DISTRIBUTION:

W. Althouse	G. Stapfer
M. Coles	R. Vogt
D. Coyne	R. Weiss
L. Jones	S. Whitcomb
A. Lazzarini	J. Worden
F. Raab	Chronological File
D. Shoemaker	Document Control Center -2
R. Spero	

Ref: LIGO-E960010-01-E

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

Technical Note	LIGO-E960010-01 -	E	03/12/96

LIGO Sites Alignment Requirements

Author(s)

A. Lazzarini

Distribution of this draft:

LIGO Science Group

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

Concurrence Signatures

Facilities Group:		Date:	4/1/96
Detector Group:		Date:	3/29/96
Systems Engineer:		Date:	25.3.96
Integration Scientist:		Date:	3/28/96
Project Manager:		Date:	25.3.96
Principal Investigator:		Date:	4/2/96

CHANGE RECORD

REVISION	AUTHORITY	PAGES AFFECTED	ITEM(S) AFFECTED

1 SCOPE

1.1. Identification

This LIGO Sites Alignment Requirements Document defines the top level requirements for establishing a grid of surveyed and calibrated benchmarks and monuments at the LIGO sites to permit installation and alignment of vacuum equipment, beam tubes, and detector components.

1.2. Purpose

LIGO Project involves two large scale (4km arms) interferometer sites located in Hanford, WA and Livingston, LA. The instruments are housed in a large vacuum system. The components of the vacuum system include the Beam Tube Modules (totaling 4 km of 1.2m diameter pipe along each arm) and the Vacuum Equipment chambers which are located at the termini of the beam tubes and at the 2km midpoints along each of the arms. This document describes the requirements for alignment of these systems to meet the LIGO scientific mission goals.

2 NOMENCLATURE AND ACRONYMS

Acronym	*Meaning*
Arm Centerline	The best fit line through the surveyed set of points. This line represents the locus in space to which the BT centerlines, the VE chamber port center, and VE vacuum manifold centerlines shall be aligned.
BT Centerline	The locus of the centers of the BT clear aperture at all points along the 4 km arms
BT	Beam Tube System
Caltech	California Institute of Technology
IFO	Interferometer
LIGO	Laser Interferometer Gravitational Wave Observatory
MIT	Massachusetts Institute of Technology
TBD	To be determined (for as yet unspecified quantities) appendix -LIGO/-VE/-CC denotes party responsible for providing data.
TBR	To be resolved/reviewed; used when a provisional data value is possibly uncertain
TIE	Total Integrated Error (over all spatial frequencies). The peak-to-peak error.
VE	Vacuum Equipment System

3 APPLICABLE DOCUMENTS

Information and requirements appearing in this note are derived from previously released LIGO technical and scientific documents. The relevant documents are listed in Table 3-1. The requirements represented here form the basis of various other LIGO documents.

Table 3-1: Documents relevant to LIGO Alignment Requirements

DOCUMENT TITLE	ID NUMBER
LIGO Science Requirements Document	LIGO-E950018
LIGO System Requirements Document (SysRD)	LIGO-E950084
Beam Tube - Civil Construction Interface Control Document	LIGO-E950089
Vacuum Equipment - Civil Construction Interface Control Document	LIGO-E950088
Beam Tube - Vacuum Equipment Interface Control Document	LIGO-E950092

4 REQUIREMENTS

4.1. Background

4.1.1. General

Before facilities construction begins, each LIGO site will have two graded berms which (in plan view) are in the shape of an "L" having 4 km long arms oriented at right angles to one another. At Hanford, these arms are oriented approximately NW and SW. At Livingston, the arms are oriented approximately SW and SE. The berm surfaces will have been graded to lie along two perpendicular intersecting lines. These perpendicular lines intersect at a vertex and define a plane which is approximately tangent to the earth's surface. The point of tangency depends on details of local topography, but for both sites the deviation (two-axis) between the normal to this plane and the local (plumb) vertical at the vertex is less than approximately 0.04° [7×10^{-4} radians].

When construction of the facilities begins, each arm will be paved with two concrete slabs approximately 15 cm (6") thick and 4.3 m (14') wide, and 2 km in length. The slabs shall be segmented by expansion joints. The surfaces of all long slabs shall be parallel to the top surface of the graded berm and to project to a common intersection at the vertex of the "L". The as-built surfaces of these slabs will define a plane relative to which the interferometer shall be parallel. The long slabs shall have surface flatness (end-to-end, over 4 km) of +/- 13 mm (+/- 1/2") total integrated error (TIE) over all spatial frequencies.

Thicker building and termination anchor foundations will be located [i] at the vertex or corner; [ii] at the arm midpoints (the 2 km points, between two slabs); and [iii] at the arm ends. The building and anchor slabs shall be graded level with respect to the local vertical at each of the building sites. The surface finish for these slabs is identical to the one for the long slabs.

The Beam Tube Modules and Vacuum Equipment chambers will be installed on these slabs and they will be aligned by the contractors fabricating the hardware. LIGO is responsible for providing to the contractors a set of benchmarks along the two arms which will allow them to install and align the hardware.

4.1.2. Coordinate System

The common coordinate system to be used in global dimensioning for interfaces is a Cartesian system with its origin located at the corner station vertex (intersection of the projected beam tube centerlines) and with its:

- x-axis aligned along the northwest beam tube centerline in Hanford, WA and along the southwest beam tube centerline in Livingston, LA and
- y-axis aligned along the southwest beam tube centerline in Hanford, WA and along the southeast beam tube centerline in Livingston, LA
- z-axis aligned upwards along the normal to the x-y plane.

The local coordinate systems at the five stations in Hanford (corner, two mids, and two ends) and three stations in Livingston (corner and two ends) have their z-axes aligned to the local vertical, with the x- and y-axes defined by the projection of the beam tube centerlines onto the local horizontal plane. This coordinate system is described in LIGO-L950128, L950210B, T950004.

4.2. LIGO Alignment

Several hierarchical alignment and surveying requirements exist. These are discussed below.

4.2.1. Knowledge of site-to-site baseline

LIGO shall provide a means to determine the baseline distance (straight line, chord through the earth) between sites to an accuracy consistent with a time-of-arrival accuracy $\delta\tau \le 1\ \mu\text{sec}$. Knowledge of the site-to-site baseline to better than $c \cdot \delta\tau = 300$ m is required.

4.2.2. Determination of the Arm Centerlines

LIGO shall provide a means by which centerlines can be located at five (5) positions along each of the two arms. One of these points, the vertex, shall be common to both arms. The nine (9) points thus located shall meet the following alignment accuracies and precision :

[1] The five positions along each arm at which the centerline must be determined are at distances {0.000 m, P1 m, P2 m, P3 m, P4 m} from the common vertex. The dimensions P1...P4 are shown in LIGO-D950021-B-E and correspond to interfaces between the Beam Tube and Vacuum Equipment Systems. Note that these dimensions are different for the WA and LA sites. These distances have allowed TIE errors in the axial direction (one-axis, i.e., along the centerline) of $\pm$ 13 mm [0.5"].

[2] A best fit line (in a least squares sense, and to be determined by the independent surveying contractor) is defined by the set of five (5) cardinal points lying along an arm.

A right circular cylinder centered on this line and having a diameter of 1 cm [0.4"] shall contain all points within that set. This holds for each arm separately.

[3] The minimum distance at the vertex between the two best fit lines in [2] shall be less than 1 cm [0.4"].

[4] These two best fit lines shall be parallel to their respective slabs to within the tolerances defined in section 4.2.3.3. These two lines shall be denoted as arm centerlines.

[5] The two arm centerlines shall define the interferometer plane. The elevation of the interferometer plane above the plane defined by the slab surfaces is nominally 1070 mm or 42.13". However, the as-finished slab surfaces shall be surveyed and these data shall be used to determine the actual interferometer plane elevation. This shall be done to maximize the adjustment headroom available in the Beam Tube support fixtures. Refer to Figures 4-1 and 4-2. The location of the arm centerline intersection shall be offset by 304.8 mm [12"] relative to the slab centerline as shown in Figure 4-3.

[6] Procedures shall be provided to allow these 9 points to be re-acquired at any later time by Others using surveying instruments. Also, the procedures shall outline the method to recreate the arm centerlines at all other points from the vertex to the 4 km ends of each arm by using these 9 points.

[7] In the interval between {0.000m, P1}, it shall be possible to determine any point on the centerline to within a TIE (two-axis) of 2 mm. Note that this space will eventually be within a building and this requirement applies even after the surface of the slab has been enclosed.

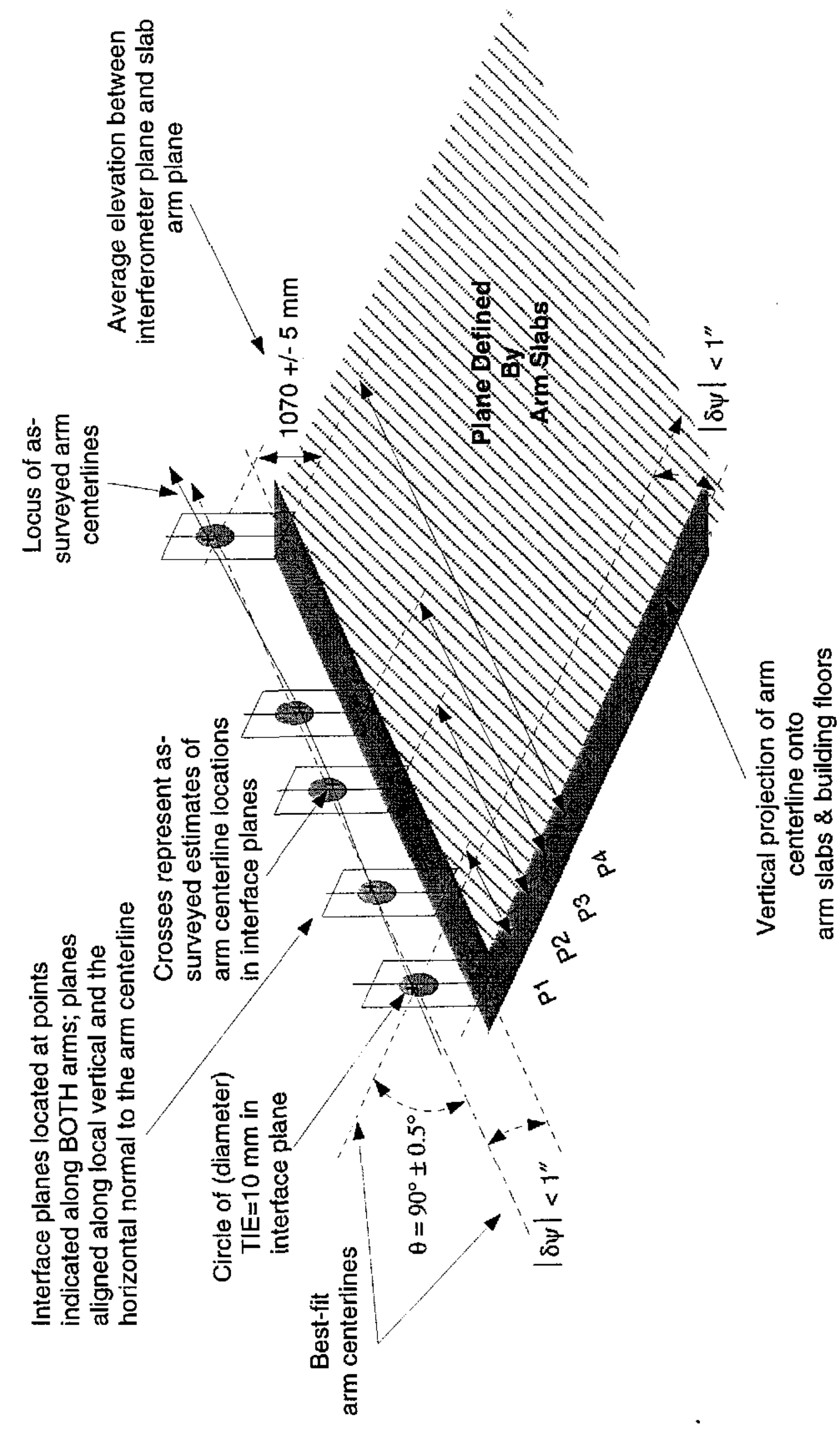
[8] In the interval between {P2,P3}, it shall be possible to determine any point on the centerline to within a TIE (two-axis) of 2 mm. Note that this space will eventually be within a building and this requirement applies even after the surface of the slab has been enclosed.

[9] In the interval between {P4, 4000.000 m}, it shall be possible to determine any point on the centerline to within a TIE (two-axis) of 2 mm. Note that this space will eventually be within a building and this requirement applies even after the surface of the slab has been enclosed.

[10] The means provided to determine the centerlines as described in [1] - [9] above shall be capable of being periodically recalibrated (if required). Such recalibration shall be sufficient to ensure the ability to maintain the error tolerances allocated above throughout the lifetime of the LIGO facilities (20 years).

These requirements are indicated schematically in Figures 4-1, 4-2, 4-3.

Figure 4-1: Schematic of the LIGO site alignment requirements--general overview



4.2.3. Angular Orientations

Three angular orientations characterize the two LIGO sites: the included angle between pairs of arms at one site; the orientation of the two sites relative to one another, referred, for example, to the great circle passing through the vertices; the orientation of the interferometer plane relative to the plane defined by the as-built arm slab surfaces.

The first two orientations affect sensitivity to gravitational radiation. Note that for either of these, sensitivity is only affected to second order in the deviation from the optimal alignment; an error $\varepsilon \cong 0.5°$ will decrease sensitivity by a factor $\cos\varepsilon \approx 1 - 4\times10^{-5} = 0.99996$

4.2.3.1 Orthogonality of the two arms at one site

The arms shall be orthogonal to within 0.5°. The angle between the arms shall be measured to at least 0.1°.

4.2.3.2 Angular orientation: WA-LA

The angular orientation of the arm pair at Hanford relative to the arm pair in Livingston affects coincident sensitivity to second order for small angular misalignments between the sites. The angular orientations of the WA NW arm ("X" arm) and the LA SE arm ("Y" arm) shall be determined relative to the great circle which passes through the vertices at the both sites. This orientation shall be measured to at least 0.5° for each site.

4.2.3.3 Orientation of the interferometer plane relative to the earth surface

The interferometer plane shall be parallel to the plane defined by the slabs along the berms to within $|\delta\psi| < 1''$. The arm centerline shall be located at the height discussed in 4.2.2, #5. The orientation of the interferometer plane relative to the slab shall be measured to an accuracy of $|\delta\psi| < 1''$ relative to the local vertical at the vertex, points P2, and P4 (refer to 4.2., #1) along both arms.