APPROVED

[signature] 7/1/98
CBI DATE
[signature] 7/2/98
LIGO DATE

CBI	IDENTIFICATION ALI-1 LIGO-E950073-09-B			
TITLE INITIAL & FINAL ALIGNMENT DURING INSTALLATION OF LIGO BEAM TUBE MODULES USING GPS SYSTEM	REFERENCE NO. 930212		SHT 1 OF 21	
	OFFICE RSE		REVISION 9	
PRODUCT LIGO BEAM TUBE MODULES CALIFORNIA INSTITUTE OF TECHNOLOGY	MADE BY SDH	CHKD BY SWP	MADE BY SDH	CHKD BY DED
	DATE 12/28/93	DATE 12/29/93	DATE 07/01/98	DATE 07/01/98

1.0 SCOPE:

This procedure defines the method of establishing the LIGO Beam Tube alignment during construction and final alignment activities at the Livingston Site. This procedure uses *Global Positioning System(GPS)* techniques with *jigs and fixtures* unique to LIGO requirements. Details for Beam Tube *Construction Layout*, *Initial Alignment* and Final Inspection of Beam Tube alignment are included in this procedure.

2.0 REFERENCES:

The alignment maintenance procedures for the Beam Tube Module are based on the following references. Words noted in *italics* are defined in the attached glossary.

1) Summary of concepts and Reference Design for a Laser Gravitational-Wave Observatory, CAL TECH; Feb-92.
2) LIGO Project Safety Manual.
3) Manufacturer's Procedures for Global Positioning System(GPS) Equipment and Computer Software.
4) Customer Site Plans and Drawings provided.
5) Acronyms and Terms Used for This Procedure
6) Delete
7) SUP-ADJUST Support Adjustment Procedure

3.0 EQUIPMENT:

The following is a listing of alignment equipment selected for use in establishing and maintaining the LIGO beam tube clear aperture requirement. Based on manufacturing tolerances, the field alignment tolerance is ± 14 millimeters. Beam Tube alignment equipment is selected based on an expected accuracy of ± 5 millimeters for GPS equipment, ± 1 millimeter for the adjustability of the beam tube supports and ± 8 millimeters for combined measurement inaccuracies.

1) Global Positioning System Package consisting of the following:
   a. *Base Station and Rover Receivers.*
   b. *Radio link* system, Portable and Fixed Stands, Etc.
   c. *Antenna* Accessories and fixtures.
   d. Personal Computer workstation formatted for DOS and MS Windows®. The computer must have a math co-processor as a minimum with RAM and storage capability required based on the manufacturer's recommendations.
   e. *Data Collector*

f. *Real Time Kinematic* and *Static* Software.
g. Satellite Positioning Almanac and Forecasting Software with modem.
h. Target Reference Rod and antenna positioner

2) Equipment Required for Positioning and Adjustments:
  i. Tools including millimeter graduated tape measures, flashlights, shop lights, equipment carts and personnel transportation.
  j. Light weight string line and tensioning system for use on lateral measurements between control supports. Spectra Product SPIDERWIRE® rated at 60 to 80 lb test or equal is used for best results.
  k. GPS Antenna Mount ALI-1. See Detail 5.6b
  l. Optical alignment scope equipped with 5mw laser and supported on centering fixture ALI-2 as noted on Figure 5.5a.
  l. Target fixture used for optical and/or laser measurements ALI-3 as detailed on Figure 5.5b.
  m. Support ring Off-Set Ring Assembly ALI-4. See Detail 5.6a.

4.0 DOCUMENTATION:

The receiving, recording, calculation and use of data is controlled by data logging form and spreadsheet programs. Raw GPS data will be stored on 100mb Zip® drives and provided to Caltech in electronic form using the GPS software manufacturer's back-up programs. Spreadsheets detailing final support positions will be provided to Caltech in 3.5" floppy disk formatted to DOS

1) Forms shall be standardized and used to record all data.
2) Data used to process coordinate points, file names, and instrument information shall be in-put to a spread sheet computer program having capabilities to sort for ranges and specific text references.
3) Standardized Documents are indexed below:
  a. Delete
  b. Data Record(Figure 4.3b)
  c. GPS Inventory/Calibration Log(Figure 4.3c)
4) A plotting format shall be used to provide a graphic representation of layout and alignment conditions when advantageous in determining relationships in visual observations. Graphing formats will be developed on a point by point situation.

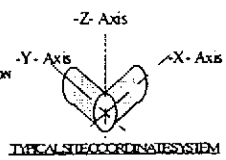
DATA RECORD

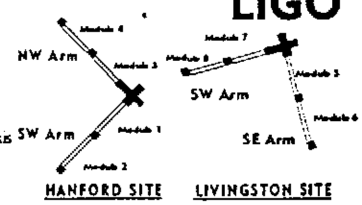
LIGO

Customer: CALTECH
Customer Contract Number: ______
CBI Contract Number: ______
CBI File Reference: ______

X-XX-X XX

FACILITY LOCATION: H = Hanford, L = Livingston
BEAM TUBE ARM: NW = Northwest, SW = Southwest, SE = South East, LIGO = Control Point
BEAM TUBE SUPPORT LOCATION: Even = Fixed Support, Odd = Guided Support
BEAM TUBE MODULE IDENTIFICATION: 1 Thru 8





LINE NUMBER	SUPPORT LOCATION IDENTIFICATION	FINAL COORDINATE POSITION (ADJUSTED CENTERLINE) -X-	±X±	-Y-	±Y±	-Z-	±Z±	ORIGINAL COORDINATE (Theoretical or Last Adjusted) -X-	-Y-	-Z-	FIELD MEASURED COORDINATE -X-	-Y-	-Z-	-Z' Compensation -Z'-	COMMENTS
01	H-LIGO - 0 01														
02	H-LIGO - 0 02														
03	H-LIGO - 0 03														
04	H-LIGO - 0 04														
05	H-LIGO - 0 05														
06	H-SW - 1 01														
07	H-SW - 1 02														
08	H-SW - 1 03														
09	H-SW - 1 04														
10	H-SW - 1 05														
11	H-SW - 1 06														
12	H-SW - 1 07														
13	H-SW - 1 08														
14	H-SW - 1 09														
15	H-SW - 1 10														
16	H-SW - 1 11														
17	H-SW - 1 12														
18	H-SW - 1 13														

EXAMPLE

Figure 4.3b

GPS EQUIPMENT
INVENTORY/CALIBRATION
LOG

LIGO

Customer: CALTECH
Customer Contract Number ______
CBI Contract Number: ______
CBI File Reference ______

EXAMPLE

LIGO
PROJECT I.D.: LIGO Example
For Information Contact:
CALTECH (818)555-1234

EQUIPMENT Identification Lable

LINE NUMBER	Project Identification Number	COMPONENT NAME	MANUFACTURER	MODEL/SERIAL NUMBER	PURCHASE ORDER REFERENCE	LATEST CALIBRATION DATE
01	LIGO - R01	GPS Multi-Channel Receiver	XYZ Technical, Inc	[illegible]-12LB0[illegible]259[illegible]002	C-11029703	12/24/96
02						
03						
04						
05						

Figure 4.3c

5.0 EXECUTION:

The alignment activity begins when the LIGO beam tube foundation *slab* is in place and in a "cured" condition. The slab is laid out for beam tube installation using GPS techniques. Specific supports are chosen as "control supports" and the layout points are measured to greater accuracy for alignment reference. Control Supports designated for Livingstion LIGO facility are fixed supports and listed below:

"X" Arm Control Supports	
X1 Support I.D.	X2 Support I.D.
Termination	Termination
L-SW-706	L-SW-806
L-SW-712	L-SW-810
L-SW-718	L-SW-816
L-SW-724	L-SW-822
L-SW-730	L-SW-828
L-SW-736	L-SW-834
L-SW-742	L-SW-840
L-SW-748	L-SW-846
L-SW-754	L-SW-852
L-SW-760	L-SW-858
L-SW-766	L-SW-864
L-SW-772	L-SW-870
L-SW-778	L-SW-876
L-SW-784	L-SW-882
L-SW-790	L-SW-888
L-SW-794	L-SW-894
Termination	Termination

"Y" Arm Control Supports	
Y1 Support I.D.	Y2 Support I.D.
Termination	Termination
L-SE-506	L-SE-606
L-SE-512	L-SE-610
L-SE-518	L-SE-616
L-SE-524	L-SE-622
L-SE-530	L-SE-628
L-SE-536	L-SE-634
L-SE-542	L-SE-640
L-SE-548	L-SE-646
L-SE-554	L-SE-652
L-SE-560	L-SE-658
L-SE-566	L-SE-664
L-SE-572	L-SE-670
L-SE-578	L-SE-676
L-SE-584	L-SE-682
L-SE-590	L-SE-688
L-SE-594	L-SE-694
Termination	Termination

Table 5.0

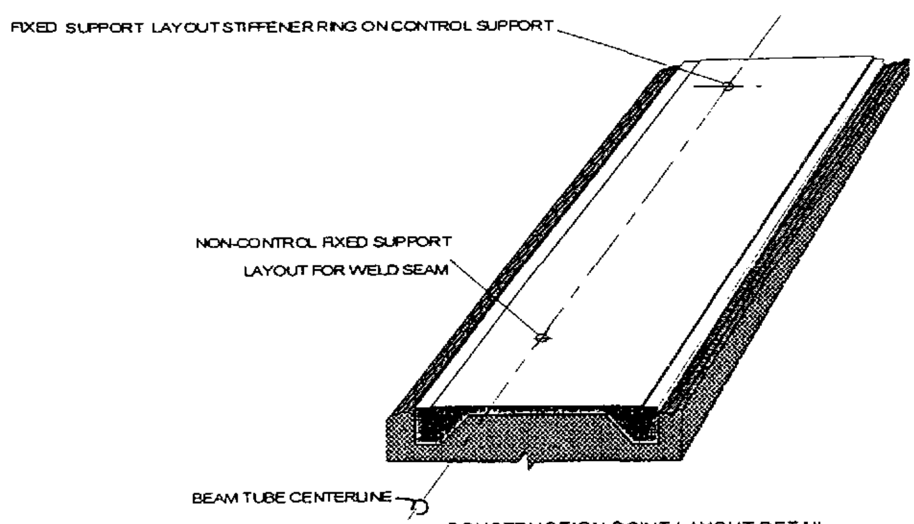
The layout is used to pre-align the control supports after the enclosure covers are installed. The remaining non-control supports are aligned using conventional laser and string line methods. Penetrations are then made at each control support and direct GPS measurements are taken from the beam tube support using the alignment fixture ALI-1(Figure 5.6b) and an antenna rod that extends above the concrete beam tube enclosure. The beam tube control supports are verified using the thru the cover GPS method and final adjustments are made as required to control supports. Re-adjust non-control supports as needed when adjacent control supports are moved. Details of this procedure are noted below:

5.1 GPS set-up and measurement of site *reference monuments*, the establishment *of a rectangular coordinate system*, the survey of the beam tube foundation slab as-built condition, and laying out of *construction points* shall be performed per the following steps:

1) Perform GPS pre-planning activities by first analyzing the satellite constellations, satellite elevations and PDOP quality. Assess the daily conditions and schedule layout activities. <u>Avoid periods which contain the following:</u>
   a. Satellite Constellations of less than five SVs(Space Vehicles)
   b. No SV's above 60 degree elevation
   c. PDOP conditions above 6.0
2) Set-up the base station receiver at the LIGO #105 reference monument and log in for satellite communication. Follow the GPS Equipment Manufacturers' guide for performing this activity. Use a minimum of 35 watts for radio transmissions[1] and in addition it is necessary to use a 35 watt booster trans/receiver located on the corner station for relaying correction signals to the Y arm. Locate and observe the site reference monument used as the base station. *Post-process* position data with precise satellite *ephemeris.* Compare the final positions with the published Caltech position. Resolve any monument movements before continuing. Use fixed length antenna rods and leveling fixtures capable of minimizing equipment error to sub-millimeter level.
3) Minimum *"time on point"* durations of 30 minutes shall be used when conditions meet those noted in 5.1(1). In areas of trees and near buildings, use additional 30 minute, 60 minute and multiple hour readings to compensate for the effects of multipath. All final data shall be post processed using L1 only and precise ephermris. All data should remain in the WGS-84 format when analyzing positions. For non-control layout positions, make one 30 minute "time on point" duration to establish horizontal positions for beam tube pre-alignment purposes.
4) Caltech has provided WGS-84 coordinates for the end and vertex points. These coordiantes are used to define the three dimensional coordinate system for the Livingston site. The Livingston LIGO facility defines the Western most arm as -X- and the southern most arm as -Y-. Elevation is defined as -Z-. All measurements to be performed and recorded using the metric system.

[1] . An FCC license is requried for this activity.

5) Layout is performed by using the Roving GPS antenna, antenna support, receiver and data collector mounted to a machine equipped with a plumb aligner bracket, fixed height antenna rod and a two axis cross slide used for positioning the antenna for layout. The construction reference points are located at or near each support location. The fixed control support layout is defined as the axial center of the support stiffener ring. Fixed non-control support layout is defined as the axial centerline of the weld seam nearest the support. Layout is not performed for the guided supports since these are dependent upon fixed support positioning. Each fixed support position is input into the data collector and a minimum 30 minute position shot identifies the point using the GPS suppliers locating software. The GPS RTK data is stored with the point identification and saved in the data collector. The static data is stored in the receiver. Examples of the layout of construction points are shown in **Figure 5.1a.**



CONSTRUCTION POINT LAYOUT DETAIL

FIGURE 5.1a

6) Use *temporary marking* for the construction layout. Points are identified with a scribe line on the concrete slab. A string line is pulled between each layout point and marked by painting as a rough layout line used to initially set and align the beam tube on the slab during installation.

7) At each control support location, a minimum three measurements with a 30 minute *"time on point"* is recorded. Assure the conditions meet those noted per 5.1(1). When differences of position data exceed the ± 5 millimeters range then additional measurements must be taken. In areas of trees and near buildings, use additional 30 minute, 60 minute and multiple hour readings to compensate for the effects of multipath. Log data in the GPS receiver for post processing. All final data shall be post processed using "L1 only" with precise ephermris. *All data should remain in the* WGS-84 format when analyzing positions. Determine the position of the layout using the average of three or more positions. This data will be used for pre-positioning the control supports prior to final alignment.

9) After each day of construction layout activity, down-load the RTK measurement data from the data collector to a floppy disk and/or PC hard drive.

5.2 Deleted. See Installseq for details

5.3 Deleted. See Installseq for details.

5.4 Deleted. See Installseq for details.

5.5 Interim Alignment and Inspection of Beam Tube Support Positions shall be performed after the installation of the beam tube support and the beam tube enclosure cover is installed.

5.5.1 Calculate Position Data for Each "Control Support" under the beam tube enclosure by the following steps:

Conventional measurement techniques will be used to measure the beam tube control supports in reference to the GPS layout points on the slab.

1) Measure and calcualte the intended a vertical distance from the beam tube centerline to the concrete slab.

$$h_x = H_x - (H_{gps} + \varnothing/2)$$

Where:

h_x - is the distance from the concrete slab to the bottom of the beam tube support stiffener.

H_x - is the Beam tube centerline described in WGS-84 coordinate height above the ellipsoid as defined by the CBI GPS calibration using Caltech provided heights at the beam tube arm brass monuments and using the MIT program for each beam tube axial position.

H_{gps} is the WGS-84 slab height above the ellipsoid as determined by the GPS slab layout procedure noted in the previous section.

$\varnothing/2$ - is one half the diameter of the beam tube support stiffener. This diameter is determined to be 57.000 ±.010 inches (1447.8 ±0.25 millimeters).

2) Measure the lateral off-set of the tube centerline from the GPS layout scribe point located on the concrete slab. Plumb line measurements from each side of the beam tube support stiffener ring are compared to determine the offset.

5.2.2 Interm Align Beam Tube Control Supports per the following(See **SUP-ADJUST** for Adjustment of Beam Tube Support Procedures):

<u>**Vertical Movement**</u>

1) Use a height gauge fixture to measure the elevation from the slab control support reference point to the support stiffener ring. Using the dimension determined in step 5.2.1 (1) adjust the beam tube stiffener ring to the correct elevation.

<u>**Lateral Movement**</u>

2) Based on the offset measurement of the control support per step 5.2.1 (2), adjust the beam tube support laterally to correct the offset.

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5.5.4 Align and Adjust Remaining Beam Tube Supports per the following:

DANGER

LASER RADIATION

AVOID DIRECT EYE EXPOSURE
LASER DIODE
5 MILLIWATT MAX OUTPUT
CLASS IIIa LASER PRODUCT

****NOTE****
THESE STEPS REQUIRE USE OF A CLASS IIIa LASER DIODE
See CBI Services Job Safety Analysis for Instruction
****

Vertical Movement

1) Install the fixed elevation fixture equipped with an alignment scope and 5 milliwatt laser (ALI-2) on the first control support. With laser directed toward termination support, assure the two fixture "pins" are in contact with the machined support stiffener ring and the fixture is level transverse to the tube. See Figure 5.5a

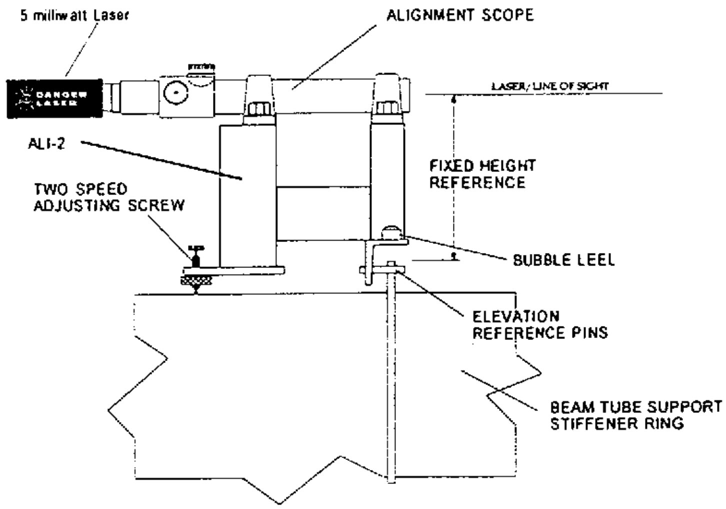


Figure 5.5a

Position the clamping target(ALI-3) with the target face adjusted to the fixed height reference of the laser line of sight on the termination machined support stiffener ring and assure the target pins are in contact with the stiffener. Level the clamping target with the bubble level mounted to the frame. See Figure 5.5b. Buck the alignment scope into the target center to establish a line of sight (or laser line, *red dot*) that is parallel with the beam tube centerline. Record the height above the stiffener of the laser/line of sight. Move the target to the first guided support ring(always use the ring nearest the vertex) and adjust the cross-hair slide to the laser/line of sight. Record the reading and calculate the difference from the height of the laser/line of sight and the reading.

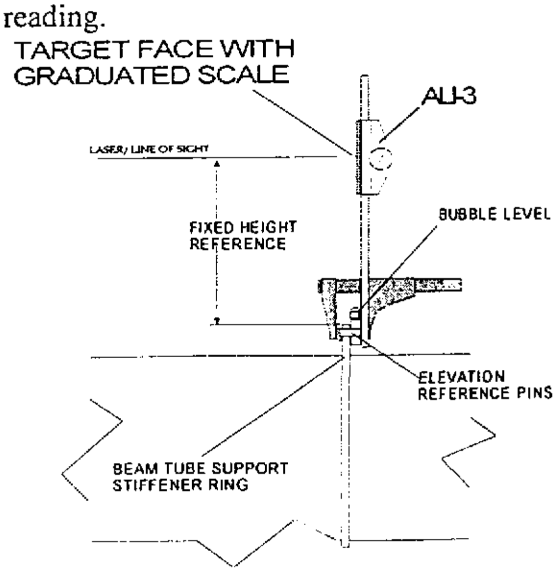


Figure 5.5b

2) Measure the elevation of the support stiffener ring from the slab surface. Record the elevation. Add the height gauge reading to the laser/line of sight difference. The sum is the height gauge reading required to align the beam tube centerline. Adjust the beam tube per the SUP-ADJUST procedure.

Lateral Movement

3) Lateral alignment of supports will be performed by measuring from the reference string lines to the beam tube support stiffener. Install a light weight line(60 to 80lb test Spider Wire® by Spectra is recommended) a distance of 0.460 meters from two ajoining control support stiffener rings. Tighten the stringline to a maximum 30 pounds force by using either a hung counter weight or a fishing reel with a drag rated at 30 lbs.(Penn 309M with HT-100 Drag is recommended). Based on these recommendations, catenary is calculated at 4.35 centimeters at the center point between the 120 meter overall distance of control supports. When field measuring support stiffener ring to string line, correct for catenary difference using the table below. Catenary corrections based on recommendation of 60 lb test line, 30 lb. pull and 0.46 meters distance at control support are listed in Table 5.5d.

CATENARY CORRECTION TABLE		
Location	Catenary (m)	Correction to 0.460 m
Control Support	0.0000 m	0.0000 m
Support 1	0.0048 m	0.0000 m
Support 2	0.0194 m	0.0004 m
Support 3	0.0435 m	0.0021 m
Support 4	0.0194 m	0.0004 m
Support 5	0.0048 m	0.0000 m
Control Support	0.0000 m	0.0000 m

Table 5.5d

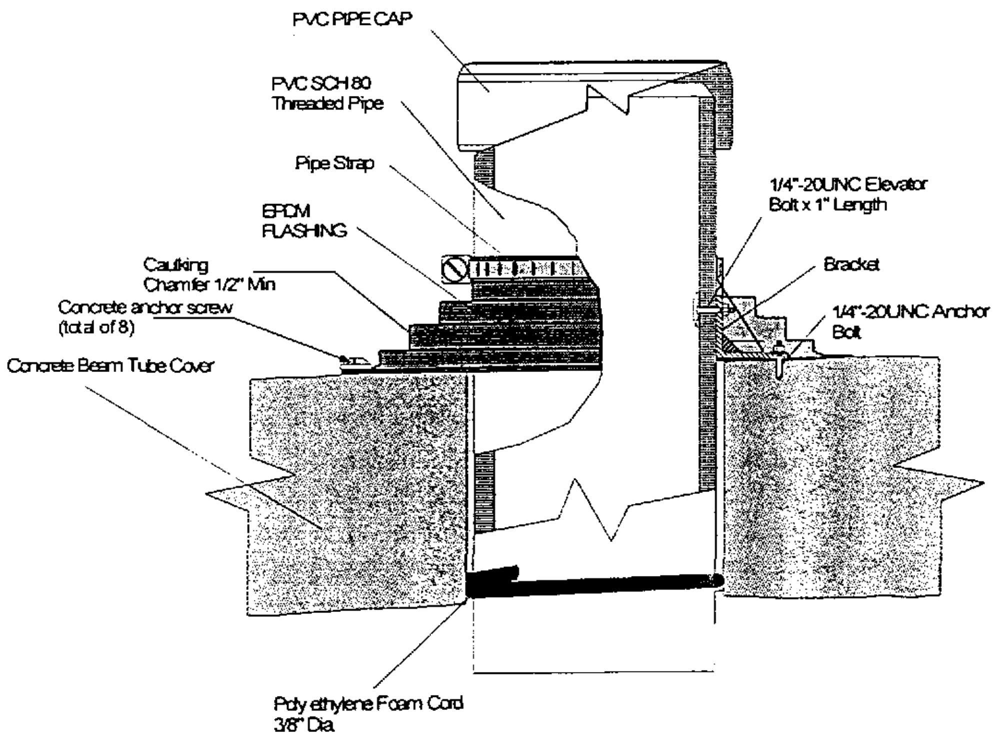
1) Measure the remaining supports from the machined support stiffener rings. For guided supports, always measure the ring assembly nearest the vertex. Determine the lateral position of the support stiffener and adjust as required based on the previous instructions.
2) After interim alignment of each support install a stainless steel tag with "Support Location Identification" as noted on the Data Record(Figure 4.3b) by wiring the tag to the support as noted:

    a. Fixed support I.D. tags are to be wired at the base of the outer vertical support tube.

    b. Guided support I.D. tag to be wired near the mid point of the upper horizontal support channel.

5.6 Final Inspection of Beam Tube Support Positions shall be performed after the GPS antenna access is completed.

5.6.1 Set-up for GPS alignment activities for "Control Supports" under the beam tube enclosure by the following steps:



Detail 5.6a

1) Layout control support inside the concrete beam tube cover above the ALI-1 fixture support stiffener off-set. The layout will always be to the right of the control support stiffener when entering the cover door from the road side. Core drill a seven inch penetration taking care to assure the beam tube is protected. Bolt a right angle bracket onto the six inch, Schedule 80 diameter PVC pipe nipple and anchor into the concrete cover Level and epoxy grout the pipe into the penetration and caulk around the pipe for purposes of filling any voids on the high side of the penetration. Install a sealing boot over the pipe and secure it to the outside beam tube concrete cover surface. Install a pipe cap over the top of the pipe. See Detail 5.6a.
2) Repeat step #1 for 64 control support locations.

5.6.2 Final Alignment Verification of Beam Tube Control Support Stiffener centerline positions is performed in the following steps:

1) Install ALI-1 fixture on control support stiffener ring and level. Punch reference point into ring using transfer punch and bushing. Verify punch mark using magnifying sight glass(figure 5.6c).
2) Install the ALI-4 support stiffener offset assembly to the beam tube where the stiffener is located under the beam tube cover penetration. Level the assembly using the dedicated leveling bar. See Detail 5.6a

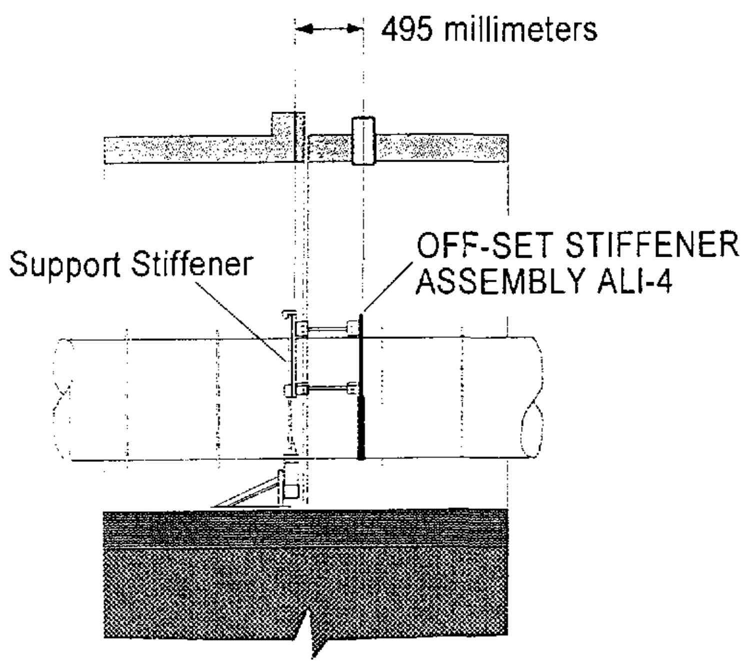


Figure 5.6a

3) Attach the Beam Tube Reference antenna fixture ALI-1 to the beam tube control support stiffener off-set assembly and level (Figure 5.6b).
4) Mount the GPS antenna to the fixture connection and fine adjust level.
5) Input antenna height data into the data collector and record location. This includes 1/2 of the beam tube support stiffener diameter, the antenna rod length and the antenna phase height measurement. Assure the data collector is set for "true height" mode.

IDENTIFICATION ALI-1			
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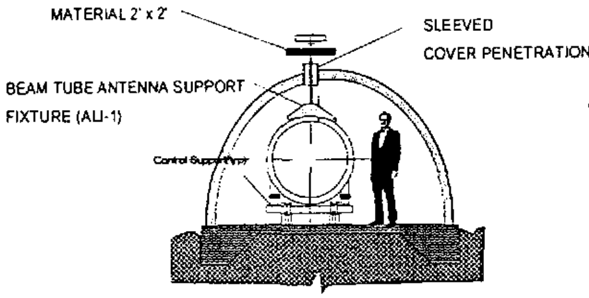
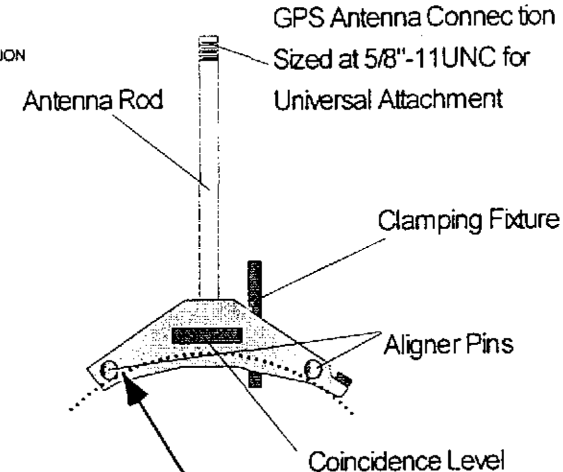
	MADE BY SDH	CHKD BY SWP	MADE BY SDH	CHKD BY DED
	DATE 12/28/93	DATE 12/29/93	DATE 07/01/98	DATE 07/01/98



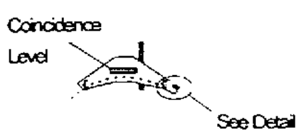
NOTES:

1) Alignment Fixture ALI-1 is attached to beam tube support stiffener using cam-type lock with handle grip for easier alignment.
2) Two pins are used for centering. Pins to be fabricated from Series 400 S.S. to limit any damage to the support stiffener.
3) Calibrate unit using level bar and vertical plumbing bracket. See Calibration sections for details.
4) Level fixture on beam tube support stiffener to 20 seconds of arc per 2 millimeters of movement.
5) All materials to be aluminum unless noted.

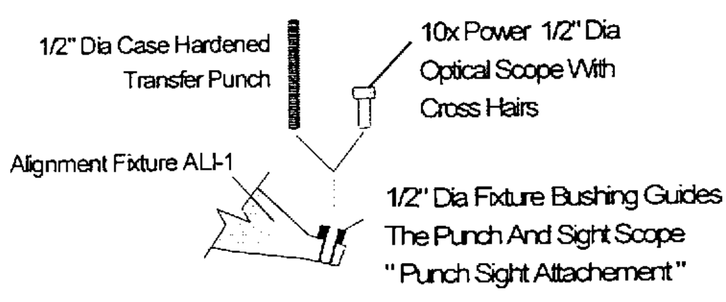


BEAM TUBE REFERENCE FIXTURE ALI-1

Figure 5.6b



BEAM TUBE REFERENCE FIXTURE ALI-1



NOTES:

1) Alignment Fixture ALI-1 is attached to beam tube support stiffener using cam-type lock with handle grip for easier alignment.
2) Two pins are used for centering. Pins to be fabricated from bronze to limit any damage to the support stiffener.
3) Calibrate unit using level bar and vertical plumbing bracket. See Calibration sections for details.
4) Level fixture on beam tube support stiffener to +/- 2 arcseconds.
5) All materials to be aluminum unless noted.

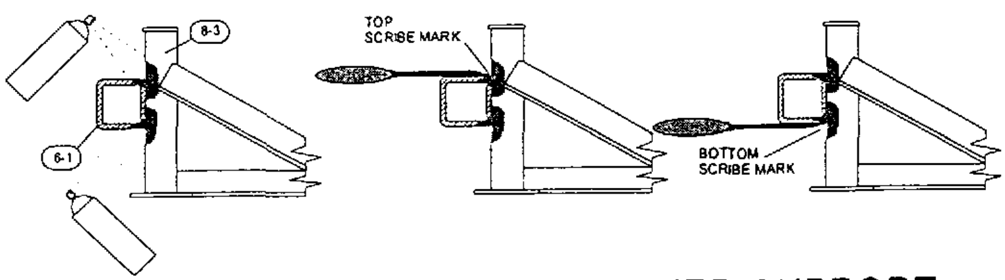
Figure 5.6c

6) Perform a minimum of three GPS observations for a minimum duration of 30 minutes each when conditions meet those in 5.1(1). Store RTK position into the data collector. Log static data in the GPS receiver for post processing. *Post-process* the data with precise *ephemeris* and analyze the results for signs of multipath and other forms of error. Determine the position of the support using the average of three or more positions. Use this data in conjunction with the theoretical data and offset measurements for final positioning the control support.
7) Review data for as-built position of control supports. Assure the above data average is within the +/- 5 millimeter range of beam tube set. If support position average exceeds +/- 5 millimeters, review the support position for available tolerance range and re-calculate positons as required to be within the total module position tolerance. Re-adjust any control support and the non-control supports immediately ajoining this support if needed to meet final alignment tolerance.

5.7 Paint Marking and Scribing Support Positions shall be performed after 5.6 is completed.

FIXED SUPPORT(typ) Match marking will be made on the "road side" areas of the fixed support assembly.

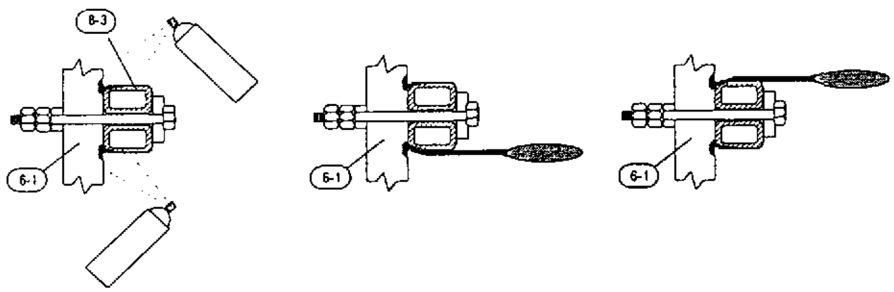
1) Clean areas to be painted using a brush or similar to remove dust, debris spider webs, etc. Paint areas to be match marked using fast drying Red Insulating Varnish with dielectric strength 2 or equal.
2) After paint is dry to the touch, align a marking tool along the top of the horizontal support tube (pc. mk. 6-1) and scribe a permanent mark on the support lug assembly vertical tube (pc. mk. 8-3). Repeat the match marking by aligning the marking tool with the bottom surface of the support tube and scribe a permanent mark. See Figure 5.7a.



ELEVATION VIEW OF FIXED SUPPORT

Figure 5.7a

3) Repeat the match marking procedure using the outer side of the support lug assembly vertical tube (pc. mk. 8-3)'as the reference surface and scribe a permanent mark on the back contact surface of the horizontal support tube (pc. mk. 6-1). Repeat the match marking by aligning the marking tool with the inside surface of the support lug assembly vertical tube (pc. mk. 8-3). See Figure 5.7b.



PLAN VIEW OF FIXED SUPPORT
Figure 5.7b

4) Visually inspect the surfaces to assure the match marks are clear and visible.

GUIDED SUPPORT(typ) Match marking will be made on the "road side" support assembly with the exception of the top vertical cable attachment. All four cable connection points will be paint marked.

5) Clean areas to be painted using a brush or similar to remove dust, debris spider webs, etc.
6) Paint areas to be match marked using fast drying Red Insulating Varnish with dielectric strength 2 or equal.
7) Match mark by spray painting the foot print of the guided support base plates (pc.mk.19-8) onto the beam tube slab. Assure coverage all around the plate. See figure 5.7c.
8) Match mark by spray painting the vertical adjustment cables at the bottom of the grommet insulator (pc.mk. 19-18). Take care when aiming the paint stream to provide a clean point of reference.

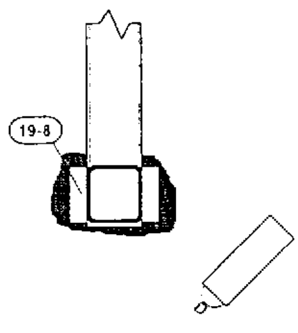


Figure 5.7c

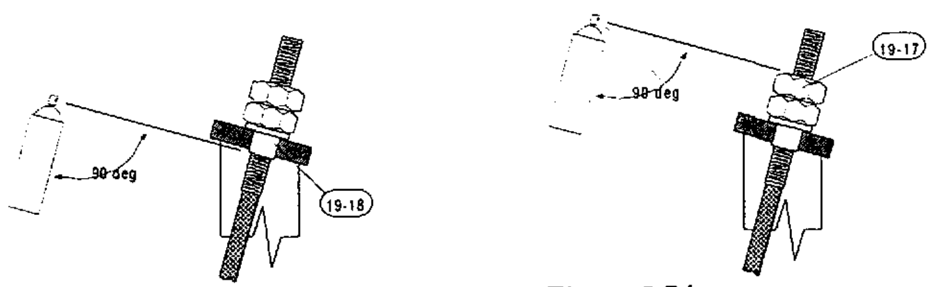


Figure 5.7d

9) Match mark by spray painting the vertical adjustment cables above the jam nuts (pc.mk. 19-17). Take care when aiming the paint stream to assure a clean match mark at the top of the nut to provide a clean point of paint. See Figure 5.7d.

6.1 GPS Quality Control

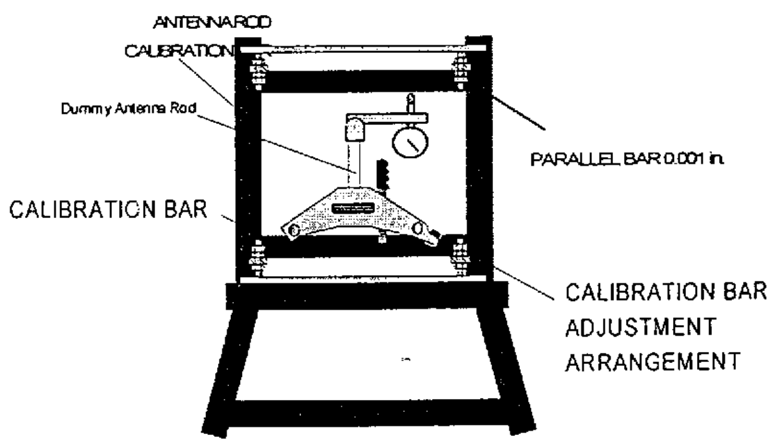
1) Quality control for GPS activities is maintained through a number of checks. The first is performed by *post-processing* data accumulated during alignment activities. For consistancy, additional accuracy confidence is achieved by re-calculating the real time position data and comparing later obtained precise satellite *ephemeris*(actual satellite position and clock corrections). The recalculated positions provide a check for the last adjusted beam tube position and either verify the accuracy confidence level or show the need for additional observations. The consistancy of data should be gauged by the following criteria: a) review each satellite position residual plot provided by the Trimble GPSurvey Software; b) check for maximum amplitude and if the standard deviation exceeds 15 millimeters, remove the satellite from the solution; c) if the graph tends to have a specific slope, than multipath error is suspected and the satellite should be removed from the solution; d) review the reference variance of the solution is greater that 10.000, than review the PDOP, HDOP and VDOP conditions during the shot for values over a total of 6.0. If the VDOP exceeds 3.0 during the

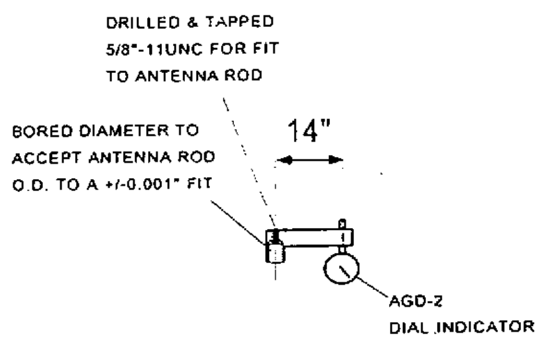
shot, discard the data and re-take the GPS measurement. Also, if the combined elevations of the GPS shots exceed the ± 5 millimeters, review the "GPSurvey"™ software program "Quick Plan"™ and print out a satellite constallation arrangement known as "skyplot." Review the sky plot and if no satellites are above the 60 degree horizon discard the solution data.

6.2 Reporting of Beam Tube Support Positions

Positions will be computed and final support locations will be provided to Caltech in both Cartesian coordinates and WGS-84 latitude, longitude and height formats.

6.3 **Calibration of ALI-1** shall be performed to meet a total +/- 0.003 inch total indicator readout(TIR). Perform the calibration in the following sequence:





ANTENNA ROD CALIBRATION BAR

CALIBRATION STAND WITH HORIZONTAL BAR

Figure 6.1

1. Level the Calibration Bar. The bar shall be flat and straight to +/- .001 inches (Figure 6.1).
2. Install the ALI-1 fixture and adjust its coincidence level to dead level (20 arcseconds/2millimeters).
3. Rotate the ALI-1 fixture 180 degrees and adjust error by one half. Continue adjusting until level is within one-half line of coincidence bubble.
4. Adjust top parallel bar to the calibration bar by use of a stick micrometer to within +/- 0.001 inch.

5. Install the dummy antenna rod bar and attach the dial indicator armature. Zero the indicator on the top parallel bar. Sweep the antenna rod 180° and take a reading on the parallel bar. Remove error by adjusting antenna rod pillow block plate. After leveling, tighten the blocks and re-check.
6. Recheck all levels and record calibration on the "GPS EQUIPMENT INVENTORY/CALIBRATION LOG"(Figure 4.3c).

6.4 **Calibration of GPS Antenna Rods** shall be performed in the following manner:

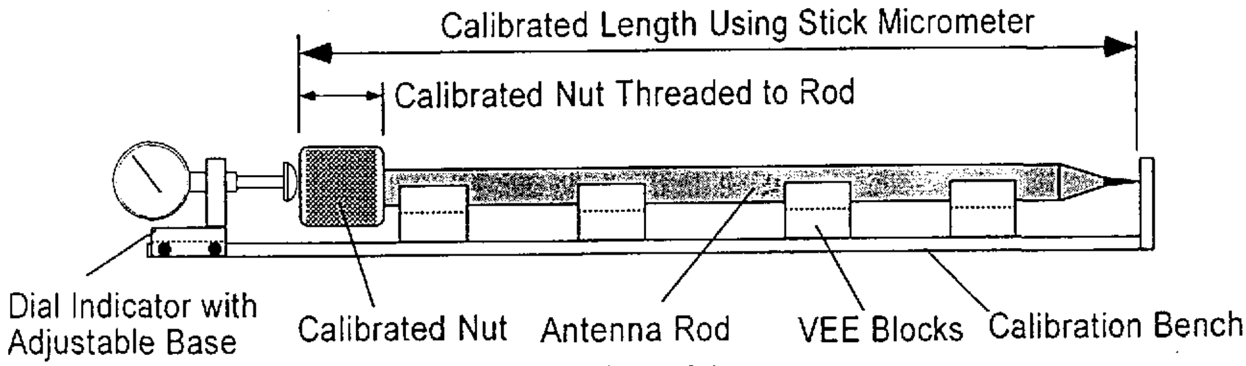


Figure 6.4

ROD LENGTH

1. Set up the calibration bench. Space VEE blocks as needed to support rod. Use a stick micrometer to set dial indicator to zero at an even length See Figure 6.4.
2. Install the calibrated nut on the 5/8"-11unc antenna connection. Set the rod in the vee blocks and make contact to the end stop. using the dial indicator, determine the length of the rod and subtract the thickness of the calibrated nut. Record this length and date of calibration on a tag and attach it to the rod.
3. Document length on the "GPS EQUIPMENT INVENTORY/CALIBRATION LOG" (Figure 4.3c).

ANTENNA SQUARE TO ROD

1. Set up the calibration stand with vee blocks, end stop.
2. Attach GPS antenna to the rod and set into the vee blocks with the rod end in contact with the end stop.
3. Set-up dial indicator on the ground plane plate or the choke ring base and rotate rod/antenna. Record the total indicator readout.
4. Document reading on the "GPS EQUIPMENT INVENTORY/CALIBRATION LOG"(Figure 4.3c).

Acronyms and Terms Used for This Procedure*

ALI-1 Fixture - GPS antenna fixture and centering jig designed to support the GPS antenna vertically above the centerline of the beam tube.

ALI-1 Procedure - Procedure to be used for alignment of Beam Tube Support Stiffeners.

ALM-B Procedure - Procedure to be used for installation and measurement of reference points.

Accuracy - The degree of conformance between the estimated or measured position. Radionavigation system accuracy is usually presented as a statistical measure of system error and for the LIGO Project is specified as "repeatable" or the accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same system.

Adjustable Support - Structural steel support system that secures to the beam tube foundation slab and connects to the support stiffener. An adjustable connection for lateral and elevation is provided for beam tube alignment.

Adjustment Bolts - "U" bolts used to secure the beam tube support components.

Antenna - Refers to GPS Receiving antenna. The GPS coordinates are referenced at the crystal point located inside the antenna cover. Manufacture specifications describe the phase center of the antenna and this information is included into the observation set-up along with the antenna rod distance included with the alignment fixture ALI-1 or the reference point stand.

Atmospheric Error - Effects of the ionosphere and troposphere on GPS satellite signals received on the surface of the earth. Ionospheric effects will be limited due to the short base lines and tropospheric effects will be a major source of error for the LIGO Project.

Base Line - The distance from the base station GPS receiver to the roving GPS receiver.

Base Station - Consist of a GPS system(receiver, antenna, radio transmitter) set on an known position. The LIGO Project will use the site reference monuments for known position determination.

Beam Tube Arm - The portion of the LIGO beam tube which extend from the vertex to the end station.

Beam Tube Final Alignment - The process of final adjusting the beam tube supports.

Calibration Menu - Feature of the GPS manufacturer software allowing the identification of rectangular coordinate systems using input positions of site reference monuments.

Caltech - Caltech. NSF. MIT, R.M.Parsons, or any other project contractor.

CBI - Chicago Bridge & Iron, CBI Technical Services, Inc. or CBI Services. Inc.

CBI Field Technician - CBI Employee or consultant trained and qualified in using GPS equipment.

Centering Jig - A feature incorporated in the ALI-1 antenna fixture for checking rotation of the beam tube after the final support is installed.

Choker Antenna - Antenna designed for limiting effects of multipath error. See Ground Plane.

Clear Aperture - LIGO Requirement for clear area inside the beam tube for which alignment tolerance stack-up is derived.

Construction Points - Points to be located by CBI for construction purposes.

Data Collector - Hand held computer capable of running and storing data using GPS software and receiving input from the receiver output.

Dial Indicators - American Gauge Design Type II linear dial type indicator calibrated to ±0,025 mm and mounted on movable magnetic base used for measuring displacement using maximum material condition direction.

Dual Frequency - GPS satellites broadcast in two frequencies(L1 at 1575.42 MHz and L2 at 1227.6mhz). High accuracy is dependent on reception and use of both frequencies.

Enclosure Cover - The concrete, parabolic beam tube cover fabricated by others and placed after final alignment activities.

End Points - Points laid out on the beam tube foundation slab corresponding to the end of each beam tube installed in order to maintain control of thermal and dimensional anomalies.

Ephemeris/ephemerides - Corrected satellite data including position data, clock drift, etc that are available from the NOAA via computer modem and used for post-processing position data.

Flatness - A condition of a surface where all of the elements are in one plane. In the case of LIGO, this is a feature of the beam tube foundation in local areas.

Frequency - See Dual Frequency.

GPS - Global Positioning System, a constellation of twenty four satellites broadcasting multiple frequencies coded for position fixing, velocity and time.

Ground Plane Antenna - Antenna developed for maximum accuracy by providing a plate designed to block reflected(multipath) satellite signals.

Installation Shelter Tracks - Points laid out on the beam tube foundation slab for the purpose of installing the rail system the clean room, weld shelter and test shelter will travel.

Jacking Cylinders - Hydraulic jacking system used for adjustments to the beam tube support during alignment activities.

Jacking Stand - A temporary support used to align the beam tube for fit-up and welding and support the beam tube until the final support is installed and aligned.

Kinematic Surveying Technique - This method is based on two receivers where it is considered possible to resolve phase ambiguities at the start of the survey. The LIGO Project will use this technique to initialize the rover to the base station before each period of observation. A radio link is provided to maintain continuos tracking between the receivers during activities.

Laser Leveling Transit - Laser mounted jig transit with leveling capabilities.

Light Weight Optical Stand - Stand suited for the positioning and support of a plumbing bracket and antenna rod for use in measuring the reference point positions.

Marked - The process of punch marking the outside of the beam tube support stiffener using the centering feature of the ALI-1 fixture.

Multi-Channel - Receivers that are capable of monitoring more than one satellite. The LIGO Project will require a minimum of a nine channel receiver for both rover and base station.

Nails - Concrete or surveyor's nails used to identify Reference Points for the Caltech alignment alternative.

NOAA - National Oceanic and Stmospheric Administration

Optical Tooling - Optical alignment instruments using split coincidence levels with a precision of 2 arc-seconds and equipped with optical micrometers.

PDOP - Position of Dilution of Precision is a ratio of the user-referenced three-dimensional position error, to the measurement error of a multilateration system(satellite constellation geometry).

Multipath - Error induced to GPS reception due to the effects of satellite signals reflecting from surfaces such as buildings, ground coverings, trees, etc. Usually effects readings as noise and can be reduced based on time of day observations.

Paint Marking - Process of using spray paint as a means of identifying movement of components.

Post-Processing - The activity of processing GPS data observed previously and re-calculated with actual satellite ephemerides. This process improves confidence in accuracy of real time measurements.

Power Cable Stands - Supports required to keep construction power cable a minimum distance from the ground surface.

Radio Link - The method of broadcasting correction and phase data from the base station to the rover. In the case of the LIGO Project, a 1 watt transmitter and booster station will be used.

Receiver - GPS receiver connected to the antenna that correlates satellite signals with its internal clock and determines position. Also computes corrections for *input/output*.

Rover - Consist of a GPS system(receiver, antenna, radio receiver) set on the point to be measured or adjusted.

Real Time - The time required to receive and compute GPS positional data and provide a rectangular coordinate valve in three dimensions. For RTK readings, this usually means 15 seconds or less.

Rectangular Coordinate System - For the LIGO Project, the system is identified as the following for each site: 1) Hanford; NW Arm is -x-, SW Arm is -y-, Up is -z-, Beam Tube Centerline at Vertex is point 0,0,0; 2) Livingston; SW Arm is -x-, SE Arm is -y-, Up is -z-, Beam Tube Centerline at Vertex is Point 0,0,0.

Reference Monuments, LIGO Site reference monuments, Site monuments or monuments are fixed monuments provided by Caltech and used as permanent points to identify each LIGO rectangular coordinate system.

Reference Points - Points that are located on each side of the beam tube enclosure cover and marked with "nails." These points are to be in-line with each adjustable support and measured using the highest degree of accuracy for future alignment monitoring.

Residuals - Differences in satellite to satellite position solutions.

RTK - Real Time Kenimatic method of differential GPS. See Kinematic Surveying Technique.

Slab - Refers to the LIGO Project beam tube concrete foundation used to support the beam tube, supports and concrete enclosure covers.

State-Plane - Hanford Site: State Plane Horizontal Datum: Washington State; Plane Lambert South Zone NAD 83/91. Project Vertical Datum NAVD 88. Livingston N/A at this time.

Static - GPS technique used for long time on point measurements.

Straightness - A condition where an element of a surface or an axis is in a straight line. In the case of LIGO, this a feature of the beam tube foundation slab over the length of each arm.

Support Locations - Points laid out on the beam tube foundation slab corresponding to the location of beam tube supports.

Support Stiffener - Beam Tube stiffener ring designed for support and sized to create a tight round fit to the tube. The outside of the stiffener is machine concentric to the inside diameter to provide a reference surface used for positioning the alignment fixture ALI-1

Time on Point - The duration in time when the GPS antenna is positioned on the measured location and actual data accumulation is in process.

Total Station - Optical alignment theodolites equipped with infrared or laser ranging systems and computer enhancements for -x-y-z- three dimensional measuring systems.