E1200797-v1

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

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 avergae 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

E1200556-v7 D. Coyne 6/26/2012

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.

1

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 (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*.

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

H1

Optics

(Debug) In[82]:=
```
nOpticsH1 = 11;
opticLabelH1 = {"PRM HR", "PR2 HR", "PR3 HR", "BS HR", "BS AR", "SRM HR", "SR2 HR", "SR3 HR", "ITMx HR", "ITMy HR", "ETMx HR", "ETMy HR"};
```

(Debug) In[84]:=
```
opticPosH1G = {{-20 208.0, -628.0, -94.1},
    {-3589.1, -530.4, -84.2},
    {-19 741.0, -175.3, -94.6},
    {-202.63, -183.9, -82.9},
    {-160.32, -226.23, -82.9},
    {305.2, -19 875.6, -113.5},
    {-594.3, -4160.4, -104.1},
    {-175.5, -19 615.9, -94.5},
    {4998.0, -200.0, -80.0},
    {-200.0,  4998.1, -80.0},
    {3 999 498.0, -200.0, -80.0},
   {-200.0 , 3 999 498.1, -80.0}};
```

(Debug) In[85]:=
```
opticOrientH1G = {{9.999826 10^ - 01,  5.872318 10^ - 03,  5.969026 × 10^ - 04},
 {-9.999674 10^ - 01,  8.054606 × 10^ - 03,  -6.194173 10^ - 04},
 {9.999368 × 10^ - 01,  -1.123096 10^ - 02,  6.194173 × 10^ - 04},
 {-.7067506313,  .7074627280,  0.000000},
   {0.7058116198 , -0.7083995938,  0.0000000000},
 {-5.714130 10^ - 02,  9.983659 × 10^ - 01,  5.963790 × 10^ - 04},
 {4.211194 × 10^ - 02,  -9.991129 10^ - 01,  1.250005 × 10^ - 05},
 {-1.379639 10^ - 02,  9.999048 × 10^ - 01,  -1.250005 10^ - 05},
 {1.000000 × 10^ + 00,  0.000000 × 10^ + 00,  0.000000 × 10^ + 00},
 {0.000000 × 10^ + 00,  1.000000 × 10^ + 00,  0.000000 × 10^ + 00},
 {-1.000000 10^ + 00,  0.000000 × 10^ + 00,  0.000000 × 10^ + 00},
 {0.000000 × 10^ + 00,  -1.000000 10^ + 00,  0.000000 × 10^ + 00}};
```

ensure that the normal vectors have unit length

(Debug) In[86]:=
```
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[87]:=
```
Do[
    If[Abs[opticOrientH1G[[i]].opticOrientH1G[[i]] - 1] > 10^-7, Print["error"],],
    {i, nOpticsH1}];
```

(Debug) In[88]:=
```
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	−20 208.	−628.	−94.1	0.999983	0.00587232	0.000596903
PR2 HR	−3589.1	−530.4	−84.2	−0.999967	0.00805461	−0.000619417
PR3 HR	−19 741.	−175.3	−94.6	0.999937	−0.011231	0.000619417
BS HR	−202.63	−183.9	−82.9	−0.706751	0.707463	0.
BS AR	−160.32	−226.23	−82.9	0.705812	−0.7084	0.
SRM HR	305.2	−19 875.6	−113.5	−0.0571413	0.998366	0.000596379
SR2 HR	−594.3	−4160.4	−104.1	0.0421119	−0.999113	0.0000125001
SR3 HR	−175.5	−19 615.9	−94.5	−0.0137964	0.999905	−0.0000125001
ITMx HR	4998.	−200.	−80.	1.	0.	0.
ITMy HR	−200.	4998.1	−80.	0.	1.	0.
ETMx HR	3.9995×10^6	−200.	−80.	−1.	0.	0.
ETMy HR	−200.	3.9995×10^6	−80.	0.	−1.	0.

Tables

H2

L1

Optics

Tables

Chambers

H1 and L1 Differences

1.3.2. Local Coordinates

IAM @ LHO

TS1 @ LHO

TS2 @ LHO

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

(Debug) In[144]:=

```
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[145]:=

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

(Debug) In[147]:=

```
tableHead = {"Xl", "Yl"};
Print[TableForm[IAMPosLlhoTS2, TableHeadings -> {IAMLabellhoTS2, tableHead}]]
```

	Xl	Yl
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

Tables

H2

IAM @ LLO

L1

Optics

Tables

Chambers

1.4. Optic Pitch & Yaw Angles

2 Theodolite/Autocolimator Alignment

2.1. Intialization

L1

H1

H1

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 {θ,ψ} solutions, then tweak as needed.

(Debug) In[300]:=

```
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], " θ,ψ", " x,y,z"]];
 alignOpticPosH1L[[i]] = opticPosH1L[[j]];
 alignOpticOrientH1L[[i]] = opticOrientH1L[[j]];
 , {i, 1, 2 * nOpticsH1}]
```

The BS has 4 cartridge alignment solutions and 2 chamber alignment solutions. Only one of the “BS HR θ,ψ” or “BS AR θ,ψ” solutions is needed; Both are listed just in case one return is weak.

(Debug) In[304]:=

```
alignLabelH1[[7]] = "TS BS&ARellpBaf x,y,z";
alignLabelH1[[8]] = "TS BS HR θ,ψ";
alignLabelH1[[9]] = "TS BS AR θ,ψ";
alignLabelH1[[10]] = "TS BS HRellpBaf 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#1 is rotated relative to LBSC2

(Debug) In[316]:=

```
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[317]:=

```
alignLabelH1 = Insert[alignLabelH1, "BS HR&ITMellpBafs x,y,z", 11];
alignLabelH1 = Insert[alignLabelH1, "BS HR θ,ψ", 12];
alignLabelH1 = Insert[alignLabelH1, "BS AR θ,ψ", 13];
alignOpticPosH1L[[11]] = opticPosH1L[[4]];
alignOpticPosH1L[[12]] = opticPosH1L[[4]];
alignOpticPosH1L[[13]] = opticPosH1L[[5]];
alignOpticOrientH1L[[11]] = opticOrientH1L[[4]];
alignOpticOrientH1L[[12]] = opticOrientH1L[[4]];
alignOpticOrientH1L[[13]] = opticOrientH1L[[5]];
```

(Debug) In[326]:=

```
tableHead = {"Xl", "Yl", "Zl", "Ul", "Vl", "Wl"};
Print[TableForm[Partition[Flatten[Transpose[{alignOpticPosH1L, alignOpticOrientH1L}]], 6], TableHeadings -> {alignLabelH1, tableHead}]]
```

	Xl	Yl	Zl	Ul	Vl	Wl
PRM HR x,y,z	−20 208.1	−627.999	−81.5892	0.999983	0.00587231	−0.0000225034
PRM HR θ,ψ	−20 208.1	−627.999	−81.5892	0.999983	0.00587231	−0.0000225034
PR2 HR x,y,z	−3589.15	−530.399	−81.9832	−0.999968	0.00805461	0
PR2 HR θ,ψ	−3589.15	−530.399	−81.9832	−0.999968	0.00805461	0
PR3 HR x,y,z	−19 741.1	−175.299	−82.3728	0.999937	−0.011231	0
PR3 HR θ,ψ	−19 741.1	−175.299	−82.3728	0.999937	−0.011231	0
TS BS&ARellpBaf x,y,z	−226.229	160.371	−82.8035	−0.7084	−0.705811	−0.000446086
TS BS HR θ,ψ	−183.899	202.681	−82.7768	0.707463	0.70675	0.000446656
TS BS AR θ,ψ	−226.229	160.371	−82.8035	−0.7084	−0.705811	−0.000446086
TS BS HRellpBaf x,y,z	−183.899	202.681	−82.7768	0.707463	0.70675	0.000446656
BS HR&ITMellpBafs x,y,z	−202.681	−183.899	−82.7768	−0.70675	0.707463	0.000446656
BS HR θ,ψ	−202.681	−183.899	−82.7768	−0.70675	0.707463	0.000446656
BS AR θ,ψ	−160.371	−226.229	−82.8035	0.705811	−0.7084	−0.000446086
SRM HR x,y,z	−594.364	−4160.4	−103.784	0.0421119	−0.999113	0
SRM HR θ,ψ	−175.559	−19 615.9	−94.6361	−0.0137964	0.999905	8.52869×10^{-6}
SR2 HR x,y,z	−175.559	−19 615.9	−94.6361	−0.0137964	0.999905	8.52869×10^{-6}
SR2 HR θ,ψ	4997.95	−199.999	−83.0987	1.	0.	−0.00061949
SR3 HR x,y,z	4997.95	−199.999	−83.0987	1.	0.	−0.00061949
SR3 HR θ,ψ	−199.999	4998.1	−79.9439	-9.03966×10^{-11}	1.	0.0000115318
ITMx HR x,y,z	−199.999	4998.1	−79.9439	-9.03966×10^{-11}	1.	0.0000115318
ITMx HR θ,ψ	3.9995×10^{6}	−199.949	−2561.62	−1.	0.	0.00062045
ITMy HR x,y,z	3.9995×10^{6}	−199.949	−2561.62	−1.	0.	0.00062045

(Debug) In[328]:=

```
nAlignsH1 = Length[alignLabelH1];
```

2.2.2. 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[329]:=

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

(Debug) Out[330]=

```
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[331]:=
```
BSARPos = alignOpticPosH1L[[ialign]]
```
(Debug) Out[331]=
```
{-226.229, 160.371, -82.8035}
```

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

(Debug) In[332]:=
```
wedge = VectorAngle[alignOpticOrientH1L[[ialign]], -alignOpticOrientH1L[[ialign + 1]]] 180 / Pi
```
(Debug) Out[332]=
```
0.0759981
```

(Debug) In[333]:=
```
BSHROrient = alignOpticOrientH1L[[ialign + 1]]
```
(Debug) Out[333]=
```
{0.707463, 0.70675, 0.000446656}
```

(Debug) In[334]:=
```
BSAROrient = alignOpticOrientH1L[[ialign]]
```
(Debug) Out[334]=
```
{-0.7084, -0.705811, -0.000446086}
```

(Debug) In[335]:=
```
iIAMOptSqRefH1[[ialign]] = 16;
IAMlhoTS2[[iIAMOptSqRefH1[[ialign]]]]
```
(Debug) Out[336]=
```
{TS2-16, 7285., 0.}
```

(Debug) In[337]:=
```
iIAMOptSqH1[[ialign]] = 12;
IAMlhoTS2[[iIAMOptSqH1[[ialign]]]]
```
(Debug) Out[338]=
```
{TS2-12, -2872., 0.}
```

(Debug) In[339]:=
```
IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2]]
```
(Debug) Out[339]=
```
-2872.
```

(Debug) In[340]:=
```
BSARPos[[1]]
```
(Debug) Out[340]=
```
-226.229
```

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

(Debug) In[341]:=
```
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[344]=
```
{TS2-18, -2872., -2475.73, -84.4696}
```

(Debug) In[345]:=
```
theoPosH1[[ialign]] = IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 4]]
```
(Debug) Out[345]=
```
{-2872., -2475.73, -84.4696}
```

(Debug) In[346]:=
```
theoOrientH1[[ialign]] = -BSAROrient
```
(Debug) Out[346]=
```
{0.7084, 0.705811, 0.000446086}
```

Separation from LAC to BS AR surface (mm):

(Debug) In[347]:=
```
theoDistanceH1[[ialign]] = Sqrt[(theoPosH1[[ialign]] - BSARPos).(theoPosH1[[ialign]] - BSARPos)]
```
(Debug) Out[347]=
```
3734.86
```

(Debug) In[348]:=
```
iIAMtheoRefH1[[ialign]] = "NA";
```

(Debug) In[349]:=
```
IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2 ;; 3]]
IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 3]]
```
(Debug) Out[349]=
```
{-2872., 0.}
```

(Debug) Out[350]=
```
{-2872., -2475.73}
```

(Debug) In[351]:=

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

(Debug) Out[352]=

```
45.1049
```

(Debug) In[353]:=

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

(Debug) Out[353]=

```
0.0255589
```

(Debug) In[354]:=

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

(Debug) Out[354]=

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	TS2-12	-2872.0	0.0	TS2-16	7285.0	0.0	TS2-18	-2872.0	-2475.7	-84.5	NA			3734.9	45.	6.	17.	0.	1.	32.		

solution 2

(Debug) In[355]:=

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

(Debug) Out[356]=

```
TS BS HR θ,ψ
```

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 ~1.456, the separation from the LAC to the BS AR surface must be at least ~9 m :

(Debug) In[357]:=

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

(Debug) Out[357]=

```
8965.55
```

(Debug) In[358]:=

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

(Debug) Out[358]=

```
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[359]:=
```
IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-19", 0, 9250 / Sqrt[2] // N}]];
iIAMOptSqH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMOptSqH1[[ialign]]]]
```

(Debug) Out[361]=
```
{TS2-19, 0, 6540.74}
```

(Debug) In[362]:=
```
iIAMOptSqRefH1[[ialign]] = 10;
IAMlhoTS2[[iIAMOptSqRefH1[[ialign]]]]
```

(Debug) Out[363]=
```
{TS2-10, 0., 0.}
```

(Debug) In[364]:=
```
alignOpticOrientH1L[[ialign]]
```

(Debug) Out[364]=
```
{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[365]:=
```
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[371]:=
```
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[376]=
```
8967.48
```

(Debug) In[377]:=
```
IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-20", theoPosH1[[ialign]]}]];
iIAMtheoH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMtheoH1[[ialign]]]]
```

(Debug) Out[379]=
```
{TS2-20, 5594.5, 6540.74, -78.9501}
```

(Debug) In[380]:=
```
theoPosH1[[ialign]] = IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 4]]
```

(Debug) Out[380]=
```
{5594.5, 6540.74, -78.9501}
```

(Debug) In[381]:=
```
theoOrientH1[[ialign]] = -BSHROrient
```

(Debug) Out[381]=
```
{-0.707463, -0.70675, -0.000446656}
```

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

(Debug) In[382]:=
```
separationAngle =
 VectorAngle[Refract[Reflect[Refract[(1 + 10^-13) theoOrientH1[[ialign]], BSHROrient, 1, 1.456], BSAROrient], -BSHROrient, 1.456, 1],
  BSHROrient]
```

(Debug) Out[382]=
```
0.00386253
```

approximate calculation of this angle:

(Debug) In[383]:=
```
2 × 1.456 (wedge Pi / 180)
```

(Debug) Out[383]=
```
0.00386252
```

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

(Debug) In[384]:=
```
BSthickness = 59.88;
theoDistanceH1[[ialign]] separationAngle + BSthickness 2 wedge Pi / 180
```

(Debug) Out[385]=
```
34.796
```

(Debug) In[386]:=
```
iIAMtheoRefH1[[ialign]] = Length[IAMlhoTS2] - 1;
```

(Debug) In[387]:=
```
zeroYawReference = IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 3]];
theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

(Debug) Out[388]=
```
44.9711
```

(Debug) In[389]:=
```
theoPitchH1[[ialign]] = Sign[theoOrientH1[[ialign, 3]]] VectorAngle[Join[theoOrientH1[[ialign, 1 ;; 2]], {0}], theoOrientH1[[ialign]]] 180 / Pi
```

(Debug) Out[389]=
```
-0.0255915
```

(Debug) In[390]:=
```
formatLHOAlignTable[ialign, ialign]
```

(Debug) Out[390]=

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 θ,ψ	-183.9	202.7	-82.8	TS2-19	0.0	6540.7	TS2-10	0.0	0.0	TS2-20	5594.5	6540.7	-79.0	TS2-19	0.0	6540.7	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[391]:=
```
ialign = 9;
alignLabelH1[[ialign]]
```

(Debug) Out[392]=
```
TS BS AR θ,ψ
```

(Debug) In[393]:=
```
iIAMOptSqRefH1[[ialign]] = 10;
IAMlhoTS2[[iIAMOptSqRefH1[[ialign]]]]
```

(Debug) Out[394]=
```
{TS2-10, 0., 0.}
```

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

(Debug) In[395]:=
```
theoOrientH1[[ialign]] = -Refract[-alignOpticOrientH1L[[ialign]], -BSHROrient, 1.456, 1]
```

(Debug) Out[395]=
```
{-0.708826, -0.705383, -0.000445826}
```

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

(Debug) In[396]:=
```
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[402]:=
```
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[407]=
```
8154.01
```

(Debug) In[408]:=
```
theoDistanceH1[[ialign]] separationAngle + BSthickness 2 wedge Pi / 180
```

(Debug) Out[408]=
```
31.654
```

(Debug) In[409]:=
```
IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-21", theoPosH1[[ialign]]}]];
iIAMtheoH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMtheoH1[[ialign]]]]
```

(Debug) Out[411]=
```
{TS2-21, 5594.5, 5388.63, -79.3198}
```

(Debug) In[412]:=
```
theoPosH1[[ialign]] = IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 4]]
```

(Debug) Out[412]=
```
{5594.5, 5388.63, -79.3198}
```

(Debug) In[413]:=
```
IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-22", 0, theoPosH1[[ialign, 2]]}]];
iIAMtheoRefH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMtheoRefH1[[ialign]]]]
```

(Debug) Out[415]=
```
{TS2-22, 0, 5388.63}
```

(Debug) In[416]:=
```
iIAMOptSqH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMOptSqH1[[ialign]]]]
```

(Debug) Out[417]=
```
{TS2-22, 0, 5388.63}
```

(Debug) In[418]:=
```
zeroYawReference = IAMlhoTS2[[iIAMOptSqH1[[ialign]], 2 ;; 3]] - IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 3]];
theoYawH1[[ialign]] = VectorAngle[theoOrientH1[[ialign, 1 ;; 2]], zeroYawReference] 180 / Pi
```

(Debug) Out[419]=
```
44.8605
```

(Debug) In[420]:=
```
theoPitchH1[[ialign]] = Sign[theoOrientH1[[ialign, 3]]] VectorAngle[Join[theoOrientH1[[ialign, 1 ;; 2]], {0}], theoOrientH1[[ialign]]] 180 / Pi
```

(Debug) Out[420]=
```
-0.025544
```

(Debug) In[421]:=
```
formatLHOAlignTable[ialign, ialign]
```

(Debug) Out[421]=

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 θ,ψ	-226.2	160.4	-82.8	TS2-22	0.0	5388.6	TS2-10	0.0	0.0	TS2-21	5594.5	5388.6	-79.3	TS2-22	0.0	5388.6	8154.0	44.	51.	38.	0.	-1.	-32.	Y	

solution 4

(Debug) In[422]:=
```
ialign = 10;
alignLabelH1[[ialign]]
```

(Debug) Out[423]=
```
TS BS HRellpBaf x,y,z
```

(Debug) In[424]:=
```
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[426]:=
```
IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-23", alignOpticPosH1L[[ialign, 1]], IAMlhoTS2[[14, 3]]}]];
iIAMtheoH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMtheoH1[[ialign]]]]
```

(Debug) Out[428]=
```
{TS2-23, -183.899, 7570.}
```

(Debug) In[429]:=
```
theoPosH1[[ialign]] = Append[IAMlhoTS2[[iIAMtheoH1[[ialign]], 2 ;; 3]], alignOpticPosH1L[[ialign, 3]]]
```

(Debug) Out[429]=
```
{-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[430]:=
```
IAMlhoTS2 = Append[IAMlhoTS2, Flatten[{"TS2-24", alignOpticPosH1L[[ialign, 1]], IAMlhoTS2[[10, 3]]}]];
iIAMtheoRefH1[[ialign]] = Length[IAMlhoTS2];
IAMlhoTS2[[iIAMtheoRefH1[[ialign]]]]
```

(Debug) Out[432]=
```
{TS2-24, -183.899, 0.}
```

(Debug) In[433]:=
```
theoOrientH1[[ialign]] = {0, -1, 0}
```

(Debug) Out[433]=
```
{0, -1, 0}
```

(Debug) In[434]:=
```
theoDistanceH1[[ialign]] = Sqrt[(theoPosH1[[ialign]] - alignOpticPosH1L[[ialign]]).(theoPosH1[[ialign]] - alignOpticPosH1L[[ialign]])]
```

(Debug) Out[434]=
```
7367.32
```

(Debug) In[435]:=
```
theoYawH1[[ialign]] = 0;
theoPitchH1[[ialign]] = 0;
```

(Debug) In[437]:=
```
formatLHOAlignTable[ialign, ialign]
```

(Debug) Out[437]=

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			TS2-23	-183.9	7570.0	-82.8	TS2-24	-183.9	0.0	7367.3	0.	0.	0.	0.	0.	0.		

summary of BS cartridge solutions

(Debug) In[438]:=

```
formatLHOAlignTable[7, 10]
```

(Debug) Out[438]=

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	TS2-12	-2872.0	0.0	TS2-16	7285.0	0.0	TS2-18	-2872.0	-2475.7	-84.5	NA			3734.9	45.	6.	17.	0.	1.	32.		
TS BS HR θ,ψ	-183.9	202.7	-82.8	TS2-19	0.0	6540.7	TS2-10	0.0	0.0	TS2-20	5594.5	6540.7	-79.0	TS2-19	0.0	6540.7	8967.5	44.	58.	16.	0.	-1.	-32.	Y	
TS BS AR θ,ψ	-226.2	160.4	-82.8	TS2-22	0.0	5388.6	TS2-10	0.0	0.0	TS2-21	5594.5	5388.6	-79.3	TS2-22	0.0	5388.6	8154.0	44.	51.	38.	0.	-1.	-32.	Y	
TS BS HRellpBaf x,y,z	-183.9	202.7	-82.8	NA			NA			TS2-23	-183.9	7570.0	-82.8	TS2-24	-183.9	0.0	7367.3	0.	0.	0.	0.	0.	0.		

Chamber

TBD

(Debug) In[439]:=

```
TableForm[IAMlhoTS2]
```

(Debug) Out[439]//TableForm=

```
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.
TS2-18    -2872.      -2475.73    -84.4696
TS2-19    0           6540.74
TS2-20    5594.5      6540.74     -78.9501
TS2-21    5594.5      5388.63     -79.3198
TS2-22    0           5388.63
TS2-23    -183.899    7570.
TS2-24    -183.899    0.
```

2.3. H2

2.4. L1