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SHEET 1 OF 1

DOCUMENT CHANGE NOTICE (DCN)

DOCUMENT No. (DOC-REV-GP. ID)	TITLE	NEW REV.
T970151-04-D	ASC Initial Alignment Procedures	C

CHANGE DESCRIPTION (FROM/TO):

REASON FOR CHANGE:

Added 4K alignment procedures and setup data.

ACTION: [X] Incorporate change [ ] Attach DCN to drawing(s) [ ] Other action (specify):

DISPOSITION OF HARDWARE (IDENTIFY SERIAL NUMBERS)

- [X] No hardware affected (record change only)
- [ ] List S/Ns which comply already:
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LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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ASC Initial Alignment Procedures

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1 SCOPE

The purpose of this document is to establish the procedures and specify the equipment required to initially align the core optic and detector subsystem components. The procedures described are used to align the core optics on the 2 km arms at the Hanford. WA site and the 4 km arms at both the Hanford and Livingston, LA sites.

Offset centerlines will first be established parallel to the X and Y arms of the interferometer at the corner, mid, and end stations. Optical tooling techniques will then be used to translate these offset centerlines parallel to the beam tube centerline.

Establishing offset centerlines offers two main benefits:

1. Beam tubes can be installed and pumped down prior to the rest of the system being installed and aligned.
2. Future alignment or alignment verification can be done with the beam tubes closed off.

Alignment of each core optic consists of 3 adjustments. They are:

1. Transverse and vertical positioning which will be accomplished by moving the LOS until a set of fiducials are sighted with a theodolite.

2. Axial positioning (along the beamline) which utilizes the electronic distance measurement feature on the theodolite.

3. Angular alignment in which the optic will be oriented by autocollimation.

2 REQUIREMENTS

Initial alignment must set the Nd Yag laser beam within the range of adjustment of the COS such that a transition to acquisition alignment can take place. The specifications required for this to occur is specified in LIGO - T970060-00-D (1):

Angular positioning	+/- 0.1 mrad (ITM, ETM,BS, RM, FM)
Transverse positioning	+/- 1 mm (ITM, ETM)
	+/- 5 mm (BS, RM, FM)
Axial positioning	+/- 3 mm (ITM, ETM,BS, RM, FM)

The angular alignment phase is most critical due to the long length of the arms, as well as the relatively small range of adjustment of the suspended optics (0.8mrad pk/pk). Our goal for angular alignment is 10% of the adjustment range of the suspended optic or .08 mrad. Over a 4 km arm length, a .08 mrad angle will bring us within 320mm to the center of our ETM (See fig. 1).

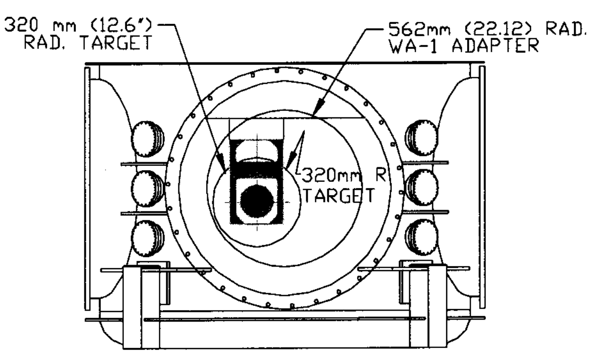


FIG 1. VIEW DOWN END STATION

The Monuments placed as of this date has been found to be within +/- 3mm by Roger's surveying (2). Over a 200 meter separation this results in an error of up to .03 mrad. The total error accumulation including monument locations, procedural and equipment errors is within our goal of .08 mrad as shown in Table 1.

Table 1: Total Error Accumulation

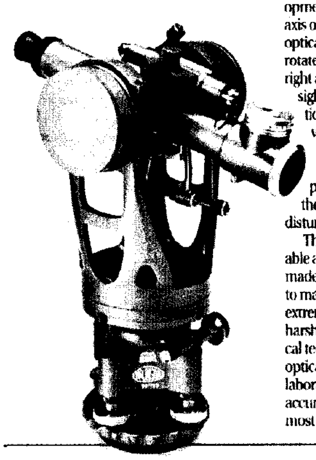
Positioning of monuments	.03 mrad (6 arc seconds)
Sighting of plunb markers	.02mrad (4 arc second)
90 degree autocollimation	.01 mrad (2 arc seconds)
90 degree rotation	.01 mrad (2 arc seconds)
Autocollimation of optic	.01 mrad (2 arc second)
Total	*.08 mrad (16 arc seconds)*

3 EQUIPMENT REQUIRED

The following equipment or their equivalent will be required:

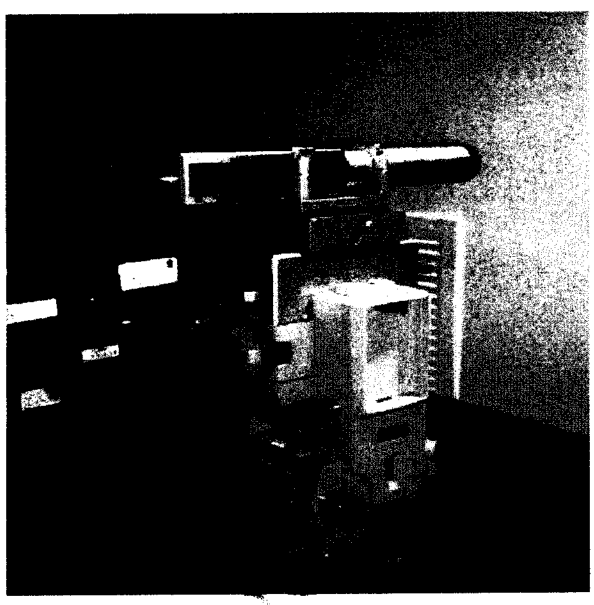
1. One (1) Sokkia Total Station Theodolite model SET2B with electronic distance measurement (EDM), autocollimating eyepiece, tripod, prism, and optical plummet (pictured below with Newport laser autocollimator).
2. One (1) Brunson model 75-H Optical Transit Squares with autocollimating eyepiece, stand, and coincidence level (pictured below).
3. One (1) Newport laser autocollimator Model LDS1000 with mounts to theodolite.
4. Two (2) 101mm dia. optical flats with mounts (Newport #4024OBD.1 & SL101.6).
5. One (1) 4.0"dia pyrex flat, 1/20 wave, double surface parallel to 1 sec, Al Si O coating both sides. Davidson #D617-4P1P
6. One (1) 12.0" PLX Lateral Transfer Hollow Retroreflector # L-20-1-15.75E
7. One (1) 12.0" PLX Lateral Transfer Hollow Periscope # P-20-1-15.75E
8. One (1) 200mm dia optical flat and mount Davidson #D617-8P2S,Al Si 0 1 side.
9. One (1) 200 ft steel tape and tension scale BMI 2473W200T.
10. One (1) Brunson Instrument stand #230-HC and one (1) model 810 stand.
11. One alignment fixture #D980001-A-D with EDM prism and scale.
12. Support stand to bridge conduit & piping LIGO dwgs. D980431 thru D980434.

75-H Optical Transit Square



One of Brunson Instrument Company's technological breakthroughs was the development of the see-thru hollow horizontal axis on the model 75-H. A partially coated, optically flat mirror is mounted inside and rotates with the hollow axis. This provides a right angle check of the telescope's line of sight relative to the horizontal axis. Additionally, the hollow axis allows you to view the mirror from either side of the instrument to turn optical right angles. The hollow axis gives you the power to use several instruments on the same optical reference line without disturbing their positions.

The model 75-H possesses the remarkable ability to "prove" each shot as it is made, removing any possibility of error due to maladjustment from rough handling, extreme temperature changes and other harsh environmental conditions. Now optical technicians no longer need to rely on the optical bench of some distant calibration laboratory. They can verify the instrument's accuracy themselves where it counts the most — ON THE JOB.



4 CALCULATED OPTIC AND THEODOLITE POSITIONS

Offset centerlines with a clear line of sight are located parallel to the beam tube centerlines in the corner, mid and end stations (see fig 3). These are defined as IAM monuments on drawings D970210 shts 1-5 for Hanford (4) and D980499 shts 1-5 (5) for Livingston. The positional accuracy of the initial alignment monuments must be within +/- 3mm of true position in Ligo Global Coordinates. This applies to X and Y position only.

The Z position is determined from actual positions of door flange centerlines. Scribes are located at each Ham and BSC door locations. The positions of these scribes are measured relative to a control point. For Hanford this control point was 1.0572 meters above BTVE1. The amount of translation required (Z_{offset}) is the difference between the calculated design values and the actual locations of the scribes. A scale is placed on the door flange such that the theodolite can measure directly the Z height. Table 2 contains scribe positions in local coordinates for the Hanford corner station as measured by Rogers Surveying.

Table 2: Elevation Scribe Positions

MONUMENT	*ELEVATION*	Z_{actual} *(M)*	Z_{design} *(M)*	$Z_{(offset)}$ *(M)*
WGV-6	100.0000 M	.0033	0.0	.0033
WGV-8	99.9719	-.0248	-.0282	.0034
WHAM1	99.9128	-.0839	-.0870	.0031
WHAM-2	99.9028	-.0939	-.0955	.0015
WHAM-4	99.9014	-.0953	-.0994	.0041
WHAM-6	99.9004	-.0963	-.0993	.0030
WHAM-7	99.8823	-.1144	-.1177	.0033
WHAM-9	99.8931	-.1036	-.1076	.0040
WHAM-10	99.8933	-.1034	-.1054	.0020
WHAM-12	99.8952	-.1015	-.1055	.0040
WBSC-2	99.9996	.0029	.0006	.0023
WBSC-4	99.9937	-.0030	-.0053	.0023
WBSC-7	99.9935	-.0032	-.0052	.0020
WBSC-8	99.9993	.0026	+.0005	.0021
WBSC-8 SW	99.9975	.0008	+.0005	.0003

Table 2: Elevation Scribe Positions

MONUMENT	*ELEVATION*	Z_{actual} *(M)*	Z_{design} *(M)*	$Z_{(offset)}$ *(M)*
LBSC-1	-	-.007	-.001	.006
LBSC-2	-	-.014	-.001	.013
LBSC1-1	-	-.011	-.002	.009
LBSC1-2	-	-.012	-.002	.009
LBSC1-3	-	-.014	-.004	.010
LBSC1-4*	-	-.010	-.004	.006
LBSC3-1*	-	-.013	-.003	.010

* Indicates preferred monument

There are several factors which effect the Z-position and pitch of the optics. The curvature of the earth and physical orientation of the beam tube have to be factored into the setup parameters.

The beam tube orientation and earrth curvature add to give the difference between global and local coordinates. This angle was calculated by Albert Lazzarini in Ligo-T980044 (6)from best fit survey data. The curvature of the earth puts our bubble levels at different angles to the straight line formed by the beam tube. We therefore add this constant angle to our beam tube orientation to properly position the theodolite. This data is summarized in table 3. The total angular compensation is added to the pitch orientation of the theodolite.

Tables 4 and 5 contain optic positions per Ligo-T970091 (3) and theodolite/autocollimator positions and orientations. The theodolite/autocollimator data was found by taking the surface normals for each of the optics (T970091) and extending the vector until it intersected the plane created by the offset centerlines (fig 2). This data includes compensations for curvature of the earth and physical orientation of the beam tubes.

The height of the theodolite does not include the offset distance between the theodolite and the autocollimator and the actual Z scribe reference. The theodolite separation can change therefore must be measured and then subtracted from the value given in tables 4 and 5 column 8.

e.g. In setting the Hanford MMT3 optic the measured separation was 153.2 mm and we used the scribe on WBSC-8 SW.

Therefore Z-final = Ztheo - Zg - Zsep

Z-final = -19.135 mm-.30 mm -153.2 mm   Zsep = measured distance

Z-final = -172.6 mm   Ztheo = value in table 5

Zg = value in table 2

Table 3: Global Direction Cosines

	CORNER	*MID STATION*	*END STATION*
X-ARM WA	-619 microrad	-305.83 microrad	7.84 micro-rad
Y-ARM WA	12.5 microrad	325.84 microrad	639.20 microrad
X-ARM LA	-312 microrad	-	314.7 microrad
Y-ARM LA	-611 microrad	-	18.77 microrad

Fig.3. LLO Scribe Locations

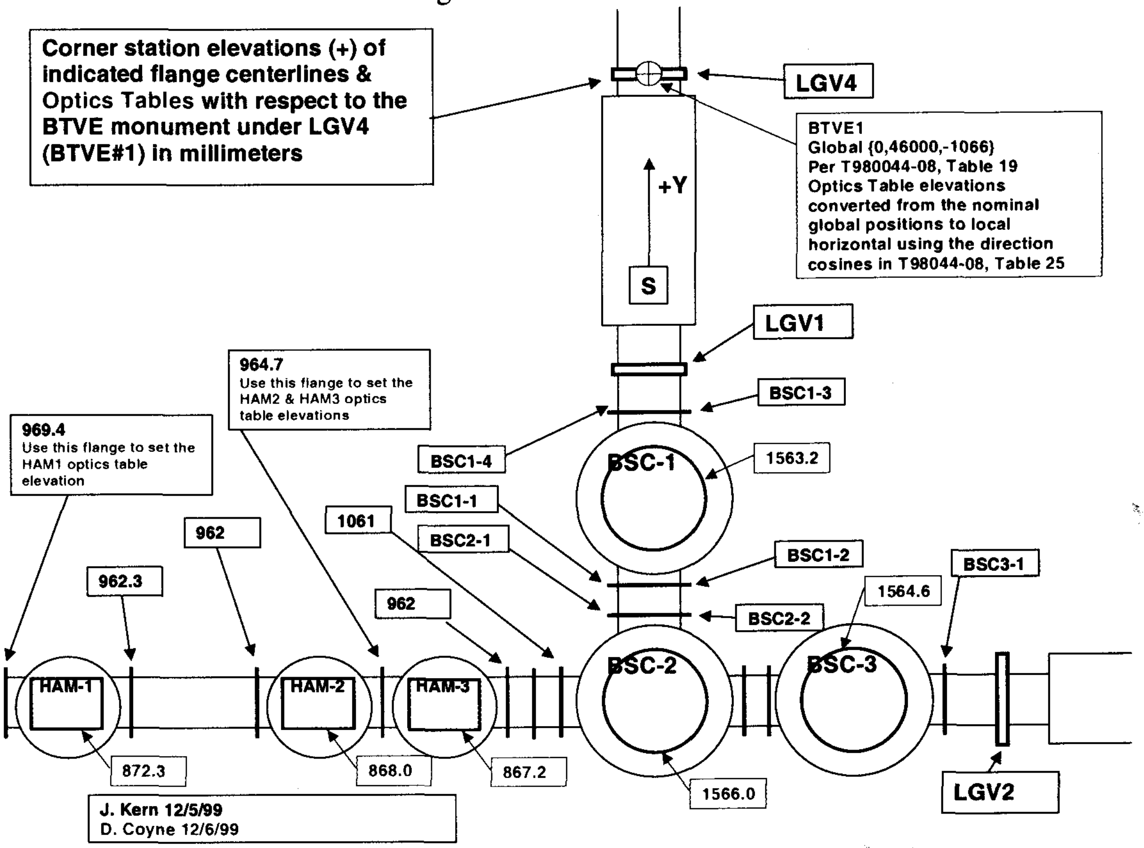


Table 4: OPTIC AND THEODOLITE POSITIONS (2K)

Optic	X optic	Y optic	Z optic	*Monument*	X theodolite	Y theodolite	Z theodolite	**Yaw** theodolite	**Pitch** theodolite	Axial distance
LIGO GLOBAL COORDINATES							LOCAL COORDINATES			
MMT3	29510.7	9062.1	43.1	IAM13	-3251.1	9305.2	19.13	90°25'30	89°55'23	32763
RM	12184	9060	43	IAM14	-3251.1	9060	-246.8	89°59'32	88°57'9"	15438
RM(a)	12184	9060	43	IAM14A	-3251.1	8657.8	-246.8	89°59'32	88°57'9"	-
OF_y	1614	9072	-95.0	IAM26	-3251.1	9072.1	-108.0	89°59'4"	89°50'43	-
$OF_{y(a)}$	971.6	9678.8	-96.7	IAM82	-3251.1	7895.3	-96.5	67°29'42	90°0'0"	-
FM_y	199.6	9072.4	-96.3	IAM29A	200.9	38154	-2.4	270°0'7"	90°11'23	29082
$FM_{y(a)}$	199.6	9072.4	-96.3	IAM81A	-3251.1	9707	-84.7	89°59'16	90°9'58"	-
ITM_y	199.6	9569.1	-98.1	IAM29	199.6	38154	-98.5	270°0'0"	90°0'2"	28585
ETM_y	199.6	2018689	-98.1	IAM121	199.6	2012861	-100.0	270°0'0"	89°58'52	5828
OF_{bs}	10184	9060	-13.2	IAM27	-3251.1	8660.7	-103.8	270°0'0	89°38'24	-
$BS_{(2k)}$	9162.6	9059.6	-14.0	IAM32	9163	-3251.2	9.3	270°0'4"	90°9'47	12311
OF_x	9166.2	400	-103.7	IAM32A	9164.4	-3251.2	-121.4	270°1'41	89°48'38	-
FM_x	9162.6	-199.6	-98.4	IAM33A	38154	-186.2	-81.9	89°58'25	90°2'38	28991
ITM_x	9686.6	-199.6	-100.3	IAM33	38154	-199.6	-123.0	0°0'0"	89°57'52	28467
ETM_x	2018807	-199.6	-100.3	IAM131	2012860	-199.6	-98.4	270°0'0"	90°1'5"	5947

(a) designates an alternate method when the line of sight is blocked by an optic or baffle.

Table 5: OPTIC AND THEODOLITE POSITIONS (4K LIVINGSTON))

Optic	X optic	Y optic	Z optic	*Monu-ment*	**X** the-odolite	**Y** the-odolite	**Z** theod-olite	**Yaw** the-odolite	**Pitch** the-odolite	*Axial* dist.
MMT3	-20883.6	207.8	25.6	IAM78	11600	-8.7	-27.6	90°22’55”	89°53’42”	32484
RM	-4596.0	212.0	26.0	IAM77	11600	214.1	-283.9	89°59’34”	88°53’57”	16199
OF_{bs}	-1740.0	212.4	-27.5	IAM77	11600	214.1	-283.9	89°59’34”	88°53’57”	-
ITM_x	4669.7	199.5	-100.9	IAM76	11600	199.5	-103.1	90°0’0”	89°58’54”	6930
$BS_{(2k)}$	-199.4	212.6	-57.0	IAM90	-199.54	11600	-175.8	89°24’11”	89°59’58”	11388
ITM_y	-199.4	4805.2	-98.1	IAM91	-199.4	11600	-102.3	90°0’0”	89°57’52”	6795
ETM_y	-199.4	3999860	-98.1	-	200.6	4002365	-98.3	270°0’0”	90°0’04”	2505
ETM_x	3999725	199.5	-100.9	-	3993700	199.5	-104.6	90°0’0”	89°58’54”	6025

5 2K ALIGNMENT PROCEDURES

5.1. ALIGNMENT OF MMT3 AND RM

1. Prepare vacuum equipment. Place clean rooms over WHAM 7, WHAM9 and WBSC8. Doors must be removed to allow loading of the LOS and line of sight for alignment equipment (See fig. 5)

2. Place the LOS with the MMT3 optic suspended onto the optics table in Wham7 in its approximate location (see fig 4).

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 13. Level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-8, aligning it to the scribe on the side of the flange.

6. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

7. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180degrees, making sure to encompass the travel the theodolite must move.Calculate the z-heightper page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Rotate towards the monument IAM12 or IAM99 which establishes the offset centerline and align to the monument. Adjust for monument calibration per LIGO-T990017 (7).

10. When aligned to the monument, zero out the horizontal angle and adjust the telescope body to zero the vertical angle. Rotate in yaw and pitch per table 4. The theodolite/autocollimator is now in its final position and should not be moved again.

11. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00" on the scale. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theeodolite crosshairs are aligned to this position and the edge of the scale.

12.Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement. To convert to Ligo Global coordinates subtract the x value of the theodolite (-3251.1mm) from the reading. Adjust the LOS until the correct x position is obtained per table 4.

13. Remove the prism to begin autocollimation of the optic hr surface with the laser autocollimator. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

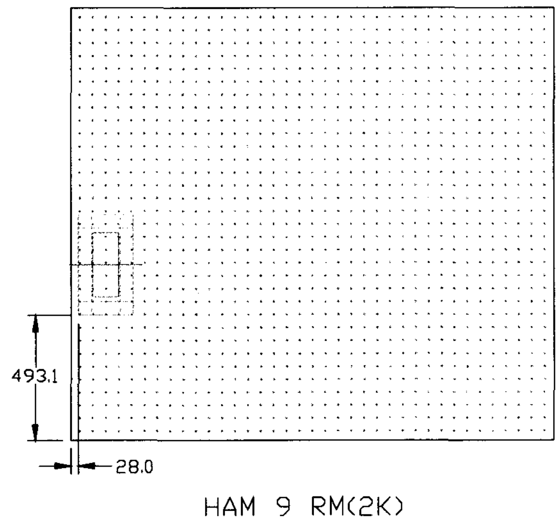
14. There will probably be 2 reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface. Locate the reflection off the HR surface and guide the reflection through the tube back toward the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets.

15. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

16. Alignment of the RM is identical to MMT3 using the positions found in table 4 and positioning over IAM-14.

17. The doors are replaced and clean rooms removed.

Fig 4. Optical Table Layout



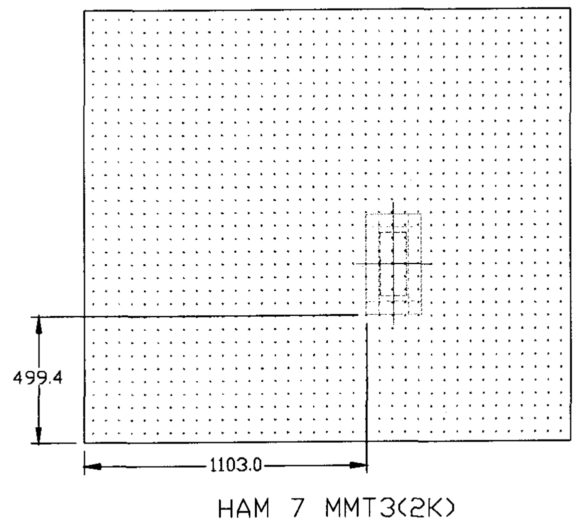
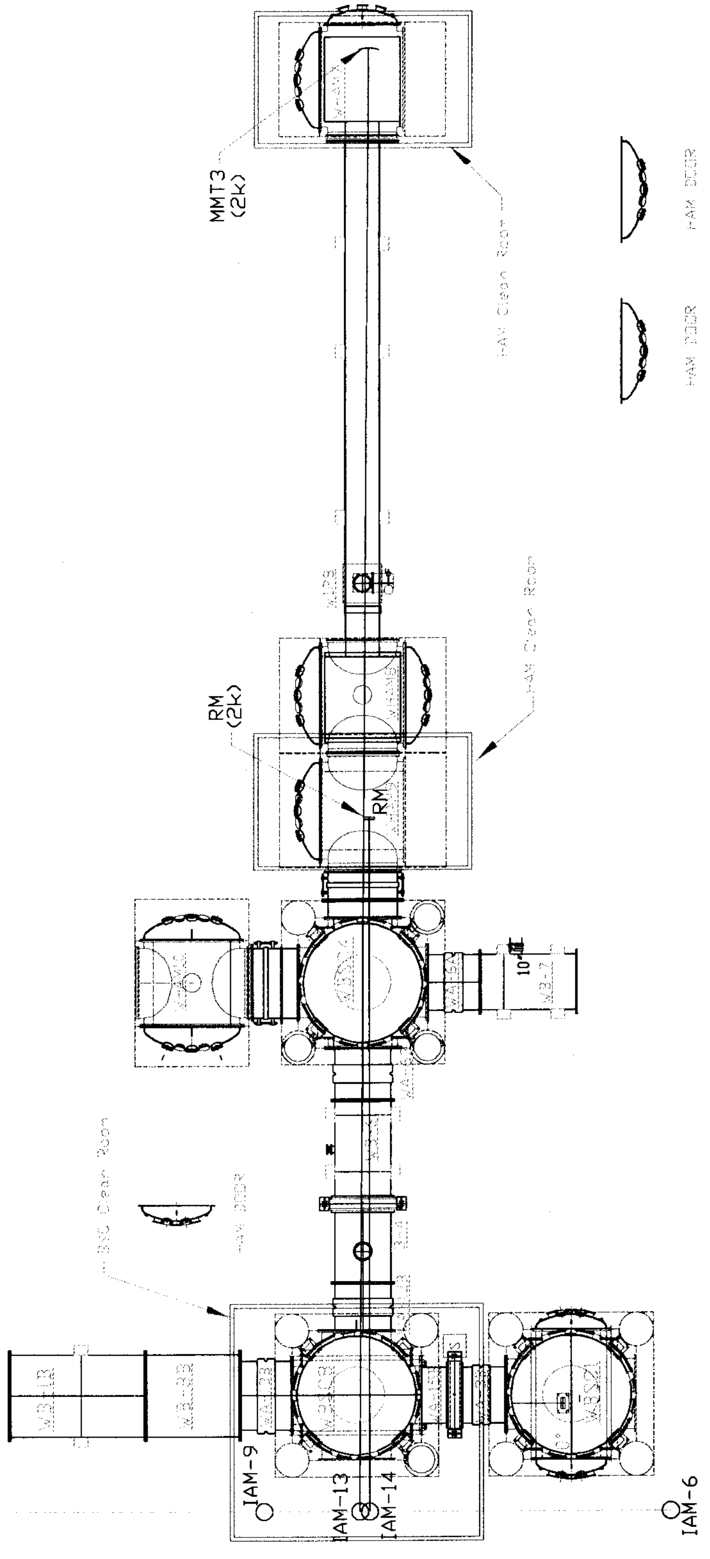


Fig. 5



5.2. ALIGNMENT OF BEAM SPLITTER OPTICAL FLAT

1. Prepare vacuum equipment. Place clean rooms over WBSC-8 and WA-1B. Remove the door on WBSC-8 and adapter WA-1B to allow loading of the LOS and a line of sight for alignment equipment.

2. Place the optical flat and mount into adapter WA-12B in its approximate location as shown in fig.6.

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 26. Level the stand with a machinist level and the theodolite with the bubble level and then internal level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-8, aligning it to the scribe on the side of the flange.

6. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

7. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

8. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

9. Check the separation between the theodolite scope and the autocollimator scope and record this value. Check that the theodolite is level 180 degrees, making sure to encompass the travel the theodolite must move. Recalculate, if necessary, the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

10. Rotate towards the monument IAM12 and IAM99 which establishes the offset centerline and align to the monument. Adjust for monument calibration per LIGO-T990017 (7).

11. Position the optical flat such that the autocollimator beam is approximately centered on the 4.0" dia. optical flat.

12. Adjust the optical flat mount until autocollimated within 1 arc sec (5 microradians).

13. The optical flat is in its final position and must not be moved or bumped.

5.3. ALIGNMENT OF THE BEAMSPLITTER

1. Prepare vacuum equipment. Place clean rooms over WBSC-4 and WBSC-8. Doors must be removed to allow loading of the LOS and line of sight for alignment equipment.

2. Place the LOS with the BS optic suspended into WBSC-4 in its approximate location as shown in fig.8.

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 32 plus .7071(A) per fig.6. Level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-7, aligning it to the scribe on the side of the flange.

6. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

7. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180degrees, making sure to encompass the travel the theodolite must move.Calculate the z-heightper page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Rotate towards the monument IAM3 which establishes the offset centerline and align to the monument. Adjust for monument calibration if necessary.

10. When aligned to the monument, zero out the horizontal angle and adjust the telescope body to zero the vertical angle. Rotate in yaw and pitch per table 4. The theodolite/autocollimator is now in its final position for positionining the optic.

11. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00" on the scale. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theeodolite crosshairs are aligned to this position vertically.

12.Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement per fig.6.

13. Place the theodolite/autocollimator over IAM32 and repeat steps 4 thru 10 above. The autocollimator should be in its final position for angular alignment per Table 4. Place the autocollimator in

analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

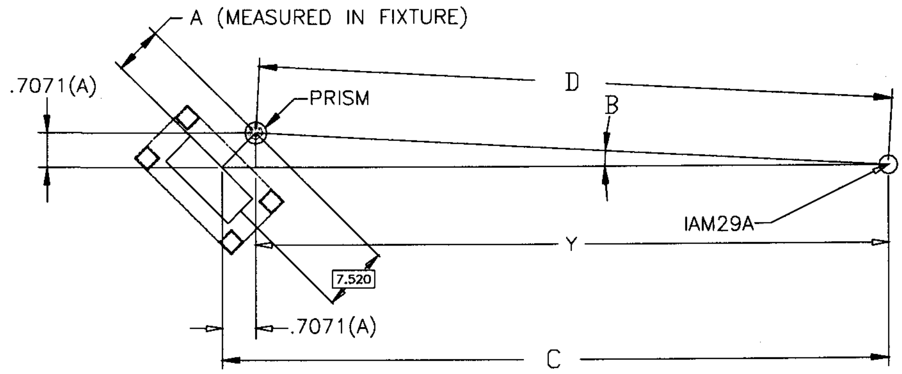
14. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the beamsplitter and hits the optical flat. Locate the reflection off the HR surface and guide the reflection through the tube back toward the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

15. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

16. Remove the optical flat and PLX retroreflector from WBE-3A2.

17. The doors are replaced and clean rooms removed.

FIG. 6



1. MEASURE DISTANCE A.
2. CALCULATE OFFSET = .7071(A).
3. CALCULATE ANGLE B
   TAN B = .7071 (A) / Y
4. SET UP THEODOLITE AND POSITION PRISM IN TRANSVERSE AND VERTICAL POSITION.
5. CALCULATE DISTANCE FROM THEODOLITE TO PRISM
   COS B = Y / D
6. SET AXIAL POSITION D WITH THEODOLITE
7. RECHECK TRANSVERSE POSITION AND MOVE IF NECESSARY

5.4. ALIGNMENT OF FM_Y, ITM_Y, FM_X, AND ITM_X

1. Measure the separation from the FM optic face to the prism mount location on the alignment fixture Ligo D980001 and record this distance. Install the scale and verify that a mark on the scale corresponds to the center of the optic and record this value.

2. Locate and verify the position of IAM-29 located on the optical lever stand under adapter WA-1B.

3. Place the LOS with the FM_y optic suspended onto the optics table in WBSC-8 in its approximate location per fig.6.

4. Mount the Brunson Transit square to the Brunson 230-HC stand and place over IAM 28 at the theodolite height for FM_y (table 4).

5. Level the transit square with the coincidence level per appendix 2. Rotate the scope towards IAM12. Adjust the optical micrometer on the Brunson square by -.077" per LIGO-T990017 (7), and sight the string and plumb bob over IAM12. The transit square is now in its final position and should not be moved again.

6. Assemble the Brunson 810 stand onto the optical lever bridge. Place the theodolite/autocollimator on the stand and level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over IAM-29 plus .7071(A) per fig 6.

7. Clamp a 300mm or greater scale to the flange protector on WGV-6, aligning it to the scribe on the side of the valve.

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Verify the squareness of the transit square with the LDS1000 laser autocollimator per appendix 3.

10. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

11. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

12. Check the separation between the theodolite scope and the autocollimator scope and record this value. Check that the theodolite is level 180 degrees, making sure to encompass the travel the theodolite must move. Recalculate, if necessary, the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

13. Rotate the theodolite/autocollimator towards the brunson square, and autocollimate off the mirror on the square. Zero out the horizontal angle. Rotate the theodolite in pitch and yaw per table 4. The

theodolite/autocollimator is now in its final position for positioning the optic and should not be moved again.

14. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00" on the scale or other value measured earlier. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theodolite crosshairs are aligned vertically.

15 .Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement see fig 6.

16. Place the theodolite/autocollimator over IAM29A and repeat steps 6 thru 13 above. If the Brunson square has not been moved, step 9 can be ommitted. The autocollimator should be in its final position for angular alignment per Table 4. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

17. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the folding mirror and hits the optical flat. Locate the reflection off the HR surface and guide the reflection through the tube back toward the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

18. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

19. Alignment of the ITM_y is similar to FM_y with the exception that the prism is in line with the optic and no angular compensation is required. Autocollimation occurs directly off the face of the optic.

20.Alignment of the FM_x and ITM_x is identical to the procedure above using the positions and angles found in table 4.

FIG. 7 OPTIC LAYOUT BSC8

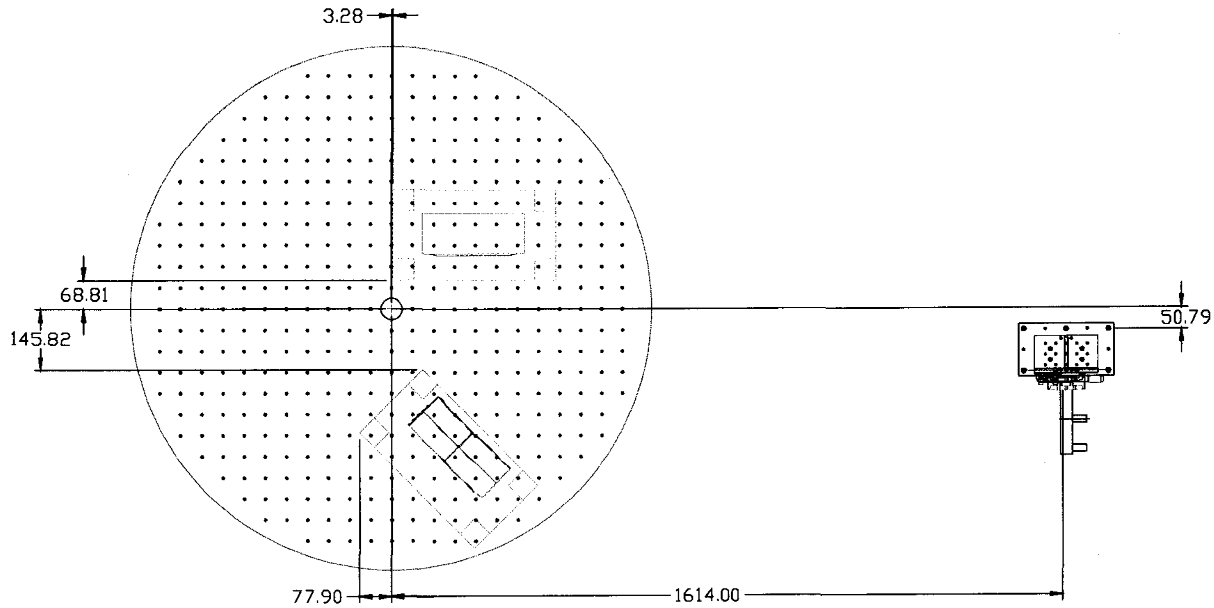
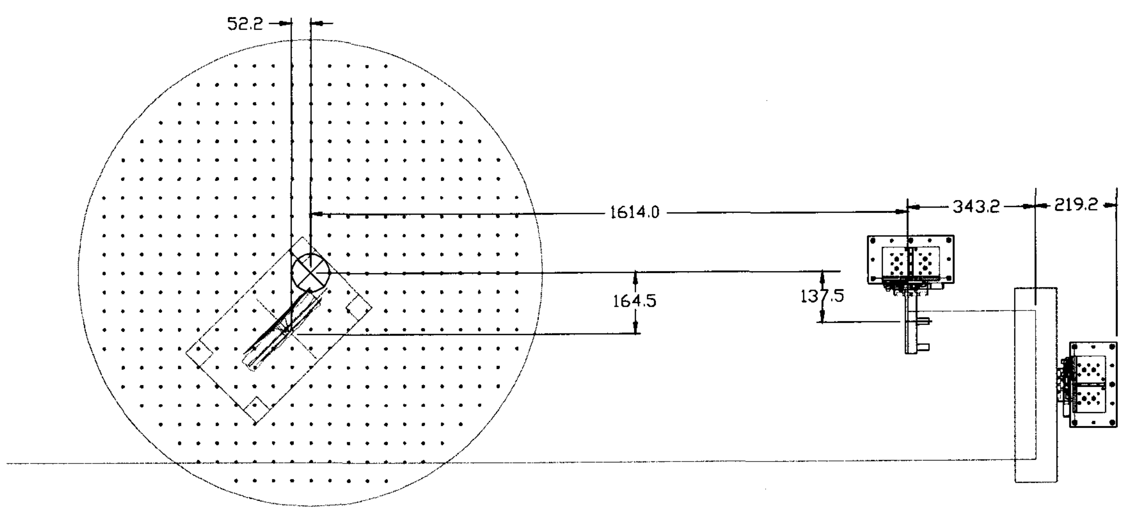


FIG. 8 OPTIC LAYOUT BSC4



5.5. ALIGNMENT OF END TEST MASSES ETM_Y AND ETM_X

1. Prepare vacuum equipment. Place a clean room over WBSC-6. Remove the door on WBSC-6 and adapter WA-14A to allow loading of the LOS and a line of sight for alignment equipment.

2. Measure the separation from the FM optic face to the prism mount location on the alignment fixture Ligo D980001 (8) and record this distance. Install the scale and verify that a mark on the scale corresponds to the center of the optic and record this value.

3. Place the PLX retroreflector into adapter WA-7A1 and the LOS with the ETMy optic suspended in WBSC-6 in their approximate location as shown in fig.9.

4. Mount the Brunson Transit square to the Brunson 230-HC stand and place over IAM 20 at the theodolite height for ETM_y (table 4).

5. Level the transit square with the coincidence level per appendix 2. Rotate the scope towards IAM19. Sight the string and plumb bob over IAM19. The transit square is now in its final position and should not be moved again.

6. Assemble the Brunson 810 stand onto the alignment bridge. Place the theodolite/autocollimator on the stand and level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over IAM-21A (400mm toward IAM-20 from IAM21) and set the height as specified in table 4.

7. Clamp a 300mm or greater scale to the flange protector on WGV-6, aligning it to the scribe on the side of the valve.

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Verify the squareness of the transit square with the LDS1000 laser autocollimator per appendix 3.

10. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

11. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

12. Check the separation between the theodolite scope and the autocollimator scope and record this value. Check that the theodolite is level 180 degrees, making sure to encompass the travel the theodolite must move. Recalculate, if necessary, the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

13. Rotate the theodolite/autocollimator towards the brunson square, and autocollimate off the mirror on the square. Zero out the horizontal angle. Rotate the theodolite in pitch and yaw per table 4. The theodolite/autocollimator is now in its final position and should not be moved again.

14. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00" on the scale or other value measured earlier. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theeodolite crosshairs are aligned to this position and the edge of the scale.

15 .Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement. In the case of the Fold Mirror a calculation will have to be made to account for the spacing being at 45 degrees.To convert to Ligo Global coordinates subtract the value obtained from the y position of the theodolite (-38154 mm) . Adjust the LOS until the correct y position is obtained per table 4.

16.. Move the Brunson 810 stand approximately over IAM21. level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over IAM-21 and set the height as specified in table 4

17. Remove the prism to begin autocollimation of the optic hr surface with the laser autocollimator. Make sure the readings on the theodolite are per table 4. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

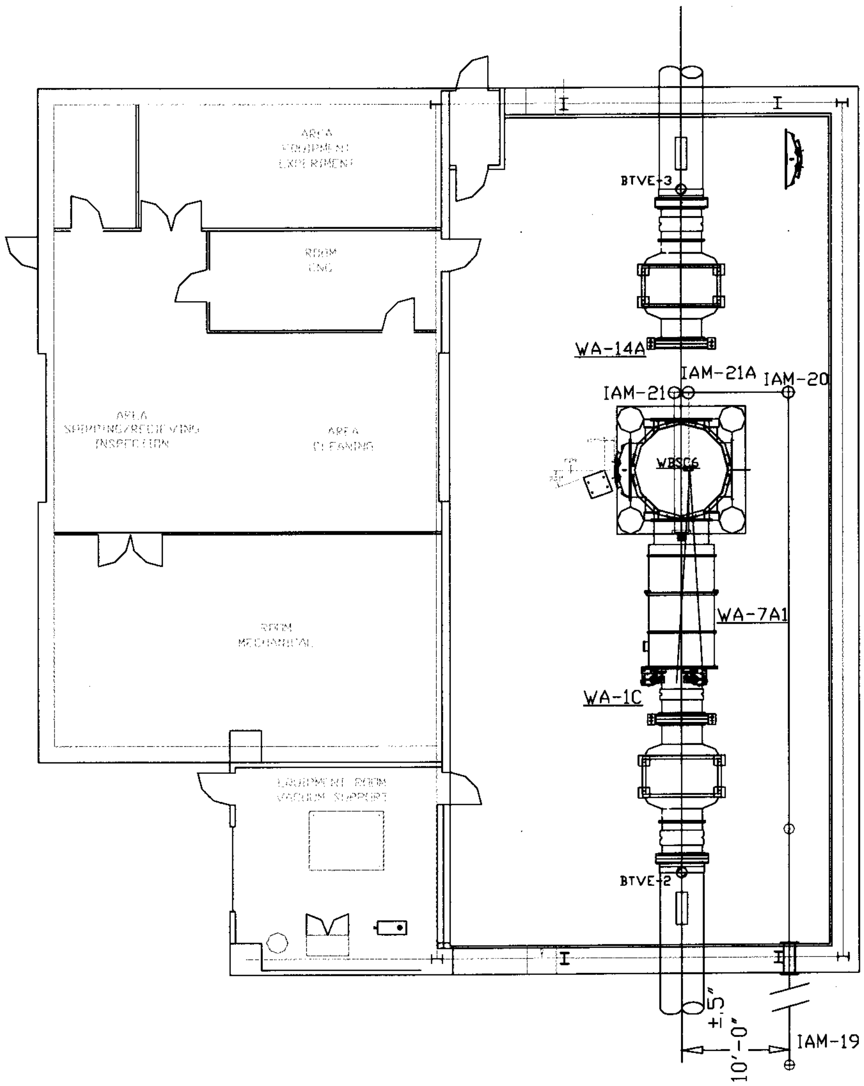
18. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the beamspitter. Locate the reflection off the HR surface and guide the reflection through the retroreflector and back to the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

19. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

19. Alignment of the other ETM's are similar using the positions found in table 4.

20. The door and adapter are replaced and clean rooms removed.

FIG.9 Y-MID STATION



6 4K ALIGNMENT PROCEDURES (LIVINGSTON)

6.1. ALIGNMENT OF MMT3, RM,OF_{bs}, AND ITM_X

1. Prepare vacuum equipment. Place a clean room over spool piece B-1A along the x-axis arm and remove spool piece B-1A.

2. Locate monument 201 along the x-axis offset centerline a distance of 11600 mm from the vertex. Buck in with the Sokkia theodolite over this point using existing markers on the x-arm wall and at the vertex. Focus on the monument on the x-axis wall, level, and zero the horizontal rotation axis.

3. Establish a line at x=11600 mm by rotating the theodolite 90deg 0'0" and marking two points on the floor. Scribe monuments at (11600, -8.7), (11600, 214.1), and (11600,199.5). Mark these monuments and record.

4. Clamp a 300 mm or greater scale on a visible flange, and align it to the side of the flange pointing up.

5. Mount the Brunson Transit square to the Brunson 230-HC stand and place over IAM-L21 at the autocollimator height for MMT3 per table 1.

6. Level the transit square with the coincidence level per appendix 2. Rotate the scope towards the monument on the wall towards the beam tube. The transit square is now in its final position and should not be moved gain.Verify the height has not changed.

7. Set up for alignment of MMT3. Assemble the Brunson 810 stand onto the alignment bridge. Place the theodolite/autocollimator on the stand and level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, roughly center the theodolite over the approp riate monument and roughly set the height per table 5.

8. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the Z-theodolite position.

9. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second(5 microradians), adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec(5 microradians).

10. Measure the separation between the theodolite scope and the autocollimator scope, and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height by subtracting from the height the difference between the actual and design height of the marker and subtracting the separation distance measured from the theodolite height. Set the crosshairs in the theodolite to the appropriate mark on the scale.

11. Verify the squareness of the transit square with the LDS1000 laser autocollimator per appendix 3.

12. Rotate the theodolite/autocollimator towards the Brunson square, and autocollimate off the mirror on the square. Zero out the horizontal angle. Rotate the theodolite in pitch and yaw per table 5. The theodolite/autocollimator is now in its final position.

13. If the optic has not been placed in the chamber. Install the LOS per LIGO E000062-C titled LOS Installation Procedures For BSC Chambers. Have someone place a light on the scribe located on the top of the LOS structure. Rotate the theodolite in pitch until the scribe is located. Move the LOS structure until the crosshairs are aligned to the scribe.

14 .Place the prism into the prism holder on the LOS fixture. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement. Move the LOS axially until the theodolite reads the correct axial distance per table 5.

15. Remove the prism to begin autocollimation of the optic hr surface with the laser autocollimator. Make sure the readings on the theodolite are per table 5. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

16. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the beamspitter. Locate the reflection off the AR surface and guide the reflection through the retroreflector and back to the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

17. Setup for Alignment of the recycling mirror. Raise or lower the Brunson transit square per table 5 and realign it to the offset centerline. Level the transit square.

18. Move the theodolite to the monument created for the RM and repeat steps 7 thru 16 above.

19. With the theodolite in the position and orientation for the recycling mirror, place an optical flat in the adapter between BSC-2 and HAM-3 per table 5. Adjust micrometers until autocollimated to within 5-10 microradians.

20. Setup for Alignment of the ITMx. Raise or lower the Brunson transit square per table 5 and realign it to the offset centerline. Level the transit square.

21. Move the theodolite to the monument created for the ITMx and repeat steps 7 thru 16 above

6.2. ALIGNMENT OF BS AND ITM_Y

1. Prepare vacuum equipment. Place a clean room over spool piece B-1B along the y-axis arm and remove spool piece B-1B.

2. Locate amonument along the y-axis offset centerline a distance of 11600 mm from the vertex. Buck in with the Sokkia theodolite over this point using existing markers on the y-arm wall and at the vertex. Focus on the monument on the y-axis wall, level, and zero the horizontal rotation axis.

3. Establish a line at x=11600 mm by rotating the theodolite -90deg 0'0" and marking two points on the floor. Scribe monuments at (11600, -199.5), and (11600,-). Mark these monuments and record.

4. Clamp a 300 mm or greater scale on a visible flange, and align it to the side of the flange pointing up.

5. Mount the Brunson Transit square to the Brunson 230-HC stand and place over the monument created earlier along the y-axis and at the autocollimator height for the beamsplitter per table 5.

6. Level the transit square with the coincidence level per appendix 2. Rotate the scope towards the monument on the wall towards the beam tube. The transit square is now in its final position and should not be moved gain.Verify the height has not changed.

7. Set up for alignment of the beamsplitter. Assemble the Brunson 810 stand onto the alignment bridge. Place the theodolite/autocollimator on the stand and level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, roughly center the theodolite over the approp riate monument and roughly set the height per table 5.

8. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the Z-theodolite position.

9. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second(5 microradians), adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller-for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec(5 microradians).

10. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height by subtracting from the height the difference between the actual and design height of the marker and subtracting the separation distance measured from the theodolite height. Set the crosshairs in the theodolite to the appropriate mark on the scale.

11. Verify the squareness of the transit square with the LDS1000 laser autocollimator per appendix 3.

12. Rotate the theodolite/autocollimator towards the Brunson square, and autocollimate off the mirror on the square. Zero out the horizontal angle. Rotate the theodolite in pitch and yaw per table 5. The theodolite/autocollimator is now in its final position.

13. If the optic has not been placed in the chamber. Install the LOS per LIGO E000062-C titled LOS Installation Procedures For BSC Chambers. Have someone place a light on the scribe located on the top of the LOS structure. Rotate the theodolite in pitch until the scribe is located. Move the LOS structure until the crosshairs are aligned to the scribe.

14 .Place the prism into the prism holder on the LOS fixture. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement. Use fig 6 for method of calculation. Move the LOS axially until the theodolite reads the correct axial distance per table 5.

15. Remove the prism to begin autocollimation of the optic hr surface with the laser autocollimator. Make sure the readings on the theodolite are per table 5. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

16. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the beamspitter. Adjust the beamsplitter until the reflected beam hits the RM HR surface, reflecting back to the beamsplitter and to the autocollimator. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

17. Setup for Alignment of ITMy. Raise or lower the Brunson transit square per table 5 and realign it to the offset centerline. Level the transit square.

18. Move the theodolite to the monument created for the ITMy and repeat steps 7 thru 16.

6.3. ALIGNMENT OF END TEST MASSES ETM_X AND ETM_Y

1. Prepare vacuum equipment. Place a clean room over LBSC-4 and spool. Remove the door on LBSC-4 and spool piece to allow loading of the LOS and a line of sight for alignment equipment.

2. Measure the separation from the ETM optic face to the prism mount location on the alignment fixture Ligo D980001 (8) and record this distance.

3. Locate monument IAM-L20 on the offset centerline at (3993700,-1854.2). To do this buck in with the Brunson transit between two targets located high on the walls. Scribe a line along the offset centerline in the vicinity of the PSI brass tag located behind the rear door of LBSC-4. Now place a 1.5 meter straight edge over the brass tag mark toward the scribe line and square it off with a precise square. Mark this monument IAM-L21.The coordinates of this monument will be (4002365,-1854.2)

4. Roughly measure from IAM-L21 6025 mm towards the beam tube. Again using the Brunson transit scribe a line along the offset centerline in this area. Remeasure 6025 mm from IAM-L21 along the scribe and mark this monument IAM-L20.

5. With the 1.5 meter straight edge and precise square, place a scribe and monument at coordinates (3993700, 199.5) and mark this IAM-L22.

6. Measure the height of the scribe located on the side of the gate valve relative to BTVE-4 and record this value.

7. Clamp a 300 mm or greater scale to the flange protector on the gate valve, aligning it to the scribe on the side of the valve pointing up.

8. Mount the Brunson Transit square to the Brunson 230-HC stand and place over IAM-L21 at the autocollimator height for ETM_y per table 1. (200.3 mm for AR, -104.6 mm for HR).

9. Level the transit square with the coincidence level per appendix 2. Rotate the scope towards the monument on the wall towards the beam tube. The transit square is now in its final position and should not be moved again.Verify the height has not changed.

10. Assemble the Brunson 810 stand onto the alignment bridge. Place the theodolite/autocollimator on the stand and level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, roughly center the theodolite over IAM-L22 and roughly set the height per table

11. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the Z-theodolite position.

12. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second(5 microradians), adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controllerfor the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec(5 microradians).

13. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height by subtracting from the height the difference between the actual and design height of the marker and subtracting the separation distance measured from the theodolite height. Set the crosshairs in the theodolite to the appropriate mark on the scale.

14. Verify the squareness of the transit square with the LDS1000 laser autocollimator per appendix 3.

15. Rotate the theodolite/autocollimator towards the Brunson square, and autocollimate off the mirror on the square. Zero out the horizontal angle. Rotate the theodolite in pitch and yaw per table 1. The theodolite/autocollimator is now in its final position.

16. If the optic has not been placed in the chamber. Install the LOS per LIGO E000062-C titled LOS Installation Procedures For BSC Chambers. Have someone place a light on the scribe located on the top of the LOS structure. Rotate the theodolite in pitch until the scribe is located. Move the LOS structure until the crosshairs are aligned to the scribe.

17 .Place the prism into the prism holder on the LOS fixture. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement. Move the LOS axially until the theodolite reads the correct axial distance per table 1.

18. Remove the prism to begin autocollimation of the optic hr surface with the laser autocollimator. Make sure the readings on the theodolite are per table 1. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

19. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the beamspitter. Locate the reflection off the AR surface and guide the reflection through the retroreflector and back to the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

20. At this point we must setup for alignment of the ETM telescope and ETM transmission monitor per LIGO T990088 titled COS IFO Alignment Procedures. This procedure will vary depending on which surface was used to align the optic.

A. If the HR surface was used for alignment per numbers found in Table 1, Place the 8.0" dia optic flat in front of the laser autocollimator while it is in its final position and autocollimate to the flat. Remove the theodolite and autocollimator by releasing the knob on the side of the Sokkia tribach. Replace the theodolite with the IR laser adapter and IR Laser autocollimator. Autocollimate to the optic flat with the IR autocollimator and remove the optic flat. Align the ETM telescope and ETM transmission monitor per LIGO T990088.

B. If the AR surface was used for alignment using numbers found in Table 1, the Brunson transit square and Sokkia theodolite/autocollimator must be reset to the heights used for aligning the HR surface. Follow steps above for aligning the transit square and theodolite at the values in Table 1 for ETMx(HR). Then place the 8.0" dia optic flat in front of the laser autocollimator while it is in its final position and autocollimate to the flat. Remove the theodolite and autocollimator by releasing the knob on the side of the Sokkia tribach. Replace the theodolite with the IR laser adapter and IR Laser autocollimator. Autocollimate to the optic flat with the IR autocollimator and remove the optic flat. Align the ETM telescope and ETM transmission monitor per LIGO T990088.

21. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

22. The door and adapter are replaced and clean rooms removed

APPENDIX 1 REFERENCES

[1] LIGO-T970060- 00-D, Alignment Sensing/ Control Preliminary Design

[2] Gary P. Wagner "Precision Survey of Beam Tube/ Vacuum Equipment Interface", Rogers Surveying, October 1,1996.

[3] LIGO-T970091-00, Determination of Core Optic Wedge Angles, Dennis Coyne

[4] LIGO-D970210, ASC Monument Locations - Wa. Site, K.Mason

[5] LIGO-D980499, ASC Monument Locations - La. Site, K.Mason

[6] LIGO-T980044, Determination of Global and Ligo Coordinate axis for the Ligo Sites, Albert Lazzarini

[7] LIGO-T990017, Calibration of Initial Alignment Survey by Sighting through Y1 Beam Tube, M.Zucker

[8] LIGO-D980001, Alignment Fixture

[3] LIGO-T990026, Calibration of Optical Levers, M.Zucker

APPENDIX 2 LEVELING PROCEDURE ON THE BRUNSON 75H TRANSIT SQUARE

1. Level scope by circular level.

2. Set scope such that 2 leveling screws are in line with scope and 2 screws are 90 deg. to scope.

3. Level scope eith tangent screw (brass knob inside transit casting).

4. Rotate 180 deg and take out half error with tangent screw and half with leveling screws until bubbles on coincidence level are in line with one another.

5. Rotate 90 deg and take out with leveling screws.

6. Rotate 180 deg from last position and take out half with tangent screws and half with leveling screws.

7. If necessary continue this method of rotating 90 deg adjusting leveling screws, then 180 adjusting half and half until bubble is level over full 360 deg.
8. When close only use leveling screws and tighten only.
9 Rotate 360 deg to make sure transit is level.

APPENDIX 3 VERIFIFICATION AND REALIGNMENT OF INDICATING MIRROR ON THE BRUNSON 75H OPTICAL TRANSIT SQUARE

The Brunson optical transit square's side indicating mirror surface is nominally parallel to the square's optical axis and vertical (azimuthal) rotation axis within 1 arcsecond . However it has been observed to go out of square during shipping as well as between setups. It is therefore imperative to check and, if required, adjust the mirror for squareness each time it is mounted for use.

NOTE: Verification of square adjustment should take approximately 45 minutes for an experienced operator, assuming all equipment is staged and ready. Restoring alignment may take from 2 to 6 hours depending on the degree of misalignment. In what follows it is assumed that the user is familiar with and experienced in the use and maintenance of transit instruments.

1. Set the transit over the desired survey position at the required height, and level using the coincidence level according to procedure in Appendix II. Let the instrument settle and thermally equilibrate for at least 15 minutes and recheck the coincidence level in all directions before proceeding.
2. Verify that the plunge axis and azimuth axis are mutually orthogonal and orthogonal to the optic axis;

A. Set the optical micrometer at zero and null the crosshair to a fixed target at least 20' away, preferably at about the same height as the transit. Be sure to lock the azimuth circle.

B. Plunge the transit to come up horizontal on the opposite side; have an assistant scribe a new reference target on a stable surface at least 20' away in the opposite direction, exactly coinciding with the crosshair position. Plunge again to double check that the two target marks and the transit lie on a common line. If there is some error, the transit can be translated slightly using fine horizontal adjustments of the mount (take out half the error by translation and finish with azimuth fine adjustment; iterate until the crosshair splits both marks when plunged).

C. Unlock the azimuth and slew the transit horizontally 180¡ to locate the second mark. Lock the coarse azimuth and use the fine adjust to split the mark with the crosshair.

D. Plunge the transit through 180 degrees and check that the crosshair once again again splits the first target. Measure any discernible error using the optical micrometer.

E. Recheck the instrument level. If not level, readjust level and start over.

If there a visible difference not attributable to a leveling error, work out its angular magnitude by dividing the micrometer value by the distance between the two temporary test targets. If the angle deviation exceeds 1 arcsecond (5 microradians) the transit square is in need of mechanical recalibration. This requires return to the factory and cannot be done in the field.

F. If the instrument is OK, remember to reset the horizontal position to the survey mark if you moved it for this test.

3. Set the LAE-1000 laser autocollimator on a rigid fine-adjust mount at the same height as the transit axis. Turn on the autocollimator and adjust it to autocollimate on the transit square's side mirror.
4. Connect an XY oscilloscope to the LAE-1000 outputs and adjust the scale to represent approximately ± 50 microradians (±10 arcseconds) full scale. Make certain that the display spot is at screen center with the X and Y inputs grounded. Place the LAE-1000 controller into "analog" mode and verify that the oscilloscope display registers the autocollimation spot. Adjust the autocollimator mount to null the display.
5. Gently release the plunge lock and slowly plunge the transit square through 360 degrees while monitoring the spot position on the oscilloscope. The spot will describe a roughly circular path on the screen, whose diameter indicates the angular runout between the mirror normal and the plunge axis.

> NOTE: There is generally 10 microradians of hysteresis which presents an irreducible limit to the precision of squareness. This may be due to bearing clearances in the transit (of order a micron excess clearance would do it). Plunging the transit in the opposite direction may reveal that the path of described by the autocollimator readout spot is different depending on the direction of rotation. It may also contain discrete jumps.

6. If the total runout seen on the autocollimator readout exceeds 15 microradians peak to peak, the mirror is in need of adjustment. This is a tricky procedure but it can be done in the field using the autocollimator. Proceed as follows:

> A. Be sure the transit azimuth and leveling screws have been firmly locked. Avoid touching the transit frame or telescope unnecessarily

during this procedure; using one finger on the eyepiece or objective housing to plunge will help minimize thermal distortion.

B. Gently remove the friction-fit sheet metal cap covering the indicating mirror. This will reveal three small socket-head adjustment screws surrounding the mirror itself.

NOTE: The construction of the mirror mount differs from the cutaway diagram shown in the manual. Our unit has three spring-loaded kinematic adjustment screws on the mirror cell face, and does NOT have a wide spherical bearing with radial adjustments as shown in the documentation. DO NOT TOUCH any screws other than the small face adjustments.

C. Obtain three long-handled hex L-keys to fit the adjustment screws and insert their short legs into the sockets, handles pointing radially away from the axis. A balldriver or T-handled driver will not afford adequate sensitivity. Use a pencil or removable marker to label the screws A, B, and C (or something like that) on the cell face.

D. By plunging the transit clockwise and counterclockwise, attempt to determine the center of the autocollimator readout pattern. Adjust the autocollimator alignment so that the center of the oscilloscope screen corresponds to this pattern center (i.e., so that the spot orbits the origin at equal distance when you plunge through a full circle).

E. Rotate the transit so that a pair of the screws (say A and B) are oriented horizontally, and note the horizontal error on the autocollimator readout. If this happens to be a point where the horizontal error is very small, pick another pair of screws (say A and C).

F. Take out half of the error with each of the two adjustment screws.

NOTE: These screws are INCREDIBLY SENSITIVE. Use a light finger touch on the end of the hex key. Anticipate the "stiction" you will need to overcome before the screw begins to move, and back off the pressure as it starts to rotate. It may take considerable practice to get the feel of it; it may be necessary to reduce the sensitivity of the oscilloscope until you do.

G. Plunge 180 and 360 to verify that the error in the plane of the two chosen screws is zero, that the remaining error is mostly vertical, and that it is symmetrical about the origin.

H. Take out the remaining error with the third screw.

I. Repeat the evaluation. If the runout still exceeds 15 microradians, repeat steps D. through H. Four or five iterations is not unusual.

J. Remember to quit when it's good enough! Experience has shown it isn't worth trying to do much better than 15 microrad peak-peak. This implies the square can only be trusted to ± 1.5 arcsecond; specifications aside, this seems to be the best the instrument can do repeatably.

K. Remove the hex keys (gently!) and replace the sheet metal cover. Record the procedure and final runout figures from the autocollimator readout in the Initial Alignment log.

7. When the total runout is within limits, proceed with setting the transit for use. If feasible, check the runout with the autocollimator occasionally during use, especially after any disturbance or moving of the transit.

BATCH START

STAPLE
OR
DIVIDER

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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ASC Initial Alignment Procedures

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Distribution of this draft:

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1 SCOPE

The purpose of this document is to establish the procedures and specify the equipment required to initially align the core optic and detector subsystem components. The procedures described can be used on the 2 km arms at the Hanford. WA site and the 4 km arms at both the Hanford and Livingston, LA sites.

Offset centerlines will first be established parallel to the X and Y arms of the interferometer at the corner, mid, and end stations. Optical tooling techniques will then be used to translate these offset centerlines parallel to the beam tube centerline.

Establishing offset centerlines offers two main benefits:

1. Beam tubes can be installed and pumped down prior to the rest of the system being installed and aligned.
2. Future alignment or alignment verification can be done with the beam tubes closed off.

Alignment of each core optic consists of 3 adjustments. They are:

1. Transverse and vertical positioning which will be accomplished by moving the LOS until a set of fiducials are sighted with a theodolite.

2. Axial positioning (along the beamline) which utilizes the electronic distance measurement feature on the theodolite.

3. Angular alignment in which the optic will be oriented by autocollimation.

2 REQUIREMENTS

Initial alignment must set the Nd Yag laser beam within the range of adjustment of the COS such that a transition to acquisition alignment can take place. The specifications required for this to occur is specified in LIGO - T970060-00-D (1):

Angular positioning	+/- 0.1 mrad	(ITM, ETM,BS, RM, FM)
Transverse positioning	+/- 1 mm	(ITM, ETM)
	+/- 5 mm	(BS, RM, FM)
Axial positioning	+/- 3 mm	(ITM, ETM,BS, RM, FM)

The angular alignment phase is most critical due to the long length of the arms, as well as the relatively small range of adjustment of the suspended optics (0.8mrad pk/pk). Our goal for angular alignment is 10% of the adjustment range of the suspended optic or .08 mrad. Over a 4 km arm length, a .08 mrad angle will bring us within 320mm to the center of our ETM (See fig. 1).

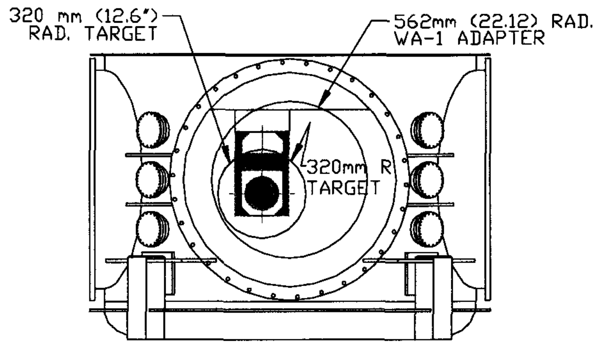


FIG 1. VIEW DOWN END STATION

The Monuments placed as of this date has been found to be within +/- 3mm by Roger's surveying (2). Over a 200 meter separation this results in an error of up to .03 mrad. The total error accumulation including monument locations, procedural and equipment errors is within our goal of .08 mrad as shown in Table 1.

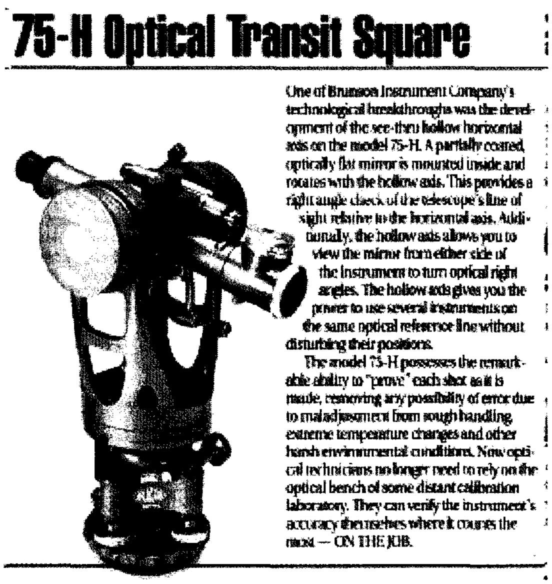
Table 1:

Positioning of monuments	.03 mrad (6 arc seconds)
Sighting of plunb markers	.02mrad (4 arc second)
90 degree autocollimation	.01 mrad (2 arc seconds)
90 degree rotation	.01 mrad (2 arc seconds)
Autocollimation of optic	.01 mrad (2 arc second)
Total	*.08 mrad (16 arc seconds)*

3 EQUIPMENT REQUIRED

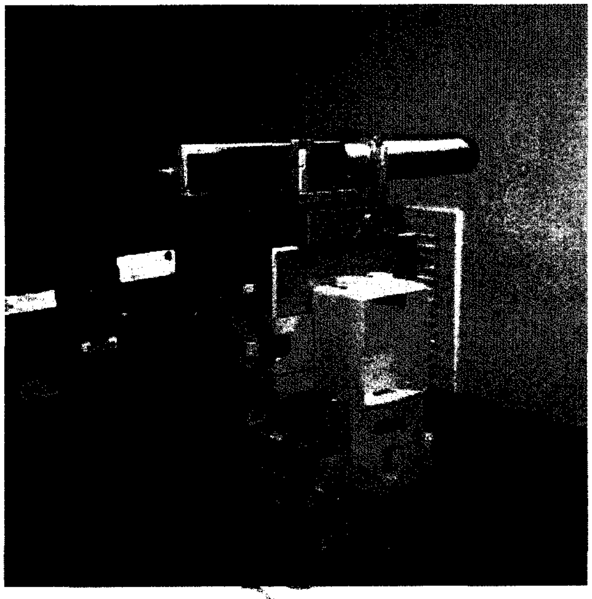
The following equipment or their equivalent will be required:

1. One (1) Sokkia Total Station Theodolite model SET2B with electronic distance measurement (EDM), autocollimating eyepiece, tripod, prism, and optical plummet (pictured below with Newport laser autocollimator).
2. One (1) Brunson model 75-H Optical Transit Squares with autocollimating eyepiece, stand, and coincidence level (pictured below).
3. One (1) Newport laser autocollimator Model LDS1000 with mounts to theodolite.
4. Two (2) 101mm dia. optical flats with mounts (Newport #4024OBD.1 & SL101.6).
5. One (1) 4.0"dia pyrex flat, 1/20 wave, double surface parallel to 1 sec, Al Si O coating both sides. Davidson #D617-4P1P
6. One (1) 12.0" PLX Lateral Transfer Hollow Retroreflector # L-20-1-15.75E
7. One (1) 12.0" PLX Lateral Transfer Hollow Periscope # P-20-1-15.75E
8. One (1) 200mm dia optical flat and mount Davidson #D617-8P2S,Al Si 0 1 side.
9. One (1) 200 ft steel tape and tension scale BMI 2473W200T.
10. One (1) Brunson Instrument stand #230-HC and one (1) model 810 stand.
11. One alignment fixture #D980001-A-D with EDM prism and scale.
12. Support stand to bridge conduit & piping LIGO dwgs. D980431 thru D980434.


75-H Optical Transit Square

One of Brunson Instrument Company's technological breakthroughs was the development of the see-thru hollow horizontal axis on the model 75-H. A partially coated, optically flat mirror is mounted inside and rotates with the hollow axis. This provides a right angle check of the telescope's line of sight relative to the horizontal axis. Additionally, the hollow axis allows you to view the mirror from either side of the instrument to turn optical right angles. The hollow axis gives you the power to use several instruments on the same optical reference line without disturbing their positions.

The model 75-H possesses the remarkable ability to "prove" each shot as it is made, removing any possibility of error due to maladjustment from rough handling, extreme temperature changes and other harsh environmental conditions. Now optical technicians no longer need to rely on the optical bench of some distant calibration laboratory. They can verify the instrument's accuracy themselves where it counts the most — ON THE JOB.



4 CALCULATED OPTIC AND THEODOLITE POSITIONS

Offset centerlines with a clear line of sight are located parallel to the beam tube centerlines in the corner, mid and end stations (see fig 3). These are defined as IAM monuments on drawings D970210 shts 1-5 for Hanford (4) and D980499 shts 1-5 (5) for Livingston. The positional accuracy of the initial alignment monuments must be within +/- 3mm of true position in Ligo Global Coordinates. This applies to X and Y position only.

The Z position is determined from actual positions of door flange centerlines. Scribes are located at each Ham and BSC door locations. The positions of these scribes are measured relative to a control point. For Hanford this control point was 1.0572 meters above BTVE1. The amount of translation required (Z_{offset}) is the difference between the calculated design values and the actual locations of the scribes. A scale is placed on the door flange such that the theodolite can measure directly the Z height. Table 2 contains scribe positions in local coordinates for the Hanford corner station as measured by Rogers Surveying.

Table 2:

MONUMENT	*ELEVATION*	Z_{actual} *(M)*	Z_{design} *(M)*	$Z_{(offset)}$ *(M)*
WGV-6	100.0000 M	.0033	0.0	.0033
WGV-8	99.9719	-.0248	-.0282	.0034
WHAM1	99.9128	-.0839	-.0870	.0031
WHAM-2	99.9028	-.0939	-.0955	.0015
WHAM-4	99.9014	-.0953	-.0994	.0041
WHAM-6	99.9004	-.0963	-.0993	.0030
WHAM-7	99.8823	-.1144	-.1177	.0033
WHAM-9	99.8931	-.1036	-.1076	.0040
WHAM-10	99.8933	-.1034	-.1054	.0020
WHAM-12	99.8952	-.1015	-.1055	.0040
WBSC-2	99.9996	.0029	.0006	.0023
WBSC-4	99.9937	-.0030	-.0053	.0023
WBSC-7	99.9935	-.0032	-.0052	.0020
WBSC-8	99.9993	.0026	+.0005	.0021
WBSC-8 SW	99.9975	.0008	+.0005	.0003

There are several factors which effect the Z-position and pitch of the optics. The curvature of the earth and physical orientation of the beam tube have to be factored into the setup parameters.

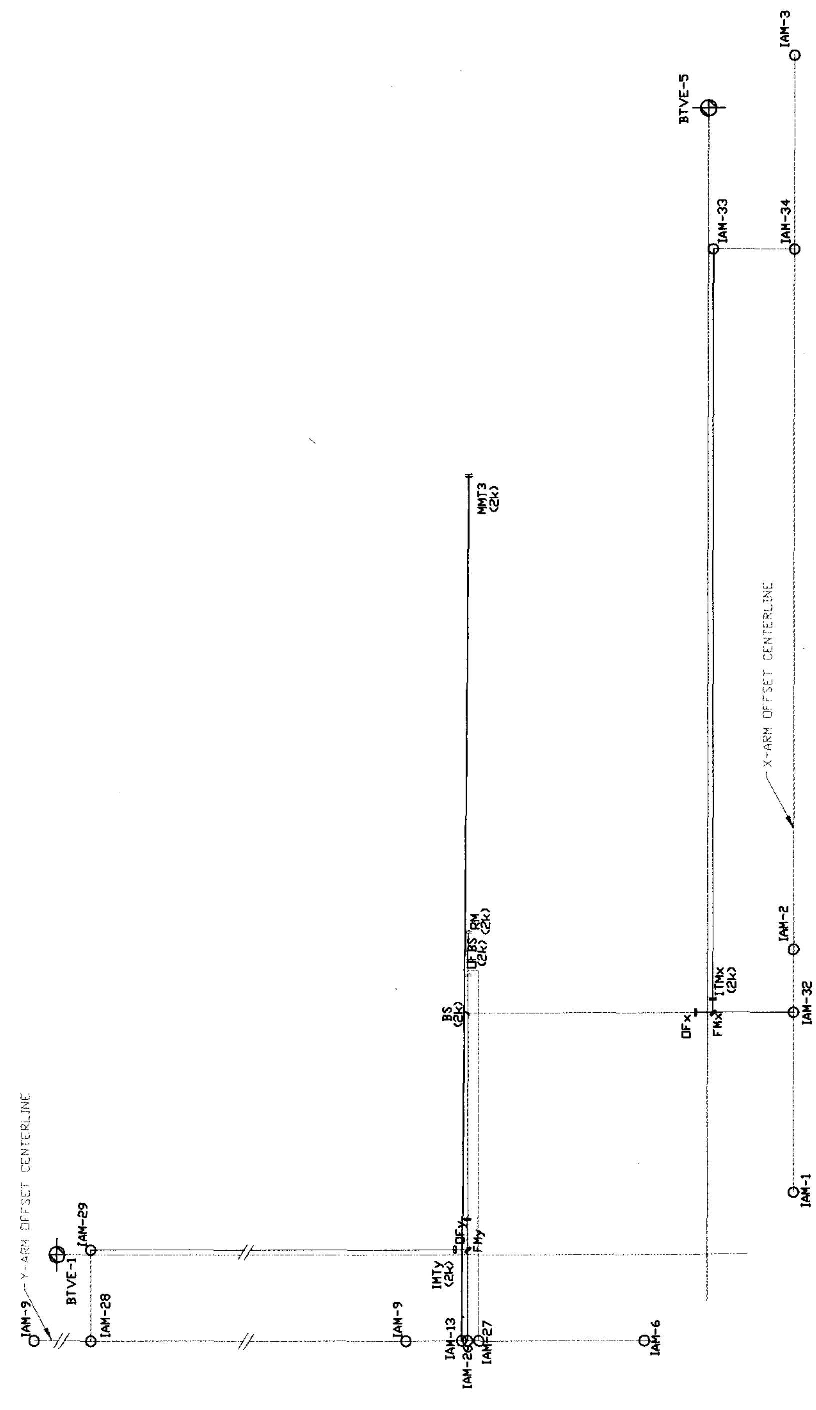
The beam tube orientation and earrth curvature add to give the difference between global and local coordinates. This angle was calculated by Albert Lazzarini in Ligo-T980044 (6)from best fit survey data. The curvature of the earth puts our bubble levels at different angles to the straight line formed by the beam tube. We therefore add this constant angle to our beam tube orientation to properly position the theodolite. This data is summarized in table 3. The total angular compensation is added to the pitch orientation of the theodolite.

Tables 4 thru 6 contain optic positions per Ligo-T970091 (3) and theodolite/autocollimator positions and orientations. The theodolite/autocollimator data was found by taking the surface normals for each of the optics (T970091) and extending the vector until it intersected the plane created by the offset centerlines (fig 2). This data includes compensations for curvature of the earth and physical orientation of the beam tubes.

Table 3:

	CORNER	*MID STATION*			*END STATION*		
ARM	*TOTAL*	*TUBE ORIENT.*	*TOTAL*	*TOTAL*	*TUBE ORIENT*	*EARTH CURV.*	*TOTAL*
X-ARM WA	-619 microrad	-619 microrad	313 microrad	-305.8 microrad	-619 microrad	626 microrad	7.8 microrad
Y-ARM WA	12.5 microrad	12.5 microrad	313 microrad	325.8 microrad	12.5 microrad	626 microrad	639.2 microrad
X-ARM LA	-312 microrad	-	-	-	-312 microrad	614 microrad	315 microrad
Y-ARM LA	-611 microrad	-	-	-	-611 microrad	614 microrad	18.8 microrad

Fig.3 Optic and Monument Locations (2k)



OPTIC AND THEODOLITE POSITIONS (2k INTERFEROMETER) HANFORD

Table 4:

Optic	X optic	Y optic	Z optic	*Monument*	**X** theodolite	**Y** theodolite	**Z** theodolite	**Yaw** theodolite	**Pitch** theodolite
LIGO GLOBAL COORDINATES							LOCAL COORDINATES		
MMT3	29510.7	9062.1	43.1	IAM13	-3251.1	9305.2	19.13	90°25’30	89°55’23
RM	12184	9060	43	IAM14	-3251.1	9060	-246.8	89°59’32	88°57’9”
RM(a)	12184	9060	43	IAM14A	-3251.1	8657.8	-246.8	89°59’32	88°57’9”
OF_y	1614	9072	-95.0	IAM26	-3251.1	9072.1	-108.0	89°59’4”	89°50’43
$OF_{y(a)}$	971.6	9678.8	-96.7	IAM82	-3251.1	7895.3	-96.5	67°29’42	90°0’0”
FM_y	199.6	9072.4	-96.3	IAM29A	200.9	38154	-2.4	270°0’7”	90°11’23
$FM_{y(a)}$	199.6	9072.4	-96.3	IAM81A	-3251.1	9707	-84.7	89°59’16	90°9’58”
ITM_y	199.6	9569.1	-98.1	IAM29	199.6	38154	-98.5	270°0’0”	90°0’2”
ETM_y	199.6	2018689	-98.1	IAM121	199.6	2012861	-100.0	270°0’0”	89°58’52
OF_{bs}	10184	9060	-13.2	IAM27	-3251.1	8660.7	-103.8	270°0’0	89°38’24
$BS_{(2k)}$	9162.6	9059.6	-14.0	IAM32	9163	-3251.2	9.3	270°0’4”	90°9’47
OF_x	9166.2	400	-103.7	IAM32A	9164.4	-3251.2	-121.4	270°1’41	89°48’38
FM_x	9162.6	-199.6	-98.4	IAM33A	38154	-186.2	-81.9	89°58’25	90°2’38
ITM_x	9686.6	-199.6	-100.3	IAM33	38154	-199.6	-123.0	0°0’0”	89°57’52
ETM_x	2018807	-199.6	-100.3	IAM131	2012860	-199.6	-98.4	270°0’0”	90°1’5”

(a) designates an alternate method when the line of sight is blocked by an optic or baffle.

The height of the theodolite does not include the offset distance between the theodolite and the autocollimator and the actual Z scribe reference. The theodolite separation can change therefore must be measured and then subtracted from the value given in tables 4 thru 6 column 8.

e.g. In setting the Hanford MMT3 optic the measured separation was 153.2 mm and we used the scribe on WBSC-8 SW.

Therefore Z-final = Ztheo - Zg - Zsep

Z-final = -19.135 -.30 -153.2

Z-final = -172.6 mm

OPTIC AND THEODOLITE POSITIONS (4k INTERFEROMETER) LIVINGSTON

Table 5:

Optic	X optic	Y optic	Z optic	*Axial* dist.	**X** theodolite	Y theodolite	Z theodolite	**Yaw** theodolite	**Pitch** theodolite
MMT3	-20883.6	207.8	25.6	32484	11600	-8.7	-27.6	90°22'55"	89°53'42"
RM	-4596.0	212.0	26.0	16199	11600	214.1	-283.9	89°59'34"	88°53'57"
OF_{bs}	-199.4	-1780.0	-58.1	23870	-199.4	-22090	-43.5	90°0'0"	90°2'6"
ITM_x	4669.7	199.5	-100.9	6930	11600	199.5	-103.1	90°0'0"	89°58'54"
$BS_{(2k)}$	-199.4	212.6	-57.0	11799	11600	-187.0	-175.4	90°0'8"	89°25'28"
ITM_y	-199.4	4805.2	-98.1	6795	-199.4	11600	-102.3	90°0'0"	89°57'52"
ETM_y	-199.4	3999860	-98.1	2505	200.6	4002365	-98.3	270°0'0"	90°0'04"
ETM_x (HR)	3999725	199.5	-100.9	6025	3993700	199.5	-104.6	90°0'0"	89°58'54"
ETM_x (AR)	3999725	199.5	-100.9	6032	3993700	199.5	200.3	90°0'0"	92°53'30"

5 ALIGNMENT OF MMT3 AND RM (2K HANFORD)

1. Prepare vacuum equipment. Place clean rooms over WHAM 7, WHAM9 and WBSC8. Doors must be removed to allow loading of the LOS and line of sight for alignment equipment (See fig. 5)

2. Place the LOS with the MMT3 optic suspended onto the optics table in Wham7 in its approximate location (see fig 4).

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 13. Level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-8, aligning it to the scribe on the side of the flange.

6. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

7. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180degrees, making sure to encompass the travel the theodolite must move.Calculate the z-heightper page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Rotate towards the monument IAM12 or IAM99 which establishes the offset centerline and align to the monument. Adjust for monument calibration per LIGO-T990017 (7).

10. When aligned to the monument, zero out the horizontal angle and adjust the telescope body to zero the vertical angle. Rotate in yaw and pitch per table 4. The theodolite/autocollimator is now in its final position and should not be moved again.

11. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00" on the scale. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theeodolite crosshairs are aligned to this position and the edge of the scale.

12.Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement. To convert to Ligo Global coordinates subtract the x value of the theodolite (-3251.1mm) from the reading. Adjust the LOS until the correct x position is obtained per table 4.

13. Remove the prism to begin autocollimation of the optic hr surface with the laser autocollimator. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

14. There will probably be 2 reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface. Locate the reflection off the HR surface and guide the reflection through the tube back toward the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets.

15. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

16. Alignment of the RM is identical to MMT3 using the positions found in table 4 and positioning over IAM-14.

17. The doors are replaced and clean rooms removed.

Fig 4. Optical Table Layout

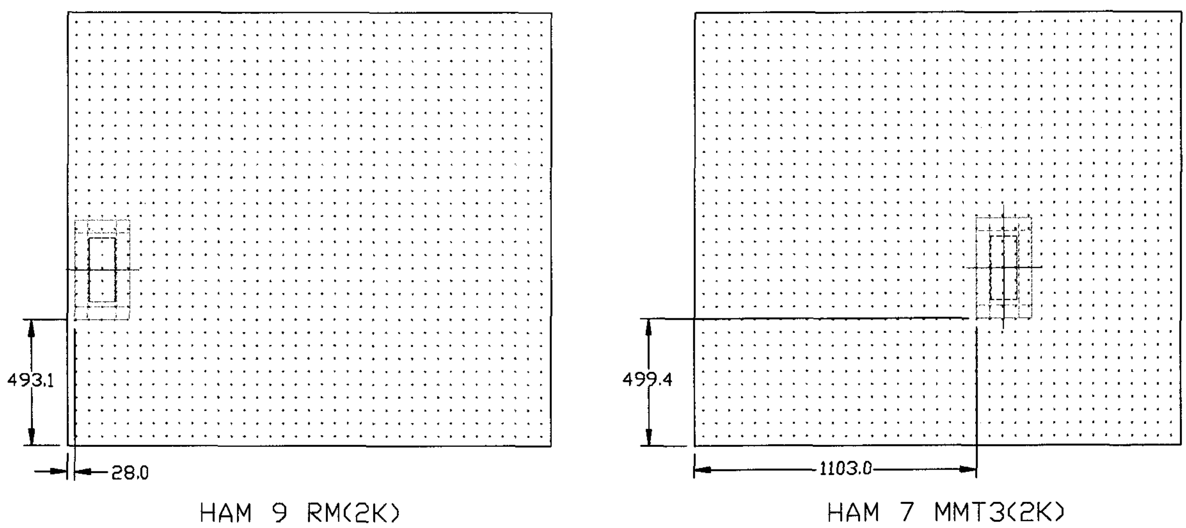
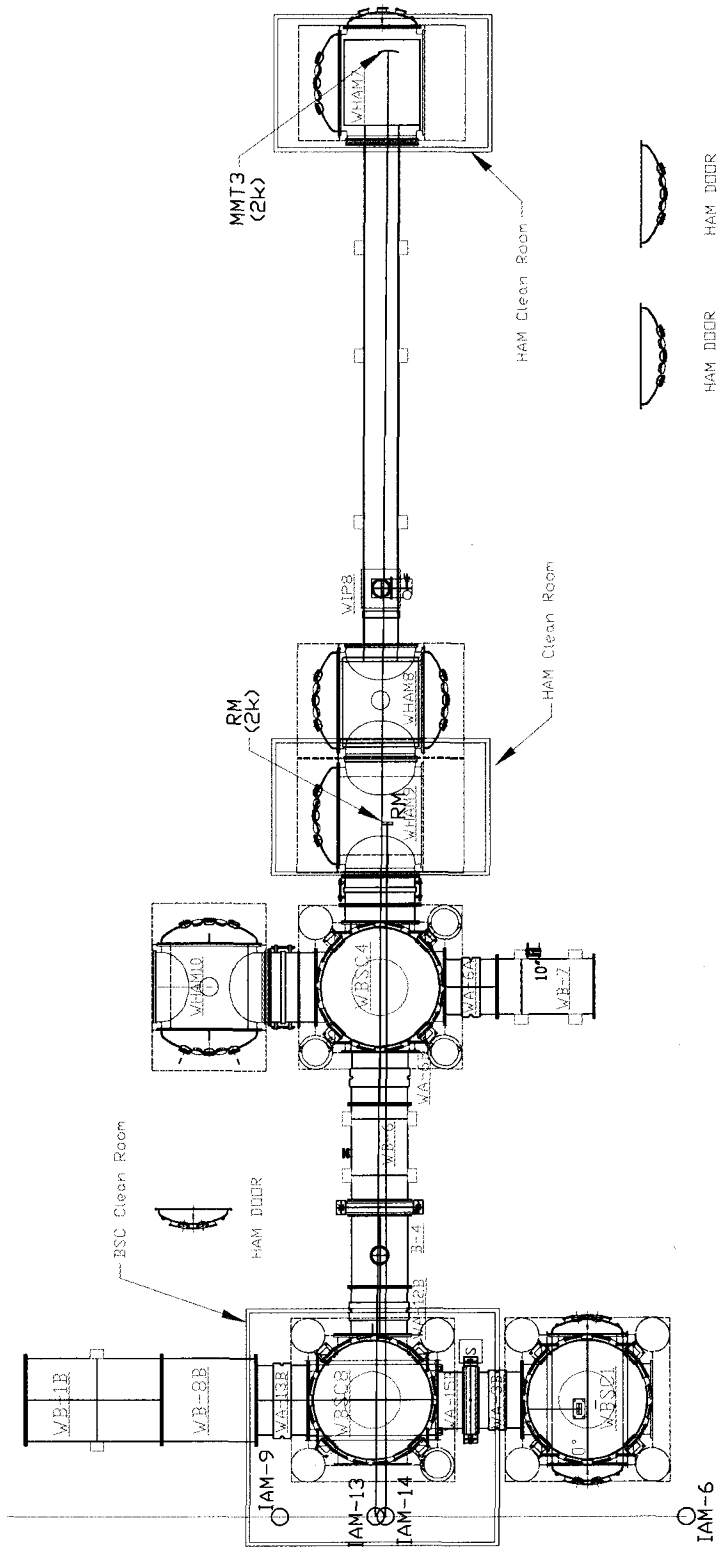


Fig. 5


MMT3
(2k)
HAM Clean Room
HAM DOOR
HAM DOOR
WIP8
HAM Clean Room
RM
(2k)
RM
WBSC4
WB-7
10"
BSC Clean Room
HAM DOOR
WB-1B
WB-8B
WBSC8
WBSC1
IAM-9
IAM-13
IAM-14
IAM-6

6 ALIGNMENT OF OPTICAL FLAT$_Y$(2K HANFORD)

1. Prepare vacuum equipment. Place clean rooms over WBSC-8 and WA-1B. Remove the door on WBSC-8 and adapter WA-1B to allow loading of the LOS and a line of sight for alignment equipment.

2. Place the optical flat and mount into adapter WA-12B in its approximate location as shown in fig.6.

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 26. Level the stand with a machinist level and the theodolite with the bubble level and then internal level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-8, aligning it to the scribe on the side of the flange.

6. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

7. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

8. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

9. Check the separation between the theodolite scope and the autocollimator scope and record this value. Check that the theodolite is level 180 degrees, making sure to encompass the travel the theodolite must move. Recalculate, if necessary, the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

10. Rotate towards the monument IAM12 and IAM99 which establishes the offset centerline and align to the monument. Adjust for monument calibration per LIGO-T990017 (7).

11. Position the optical flat such that the autocollimator beam is approximately centered on the 4.0" dia. optical flat.

12. Adjust the optical flat mount until autocollimated within 1 arc sec (5 microradians).

13. The optical flat is in its final position and must not be moved or bumped.

7 ALIGNMENT OF FM_Y, ITM_Y.FM_X, AND ITM_X (2K HANFORD)

1. Measure the separation from the FM optic face to the prism mount location on the alignment fixture Ligo D980001 and record this distance. Install the scale and verify that a mark on the scale corresponds to the center of the optic and record this value.

2. Locate and verify the position of IAM-29 located on the optical lever stand under adapter WA-1B.

3. Place the LOS with the FM_y optic suspended onto the optics table in WBSC-8 in its approximate location per fig.6.

4. Mount the Brunson Transit square to the Brunson 230-HC stand and place over IAM 28 at the theodolite height for FM_y (table 4).

5. Level the transit square with the coincidence level per appendix 2. Rotate the scope towards IAM12. Adjust the optical micrometer on the Brunson square by -.077" per LIGO-T990017 (7), and sight the string and plumb bob over IAM12. The transit square is now in its final position and should not be moved again.

6. Assemble the Brunson 810 stand onto the optical lever bridge. Place the theodolite/autocollimator on the stand and level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over IAM-29 plus .7071(A) per fig 6.

7. Clamp a 300mm or greater scale to the flange protector on WGV-6, aligning it to the scribe on the side of the valve.

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Verify the squareness of the transit square with the LDS1000 laser autocollimator per appendix 3.

10. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

11. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

12. Check the separation between the theodolite scope and the autocollimator scope and record this value. Check that the theodolite is level 180 degrees, making sure to encompass the travel the theodolite must move. Recalculate, if necessary, the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

13. Rotate the theodolite/autocollimator towards the brunson square, and autocollimate off the mirror on the square. Zero out the horizontal angle. Rotate the theodolite in pitch and yaw per table 4. The theodolite/autocollimator is now in its final position for positioning the optic and should not be moved again.

14. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00" on the scale or other value measured earlier. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theodolite crosshairs are aligned vertically.

15 .Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement see fig 6.

16. Place the theodolite/autocollimator over IAM29A and repeat steps 6 thru 13 above. If the Brunson square has not been moved, step 9 can be ommitted. The autocollimator should be in its final position for angular alignment per Table 4. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

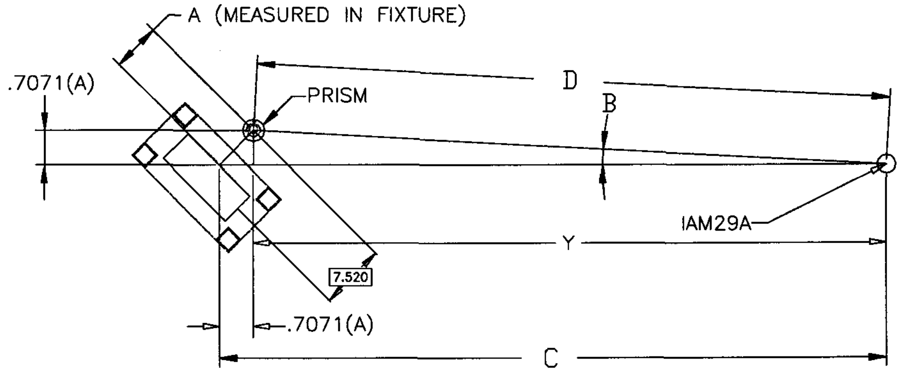
17. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the folding mirror and hits the optical flat. Locate the reflection off the HR surface and guide the reflection through the tube back toward the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

18. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

19. Alignment of the ITM_y is similar to FM_y with the exception that the prism is in line with the optic and no angular compensation is required. Autocollimation occurs directly off the face of the optic.

20.Alignment of the FM_x and ITM_x is identical to the procedure above using the positions and angles found in table 4.

FIG. 6



1. MEASURE DISTANCE A.
2. CALCULATE OFFSET = .7071(A).
3. CALCULATE ANGLE B
   TAN B = .7071 (A) / Y
4. SET UP THEODOLITE AND POSITION PRISM IN TRANSVERSE AND VERTICAL POSITION.
5. CALCULATE DISTANCE FROM THEODOLITE TO PRISM
   COS B = Y / D
6. SET AXIAL POSITION D WITH THEODOLITE
7. RECHECK TRANSVERSE POSITION AND MOVE IF NECESSARY

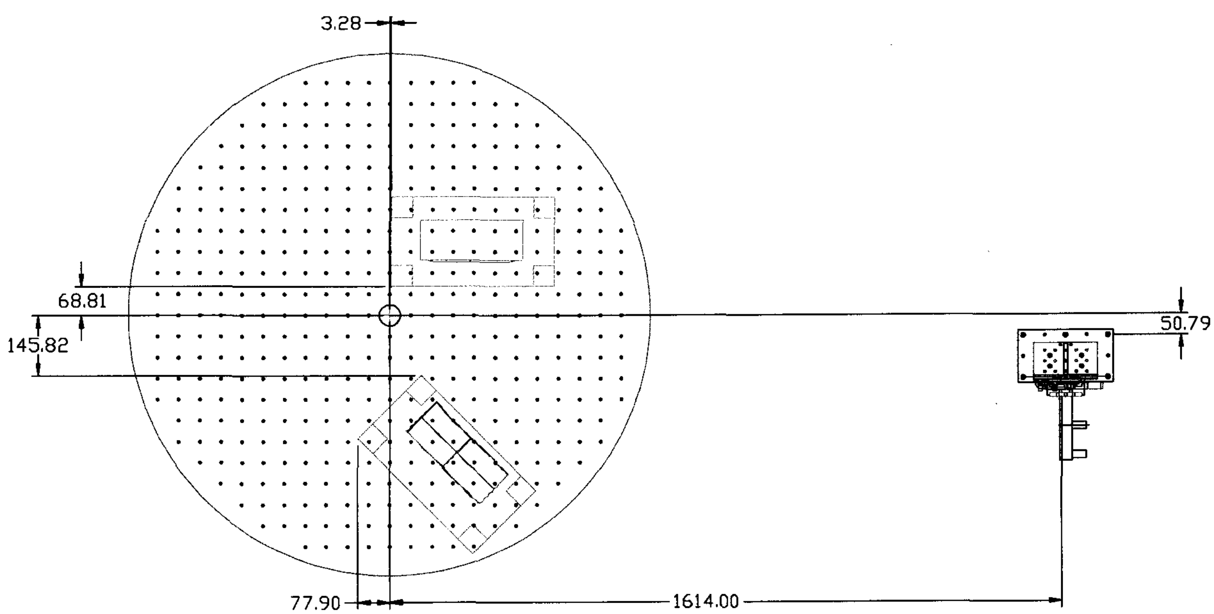


Fig. 7 Optic Layout BSC8

8 ALIGNMENT OF OPTICAL FLAT$_{BS}$(2K HANFORD)

1. Prepare vacuum equipment. Place clean rooms over WBSC-8 and WBSC-4. Remove the door on WBSC-8 and adapter WBE-3C to allow loading of the LOS and a line of sight for alignment equipment.

2. Place the 2 sided optical flat (Davidson D617-4) and PLX retroreflector into adapter WBE-3A2 in its approximate location as shown in fig.8.

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 27. Level the stand with a machinist level and the theodolite with the bubble level and then internal level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-8, aligning it to the scribe on the side of the flange.

6. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

7. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

8. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

9. Check the separation between the theodolite scope and the autocollimator scope and record this value. Check that the theodolite is level 180 degrees, making sure to encompass the travel the theodolite must move. Recalculate, if necessary, the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

10. Rotate towards the monument IAM12 and IAM99 which establishes the offset centerline and align to the monument. Adjust for monument calibration per LIGO-T990017 (7).

11. Position the PLX retroreflector such that the autocollimator beam enters and exits the retroreflector without clipping the beam. Adjust the optical flat until autocollimated within 1 arc sec (5 microradians) without clipping the beam.

13. The optical flat is in its final position and must not be moved or bumped.

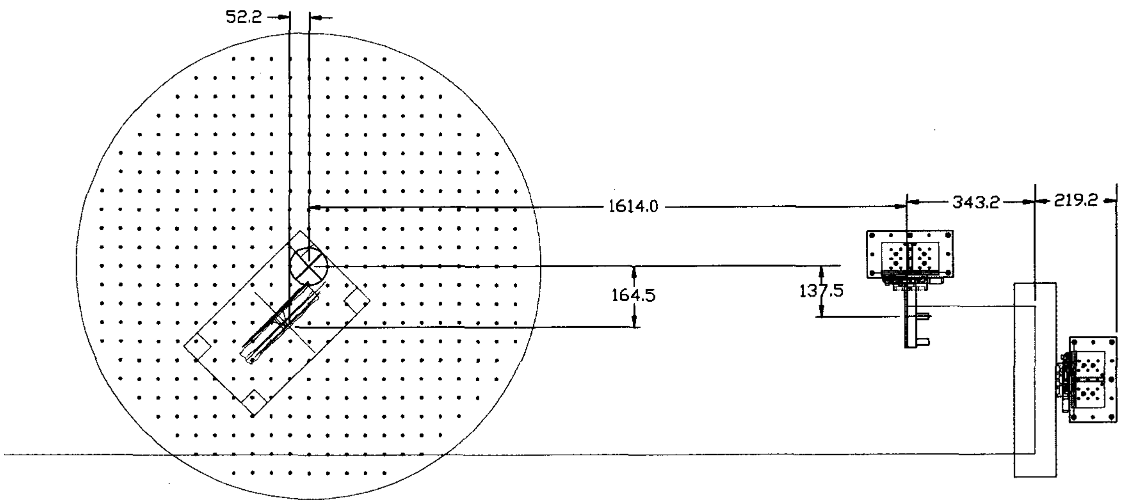


Fig. 8 Optic Layout BSC4

9 ALIGNMENT OF THE BEAMSPLITTER (2K HANFORD)

1. Prepare vacuum equipment. Place clean rooms over WBSC-4 and WBSC-8. Doors must be removed to allow loading of the LOS and line of sight for alignment equipment.

2. Place the LOS with the BS optic suspended into WBSC-4 in its approximate location as shown in fig.8.

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 32 plus .7071(A) per fig.6. Level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-7, aligning it to the scribe on the side of the flange.

6. Set the 8.0” diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

7. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180degrees, making sure to encompass the travel the theodolite must move.Calculate the z-heightper page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Rotate towards the monument IAM3 which establishes the offset centerline and align to the monument. Adjust for monument calibration if necessary.

10. When aligned to the monument, zero out the horizontal angle and adjust the telescope body to zero the vertical angle. Rotate in yaw and pitch per table 4. The theodolite/autocollimator is now in its final position for positionining the optic.

11. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00” on the scale. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theeodolite crosshairs are aligned to this position vertically.

12.Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement per fig.6.

13. Place the theodolite/autocollimator over IAM32 and repeat steps 4 thru 10 above. The autocollimator should be in its final position for angular alignment per Table 4. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

14. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the beamsplitter and hits the optical flat. Locate the reflection off the HR surface and guide the reflection through the tube back toward the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

15. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

16. Remove the optical flat and PLX retroreflector from WBE-3A2.

17. The doors are replaced and clean rooms removed.

10 ALIGNMENT OF END TEST MASSES ETM_Y AND ETM_X (2K INTERFEROMETER)

1. Prepare vacuum equipment. Place a clean room over WBSC-6. Remove the door on WBSC-6 and adapter WA-14A to allow loading of the LOS and a line of sight for alignment equipment.

2. Measure the separation from the FM optic face to the prism mount location on the alignment fixture Ligo D980001 (8) and record this distance. Install the scale and verify that a mark on the scale corresponds to the center of the optic and record this value.

3. Place the PLX retroreflector into adapter WA-7A1 and the LOS with the ETMy optic suspended in WBSC-6 in their approximate location as shown in fig.9.

4. Mount the Brunson Transit square to the Brunson 230-HC stand and place over IAM 20 at the theodolite height for ETM_y (table 4).

5. Level the transit square with the coincidence level per appendix 2. Rotate the scope towards IAM19. Sight the string and plumb bob over IAM19. The transit square is now in its final position and should not be moved again.

6. Assemble the Brunson 810 stand onto the alignment bridge. Place the theodolite/autocollimator on the stand and level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over IAM-21A (400mm toward IAM-20 from IAM21) and set the height as specified in table 4.

7. Clamp a 300mm or greater scale to the flange protector on WGV-6, aligning it to the scribe on the side of the valve.

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Verify the squareness of the transit square with the LDS1000 laser autocollimator per appendix 3.

10. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

11. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

12. Check the separation between the theodolite scope and the autocollimator scope and record this value. Check that the theodolite is level 180 degrees, making sure to encompass the travel the theodolite must move. Recalculate, if necessary, the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

13. Rotate the theodolite/autocollimator towards the brunson square, and autocollimate off the mirror on the square. Zero out the horizontal angle. Rotate the theodolite in pitch and yaw per table 4. The theodolite/autocollimator is now in its final position and should not be moved again.

14. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00" on the scale or other value measured earlier. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theeodolite crosshairs are aligned to this position and the edge of the scale.

15 .Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement. In the case of the Fold Mirror a calculation will have to be made to account for the spacing being at 45 degrees.To convert to Ligo Global coordinates subtract the value obtained from the y position of the theodolite (-38154 mm) . Adjust the LOS until the correct y position is obtained per table 4.

16.. Move the Brunson 810 stand approximately over IAM21. level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over IAM-21 and set the height as specified in table 4

17. Remove the prism to begin autocollimation of the optic hr surface with the laser autocollimator. Make sure the readings on the theodolite are per table 4. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

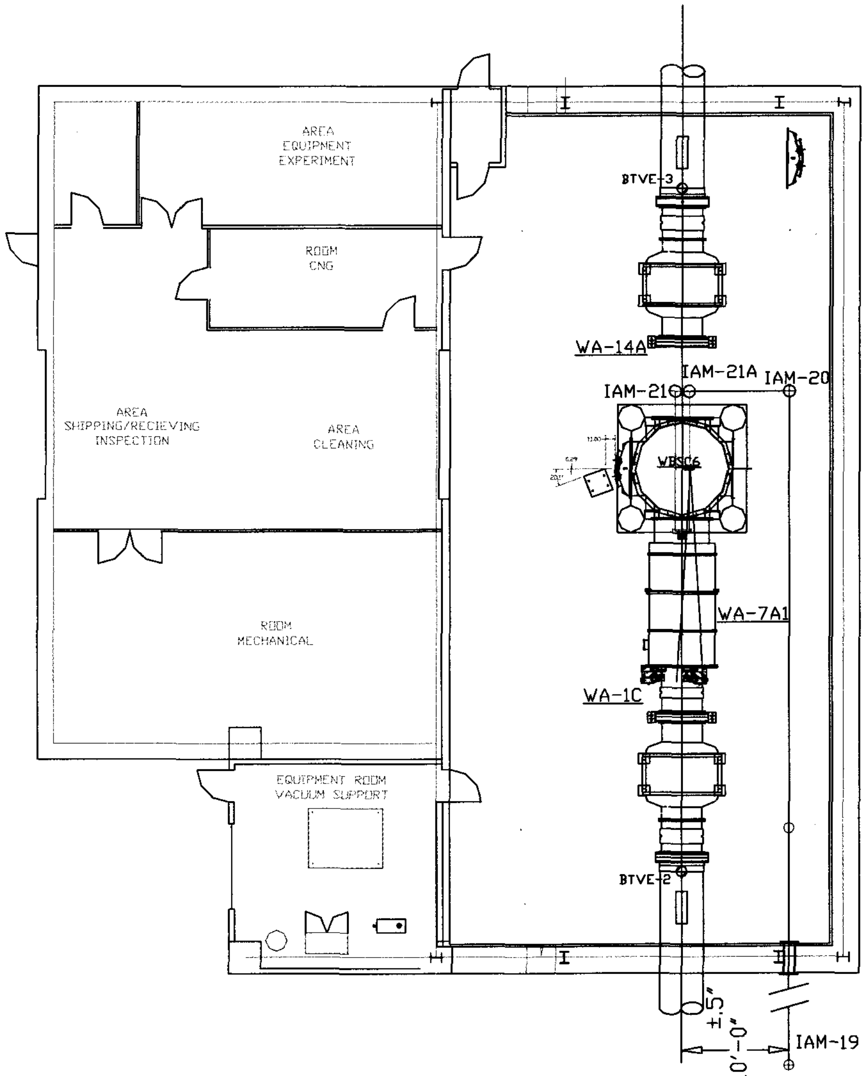
18. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the beamspitter. Locate the reflection off the HR surface and guide the reflection through the retroreflector and back to the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

19. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

19. Alignment of the other ETM's are similar using the positions found in table 4.

20. The door and adapter are replaced and clean rooms removed.

FIG.9 Y-MID STATION



11 ALIGNMENT OF END TEST MASS ETM_X (4K LIVINGSTON INTERFEROMETER)

1. Prepare vacuum equipment. Place a clean room over LBSC-4 and spool. Remove the door on LBSC-4 and spool piece to allow loading of the LOS and a line of sight for alignment equipment.

2. Measure the separation from the ETM optic face to the prism mount location on the alignment fixture Ligo D980001 (8) and record this distance.

3. Locate monument IAM-L20 on the offset centerline at (3993700,-1854.2). To do this buck in with the Brunson transit between two targets located high on the walls. Scribe a line along the offset centerline in the vicinity of the PSI brass tag located behind the rear door of LBSC-4. Now place a 1.5 meter straight edge over the brass tag mark toward the scribe line and square it off with a precise square. Mark this monument IAM-L21.The coordinates of this monument will be (4002365,-1854.2)

4. Roughly measure from IAM-L21 6025 mm towards the beam tube. Again using the Brunson transit scribe a line along the offset centerline in this area. Remeasure 6025 mm from IAM-L21 along the scribe and mark this monument IAM-L20.

5. With the 1.5 meter straight edge and precise square, place a scribe and monument at coordinates (3993700, 199.5) and mark this IAM-L22.

6. Measure the height of the scribe located on the side of the gate valve relative to BTVE-4 and record this value.

7. Clamp a 300 mm or greater scale to the flange protector on the gate valve, aligning it to the scribe on the side of the valve pointing up.

8. Mount the Brunson Transit square to the Brunson 230-HC stand and place over IAM-L21 at the autocollimator height for ETM_y per table 5. (200.3 mm for AR, -104.6 mm for HR).

9. Level the transit square with the coincidence level per appendix 2. Rotate the scope towards the monument on the wall towards the beam tube. The transit square is now in its final position and should not be moved again.Verify the height has not changed.

10. Assemble the Brunson 810 stand onto the alignment bridge. Place the theodolite/autocollimator on the stand and level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, roughly center the theodolite over IAM-L22 and roughly set the height per table 5.

11. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the Z-theodolite position.

12. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second(5 microradians), adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controllerfor the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec(5 microradians).

13. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height by subtracting from the height the difference between the actual and design height of the marker and subtracting the separation distance measured from the theodolite height. Set the crosshairs in the theodolite to the appropriate mark on the scale.

14. Verify the squareness of the transit square with the LDS1000 laser autocollimator per appendix 3.

15. Rotate the theodolite/autocollimator towards the Brunson square, and autocollimate off the mirror on the square. Zero out the horizontal angle. Rotate the theodolite in pitch and yaw per table 5. The theodolite/autocollimator is now in its final position.

16. If the optic has not been placed in the chamber. Install the LOS per LIGO E000062-C titled LOS Installation Procedures For BSC Chambers. Have someone place a light on the scribe located on the top of the LOS structure. Rotate the theodolite in pitch until the scribe is located. Move the LOS structure until the crosshairs are aligned to the scribe.

17 .Place the prism into the prism holder on the LOS fixture. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement. Move the LOS axially until the theodolite reads the correct axial distance per table 5.

18. Remove the prism to begin autocollimation of the optic hr surface with the laser autocollimator. Make sure the readings on the theodolite are per table 5. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

19. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the beamspitter. Locate the reflection off the AR surface and guide the reflection through the retroreflector and back to the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

20. At this point we must setup for alignment of the ETM telescope and ETM transmission monitor per LIGO T990088 titled COS IFO Alignment Procedures. This procedure will vary depending on which surface was used to align the optic.

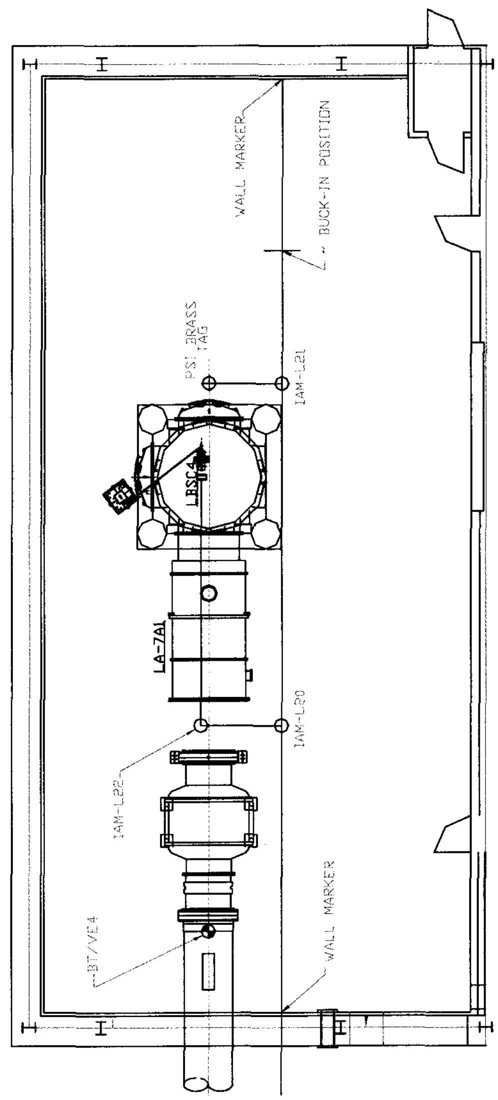
A. If the HR surface was used for alignment per numbers found in Table 5, Place the 8.0" dia optic flat in front of the laser autocollimator while it is in its final position and autocollimate to the flat. Remove the theodolite and autocollimator by releasing the knob on the side of the Sokkia tribach. Replace the theodolite with the IR laser adapter and IR Laser autocollimator. Autocollimate to the optic flat with the IR autocollimator and remove the optic flat. Align the ETM telescope and ETM transmission monitor per LIGO T990088.

B. If the AR surface was used for alignment using numbers found in Table 1, the Brunson transit square and Sokkia theodolite/autocollimator must be reset to the heights used for aligning the HR surface. Follow steps above for aligning the transit square and theodolite at the values in Table 1 for ETMx(HR). Then place the 8.0" dia optic flat in front of the laser autocollimator while it is in its final position and autocollimate to the flat. Remove the theodolite and autocollimator by releasing the knob on the side of the Sokkia tribach. Replace the theodolite with the IR laser adapter and IR Laser autocollimator. Autocollimate to the optic flat with the IR autocollimator and remove the optic flat. Align the ETM telescope and ETM transmission monitor per LIGO T990088.

21. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

22. The door and adapter are replaced and clean rooms removed.

IAS-MONUMENT_LOCATIONS_LIGO_GLOBAL			
	X-COORDINATE(MM)	Y-COORDINATE(MM)	Z-COORDINATE(MM)
PSI-B/T	4002365	0	-
IAM-L21	4002365	-1854.2	-
IAM-L20	3993700	-1854.2	-
IAM-L22	3993700	199.5	-
BT/VE-4	3988500	0	-1.080



APPENDIX 1 REFERENCES

[1] LIGO-T970060- 00-D, Alignment Sensing/ Control Preliminary Design

[2] Gary P. Wagner "Precision Survey of Beam Tube/ Vacuum Equipment Interface", Rogers Surveying, October 1,1996.

[3] LIGO-T970091-00, Determination of Core Optic Wedge Angles, Dennis Coyne

[4] LIGO-D970210, ASC Monument Locations - Wa. Site, K.Mason

[5] LIGO-D980499, ASC Monument Locations - La. Site, K.Mason

[6] LIGO-T980044, Determination of Global and Ligo Coordinate axis for the Ligo Sites, Albert Lazzarini

[7] LIGO-T990017, Calibration of Initial Alignment Survey by Sighting through Y1 Beam Tube, M.Zucker

[8] LIGO-D980001, Alignment Fixture

[3] LIGO-T990026, Calibration of Optical Levers, M.Zucker

APPENDIX 2 LEVELING PROCEDURE ON THE BRUNSON 75H TRANSIT SQUARE

1. Level scope by circular level.

2. Set scope such that 2 leveling screws are in line with scope and 2 screws are 90 deg. to scope.

3. Level scope eith tangent screw (brass knob inside transit casting).

4. Rotate 180 deg and take out half error with tangent screw and half with leveling screws until bubbles on coincidence level are in line with one another.

5. Rotate 90 deg and take out with leveling screws.

6. Rotate 180 deg from last position and take out half with tangent screws and half with leveling screws.

7. If necessary continue this method of rotating 90 deg adjusting leveling screws, then 180 adjusting half and half until bubble is level over full 360 deg.

8. When close only use leveling screws and tighten only.

9 Rotate 360 deg to make sure transit is level.

APPENDIX 3 VERIFIFICATION AND REALIGNMENT OF INDICATING MIRROR ON THE BRUNSON 75H OPTICAL TRANSIT SQUARE

The Brunson optical transit square's side indicating mirror surface is nominally parallel to the square's optical axis and vertical (azimuthal) rotation axis within 1 arcsecond . However it has been observed to go out of square during shipping as well as between setups. It is therefore imperative to check and, if required, adjust the mirror for squareness each time it is mounted for use.

NOTE: Verification of square adjustment should take approximately 45 minutes for an experienced operator, assuming all equipment is staged and ready. Restoring alignment may take from 2 to 6 hours depending on the degree of misalignment. In what follows it is assumed that the user is familiar with and experienced in the use and maintenance of transit instruments.

1. Set the transit over the desired survey position at the required height, and level using the coincidence level according to procedure in Appendix II. Let the instrument settle and thermally equilibrate for at least 15 minutes and recheck the coincidence level in all directions before proceeding.

2. Verify that the plunge axis and azimuth axis are mutually orthogonal and orthogonal to the optic axis;

A. Set the optical micrometer at zero and null the crosshair to a fixed target at least 20' away, preferably at about the same height as the transit. Be sure to lock the azimuth circle.

B. Plunge the transit to come up horizontal on the opposite side; have an assistant scribe a new reference target on a stable surface at least 20' away in the opposite direction, exactly coinciding with the crosshair position. Plunge again to double check that the two target marks and the transit lie on a common line. If there is some error, the transit can be translated slightly using fine horizontal adjustments of the mount (take out half the error by translation and finish with azimuth fine adjustment; iterate until the crosshair splits both marks when plunged).

C. Unlock the azimuth and slew the transit horizontally 180¡ to locate the second mark. Lock the coarse azimuth and use the fine adjust to split the mark with the crosshair.

D. Plunge the transit through 180 degrees and check that the crosshair once again again splits the first target. Measure any discernible error using the optical micrometer.

E. Recheck the instrument level. If not level, readjust level and start over.

If there a visible difference not attributable to a leveling error, work out its angular magnitude by dividing the micrometer value by the distance between the two temporary test targets. If the angle deviation exceeds 1 arcsecond (5 microradians) the transit square is in need of mechanical recalibration. This requires return to the factory and cannot be done in the field.

F. If the instrument is OK, remember to reset the horizontal position to the survey mark if you moved it for this test.

3. Set the LAE-1000 laser autocollimator on a rigid fine-adjust mount at the same height as the transit axis. Turn on the autocollimator and

adjust it to autocollimate on the transit square's side mirror.

4. Connect an XY oscilloscope to the LAE-1000 outputs and adjust the scale to represent approximately ± 50 microradians (±10 arcseconds) full scale. Make certain that the display spot is at screen center with the X and Y inputs grounded. Place the LAE-1000 controller into "analog" mode and verify that the oscilloscope display registers the autocollimation spot. Adjust the autocollimator mount to null the display.

5. Gently release the plunge lock and slowly plunge the transit square through 360 degrees while monitoring the spot position on the oscilloscope. The spot will describe a roughly circular path on the screen, whose diameter indicates the angular runout between the mirror normal and the plunge axis.

> NOTE: There is generally 10 microradians of hysteresis which presents an irreducible limit to the precision of squareness. This may be due to bearing clearances in the transit (of order a micron excess clearance would do it). Plunging the transit in the opposite direction may reveal that the path of described by the autocollimator readout spot is different depending on the direction of rotation. It may also contain discrete jumps.

6. If the total runout seen on the autocollimator readout exceeds 15 microradians peak to peak, the mirror is in need of adjustment. This is a tricky procedure but it can be done in the field using the autocollimator. Proceed as follows:

> A. Be sure the transit azimuth and leveling screws have been firmly locked. Avoid touching the transit frame or telescope unnecessarily during this procedure; using one finger on the eyepiece or objective housing to plunge will help minimize thermal distortion.

B. Gently remove the friction-fit sheet metal cap covering the indicating mirror. This will reveal three small socket-head adjustment screws surrounding the mirror itself.
NOTE: The construction of the mirror mount differs from the cutaway diagram shown in the manual. Our unit has three spring-loaded kinematic adjustment screws on the mirror cell face, and does NOT have a wide spherical bearing with radial adjustments as shown in the documentation. DO NOT TOUCH any screws other than the small face adjustments.

C. Obtain three long-handled hex L-keys to fit the adjustment screws and insert their short legs into the sockets, handles pointing radially away from the axis. A balldriver or T-handled driver will not afford adequate sensitivity. Use a pencil or removable marker to label the screws A, B, and C (or something like that) on the cell face.
D. By plunging the transit clockwise and counterclockwise, attempt to determine the center of the autocollimator readout pattern. Adjust the autocollimator alignment so that the center of the oscilloscope screen corresponds to this pattern center (i.e., so that the spot orbits the origin at equal distance when you plunge through a full circle).
E. Rotate the transit so that a pair of the screws (say A and B) are oriented horizontally, and note the horizontal error on the autocollimator readout. If this happens to be a point where the horizontal error is very small, pick another pair of screws (say A and C).
F. Take out half of the error with each of the two adjustment screws.
NOTE: These screws are INCREDIBLY SENSITIVE. Use a light finger

touch on the end of the hex key. Anticipate the "stiction" you will need to overcome before the screw begins to move, and back off the pressure as it starts to rotate. It may take considerable practice to get the feel of it; it may be necessary to reduce the sensitivity of the oscilloscope until you do.

G. Plunge 180 and 360 to verify that the error in the plane of the two chosen screws is zero, that the remaining error is mostly vertical, and that it is symmetrical about the origin.

H. Take out the remaining error with the third screw.

I. Repeat the evaluation. If the runout still exceeds 15 microradians, repeat steps D. through H. Four or five iterations is not unusual.

J. Remember to quit when it's good enough! Experience has shown it isn't worth trying to do much better than 15 microrad peak-peak. This implies the square can only be trusted to ± 1.5 arcsecond; specifications aside, this seems to be the best the instrument can do repeatably.

K. Remove the hex keys (gently!) and replace the sheet metal cover. Record the procedure and final runout figures from the autocollimator readout in the Initial Alignment log.

7. When the total runout is within limits, proceed with setting the transit for use. If feasible, check the runout with the autocollimator occasionally during use, especially after any disturbance or moving of the transit.

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ASC Initial Alignment Procedures

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1 SCOPE

The purpose of this document is to establish the procedures and specify the equipment required to initially align the core optic and detector subsystem components. The procedures described can be used on the 2 km arms at the Hanford. WA site and the 4 km arms at both the Hanford and Livingston, LA sites.

Offset centerlines will first be established parallel to the X and Y arms of the interferometer at the corner, mid, and end stations. Optical tooling techniques will then be used to translate these offset centerlines parallel to the beam tube centerline.

Establishing offset centerlines offers two main benefits:

1. Beam tubes can be installed and pumped down prior to the rest of the system being installed and aligned.
2. Future alignment or alignment verification can be done with the beam tubes closed off.

Alignment of each core optic consists of 3 adjustments. They are:

1. Transverse and vertical positioning which will be accomplished by moving the LOS until a set of fiducials are sighted with a theodolite.

2. Axial positioning (along the beamline) which utilizes the electronic distance measurement feature on the theodolite.

3. Angular alignment in which the optic will be oriented by autocollimation.

2 REQUIREMENTS

Initial alignment must set the Nd Yag laser beam within the range of adjustment of the COS such that a transition to acquisition alignment can take place. The specifications required for this to occur is specified in LIGO - T970060-00-D (1):

Angular positioning	+/- 0.1 mrad (ITM, ETM,BS, RM, FM)
Transverse positioning	+/- 1 mm (ITM, ETM)
	+/- 5 mm (BS, RM, FM)
Axial positioning	+/- 3 mm (ITM, ETM,BS, RM, FM)

The angular alignment phase is most critical due to the long length of the arms, as well as the relatively small range of adjustment of the suspended optics (0.8mrad pk/pk). The clear aperture target area is also reduced due to the 200 mm horizontal and 100 mm vertical offset of the beam centerline, leaving a clear aperture of +/- 568 mm. See Table 1.

Our goal for angular alignment is 10% of the adjustment range of the suspended optic or .08 mrad. .Over a 4 km arm length, a .08 mrad angle will bring us within 320mm to the center of our ETM, which is within our clear apperture requirement of +/- 568 mm. Monument accuracy has been found to be within +/- 3mm (2). Over a 200 meter separation this results in an error of up to .03 mrad. The total error accumulation including monument locations, procedural and equipment errors is .08 mrad.

3 EQUIPMENT REQUIRED

The following equipment or their equivalent will be required:

1. One (1) Sokkia Total Station Theodolite model SET2B with electronic distance measurement (EDM), autocollimating eyepiece, tripod, prism, and optical plummet.
2. One (1) Brunson model 75-H Optical Transit Squares with autocollimating eyepiece, stand, coincidence level, and optical plummet.
3. Four (4) 200mm dia. optical flats with mounts.
4. One (1) laser autocollimator mounted and aligned to the theodolite.
5. One (1) 12.0" PLX Lateral Transfer Hollow Retroreflector
6. Two (2) Optical Plummets and stands.
7. One (1) Transverse measurement straightedge with measuring tape.
8. Two (2) Mounting brackets for Lateral Transfer Hollow Retroreflector.
9. One (1) LOS Alignment Fixture

Table 1:

Positioning of monuments	.03 mrad (6 arc seconds)
Sighting of plunb markers	.02mrad (4 arc second)
90 degree autocollimation	.01 mrad (2 arc seconds)
90 degree rotation	.01 mrad (2 arc seconds)
Autocollimation of optic	.01 mrad (2 arc second)
Total	*.08 mrad (16 arc seconds)*

4 DETERMINING OFFSET CENTERLINE

Two offset centerlines with a clear line of sight will be located along the outside of the X and Y arms for the cornerstation, and along the inside of both mid and end stations. See fig (1), and refer to drawings D970210, sheets 1-5 for detailed position requirements.

The positional accuracy of the initial alignment monuments must be within +/- 5mm of true position. Monuments located using the trimble 4000SSI global positioning system have been shown to be accurate within these tolerances by Rogers Surveying (2). Triangulation measurements off the existing beamtube centerline and monuments has been used to verify monument positions. This technique if carefully done will also yield positions within tolerance.

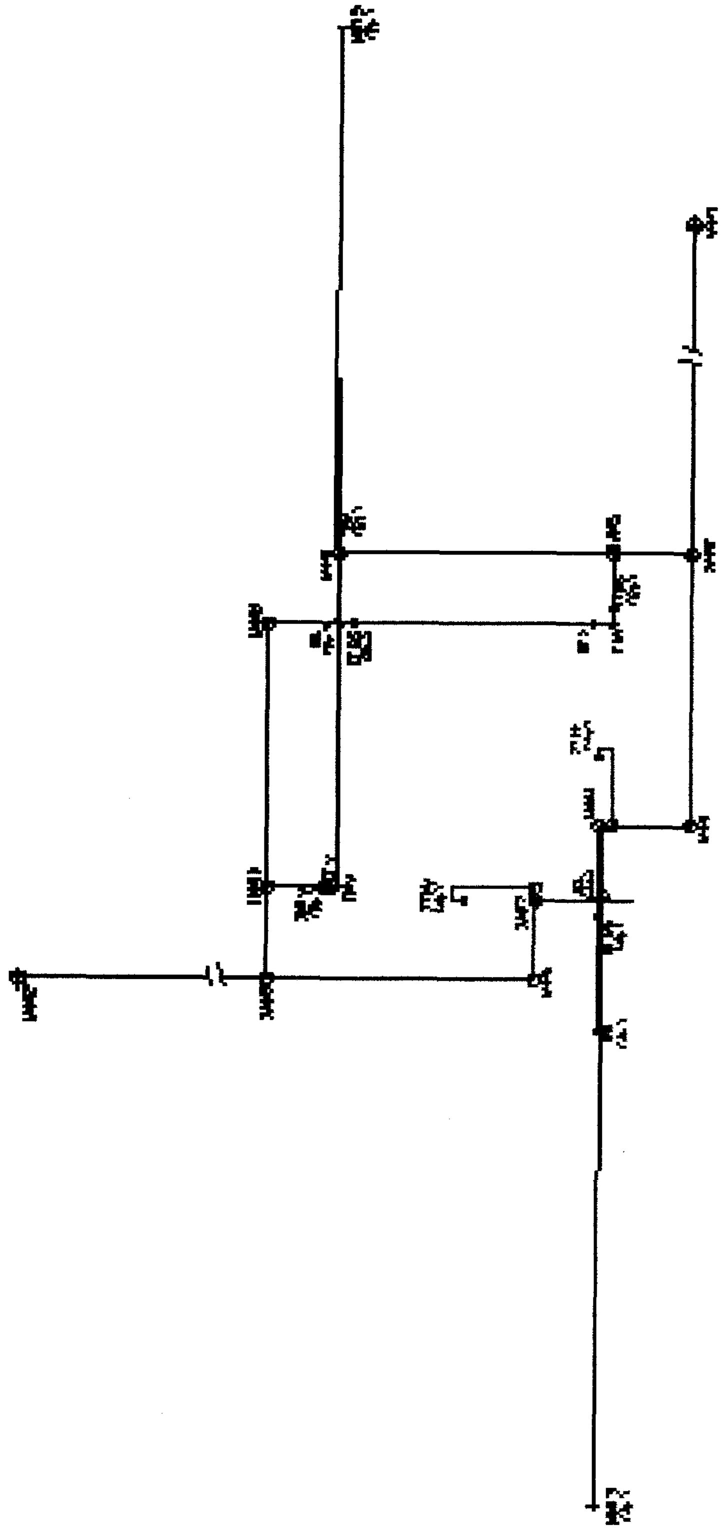
The Brunson transit square is positioned over a monument within the corner, mid, or end station by sighting down through the stand with an optical plummet. A stand with a plumb bob will be positioned over a monument approximately 200 meters from the transit square. The transit square will now be used to sight the plumb bob, thus establishing our offset centerline.

5 ALIGNMENT FIXTURES

An alignment fixture will be required to adjust the core optic support in X, Y, and Yaw (vertical axis). The fixture shall be placed around the optic support and provide course adjustments for linear translations and fine adjustments for angular adjustment. Ultrafine angular adjustments (<5 microradian [1 sec]) will be accomplished with permanant magnets. This allows ultrafine adjustment after the optic support has been secured in place.

Coordinate positions and angular orientations of the HR surface of the optic can be found in table 2. This data was derived by taking surface orientation data from Ligo Document T970091-00 (3) and projecting unit vectors to the planes established with the offset centerlines.

FIG. 1



PTIC AND THEODOLITE POSITIONS (2k INTERFEROMETER)

Table 2:

Optic	X optic	Y optic	Z optic	*Monu-ment*	**X** the-odolite	**Y** the-odolite	**Z** theod-olite	**Yaw** theodo-lite	**Pitch** theodo-lite
MMT 3	29402	9060	45	IAM8	11543	9181.0	12.0	0°23’17”	0°6’22”
RM	12184	9060	43	IAM8	11543	9060	30.88	0	1°4’59”
OF_y	200	9322	-96.2	IAM10	200	11428	-89.2	-0°0’6”	0°11’59”
ITM_y	200	9598	-99	IAM10	200	11428	-89.2	0	0
OF_x	9163	400	-97	IAM11	9163	11428	-60.4	-0°0’6”	0°11’25”
OF_{bs}	9163	8552	-10.6	IAM11	9163	11428	-30.4	0	0°23’41”
FM_x	9163	-200	-99	IAM5	11543	-200	-106.9	-0°0’6”	0°11’25”
ITM_x	9713	-200	-101	IAM5	11543	-200	-101	0	0
FM_y	200	9072	-97	IAM8	11543	9072	-134.7	0°0’6”	0°11’25”
$BS_{(2k)}$	9163	9060	-14.1	IAM8	11543	9060	-30.5	0	0°23’41”
ETM_y	200	2009598	-99	IAM14	200	1999350	-99	0	0
ETM_x	2009713	-200	-101	IAM16	1999466	-200	-101	0	0

OPTIC AND THEODOLITE POSITIONS (4k INTERFEROMETER)

Table 3:

Optic	X optic	Y optic	Z optic	*Monument*	**X** theodolite	**Y** theodolite	**Z** theodolite	**Yaw** theodolite	**Pitch** theodolite
MMT 3	-20779	209.8	27.8	IAM4	2362.2	77.6	-9.5	0°19'38"	0°5'32"
RM	-4596	212	26	IAM4	2362.2	213	-105.5	0°0'28"	1°4'59"
OF_{bs}	-700.6	212	-57	IAM4	2362.2	212	-74.6	0	0°23'41"
ITM_x	4677	200	-101	IAM4	2362.2	-200	-101	0	0
$BS_{(2k)}$	-200	212	-57	IAM7	-200	2362.2	-71.8	0	0°23'41"
ITM_y	-200	4811	-99	IAM7	200	2362.2	-99	0	0
ETM_x	4004677	200	-99	IAM22	4002362	200	-99	0	0
ETM_y	-200	4004811	-101	IAM25	-200	4002369	-101	0	0

6 ALIGNMENT OF INPUT OPTICS MMT3 AND RM (2K INTERFEROMETER)

The first alignment task will be to align the input optics MMT3 and RM on the 2k interferometer. Before alignment can take place, (2) BSC clean rooms must have been placed over BSC4 and BSC7. Also (2) HAM clean rooms placed over WHAM9 and WHAM7. (See fig. 2)

Adapters WBE-3A located between WBSC4 and WHAM9 and WA-13B at WBSC7 are removed. Also the inner doors on WHAM9 and WHAM7 are removed for loading of LOS assemblies.

The Brunson transit square is placed over IAM2,accurately locating the instrument with the optical plummet and adjusted to the height of the theodolite height requirement for MMT3 (table 2). Locate a plumb bob over IAM3 positioned 200 meters along the X-arm. The transit jig is leveled with the coincidence level and rotated until the plumb bob can be centered within the crosshairs.

The theodolite is set over IAM8 with the optical plummet and leveled at the height specified in table 1. The telescope is rotated toward the mirror on the transit square and is rotated until the theodolite is autocollimated to the optical square. the theodolite is then rotated to the angles specified in table 2.

Vertical and transverse positions are set by moving the LOS until the fiducials are sighted with the theodolite. Axial position is set by placing the prism on the alignment fixture and measuring the distance with the EDM (electronic distance measurement) feature on the theodolite.

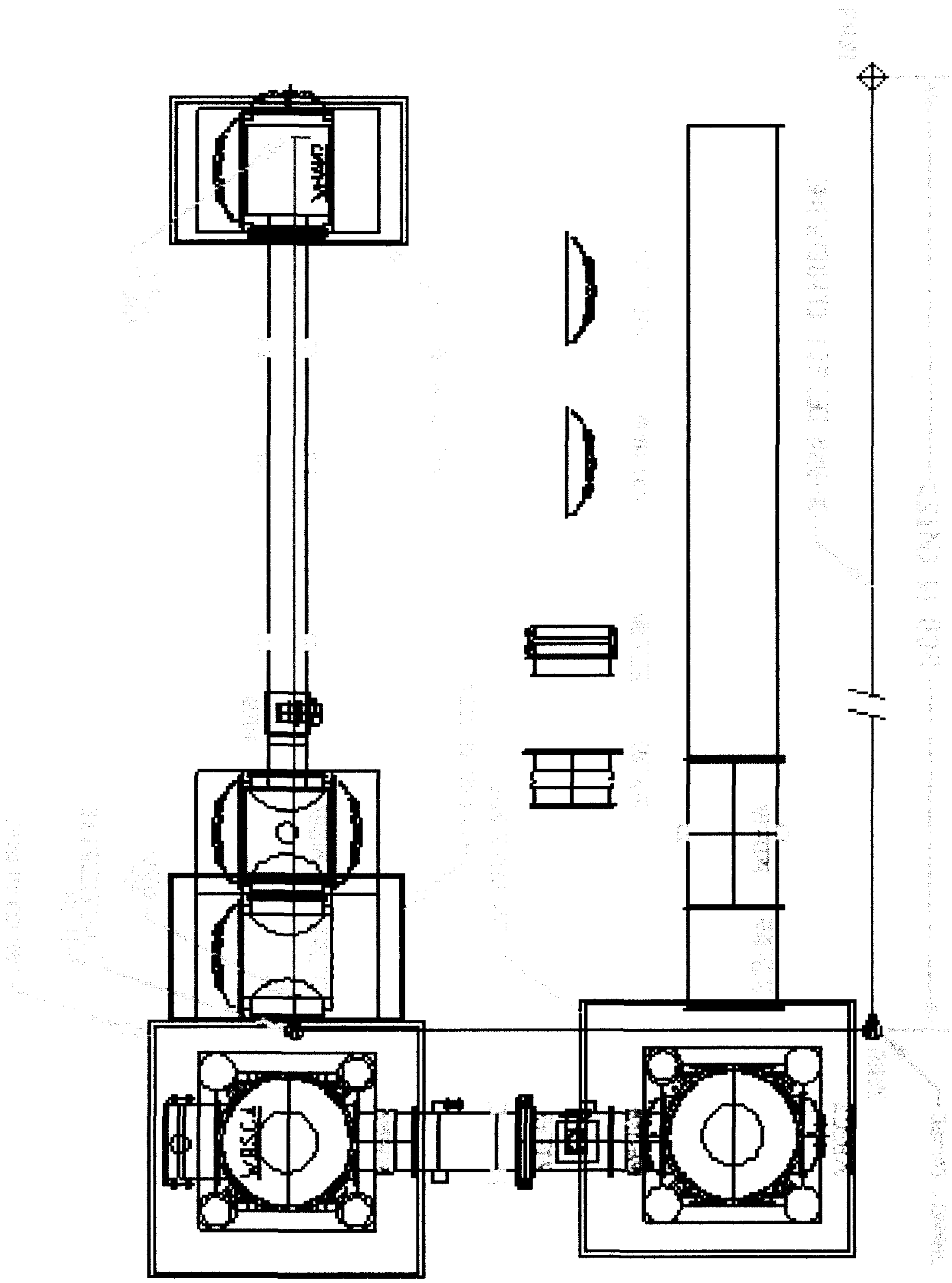
With all linear adjustments complete the laser autocollimator is turned on and the alignment fixture adjusted until the reflected beam is within .05 milliradian. The LOS is clamped in place and the alignment fixture removed without moving the laser autocollimator. The optic is now accurately positioned to within 5 microradians using the permanant magnets on the LOS assembly.

.With alignment of the optic completed, the optical lever is positioned to view the optic through the viewports in the door at WHAM7. The diode laser is turned on and the photodetector is adjusted to pick up the reflected beam on the center of the photodetector. This position is noted as the initial optic position. The purpose of these optical levers will be to detect any change in the aligned optics caused by opening of the gate valves to vacuum, settling, thermal noise, etc.

This same procedure is used to align the RM (2k) using values from table 2.

The doors and adapters are replaced and clean rooms removed.

FIG. 2



7 ALIGNMENT OF CORE OPTICS OF_Y, ITM_Y, OF_X, AND OF_{BS} (2K INTERFEROMETER)

BSC clean rooms are to be placed over WBSC4, 7, and 8. Adapters WB-3C at BSC4, WA-13B at WBSC8, and WA-12B at WBSC7 are removed and placed on movable fixtures. (fig.3)

The Brunson transit square is placed over IAM9, at the theodolite height for OF_y (table 2) using the optical plummet. A plumb bob is positioned over IAM12 located 200 meters along the y-arm. The transit square is leveled and rotated until the plumb bob is centered within the crosshairs.

The theodolite is placed over IAM10 with the optical plummet and leveled at a height specified in table 1. The positioning and angular alignment is set in the same manner asMMT3. OF_y and IMT_y can now be positioned and aligned.

As with the input optics, the optical lever for IMT_y will be positioned, activated, and the adaptor replaced.

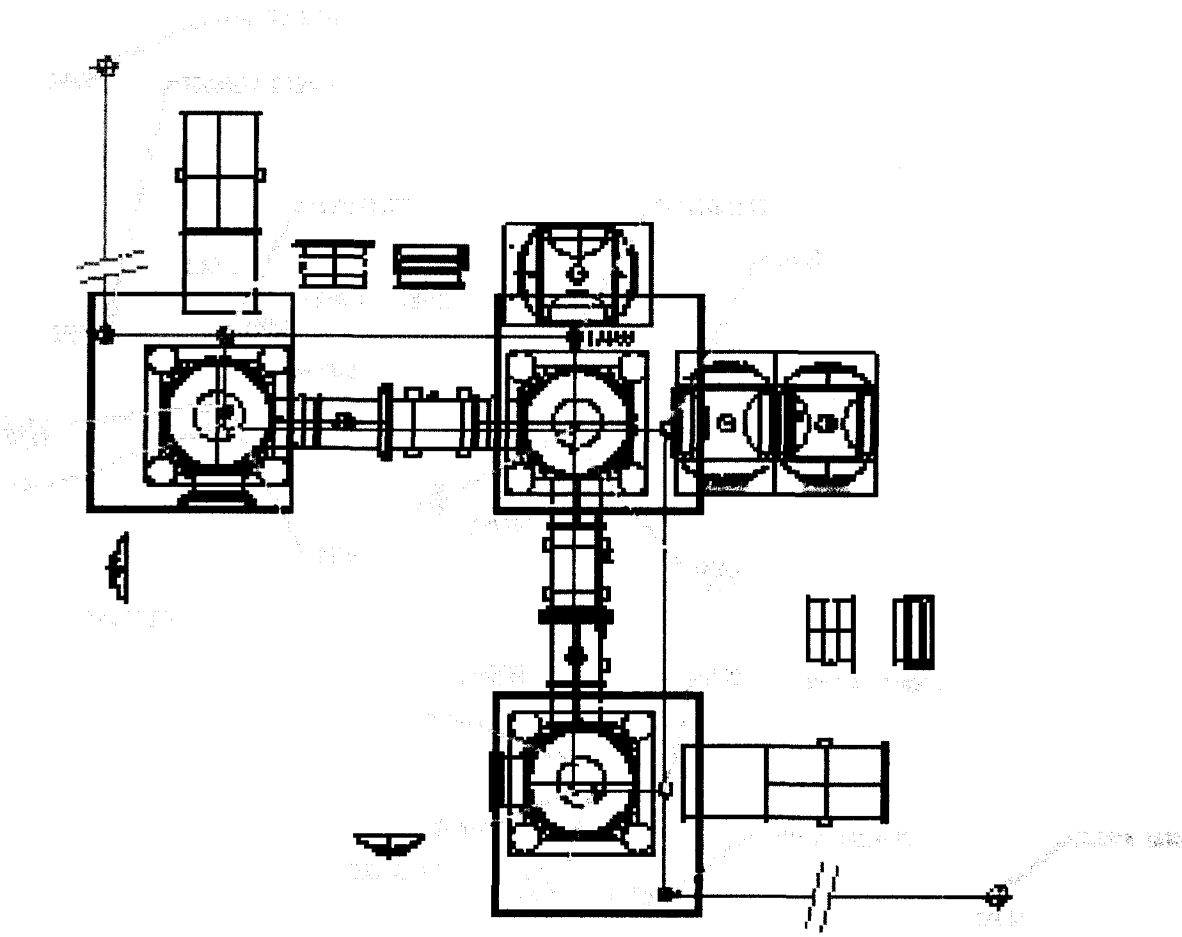
The theodolite is moved to monument IAM11 to position and align optical flats OF_x and $OFBS_{(2k)}$. Optical levers are not required on all optical flats.

The transit square is move to monument IAM2 and the x-axis offset centerline is established with monument IAM3. The theodolite is placed over IAM5, where FM_x is positioned and aligned using the back reflection from optical flat OF_x. Once autocollimated, the optical flat OF_x is removed. The theodolite is then moved to position and align ITM_x.

The theodolite is then moved to IAM14, where FM_y is positioned and autocollimated using optical flat OF_y, and $BS_{(2k)}$ is positioned and autocollimated using optical flat $OFBS_{(2k)}$. Once aligned the optical flats are removed.

All optical levers are positioned and activated. Doors and adapters are replaced and clean rooms removed.

FIG.3



8 ALIGNMENT OF END TEST MASSES ETM_X AND ETM_Y (2K INTERFEROMETER)

A BSC clean room is placed over WBSC5 and a HAM clean room placed over WA-14A in the x-arm midstation. The adapter WA-14A and the outside access door is removed. (See fig.4)

The Brunson transit square is placed over IAM14 with the optical plummet at the height of ETMx and leveled with the coincidence level. A plumb bob is placed over IAM13. The transit square is rotated until the plumb bob is centered within the crosshairs.

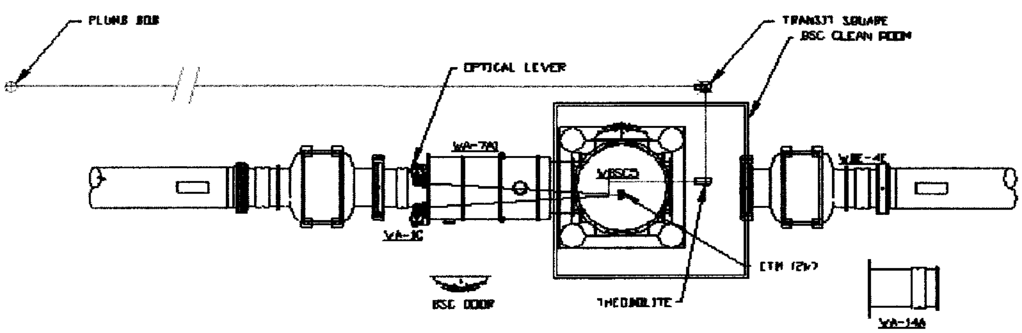
The theodolite is positioned over IAM15 and rotated toward the mirror on the transit until it can be autocollimated off the transit square. The theodolite is then rotated 90 degrees and zeroed. The prism is mounted to the alignment fixture and the theodolite rotated until it picks up the center of the prism. A distance measurement is made which will measure the axial and transverse distances from the theodolite over monument IAM15.

The PLX retroreflector is mounted to the optical table as shown in FIG. 4 and the theodolite set back to its zero position. Using the electronic laser autocollimator, the optic is rotated until the HR surface is autocollimated to within .01mrad (2 arc sec).

After each optic is aligned, the optical lever is positioned on the optic and activated. All adapters and doors are replaced, and the clean rooms removed.

This same procedure is used to set ETMy using monuments IAM16, 17, and 18.

FIG. 4



9 ALIGNMENT OF INPUT OPTIC MMT3 AND CORE OPTICS RM, OF_{BS}, ITM_X, AND ITM_Y (4K INTERFEROMETER)

A BSC clean room is placed over BSC2 and Ham clean rooms placed over Wham1 and Wham3. The two WBE-2a adapters adjacent to bsc2 and doors on Wham1 and Wham3 are removed as shown in FIG 5.

The Brunson transit square is placed over IAM1 at the height of MMT3 and a plumb bob placed over IAM3 to establish an offset centerline. The theodolite is placed over IAM4 at the height of MMT3 facing toward the transit square. The theodolite is autocollimated to the optical flat of the transit square and then rotated 90 degrees toward MMT3 and set to zero.

Axial and transverse measurements are made by sighting the prism and fiducial. The theodolite is rotated in pitch and yaw per table 3. The electronic laser autocollimator is activated and the optic adjusted within .05 mrad (2 arcsec).

Set the theodolite back to its zero position and follow the same procedure to align RM and OF_{bs}.

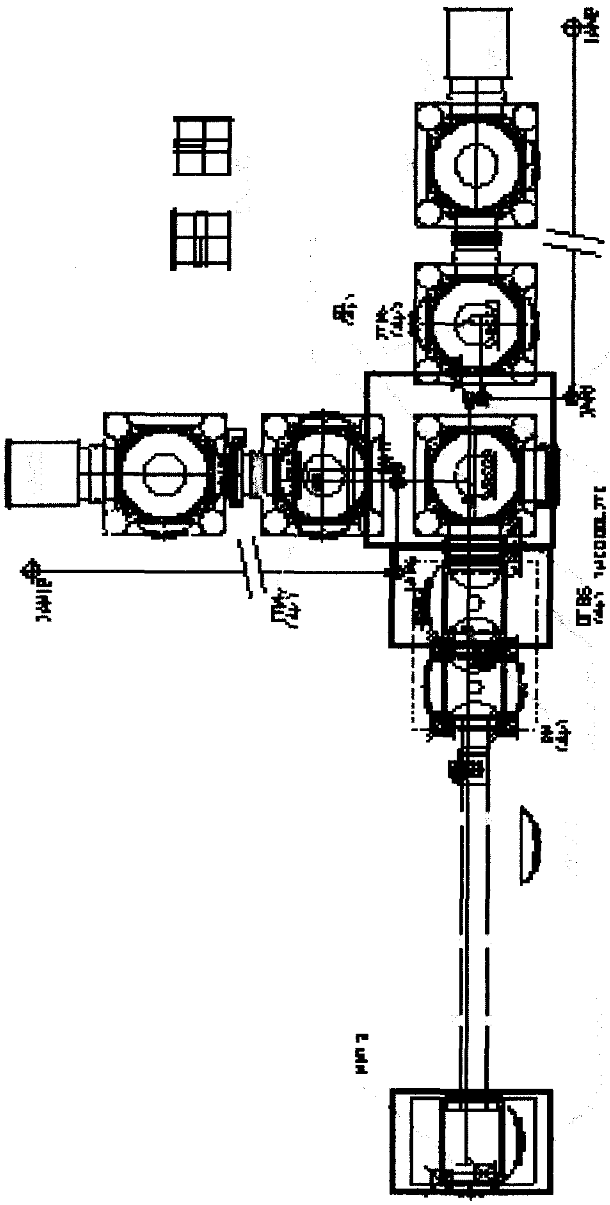
The theodolite is then moved 400 mm in negative Y and squareness reset with the transit square by autocollimation. Rotate the theodolite 90 degrees and position ITM_x along the axial, transverse and vertical axis. The PLX retroreflector is then mounted to the optical table and the angular position set using the laser autocollimator and the angular orientation values in table 3.

Next move the transit square and plumb bob to IAM6 and IAM12 along the Y-axis of the interferometer. Place the theodolite over IAM 7 at the height of the BS and set the position of the BS. The angular orientation is aligned by autocollimation using the optical flat as a back reflector. Remove the optical flat once the BS is aligned.

The theodolite is then moved 400 mm in the x-direction and IMT_y is aligned in the same manner as IMT_x.

After each optic is aligned, the optical lever is positioned on the optic and activated. All adapters and doors are replaced, and the clean rooms removed.

FIG.5



10 ALIGNMENT OF END TEST MASSES ETM_X AND ETM_Y (4K INTERFEROMETER)

A BSC clean room is placed over WBSC9 and a HAM clean room placed over WBE-4A in the x-arm endstation. The rear access door and one of the side access doors is removed. (See fig.6)

The Brunson transit square is placed over IAM21 with the optical plummet at the height of ETMx and leveled with the coincidence level. A plumb bob is placed over IAM20. The transit square is rotated until the plumb bob is centered within the crosshairs.

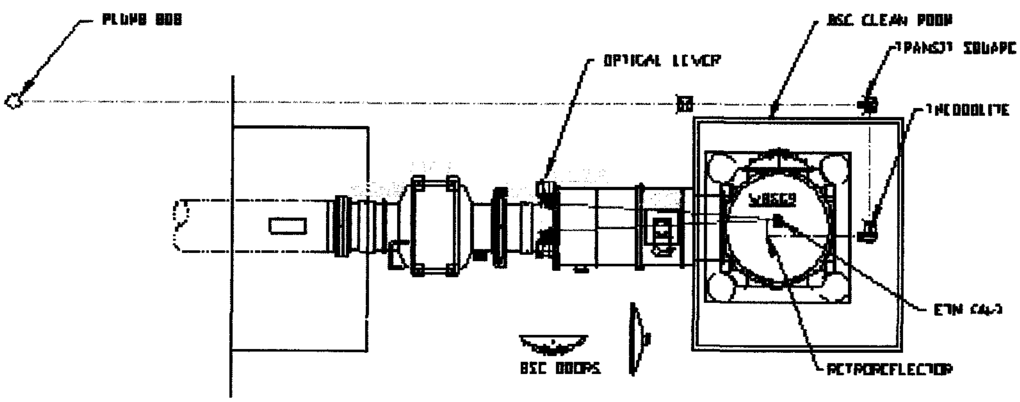
The theodolite is positioned over IAM22 and rotated toward the mirror on the transit until it can be autocollimated off the transit square. The theodolite is then rotated 90 degrees and zeroed. The prism is mounted to the alignment fixture and the theodolite rotated until it picks up the center of the prism. A distance measurement is made which will measure the axial and transverse distances from the theodolite over monument IAM15.

The PLX retroreflector is mounted to the optical table as shown in FIG. 4 and the theodolite set back to its zero position. Using the electronic laser autocollimator, the optic is rotated until the HR surface is autocollimated to within .01mrad (2 arc sec).

.After each optic is aligned, the optical lever is positioned on the optic and activated. All adapters and doors are replaced, and the clean rooms removed.

This same procedure is used to set ETMy using monuments IAM23, 24, and 25..

FIG.6



11 CONCLUSION

In order for this procedure to be successful the following is required:

1. New monuments must be added and placed within +/- 3 mm of their true position.
2. Openings which can be opened and closed off must be made in the corner, mid, and end stations as shown in drawings D9702101, D9702102, and D9702103.
3. A direct line of sight must be attainable between monuments.
4. Accurate alignment fixtures are required to position the optics.

Additional requirements can be found in Ligo Document T980002-00

From the latest reports on monument positioning, it appears they can be located with enough accuracy to establish our offset center lines within the tolerance specification in section 2. Cameras capable of viewing the Nd Yag wavelength of 1064 nm will be placed at strategic positions along the path of the beam. The cameras at the mid and end stations will be used to find the laser beam after all gate valves are opened and to assist in steering the beam to the center of the optics. .

APPENDIX 1 REFERENCES

[1] LIGO-T970060- 00-D, Alignment Sensing/ Control Preliminary Design

[2] Gary P. Wagner "Precision Survey of Beam Tube/ Vacuum Equipment Interface", Rogers Surveying, October 1,1996.

[3] LIGO-T970091-00, Determination of Core Optic Wedge Angles, Dennis Coyne

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3 EQUIPMENT REQUIRED

The following equipment or their equivalent will be required:

1. One (1) Sokkia Total Station Theodolite model SET2B with electronic distance measurement (EDM), autocollimating eyepiece, tripod, prism, and optical plummet.
2. One (1) Brunson model 75-H Optical Transit Squares with autocollimating eyepiece, stand, coincidence level, and optical plummet.
3. Four (4) 200mm dia. optical flats with mounts.
4. One (1) laser autocollimator mounted and aligned to the theodolite.
5. One (1) 12.0" PLX Lateral Transfer Hollow Retroreflector
6. Two (2) Optical Plummets and stands.
7. One (1) Transverse measurement straightedge with measuring tape.
8. Two (2) Mounting brackets for Lateral Transfer Hollow Retroreflector.
9. One (1) LOS Alignment Fixture

Table 1:

Positioning of monuments	.03 mrad (6 arc seconds)
Sighting of plunb markers	.02mrad (4 arc second)
90 degree autocollimation	.01 mrad (2 arc seconds)
90 degree rotation	.01 mrad (2 arc seconds)
Autocollimation of optic	.01 mrad (2 arc second)
Total	*.08 mrad (16 arc seconds)*

4 DETERMINING OFFSET CENTERLINE

Two offset centerlines with a clear line of sight will be located along the outside of the X and Y arms for the cornerstation, and along the inside of both mid and end stations. See fig (1), and refer to drawings D970210, sheets 1-5 for detailed position requirements.

The positional accuracy of the initial alignment monuments must be within +/- 5mm of true position. Monuments located using the trimble 4000SSI global positioning system have been shown to be accurate within these tolerances by Rogers Surveying (2). Triangulation measurements off the existing beamtube centerline and monuments has been used to verify monument positions. This technique if carefully done will also yield positions within tolerance.

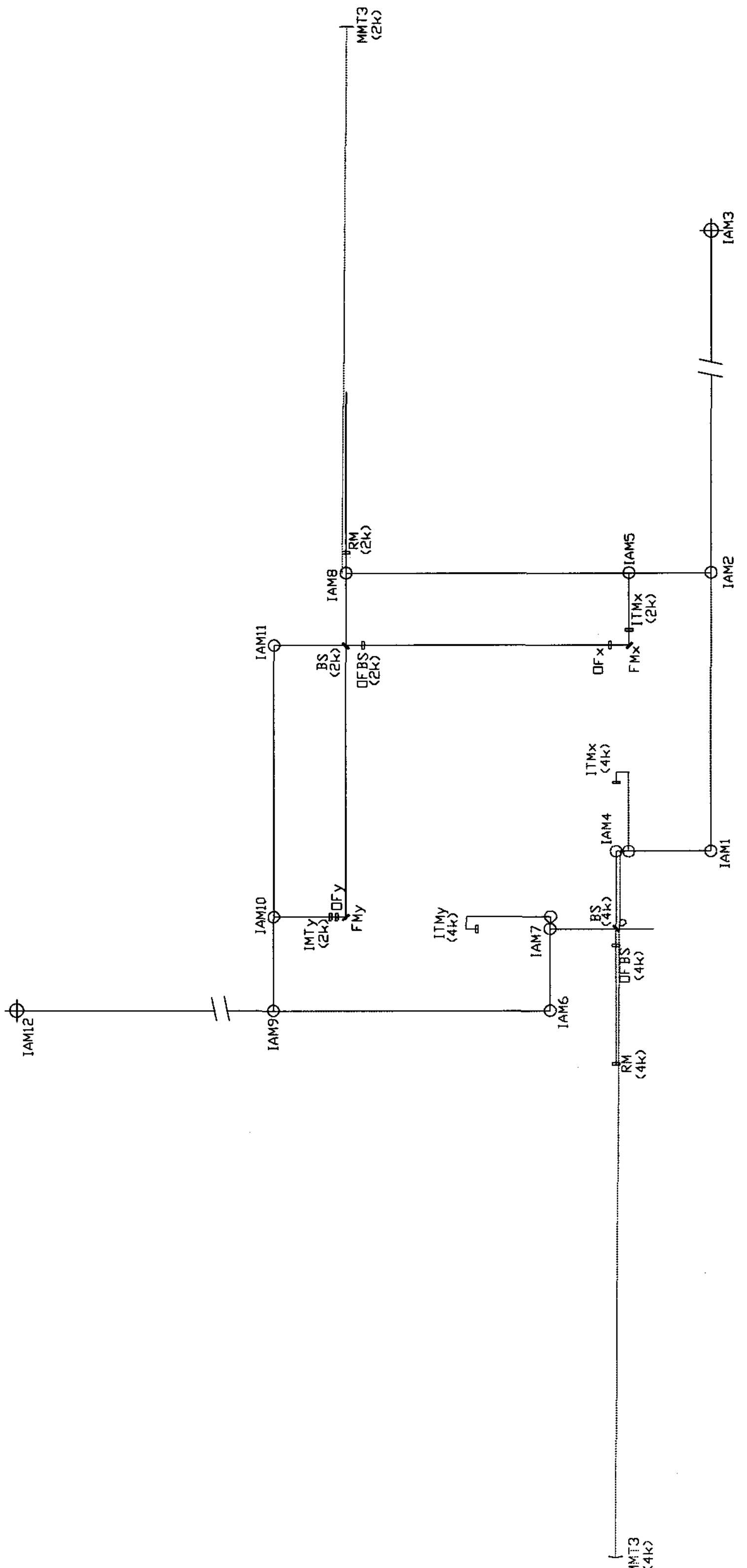
The Brunson transit square is positioned over a monument within the corner, mid, or end station by sighting down through the stand with an optical plummet. A stand with a plumb bob will be positioned over a monument approximately 200 meters from the transit square. The transit square will now be used to sight the plumb bob, thus establishing our offset centerline.

5 ALIGNMENT FIXTURES

An alignment fixture will be required to adjust the core optic support in X, Y, and Yaw (vertical axis). The fixture shall be placed around the optic support and provide course adjustments for linear translations and fine adjustments for angular adjustment. Ultrafine angular adjustments (<5 microradian [1 sec]) will be accomplished with permanant magnets. This allows ultrafine adjustment after the optic support has been secured in place.

Coordinate positions and angular orientations of the HR surface of the optic can be found in table 2. This data was derived by taking surface orientation data from Ligo Document T970091-00 (3) and projecting unit vectors to the planes established with the offset centerlines.

FIG. 1


MMT3
(2k)
RM
(2k)
IAM8
IAM5
IAM2
IAM3
IAM11
BS
(2k)
OFBS
(2k)
OFx
FMx
ITMx
(2k)
ITMx
(4k)
IAM4
IAM1
IAM10
IMTy
(2k)
OFy
FMy
ITMy
(4k)
IAM7
BS
(4k)
OFBS
(4k)
IAM12
IAM9
IAM6
RM
(4k)
MMT3
(4k)

PTIC AND THEODOLITE POSITIONS (2k INTERFEROMETER)

Table 2:

Optic	X optic	Y optic	Z optic	*Monu-ment*	**X** the-odolite	**Y** the-odolite	**Z** theod-olite	**Yaw** theodo-lite	**Pitch** theodo-lite
MMT 3	29402	9060	45	IAM8	11543	9181.0	12.0	$0^{o}23'17''$	$0^{o}6'22''$
RM	12184	9060	43	IAM8	11543	9060	30.88	0	$1^{o}4'59''$
OF_y	200	9322	-96.2	IAM10	200	11428	-89.2	$-0^{o}0'6''$	$0^{o}11'59''$
ITM_y	200	9598	-99	IAM10	200	11428	-89.2	0	0
OF_x	9163	400	-97	IAM11	9163	11428	-60.4	$-0^{o}0'6''$	$0^{o}11'25''$
OF_{bs}	9163	8552	-10.6	IAM11	9163	11428	-30.4	0	$0^{o}23'41''$
FM_x	9163	-200	-99	IAM5	11543	-200	-106.9	$-0^{o}0'6''$	$0^{o}11'25''$
ITM_x	9713	-200	-101	IAM5	11543	-200	-101	0	0
FM_y	200	9072	-97	IAM8	11543	9072	-134.7	$0^{o}0'6''$	$0^{o}11'25''$
$BS_{(2k)}$	9163	9060	-14.1	IAM8	11543	9060	-30.5	0	$0^{o}23'41''$
ETM_y	200	2009598	-99	IAM14	200	1999350	-99	0	0
ETM_x	2009713	-200	-101	IAM16	1999466	-200	-101	0	0

OPTIC AND THEODOLITE POSITIONS (4k INTERFEROMETER)

Table 3:

Optic	X optic	Y optic	Z optic	*Monument*	**X** theodolite	**Y** theodolite	**Z** theodolite	**Yaw** theodolite	**Pitch** theodolite
MMT 3	-20779	209.8	27.8	IAM4	2362.2	77.6	-9.5	0°19'38"	0°5'32"
RM	-4596	212	26	IAM4	2362.2	213	-105.5	0°0'28"	1°4'59"
OF_{bs}	-700.6	212	-57	IAM4	2362.2	212	-74.6	0	0°23'41"
ITM_x	4677	200	-101	IAM4	2362.2	-200	-101	0	0
$BS_{(2k)}$	-200	212	-57	IAM7	-200	2362.2	-71.8	0	0°23'41"
ITM_y	-200	4811	-99	IAM7	200	2362.2	-99	0	0
ETM_x	4004677	200	-99	IAM22	4002362	200	-99	0	0
ETM_y	-200	4004811	-101	IAM25	-200	4002369	-101	0	0

6 ALIGNMENT OF INPUT OPTICS MMT3 AND RM (2K INTERFEROMETER)

The first alignment task will be to align the input optics MMT3 and RM on the 2k interferometer. Before alignment can take place, (2) BSC clean rooms must have been placed over BSC4 and BSC7. Also (2) HAM clean rooms placed over WHAM9 and WHAM7. (See fig. 2)

Adapters WBE-3A located between WBSC4 and WHAM9 and WA-13B at WBSC7 are removed. Also the inner doors on WHAM9 and WHAM7 are removed for loading of LOS assemblies.

The Brunson transit square is placed over IAM2,accurately locating the instrument with the optical plummet and adjusted to the height of the theodolite height requirement for MMT3 (table 2). Locate a plumb bob over IAM3 positioned 200 meters along the X-arm. The transit jig is leveled with the coincidence level and rotated until the plumb bob can be centered within the crosshairs.

The theodolite is set over IAM8 with the optical plummet and leveled at the height specified in table 1. The telescope is rotated toward the mirror on the transit square and is rotated until the theodolite is autocollimated to the optical square. the theodolite is then rotated to the angles specified in table 2.

Vertical and transverse positions are set by moving the LOS until the fiducials are sighted with the theodolite. Axial position is set by placing the prism on the alignment fixture and measuring the distance with the EDM (electronic distance measurement) feature on the theodolite.

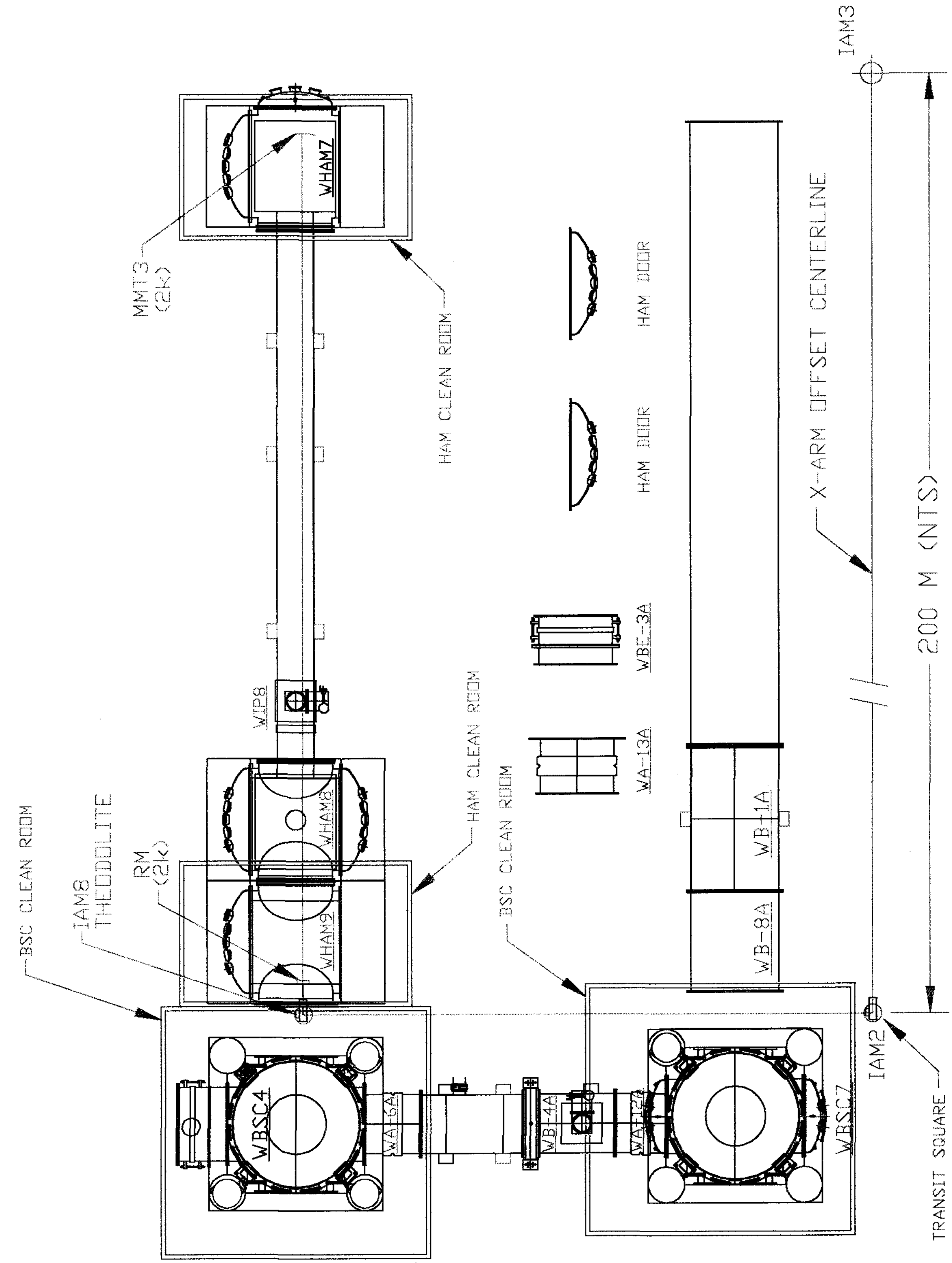
With all linear adjustments complete the laser autocollimator is turned on and the alignment fixture adjusted until the reflected beam is within .05 milliradian. The LOS is clamped in place and the alignment fixture removed without moving the laser autocollimator. The optic is now accurately positioned to within 5 microradians using the permanant magnets on the LOS assembly.

.With alignment of the optic completed, the optical lever is positioned to view the optic through the viewports in the door at WHAM7. The diode laser is turned on and the photodetector is adjusted to pick up the reflected beam on the center of the photodetector. This position is noted as the initial optic position. The purpose of these optical levers will be to detect any change in the aligned optics caused by opening of the gate valves to vacuum, settling, thermal noise, etc.

This same procedure is used to align the RM (2k) using values from table 2.

The doors and adapters are replaced and clean rooms removed.

FIG. 2


IAM3
X-ARM OFFSET CENTERLINE
200 M (NTS)
IAM2
TRANSIT SQUARE
WHAM7
MMT3 (2k)
HAM CLEAN ROOM
HAM DOOR
HAM DOOR
WBE-3A
WA-13A
WTP8
HAM CLEAN ROOM
BSC CLEAN ROOM
WHAM8
WHAM9
WB-1A
WB-8A
BSC CLEAN ROOM
IAM8 THEODOLITE
RM (2k)
WBSC4
WA-6A
WB-4A
WA-12A
WBSC7

7 ALIGNMENT OF CORE OPTICS OF_Y, ITM_Y, OF_X, AND OF_{BS} (2K INTERFEROMETER)

BSC clean rooms are to be placed over WBSC4, 7, and 8. Adapters WB-3C at BSC4, WA-13B at WBSC8, and WA-12B at WBSC7 are removed and placed on movable fixtures. (fig.3)

The Brunson transit square is placed over IAM9, at the theodolite height for OF_y (table 2) using the optical plummet. A plumb bob is positioned over IAM12 located 200 meters along the y-arm. The transit square is leveled and rotated until the plumb bob is centered within the crosshairs.

The theodolite is placed over IAM10 with the optical plummet and leveled at a height specified in table 1. The positioning and angular alignment is set in the same manner asMMT3. OF_y and IMT_y can now be positioned and aligned.

As with the input optics, the optical lever for IMT_y will be positioned, activated, and the adaptor replaced.

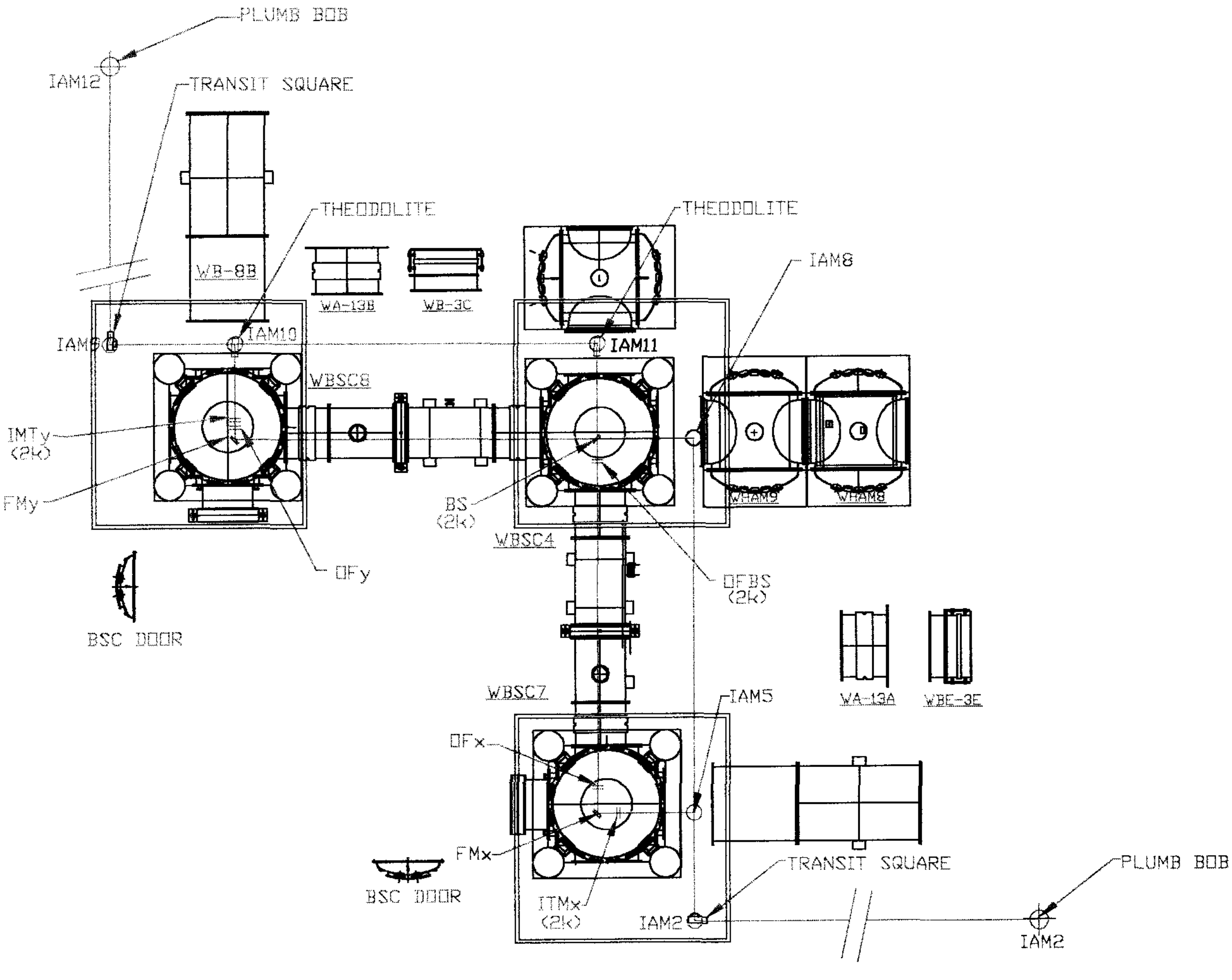
The theodolite is moved to monument IAM11 to position and align optical flats OF_x and $OFBS_{(2k)}$. Optical levers are not required on all optical flats.

The transit square is move to monument IAM2 and the x-axis offset centerline is established with monument IAM3. The theodolite is placed over IAM5, where FM_x is positioned and aligned using the back reflection from optical flat OF_x. Once autocollimated, the optical flat OF_x is removed. The theodolite is then moved to position and align ITM_x.

The theodolite is then moved to IAM14, where FM_y is positioned and autocollimated using optical flat OF_y, and $BS_{(2k)}$ is positioned and autocollimated using optical flat $OFBS_{(2k)}$. Once aligned the optical flats are removed.

All optical levers are positioned and activated. Doors and adapters are replaced and clean rooms removed.

FIG.3


PLUMB BOB
IAM12
TRANSIT SQUARE
THEODOLITE
THEODOLITE
IAM8
WB-8B
WA-13B
WB-3C
IAM9
IAM10
IAM11
WBSC8
IMTy
(2k)
FMy
BS
(2k)
WBSC4
WHAM9
WHAM8
OFy
OFBS
(2k)
BSC DOOR
WA-13A
WBE-3E
WBSC7
IAM5
OFx
FMx
BSC DOOR
ITMx
(2k)
IAM2
TRANSIT SQUARE
PLUMB BOB
IAM2

8 ALIGNMENT OF END TEST MASSES ETM_X AND ETM_Y (2K INTERFEROMETER)

A BSC clean room is placed over WBSC5 and a HAM clean room placed over WA-14A in the x-arm midstation. The adapter WA-14A and the outside access door is removed. (See fig.4)

The Brunson transit square is placed over IAM14 with the optical plummet at the height of ETMx and leveled with the coincidence level. A plumb bob is placed over IAM13. The transit square is rotated until the plumb bob is centered within the crosshairs.

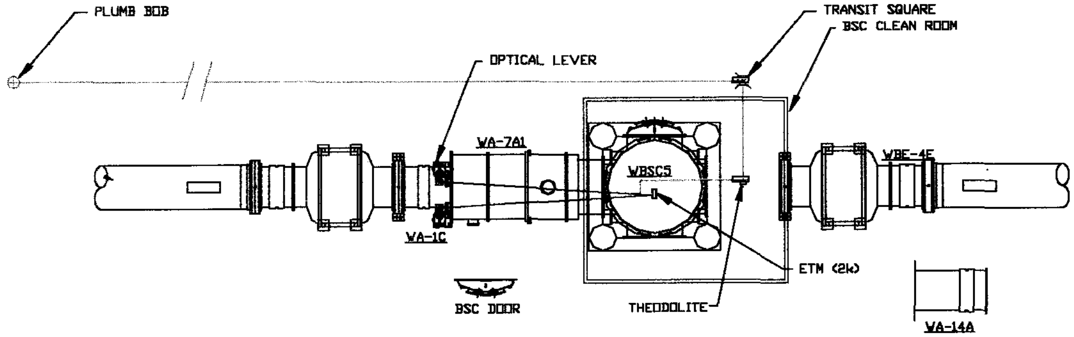
The theodolite is positioned over IAM15 and rotated toward the mirror on the transit until it can be autocollimated off the transit square. The theodolite is then rotated 90 degrees and zeroed. The prism is mounted to the alignment fixture and the theodolite rotated until it picks up the center of the prism. A distance measurement is made which will measure the axial and transverse distances from the theodolite over monument IAM15.

The PLX retroreflector is mounted to the optical table as shown in FIG. 4 and the theodolite set back to its zero position. Using the electronic laser autocollimator, the optic is rotated until the HR surface is autocollimated to within .01mrad (2 arc sec).

After each optic is aligned, the optical lever is positioned on the optic and activated. All adapters and doors are replaced, and the clean rooms removed.

This same procedure is used to set ETMy using monuments IAM16, 17, and 18.

FIG. 4



9 ALIGNMENT OF INPUT OPTIC MMT3 AND CORE OPTICS RM, $OF_{BS,}ITM_{X,}$ AND $ITM_{Y.}$ (4K INTERFEROMETER)

A BSC clean room is placed over BSC2 and Ham clean rooms placed over Wham1 and Wham3. The two WBE-2a adapters adjacent to bsc2 and doors on Wham1 and Wham3 are removed as shown in FIG 5.

The Brunson transit square is placed over IAM1 at the height of MMT3 and a plumb bob placed over IAM3 to establish an offset centerline. The theodolite is placed over IAM4 at the height of MMT3 facing toward the transit square. The theodolite is autocollimated to the optical flat of the transit square and then rotated 90 degrees toward MMT3 and set to zero.

Axial and transverse measurements are made by sighting the prism and fiducial. The theodolite is rotated in pitch and yaw per table 3. The electronic laser autocollimator is activated and the optic adjusted within .05 mrad (2 arcsec).

Set the theodolite back to its zero position and follow the same procedure to align RM and $OF_{bs.}$

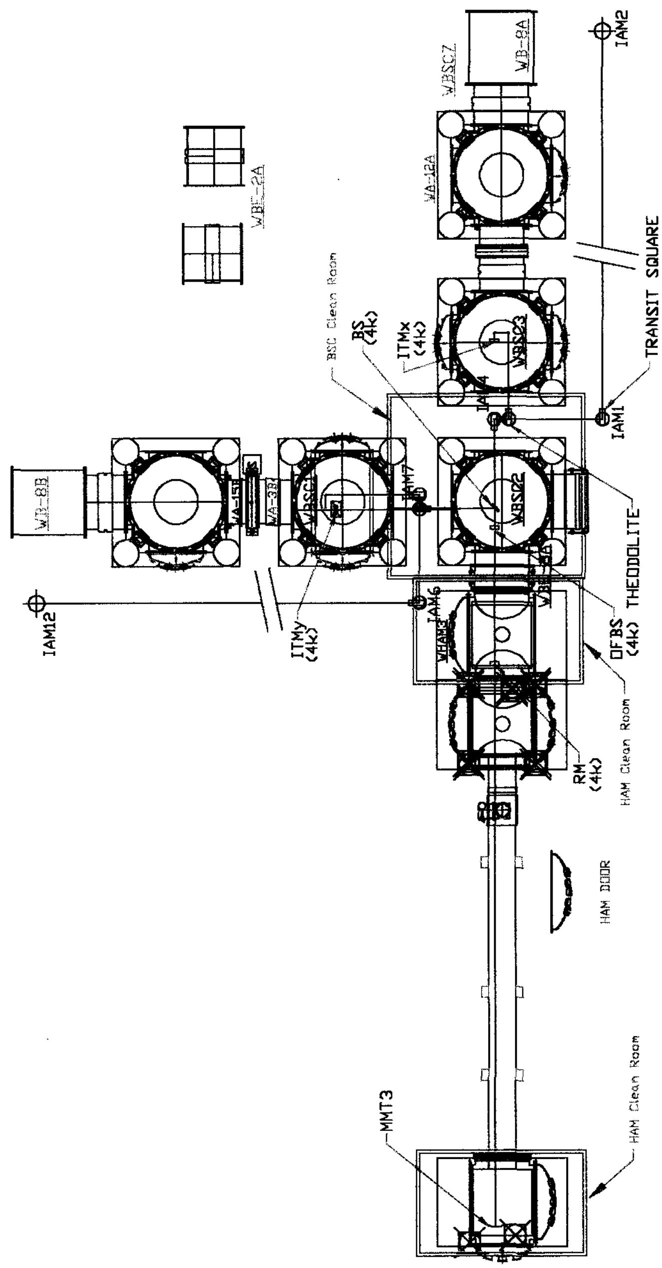
The theodolite is then moved 400 mm in negative Y and squareness reset with the transit square by autocollimation. Rotate the theodolite 90 degrees and position ITM_x along the axial, transverse and vertical axis. The PLX retroreflector is then mounted to the optical table and the angular position set using the laser autocollimator and the angular orientation values in table 3.

Next move the transit square and plumb bob to IAM6 and IAM12 along the Y-axis of the interferometer. Place the theodolite over IAM 7 at the height of the BS and set the position of the BS. The angular orientation is aligned by autocollimation using the optical flat as a back reflector. Remove the optical flat once the BS is aligned.

The theodolite is then moved 400 mm in the x-direction and IMT_y is aligned in the same manner as $IMT_{x.}$

After each optic is aligned, the optical lever is positioned on the optic and activated. All adapters and doors are replaced, and the clean rooms removed.

FIG.5


IAM2
WB-8A
WBSC7
WA-12A
TRANSIT SQUARE
WBE-2A
BSC Clean Room
BS
(4k)
ITMx
(4k)
WBSC3
IAM1
WB-8B
WBSC1
IAM7
WBSC2
THEODOLITE
IAM12
ITMy
(4k)
IAM6
OFBS
(4k)
WHAM3
HAM Clean Room
RM
(4k)
HAM DOOR
MMT3
HAM Clean Room

10 ALIGNMENT OF END TEST MASSES ETM_X AND ETM_Y (4K INTERFEROMETER)

A BSC clean room is placed over WBSC9 and a HAM clean room placed over WBE-4A in the x-arm endstation. The rear access door and one of the side access doors is removed. (See fig.6)

The Brunson transit square is placed over IAM21 with the optical plummet at the height of ETMx and leveled with the coincidence level. A plumb bob is placed over IAM20. The transit square is rotated until the plumb bob is centered within the crosshairs.

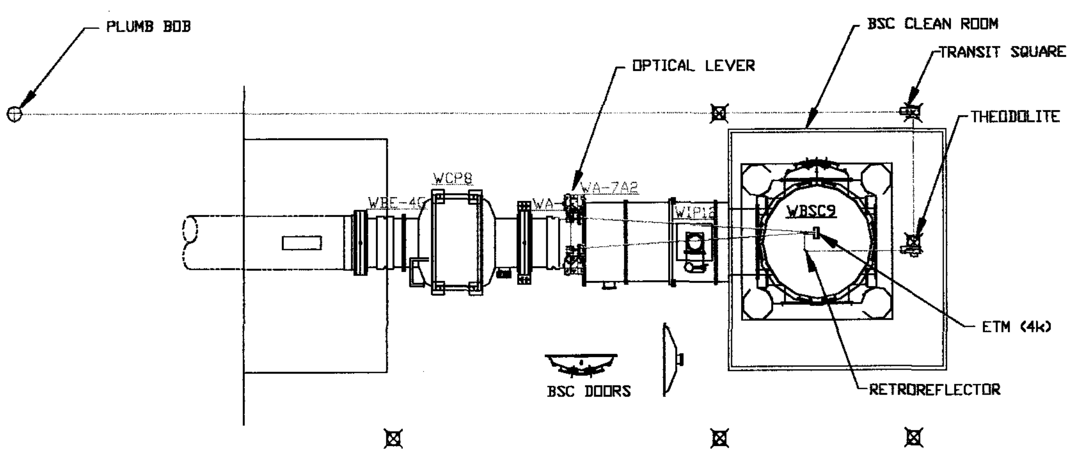
The theodolite is positioned over IAM22 and rotated toward the mirror on the transit until it can be autocollimated off the transit square. The theodolite is then rotated 90 degrees and zeroed. The prism is mounted to the alignment fixture and the theodolite rotated until it picks up the center of the prism. A distance measurement is made which will measure the axial and transverse distances from the theodolite over monument IAM15.

The PLX retroreflector is mounted to the optical table as shown in FIG. 4 and the theodolite set back to its zero position. Using the electronic laser autocollimator, the optic is rotated until the HR surface is autocollimated to within .01mrad (2 arc sec).

.After each optic is aligned, the optical lever is positioned on the optic and activated. All adapters and doors are replaced, and the clean rooms removed.

This same procedure is used to set ETMy using monuments IAM23, 24, and 25..

FIG.6



11 CONCLUSION

In order for this procedure to be successful the following is required:

1. New monuments must be added and placed within +/- 3 mm of their true position.
2. Openings which can be opened and closed off must be made in the corner, mid, and end stations as shown in drawings D9702101, D9702102, and D9702103.
3. A direct line of sight must be attainable between monuments.
4. Accurate alignment fixtures are required to position the optics.

Additional requirements can be found in Ligo Document T980002-00

From the latest reports on monument positioning, it appears they can be located with enough accuracy to establish our offset center lines within the tolerance specification in section 2. Cameras capable of viewing the Nd Yag wavelength of 1064 nm will be placed at strategic positions along the path of the beam. The cameras at the mid and end stations will be used to find the laser beam after all gate valves are opened and to assist in steering the beam to the center of the optics. .

APPENDIX 1 REFERENCES

[1] LIGO-T970060- 00-D, Alignment Sensing/ Control Preliminary Design

[2] Gary P. Wagner "Precision Survey of Beam Tube/ Vacuum Equipment Interface", Rogers Surveying, October 1,1996.

[3] LIGO-t970091-00, Determination of Core Optic Wedge Angles, Dennis Coyne

BATCH
START

STAPLE
OR
DIVIDER

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LIGO-C972311-00-D

FAX TRANSMITTAL

Post-it® Fax Note 7671	Date 11/13/97	# of pages ▶ 6
To A LAZZARINI	From A SIBLEY	
Co./Dept.	Co.	
Phone #	Phone #	
Fax #	Fax #	

Ref: **Review of ASC Alignment Document**

Dear Allen:

I am attaching my initial review of LIGO Document T970151-D. I will also forward original copies of this document for your review and distribution as appropriate.

I would certainly like to discuss this further with the appropriate personnel as well as have the opportunity to bid on setting the monuments and equipment. This could best be accomplished with a face to face meeting with the parties accountable.

If you choose to stay with the proposed equipment and procedures it might be worth while to have us do a mock run through to prove the proposed technique.

Thanks,

Mike

P.S. I still do not have the final elevations of the relocated BTVE monuments to plug into the best fit plane model.

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY – LIGO

REVIEW OF DOCUMENT "LIGO-T970151-00-D" "ASC INITIAL ALIGNMENT" Dated 7/29/97

Submitted to:

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November 11, 1997

SCOPE

The purpose of this document is to provide a review and comments to the document draft titled "ASC Initial Alignment" (LIGO T970151-00-D).

Although we do refer to other types of equipment during this initial review, in most cases we elected not to propose alternative methods or specific equipment. We would welcome the opportunity to have further discussions with the appropriate LIGO personnel regarding other possibilities for consideration.

We also anticipate some future discussion with appropriate LIGO personnel regarding Comments presented herein.

COMPANY QUALIFICATIONS

Our company, The IMTEC Group, Ltd., has been involved with the early construction stages of the LIGO project and we have visited both the Hanford, WA and Livingston, LA sights. We have some familiarity with the overall scale of this alignment project and the problems to be encountered in maintaining a critical alignment.

Our company is focused on providing precision measurement and alignment services for industry.

1) We provide contract consulting and measurement services.

2) We are distributor's for certain industrial measurement products.

3) We rent computerized industrial measurement systems.

Our industrial measurement services group is experienced with conventional optical tooling, multiple head theodolite systems, enhanced electronic theodolite systems, laser interferometers and close range industrial photogrammetry.

Each IMTEC associate has a minimum of 15 years experience in the industrial measurement field with all of the aforementioned technologies and many are specialists in a specific area.

COMMENTS ON SECTION 3-EQUIPMENT REQUIRED

The following general comments are offered for information.

The document describes monuments inside and outside the enclosure to effect an orthogonal alignment based on traditional optical techniques, i.e. optical transit squares and autocollimation. While the conventional optic techniques have been used successfully for nearly 4 decades, this technology is time consuming and difficult to effect accurately without highly skilled personnel trained for field calibration of the optical equipment as well as its application and use. Many state-of-the-art computerized 3 dimensional measurement techniques are available for consideration. Although the 3-D equipment is more expensive if procurement is planned, it often makes up for the price differential in time savings and precision. 3-D equipment can be utilized by employing contract measurement service companies, and it can often be rented.

Using 3-D technology, "tooling points" are often placed on key components and their coordinate values with respect to a pre-determined control or coordinate system are measured. The "tooling points" then describe the "true" position of the equipment in 3-D space, after initial measurement, and its coordinate becomes the "nominal" or "design" value for subsequent alignment or measurement tasks. Most industrial software allows the user to re-establish the "design" coordinate system utilizing a least-squares method with, or without constraints, the results then showing the precision with which the coordinate system has been re-established. Using this type of technology, setup time is greatly reduced and precision is enhanced.

The Brunson transit squares are "short range" instruments. They reach infinity focus nominally at 35-40 meters. Everything beyond 35-40 meters, which is in the field of view, is in focus. These instruments are at their optimum when used at a distance of 30 meters or less. Autocollimating at any distance greater than this is impractical if not nearly impossible. Autocollimating at distances greater than 15 to 20 meters is extremely difficult due to the size of the reticule and the weakness of the light source.

The Brunson Model 75-H is an optical transit square with a mirror on the trunnion axis. For comparison, the Brunson Model 76RH is a telescopic transit square with an optic fixed at infinity focus on the trunnion axis. Both have a "hollow-axis" such that the main (focusable) telescope must be rotated to 180° zenith to sight a point located below the instrument mount. The instrument alidade must then be rotated through 180° while sighting the point of interest to be sure that the instrument is located over the observed point, a difficult process.

To hold the angular alignment in the vertical plane using a coincidence level, both earth curvature and refraction will have to be considered if any distance is involved to hold a .005 mrad tolerance.

Brunson manufactures several optical flats. The Model 185 is a first order, polished carbide mirror selling at around $1000. The less expensive Model 185-10 is a second order coated optical flat. The quality of the 185-10 is not sufficient to autocollimate at distances greater than 3-4 meters. The stability of the optical flat being permanently mounted kinematically for the alignment reference for subsequent alignment set-ups should be re-examined since the procedure does not describe a technique to determine if a mirror has moved.

COMMENTS ON SECTION 4-DETERMINING OFFSET CENTERLINE

Monuments Located Outside the Enclosure-

It is interprated from the ASC Initial Alignment document that the Detector Group located monuments outside the enclosure describing the offset centerline of each arm at the corner, mid and end stations are proposed to be offset at approximately 200 meters from the beam centerline. It is understood that the reason for selecting the 200 meter distance was to control the angular positioning of the placement of the scribe lines on the monuments based on a ±5 mm true position. These monuments could be positioned easily and precisely utilizing 3-D measurement technology.

Monuments Located Within the Enclosure-

It understood that these are the primary alignment monuments to be used for initial and periodical alignment checks of component equipment such as checking the equipment and designated components prior to and after applying the vacuum. It appears you propose that these monuments be placed with differential GPS to a ± 5 mm tolerance. Consideration should be given to placing these monuments with a 3-dimensional measuring system. Differential GPS as specified in the document reviewed may not work well inside the enclosure given the short base line between the monuments.

Using a 3-dimensional system, these monuments could be established with the same precision described for the monuments located outside the enclosure.

COMMENTS ON SECTION 5-ALIGNMENT FIXTURES

Regarding the second from the last paragraph, incorporating prism mounts, if a 3-dimensional measurement technology is used, possibly retro-reflective adhesive targets could take the place of the prism. If this type of target is not acceptable, a retro-reflective kinematic target with a standard 0.2500 inch shank and 0.5000 inch offset could be used. This would mean only a drilled and reamed hole for the target mount. Standard EDM measurement with typical geodetic prisms will provide ≈ 3 mm precision while an industrial 3-D system will provide ≤ 0.8 mm axial positioning for the worst case and possibly as good as <0.2 mm.

COMMENTS ON SECTION 6 AND 7 – ETM ALIGNMENT (END STATION)

The Brunson Model 75H has a filar-bifilar type reticule which blocks at a minimum, 5 arc-seconds from the field of view. Most theodolites have a filar type reticule which blocks 2-3 arc seconds from the field of view. The jig transit could introduce an angular error of up to 5-8 arc-seconds at 200 meters while the registering the reticule to the target on a standard optical plummet. Remember, the jig transit reaches infinity focus between 35-40 meters, therefore everything beyond this distance, which is in the field of view is in focus and the target on the optical plummet will be very small when viewed at 200 meters. Also it is anticipated that air currents through the viewports may easily cause the target on the plummet to "dance" around. It will be necessary to correct for earth curvature and refraction correction if using the coincidence vial. The amount of this correction is 3.2-3.5 mm at 200 meters.

Referring to Figure 4, the short base line between the transit square and the theodolite would allow for collimation between these two instruments. The axial position of the optical flat would have to be close (15-20 meters) to the transit square and not the optical plummet as indicated on the figure. To provide a permanent kinematic mount for a single mirror is not practical unless stability of the mount has been verified by another means over time. It may be beneficial to simply re-establish the set-up, each time an alignment check is required.

The error budget shown in Table 1 is entirely possible if extreme care is taken and the working environment is stable enough to support the precision desired.

Placing the theodolite on the centerline is easily done with the integral optical plummet provided that the instrument is mounted on a stage to allow for precisely "bucking-in" to the scribe or punch mark on the centerline monument. Placement of the transit square over the scribe or punch mark is difficult as there is on optical plummet provision in this instrument.

COMMENTS ON SECTION 8 – CORNER STATION ALIGNMENT

This section of the document is difficult to follow due to its reference to section 6. The implied reference and a specific deviation from the methods of Section 6 are not distinguished.

For the portion of this (Section 8) procedure which are similar to section 6, the comments related to the use of the optical transit square, optical flat (including mounting and placement), viewports and use of the coincidence vial apply.

In the discussion of the "first setup", the document is not clear regarding the axial location of the Brunson bore target used for positioning the theodolite at the center of the beam tube. The Brunson 406 target is very difficult to align depending on the precision that is required. Some other options can be discussed. (For example, it may be possible to use either retro-reflective or kinematic prism targets with a number of observations with the theodolite around the I.D. of the beam tube and do a best fit circle to establish this feature with reference targets.) Additionally, it is not clear that moving the test masses to the desired alignment has any effect on the "buck-in" or placement of the two instruments proposed. As described, the angular position of the optical transit square could be held with autocollimation to the optical flat provided that it is positioned within a workable range. This does not apply to holding the position of the theodolite registered on a target. Also, it is not clear if the theodolite is also collimated to the transit square to insure or validate the 90° alignment during the first setup.

The same comments above also apply to the second setup. Additionally, with respect to the beam splitter angular position paragraph 3 states that "the beam splitter is aligned in the axial and transverse directions using the prism rotated 45 degrees." It is not clear if this is integral equipment prism or the EDM prism. This section also states that the theodolite is moved until it is in line with the beam axis as though it was not in line with the beam axis as described in the second sentence. The last two sentences describe positioning the theodolite in two attitudes by autocollimation with different reflective surfaces. This will be difficult to accomplish and will only position the beam splitter with respect to angularity, not axially or transversely.

Again the fourth and fifth paragraph are not clear. If the theodolite is in position, then the 2 km folding mirror will have to be adjusted to the line if sight of the theodolite. Autocollimation is implied, not described. After rotating the theodolite 180° the method for aligning the recycling mirror is not described.

It appears then that the transit as located in the second setup is replaced with the theodolite and the procedure is then repeated. All previous comments apply.

CONCLUSION

We welcome any further discussions with interested and appropriate LIGO personnel that may be deemed necessary to further this portion of the project.