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NOTE 87-15
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ALIGNMENT OF THE ITC

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Abstract

Procedures are outlined for the alignment of the ITC both by mechanical means and through the use of cosmic rays. Using a Monte Carlo simulation it is shown that a few hundred cosmic rays will be sufficient.

A scheme is presented for relating the measured digitisings of the ITC to coordinates. It is used to investigate possible sources of inaccuracy in the alignment, and no serious problems are found.

I Alignment Procedure

Introduction

This part of the note is based upon the work presented at the Alignment meeting at CERN on 4th June 1987 *. Further details may be found in the minutes of that meeting.

The problem to be addressed is to find the relative alignment of the ITC coordinate system to that of the TPC. This requires the specification of 6 numbers: 3 translations and 3 rotations. The coordinate system chosen to define these offsets is the standard Cartesian system (X,Y,Z), with Z along the beam axis and Y vertical. The rotations chosen are the standard ϕ angle defining the rotation about Z, and two tilt angles ω and ψ, about axes Y and X respectively. See Figure 1.

The precision to which the offsets must be known is determined by the requirement that the resulting error in a hit coordinate is negligible compared to other sources of error, such as the resolution of the chamber and variations in the wire positions. This gives a desired precision of 30–50 μm in the X and Y coordinates of any hit.

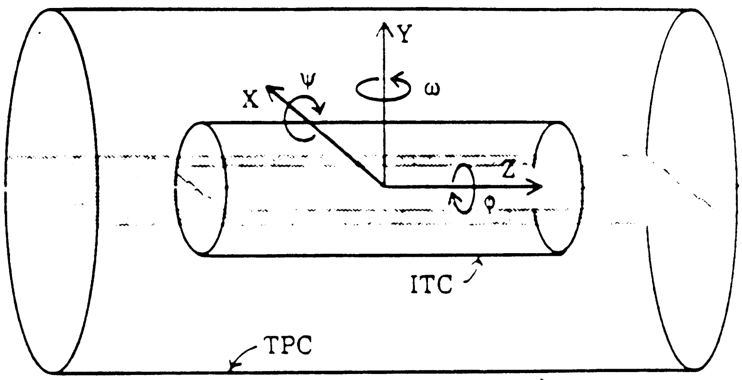


Figure 1 *Definition of coordinates*

* Previously released as an Imperial College note [1].

Mechanical alignment

It is estimated [2] that the alignment by mechanical means will be accurate to 250 μm in all coordinates at any point.

Survey marks, in the form of scribed lines, exist on the end flanges of the ITC, accurate to 100 μm. However, they will not be visible after the assembly of the detectors in the pit, due to the Luminosity Tracking Chambers, and the pumps that sit at either end of the beam pipe segment with their supports.

The proposed scheme for mechanical alignment is to provide a precision seating for the ITC, that may be accurately surveyed and adjusted if necessary. The chamber is then simply lowered into position. The seating will take the form of a V-block, made by two machined brackets attatched to each endplate of the TPC. The end flanges of the ITC will rest on these brackets, and its rotational position will be defined by a third bracket at the top of the chamber at each end.

To allow the seating to be surveyed, it is proposed to construct a ring of the same radius as the end flanges, with an adjustable cross-hair. This would then be positioned on each of the V-blocks in turn and measured.

Cosmic ray alignment

Once the ITC and TPC have been assembled and are sitting in the pit, it is intended to measure their alignment using cosmic rays that pass through both detectors. As the experiment is 150 m underground the cosmic rays will be predominantly vertical, and their rate will be low, estimated at about 0.2 s^{-1} passing through the ITC [3].

A Monte Carlo simulation has been used to develop the procedure for alignment using cosmic rays, and to predict some results. The Monte Carlo used was Galeph (19.0), with modifications to include cosmic ray generation, misalignment of the ITC and sagging of the ITC wires [4]. The effect of the detectors on the hit coordinates was simulated by the introduction of resolution smearing and two-hit separation [5]; the problems of relating the measured digitisings to coordinates in the detectors will be considered in the second part of the note.

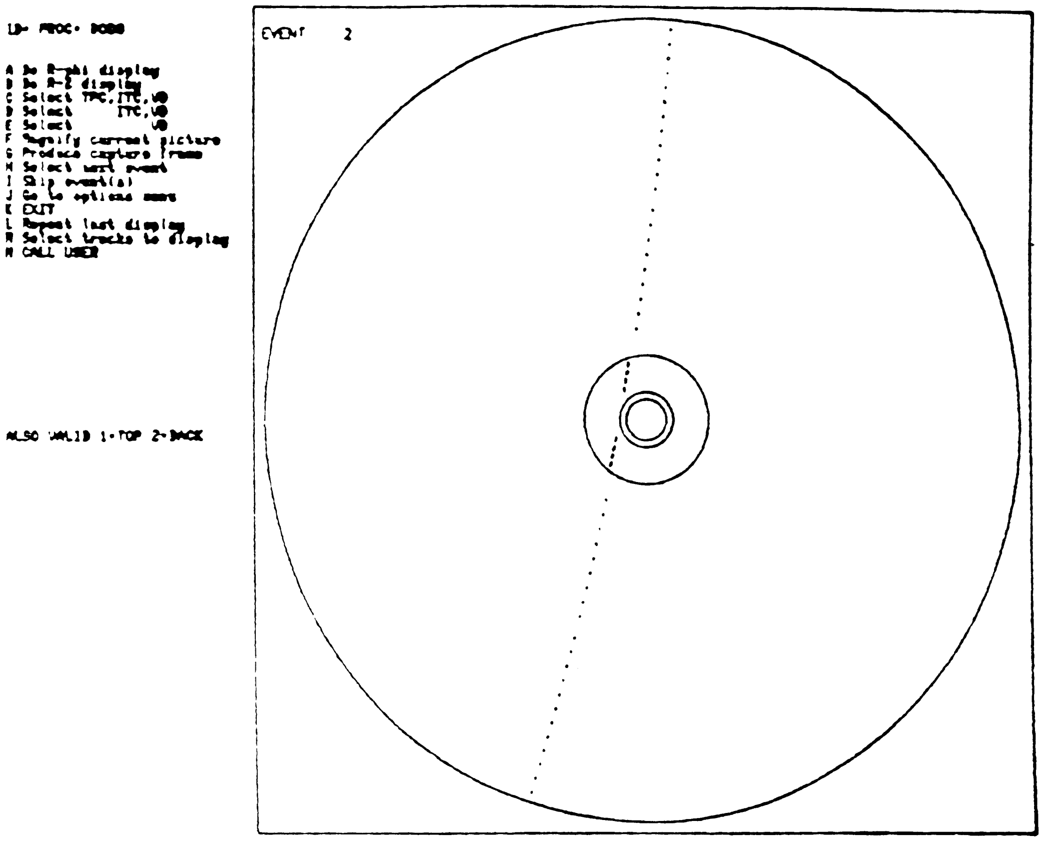
The program developed for the measurement of the alignment [6] runs in the Oberon analysis framework at Imperial College [7]. It functions as follows: for each event tracks are fit in the ITC and TPC independently, and the fit parameters are stored. When all the events have been processed, the alignment offsets are extracted from a comparison of the track fit parameters. This involves two least-squares fits and an iterative procedure. Finally a Gaussian fit to each offset parameter is given, providing an error on its measurement.

Track fitting

The hit multiplicities of the ITC and TPC are required to lie within defined ranges (16 hits in the ITC and 30–42 hits in the TPC), to ensure that good tracks are found. A typical event is displayed in Figure 2. Tracks are fit as a circle in the R-ϕ projection (transverse to Z) and a straight line in the S-Z projection, where S is the distance along the track in the R-ϕ view. S $\rightarrow$ -S when Y < 0 so that a straight line may be fit using all hits.

The parameters determined by these fits are illustrated in Figure 3.

R-ϕ



S-Z

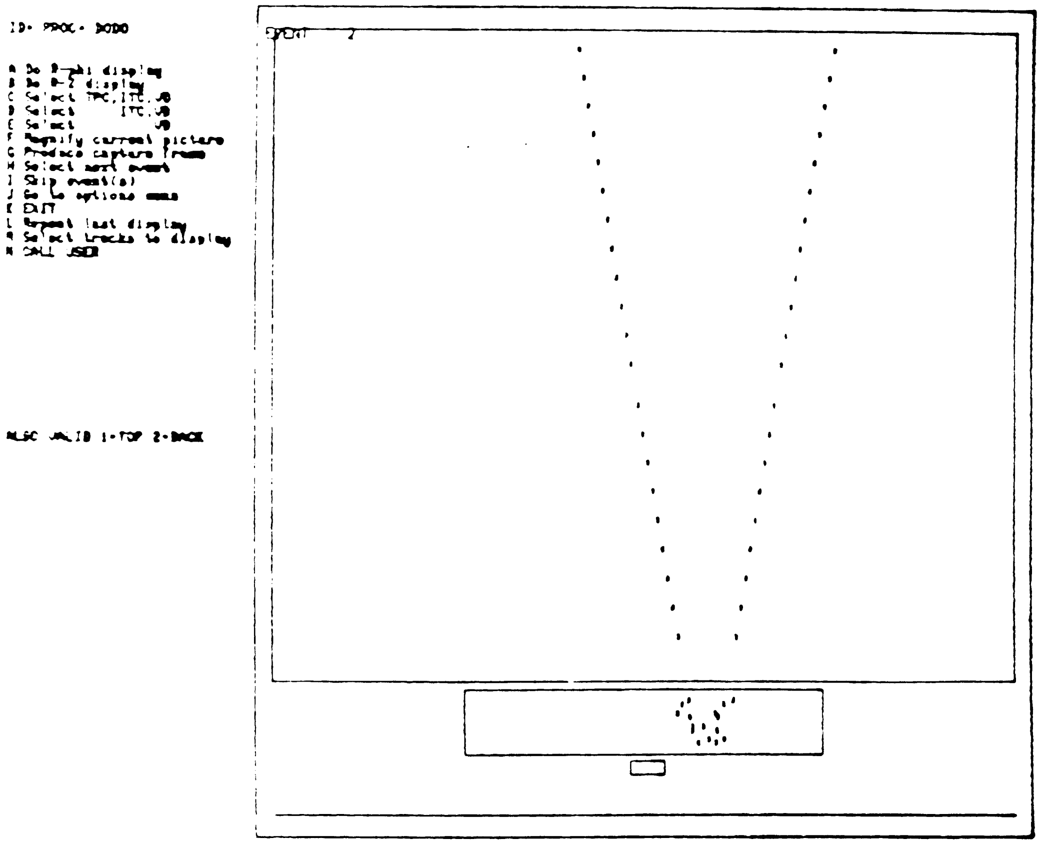


Figure 2 Event display

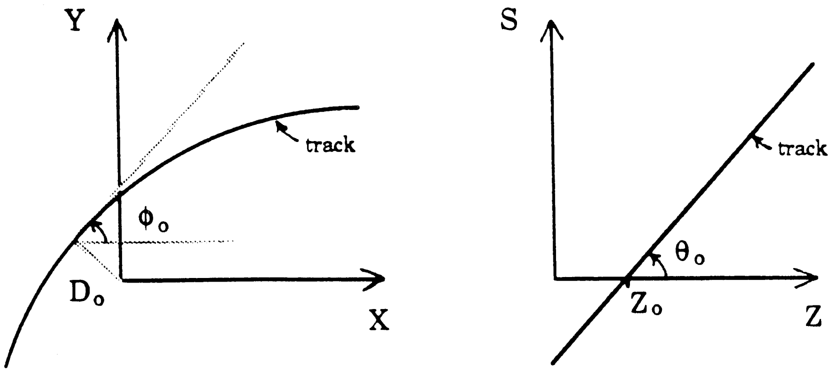


Figure 3 *Track fit parameters*

The fit parameters are as follows:

D_0	Distance of closest approach of track to the origin in R-ϕ (> 0 if circle contains origin, < 0 otherwise)
ϕ_0	ϕ angle of track at D_0 point ($0 < \phi_0 < \pi$)
R_0	Radius of curvature of track
Q	Sign of track (= charge of particle)
Z_0	Z coordinate of track at D_0 point
θ_0	Dip angle of track at D_0 point ($0 < \theta_0 < \pi$)

These parameters are taken from the track fits in both the ITC and the TPC and stored for each event.

Alignment offset calculation

In what follows, the alignment offsets are denoted by δ, and measured differences (ITC –TPC) are denoted by Δ. For the difference in closest approach distance ΔD_0 to be in the same sense for tracks of different charge, a factor of Q must be included in its definition, that is: $\Delta D_0 \rightarrow Q\,\Delta D_0$, where Q is taken from the TPC fit. See Figure 4.

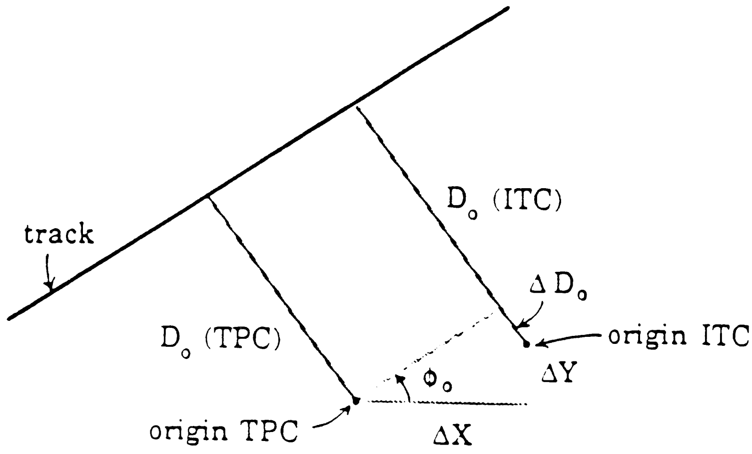


Figure 4 *Calculation of transverse offsets*

From simple geometry:

$$\Delta D_o = \Delta X \sin \phi_o - \Delta Y \cos \phi_o$$

The tilt angles introduce a Z dependence into the transverse offsets of the chamber in R-ϕ:

$$\Delta X = \delta X + Z_o \,\delta\omega$$

$$\Delta Y = \delta Y + Z_o \,\delta\psi$$

giving:

$$\Delta D_o = (\delta X + Z_o \,\delta\omega) \sin \phi_o - (\delta Y + Z_o \,\delta\psi) \cos \phi_o$$

Rearranging this gives:

$$\frac{\Delta D_o + (\delta Y + Z_o \,\delta\psi) \cos \phi_o}{\sin \phi_o} = Z_o \,\delta\omega + \delta X$$

The second term in the numerator on the left is suppressed by a factor $\cos \phi_o$, which is small for near-vertical cosmic rays, so to a first approximation we may put $\delta Y = \delta\psi = 0$. Then this becomes the equation of a linear fit of ΔD_o v. Z_o, from which the values of δX and $\delta\omega$ can be extracted. Their values are fed into the corresponding equation for δY and $\delta\psi$:

$$\frac{(\delta X + Z_o \,\delta\omega) \sin \phi_o - \Delta D_o}{\cos \phi_o} = Z_o \,\delta\psi + \delta Y$$

so that δY and $\delta\psi$ may be calculated. These values are then used in turn to improve the calculation of δX and $\delta\omega$, and an iterative procedure follows. The presence of a factor ($1/\cos\phi_o$) in the equation for δY and $\delta\psi$ necessitates a cut on $|\cos\phi_o|$, since this factor blows up for $\phi_o \approx 0$. A cut of $|\cos\phi_o| > 0.3$ is chosen, as illustrated in Figure 5. The linear fits are accomplished using a least-squares method [8], with Z_o and ϕ_o taken from the TPC track fit. The iteration converges rapidly: a requirement that the change in calculated Y offset should be less than 1 μm is typically achieved after 2 iterations.

The offset in Z is measured simply from the difference in Z_o:

$$\delta Z = \Delta Z_o$$

Since the ITC Z resolution is poor, this is not very accurately determined. However for the same reason it is not important, and the accuracy of the mechanical positioning of the chamber will be adequate.

Finally the offset in ϕ is given by the difference in ϕ_o, but with a correction due to the tilt angles:

$$\delta\phi = \Delta\phi_o - \cot\theta_o\,(\delta\omega \sin\phi_o - \delta\psi \cos\phi_o)$$

A separate histogram may now be filled for each of the 6 offset parameters, and a Gaussian fit [9] applied.

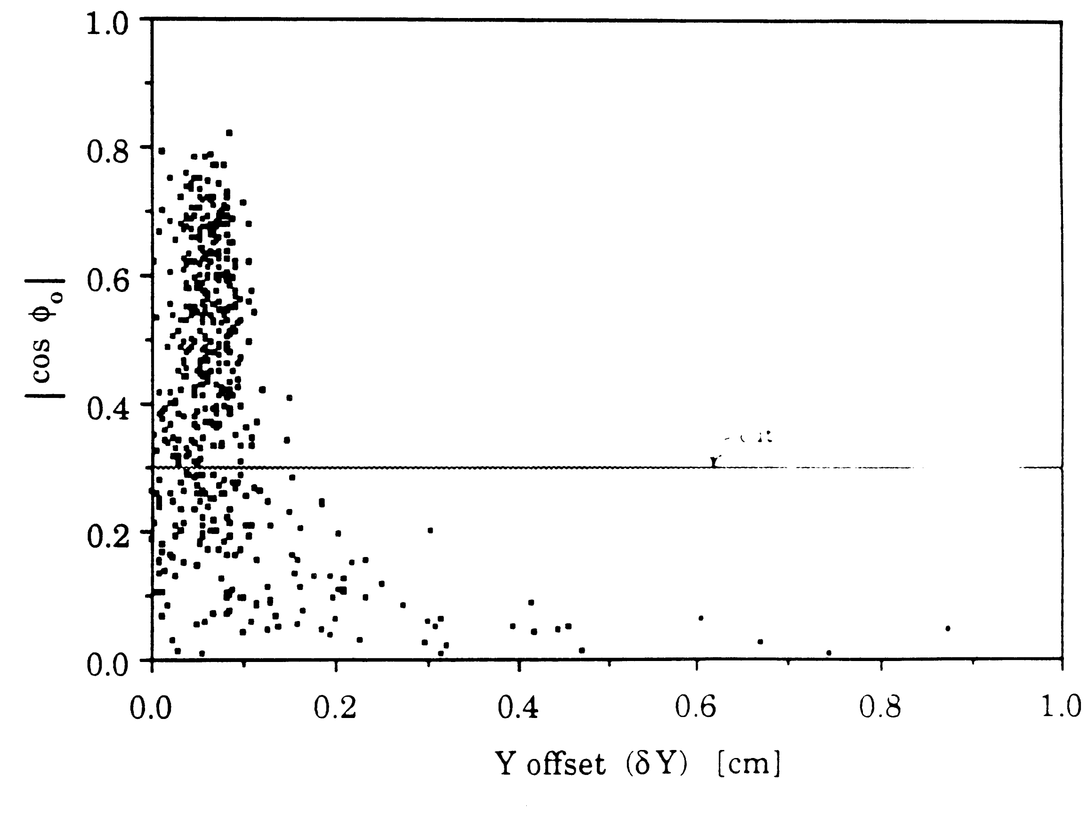


Figure 5 *Cut on $|\cos\phi_o|$*

Results

Cosmic rays were generated with a flat momentum distribution between limits of 2–20 GeV/c, with a flat distribution in ϕ between limits of $\pi/2 \pm \pi/4$, and passing through the full length of the TPC *. The detector parameters used were as follows:

R-ϕ resolution ITC	100 μm
Z resolution ITC	3.0 cm
R-ϕ resolution TPC (basic)	180 μm
R-ϕ resolution TPC (β dependence)	0.12 cm
Z resolution TPC (basic)	500 μm
Z resolution TPC (drift length term)	25 μm
R-ϕ 2 hit separation TPC	0.9 cm
Z 2 hit separation TPC	1.5 cm

The calculation of the alignment offsets is best illustrated with an example: an arbitrary misalignment between the ITC and the TPC is chosen, as shown in the INPUT row of Table 1, and 500 events are selected with a good track fitted in both chambers. The resulting alignment parameter distributions are shown in Figure 6, along with their fits. The calculated values and errors for the offsets are shown in Table 1.

	δX [μm]	δY [μm]	δZ [μm]	$\delta\phi$ [μrad]	$\delta\omega$ [μrad]	$\delta\psi$ [μrad]
INPUT	200	600	-1000	800	-400	500
Iteration 1	197	594				
Iteration 2	207	594				
OUTPUT	207	594	-993	777	-392	507
Error (σ)	7	13	355	12	16	32

***Table 1** Example of offset calculation*

* These correspond to the suggested values in Ref. 4.

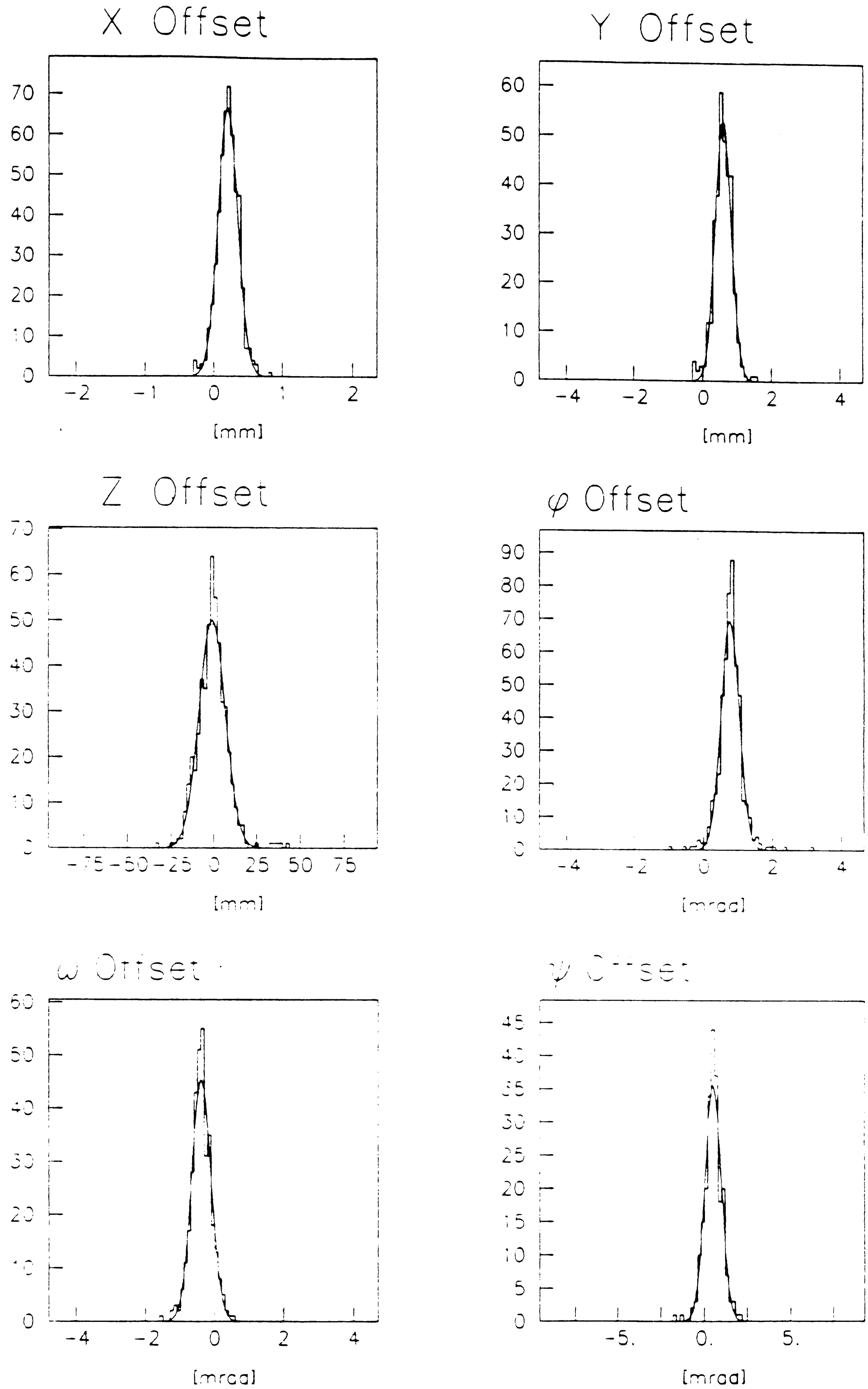


***Figure 6** Alignment parameter distributions*

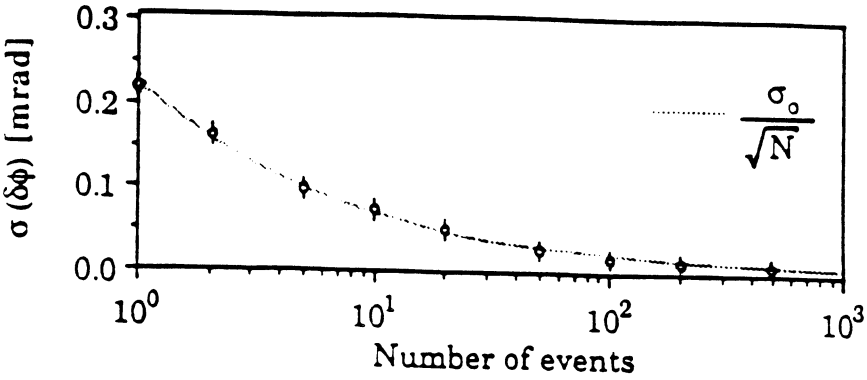


Figure 7 *Variation of error with number of events*

The error on the measurement of an offset parameter corresponds to the error on the calculation of the mean of a distribution, which is determined by the number of entries into the histogram. For a distribution of N values of parameter a, with mean â:

$$\sigma(\hat{a}) = \frac{\sigma(a)}{\sqrt{N}}$$

This relationship was verified for the ϕ offset, see Figure 7. The measured error obviously depends on the resolution fed into the Monte Carlo. If the resolutions are doubled, so are the errors.

The results are summarised in Figure 8, where the number of events refers to the number of good reconstructed cosmic rays. The reduction due to the $|\cos \phi_0|$ cut (for the Y and ψ offset calculations) must be considered: for the parameters used here, this gives a reduction of about 65 % in the number of events available for the calculation of these offsets.

An angular error of 1 mrad corresponds to a maximum spatial error of about 250 μm for ϕ and 1 mm for the tilt angles ω and ψ. Thus it can be seen from Figure 8 that the desired precision of 30–50 μm in the X and Y coordinates of any hit may be achieved with a few hundred cosmic rays, and the corresponding error on the Z offset will be ≈ 300 μm.

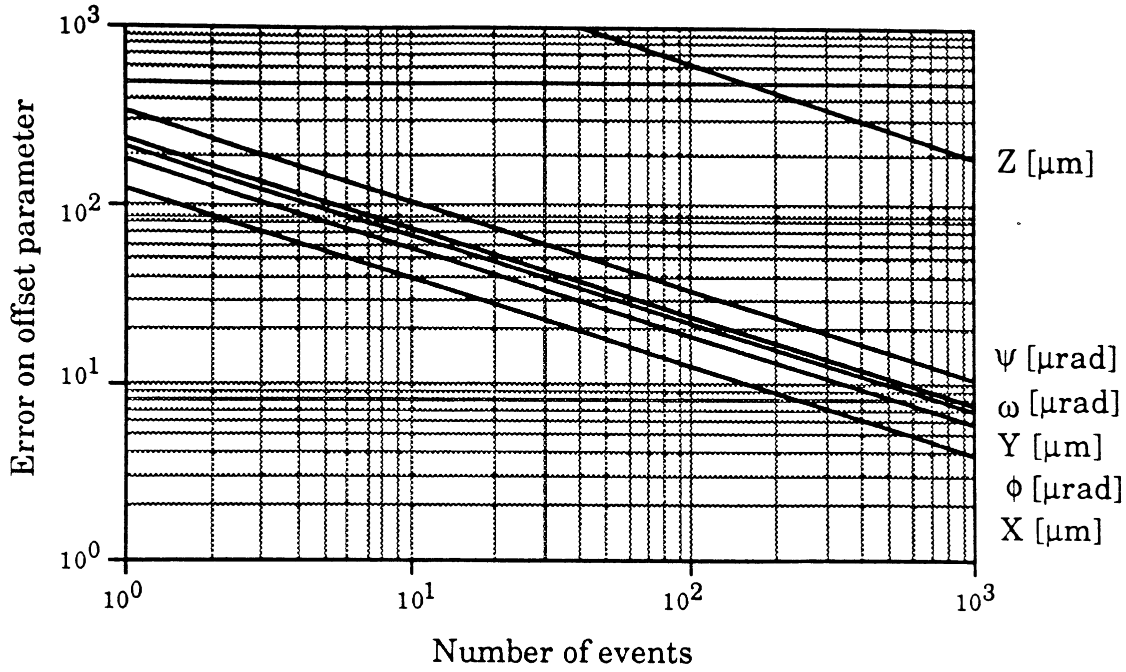


Figure 8 *Errors on alignment parameters*

Wire sag measurement

The wires in the ITC sag under the influence of gravity. From the material and tension of the wires it is estimated that the maximal sag will be about 120 μm at the centre of the chamber relative to the ends. The procedure outlined above may be simply modified to provide a measure of this sag. Approximating the wire shape as parabolic, we may put:

$$\Delta Y = \delta Y + Z_0\, \delta\psi + (Z_0^2 - L^2/4)\, \delta U$$

in the equation for ΔD_0, where δU is the sag parameter, and L is the ITC length. The fit for δY, $\delta\psi$ and δU thus becomes a fit to a parabola, and is simply performed [10).]

The accuracy to which the sag is measured by this method is found to be:

$$\sigma(\delta U) \approx 6.4 \times 10^{-6}\, N^{-1/2}\ \mathrm{cm}^{-1}$$

So for 500 events, the error on the measured sag over 1 m will be about 30 μm.

II Influence of Digitisation

Introduction

This part of the note is based on work prepared for the ALEPH plenary meeting at CERN on 16–19th September 1987 *. In the previous part, the effect of the detectors on the hit coordinates was simulated by the introduction of resolution smearing and two-hit separation, but the fundamental problems of relating the measured digitisings to coordinates in the ITC and the TPC were not addressed. It is the aim of this part to do so, for the ITC.

The coordinates of a hit in the R-ϕ projection of the ITC are calculated by timing the drift of ionisation electrons to the sense wire of the hit drift-cell using a TDC. The drift time is calculated from the difference of the measured time and a reference time 't_0' provided by the trigger. The correspondence between the drift time and the drift distance is given by a drift-time relationship. For a well designed cell this is close to linear, but in general there will be small deviations. To obtain a precise measurement of the relationship requires substantial statistics, and it is expected that it will not have been accurately determined when the alignment using cosmic rays is performed. It is therefore necessary to investigate the influence of uncertainty in the drift-time relationship on the alignment: in particular, if a linear relationship is assumed, the result of an actual nonlinearity must be determined.

A second potential source of error is that t_0 from the trigger may not be precise. The intended trigger for cosmic rays will use the hadron calorimeter, and a jitter of about 20 ns is expected on t_0. The influence of this on the alignment measurement must be determined.

* Previously released as an Imperial College note [11].

Decoding the digitisings

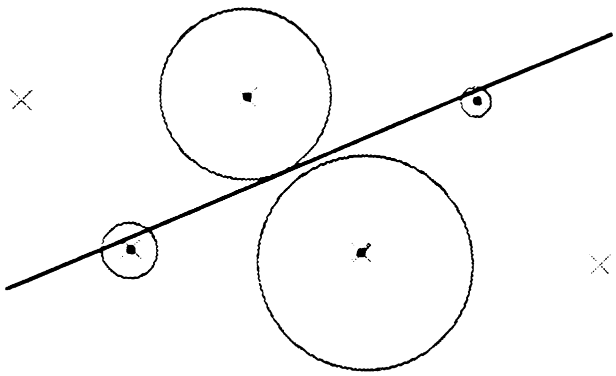
The digitisation is simulated using Galeph (19.0), with modifications to provide a realistic resolution for the ITC and to allow a user-defined drift-time relationship [12].

The digitisings take the form of TDC readings for the drift time, and for the Z measurement. The difference in time of the arrival of the signal at either end of the hit wire is translated into a Z-coordinate of the hit using a time-expansion procedure [13]. The drift time is calculated by correcting the TDC reading with the time-of-flight of the particle responsible for the digitising, and with the time taken for the signal to travel down the wire.

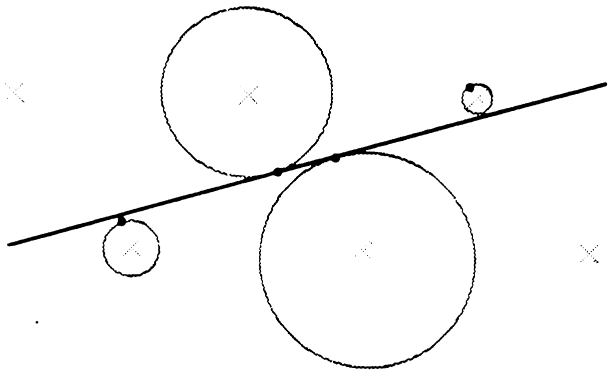
The drift time is translated into a drift distance using the drift-time relationship. It is then necessary to resolve the ambiguity: the drift distance may be in any radial direction from the wire. The procedure used is illustrated in Figure 9, where the wires are shown as crosses, and each hit wire is surrounded by a circle of radius equal to the calculated drift distance. The resolution of the ambiguity corresponds to the choice of a point on the circumference of each circle. This is achieved using three fits; the points used in each fit are marked as dots, and the fitted lines are also shown.

First a track is fitted using the coordinates of the hit wires, weighting the hits with short drift times heavily. The ambiguity is then chosen by taking the point on the circle at which the tangent is parallel to the fitted track, on the side nearer to the track. The weighting ensures that the ambiguity is correctly chosen for hits with long drift times, but the choice for those with short drift times remains uncertain (a). A second fit is then performed using the hit coordinates from the first fit, but weighting the hits with *long* drift times heavily, so that the correct choice of ambiguity is made for those with short drift times (b). Finally, an unweighted fit is made to give the reconstructed track (c).

(a)



(b)



(c)

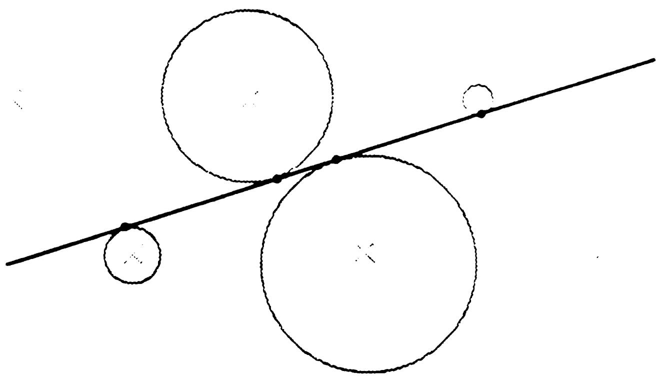


Figure 9 *Track fitting procedure*

The weights for the first fit are chosen by interpreting the drift distance d as an error on the point to be used in the fit, and therefore using a weight proportional to its inverse-square. To avoid problems with very short drifts, a term is introduced that represents the intrinsic resolution of the detector, d_0 (taken as 100 μm), so the final weight w is given by:

$$w = \frac{1}{\left(d^2 + d_0^2\right)}$$

On similar grounds, the weights in the second fit are chosen as:

$$w = d^2$$

The performance of the scheme is insensitive to the detailed form of the weights.

The residuals of the hits from the track are then calculated. A cut may be applied to reject offset hits; after the most offset hit is rejected, the fit is recalculated and the procedure is iterated. This was not required for the work presented here, as the cosmic ray data are relatively clean, and only events with 16 hits (the number expected from a single straight-through track) are used.

t_0 may next be measured, on an event-by-event basis. The measurement is made by minimising the sum of squares of the residuals with respect to t_0. This will be discussed below.

Finally, the true drift-time relationship may be determined, using the distance between the fitted track and the hit wires, plotted against the drift time measured at each wire. When sufficient statistics have been taken, the shape of the distribution can be parameterised, and used for the recalculation of drift distances (instead of the initial linear relationship). This procedure may then be iterated to provide an accurate measurement of the drift-time relationship.

The track fitting procedure described here was developed for the analysis of data from the ITC beam test of August 1987 [14)]. Typical residuals from the R-ϕ and Z fits are shown in Figure 10 (a) and (b). Also shown is the drift-time relationship that was measured, after the 'first iteration', i.e. assuming an initially linear relationship (c).

The hit coordinates determined by the track fitting procedure are then used in the alignment routines described in the first part of the note. The TPC hit simulation is unchanged; it will be the subject of future investigation.

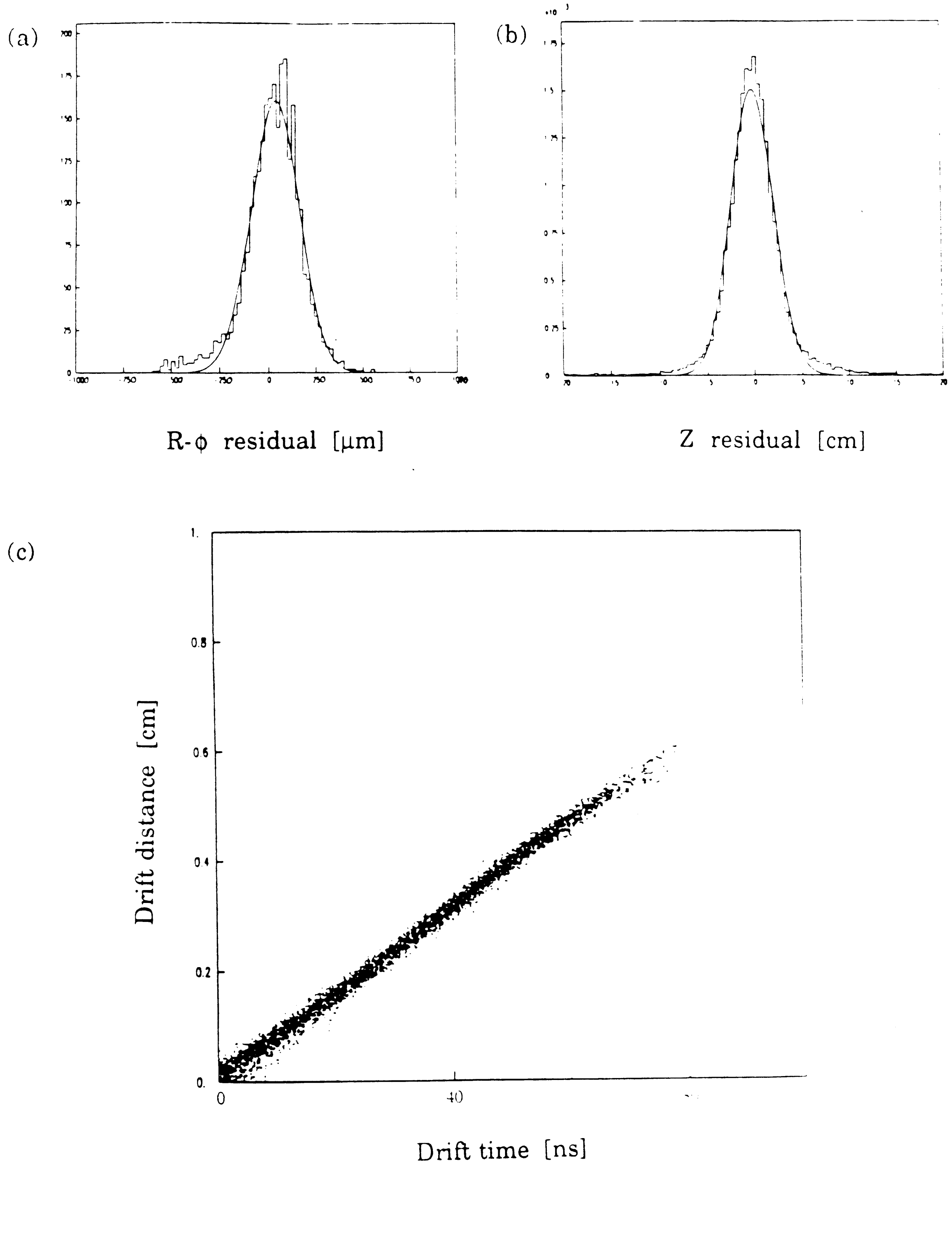


Figure 10 *Track fit results*

Nonlinear drift-time relationship

The effect of uncertainty in the drift-time relationship was investigated by generating events with a nonlinear relationship, and then reconstructing them assuming a linear relationship.

The nonlinear drift-time relationship used was parabolic, as illustrated in Figure 11. It had the form:

$$t = \frac{d}{v} + \alpha\, d^2$$

α could be expressed in terms of a dimensionless 'nonlinearity parameter' γ (the ratio of the quadratic and linear components of the drift time at maximum drift distance D):

$$\alpha = \frac{\gamma}{D\, v}$$

The linear component v was adjusted to ensure that the average value of the drift speed did not alter from a standard value, u (taken as 50 µm/ns).
That is:

$$\int_0^D \left(t - \frac{d}{u} \right) d\, d = 0$$

giving:

$$v = \left(\frac{1}{u} - \frac{2\, \alpha\, D}{3} \right)^{-1}$$

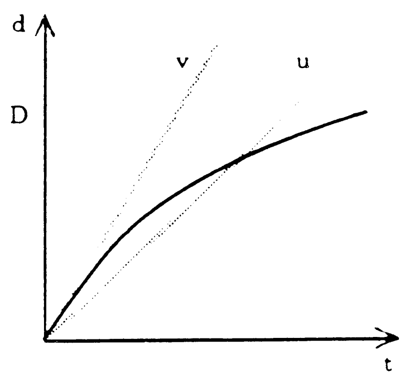


Figure 11 *Nonlinear parameterisation*

Events were generated using different values for the nonlinearity, and reconstructed assuming a linear drift-time relationship with a drift speed of 50 µm/ns. The effect on the alignment was determined by calculating the error on each of the six offset parameters (corresponding to the 3 translations and 3 rotations possible) found by the alignment procedure, for a data-set of 500 events. The error is measured in µm for the spatial parameters and µrad for the angular. See Figure 12.

The degree of nonlinearity expected in the real data might be estimated from Figure 10 (c). This, however, will give an underestimate, as it represents only the first iteration in the fit for the drift-time relationship, and was measured without magnetic field. The presence of a magnetic field introduces both nonlinearity and an asymmetry between the sides of each drift-cell. A better estimate of the expected nonlinearity is available from data taken with a test chamber in a magnetic field [15]. A parabolic parameterisation of the drift-time relationship was used, with the resulting distribution shown in Figure 13. The measured nonlinearity parameter has a value of about 0.3. For values of this order, the effect of the nonlinearity on the measurement of the alignment is small. Note that (in Figure 12) the Z parameter is barely effected by nonlinearity, as one would expect.

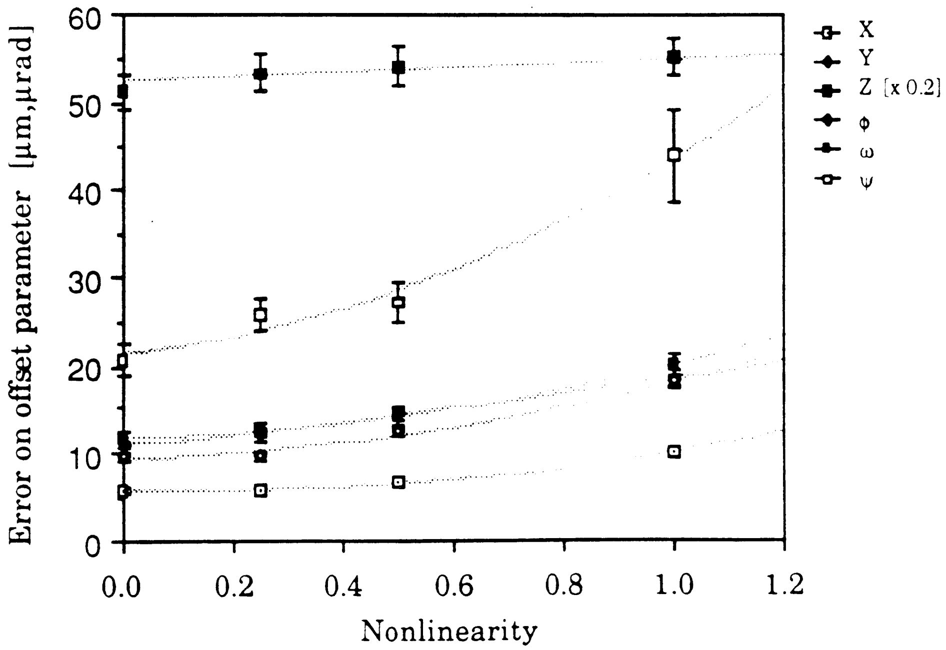


Figure 12 *Effect of nonlinearity*

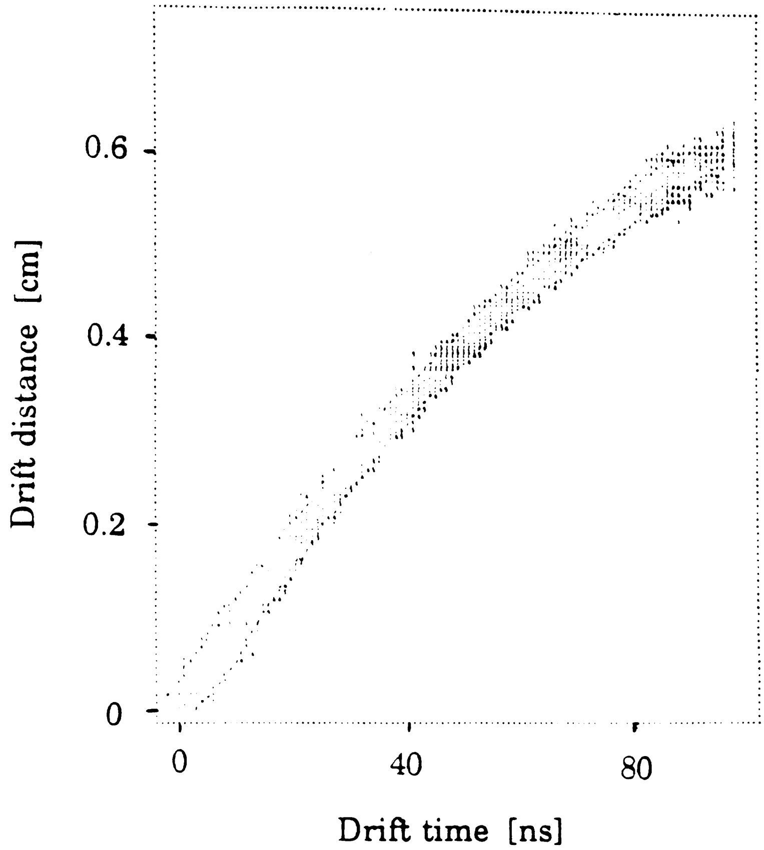


Figure 13 *Drift-time relationship from test chamber*

The influence of an incorrect choice of drift speed was investigated. Events were generated with a linear drift-time relationship, and a drift speed of 50 µm/ns. They were then reconstructed assuming a different speed. See Figure 14. As can be seen, the influence of this on the alignment precision is severe, for all parameters but Z. This, however, is not a problem, as it is possible to determine the average drift speed to better than 1 µm/ns, from the centring of the R-ϕ residuals. See Figure 15.

The modifications to the resolution simulation in Galeph include the provision of a drift-distance dependent resolution, with best resolution at intermediate distances. For the measurements shown above, this feature was not used, and a single value of 100 µm set for the resolution parameter. Some data were, however, generated with minimum and maximum value parameters of 100 µm and 180 µm respectively, and it was found that the precision of measurement of the alignment parameters was reduced only by a few percent.

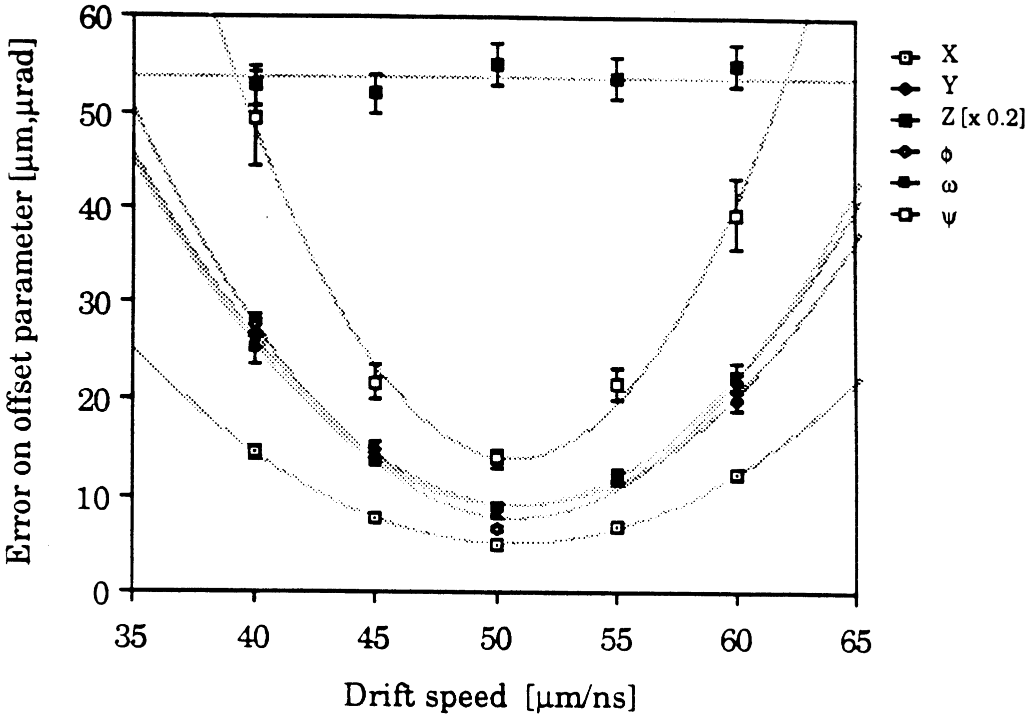


Figure 14 *Effect of incorrect drift speed*

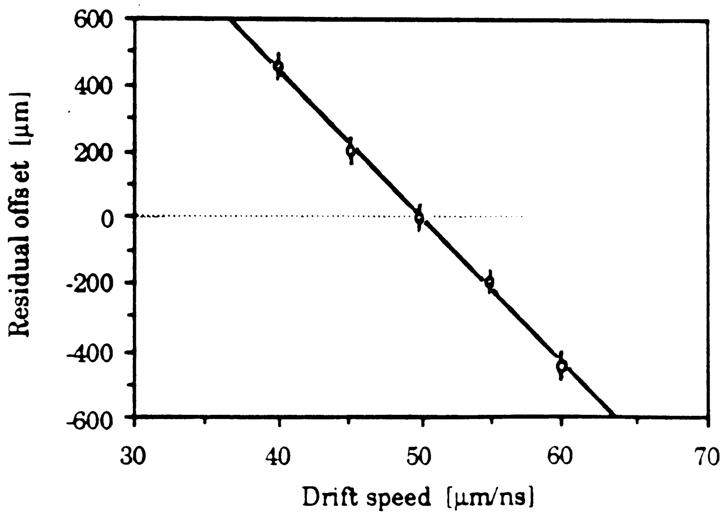


Figure 15 *Determination of drift speed*

Jitter on t_0

The effect of the t_0 jitter was investigated by adding a normally distributed random offset to t_0 for each event before reconstruction. The data used were generated and reconstructed with a linear drift-time relationship. The influence of the t_0 jitter is shown in Figure 16, for the X-offset parameter.

As can be seen, the effect becomes severe for large values of the jitter. This is remedied using the event-by-event measurement of t_0 mentioned above. The measurement is made by minimising the sum of the squares of the R-ϕ residuals with respect to t_0. For a measured drift distance d, and an assumed drift speed v, the residual r is given by:

$$r = d - v\,(t - t_0)$$

If we put:

$$r_i = a_i + b_i\, t_0$$

for hit i, then the sum of squares of the residuals S is given by:

$$S = \sum_i r_i^2 = \sum_i (a_i + b_i\, t_0)^2$$

and minimising this gives:

$$\frac{dS}{d\,t_0} = \sum_i \left(2\, a_i\, b_i + 2\, b_i^2\, t_0\right) = 0$$

hence:

$$t_0 = -\frac{\sum_i a_i\, b_i}{\sum_i b_i^2}$$

If we neglect the influence of t_0 on d, then we may put:

$$a = d - v\,t\,,\quad b = v$$

for each hit. Thus a new value for t_0 is found. The track is then refitted using the new value, and the procedure is iterated, until the change in t_0 is less than a given tolerance.

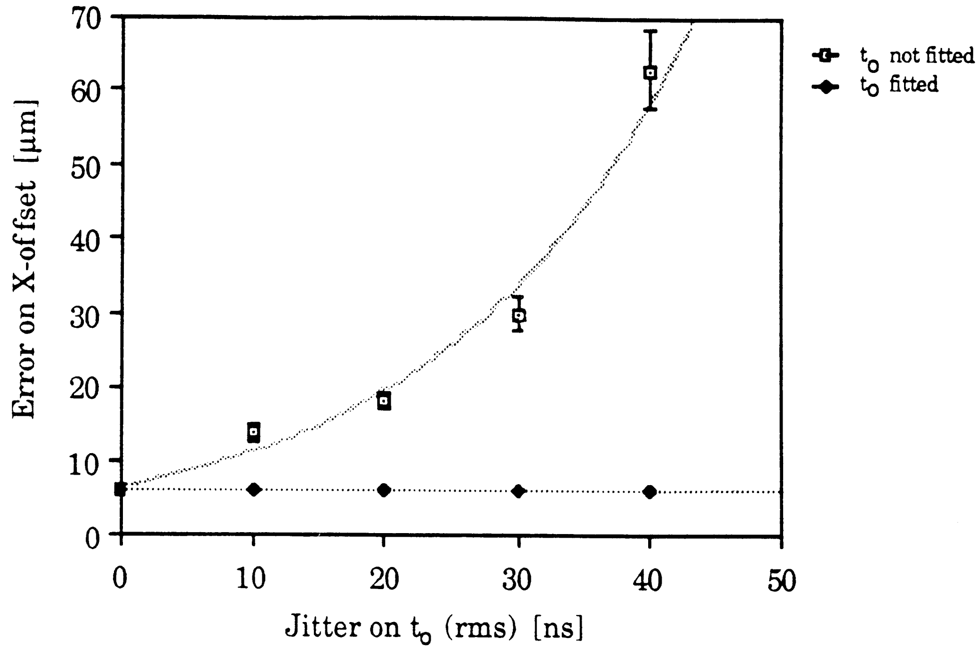


Figure 16 *Effect of t_0 jitter*

The performance of this technique for determining t_0 is illustrated in Figure 17, using data generated with $t_0 = 0$. A simulated jitter is introduced with 10 ns rms, and an offset of 10 ns is also added, to give the starting value for t_0 shown in (a). The tolerance on t_0 for the iteration was taken as 0.5 ns. The measured value (b) agrees with the true value, with a width of about 0.8 ns rms. The iteration converges rapidly, as shown in (c).

Using the fit for t_0, no degradation of the accuracy of the alignment is introduced by any value taken for the jitter or offset of t_0. This is shown in Figure 16 for the X offset parameter.

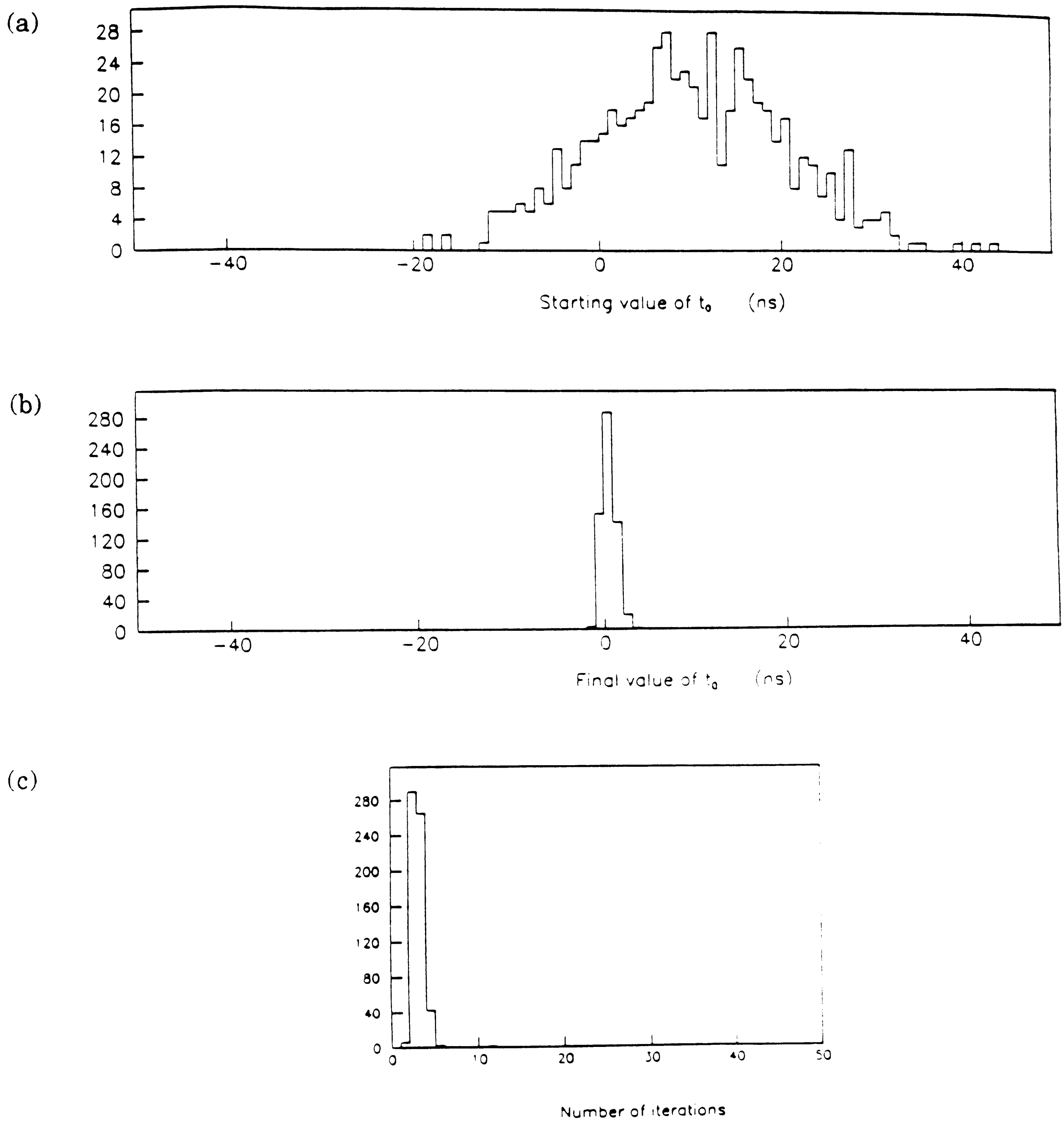


***Figure 17** Determination of t_0*

Conclusion

A procedure has been developed for the alignment of the ITC using cosmic rays. The 6 offsets that relate the coordinate system of the ITC to that of the TPC are measured using a comparison of the parameters of cosmic ray tracks fitted independently in the two detectors; a separate Gaussian fit is provided for each of the offset parameters. The accuracy to which these offsets are measured has been investigated using a Monte Carlo simulation, and a few hundred cosmic rays are found to be sufficient.

A procedure for relating the measured digitisings to coordinates for the ITC has been successfully implemented. It has been used to investigate possible sources of inaccuracy in the alignment of the ITC. An uncorrected nonlinear component in the drift-time relationship is found not to significantly effect the alignment, providing the correct value is taken for the average drift speed; this is ensured by centring the R-ϕ residuals. Any errors that might be introduced by the use of an incorrect value for t_0 are avoided with the event-by-event measurement of t_0.

References

1) R. Forty *Alignment of the ITC* ALEPH-IC-87-8.
2) D. Miller. See his notes on mechanical alignment of the ITC.
3) ALEPH 87-64, NOTE 87-12.
4) R. Beuselinck ALEPH-IC-87-3.
5) Some details were presented by M. Cattaneo at the CERN Physics workshop of 17th February 1987.
6) Program location: ZIVA::[RFRTY.OBERON]COSMIC.FOR
7) J. Sedgbeer. Routines in ZIVA::[JKSDGBR.VERT]
8) LFIT: CERN Program Library routine E250.
9) HFITGA: HBOOK routine.
10) PARLSQ: CERN Program Library routine E255.
11) R. Forty *Influence of Digitisation on the ITC Alignment* ALEPH-IC-87-11.
12) R. Beuselinck. Private communication.
13) Details presented by P. Dornan at the November 1984 plenary meeting.
14) Some results were presented by M. Cattaneo at the September 1987 plenary meeting.
15) A. Heinson. Thesis in preparation.