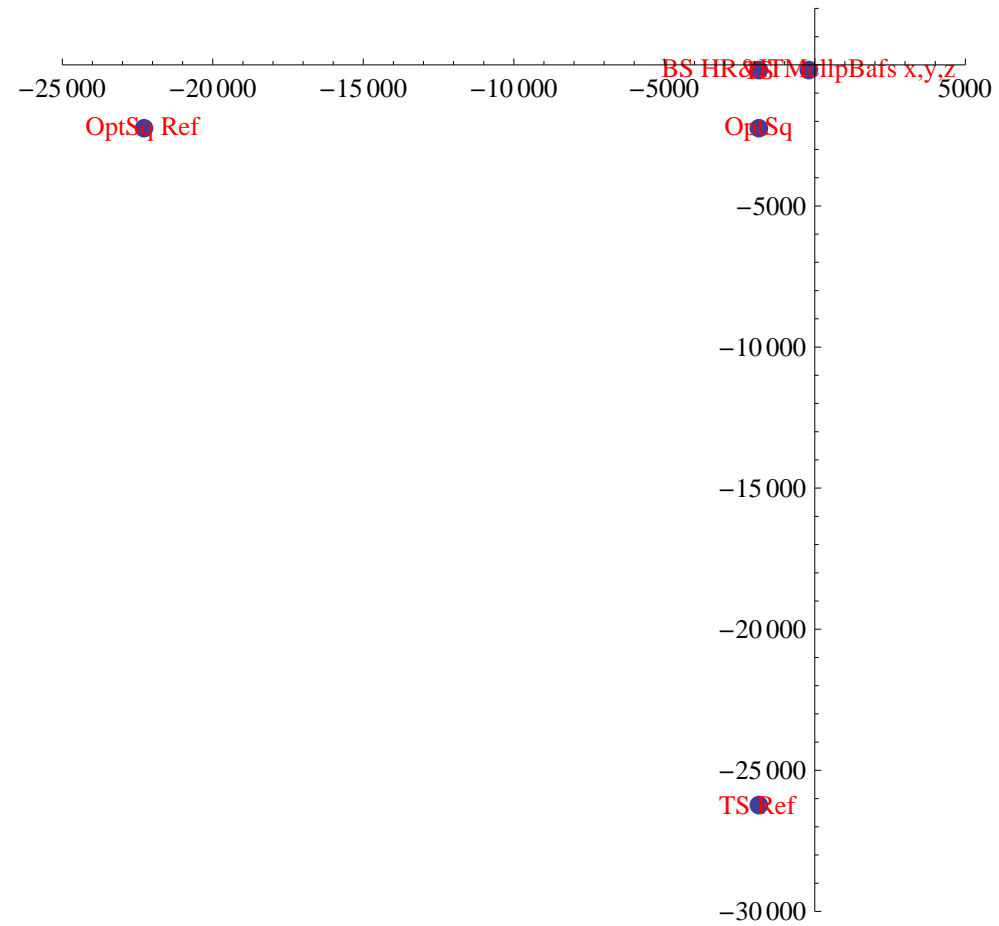
(Debug) Out[792]=
  0.0163914

(Debug) In[793]:=
  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[797]:=
  Show[dataPlot, Graphics[{Red, PointLabels}], AspectRatio -> 1, PlotRange -> {{-25 000, 5000}, {-30 000, 2000}}]
```

(Debug) Out[797]=



```
(Debug) In[803]:=
  formatIAMAlignTable[11, 11]
```

(Debug) Out[803]=

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	-202.7	-183.9	-82.7	L1 IAM 378	-1858.0	-2245.5	L1 IAM 382	-22283.5	-2245.5	am 506	-1858.0	-183.2	-83.2	L1 IAM 379	-1858.0	-26231.2	1655.3	89.	58.	24.	0.	0.	59.		

```
(Debug) In[798]:=
  TableForm[IAMllo[[51 ;; Length[IAMllo]]]]
```

(Debug) Out[798]/TableForm=

```
am 500    -1858.    -120.223
am 501    -1858.     0
am 502    -1858.   -144.37
am 503    -1858.  -544.433
am 504    -1858.    24.2371
am 505    -1858.     0
am 506    -1858.  -183.169
```

**solution 2**

```
(Debug) In[799]:=  
  ialign = 12;  
  alignLabelL1[[ialign]]
```

```
(Debug) Out[800]=  
  BS HR  $\theta, \psi$ 
```

SOLUTION TBD -- BUT DOES NOT REQUIRE A MONUMENT ON THE PIPE BRIDGE

**solution 3**

```
(Debug) In[801]:=  
  ialign = 13;  
  alignLabelL1[[ialign]]
```

```
(Debug) Out[802]=  
  BS AR  $\theta, \psi$ 
```

SOLUTION TBD -- BUT DOES NOT REQUIRE A MONUMENT ON THE PIPE BRIDGE

**2.4.7. SRM Alignment**

**2.4.8. SR2 Alignment**

**2.4.9. SR3 Alignment**

**2.4.10. ITMx Alignment**

**2.4.11. ITMy Alignment**

**2.4.12. ETMx Alignment**

**2.4.13. ETMy Alignment**

**2.4.14. Summary of Alignment Solutions**

