MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Laser Interferometer Gravitational Wave Observatory (LIGO) Project

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Refer to: LIGO-T990017-00-D
Date: 23 February, 1999

Subject: **Calibration of initial alignment survey by sighting through Y1 beam tube module**

Abstract

Alignment of three Initial Alignment Monuments (IAM) placed by surveyors to support core optics installation was checked against the Y1 beam tube module axis using viewports mounted on the tube endcaps. Depending on methodology and atmospheric conditions at the time of core optic installation, these monuments would have indicated an azimuthal direction in error by 3 to 7 arcseconds. While this by itself is within the total ±20 arcsec allowance for getting the beam through the tube initially, it uses up a large fraction of the error budget.

Motivation

The calibration of the IAM-6, -9 and -12 initial alignment reference monuments in the Hanford LVEA against the Y1 beam tube module's clear aperture used windows added to the tube endcaps prior to the tube's bakeout. The project, undertaken from 1/11 through 1/17/99, was motivated partly by discussions with Kevin Rausch of Rogers Surveying. Kevin felt the achievable accuracy of the surveyed IAM monuments he installed might fall short of our goal of threading the tube successfully by "dead reckoning." The project was made possible by the use of ported endcaps on the tube ends for this bake, which had been built in response to the problem of gate valve O-rings sticking to their seats after bakeout under compression. Note that for subsequent beamtube module bakes this problem is being resolved by reducing the seal pressure on the O-rings, so the ported end caps will not be installed unless required for some other reason. I think the discussion below may point to such a reason, namely QA and calibration the remaining initial alignment monuments at Hanford and Livingston.

Our primary initial alignment requirement is to preset the azimuth[1] (yaw) of an ITM or ETM to within 20 arcseconds or better. This gets its reflection of an axial ray back through the beam tube. The three to five surveying steps required for transferring angles from the IAS monuments to the hanging optic will each accumulate 2 to 4 arcseconds of instrumental and random error. We've thus allocated the "original" accuracy of the monuments to be on the same order, about 2" (10^{-5} radian). Kevin estimated that the number of intermediate relay steps (about 4) he needed to interpolate the IAM monuments from established global marks at the beam tube module ends might lead to horizontal errors two to five times larger than this. While not as serious as the thermal systematic errors associated with establishing altitude (pitch or level), he demonstrated that azi-

1. Altitude (pitch) is determined by a level.

muthal sightings are still affected by atmospheric refraction at this level. He did this by repeatedly acquiring the same outdoor target (IAM-12) “blind” and independently measuring the error in each acquisition against a second fixed target inside the building. Over four or five measurements taken during the course of an hour, he found the spread was approximately 1 mm per 50 m or about 4”. [1]

Assessment of systematic errors

While more direct, sighting through the beamtube aperture still has two nontrivial problems;

- How to compensate for deviation caused by the sighting viewport and the transition from air into vacuum
- How to transfer the sight direction to permanent fixtures or monuments which can be referred to later during COC installation (when, in general, the BT will be valved off).

Due to time constraints we provided the BT bakeout team with off-the-shelf Kovar-sealed ports with no special flatness or parallelism requirements (MDC model VP-800, Corning 7056 glass zero-length in an 8” OD ConFlat flange). Such windows are typically flat to a few waves per cm, but we did not have time to test them before installation so we didn’t know their flatness a priori.

The dominant systematic effect of this uncertainty is the prismatic wedge of the glass port over the aperture used by the theodolite. The line-of-sight deviation δ_w is just $(n-1)w$ where w is the wedge angle and n is the index of refraction. To achieve < 2” deviation the port surfaces would have to be parallel to < 4”, or about 1/3 wave per cm in optics terms. This is better than one might expect for this type of port, although not at all unrealistic for a “real” optical window. Should we get the opportunity to do this again on other beamtube modules we will look into getting some bakeable high-parallelism, flat optical windows (e.g., Insulator Seal VacOptics or equivalent). To compensate the effect with these windows, however, we removed the window and tested its deviation directly on a bench using a test flat and an autocollimator (see below).

A smaller effect is caused by deviation due to the wedge of air which is absent on the vacuum side, if the port surfaces are not set normal to the beam. If a wedge-free port is tilted by angle t, the deviation δ_t is $t(n_{air}-1) \sim 10^{-4}\, t$. Thus a tilt angle of order 6 degrees would be needed to generate a 2” error. Such an angle is unlikely, and would be easy to measure mechanically in any case.

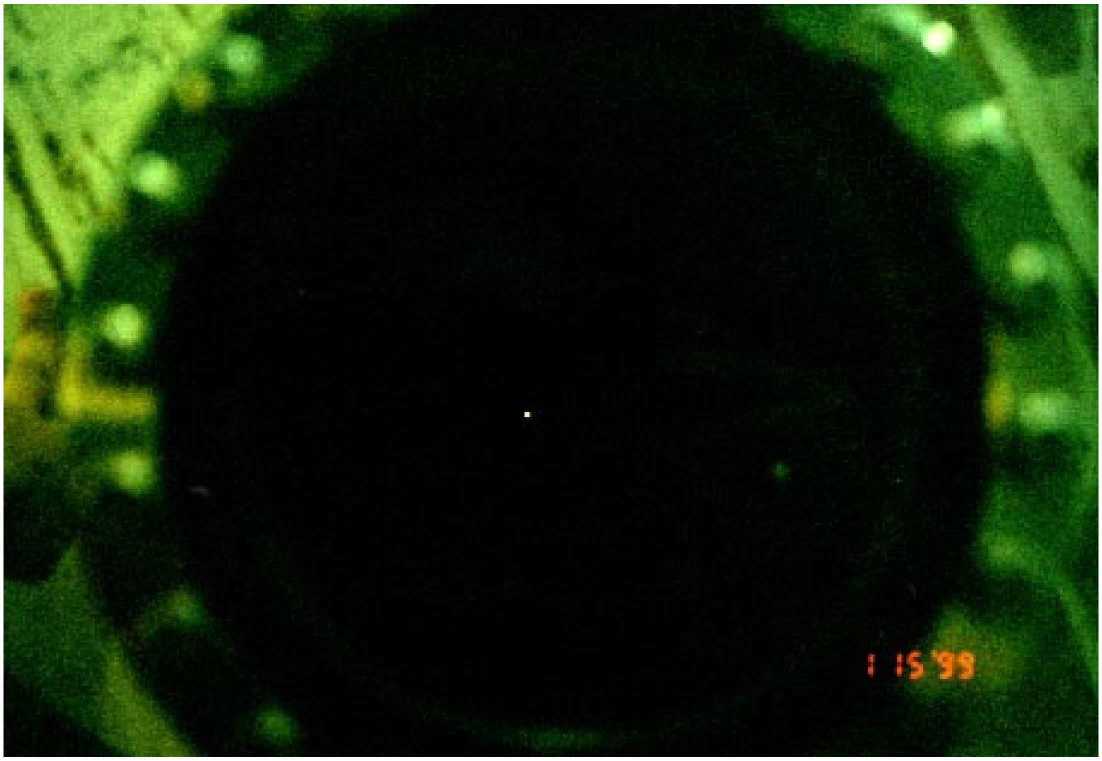
Method

I mounted a 70W Waldman halogen lamp (one of the ISC chamber illuminators) on the OD of the Y midstation viewport, using extra long set screws (the port is 8” OD and the illuminator is designed for a 10” OD flange). I powered it with 24VDC at about 2.6 A. This lamp was clearly visible as a point of light from the other end of the tube (Figure XX). At the corner station I assembled a Brunson 810 transit stand in the gap between the cryopump and the window using two short legs, which rested on the raised concrete beamtube termination slab, and one long leg,

1. Kevin Rausch, private communication.

which rested on a fiberglass-composite HAM SEI assembly platform placed under the cryopump nozzle. I placed the Sokkia Set IIB total station theodolite atop this stand and centered it on the viewport aperture to an accuracy of about 1/32 inch (Figure).

Figure 1: Photo through beam Y1 beam tube under vacuum with lamp at Y mid station



I leveled the Sokkia using its spirit level, and then fine-leveled it using its digital readout. Looking through the theodolite it was possible to just barely resolve the lamp as a disk, perhaps twice the width of the crosshair. With practice I could find the center of this disk with a repeatability of about 1” on the digital readout.

My initial intention was to mount the Newport LDS1000 laser autocollimator atop the Sokkia, boresight the two using an optical reference flat, and then use the LDS1000 to align our optical transit square. This did not work out; after considerable difficulty I determined that the LDS1000 mount had a tendency to drift after the boresighting step, rendering the final alignment useless[1]. An additional problem was that, with the theodolite at the beamtube centerline, the piggyback LDS1000’s beam was too high for the transit square to see through our IAM viewing port in the LVEA wall. (This is the only way to pick up IAM-12 from inside the building without additional translation steps.)

Instead I mounted the Sokkia visual autocollimator accessory to the theodolite eyepiece. With some training it was possible to repeat autocollimation to a fixed mirror within about 1”. There appeared to be a slight systematic angular movement of the retroreflected crosshair image associ-

1. The mount and procedure for using it have since been updated.

ated with focusing the theodolite, perhaps due to a decentered element, so I consistently left the focus alone after optimizing the image of the lamp 2 km away. This would in fact be the true “infinity” focus position if viewport distortions had no net power; in any case it had to be pretty close.

Figure 2: Theodolite mounted on tripod stand between cryopump and Y1 beam tube end cap viewport in Hanford LVEA. Operator is John Worden of LHO.

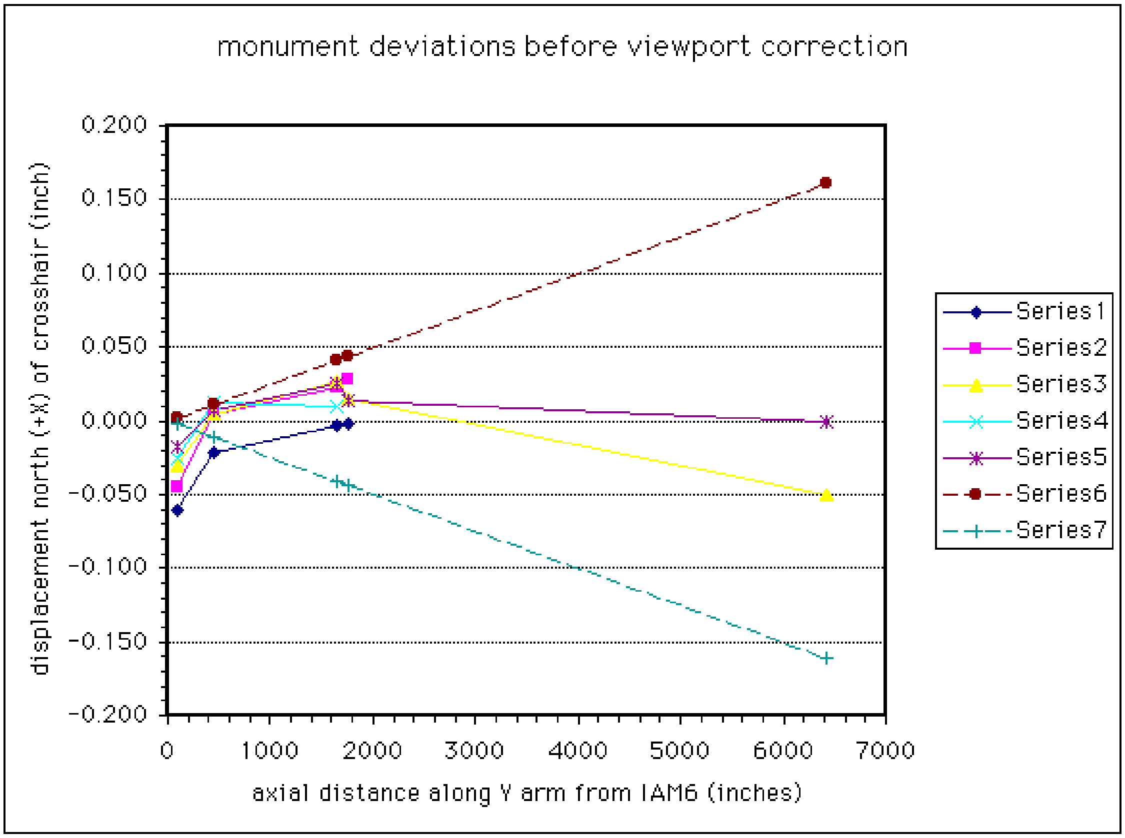
The Brunson 75H optical transit square (Figure 3)was set up on its cast iron transit stand and elevated to the same height as the theodolite. It was placed horizontally on line with the nominal 10’9” offset monument line common to IAM-6, IAM-9 and IAM-12. Unfortunately the axial Y position was constrained by the available space for the theodolite in the gap, and the transit fell directly over a caulked seam between the LVEA technical slab and the wall footing. As a result, instead of establishing a new monument directly below the transit I placed a mark on the wall just underneath the IAM viewing port (designated IAM-99) and another on the technical slab near the transit stand base (designated IAM-98). The transit square was leveled in all directions using its coincidence level.

Figure 3: Optical transit square set up in line with IAM-6, -9 and -12 for reading out monument offsets.

The parallel transfer of the corrected sight direction to the IAM reference monuments was done in essentially the reverse order of the steps used for installing a core optic. The theodolite was crosshair was aligned to the lamp image through Y1, and the horizontal scale was nulled to read 0°0'0" at this point. The theodolite was then rotated 90 degrees left to 270°0'0", where it found the transit square's side mirror. When the theodolite's autocollimator illuminator was turned on, the reflected image of the theodolite crosshairs then appeared superimposed on the direct crosshairs. The fine azimuth of the transit square was then iteratively adjusted to bring the crosshairs into coincidence, indicating perpendicularity of the transit mirror.

With the transit thus set parallel to the tube axis I then sighted scribe targets placed over IAM-6 and IAM-9. IAM-98 and IAM-99 were directly sighted. IAM-12 was sighted using the string of a plumb bob placed over the monument. I needed some assistance removing tumbleweeds to maintain a line of sight outdoors, and in two of the runs I was unable to pick up IAM-12 outside at all. Wind pushing the pendulum affected the IAM-12 readings, and the turbulence of air escaping through the open porthole made the image of the string fairly fuzzy, but it was possible to interpolate the center fairly repeatably by waiting several swing periods and splitting the fattened image of the string. I used the Brunson's optical micrometer to record the lateral offset of each scribe (in thousandths of an inch). I estimated my lateral position errors to be ±.015 in. for IAM-6 and IAM-9, ±.005 in. for IAM-98 and IAM-99 (right near the transit), and ±.050 in. for IAM-12. The raw monument offsets for the 5 runs are shown in Figure 4.

Figure 4: Monument deviations for 5 measurement series before viewport correction. Series 6 and 7 are fiducial ±25 μrad (± 5") trends for slope comparison. Translation of the transit between series has not been removed (i.e., zero is arbitrary for each series).



Compensating the viewport wedge

The deviation of the viewport was measured at a wavelength of 670 nm using the LDS1000 laser autocollimator and an optical flat. Before closing the gate valve to backfill and remove the port, I checked the angle of the viewport's surface normal by looking at my own reflection. Noting that the point of light from the distant lamp coincided within 1/8 in. with the center of my reflected pupil, held about 18 in. from the viewport, I estimated that the surface was normal to the tube axis within ±3.5 mrad (± 0.2°). As a result the "air wedge" component of the deviation was negligible for this setup (of order ± 0.35 μrad).

Before removing the port from the endcap I scribed the vertical orientation on the rim using a combination square. The port was then removed and placed on edge atop a Brunson 810 tripod stand. The optical flat was supported on a second Brunson 810 stand, and the autocollimator mount was clamped to a welded steel table (Figure 5). To avoid confusing the autocollimator with multiple surface reflections, I put it about two meters away from the port and arranged the port's ghost reflections well outside the autocollimator aperture (typically 60 to 80 mm below the objective lens). Because shifting my own weight on the LVEA floor appeared to cause flexural deviations of order an arcsecond, I sat on a stool nearby the port stand so I could remove and replace the port without shifting my weight

Figure 5: Setup for measuring the transmissive angular deviation of the viewport after removal from the beam tube endcap.

By nulling the test flat to the autocollimator through the port, and then removing the port and noting the change, I measured the deviation of the line of sight directly. The measured deviation was repeatable to about ±3 µrad, and was fairly robust under the following tests:

- Rotating the port around its surface normal by 90° produced the expected exchange of measured pitch and yaw deviations (the port was oriented to bring the ghost reflections to the same spot, 70 mm vertically below the autocollimator aperture, thus insuring the normal was fixed in lab space).
- Rotating the port by 180° about its surface normal inverted both horizontal and vertical deviations (again, the port was adjusted to keep the normal fixed in space).
- Flipping the port about a vertical axis inverted the measured horizontal deviation and left the vertical deviation unchanged, as expected.
- Moving the surface normal so that the ghost reflection returned 75 mm above, right or left of the autocollimator, rather than 75 mm below, had no appreciable effect.

Finally, to gauge the sensitivity of the measured deviation to lateral position errors of the theodolite view aperture within the port, I made two line scans of the deviation using the Brunson 810's horizontal slide (the "vertical" scan was made by rotating the port 90° as above). The results of this scan are shown in Figure 6 and Figure 7. There's no appreciable variation seen over the estimated ±1 mm error in centering autocollimator to the same aperture used by the theodolite. As expected the distortion grows as one nears the fused outer edges of the glass.
The true direction was thus concluded to be (17 ± 3) μrad [(3.5 ± 0.6)"] to the left of the apparent direction viewed through this port (designated Z29), as oriented on the beam tube. It's worth noting that the vertical deviation was on the same order, implying that this port's front and back surfaces were parallel to about one wave over the 30 mm sampled aperture.

Figure 6: Scan of *relative* angular beam deviation vs. horizontal translation of autocollimator beam across the viewport surface, with respect to the deviation at the center.

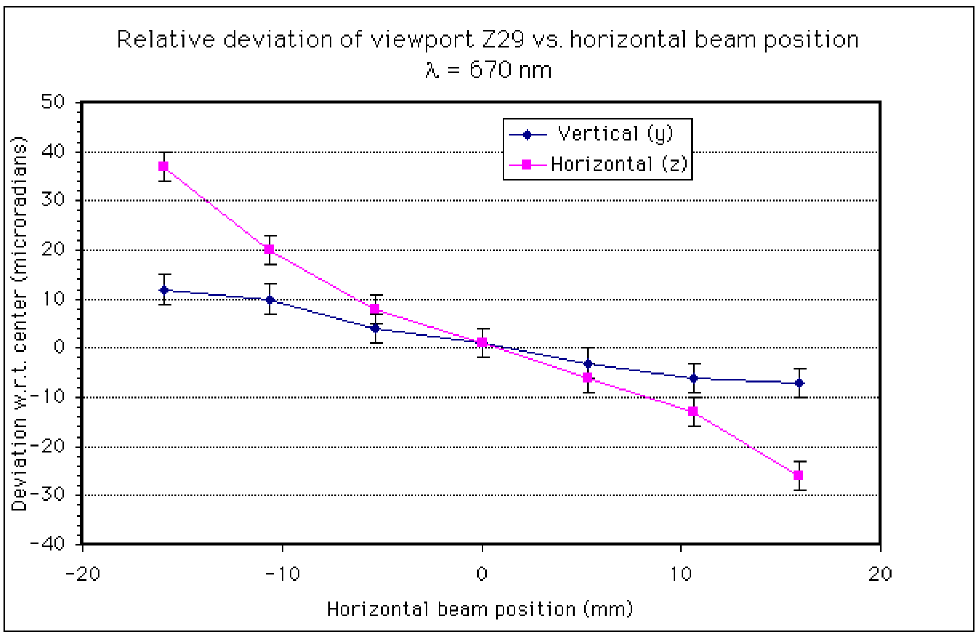


Figure 7: Scan of *relative* angular beam deviation vs. vertical translation of autocollimator beam across the viewport surface, with respect to the deviation at the center.

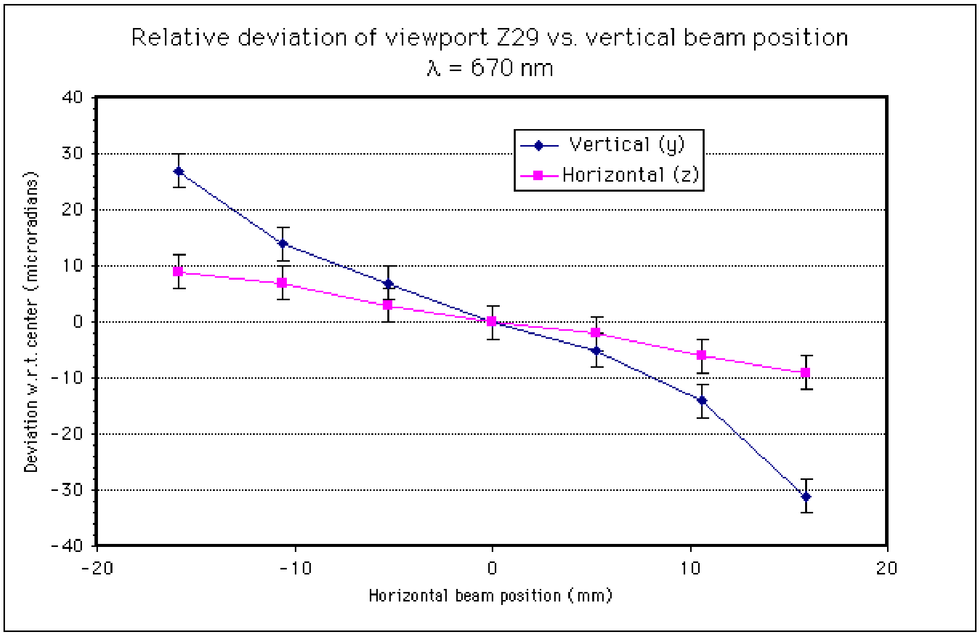
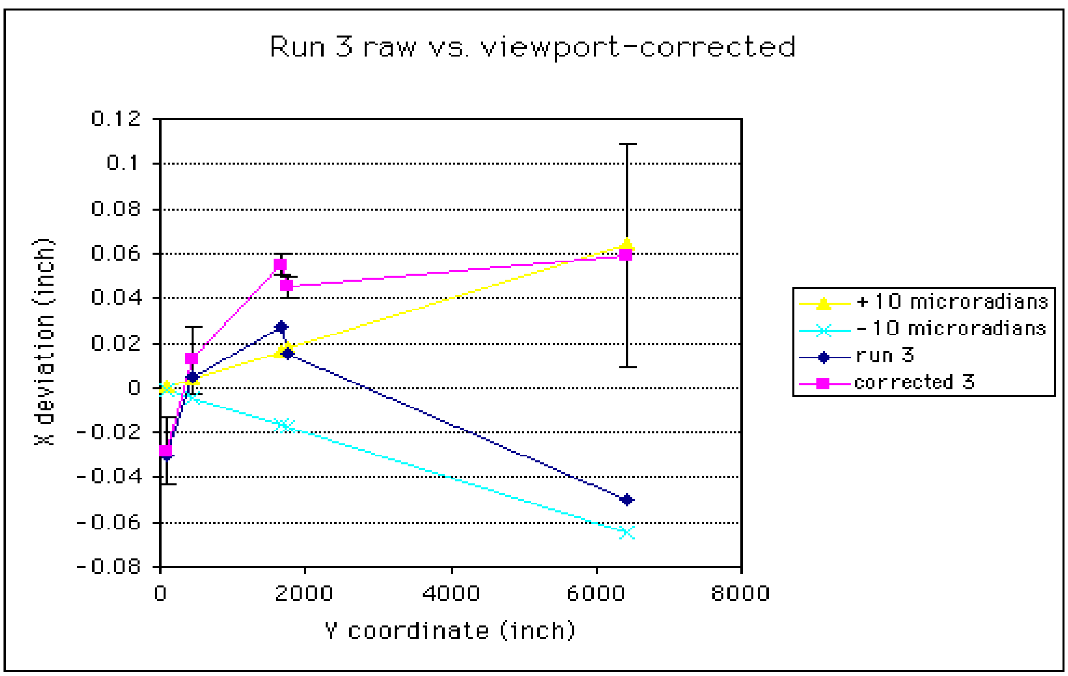


Figure 8: Sample of raw monument offsets vs. viewport corrected offsets (run #3). Fiducial ±10 μrad reference lines are shown for comparison. Errorbars represent estimated transit reading errors and do not include contributions from instrument calibration or imperfect compensation of the viewport wedge.



Average of corrected monument offsets and conclusion

The offsets computed for the 5 runs were corrected for viewport deviation and translated along the

X axis to a common X-origin centered at IAM-9 to allow averaging. The resulting averaged offsets are shown in Table 1.

Table 1: Corrected X offsets and resulting angular errors for IAM monuments along Y arm in LHO LVEA, relative to IAM-9 (near WBSC8). Angular deviation (right columns) is the angle from "true Y" to the two-point line of sight joining IAM-9 to the selected monument. (All linear dimensions in inches; for reference, IAM-9 is nominally at X= -128 in.).

Monument	Y (nom.)	ΔX	Deviation (μ rad)	Deviation (arc sec)
IAM-6	93	-0.043±0.010	-120±28	-25±6
IAM-9	450	NA	NA	NA
IAM-98	1,654	+0.036±0.020	-30±17	-6±3
IAM-99	1,762	+0.037±0.020	-28±15	-6±3
IAM-12	6,418	+0.077±0.100	-13±17	-3±3

Note that the choice of IAM-9 as the fiducial origin is motivated by convenience (many initial alignment setups for the 2k interferometer will start with the transit at or near IAM-9). Unfortunately this choice tends to exaggerate the apparent angular error associated with the abnormally large displacement error of IAM-6, which is very near IAM-9. On the other hand, it is worth noting that IAM-98 and IAM-99 were derived from IAM-6, 9 and 12 for the purpose of these tests and are not independent. Without a priori knowledge, we might (probably would) have chosen IAM-6 and IAM-12 as the "best" pair, since they are the farthest apart, in which case our best fit would deviate by closer to 4" and our "worst case" including sight errors might be as large as 7".

These results suggests several points;

- the original IAM monument placements for this instance can indeed be used to develop a line which lies within approxi.mately 3 to 4 arcseconds of parallelism to the beamtube axis (outside our budget allowance, but close to Rausch's estimate), providing the right monuments are used; however,
- the typical sighting error for the outdoor monument from positions within the building is likely to be on the same order unless improvements in the effects of turbulence, wind and target visibility are made
- it will be difficult to keep additive cumulative errors from the process of translating this reference to the suspended optic from exceeding the 20" total error budget for bringing the beam through the tube.

Since these results are only available for one of the 6 initial alignment references needed at Hanford (and none of the four needed at Livingston) we really can't say much about the likelihood that "typical" monument placements will be adequate to thread the beam tube. Admittedly repetition of this procedure on other modules will consume significant time and energy, since removal of the spools and installation of the ported module end caps is no longer automatically done in the bakeout process. However, this cost needs to be balanced against the cost of a protracted alignment search using the IR beam during commissioning of each interferometer.

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