PRECISE ALIGNMENT METHOD FOR TRISTAN ACCELERATOR

K. Endo

National Laboratory for High Energy Physics (KEK)
l-l Oho, Tsukuba-shi, Ibaraki-ken 305, Japan

Abstract Conventional alignment method was applied to the TRISTAN e+e- storage collider. It consists of length measurements based on the astral survey procedure, short chord and perpendicular. All magnets were aligned accurately according to the results obtained from the computational analysis of the survey data. The processes of the precise alignment and an additional topics, which has been adopted as a local re-alignment, are given in this report.

Introduction

The TRISTAN synchrotron is a colliding storage accelerator of electron and positron composed of the 30 GeV main ring (MR), the 8 GeV accumulation ring (AR) and the 2.5 GeV electron linac. Fig.1 shows the layout of the accelerator complex at KEK. The linac is an injector used for both photon factory and TRISTAN. The circumferences of MR and AR are 3018 and 377 m, respectively. The normal cell structures are given in Fig.2 for both rings. The MR has four long experimental insertions of 194 m at 4 interaction points, whereas AR has two of 19 m at 2 interaction points.

To attain a desirable performance of the synchrotron, the magnet alignment should be made within an allowable limit which is estimated from the the closed orbit distortions. In a large synchrotron, magnets are installed in a narrow tunnel constructed along a beam orbit. This makes the alignment difficult and special method must be applied. In many synchrotrons the astral survey technique developed by Laslett and Smith [1] has been employed [2,3]. This technique is one of the triangulation and depends on the linearization of the triangular relations of the short chord and perpendicular. It requires fairly accurate positioning of the magnets at the installation stage to make this method applicable. Therefore the magnet alignment were made in two stages - installation stage and alignment stage.

The survey measurements are made on the overlapped flat triangles which are composed of the successive three points (or magnets). The short chord means the sides containing a middle point and the perpendicular is the shortest distance to the side between two extreme points from the middle one. In the alignment stage the these points are assumed as the hole centers drilled precisely on the plates attached horizontally on the top of every magnet, whereas in the installation stage points were marked on the tunnel floor at every apex of polygon made by the inlet and exit central lines of every main dipole magnet. In both MR and AR rings the same alignment method was applied.

Both short chord and perpendicular data were processed using computer code to derive the positional errors of all points. The magnet displacements were corrected by adjusting the bolts of the positioning mechanism according to the computer output.

Installation stage

Before the magnet installation the apex points of polygon (monuments) given by the main dipoles were marked on the iron plates buried in the concrete floor. The coordinates of the apex points were calculated at first and then the several points, which would help the survey of whole synchrotron ring, were marked on the tunnel floor following the surface geodesic survey. As the tunnel was constructed by the open-cut method, the tunnel floor was observed directly from the ground level. These are the original points marked prior to marking the apex points. After the completion of the tunnel, the original points have never been observed from the outside and only help the generation of the apex points - in another words, the TRISTAN synchrotron ring has no fixed coordinate origin. By using a theodolite T2, an electronic tachymeter AGA112 and a steel tape, the apex points were determined with an accuracy of ±1 mm (rms). The straight lines were drawn on the floor connecting the neighboring apex points, the additional points were marked on these lines which were used to position the magnets with an accuracy of ±2 mm at the installation stage. The positional errors of the apex points obtained by the short chord and angle measurements are given in Fig. 3. The short chords were measured with a calibrated iron steel tape having the scale of 1 mm. Reading of the steel tape was made with an accuracy of ±0.1 mm by estimation applying 10 kg tension at both ends. The perpendiculars were derived using the short chord distances and corresponding angles measured with one second theodolite. An accuracy of the estimated displacements of the apex points from the design is ±1 mm (rms). If the additional points had an error of ±1 mm relative to the apex points, the installation error of the magnets would be ±2 mm (rms).

Alignment stage

For the precise alignment of the magnets, more accurate survey is required because the orbit error will be amplified about tenfold of the positional error of the focusing magnets (quadrupoles). Since the transverse displacement of the quadrupoles are the main source of the orbit distortion arising from the misalignment, the precise survey is applied only to the quadrupoles. If the allowable positional error arising from the magnet displacements is within ±1 mm (rms), the alignment error shall be within ±0.1 mm.

Before the survey in the horizontal plane, all quadrupoles and dipole magnets were adjusted in level and tilt. The tilt was corrected by using the coincidence level of Carl Zeiss Jena and the height by using the precision level N3 of Wild. Standard level of magnets, which gives the center of the height gauges when they are placed on the magnets, were marked on the tunnel wall near at every quadrupole by sticking the seal printed the scale and pointing mark. When sticking seals, the laser beam was used through the level. The beam height was determined from the beam axis of the detector at one of the colliding points.

At this alignment stage the short chord and perpendicular measurements were applied. To attain higher accuracy, more accurate instruments were used. The commercially available instrument, distometer of Kern & Co. (Fig.4), was used for the short chord measurement [4]. It uses the calibrated invar wire of 1.6 mm dia. Its accuracy is ±0.025 mm but it required the careful treatment and the frequent calibration with the laser interferometer on the special bench as shown in Fig.5.

The perpendicular measurement adopted the nylon string method which was originally developed at CERN [5] and modified to the present instrument of Fig.6. Stretching the nylon string of 0.2 mm dia. between the next neighboring quadrupoles with the tension of about 500 g using the fishing reel, the perpendicular from the middle quadrupole between them is obtained from the position of the reading microscope mounted on the instrument. Its accuracy is ±0.02 mm after the calibration by the same method as in the case of the distometer.

In both measurements, the accurate sockets were attached on the magnets to mount the instruments. Fig.7 shows how the measurements were done. A setting of the distometer is given in Fig.7(a) and the 8 kg tension can be applied through the built-in spring by rotating the fine adjustment ring until the pointer of the dial gauge of force measuring unit points to zero. Then the correct reading is obtained from the length measuring dial gauge. Both dial gauges must be calibrated beforehand. As the measuring range is 100 mm, several invar wires with different lengths are required to cover the different spacings of the magnets. Comparison between two wires with different diameters, 1.0 mm and 1.6 mm, before the measurement had resulted in the better reproducibility for the 1.6 mm dia. Wires must be handled carefully so as not to give a kink and kept stretched in a good condition to maintain an accuracy. The length of the invar wire was calibrated both before and after a set of measurements. If there was a difference in calibrations more than 0.05 mm, all data concerned were thrown away and re-measured.

In Fig.7(b) a setting of the offset measuring device is given. A nylon string is stretched between two extreme magnets and an offset reading device is placed on the middle magnet. The offset reading device is rotatable around the central axis of the mounting socket so that its arm can be set at right angles to the nylon string. A reading microscope with a magnification of 50 is mounted on the arm and is slid by a worm gear. A rotating knob is attached to the gear axis and one rotation of the knob gives an advance to the microscope by 2 mm. The knob has a fine scale of 0.01 mm which is calibrated with the laser interferometer on the bench. A rough scale of 1 mm is marked on the arm. Using the rough and fine scales, the offset position can be read to an order of 0.001 mm by estimation. A backlash error is avoided to bring the cross hairs close to the surface of the nylon string always from the same side.

In the repeated measurements after displacing magnets to correct their positions, data before and after displacements were compared to check the measurement errors and miss displacements. The magnitude of the correction displacement of each magnet is given by the results of the following section. A procedure consisting of survey, data process and correction is repeated several times until the rms error of the mis-alignment becomes less than the tolerable limit.

Processing the survey data

Trigonometric relations among three successive points (i-1, i, i+1) of Fig.8 are as follows [2],

$$S_{i-1}^2 = R_{i-1}^2 + R_i^2 - 2R_{i-1}R_i \cos \Theta_{i-1} \tag{1}$$

$$S_i^2 = R_i^2 + R_{i+1}^2 - 2R_iR_{i+1} \cos \Theta_i \tag{2}$$

$$L_{i-1}^2 = R_{i-1}^2 + R_{i+1}^2 - 2R_{i-1}R_{i+1} \cos(\Theta_{i-1} + \Theta_i) \tag{3}$$

$$P_iL_{i-1} = 2\sqrt{t(t - S_{i-1})(t - S_i)(t - L_{i-1})} \tag{4}$$

$$t = \frac{1}{2}(S_{i-1} + S_i + L_{i-1}), \tag{5}$$

where S and P are the short chord length and perpendicular distance, respectively. R and Θ are the radial distance and the angle with regard to the ring center respectively and t is the half circumference of the triangle. Eliminating L_{i-1} from above relations,

$$P_i^2 \{ R_{i-1}^2 + R_{i+1}^2 - 2R_{i-1}R_{i+1} \cos(\Theta_{i-1} + \Theta_i)\}$$
$$= \{ R_{i-1}R_i \sin \Theta_{i-1} + R_iR_{i+1} \sin \Theta_i - R_{i-1}R_i \sin(\Theta_{i-1} + \Theta_i)\}. \qquad (6)$$

Differentiating both sides and substituting p_i, r_i and $\theta_{i+1}-\theta_i$ for $\Delta P_i, \Delta R_i$ and $\Delta\Theta_i$ respectively, the offset error p_i is obtained.

$$\begin{aligned}
p_i = & \{\frac{B}{A}[R_i\sin\Theta_{i-1}-R_{i+1}\sin(\Theta_{i-1}+\Theta_i)]-\frac{P_i^2}{A}[R_{i-1}-R_{i+1}\cos(\Theta_{i-1}+\Theta_i)\}r_{i-1} \\
& +\{\frac{B}{A}[R_{i+1}\sin\Theta_i+R_{i-1}\sin\Theta_{i-1}]\}r_i \\
& +\{\frac{B}{A}[R_i\sin\Theta_i-R_{i-1}\sin(\Theta_{i-1}+\Theta_i)]-\frac{P_i^2}{A}[R_{i+1}-R_{i-1}\cos(\Theta_{i-1}+\Theta_i)]\}r_{i+1} \\
& +\{\frac{B}{A}[R_{i-1}R_i\cos\Theta_{i-1}-R_iR_{i+1}\cos\Theta_i]+\frac{P_i^2}{A}R_{i-1}R_{i+1}\sin(\Theta_{i-1}+\Theta_i)\}\theta_{i-1} \\
& +\{\frac{B}{A}[R_{i-1}R_i\cos\Theta_{i-1}-R_iR_{i+1}\cos\Theta_i]\}\theta_i \qquad (7) \\
& +\{\frac{B}{A}[R_iR_{i+1}\cos\Theta_i-R_{i-1}R_{i+1}\cos(\Theta_{i-1}+\Theta_i)]-\frac{P_i^2}{A}R_{i-1}R_{i+1}\sin(\Theta_{i-1}+\Theta_i)\}\theta_{i+1},
\end{aligned}$$

where A and B are defined as

$$A = P_i \{ R_{i-1}^2 + R_{i+1}^2 - 2R_{i-1}R_{i+1}\cos(\Theta_{i-1}+\Theta_i)\}$$
$$B = R_{i-1}R_i \sin \Theta_{i-1} + R_iR_{i+1} \sin \Theta_i - R_{i-1}R_{i+1} \sin(\Theta_{i-1}+\Theta_i).$$

Differentiating Eq.(2) and substituting s_i, r_i and $\theta_{i+1}-\theta_i$ for $\Delta S_i, \Delta R_i$ and $\Delta\Theta_i$ respectively, the similar relation can be obtained for the short chord error s_i.

$$\begin{aligned}
s_i = & \frac{1}{S_i}[R_i - R_{i+1} \cos \Theta_i] r_i + \frac{1}{S_i}[R_{i+1} - R_i \cos \Theta_i] r_{i+1} \\
& - \frac{1}{S_i}[R_iR_{i+1} \sin \Theta_i] \theta_i + \frac{1}{S_i}[R_iR_{i+1} \sin \Theta_i] \theta_{i+1}. \qquad (8)
\end{aligned}$$

Eqs.(7) and (8) are formulated in a matrix form applying them to all points (i=1, 2, 3, ... , n). That is,

$$\begin{pmatrix} p_i \\ s_i \end{pmatrix} = \begin{pmatrix} M \end{pmatrix} \begin{pmatrix} r_i \\ \theta_i \end{pmatrix} \quad (i = 1,2 \;, \ldots\ldots, \; n), \qquad (9)$$

where M is a (2n x 2n) matrix which consists of coefficients of r_i and θ_i in Eqs.(7) and (8) (n=392 for MR and n=96 for AR). According to the least squares method, $(r_i \, \theta_i)^T$ is obtained as

$$\begin{pmatrix} r_i \\ \theta_i \end{pmatrix} = (M^TM)^{-1} M^T \begin{pmatrix} p_i \\ s_i \end{pmatrix} \qquad (i = 1,2,\ldots\ldots,n), \qquad (10)$$

where the superscript T means the transpose of the matrix. The p_i and s_i are the deviations of the perpendicular and short chord distances from the design values, respectively. The positional errors of magnets can be reduced from r_i and θ_i obtained from Eq.(10) in a form of the parallel displacements with regard to the present positions. Eqs.(7) and (8) are applicable even for three magnets aligned on the straight line.

Matrix M has 3 degrees of freedom, so its rank must be reduced. It can be done by defining that one magnet has no both radial and angular error and its nearest neighbor magnet has no radial error. Therefore the new matrix is 2n by 2n-3 and the solutions has a ring center different from the design. To minimize the displacement of the ring center, r_i and θ_i are re-processed so as to minimize the total square sum of displacement of every magnet by giving the rotation and parallel translation without deforming the geometry. Accordingly the shift of the ring center will be small enough but the ring has no fixed center [6,7].

If the survey data have random errors, the unwanted harmonics will appear in the solution. In general the low order harmonics have large amplitudes, so the harmonics with orders far from the betatron oscillation frequencies shall be rejected from the solution. If r_i or $R_i\theta_i$ is expressed in a function **f(O),** its Fourier expansion is as follows,

$$f(\Theta) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos k\Theta + b_k \sin k\Theta), \qquad (11)$$

where a_k and b_k are the Fourier coefficients;

$$a_k = \frac{1}{\pi} \int_0^{2\pi} f(\Theta) \cos k\Theta \, d\Theta \qquad (k = 0,1,2, \ldots) \qquad (12)$$

$$b_k = \frac{1}{\pi} \int_0^{2\pi} f(\Theta) \sin k\Theta \, d\Theta \qquad (k = 1,2, \ldots). \qquad (13)$$

Eliminating harmonics less than 19-th for MR, the residual errors are estimated from the numerical simulations as ±0.1 mm at the curved section and ±0.5 mm at the experimental straight section for the assumed rms survey error of 0.01 mm. Therefore, the alignment at the straight section was done by the direct observation with the theodolite. The r_i and $R_i\theta_i$ are converted to the practical values indicating the parallel displacements with regard to the present location. Fig.9 is the results obtained from above procedures.

Essentially the same mathematical method was applied to correct the monuments at the installation stage. In this case r_i and $R_i\theta_i$ were used for the correction of the monuments. Fig.3(b) is the results obtained after the second cycle of measurements and corrections.

Local re-alignment

After the beam operation has begun, several parts of the vacuum system were frequently repaired, replaced or improved because of maintenance or modification. In these cases several quadrupoles were removed and re-aligned. The removed magnets were aligned with respect to the adjacent unremoved quadrupoles. Instruments described above can be usable but they require a lot of time for calibration. To align in a reasonable time a three dimensional survey system, ECDS2 of Kern & Co., has been introduced since 1988 [8]. It consists of two one-second electronic theodolites E2, a scale bar to give an absolute length and a computer for data taking and processing as shown in Fig.10. To increase a portability the computer has been replaced an original one with a domestic laptop with a built-in co-processor, J3100 of Toshiba Co.

A spherical target of Rank Taylor Hobson Ltd. is used which are convenient to get a good sight because its targeting center coincides with the spherical center and it can be rotated on the top of the socket with a spherical concave so as to face the theodolite.

In the three dimensional survey the short chord and perpendicular distances are obtained from the angle measurements with two theodolites located apart [9]. A global coordinate system, which surrounds the magnets concerned, is defined from the survey for the bundle adjustment and the on-line measurement of the spherical target placed precisely on the magnet gives (x,y,z) coordinates. The origin of the coordinates is at one of the theodolites. Measuring three successive magnets, the short chord length and the offset are calculated with the special functions in the program. If there is a recognized difference in the magnet height, the related coordinate can be modified before calculations with the help of an editor in the program.

An accuracy of the alignment of this method is ±0.05 mm radially and ±1 mm azimuthally when it is applied in a small area. The large azimuthal error is due to an oblique sighting of magnets at both ends which is inevitable in the narrow tunnel. This is relieved somewhat by the fact that the beam is less sensitive to the longitudinal misalignment of the magnet compared with the transverse misalignment.

In the large area such as in an experimental hall where the big detector is located, the distance of sighting is more than 10 m, so an accuracy becomes poor seriously. It is difficult to align magnets on both sides of the detector which interrupts the direct sighting. To overcome this situation another method has been being tried using laser beam through the theodolite, level and optical plummet.

References

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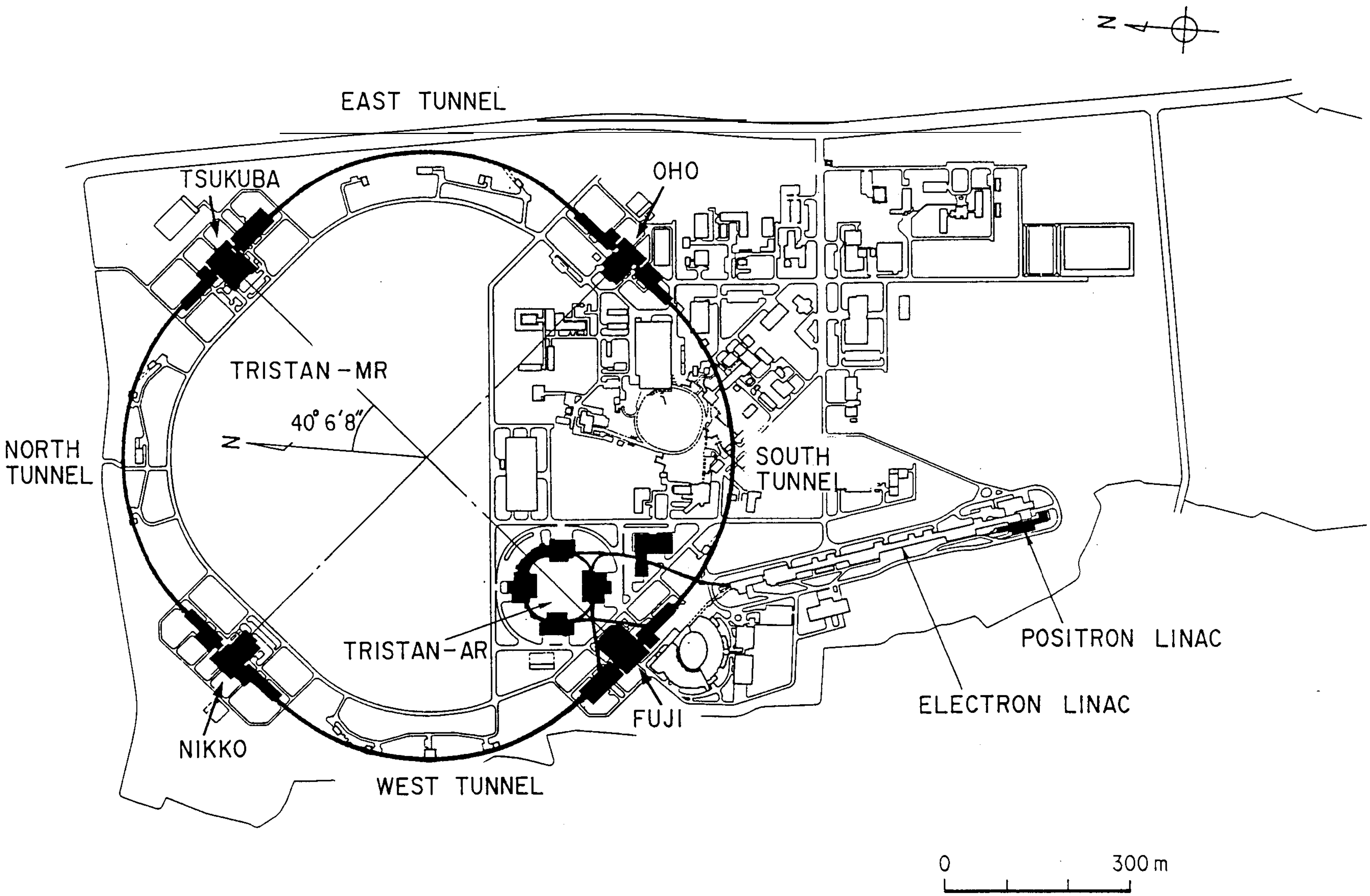


Fig. Layout of TRISTAN synchrotron.

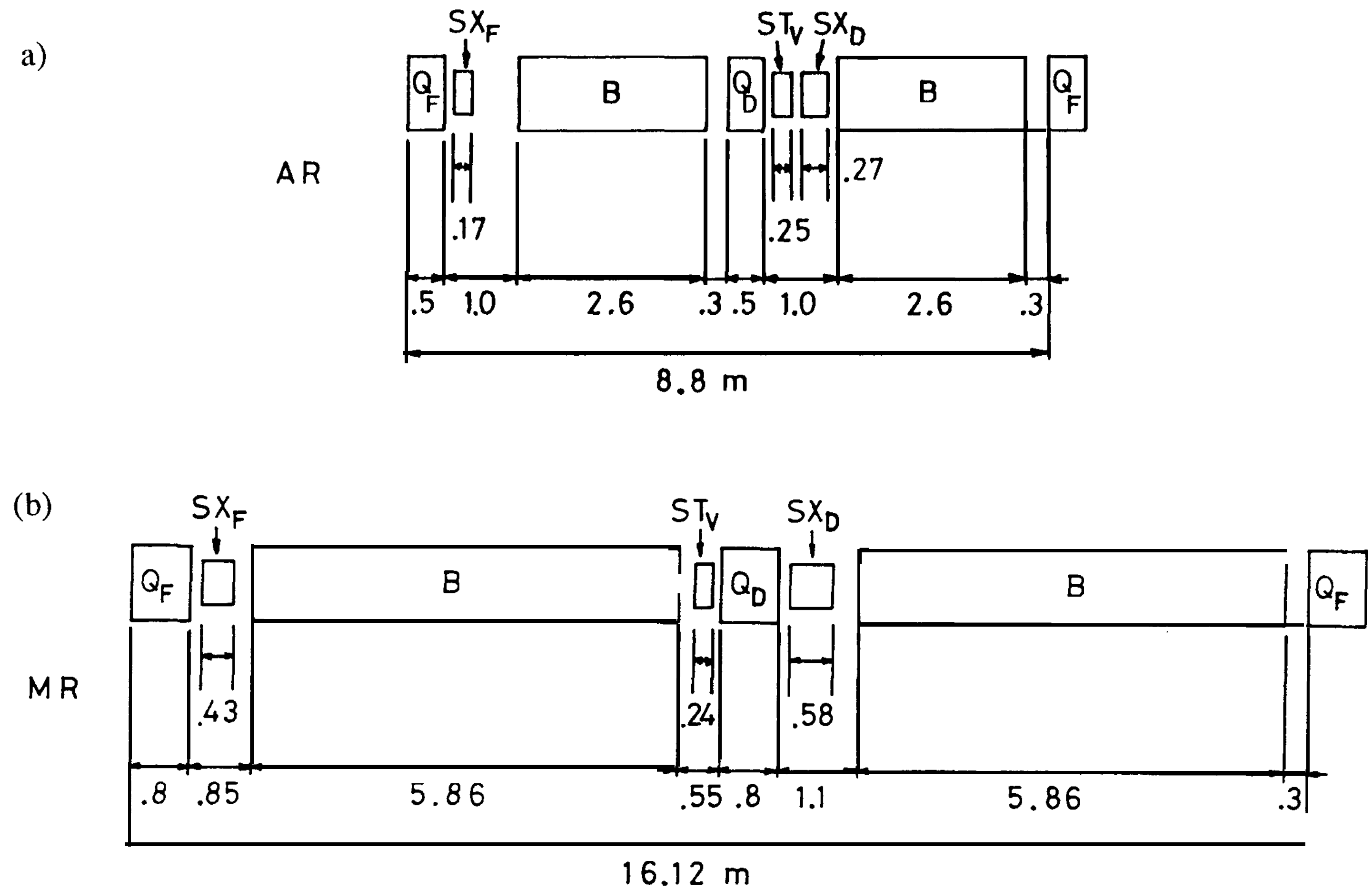
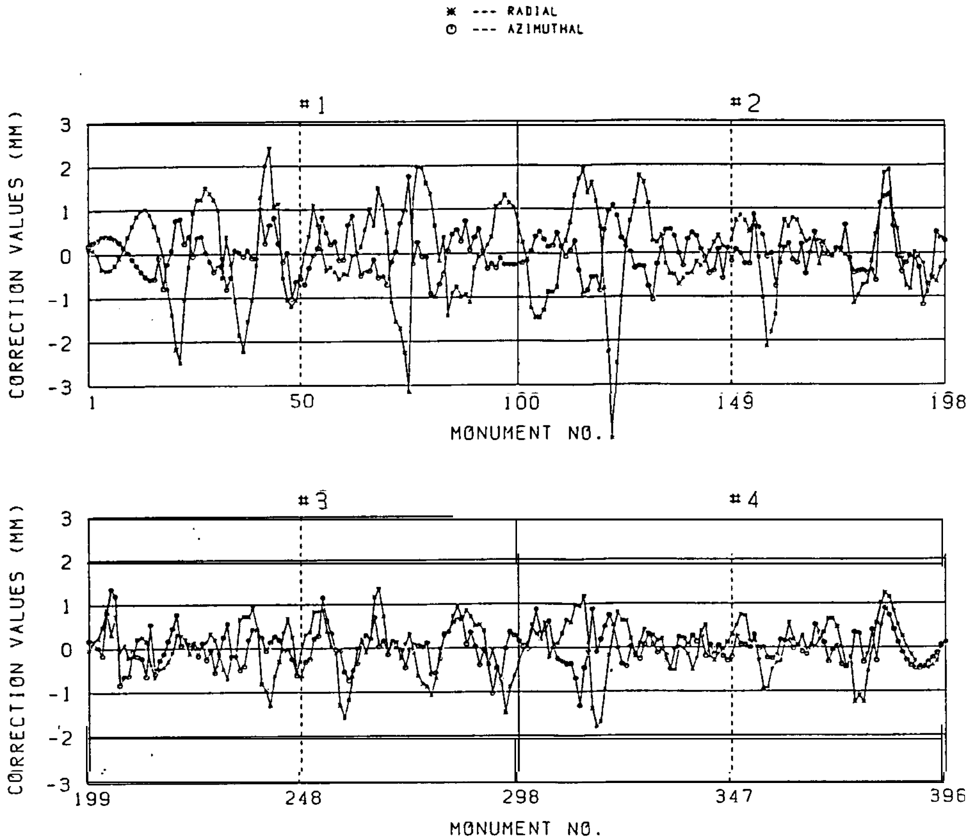
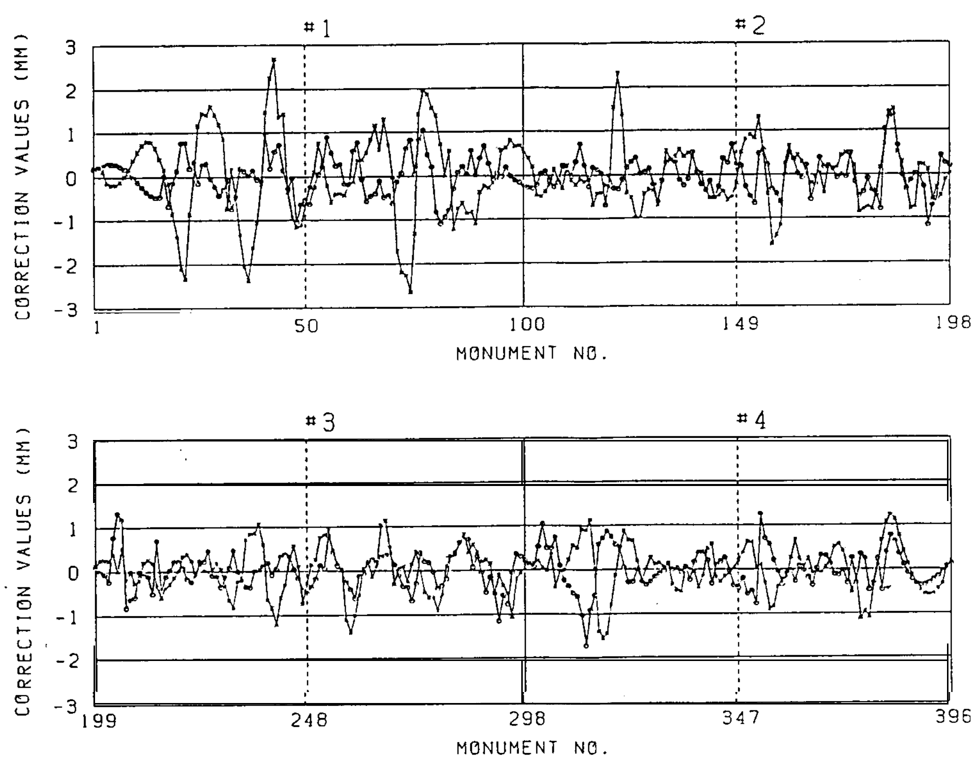


Fig.2 Normal cell structures of (a) AR and (b) MR (B=Bending, Q=Quadrupole, SX=Sextupole, ST_V=Vertical steering magnet).



(a)



(b)

Fig.3 Positional error of monuments, (a) before and (b) after correction.

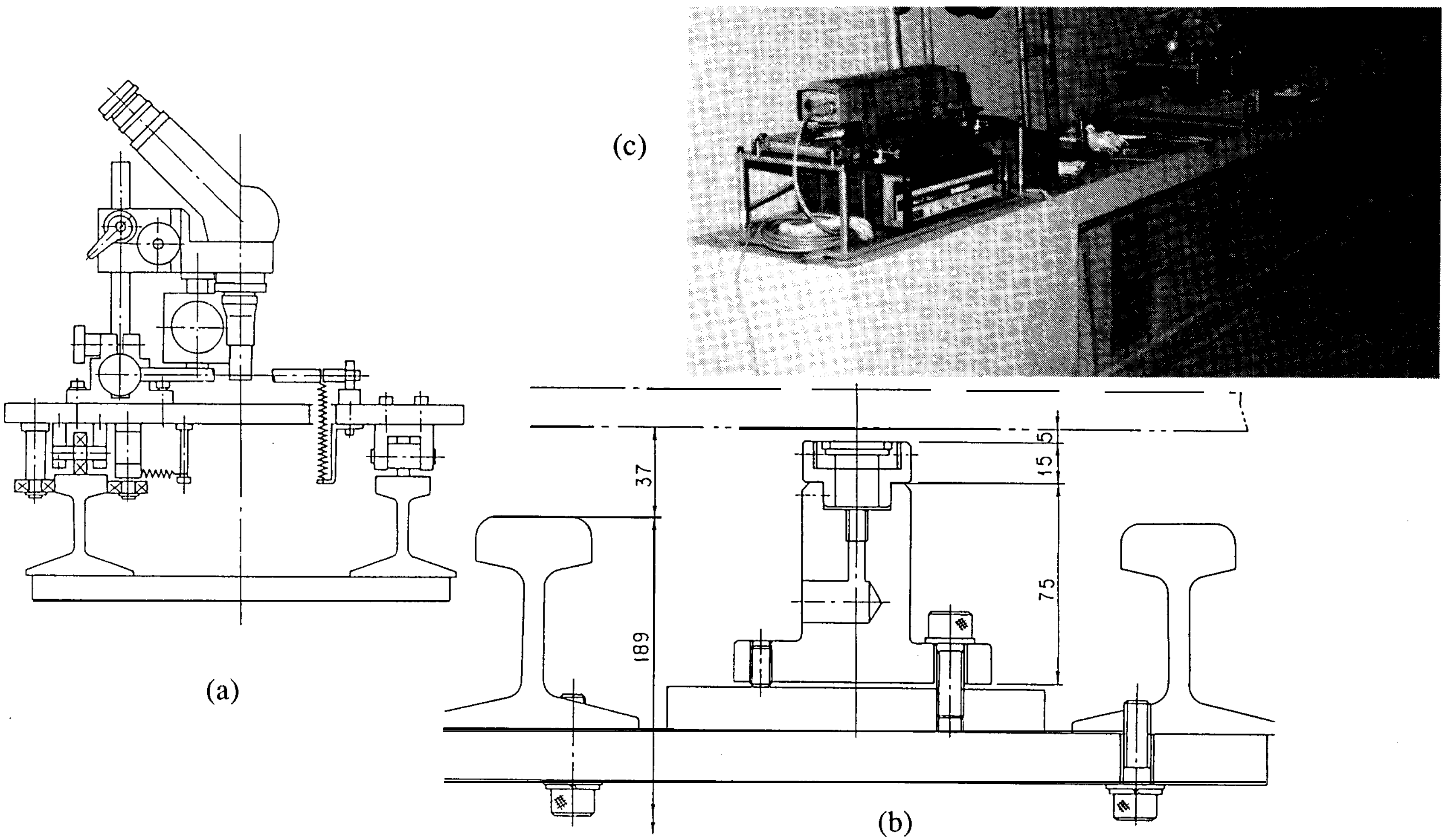
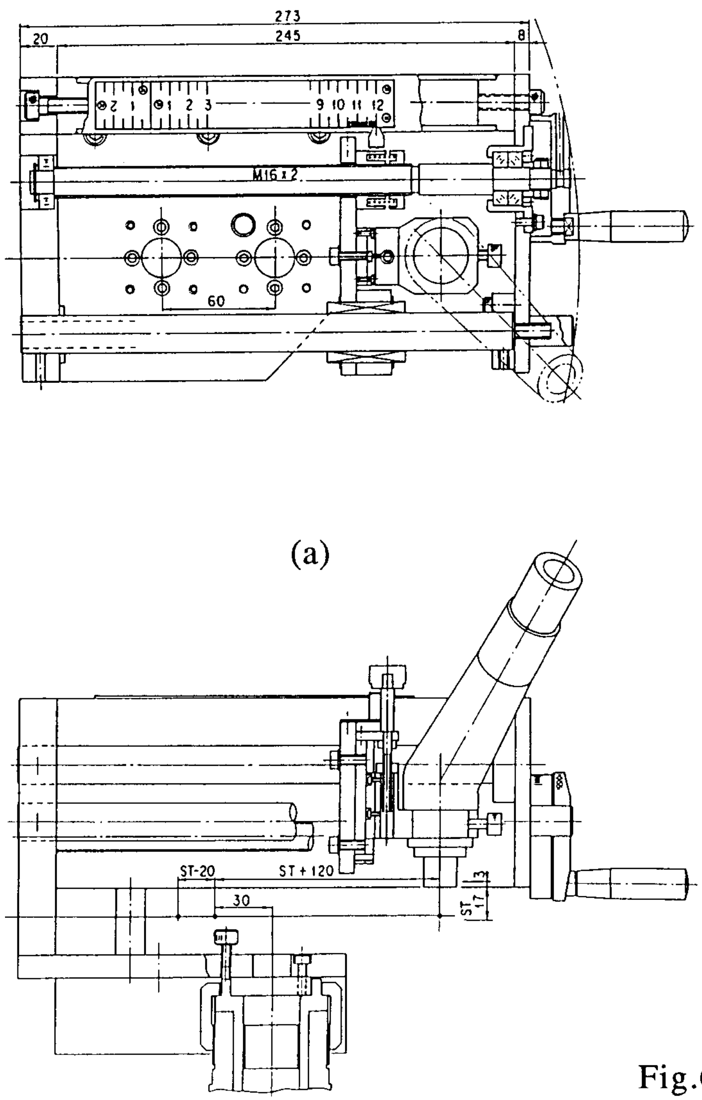
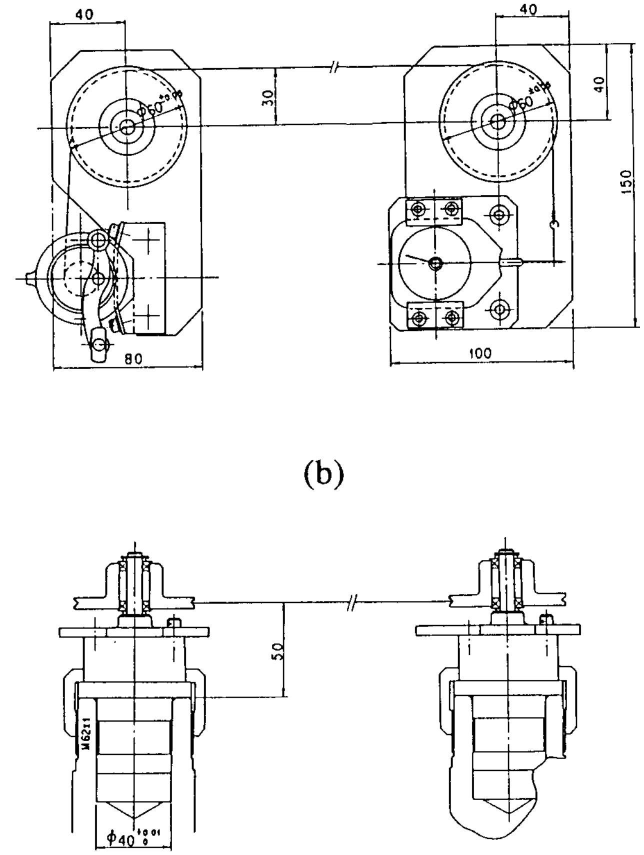


Fig.5 Cross-section of the calibration bench - (a) reading microscope mounted on rails, (b) socket to fix the setting bolt of invar wire or cross hairs, and (c) laser interferometer.



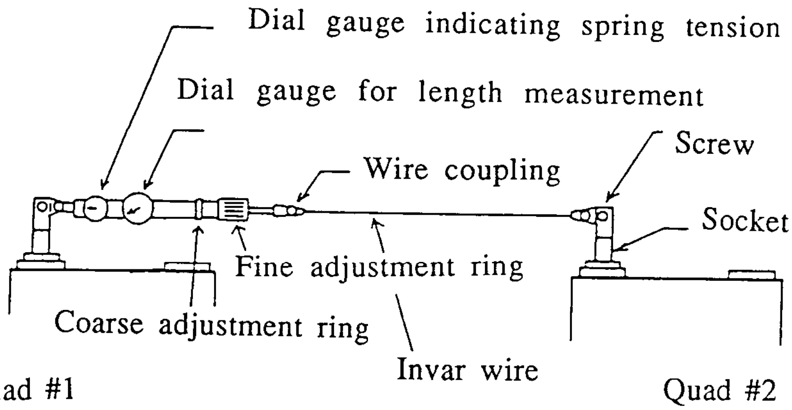
(a)



(b)

Fig.6 Offset measuring device, (a) reading microscope and (b) reals to support a nylon string.

(a)



(b)

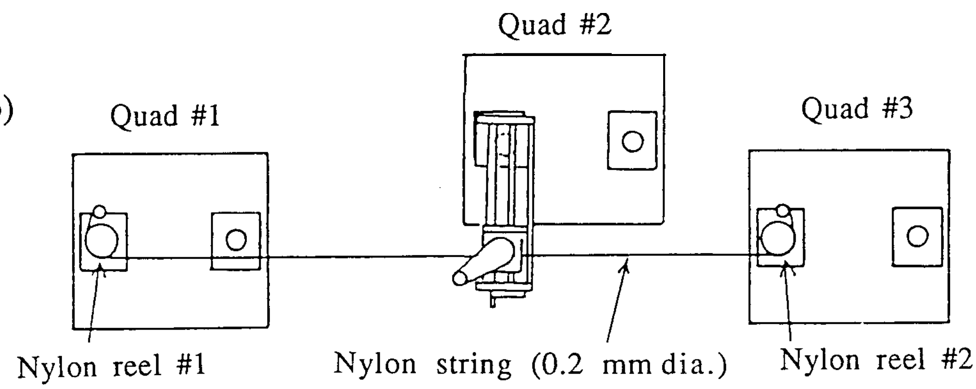


Fig.7 Setting of (a) distometer and (b) offset measuring device.

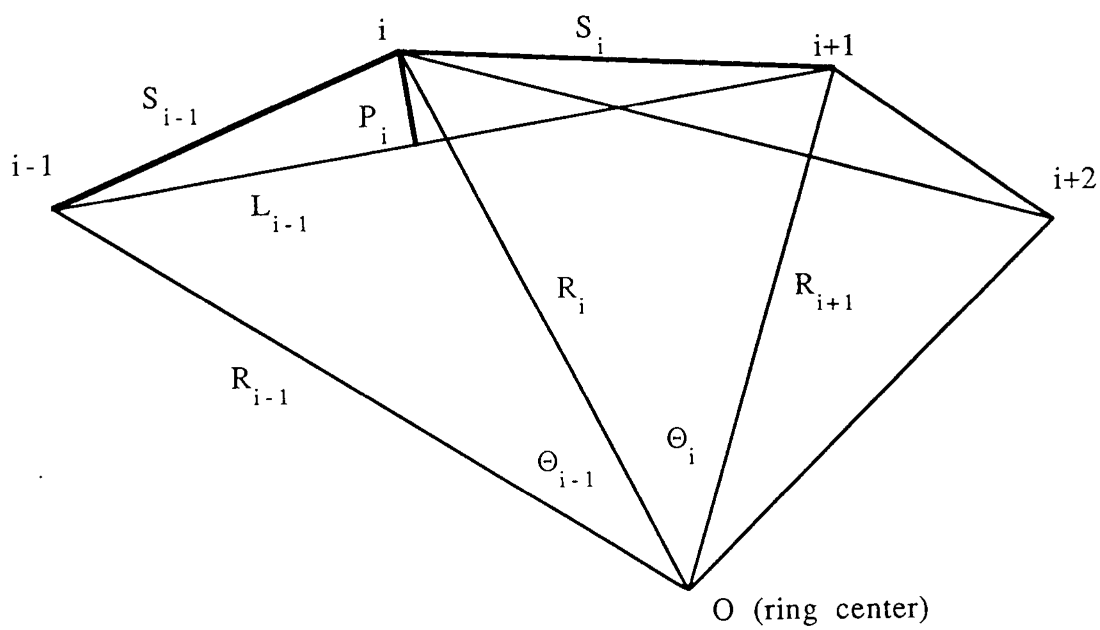
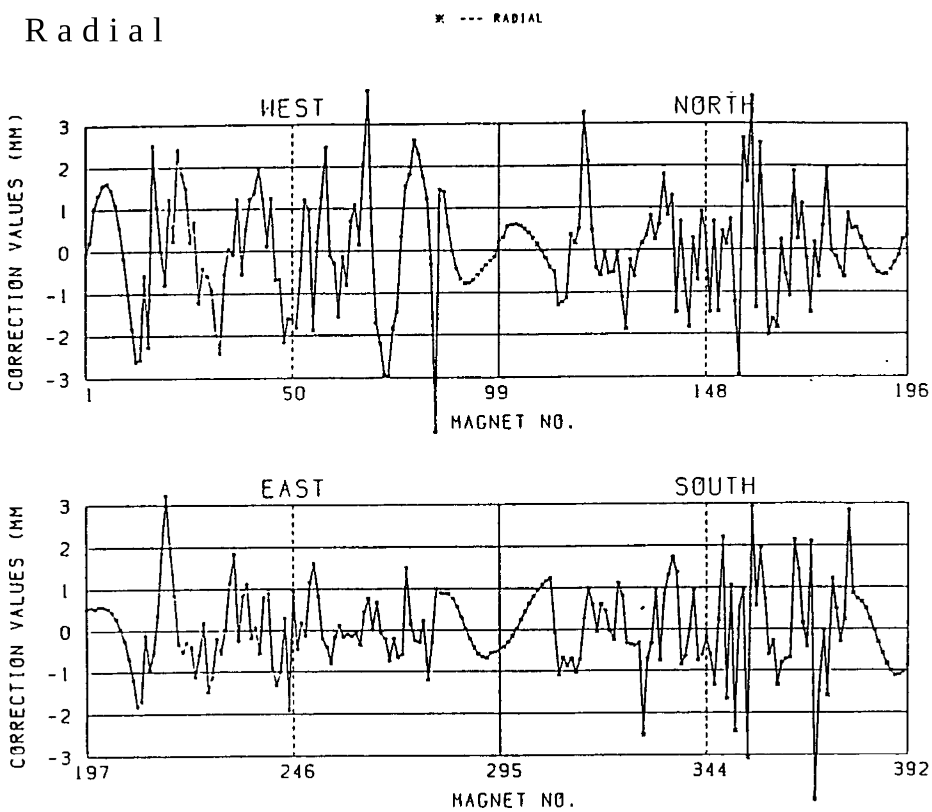


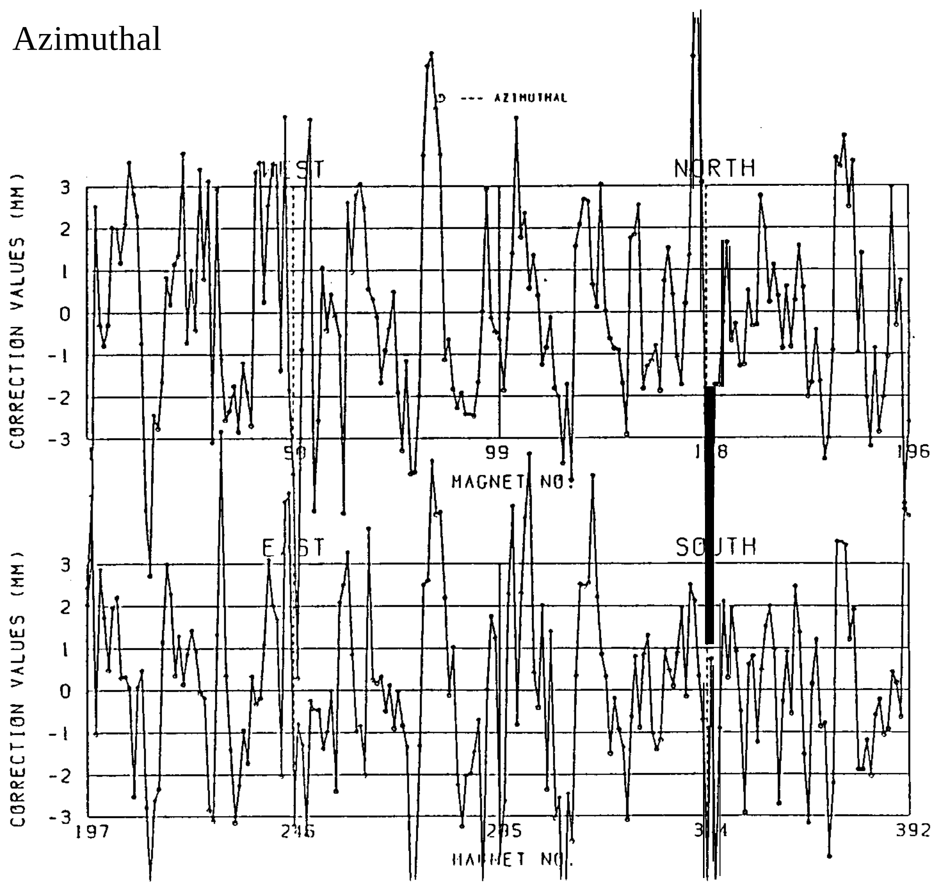
Fig.8 Notations appearing in the trigonometric relations of triangle (i-1, i, i+1).

Radial

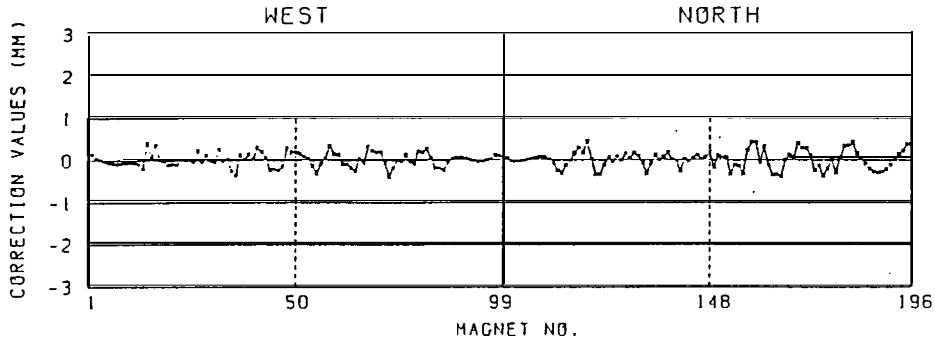


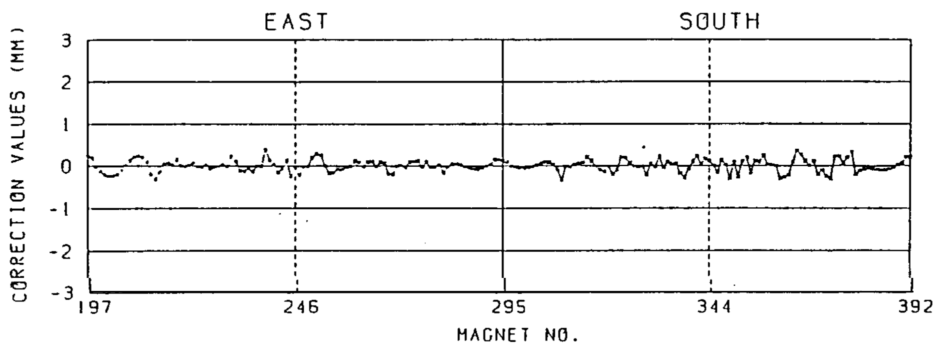
(a)

Azimuthal



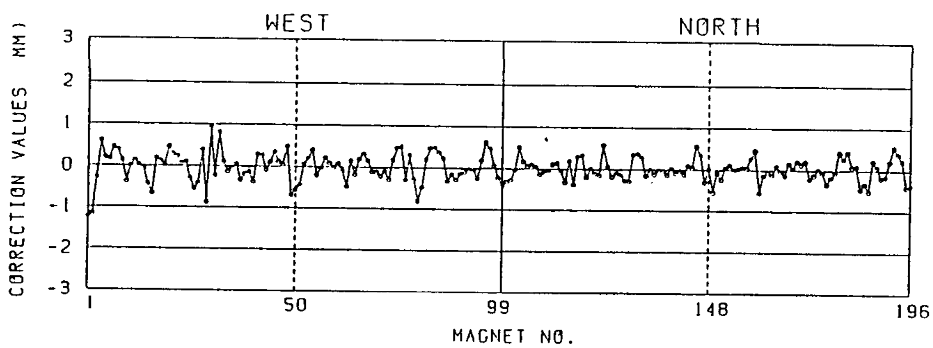
Radial





(b)

Azimuthal



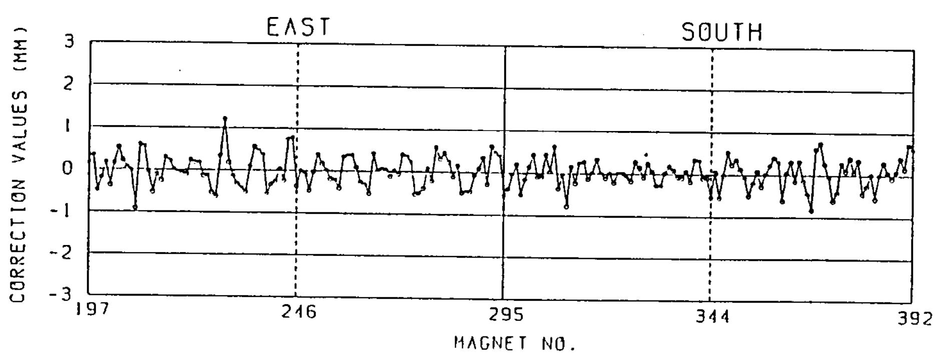


Fig.9 Results of the precise alignment - (a) the radial and azimuthal errors of quadrupoles before correction. (b) the final misalignments after three cycles of displacements.

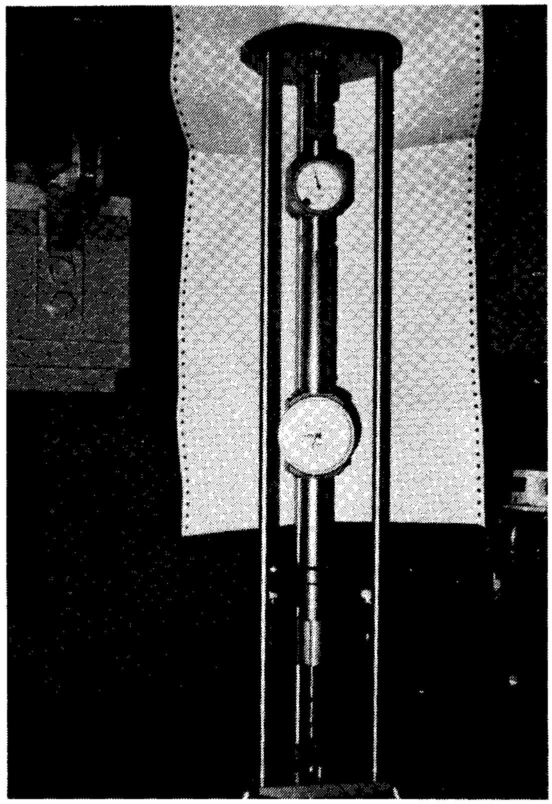


Fig.4 Distometer used for the short chord measurements.

Fig.10 Local alignment at the curved section with a three dimensional survey system.