Survey and Alignment at the Advanced Light Source

Gary F. Krebs, Ted Lauritzen, and William Thur
Lawrence Berkeley Laboratory

Introduction

This paper describes survey and alignment at the Lawrence Berkeley Laboratories Advanced Light Source (ALS) accelerators from 1993 to 1995. The ALS is a 1.0 - 1.9 GeV electron accelerator producing extremely bright synchrotron light in the UV and soft-X-ray wavelengths. At the ALS, electrons are accelerated in a LINAC to 50 MeV, injected into a booster ring for further acceleration and finally injected into the storage ring. This is shown schematically in Fig. 1. The storage ring, some 200 m in circumference, has been run with electron currents above 400 ma with lifetimes as high as 24 hours. The ALS is a third generation light source and requires for efficient storage ring operation, magnets aligned to within 150µm of their ideal position. To accomplish this a network of monuments was established and their positions measured with respect to one another. The data was reduced using GEONET® and STAR*NET® software. Using the monuments as reference points, magnet positions were measured and alignment confirmed using the Kern Electronic Coordinate Determination System (ECDS®). A number of other papers dealing with survey and alignment (S&A) at the ALS[(1-3)] have been written that may further elucidate some details of the methods and systems described in this paper.

The Storage Ring

The Storage ring is made up of 12 curved sectors each 9.6 meters in length connected with 6.7 meter long straight sections as shown in Fig. 1. Each curved sector is composed of a steel girder with 17 magnets. The magnets are mounted to the girders with six strut adjustment systems!“). This system allows magnet position adjustment in all six degrees of freedom. As well as individual magnet adjustments, a girder of magnets may be adjusted as a whole using a separate six strut adjustment system anchored in the concrete floor. Four ‘target’ posts are welded to the top surface of each magnet. The posts accommodate either targets for survey or tooling balls for alignment purposes. The posts are fiducialized with respect to the magnets magnetic center to an accuracy of 50 μm. Other components within the storage ring which are fiducialized, surveyed and aligned with respect to monuments include insertion devices, the storage ring vacuum chamber and beam position monitors as well as beam line front ends. Table 1 lists the required tolerances for the various storage ring magnets. Booster ring magnet tolerances are typically double those of the storage ring. Shown in Figures 2a and 2b are the global ALS and local magnet coordinate systems, respectively.

Table 1

Object	Δw [mm]	Δu [mm]	Δv [mm]	Δu' [mr]	Δv' [mr]	Δw' [mr]
B	0.15	0.15	0.15			0.25
QD	0.3	0.15	0.15			0.5
QF	0.3	0.15	0.15			0.5
QFA	0.3	0.15	0.15			0.5
SF	0.5	0.15	0.15			
SD	0.5	0.15	0.15			
HVC	1.0	1.0	1.0			2.0
BPM	0.15	0.15	0.15			

where,

B: Bend magnet
QD: defocusing quadrupole
QF: focusing quadrupole
QFA: focusing quadrupole
u': pitch
w': roll
SF: focusing sextupole
SD: defocusing sextupole
HVC: horiz./vert. corrector
BPM: beam position monitor
v': yaw
-: can be calculated from table values

The Floor

The ALS storage ring floor is made up of two separate slabs of concrete. Elevation studies carried out to measure the course variation in floor elevation[3] showed that the upper surface of the composite slabs spanned ±23 mm. Initially, a 12 in. slab was poured. Two weeks later the upper 6 in. slab was poured. Two slabs of concrete were poured to expedite the construction of utility trenches. This method of construction, as discovered later, resulted in some unanticipated difficulties. Magnets, mounted on girders whose struts were imbedded in the lower concrete slab, decoupled from monuments which were imbedded in the upper slab. With surveying instruments resting on the upper slab, movement of the upper slab was observed due to nearby foot traffic. In October 1994 the storage ring monuments were cored out of the upper concrete slab and new monuments embedded in the lower concrete slab.

Monuments/Equipment

Over 120 floor monuments have been located throughout the ALS, as shown in Fig. 2a, each giving three dimensional reference information. Monuments are made of 2 inch diameter hardened stainless steel with a precision machined conical recess that accepts a 3.5 in. Taylor-Hobson target ball. The monuments are imbedded in the concrete floor such that the Taylor-Hobson ball is just above the floor surface. A side view is shown in Fig. 3a. The storage ring floor has 3 monuments per sector for a total of 36 monuments. Each sector has one “primary” monument which can be viewed through a port hole in the roof shielding. These viewing ports allow storage ring primary monuments to be tied into each other as well as the overall network outside the storage ring shielding. As well, survey work can be carried out while the storage ring is in operation.

Distance measurements are obtained using a Kern Mekometer 5000[6] which has a relative accuracy of 10^{-7}. Angles are measured using Kern E2 theodolites which have an accuracy of 1/3 arc second. To obtain vertical coordinates, the differences in elevation between monuments are measured using a Nedo Invar scale and a Wild N3 sight level (accuracy of 10 μm at 6 meters).

In 1994 a new survey instrument stand was developed which we call a monopod. This device, conceived of by Bill Baldock at the ALS, is composed of a 6 inch diameter carbon fiber tube with leveling capabilities mounted inside a support tripod. The top of the monopod has a Tribrach instrument mounting device modified to accommodate either an optical plummet, a Kern theodolite, a Mekometer or a Taylor-Hobson ball. The bottom of the monopod rests on top of a Taylor-Hobson ball which in turn sits on top of the floor monument. The carbon fiber tube with its near-zero coefficient of thermal expansion has a calibrated length, obviating the need for continual instrument stand height measurements. Presently, we incorporate monopods of 6 foot and 15 foot lengths. The 15 foot length monopod can be mounted on a primary monument inside the storage ring while the upper end protrudes through the roof shielding allowing us to measure the storage ring primary monument network while the storage ring is in operation. A schematic of the monopod is shown in Figure 3a and 3b. Initially, a small network of monuments was measured three times to determine the reproducibility of the surveying instruments-monopod system. The average standard deviation for monument coordinates was found to be 60µm.

GEONET/STAR*NET

PC-GEONET is a data handling and analysis software package developed by the SLAC S&A group. GEONET® requires input angle and distance information between monuments. In 1995 we began using STAR*NET®[5], software equivalent to GEONET® but somewhat more user friendly. Upon command, STAR*NET® carries out a least mean square fit on the over-constrained network. In practice, usually a test network is established containing information on which angles and distances will be measured and with what instrumental accuracy. The software produces a graphic showing the network and the error ellipses. To minimize surveying time, one generally reduces the number of measurements made to the over constrained network until the error ellipses become too large. Since distance measurements are far more time consuming to carry out, usually these measurements are the first to be eliminated.

After designating a coordinate system origin, the surveyed coordinates of the monuments are calculated. Shown in Fig. 4 are the angles and distances used in the ALS network. The error ellipses from a least squares fit to the data are given in Table 2 for the storage ring monuments. Two surveys of the entire ALS network were initially carried out by the SLAC alignment group[7] during February of 1992 and March 1993. In November-December 1994 ALS technicians carried out a complete monument survey using monopods. The results of these and other recent surveys are discussed in the following section.

Monument Positions

The difference in storage ring monument positions found from surveys taken in 1992 and 1993 are shown as vectors in Fig. 5a and 5b for the horizontal and vertical planes, respectively. To calculate the difference between the two surveys we have fixed the coordinates of monument P126 and the angle from P126 to P90, see Fig. 2a. We see in Fig. 5a changes in the horizontal plane in sectors 6 and 7 of as much as 750 μm, over a period of one year. Smaller changes, around 400μm, occur in sectors 5 and 11. In the vertical plane we see changes ranging from 10 μm to 450 μm, over a period of one year. Most of the downward vertical changes occur in sectors 6 and 7 and can be correlated with horizontal changes. The largest upward vertical changes occur in sectors 2,3,9 and 10. Generally, over a period of a year, the storage ring floor has sunk down and spread outward about an axis between sectors 3 and 9. It is not yet understood to what degree these changes are due to floor loading and/or ground moisture variations.

In addition to the three dimensional monument measurements, several independent elevation-only measurements of the storage ring monuments were carried out between 1993 and 1995. Shown in Fig. 6a are the changes in elevation of the storage ring monuments from February 1993 to October 1993. A drop in elevation of the monuments around sectors 6, 7, and 8 is around 750 μm. We attribute this drop to floor loading; in May-June 1993 undulators were placed in the storage ring straight sections between sectors 6 and 7 and between sectors 7 and 8. Each undulator weights approximately 30 tons. Smaller variations in elevation around the storage ring are attributed to continued floor settling from the weight of magnets and girders in addition to seasonal variations. The change in monument elevations from October 1993 to May 1994 are shown in Fig. 6b. The elevation changes in the monuments diminished somewhat in the sector 6, 7 and 8 regions and were around 300μm. Finally, in Fig. 6c we see elevation changes in monuments for the heavily loaded floor region around sector 6, 7, and 8 has slowed considerably to around ~ 100 μ m. Other data taken from a liquid level system attached to storage ring girders, shown in Fig. 6d, is consistent with these results. The liquid level data indicates that after the storage ring floor was loaded, the elevation of the floor dropped very little for the first three months. The following three months show a faster drop in elevation to about 350 μ m before leveling off.

After relocating storage ring monuments in the lower floor slab, a survey of the ALS network was carried out in November-December 1994. Data were analyzed with STAR*NET® .The average error ellipse axes for the monuments over the entire ALS network was found to be 89 μm. Error ellipse axes for the storage ring monuments were even smaller, ~60 μm. A subsequent survey in September 1995 of the storage ring monuments indicated position changes as shown in Figure 7. The average change in monument coordinates over the 8 month period was 120μm.

Measuring Magnet Locations

The ECDS®[8] is used to measure magnet locations with respect to known floor monument, positions. An arbitrarily located theodolite is used to measure angles to a given magnets four targets from different locations. Typically, to determine the coordinates of the magnet targets with sufficient resolution, our survey team views the targets from three separate locations and includes in each setup a measurement of the angles to two floor monuments. The known distance between monuments is used as a scale bar. A computer then calculates the coordinates of the magnet targets. The theodolites are connected directly to the computer thus reducing the chance of a data entry blunder. ECDS® has an advantage over some other measurement schemes in that it does not require centering over a monument. The process of measuring all 17 magnets on a girder takes a crew of 5 surveyors approximately 8 hours. Typically, this system gives the coordinates of each magnets four targets to an accuracy of 70 μm.

Having determined the magnet locations on a given girder, magnets are realigned with respect to the ideal orbit using EXCEL® spreadsheets[2]. For future alignments, EXCEL® spreadsheets are then used to calculate the corrections required to move the girder such that the distance the magnets are from their ideal position is at a minimum. After girder realignment, a confirmation survey is carried out to determine if the magnets are within the required tolerances shown in Table 1. If the magnets are found to exceed the required tolerance, the process is repeated. Usually, our surveying team is able to carry out the process in one iteration.

The initial alignment of the 204 storage ring magnets was carried out through the Winter and Spring of 1992-3. The resulting differences between the actual magnet positions and their ideal positions for some typical cases are shown in the magnets local coordinate system in Figure 8a, 8b, and 8c. We notice some of the magnet positions are off from their ideal position by nearly one mm. However, the magnets are relatively smooth with respect to one another. In only a few cases are there changes in position from one magnet to the next greater than 300 μm. During operation of the storage ring these differences were bridged using storage ring corrector magnets, and in April 1993 the first stored beam was realized at the ALS. Also shown in Figures 8a, 8b and 8C are the differences between the magnets position and their ideal positions after storage ring magnet and girder realignment during the Summer of 1993. The average distance from their ideal position for all the coordinates is about zero. The direction in the horizontal plane perpendicular to the electron beam has σ = 50 μm. Correspondingly, in the beam direction, σ = 60 μm, while in the vertical direction σ = 40 μm. When the storage ring was operated after this girder realignment, it was possible to store beam without the use of any corrector magnets.

After 2 years without any alignment the storage ring girders were surveyed and aligned in the Fall of 1995. The magnet coordinates both before and after girder alignment are shown in Fig. 9 for girders 1, 4 and 8. After alignment, magnets deviated from their ideal positions by an average of only 60 μm. When we compare relative magnet positions from 1995 to their positions in 1993, we conclude that the magnets are stable on their girders.

<u>Summarv</u>

We have used GEONET® and STAR*NET® software and standard surveying instruments along with our monopods to measure the ALS

monument network. Storage ring monument locations were established to within about 60 μm. Monument motion can be attributed to floor loading and to some as yet unknown degree to moisture variation with the season. Storage ring magnets have remained stable on their girders, simplifying the realignment process. In the future the ALS survey & alignment group will explore equipment and techniques, such as photogrammetry, LASER tracking and higher precision liquid levels to help speed up the survey and alignment process.

Acknowledgments

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References:

(1) Survey and Alignment Data Analysis for the ALS Storage Ring. R. Keller. IEEE 1993 Particle Accelerator Conference, Washington D.C., May 1991.

(2) Proceedings of the Third International Workshop On Accelerator Alignment. Sept. 28-Oct. 1, 1993. CERN. Survey and Alignment Data Analysis for the ALS Storage Ring using Computer Spreadsheets. R. Keller, page I/29.

(3) 2nd International Workshop on Accelerator Alignment. R.Keller, T.Lauritzen, H.Friedsam. DESY, Deutsches Elektronen Synchrotron, Hamburg Germany, September 1990.

(4) Six strut system. T.Lauritzen (LBL)

(5) STARPLUS SOFTWARE, INC 460 Boulevard Way,
Oakland, CA 94610.

(6) The ME 5000 Mekometer- a new precision distance meter.
D.Meier, R.Loser. Kern & Co. Ltd.. CH-5001 Aaray, Switzerland. Also: Proceedings of the Workshop on The Use and the Calibration of the ME5000 Mekometer. June 1992. Stanford Linear Accelerator Center. SLAC-403

(7) Internal ALS notes. G.Krebs

(8) Electronic Coordinate Determination System: System, version 2, 1991. B.Baldock. ALS Internal Notes.

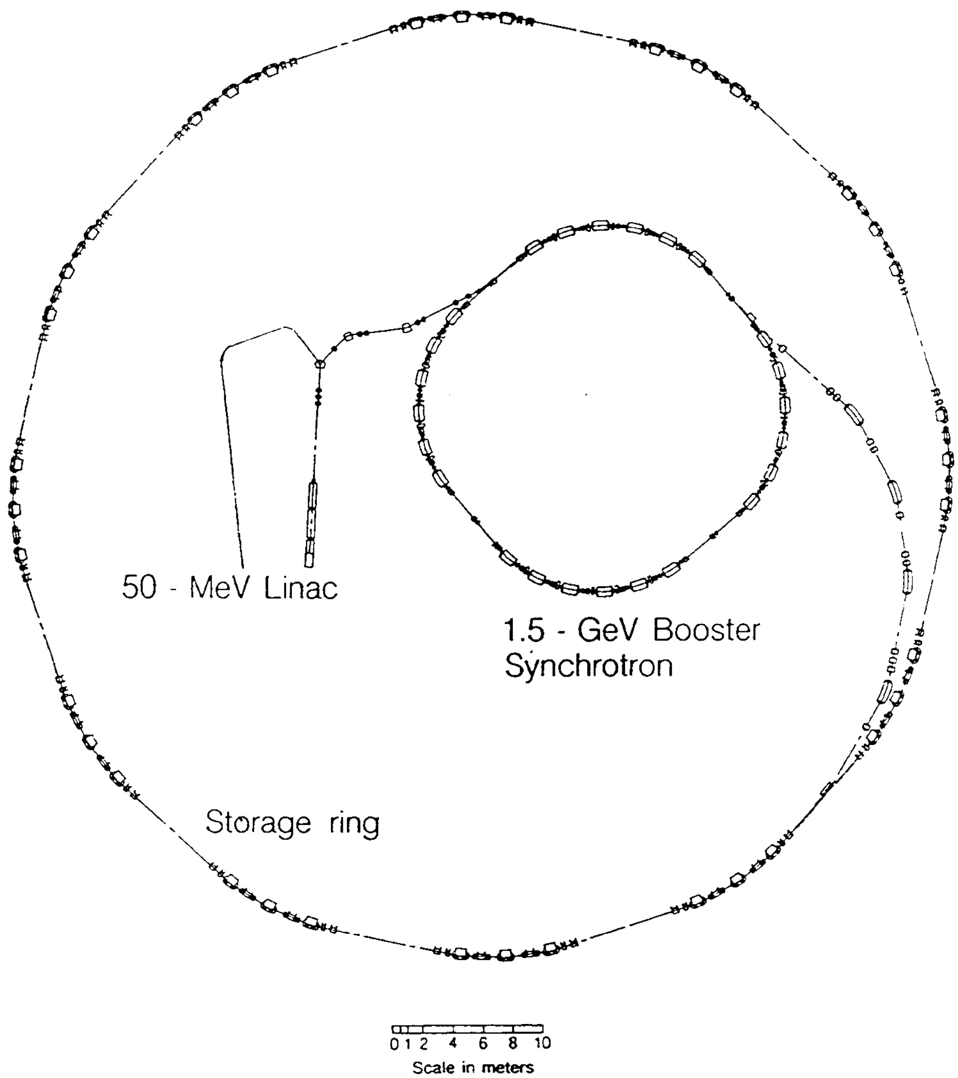
50 - MeV Linac
1.5 - GeV Booster
Synchrotron
Storage ring
0 1 2 4 6 8 10
Scale in meters

Figure 1

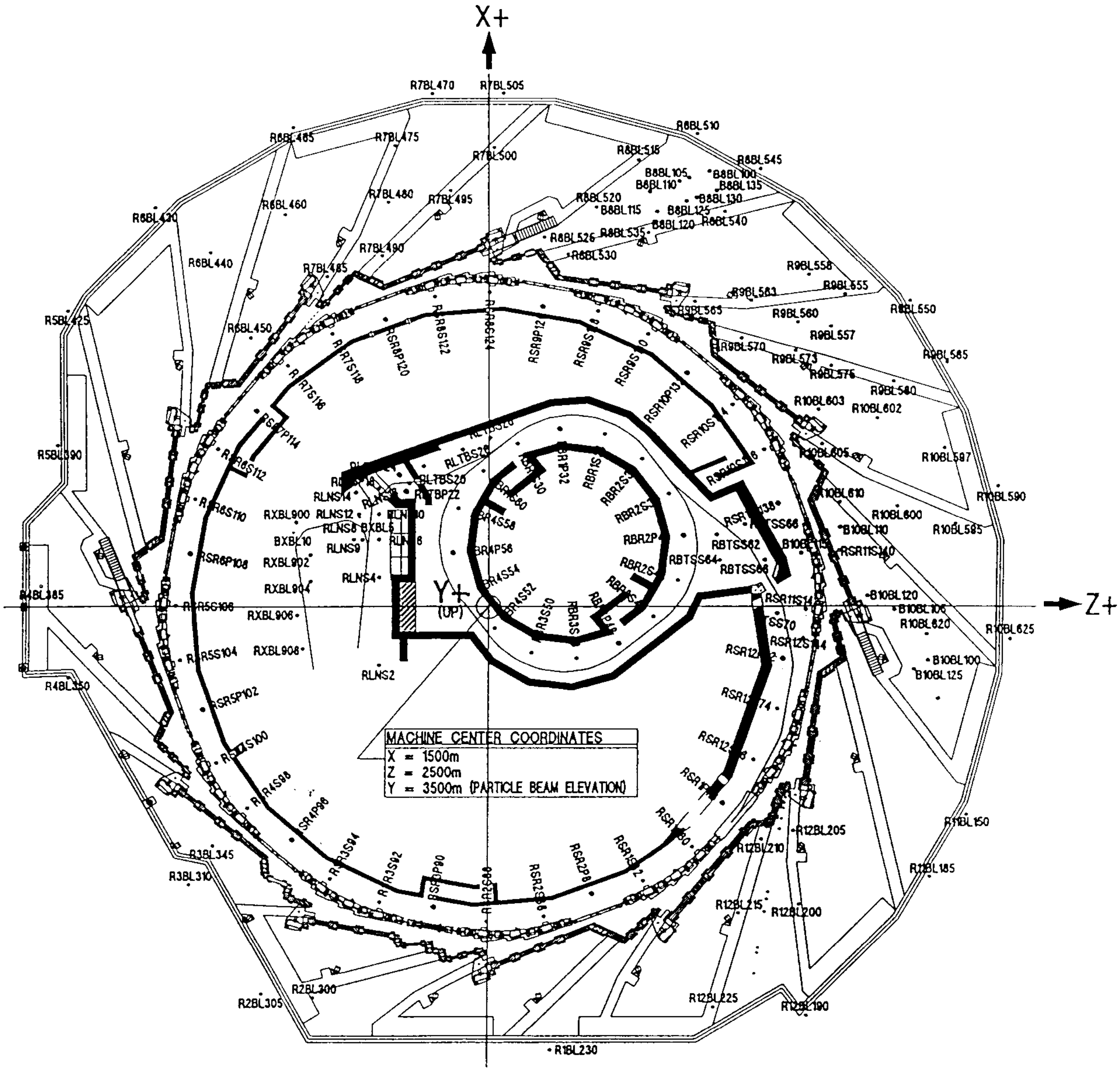

Figure 2a
The ALS-Coordinate System showing the monument network for the accelerators and beamline areas.

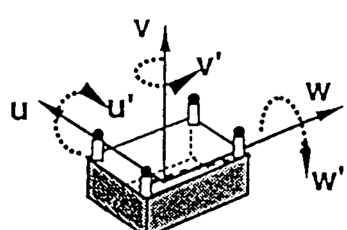

Figure 2b
The magnets' "Local Coordinate System" where the origin is at the magnets' center, w is in the beam direction and u', v' and w' are a magnets' pitch, yaw and roll, respectively.

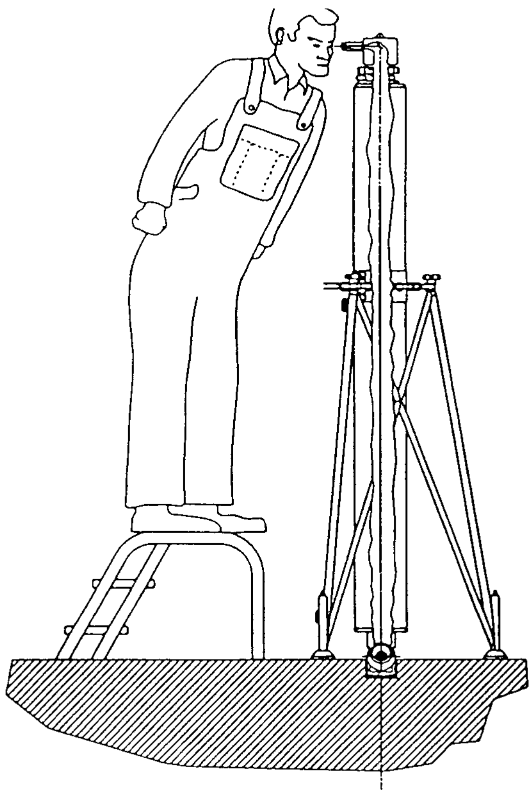

Figure 3a
A Monopod plumbed on a Taylor-Hobson ball resting in a floor monument.

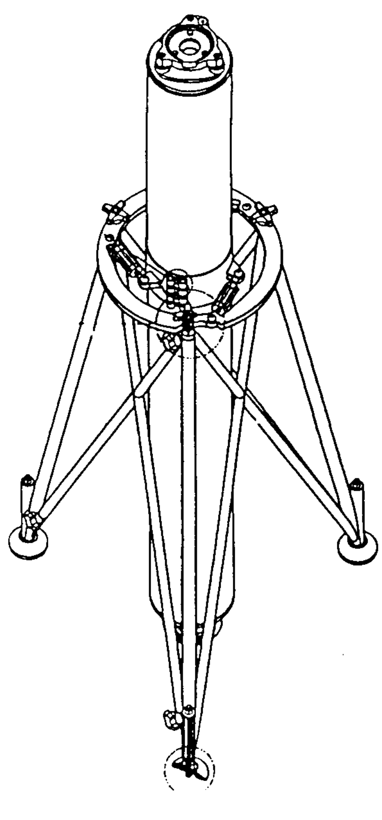

Figure 3b
The Monopod showing the adjusting mechanism.

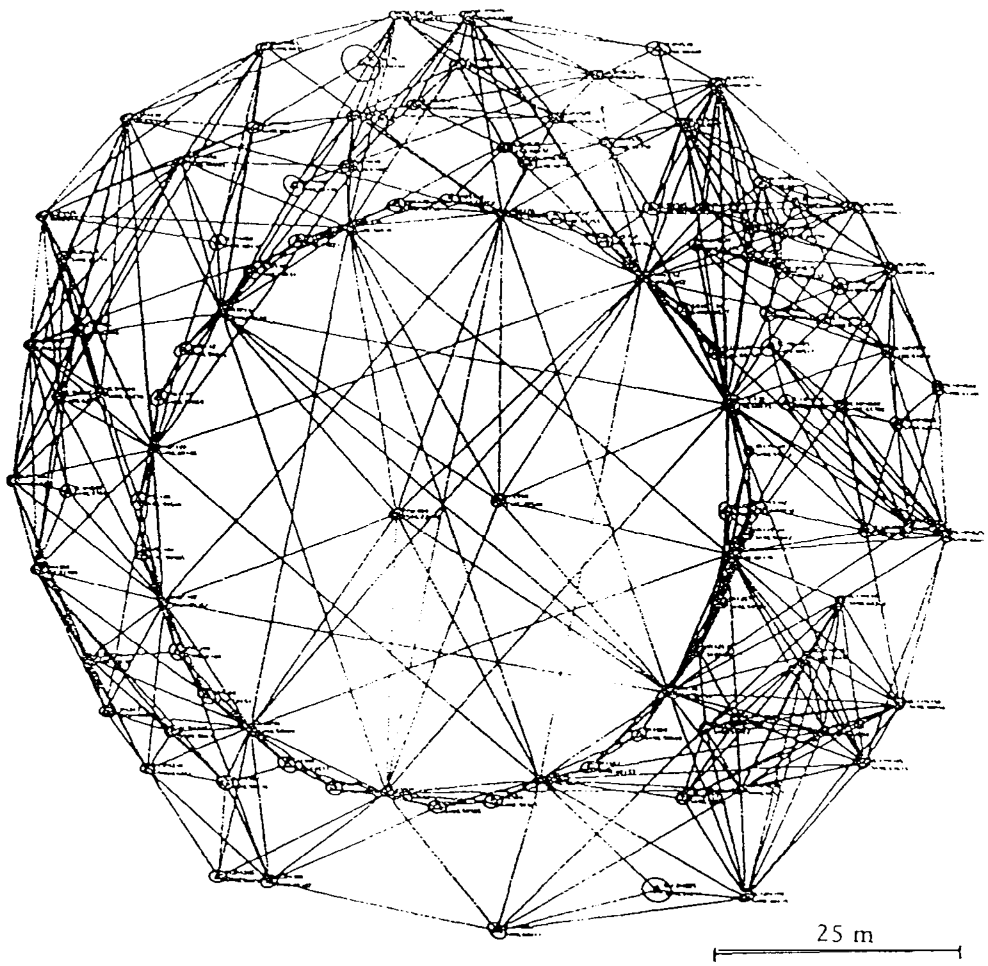

Figure 4
The ALS Monument Network 1995

Monumen	Semi-major axis [mm]	Semi-minor axis [mm]	Monumen	Semi-major axis [mm]	Semi-minor axis [mm]	Monument	Semi-major axis [mm]	Semi-minor axis [mm]
SR12P72	0.00	0.00	SR4P96	0.07	0.06	SR8P120	0.09	0.05
SR12S74	0.07	0.05	SR4S98	0.11	0.07	SR8S122	0.13	0.07
SR12S76	0.07	0.06	SR4S100	0.09	0.08	SR8S124	0.11	0.07
SR1P78	0.06	0.06	SR5P102	0.08	0.06	SR9P126	0.12	0.07
SR1S80	0.08	0.07	SR5S104	0.09	0.08	SR9S128	0.11	0.07
SR1S82	0.10	0.07	SR5S106	0.10	0.08	SR9S130	0.12	0.07
SR2P84	0.07	0.05	SR6P108	0.07	0.00	SR10P132	0.08	0.05
SR2S86	0.11	0.08	SR6S110	0.10	0.08	SR10S134	0.10	0.07
SR2S88	0.10	0.08	SR6S112	0.10	0.07	SR10S136	0.09	0.07
SR3P90	0.10	0.07	SR79114	0.09	0.06	SR11P138	0.07	0.06
SR3S92	0.10	0.07	SR7S116	0.11	0.07	SR11S140	0.07	0.06
SR3S94	0.12	0.07	SR7S118	0.12	0.07	SR11S142	0.07	0.05
						SR11S144	0.07	0.06

Table 2
Typical Storage Ring Error Ellipses in mm from the 1995 Network

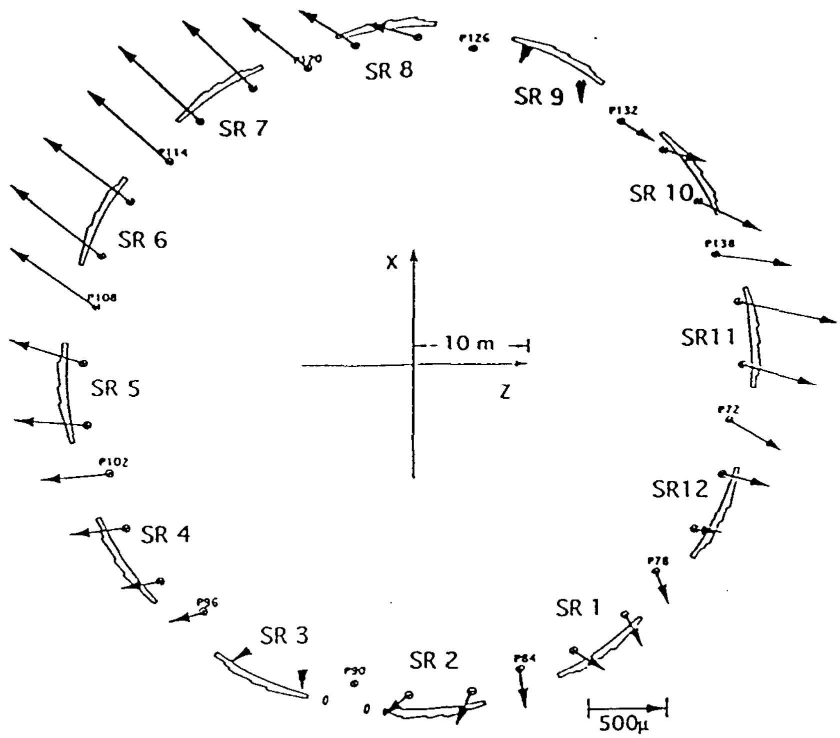

Figure 5a
The ALS storage ring monument motion in the horizontal plane (Mar. 93-Feb. 92)

Figure 5b
The ALS storage ring monument motion in the vertical plane (Mar. 93-Feb. 92)

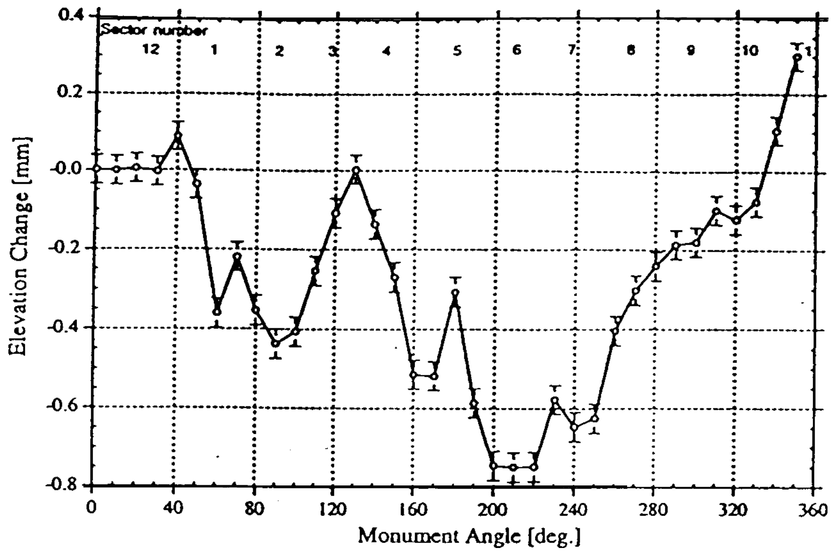

Figure 6a
Storage ring monument elevation changes from Feb. 1993 to Oct. 1993.

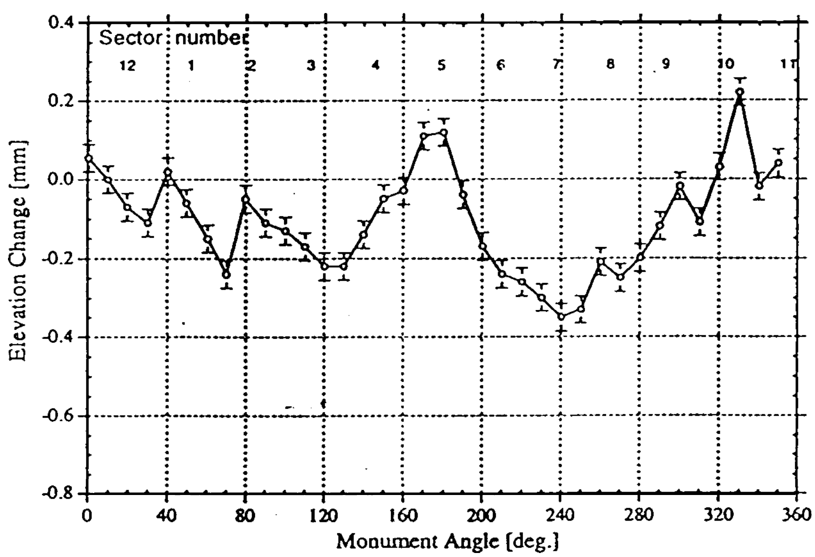

Figure 6b
Storage ring monument elevation changes from Oct.. 1993 to May 1994.

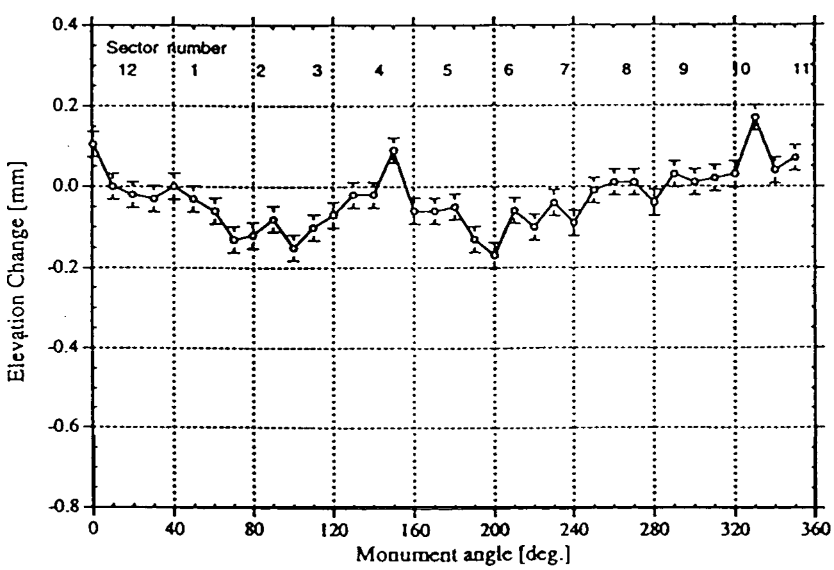

Figure 6c
Storage ring monument elevation changes from Feb. 1994 to June 1994

Liquid Levels

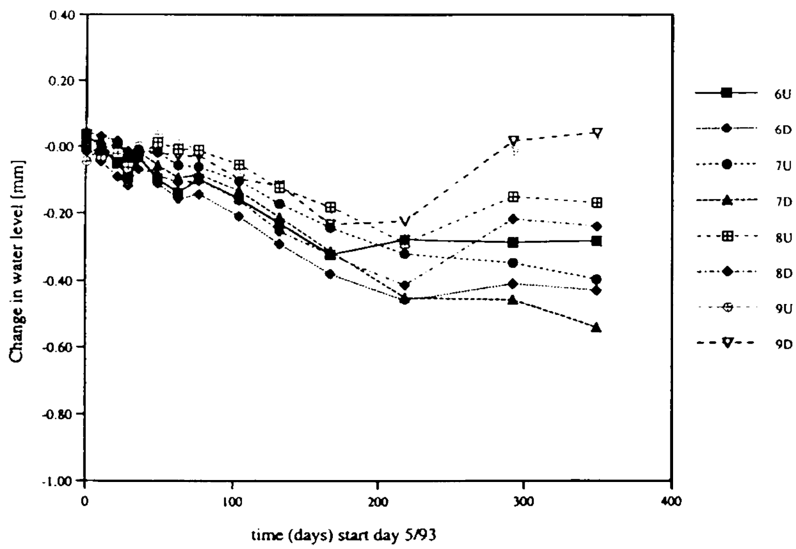

Figure 6d.
The change in water level in the area of floor loading.

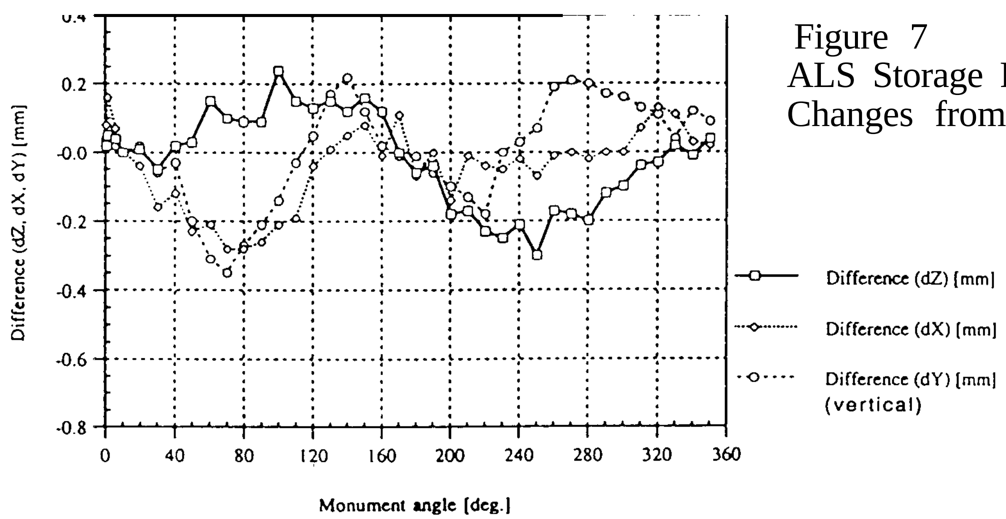

Figure 7
ALS Storage Ring monument Changes from 1/95 to 8/95

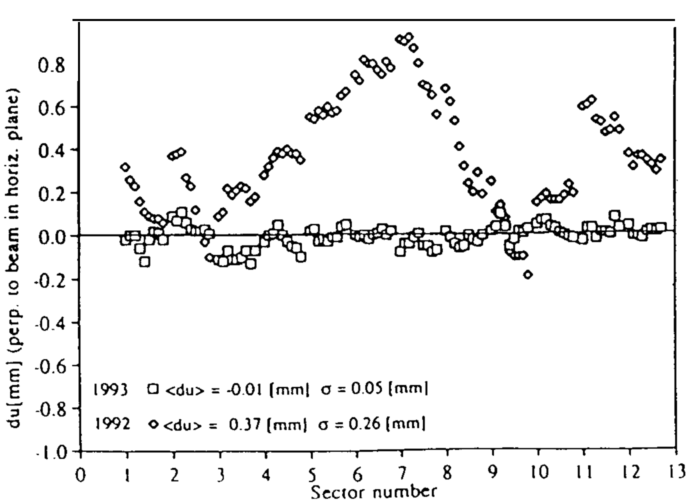

Figure 8a
Storage Ring magnet locations (horiz. plane) after alignment in 1992 and 1993

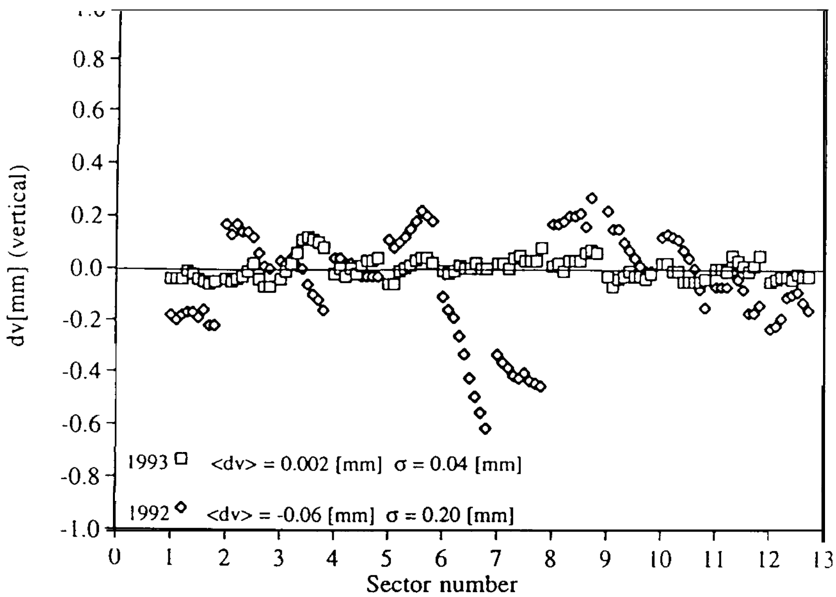

Figure 8b
Storage Ring magnet deviations (vertical) after alignment in 1992 and 1993

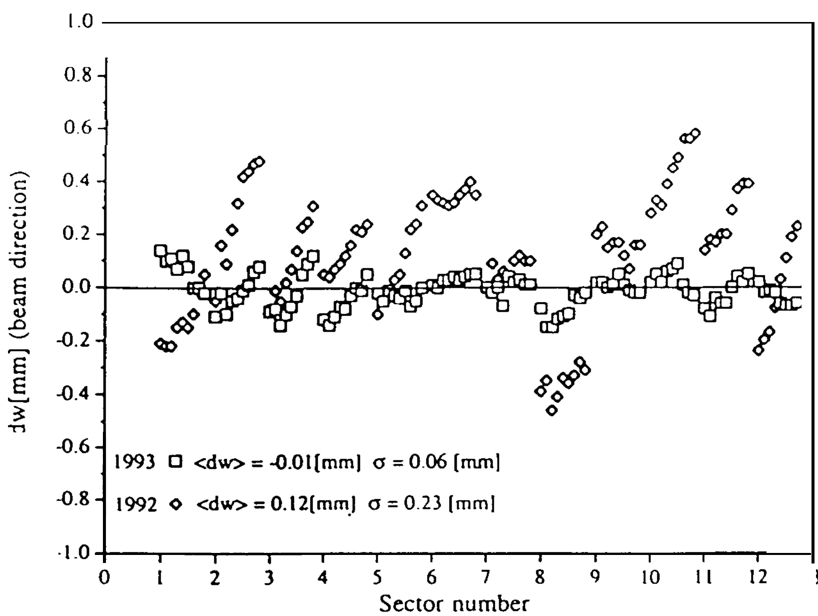

Figure 8c
Storage Ring magnet deviations (beam direction) after alignment in 1992 and 1993

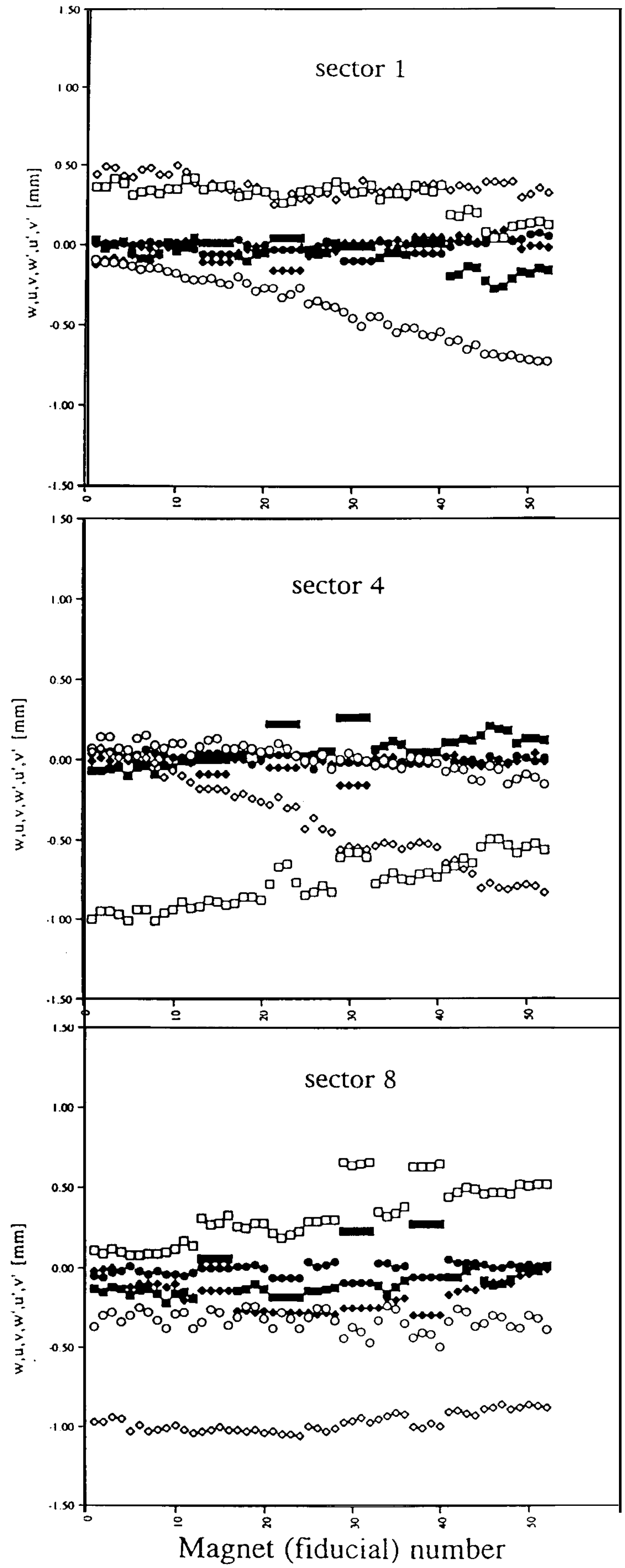

Figure 9
Deviations of Storage Ring magnets in the local magnets coordinate system before and after alignment in 1995 in sectors 1,4,8.

- □ w [mm] before alignment
- ◇ u [mm] before alignment
- ○ v [mm] before alignment
- ■ w' [mm] after alignment
- ◆ u' [mm] after alignment
- ● v' [mm] after alignment