CHARA TECHNICAL REPORT

No. 60 5 February 1998

OPLE Sleeper and Rail Installation Trip Report

T. ten Brummelaar, W.I. Hartkopf, C. Hopper, H.A. McAlister, S.T. Ridgway[2], L.C. Roberts, L. Sturmann (CHARA)

1. OVERVIEW

The Optical Path Length Equalizers (OPLEs) consist of retroreflectors transported on carts, running on a rail system. The concept and design has been documented elsewhere. Here, part of the installation procedure will be described, both for archival purposes and for reference in future installations.

At the completion of the contracted construction, the OPLE T–supports were installed and approximately leveled. This included concrete beams, with transverse steel box members (crosspieces), forming a virtual roadbed for the track system. It was determined that the contracted installation of the next components would be unreasonably expensive – probably because the operations were quite non-standard for the business community which provides low-cost construction services.

The CHARA group decided to undertake the installation and alignment of the remaining components as a small group project, and the authors of this report spent, cumulatively, about 30 work days at Mt. Wilson on these tasks.

The first task required installation of the 2×3–inch steel sleepers, which had been machined to flatness by the technique of Blanchard grinding. These pieces were aligned to put the top surfaces into a common plane. The circular shafts were installed on the sleepers, with T–rail supports; an experimental section of drive rail was then installed, together with a variety of associated hardware.

This report is adapted from notes in the nature of a log, made at the time and updated afterward, hence the unusually informal character.

2. THE SLEEPERS

The box -beam sleepers were nominally aligned to $1/4''$, chosen as a standard construction tolerance for a large structure. In general they did meet this requirement, but some were

[1] Center for High Angular Resolution Astronomy, Georgia State University, Atlanta GA 30303-3083
TEL: (404) 651-2932, FAX: (404) 651-1389, FTP: ftp.chara.gsu.edu, WWW: http://www.chara.gsu.edu

[2] joint appointment to NOAO/KPNO and CHARA

out of tolerance, and quite a few others were adjusted to allow more adjustment range in the bolts supporting the sleepers.

The most difficult stage of preparation was installing the lower bolt (that is, above the box-beam sleepers but below the solid sleepers). This had to be run about 4 inches over a threaded rod which was cut (often damaging threads at the start), and in addition often had paint on the threads near the end. Experiments with hand turning a die showed an unreasonably large total time required. Experiments with a hand drill powered die did not work well, due to the mess of flying lubrication, so this was abandoned, except for particularly bad cases. A hand drill powered socket, with a custom-made very long socket, worked very well, although attention was required to avoid running into the stop. In fact this operation was one of the more risky, as the high angular momentum of the drill could deliver a substantial kick in the case of a mistake.

Installing the sleepers (320 of them, about 80 pounds each) required a minimum of two people working together. The work was done in 4 days, with different combinations of people at different times. For our staff, the most intensive acceptable level of activity required giving each participant about 1/3 of the time off to rest. Installing the nuts and washers below and above the sleepers was another couple man days work. Note that four rows of sleepers were installed, each with a carrying capacity of two OPLE lines, for a total of eight, although only five will be brought up within the scope of the initial project.

The surfaces of the sleepers were generally in good condition, but there were some burrs on the edges and some gouges from handling. These were removed by filing all edges lightly, then rubbing the top surfaces with an Arkansas stone. The stone removed many high spots, mostly around screw threads and hence not very significant for our application, but also many edges and humps. This required about 4 man days and was especially unpopular work.

After the sleepers were scraped, they were wiped clean with a rag moistened with WD-40, then oiled generously with a rag dipped in chain saw oil. There was considerable discussion over the wisdom of this choice. The logic of chain saw oil was that (a) it was available on the mountain, and (b) it was designed to protect steel from rusting in a poorly controlled environment. It was agreed a way oil would be preferred. Perhaps a medium thick grade would be suitable for the sleepers.

3. PRELIMINARY ALIGNMENT OF SLEEPERS

The alignment process was steadily improved as we learned what worked best. The following summary recounts part of the learning process, and the methods actually used.

The goal of this stage of alignment is to place the top surfaces of the sleepers in a common plane. The difficult part is defining a plane over a distance of 50 meters. The ground top surfaces of the sleepers are specified to deviate from flatness by no more than 0.08 mm over their length. Conformance to this specification has not been confirmed. The objective of initial alignment is to obtain a uniform plane with deviations over 50 meters of no more than about 1 mm, and deviations over 1 meter no greater than those due to the irregularities of the sleepers themselves.

A laser was installed on an optical bench, with a 1/16-inch hole about 2 meters away. This produced a nice circular diffraction pattern. However, it was very difficult to align (too many degrees of freedom) to the target. Also, at 50 meters it was not possible to read the position to better than about 1-2 mm. There are also significant concerns about both seeing and refraction due to stratification over 160 feet.

An electronic theodolite was installed on an optical table, at one end of the OPLE area. The concept was to leave the theodolite in place during alignment, moving it only in azimuth to pick up different parts of the rail support system. The theodolite was installed free standing. It was not possible to clamp it optical table style without distortion and we had no way to hold it down from below the as it is intended to be mounted. We left it free standing, but with three blocks to keep it from translating.

The theodolite was leveled and then locked in the vertical position. The readout of horizontal and vertical angle changed from time to time by 5 arcsec. (Since this is the instrument's resolution, it may not mean anything). Also, the readout reset to zero when turned on. We therefore decided to leave the power off. In fact the readout was not required, since we used it only for a level reference to adjust the sleepers to a common elevation.

A movable target was placed on various sleepers and sighted with the theodolite. In order to provide immediate feedback, a CCD camera was adapted to the theodolite (no such commercial accessory was found). The CCD camera viewed the theodolite reticle and the target. Displays were provided at the theodolite (for focusing) and at the sleeper under adjustment. Manual focus of the theodolite was still required, but the camera eliminated nearly a full FTE at the eyepiece and greatly speeded the alignment operation.

During an initial trial, we surveyed a number of rails, and at one point the vertical position jumped about 10 arcsec. This may have been due to a loose vertical lock, but as a precaution, we established a reference point on the far wall. Henceforth, we switched to it regularly to be sure nothing had drifted.

3.1. Row 1 (Eastern Arm Row)

For the first row of sleepers the theodolite was used to level every 5th sleeper. A target was placed on the end of the rail, near one of the two bolts. A very accurate level was placed on the rail lengthwise (0.0005 inch per 10 inches per division), and a bullseye level for crosswise tilt. The sleeper support bolts were adjusted until the target was at the correct height and the lengthwise (along the sleeper) level bubble was centered. The perpendicular (across the sleeper) level bubble was centered by tilting the sleeper by hand (taking advantage of the motion allowed by the spherical washers).

Next, the level was propagated to the intermediate sleepers using a precision level (0.0005 inch per 10 inches per division) mounted on an extended bar. The extender bar had a three-point tooling ball support, with a lengthwise spacing of exactly 24 inches, to span between two sleepers. In theory, this is set with the tooling balls on the mid-line of the sleepers to reduce sensitivity to roll of the sleepers. In practice, spacing between adjacent sleepers varied somewhat from the nominal 24 inches, so the extender bar was centered by eye as well as possible. The level reading was found to vary considerably as it was moved off center, so this was critical for good leveling.

Starting at one of the optically aligned sleepers, the level was transferred first to an adjacent rail, and then to the one after it, thus bringing three adjacent sleepers into conformance. In this process, the level is used first at one end of the sleepers and then at the other, alternately, iterating until the levels at the two ends are consistent. (The level along the rail is ignored – gravitational sag is expected, as well as some bend within specification). The precision machine level itself is not perfect. To minimize propagated errors, it is used in one orientation in going from the optically aligned sleeper to the adjacent, and then reversed when transferring to the next sleeper, in order to approximately null the systematic error.

Now skipping to the next optically aligned sleeper, the same process is followed coming back in the opposite direction. To clarify the sequence, if a group of sleepers is numbered 1-2-3-4-5-6, and numbers 1 and 6 have been optically leveled, then the machine level is used to align from 1 to 2 to 3, then from 6 to 5 to 4. At the completion of this sequence, the six consecutive sleepers have been nominally leveled. The two center sleepers have been independently leveled from different directions. Now closure is used to reduce the gradients. The difference in level between the two center sleepers is noted, separately at each end. This is most accurately accomplished by using the level in both orientations and reversing the level and averaging the results. Typically, the error is divided by three. One third is removed by adjusting each of the two adjacent sleepers (3 and 4), and one third is left in. This spreads the error between the two optically aligned sleepers over three steps. On rare occasions, the error between the center sleepers was small and no further adjustments were made. More frequently, this error was large; in this case the entire set of sleepers was readjusted to average the error over the whole span.

The optical angular resolution of the theodolite is 3-4 arcsec. Over the full 50 meter length of the OPLE rails, this corresponds to about 1 mm. The error found between the two center sleepers (3-4 in the procedure just described) is usually about 0.2 mm, but sometimes up to 2–3× greater. This suggests that the visual centering of the theodolite reticle on the target may often be accurate to about 6× better than the telescope resolution, but not always.

The reduced gradients after spreading them out are about 0.05 mm per sleeper spacing, which is considered quite good.

3.2. Theodolite and Level Comparison

The error in the theodolite measurement increases linearly with distance, since the error is in angular measure. Designating the theodolite error as δ_ϕ, over a distance L the error is,

$$\Delta_h = L\delta_\phi \tag{1}$$

However, in case of the machine level the uncertainty (with proper practice) increases as the square root with the number of steps N we make. After N steps the uncertainty in vertical position for the machine level is,

$$\Delta_h = \delta_h\sqrt{N} \tag{2}$$

If we adopt the manufacturer' specification for the machine level error (0.0005 in per 10 in), and apply it over the distance between sleepers (24 in = 60.96 cm), and if we adopt the optical resolution for the theodolite (4 arcsec) we find that the level wins for $N \geq 6$). This calculation may tend to favor small values of N, since it seems possible to center the theodolite to better than the telescope diffraction limit, and it is relatively difficult to use the machine level to its ultimate precision, due to the long settling time for the bubble. Thus, this is only a guide, although experience suggests that it is probably a good one.

3.3. Row 3 (Southern Arm)

The sequence here follows the chronological sequence, and row 3 was aligned next. A different combination of operations was used, as we were experimenting and learning as we went.

Here the theodolite was used every 5 sleepers (as in row 1) for the 40 sleepers farthest from the theodolite itself, then every 3 sleepers for the next 20, and every other sleeper for the closest 20. Interpolations were adjusted accordingly. The logic, of course, was to adapt the method to the relative strengths of the theodolite and machine level.

Also, a different optical scheme was developed. A combination of mirrors and a beamsplitter were used with the theodolite so that the theodolite field included two targets, one on each end of a sleeper (actually, one target over each of the two support bolts, which are set in several cm from the ends). The theodolite optical paths were set up to be parallel to the OPLE lines. Consequently, when the targets were advanced to a new sleeper, it was not necessary to change the theodolite pointing, but only the focus. In this way, the setup was quicker and the video display showed directly the adjustment of both ends of the sleepers.

Following completion of the row 3 alignment, Laszlo measured the sleeper-to-sleeper error for this row, using the level. In plotting up his results, he found significant scatter in the heights of the theodolite-adjusted sleepers for those farthest from the instrument, with fairly smooth interpolations made by the level for the intermediate sleepers. This scatter decreased significantly for the closer half of the sleepers.

3.4. Row 2 (Western Arm)

For row 2, based on the sleeper to sleeper plot, we decided on a different tactic than used for rows 1 and 3. The theodolite was used only to adjust the height of the closest sleeper. Theo and Bill then leveled each sleeper in turn relative to its neighbor (i.e., sleeper 2 relative to 1, then 3 relative to 2, et cetera). The level was reversed each time we moved from one sleeper to the other to avoid systematic errors.

The process for each sleep wasas follows: First, the bolts holding the sleeper in position were loosened and a rough alignment was made with the level. At this time a small "bubble" level was also used to get the sleeper rotated around it's long axis so it was level. The bolts were then tightened by hand and then an extra half turn using a spanner. A fine adjustment was then done on either side of the sleeper. The last step usually required iteration.

The theodolite was used occasionally to check for any drift, but no adjustments to the level results were made. Total drift over the full set of sleepers was under 1 mm. This appeared to be the most accurate method, and it may be worth readjusting heights of rows 1 and 3, although we do not recommend doing this until some experience is gained at the next stage, alignment of the OPLE shafts. Alignment of a full row by this method takes two people about 8 hours (we recommend this be split over two days).

3.5. Row 4 (Spares)

Since row 4 will not be used in the initial five telescope configuration, it was not aligned at this time.

3.6. Shaft Installation

The OPLE carts run on circular steel rods which we are tempted to call rails, but in the manufacturer's[3] terminology, they are shafts, so we will try to follow that here. The extruded aluminum T–supports for the shafts are called rails. Unfortunately, other technical reports, especially earlier ones, may use a different terminology.

In a technical report to be written, the configuration will be described: the shafts are bolted to little T–support rails, the T–support rails are clamped to the sleeper, and the rail ends are butted together with longer T–support rail sections.

The first shaft was installed on its T–support rails. By studying the interfaces of the T–supports to the sleepers, it was found that one support had a burr, which was removed with the Arkansas stone. We subsequently polished the bottoms of all T–supports with the stone and wiped them off before attaching them to the rails. The T's were still poorly matched to the sleeper surfaces. Then the rail was slid lengthwise until the T–support bolts were exposed. These were loosened, then tightened while the rail was pushed down. This allowed the T to settle into a much better position, adapted to the local slope of each sleeper, which of course varies within the sleeper surface specification.

3.7. Problems with the Shaft Support T–Rails

Some of the T–supports did not attach properly to the shafts. On inspection, it was found that in about 50% of the pieces, the countersink holes were not concentric with the through holes. This was a problem in itself. There was also an interaction with the bolts. The low–cost bolts have heads which are not concentric with the threaded body. Thus when an eccentric bolt was turned in an eccentric countersink hole, the offsets would conflict. In some cases the offset was tolerable, and in many not. Consequently, a large number of T–supports (about half) were returned to the distributor for redrilling of the countersink.

3.8. Problems with the Shafts

Well before row 1 was fully populated with shafts, it was found that a significant fraction of the shafts were incorrectly drilled, in the sense that the threaded holes for the T–supports were not spaced correctly relative to the end. As a result the shaft ends would not form a proper butt joint, but left a space of up to 1–2 mm. As of this writing, this situation is under discussion with the distributer of the shafts. The most likely solution will be to drill out bolt holes, or even mill slots, in the T–supports to accommodate the shaft errors.

3.9. Retrospective on Shaft and T–Support Purchase

The purchase order for these items clearly spelled out the requirements, which were well within the standard tolerances according to the manufacturer's literature. Unfortunately, the sheer bulk of the materials (more than 10,000 pounds of steel shaft) and the delivery to a remote site made it impractical to quality control the delivery before the requisition was automatically accepted and paid for by the University purchasing department.

[3] Thomson Industries, Inc, Port Washington, NY 11050.

4. END OF THE DECEMBER EXPEDITION

When it was noticed that an even multiple of the shaft length would give a 2-foot overhang, we decided it best to have the overhang at the east end. Most of the already-placed optical rails were moved accordingly, with only a single set of three (or was it only 2?) rails left bolted together to illustrate the occasional large inter-rail gap for the Thompson rep. The T–supports for the remaining rails installed on the sleepers were left loose, since further adjustment might be needed when new rail-joining T's are installed. (Also, some settling of the sleepers under the weight of the rails might be expected before the next alignment expedition.) The already-tightened T's for the rails which were moved were *not* loosened as they should have been – these must be readjusted during the next trip.

Finally, available drive rails were set approximately in position, populating about 1/3 of the first row.

5. SHAFT LUBRICATION

The shafts should be lubricated after installation. Steve contacted Patrick (Last name?), an application engineer at Thomson (516-883- 8000) and learned that the shafts are shipped with a light rust preventing grease. There is no need to remove this before using the shafts. The recommended lubricant and rust preventative coating for the shafts is an EP2 grease (EP = extreme pressure), available from industrial supply houses.

Further thought needs to be given to the issue of lubricating the Thomson shafts. JPL has removed the shaft wipers from their linear bearings, presumably to eliminate stiction. This will allow anything adhering to the greased shaft to be carried into the recirculating balls. Also, the grease needs to be selected with great care. Charles has on several occasions found telescopes that were inoperable because they were greased with too heavy grease or too much grease. Fine motion of the carts may be compromised by the wrong type shaft lubricant.

6. ADDENDUM: REPORT OF THE DECEMBER 11-16 TRIP TO MT. WILSON (Sturmann & Hartkopf)

We started installing the already fixed T-supports (larger countersink holes) for the two north-most rails. It turned out soon that some of them still could not be installed because the through holes did not match the holes on the shafts. The discrepancies were as much as 1/8″ in some cases. As a first attempt to fix this problem, we re-drilled 10 T–supports and then successfully installed them. During the installation, we also tightened all bolts along the first two pairs of rails.

On the following days we attempted to install all remaining shafts, but found more problems with non-matching holes. Finally, all shafts were placed to the sleepers but the individual segments could not be butted together properly in several cases. We placed short T–supports to support the ends of the shafts. At this point we decided to make a quick statistical study of the distance of holes from the end of shafts. We found a large scatter (see Figures 1 and 2). The only viable solution of the problem is to make slots on the

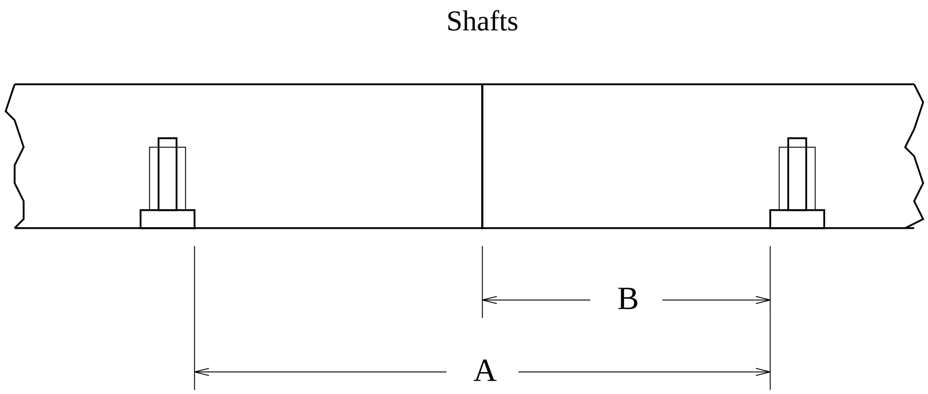


FIGURE 1. Illustration of points used for measuring hole-to-hole distance for a pair of shafts butted end-to-end (= A), plus distance from hole to shaft end for a given shaft (= B).

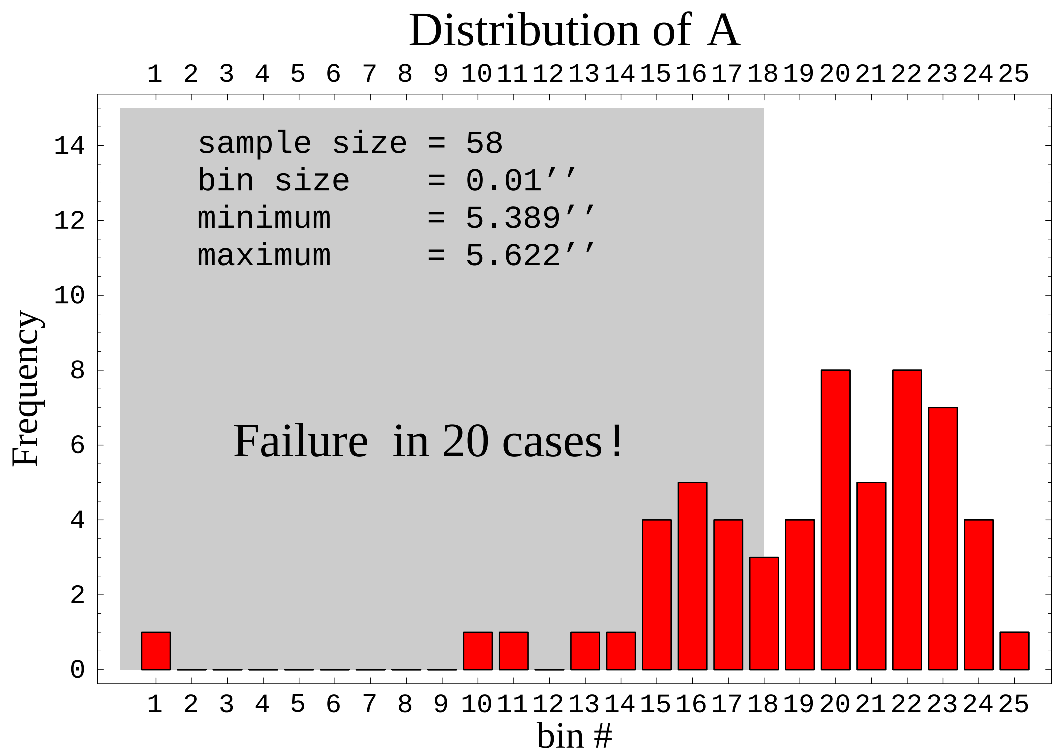
T–supports[4].

We installed the missing V-grooved wheel on the cart in the OPLE building. During the installation we noticed that the ball bearings in the hub had some dirt in them and the wheel did not spin freely. We tried to wash the dirt out with WD-40 without disassembling the hub. The washing has apparently helped but we suggest checking them out again and cleaning the bearings after removing them from the hub.

The first pair of rails were straightened in the horizontal plane by using the theodolite. The method we used was very simple and quite effective. The theodolite was placed on the optical table in such a way that by changing only the altitude angle we could scan the entire rail. The theodolite was aimed to the far end of the rail first. The line of sight of the theodolite made a small angle α with the direction of the rail. Due to this small angle the vertical dimension along the rail was compressed by a factor of $\sin(\alpha)$ while the horizontal was intact. Looking through the theodolite we were able to detect very small (<1 mm) misalignments in the local horizontal position of the rail. The rails were pushed/pulled by hand until they appeared straight in the theodolite. This method failed close to the theodolite because the angle α was progressively larger which means lesser sensitivity and also the length of the rail segment we could see through the theodolite at a time was progressively shorter. Therefore, in order to align the first half of the rails we moved the theodolite to the far end and looked backward. This method could be refined by observing the reflection off the top of the rail from a linear light source (for example, a florescent tube) hanging vertically.

After wiping off the first 1/3 of the first pair of rails with WD-40 we put the cart on the rail and made a couple of test runs. As far as we could tell, it ran smoothly.

[4]A drawing of the suggested alteration of the T–supports was faxed to Bob Cadman.



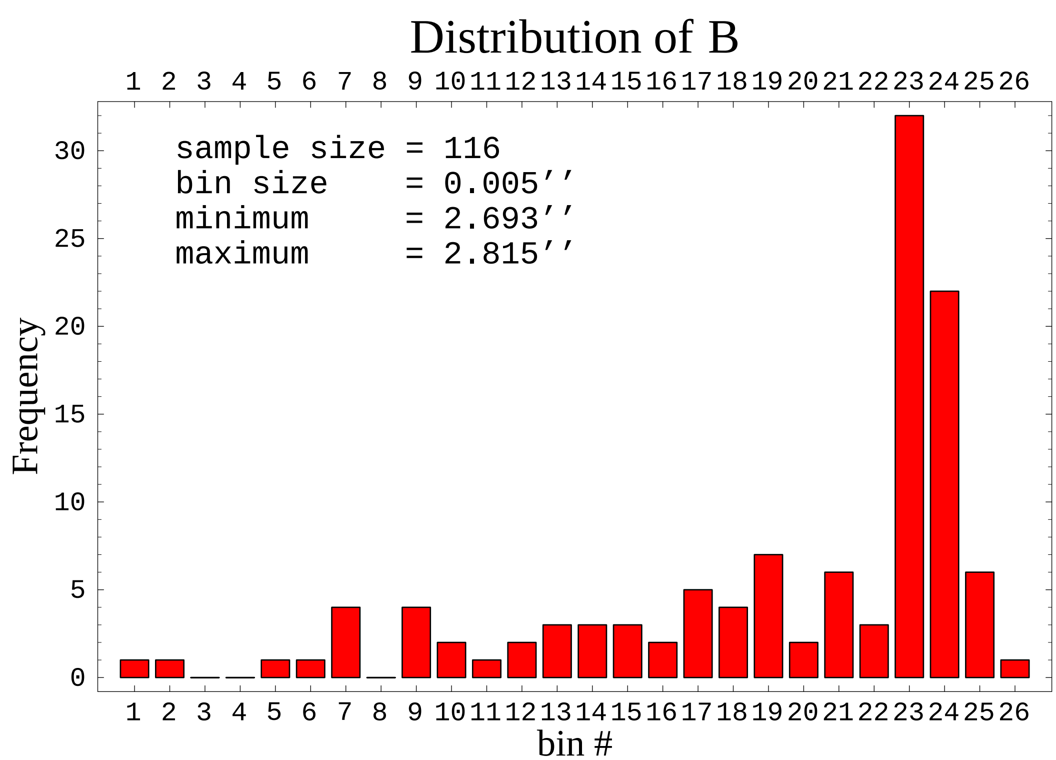


FIGURE 2. Distributions of measured distances A (above) and B (below). See Figure 1 for definitions of these distances.