LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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ASC Initial Alignment Procedures

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Detector Group

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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.

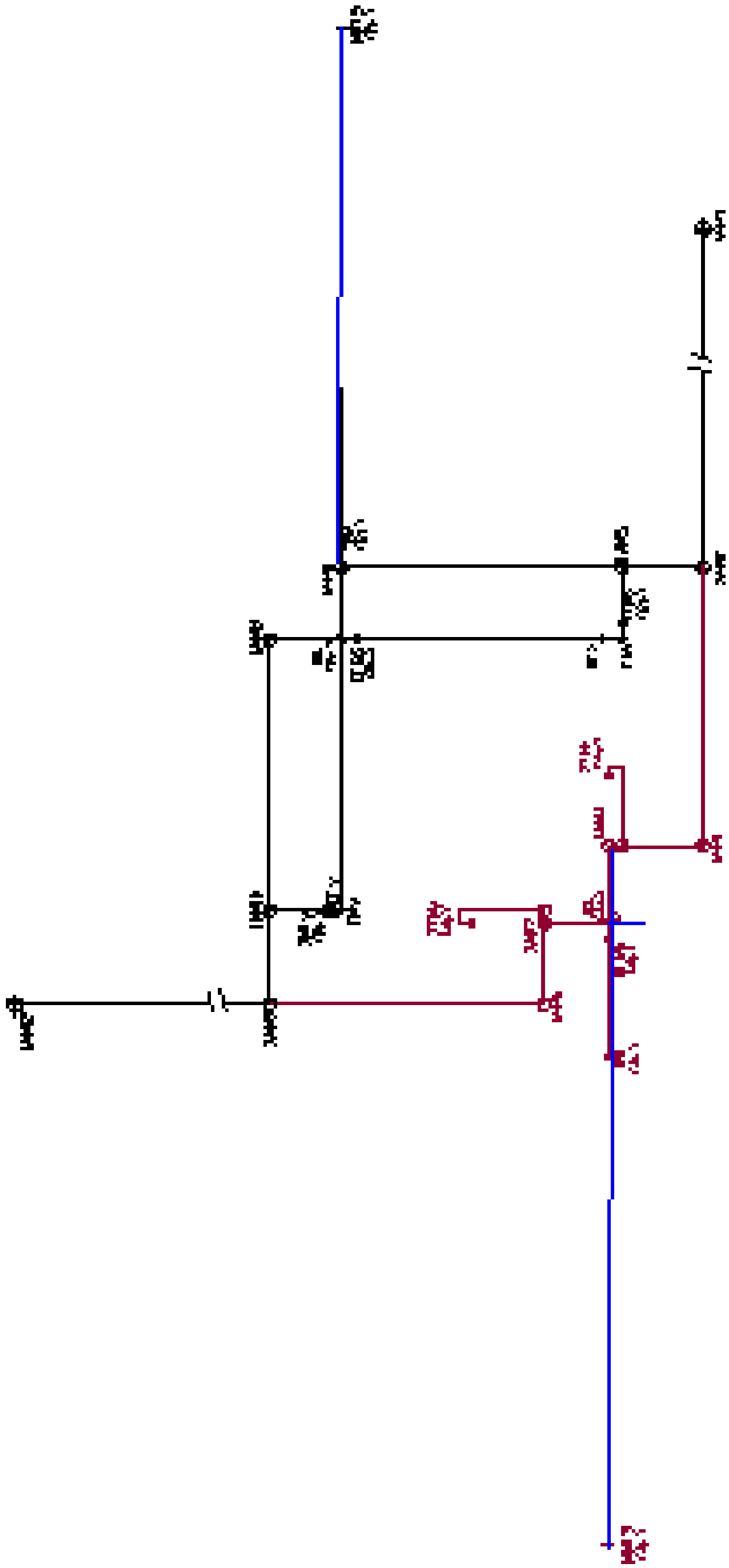
The Brunson transit square is positioned over a monument within the corner, mid, or end station by sighting down through the stand with an optical plummet. A stand with a plumb bob will be positioned over a monument approximately 200 meters from the transit square. The transit square will now be used 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^o23’17”	0^o6’22”
RM	12184	9060	43	IAM8	11543	9060	30.88	0	1^o4’59”
OF_y	200	9322	-96.2	IAM10	200	11428	-89.2	-0^o0’6”	0^o11’59”
ITM_y	200	9598	-99	IAM10	200	11428	-89.2	0	0
OF_x	9163	400	-97	IAM11	9163	11428	-60.4	-0^o0’6”	0^o11’25”
OF_{bs}	9163	8552	-10.6	IAM11	9163	11428	-30.4	0	0^o23’41”
FM_x	9163	-200	-99	IAM5	11543	-200	-106.9	-0^o0’6”	0^o11’25”
ITM_x	9713	-200	-101	IAM5	11543	-200	-101	0	0
FM_y	200	9072	-97	IAM8	11543	9072	-134.7	0^o0’6”	0^o11’25”
$BS_{(2k)}$	9163	9060	-14.1	IAM8	11543	9060	-30.5	0	0^o23’41”
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	*Monu-ment*	**X** the-odolite	**Y** the-odolite	**Z** theod-olite	**Yaw** theodo-lite	**Pitch** theodo-lite
MMT 3	-20779	209.8	27.8	IAM4	2362.2	77.6	-9.5	$0^o19'38''$	$0^o5'32''$
RM	-4596	212	26	IAM4	2362.2	213	-105.5	$0^o0'28''$	$1^o4'59''$
OF_{bs}	-700.6	212	-57	IAM4	2362.2	212	-74.6	0	$0^o23'41''$
ITM_x	4677	200	-101	IAM4	2362.2	-200	-101	0	0
$BS_{(2k)}$	-200	212	-57	IAM7	-200	2362.2	-71.8	0	$0^o23'41''$
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.

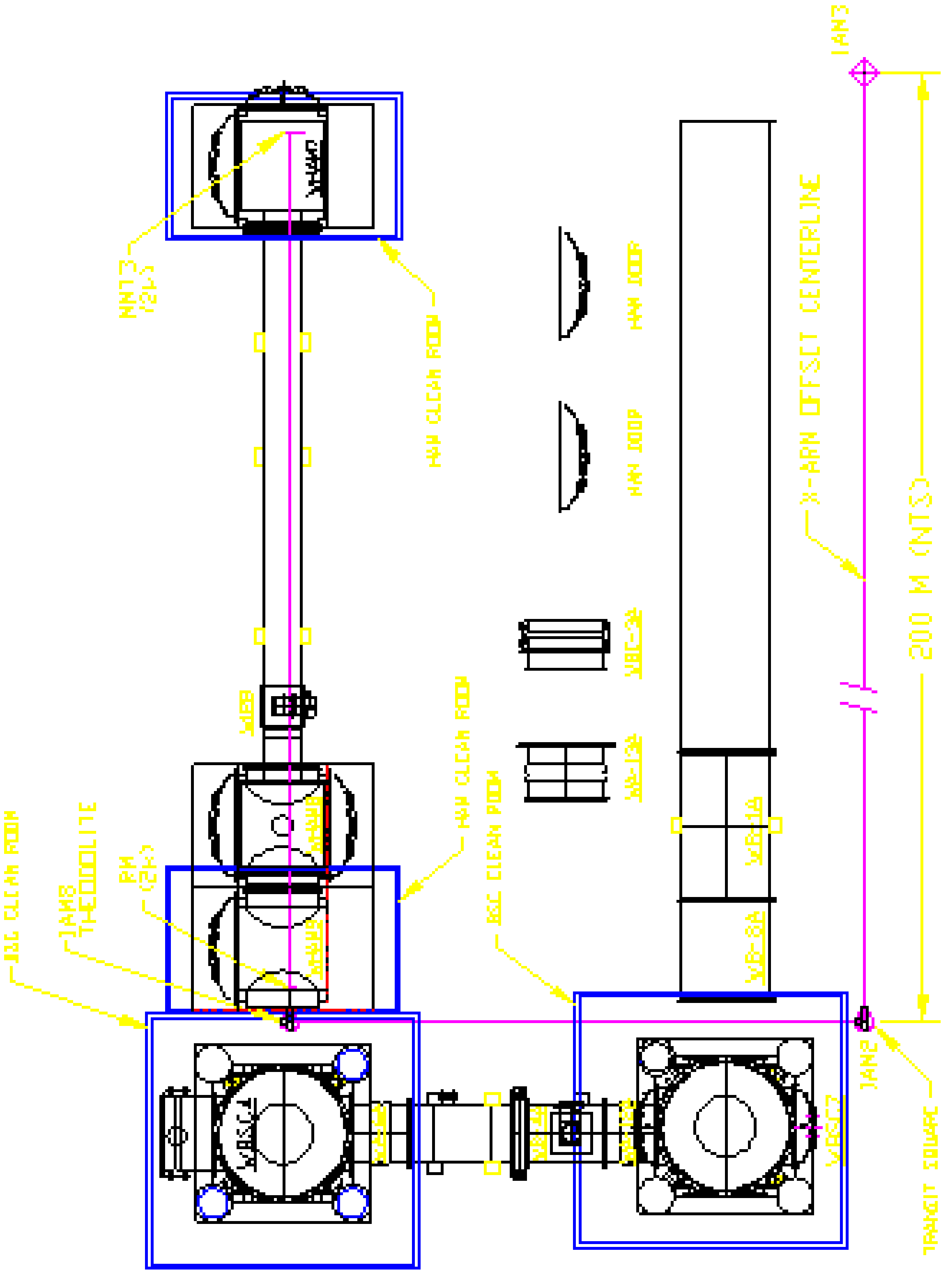
With all linear adjustments complete the laser autocollimator is turned on and the alignment fixture adjusted until the reflected beam is within .05 milliradian. The LOS is clamped in place and the alignment fixture removed without moving the laser autocollimator. The optic is now accurately positioned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


IAN3
X-ARM OFFSET CENTERLINE
200 M (NTS)
HAM CLEAN ROOM
HAM DOOR
HAM DOOR
HAM CLEAN ROOM
BSC CLEAN ROOM
BSC CLEAN ROOM
IAM8 THEODOLITE
RM (2X)
MNT3 (2X)
IAN2
TRANSIT SQUARE

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.

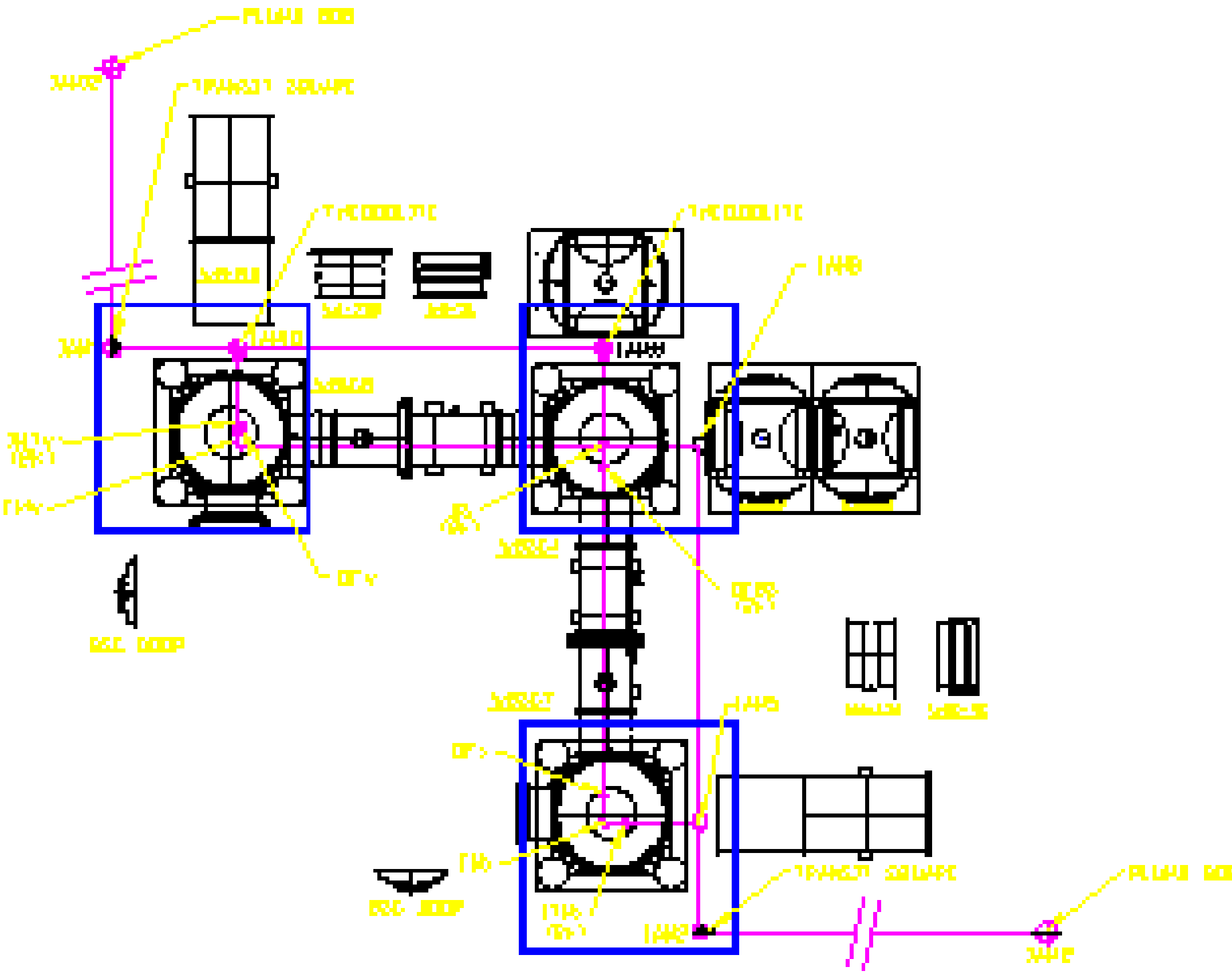
The theodolite is moved to monument IAM11 to position and align optical flats OF_x and $OFBS_{(2k)}$. Optical levers are not required on all optical flats.

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.

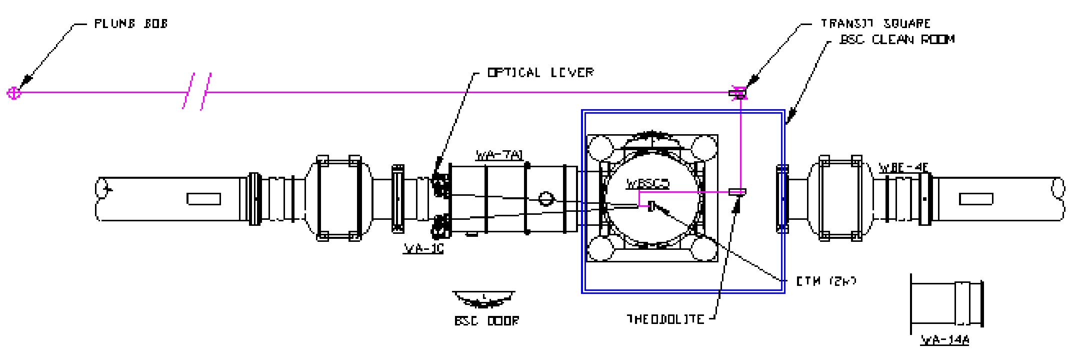
The theodolite is positioned over IAM15 and rotated toward the mirror on the transit until it can be autocollimated off the transit square. The theodolite is then rotated 90 degrees and zeroed. The prism is mounted to the alignment fixture and the theodolite rotated until it picks up the center of the 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.

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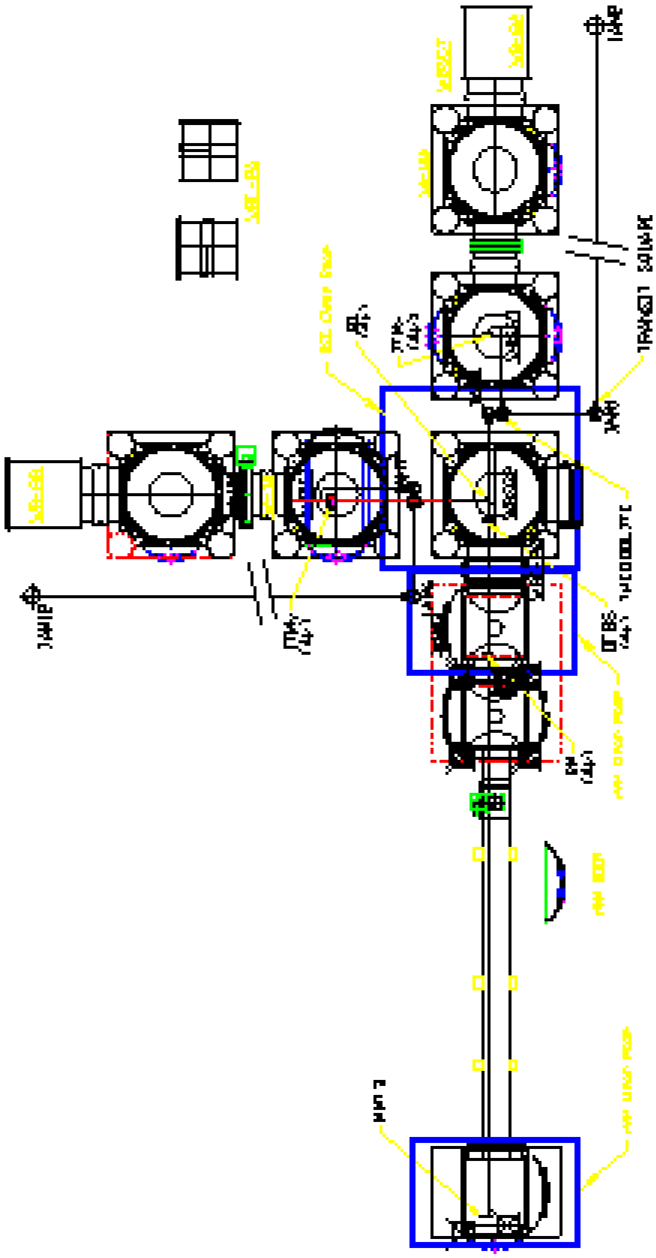
FIG.5



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.

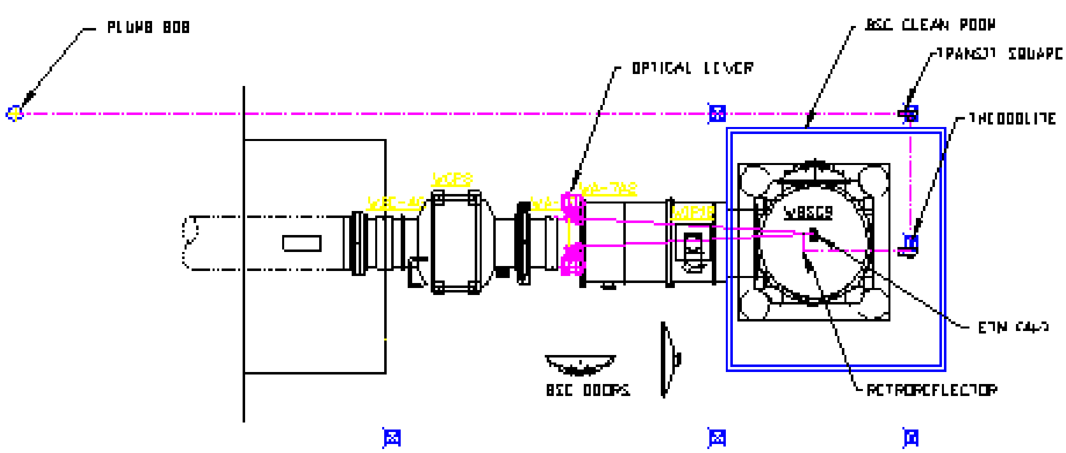
The theodolite is positioned over IAM22 and rotated toward the mirror on the transit until it can be autocollimated off the transit square. The theodolite is then rotated 90 degrees and zeroed. The prism is mounted to the alignment fixture and the theodolite rotated until it picks up the center of the 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