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PRE-ALIGNMENT OF VIRGO INTERFEROMETER

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1 CHANGE RECORD

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Approved by:

1.1 Table of contents

Figures

Tables

1 Scope

This document will establish the procedures and will recommend the equipment required for accomplishing the initial angular alignment of the main interferometer mirrors (core optics) and the injection and detection benches. Two procedures will be described: 1) Procedure with the beam tube closed, and 2) Procedure with the beam tube open.

Procedure (1) is based on procedures that were used to align the core optics in the LIGO interferometers (seeLIGO-T970151-C: ASC Initial Alignment Procedures). Offset centerlines will first be established parallel to the north and west arms of the interferometer at the central building and at the 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.

Procedure (2) is an innovative procedure proposed by VIRGO that has not yet been implemented. However, a preliminary experiment was successfully performed in which the lateral separation between two 25mm diameter, low power visible light sources (point light) was viewed with the Leica total station inside the beam tube tunnel at a distance of approximately 3000m with an angular error of less than 20 microradians. The transmissivities of the AR and HR coatings on the interferometer mirrors are relatively high in the visible spectrum, so it is highly probable that a similar point light source placed at the end of the interferometer can be detected and resolved with similar results after passing through the end mirror, the length of the beam tube, and through the central interferometer mirrors, in accordance with the procedures which will be described later in this document.

The alignment procedures described in this document are limited to the angular alignment of the interferometer mirrors. Transverse and axial positioning of the core optics is not part of this procedure; it is assumed that the optics will have been positioned transversely and axialy within the VIRGO requirements prior to the procedures described.

2 Reference Documents

1) LIGO-T970151-C: ASC Initial Alignment Procedures

2) VIR-SPE-LAS-xxx: Monuments for locating the offset center lines

3) VIR-SPE-LAS-xxx: Wedge Angle Specification
4) VIR-SPE-LAS-1300-138: VIRGO Geometry Reference Systems II
5) VIR-NOT-CAS-1390-210: Beam Deviation Due to De-centering of Power Recycling Mirror Curved Surface

3 Constraints and Interfaces

3.1 Constraints

The alignment procedure is constrained by the following:

1) the constraint of placing optical surveying equipment on the beam centerline only in the location between the input tower and the power recycling tower and between the detection bench and the signal recycling tower (by removal of the connecting Brewster angle links),
2) the inability to place optical surveying equipment on the beam centerline directly facing the HR sides of the input mirrors and end mirrors,
3) the availability of opening the beam arm tubes during the alignment procedure, and
4) the low reflectivity of the interferometer mirrors at visible wavelengths.
5) The de-centering of the power recycling mirror

3.2 Interface

The wedge angles of the various interferometer mirrors cause deviations of the optical beam, which must be accounted for in the alignment procedure. The wedge angle specifications are shown in Table 1: Interferometer Mirror Wedge Angle Specifications (see VIR-SPE-LAS-xxx: Wedge Angle Specification)

Table 1: Interferometer Mirror Wedge Angle Specifications

Mirror	*Wedge Angle*	*Wedge Angle Tolerance*
Power Recycling	?	?
Beam Splitter	1.1 mrad	+/- 0.075 mrad
Input mirror	< 1microrad	
End mirror	1.1 mrad	+/- 0.1 mrad

4 General Requirements

- Angular positioning +/- 100 microrad

- Transverse positioning +/- 1 mm (ITM, ETM)
- Axial positioning +/- 5 mm (BS, RM)

The angular alignment phase is most critical due to the long length of the arms and the relatively small range of adjustment of the suspended optics (1 mrad pk/pk). Our goal for angular alignment is 10% of the adjustment range of the suspended optic or 0.1 mrad. Over a 3 km arm length, a 0.1 mrad angle will bring us within 300mm of the center of the input and end mirrors.

The Monuments placed as of this date are estimated to be within +/- 2mm. Over a 125 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 0.1 mrad as shown in Table 1.

Table 2: Total Error Accumulation

Positioning of monuments	0.03 mrad (6 arc sec)
Sighting of plumb markers	0.02 mrad (4 arc sec)
90 degree autocollimation	0.01 mrad (2 arc sec)
90 degree rotation	0.01 mrad (2 arc sec)
Autocollimation of optic	0.01 mrad (2 arc sec)
Total	*0.08 mrad (16 arc sec)*

5 Pre-alignment Procedure with Beam Tube Closed

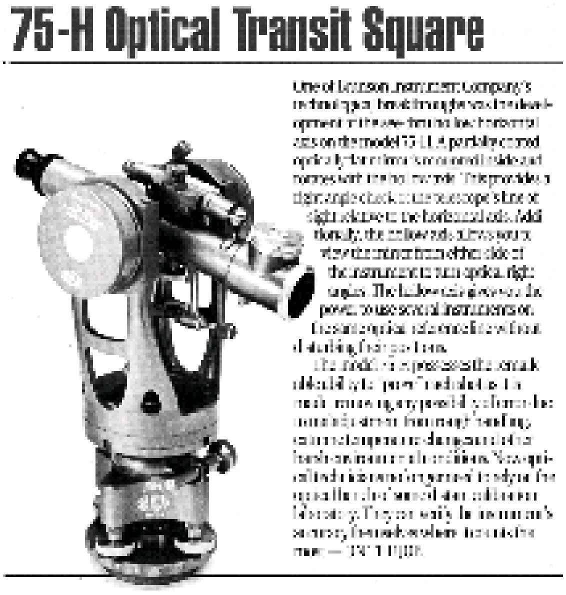
5.1 Equipment Required

5.1.1 Surveying Equipment

The following equipment or their equivalent will be required:

- 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); or equivalent
- One (1) Brunson model 75-H Optical Transit Squares with autocollimating eyepiece, stand, and coincidence level (pictured below).
- One (1) Newport laser autocollimator Model LDS1000 with mounts to theodolite.
- Two (2) 101mm dia. optical flats with mounts (Newport #4024OBD.1 & SL101.6).
- One (1) 200mm dia. optical flat and mount Davidson #D617-8P2S, AlSi0 1 side.

- One (1) Brunson Instrument stand #230-HC and one (1) model 810 stand.
- Support stand to bridge across the conduit & piping
- 100mm aperture plate in front of steering mirror SM6 on the input bench



5.1.2 COS IR Autocollimator

- One (1) 840nm 4Watt IR autocollimator LIGO COS design

5.2 Calculated Optic and Theodolite Positions

Offset centerlines with a clear line of sight are located parallel to the beam tube centerlines in the center building and in the end stations (see

Figure 1: Alignment of Central Interferometer--Beam Tube Closed

And

Figure 2: Alignment of End Mirrors--Beam Tube Closed). Monuments for locating the offset centerlines are shown on VIR-SPE-LAS-xxx: Monuments for locating the offset center lines; the global positions of the monuments are listed in Table 4: Monument Positions.

The theodolite and mirror positions are listed in Table 7: Theodolite Positions.

The positional accuracy of the initial alignment monuments must be within +/- 3mm of true position in Global Coordinates. This applies to N and W position only.

Table 3: Elevation Scribe Locations, contains scribe elevations in local co-ordinates. The vertical position is determined from actual positions of tower flange centerlines. Scribes are located at each tower flange location. The positions of these scribes are measured relative to a control point that is x? meters above the reference ground. 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 tower flange such that the theodolite can measure directly the vertical height.

Table 3: Elevation Scribe Locations

LOCATION	*ELEVATION*	$Z_{actual}(m)$	$Z_{design}(m)$	$Z_{offset}(m)$
IT				
DT				
NT				
WT				

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/autocollimator separation can change and therefore must be measured and then subtracted from the value given in Table 7: Theodolite Positions.

Table 4: Monument Positions

Monu-ment	X	Y
M1		
M2		
M3		
M4		
M5		
M6		
M7		
M8		
M9		
M10		
M11		
M12		
M13		
M14		
M15		
M16		

5.2.1 Theodolite Pitch Correction

Due to the curvature of the earth and the orientation of the interferometer optical plane, the local ground horizontal plane is not parallel to the direction of the beam axis. The alignment theodolite/autocollimator, when facing the high reflectance sides of the center mirror (ITM) and the end mirror (ETM), must be tilted in the elevation direction with respect to local horizontal in order to point along the beam axis. The required pitch angles for the two mirrors of each arm were calculated in VIR-SPE-LAS-1300-138: VIRGO Geometry Reference Systems II VIR-SPE-LAS-1300-138: VIRGO Geometry Reference Systems II and are listed in Table 5: Global Alignment Correction Angle. A positive angle indicates an upward pitch, and a negative angle indicates a downward pitch.

Table 5: Global Alignment Correction Angle

ARM	*CENTER*	*END*
N-ARM	-0.24 mrad	-0.24 mrad
W-ARM	-0.69 mrad	0.21 mrad

5.2.2 Theodolite Yaw Correction

The 1mrad wedge angle of the beam splitter (BS) causes the beam to deviate from the arm direction as it passes through the BS. The deviation angle is dependent upon the index of refraction of the fused silica substrate of the BS and is greater for shorter wavelengths. The deviation angles at various wavelengths of light and the errors which result from using light with wavelength different from 1064 nm are shown in Table 6: Beam Splitter Deviation Angles. The deviation angle error is significant for 502nm wavelength light and the theodolite yaw pointing angle should be corrected accordingly.

Table 6: Beam Splitter Deviation Angles

WAVELENGTH, nm	*INDEX*	*DEVIATION ANGLE, mrad*	*ANGLE ERROR, microrad*
1064	1.44963	0.791	0
830	1.45282	0.796	5
633	1.45702	0.803	12
502	1.46223	0.811	20

The theodolite yaw and pitch orientation angles at each of the alignment locations, when the 633nm wavelength autocollimator is used for the beam-tube-closed procedure, are shown in Table 7: Theodolite Positions and Local Orientation Angles—Beam Tube closed.

Table 7: Theodolite Positions and Local Orientation Angles—Beam Tube closed

Location	**X** theodolite	**Y** theodolite	**Z** theodolite	**Yaw** theodolite mrad	**Pitch** theodolite mrad	*Axial* dist.
M7				0.803 cw	0.24 down	
M8				0.803 ccw	0.69 down	
M12				0.000	0.24 down	
M16				0.000	0.21 up	

The yaw correction angles for the theodolite, when used with a 500nm point source for the beam-tube-open procedure, are shown in Table 8: Theodolite Yaw Correction Angle—Beam Tube Open

Table 8: Theodolite Yaw Correction Angle—Beam Tube Open

THEODOLITE LOCATION	*MIRROR UNDER ALIGNMENT*	*YAW CORRECTION ANGLE, microrad*
M7	PR	20 ccw
M7	NI	0
M8	WI	0
M7	BS	20 ccw
M12	NE	20 cw
M16	WE	20 ccw

5.3 Procedure for Setting Up the Total Station (e.g. North End)

1. Mount the Brunson Transit square to the Brunson 230-HC stand and place over M 10 at the theodolite height for NE (see Table 3: Elevation Scribe).

2. Level the transit square with the coincidence level per appendix 2. Rotate the scope towards M11. Sight the string and plumb bob over M11. The transit square is now in its final position and should not be moved again.

3. 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 M12 and set the height as specified in Table 3: Elevation Scribe

4. Clamp a 300mm or greater scale to the north end tower and align to the scribed beam height on the side of the tower.

5. 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 Table 3: Elevation Scribe and set the crosshairs in the theodolite to the appropriate mark on the scale.

6. Verify the squareness of the transit square with the LDS1000 laser autocollimator per section 8.

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 analogue 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 Table 3: Elevation Scribe and set the crosshairs in the theodolite to the appropriate mark on the scale.

10. 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.

11. 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 analogue 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.

12. 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. 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 permanent magnets to within 5-10 microradians.

13. 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).

5.4 Alignment Procedures—Beam Tube Closed

Refer to

Figure 1: Alignment of Central Interferometer--Beam Tube Closed. This procedure requires that the beam deviation angle caused by the de-centering of the power recycling mirror be known.

5.4.1 Alignment of Power Recycling Mirror

- Remove the Brewster window link between the injection tower and the power recycling tower
- Place the total station with the laser autocollimator above monument M7 on the optical axis of the north beam
- Align the theodolite perpendicular to the offset centerline by means of the Optical Transit Square placed above monument M5
- Rotate the theodolite/autocollimator by 90.0000 degrees with correction for the BS deviation angle and the power recycling mirror deviation angles horizontally and by the global alignment correction angle vertically so that the laser autocollimator points along the north beam axis toward the AR reflectance side of the power recycling mirror

- (note: it will be necessary to distinguish between the AR side reflection and the HR side reflection if there is a significant wedge in the mirror; the HR side reflection must be chosen)
- Adjust the alignment of the power recycling mirror until the HR side reflected beam is autocollimated to within 10 microrad

5.4.2 Alignment of North Input Mirror

- Remove the theodolite and place the 4W COS IR autocollimator on the optical axis of the north beam above M7 in the same location at the Brewster window link between the injection tower and the power recycling tower
- Align the COS autocollimator by autocollimating from the high reflectance surface of the power recycling mirror
- Misalign the power recycling mirror so that the reflection is not seen within the field of view of the autocollimator
- Adjust the alignment of the north input mirror until the HR side is autocollimated to within 30 microrad

5.4.3 Alignment of Beam Splitter Mirror

- Remove the Brewster window link between the detection tower and the signal recycling tower
- Place the total station with the laser autocollimator on the optical axis of the west beam above monument M8
- Align the theodolite perpendicular to the offset centerline by means of the Optical Transit Square placed above monument M2
  Rotate the theodolite/autocollimator by 90.0000 degrees horizontally and by the global alignment correction angle vertically so that the laser autocollimator points along the west beam and reflects toward the north input mirror (note: it will be necessary to distinguish between the AR side reflection and the HR side reflection of the BS since there is a significant wedge in the BS; the 50% side reflection must be chosen
- Adjust the alignment of the BS mirror until the beam is autocollimated from the HR side of the previously aligned north input mirror to within 10 microrad

5.4.4 Alignment of West Input Mirror

- Project the aligned COS autocollimator (see 5.4.2) along the north beam optical axis and reflect from the 50% side of the BS toward the west input mirror
- Adjust the alignment of the west input mirror until the HR side is autocollimated to within 10 microrad

5.4.5 Alignment of Detection Bench beams

- Project the aligned COS autocollimator located at M7 along the north beam optical axis View the output beam by looking toward the BS from the detection bench with an IR video camera with 75mm zoom lens

Note the two projected reticle patterns from the west beam and the north beam If necessary, re-align the beam splitter mirror until the projected reticle pattern from the north beam coincides with the reticle pattern from the west beam

5.4.6 Alignment of Input Bench

- Remove the theodolite and place the 4W COS IR on the optical axis of the west beam above M8 in the Brewster window link between the detection tower and the signal recycling tower
- Align the COS autocollimator by autocollimating from the high reflectance surface of the west input mirror
- Move the input bench if necessary to align the aperture plate with the projected reticle pattern from the COS autocollimator, by observing the projected reticle pattern on the 100mm aperture plate in front of steering mirror SM6 on the input bench

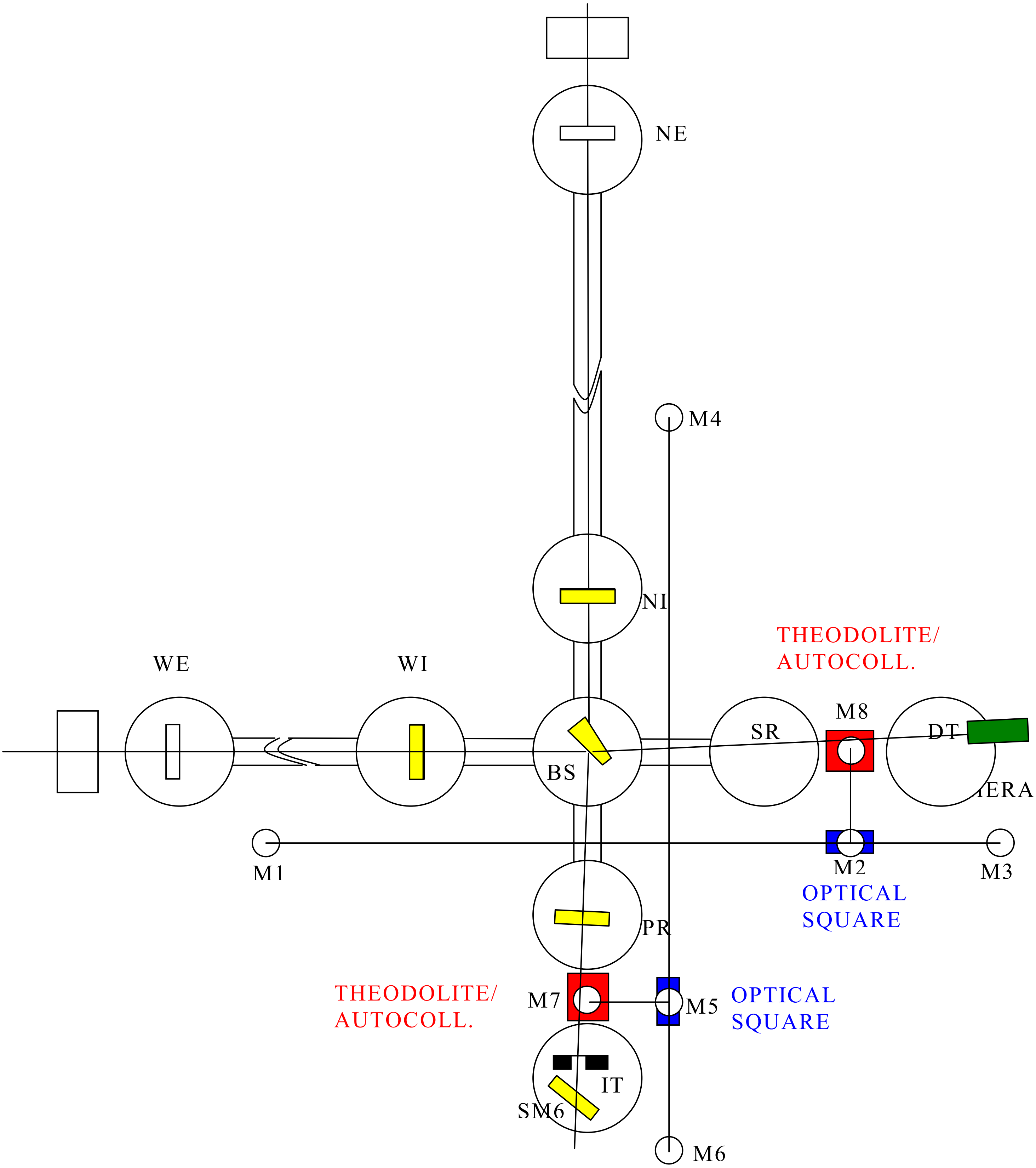


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Figure 1: Alignment of Central Interferometer--Beam Tube Closed

5.4.7 Alignment of Input Bench Steering Mirror

- Turn on the 1064 nm input laser
- Align the final steering mirror SM6 of the input bench so that the beam retro-reflects from the aligned power recycling mirror.

The alignment of SM6 can be accomplished in the following two steps:

1) Align roughly the SM6 mirror so that the retro-reflected beam is centered approximately on the curved mode cleaner mirror, by using the video camera in the mode cleaner chamber (CMC-YaG) to image the beam when it hits the periphery of the curved mode cleaner mirror and by walking the beam across the mirror.
2) Perform the final steering of SM6 so that the retro-reflected beam passes back clearly through the aperture of the Faraday isolator 2, by using the video camera at the reflected port on the laser table (Citf2) to image the beam when it is transmitted back through the Faraday isolator 2.

5.4.8 Alignment of West End Mirror

Refer to

Figure 2: Alignment of End Mirrors--Beam Tube Closed

- Place the total station above monument M16 with the laser autocollimator on the optical axis of the west beam, at the output end of the west end tower
- Place the optical square above monument M14 and follow the procedure for aligning the input mirrors, see 5.4.2

5.4.9 Alignment of North End Mirror

- Place the total station above monument M12 and the optical square above monument M10; follow the procedure for aligning the west end mirror

6 Prealignment Procedure with Beam Tube Open

6.1 Equipment Required

- Leica Total Station
- Point light source
- Point light source mount at Brewster window link location
- Point light source mount at end tower location
- Steering optics and mounting stand for total station at End location

- Steering optics and mounting stand for total station at Brewster window link location
- COS autocollimator (optional)
- 100mm aperture plate in front of steering mirror SM6 on the input bench

6.2 Alignment Procedures—Beam Tube Open

Refer to

Figure 3: Alignment of the Central Interferometer—Beam Tube Open

6.2.1 Alignment of Power Recycling Mirror

- Place the total station beside the Brewster window link between the injection tower and the power recycling tower and view toward the north tube end by reflecting from the Brewster window surface, as shown in Figure 4: Brewster Link Optical System
- Place the point light source on the beam centerline outside the north end tower, facing toward the north input mirror (Note: the point light source may be an illuminated surveying target)
- Align the theodolite with the point light source and make the yaw angle correction shown in Table 8: Theodolite Yaw Correction Angle—Beam Tube Open
- Adjust the alignment of the power recycling mirror until the HR side reflected beam is autocollimated to within 10 microrad (note: it may be necessary to place a linear polarizer at the output of the theodolite to reduce glare from the light that transmits through the Brewster window)

6.2.2 Alignment of North Input Mirror

- Misalign the power recycling mirror so that the reflection is not seen within the field of view of the theodolite
- Make the yaw angle correction shown in Table 8: Theodolite Yaw Correction Angle—Beam Tube Open
- Adjust the alignment of the north input mirror until the HR side is autocollimated to within 10 microrad

6.2.3 Alignment of West Input Mirror

- Place the total station beside the Brewster window link between the signal recycling tower and the detection tower and view toward the west tube end by reflecting from the Brewster window surface
- Place the point light source on the beam centerline outside the west end tower, facing toward the west input mirror
- Align the theodolite with the point light source and make the yaw angle correction shown in Table 8: Theodolite Yaw Correction Angle—Beam Tube Open

- Adjust the alignment of the west input mirror until the HR side reflected beam is autocollimated to within 10 microrad (note: it may be necessary to place a linear polarizer at the output of the theodolite to reduce glare from the light that transmits through the Brewster window)

6.2.4 Alignment of Beam Splitter Mirror

- Place the total station beside the Brewster window link between the power recycling tower and the injection tower and view toward the north tube end by reflecting from the Brewster window surface as previously
- Place the point light source on the beam centerline outside the north end tower, facing toward the north input mirror as previously
- Align the theodolite with the point light source and make the yaw angle correction shown in Table 8: Theodolite Yaw Correction Angle—Beam Tube Open
- Misalign the power recycling mirror and the north input mirror so that their reflections are not seen within the field of view of the theodolite
- Autocollimate from the west input mirror by reflecting from the 50% surface of the BS (Note: it will be necessary to determine that the reflection is from the 50% surface and not the AR surface of the BS)
- Adjust the alignment of the BS mirror until the theodolite is autocollimated from the HR side of the west input mirror to within 10 microrad (Note: if there is insufficient reflectivity from the BS to perform the autocollimation then use the alternate COS autocollimator procedure

Note: It may be difficult to see the autocollimation after reflecting twice from the BS and once from the WI mirrors; in that case, use the optional 4W COS autocollimator procedure

6.2.5 Alignment of Beam Splitter Mirror (Alternate method using COS autocollimator)

- After aligning the power recycling mirror, remove the theodolite and place the 4W COS IR autocollimator in the same location at the Brewster window between the injection tower and the power recycling tower
- Align the 4W COS IR autocollimator by autocollimating from the high reflectance surface of the power recycling mirror
- Misalign the power recycling mirror so that the reflection is not seen within the field of view of the theodolite
- Autocollimate from the west input mirror by reflecting from the 50% surface of the BS (Note: it will be necessary to determine that the reflection is from the 50% surface and not the AR surface of the BS)

Adjust the alignment of the BS mirror until the theodolite is autocollimated from the HR side of the west input mirror to within 30 microrad

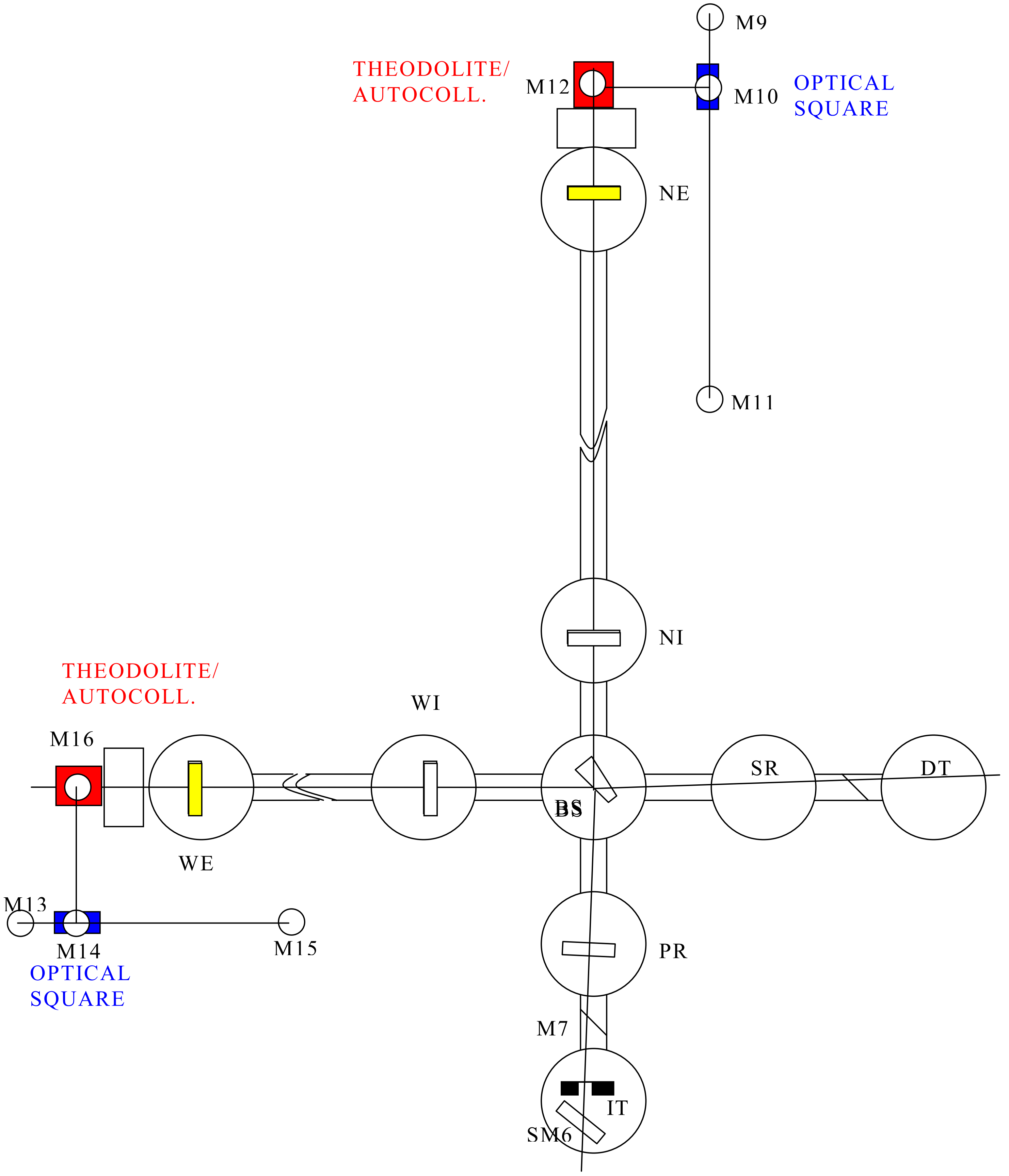

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Figure 2: Alignment of End Mirrors--Beam Tube Closed

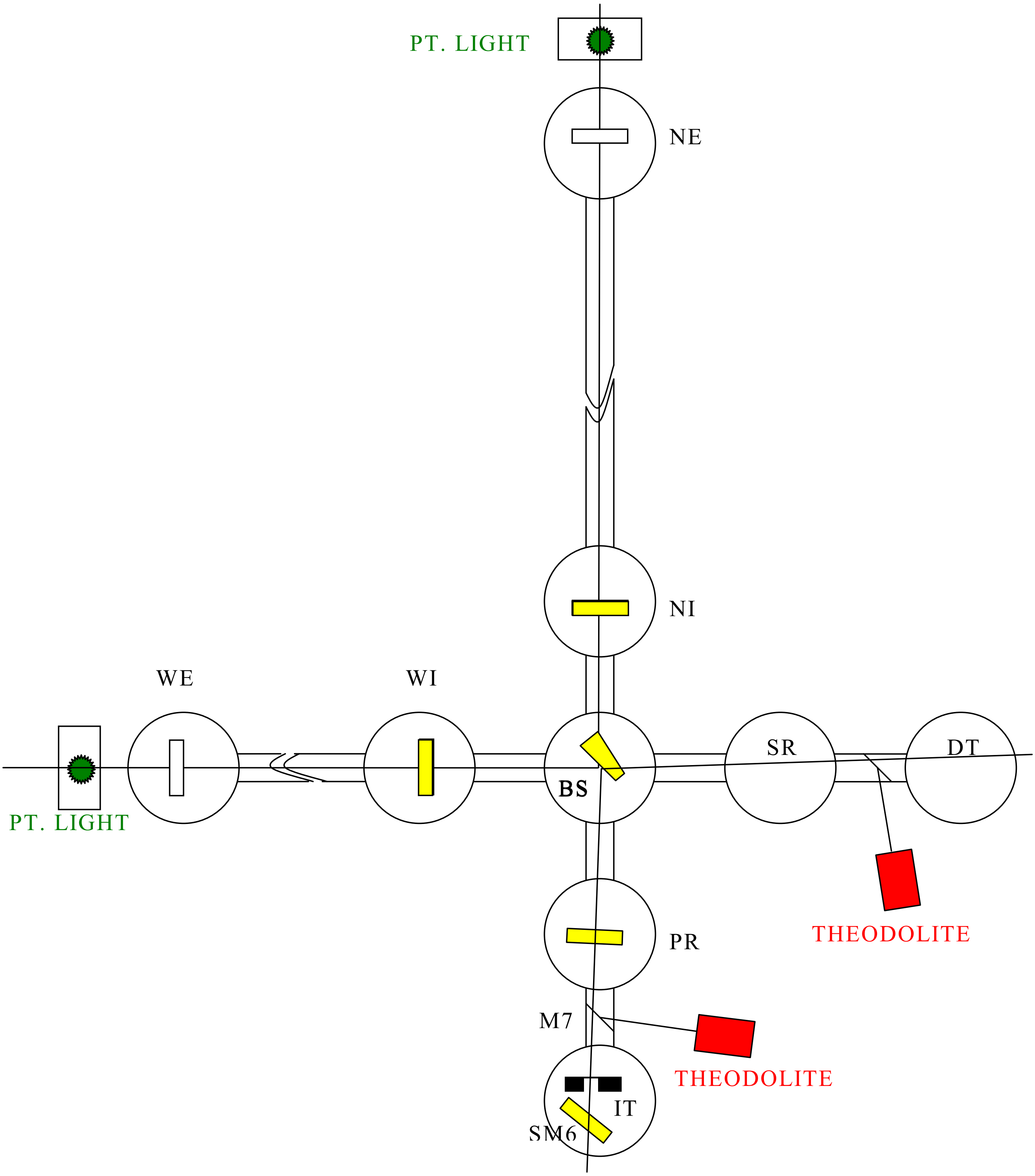
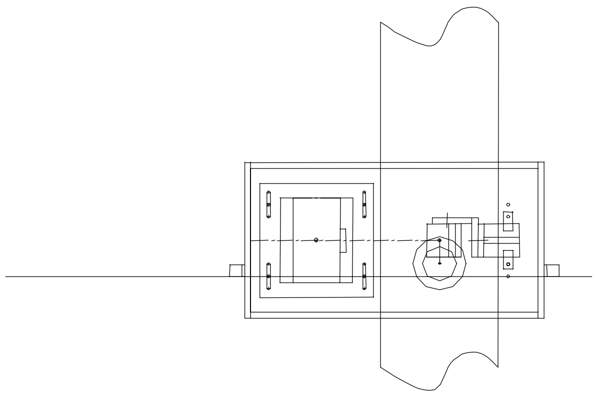


Figure 3: Alignment of the Central Interferometer—Beam Tube Open



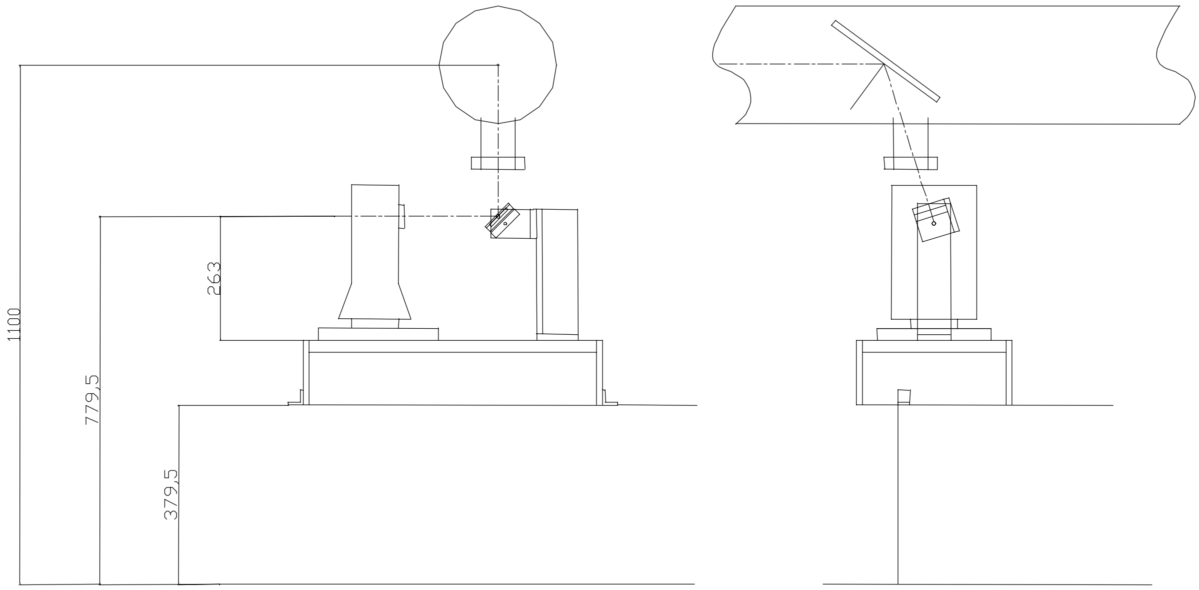


Figure 4: Brewster Link Optical System

6.2.6 Alignment of West End Mirror

Refer to Figure 5: Alignment of End Mirrors—Beam Tube Open

- Place the total station behind the west end tower and view toward the central interferometer by reflecting from a steering mirror placed on the west end transmission bench
- Place the point light source beside the Brewster window link between the signal recycling tower and the detection tower so that it is visible from the west tube end by reflecting from the Brewster window surface
- Align the theodolite with the point light and make the yaw angle correction shown in Table 8: Theodolite Yaw Correction Angle—Beam Tube Open
- Adjust the alignment of the west end mirror until the HR side reflected beam is autocollimated to within 10 microrad

6.2.7 Alignment of North End Mirror

- Place the total station behind the north end tower and view toward the central interferometer by reflecting from a steering mirror placed on the north end transmission bench
- Place the point light source beside the Brewster window link between the power recycling tower and the injection tower so that it is visible from the north tube end by reflecting from the Brewster window surface
- Follow the procedure for aligning the west end mirror

6.2.8 Alignment of Input Bench Steering Mirror

- Turn on the 1064 nm input laser
- Align the final steering mirror of the input bench so that the beam retro-reflects from the aligned power recycling mirror (see 6.2.8)

6.2.9 Alignment of Detection Bench beams using COS autocollimator

- After aligning the power recycling mirror, remove the theodolite and place the 4W COS IR autocollimator in the same location at the Brewster window between the injection tower and the power recycling tower
- Project the COS autocollimator along the north beam optical axis and align with the power recycling mirror
- View into the output beam from the detection bench toward the BS with an IR video camera with 75mm zoom lens

- View the two projected reticle patterns, from the west beam and the north beam
- If necessary, re-align the beam splitter mirror until the projected reticle pattern from the north beam coincides with the reticle pattern from the west beam

6.2.10 Alignment of Input Bench using COS autocollimator

- After aligning the west input mirror, remove the theodolite and place the 4W COS IR autocollimator in the same location at the Brewster window between the detection tower and the signal recycling tower
- Align the COS autocollimator by autocollimating from the high reflectance surface of the west input mirror
- Move the input bench if necessary to align the aperture plate with the projected reticle pattern from the COS autocollimator, by observing the projected reticle pattern on the 100mm aperture plate in front of steering mirror SM6 on the input bench

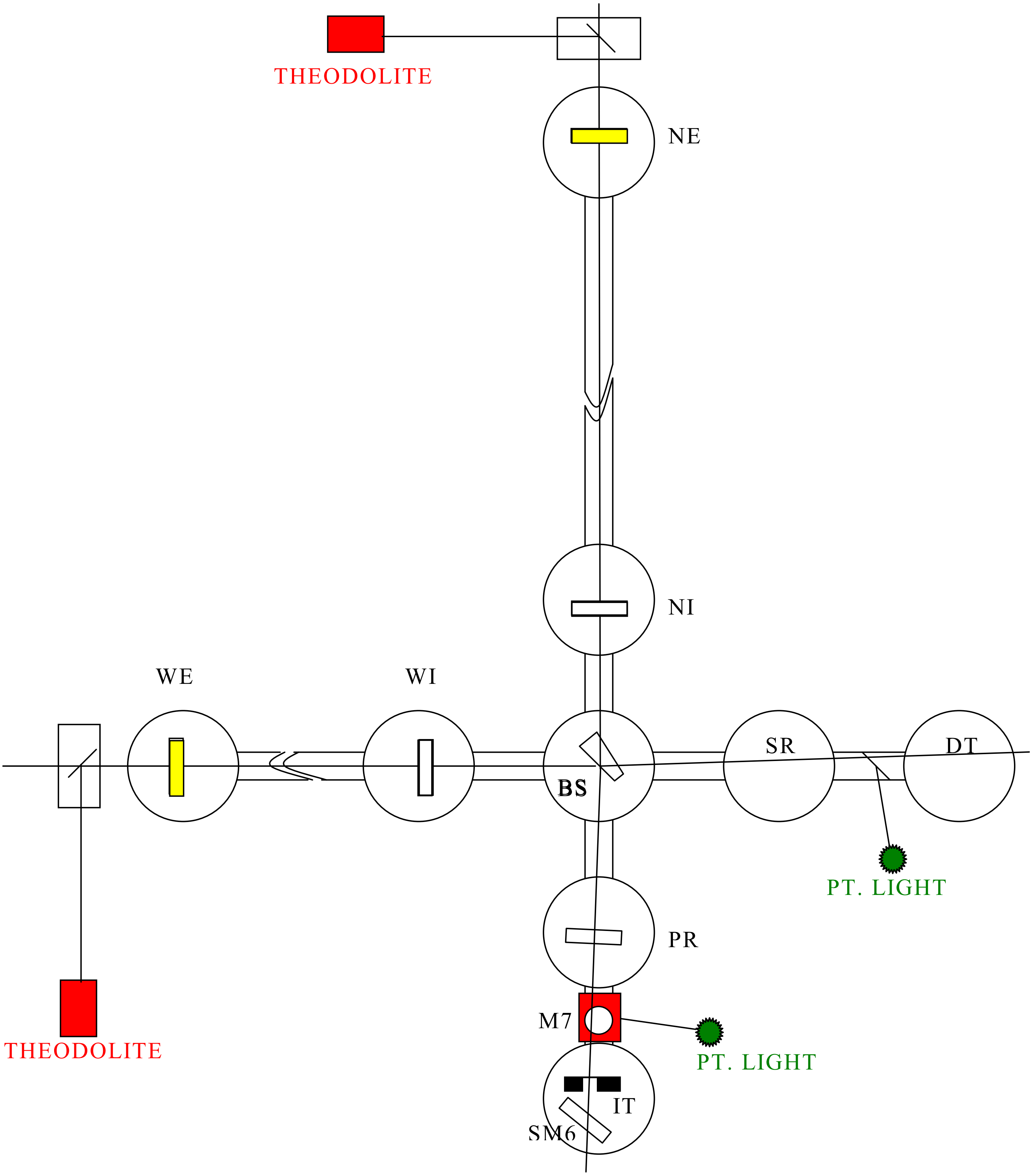


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Figure 5: Alignment of End Mirrors—Beam Tube Open

7 Appendix 1: Leveling Procedure For 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 screws are 90 deg. to scope.

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

4. Rotate 180 deg and take out half error with tangent screw and half with levelling 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 levelling screws, then 180 rotation, 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.

8 Appendix 2: Verification 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 axes are mutually orthogonal and orthogonal to the optic axis with the following procedure:

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. 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 degrees 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 is a visible difference not attributable to a levelling 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 then 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, the remaining error is mostly vertical, and 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 are 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 movement of the transit.