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Alignment of LIGO Beam Tubes

Michael Burka

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1 Summary

The tube support foundations are expected to settle by more than the specified alignment tolerance vertically. Therefore, the supports must be designed with provision for re-aligning the tube relative to the support. The anticipated settlement over the life of the system is an inch, so several inches of adjustment should be designed in, plus whatever is required for the initial alignment. Lateral drift of the support points is anticipated to be less than the specified tolerance, but it would still be prudent to provide a couple of inches of adjustment. The initial alignment of the tubes and tanks can be accomplished with conventional survey instruments once a few fiducial marks have been accurately fixed. These fiducials can be fixed using the Global Positioning System. A procedure for monitoring the alignment of the tubes is outlined below.

2 Introduction

The alignment question can be broken down into several discrete parts.

- How is each tube to be aligned, initially?
- How is the alignment to be monitored and verified?
- How often is the alignment to be monitored and verified?
- What are the alignment constraints on the tanks, and how are they to be aligned?

3 Specifications and settlement

The environmental specifications report sets a limit of one centimeter on the allowed drift of any part of the beam tube. The tube will be supported every forty to sixty feet, and the tentative specification on settlement of the supports is one inch over four kilometers, and one-quarter inch between adjacent supports. One anticipates that two-thirds of the settlement will occur during the first year after construction, and 90% during the first two years. If the supports are anchored in clay, then there may be a lateral displacement due to clay expansion which is of order 10-20% of the vertical settlement. Thus, the anticipated motion of the tubes is of the same order of magnitude as the alignment tolerance. Therefore, the system will have to be built with provision for repositioning the tube relative to its supports, and a periodic monitoring technique will be required. Since the anticipated time scale of settlement is long, and the anticipated motion is not much greater than the tolerance, it is not necessary to have continuous monitoring or servo control of the tube alignment.

It must be borne in mind that the "aligned" tubes will have a carefully planned random misalignment, and that an aligned tube is not necessarily a straight tube. The tube itself cannot be used as an alignment guide, although it is perfectly acceptable to attach fiducial markers to the tube and to use those markers for alignment.

4 Initial alignment

Standard surveying equipment is not accurate enough to survey the tube supports to one centimeter over four kilometers. One centimeter over four kilometers is about half an arc-second, while standard theodolites are typically accurate to one arc-second. Also, standard theodolites do not have optics tailored for four kilometer distances.

If we can establish a few fiducial marks along the length of each tube, then these marks can be used as reference points for the alignment of individual sections of tube. One way to accurately fix such fiducial marks is to use the Global Positioning System. This is a system of position measurement which relies upon radio signals generated by defense department satellites. It is not a real-time measurement system, so it cannot be used for real-time alignment.

The procedure would be to fix markers in the ground using conventional survey techniques. These markers would be spaced every few hundred meters, and would be a few meters off of the tube centerline. A GPS survey crew would then measure the relative positions of these markers to whatever accuracy is desired, up to one millimeter in all directions.

To measure the relative position vector of a pair of points, the GPS survey team sets up radio receivers at the two positions. Each receiver records signals from the orbiting GPS satellites, and records these signals on floppy disks, or whatever. A minimum of fifteen minutes recording time is required, and up to six hours can be required for one millimeter accuracy. A minimum of two satellites must be in view, and the most accurate measurements require line-of-sight to five or more. Accurate ephemerides of the satellites are published about three days after the survey date, and at this time the recorded data and the ephemerides are crunched to produce relative position vectors.

Once the positions of our markers have been fixed, the tube sections can be positioned relative to the markers using conventional survey techniques. At distances of a few hundred meters, this can be done to the required accuracy. The tanks can also be surveyed into position using these marks. The accuracy with which the tanks must be positioned is probably governed by the internal tank baffle plan, but the tank tolerance cannot be tighter than the tube alignment tolerance, so the techniques used to position the tubes will be precise enough for the tanks.

5 Monitoring alignment

5.1 Requirements

The method of monitoring the tube alignment must meet several requirements:

- It must be accurate to the specified tolerance of one centimeter relative motion of any two support points.
- It must be operable from the center and end stations, and not require human access to the tube. It would be highly preferable to have a system which could be operated from the central station alone.
- It must be compatible with detector operation.

- It must be something which is either permanently set up, or can be set up easily, so that the alignment can be checked during or soon after major storms, earth tremors, frosts, etc.

5.2 Proposed method

One possible method is based on an idea suggested by Rai. It is shown conceptually in Figure 1. Imagine that a "target" with a crosshair is mounted to each tube support. If a telescope is placed at the same elevation as the horizontal lines and is offset by a distance x, then the horizontal lines of all of the targets should line up. If a particular target does not line up, then that is an indication that its support has moved vertically relative to the others. Similarly, a telescope mounted above the targets will enable monitoring of horizontal alignment. The telescopes would not have to be mounted rigidly in place, since they could be aligned by lining up most of the crosshairs and looking for the few that don't line up.

One can make a few numbers to see that the realization of this scheme is a bit trickier than its conceptualization. Define a few quantities:

- d is the distance between supports, probably 40 feet (=1220 cm.)
- x is the offset of the telescope from the targets
- $l(n)$ is the distance along the tube from the telescope to the n^{th} target
- $w(n)$ is the width of the visible portion of the n^{th} target

Suppose that one wishes to monitor the alignment of the entire tube from one fixed telescope location. The diffraction limit dictates that a telescope which can discern one centimeter of motion at four kilometers have an aperture of

$$D = 1.22\lambda \times \frac{4 \times 10^5 cm}{1 cm}$$

or about ten inches. The telescope offset x is given by $x = w_{min} l_{max}/d = 3.3$ meters.

Now, the offset is not the telescope's offset from the tube, it is the offset from the edge of the target cards. The most efficient arrangement is that shown in Figure 2. If, as shown, the target is located in the upper left corner of the enclosure, then horizontal alignment would be monitored from a position in the lower left corner, and vertical alignment would be monitored from a position in the upper right corner.

Current thinking about the enclosure has only about a foot of clearance above and on each side of the tube, and two feet below. This does not allow for the 3.3 meter offset needed to monitor entire tube alignment from the central station. It does permit half that offset, so the monitoring could be accomplished from the center station to just past halfway, and from the end stations to just past halfway. This also relaxes the diffraction limit, so smaller telescopes could be used.

A few points to bear in mind:

- The targets will have to be brightly illuminated.
- The width of the crosshairs should be one centimeter, so that it is easy to see when a particular target is one centimeter out of alignment.
- The targets will have to be rigid, and will have to be firmly affixed to the supports.
- In addition to the crosshairs, the targets should be numbered, so that one can identify a misaligned post.
- The numbers and crosshairs should be printed on both sides of each target.
- It will not be possible to have all of the targets in view at once. The telescope will have to be repositioned several times in order to check each coordinate alignment of each half of each tube. The maximum number that can be seen at once is a function of their distance from the telescope. If the targets are thirty centimeters wide, and if one requires a minimum visible width of one centimeter, then every target from 100 meters to the mid-station can be seen from one telescope position, but the telescope will have to be repositioned to align the closest hundred meters. The telescope can be positioned so that segments already aligned overlap with those to be aligned after the repositioning.
- Vacuum tanks might obstruct one's view. If there are mid-stations then there may need to be alignment monitoring done from the mid-stations. How one handles the tanks in the mid-station depends upon how many there are. If there is just one, then it gets two targets. If it is aligned with each of the two kilometer segments, then they are aligned with each other. If there are more than two tanks in the mid-station, then it may be necessary to have survey equipment in the mid-station

to traverse the tanks. At the end and center stations, the telescopes will have to be located so as not to be obstructed by the tanks.

6 Frequency of monitoring

The system outlined above is not a continuous monitoring procedure. One imagines that it would take two people most of a day to verify the alignment of both tubes at one site. The anticipated drift of the supports is a small number, especially after the first two years of operation. Therefore, the alignment should be verified every two weeks initially, as well as after events such as earth tremors and heavy rains. This schedule can be relaxed as time goes by if the system exhibits stability.

7 Acknowledgments

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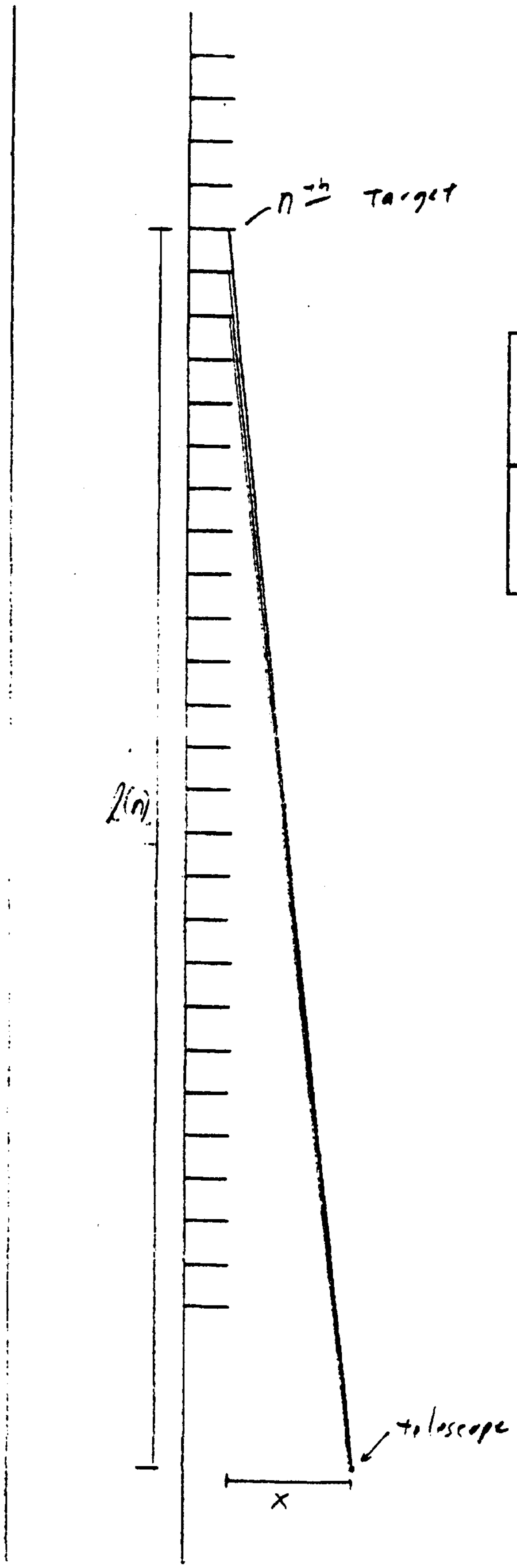

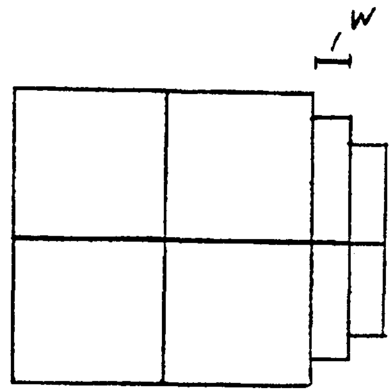

d = distance between targets

x = telescope offset

l(n) = distance along tube from Telescope to n th target

w(n) = width of visible region of n th target

Figure 1

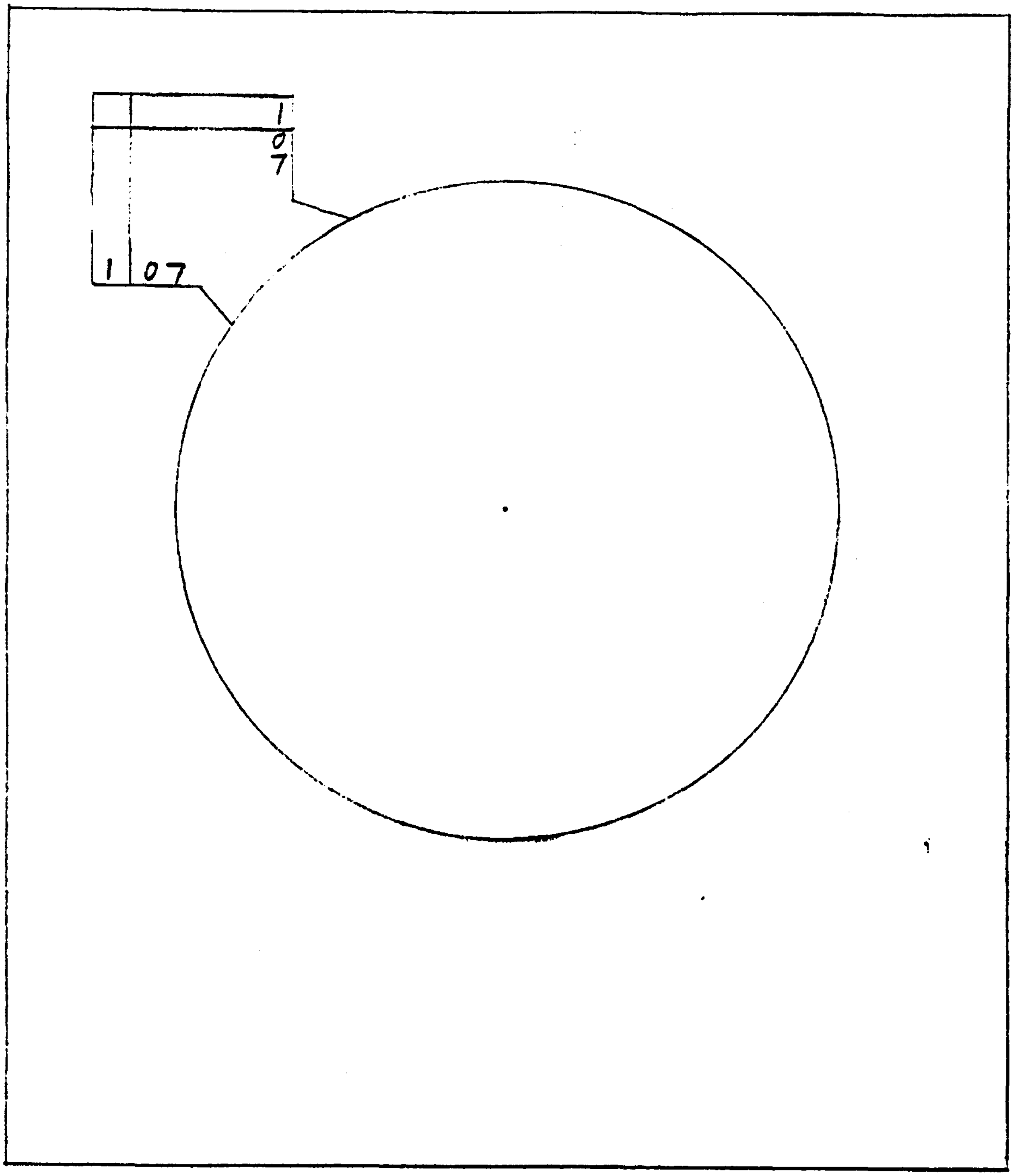

Figure 2