Chapter 1

Spectrometer Alignment

The alignment of the spectrometer is important for track reconstruction. Alignment is a part of pre-processing which ensures all the tracking detectors are centered relative to each other and therefore enables the track resolution to be as accurate as possible. Without accurate alignment, track reconstruction is not possible and it is therefore not possible to analyze any data. The author of this thesis oversaw collection of alignment data and was responsible for performing the alignment of the COMPASS spectrometer in 2015.

The objective of the alignment procedure is to produce a file called the detectors.dat. This file describes the parameters for all detectors at COMPASS and in particular, gives their orientation in space. For a tracking detector plane, there are four parameters the alignment procedure updates: the x central position, y central position, angle and the pitch. The pitch refers to a sense wire distance for wire chambers or central strip separation distance for detectors with strip readouts. One or two detectors.dat files was produced for each data taking period, depending on how many alignment runs were recorded that period. The goal of the alignment procedure is to have all four parameters aligned relative to a global reference frame in the COMPASS lab system.

The alignment procedure works by minimizing the distance between all the detector plane hit positions and a track position. This distance will from here on be referred to as the residual distance. One residual is determined per track per detector associated with the track. The task of simultaneously minimizing all the residuals is difficult because there are over 300 detectors planes described in the detectors.dat. To accomplish this minimization, a large amount of quality data is needed and several specific matrix manipulations are utilized in the minimization procedure. This chapters gives an overview of the alignment procedure and includes some results from 2015. For a more complete review see reference [2].

1.1 Alignment Data

The alignment data comes from a dedicated low intensity muon beam. The intensity in 2015 was approximately $10^5 \mu^-$/spill. A muon beam is desirable for alignment data because the beam muons interact less and therefore allow the alignment procedure to assume straight tracks in the minimization problem. The lower intensity is chosen because this allows for the assumption that only one track occurs per event and also the low intensity beam ensures a reduction of detector pile up effects. Reduction in pile up effects, makes reconstruction in the central detector areas possible, and therefore the beam killers on DC00, DC01, DC04 and DC05 can be set to nominal voltage and as well all the GEM detectors can have their central high voltages turned up to an amplification voltage.

A dedicated trigger system is setup during alignment runs to maximize the illumination of the tracking detectors. The triggers used are a beam trigger, veto trigger and a halo trigger. The alignment runs used in 2015 are listed in Table 1.1.

Two alignment runs of good quality are recorded either at the beginning, middle or end of a data taking period. The first alignment run is with the spectrometer magnets off and the second is with the spectrometer magnets on. The spectrometer magnets off run is used as a first iteration for the alignment procedure to initialize the tracking detector positions. The final alignment positions are then determined from the spectrometer magnets on data.

One physics run was also used to align detectors far from the beam line. Particularly, the outer region of the straw detectors did not receive enough statistics from the aligning runs. Therefore the alignment of the outer straw regions was performed with normal physics data.

In 2015 the alignment runs were performed when the target solenoid was polarizing the target. The chicane magnets upstream of the target were therefore turned off to ensure the beam momentum was traveling along the target axis. Normally to achieve the reduced intensity, the T6 target is switch to an air target. However in 2015, the T6 target head was not able to switch between the different target lengths and therefore the maximum 500 mm target head was always in use. Therefore to achieve the desired intensity, a set of collimeters upstream of the target reduced the aperture of the beam line till the correct intensity was achieved.

1.2 Procedure

The starting point for alignment is a detectors.dat file with the tracking detector positions determined from a survey. The surveys are performed with the spectrometer magnets off and the precision from a survey is around 1 mm. Almost all of the detectors at COMPASS have a position resolution better than the survey precision. Furthermore, several detectors near SM1 can shift in position due to the magnetic field and therefore need a position determination with the spectrometer magnets on. For these reasons the alignment

Period	Sub-period	Magnets off run	Magnets on run	Physics run	detectors.dat name
W07	one & two	259360	259361	259363	detectors.259361.transv.dat
W08	one & two	260072	260073	260100	detectors.260073.transv.dat
W09	one	260625	260626	260661	detectors.260626.transv.dat
	two	260625	260876	261312	detectors.260876.transv.dat
W10	one	261512	261513	261602	detectors.261513.transv.dat
	two	261512	261513	261974	detectors.261970.transv.dat
W11	one & two	262423	262425	262612	detectors.262370.transv.dat
W12	one & two	263139	263140	263175	detectors.263140.transv.dat
W13	one & two	263636	263637	263851	detectors.263637.transv.dat
W14	one & two	none	264428	264429	detectors.264163.transv.dat
W15	one & two	264614	264722	264736	detectors.264619.transv.dat

Table 1.1: COMPASS 2015 alignment data runs

procedure is needed to improve on the survey precision and achieve the best possible track resolutions.

Alignment Parameters

To best describe each detector relative to every other detector there are two reference systems of interest.

The first reference system is the COMPASS main reference system labeled *Oxyz*. This reference system can also be referred to as the COMPASS lab system, where the z-axis is along the beam momentum direction, the y-axis points vertically and the x-axis is such that the coordinate system is right handed. The origin of this reference system is at the center of the target from the original COMPASS setup.

The second reference system is the local reference system, which is labeled as *O'uvz*. This reference system is different for each detector and has its origin at the center of each detector center. The z-axis coincides with the z-axis in the COMPASS main reference system while the u-axis is in the direction along the measured coordinate of the detector, and the v-axis is perpendicular to the direction of the measured coordinate of this detector. As an example, a drift chamber with vertical wires measures a coordinate along the horizontal direction and therefore it's u-axis is in the horizontal direction and it's v-axis is in the vertical direction. A drift chamber with horizontal wires, however, measures a coordinate along the vertical direction and therefore it's u-axis is in the vertical direction and it's v-axis is in the horizontal direction.

The alignment parameters are defined in *O'uvz*. The alignment procedure updates the starting detectors.dat file by the shifts

$$\delta \mathrm{u}: \text{ shift in u direction,} \tag{1.1}$$

$$\delta \theta: \text{ shift in rotation angle,} \tag{1.2}$$

$$\delta \mathrm{z}: \text{ shift in z direction,} \tag{1.3}$$

$$\delta \mathrm{p}: \text{ shift in pitch.} \tag{1.4}$$

The shift in z direction has never converged however. As a result the z-coordinate from the survey is used as the final z position and the shift in pitch is used as an effective shift in the z direction.

Residual Function

The goal of the alignment procedure is to minimize the sum of all the residuals from each track and each detector associated with the track. Due to the fact that the alignment tracks are assumed to be straight, each track can be defined by four parameters. The track parameters, α_{T}, are

i: $(\mathrm{x}^0, \mathrm{y}^0)$ the x and y coordinates at the main reference origin

ii: $(\mathrm{t}_{\mathrm{x}}^0, \mathrm{t}_{\mathrm{y}}^0)$ the tangents of the track momentum in the x and y directions at the origin of the main reference system

where the track parameters are defined for each track. The alignment parameters , α_{D}, on the other hand are defined for each detector and are the same for all tracks. The alignment procedure minimizes the χ^2 function

$$\chi^2 = \sum_{i=1}^{i=n_{\mathrm{tracks}}} \sum_{j=1}^{j=n_{\mathrm{detectors}}} \frac{\mathrm{F}_{i,j}^2(\alpha_{\mathrm{T},i}, \alpha_{\mathrm{D},j})}{\sigma_j^2}, \tag{1.5}$$

where σ_j^2 is the position resolution of detector j, $\mathrm{F}_{i,j}$ is the residual distance of each detector j for each track i it is associated with.

The residual distance, F, depends on the track parameters and the detector parameters. For magnets off data the tracks are not bent at all and are therefore straight tracks. The track positions at position z are

$$\mathrm{x} = \mathrm{x}^0 + \mathrm{t}_{\mathrm{x}}^0(\mathrm{z} - \mathrm{z}^0), \tag{1.6}$$

$$\mathrm{y} = \mathrm{y}^0 + \mathrm{t}_{\mathrm{y}}^0(\mathrm{z} - \mathrm{z}^0), \tag{1.7}$$

where z^0 refers to the position at the origin in *Oxyz*. Rotating these track positions from the main references system, *Oxyz*, to the detector reference system, *O'uvz*, the residual distance is

$$\mathrm{F} = \cos(\theta)[\mathrm{x}^0 + \mathrm{t}_\mathrm{x}^0(\mathrm{z} - \mathrm{z}^0)] + \sin(\theta)[\mathrm{y}^0 + \mathrm{t}_\mathrm{y}^0(\mathrm{z} - \mathrm{z}^0)] - \mathrm{u}, \tag{1.8}$$

where u is the measured hit position from the detector at position z. To show the dependence on the alignment parameters

$$\mathrm{F}(\alpha_\mathrm{T}, \alpha_\mathrm{D} + \delta\alpha_\mathrm{D}) = (1 + \delta\mathrm{p})\Big\{\cos(\theta + \delta\theta)[\mathrm{x}^0 + \mathrm{t}_\mathrm{x}^0(\mathrm{z} - \mathrm{z}^0)] + \sin(\theta + \delta\theta)[\mathrm{y}^0 + \mathrm{t}_\mathrm{y}^0(\mathrm{z} - \mathrm{z}^0)]\Big\} - (\mathrm{u} + \delta\mathrm{u}). \tag{1.9}$$

In Eq. 1.9, the change in pitch would intuitively affect the u position, however the change in pitch was moved to the track coordinates to make derivatives of F independent of u. This has no effect on the minimization of F.

In the case of magnets on data, the track positions need to have further modifications. The magnetic field will bend the tracks so the track positions determined in Eq. 1.6 need to have further corrections. The track positions with SM1 and SM2 on are

$$\mathrm{x} = \mathrm{x}^0 + \delta\mathrm{x} + (\mathrm{t}_\mathrm{x}^0 + \delta\mathrm{t}_\mathrm{x})(\mathrm{z} - \mathrm{z}^0), \tag{1.10}$$

$$\mathrm{y} = \mathrm{y}^0 + \delta\mathrm{y} + (\mathrm{t}_\mathrm{y}^0 + \delta\mathrm{t}_\mathrm{y})(\mathrm{z} - \mathrm{z}^0), \tag{1.11}$$

where the δ_x, $\delta\mathrm{t}_\mathrm{x}$, δ_y and $\delta\mathrm{t}_\mathrm{y}$ changes are determined from CORAL during the reconstruction process. Even though the spectrometer magnets have nominally vertical magnetic fields, there are still fringe fields which are not vertical. It is for this reason that CORAL also calculates an updated track position in the y-coordinate.

The residual dependence on the alignment parameters defined for magnetic fields on is then

$$\begin{aligned}\mathrm{F}(\alpha_\mathrm{T}, \alpha_\mathrm{D} + \delta\alpha_\mathrm{D}) = (1 + \delta\mathrm{p})\Big\{&\cos(\theta + \delta\theta)[\mathrm{x}^0 + \delta\mathrm{x} + (\mathrm{t}_\mathrm{x}^0 + \delta\mathrm{t}_\mathrm{x})(\mathrm{z} - \mathrm{z}^0)] \\ &+ \sin(\theta + \delta\theta)[\mathrm{y}^0 + \delta\mathrm{y} + (\mathrm{t}_\mathrm{y}^0 + \delta\mathrm{t}_\mathrm{y})(\mathrm{z} - \mathrm{z}^0)]\Big\} - (\mathrm{u} + \delta\mathrm{u}).\end{aligned} \tag{1.12}$$

χ^2 Minimization

The χ^2 function, Eq. 1.5, is analytically minimized. That is, the derivatives of Eq. 1.5 with respect to all the track and alignment parameters are set to zero and these parameters are solved for. This can be written

$$\frac{1}{2}\frac{\partial\chi^2}{\partial\alpha_k} = \sum_i^{n_\mathrm{tracks}} \sum_j^{n_\mathrm{detectors}} \frac{1}{\sigma_j^2}\frac{\partial\mathrm{F}_{i,j}}{\partial\alpha_k}\mathrm{F}_{i,j} = 0. \tag{1.13}$$

To perform this calculation the residual function is Taylor expanded in the track and alignment parameters as

$$\mathrm{F} = \mathrm{F}^0 + \sum_k \frac{\partial \mathrm{F}}{\partial \alpha_k}\alpha_k. \tag{1.14}$$

Using this approximation for F, Eq. 1.13 can be written as a matrix equation where the dimensions of the matrix are $(4\mathrm{n}_{\mathrm{detector}}+4\mathrm{n}_{\mathrm{tracks}})\times$ $(4\mathrm{n}_{\mathrm{detector}}+4\mathrm{n}_{\mathrm{tracks}})$. This matrix form is written as

$$\begin{bmatrix} \sum_i^{n_{\mathrm{tracks}}}\sum_j^{n_{\mathrm{detectors}}}\frac{1}{\sigma_j^2}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{D}_1}}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{D}_1}} & \dots & \sum_j^{n_{\mathrm{detectors}}}\frac{1}{\sigma_j^2}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{D}_1}}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{T}_{4\mathrm{n}_{\mathrm{tracks}}}}} \\ \vdots & \ddots & \vdots \\ \sum_j^{n_{\mathrm{detectors}}}\frac{1}{\sigma_j^2}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{T}_{4\mathrm{n}_{\mathrm{tracks}}}}}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{D}_1}} & \dots & \sum_j^{n_{\mathrm{detectors}}}\frac{1}{\sigma_j^2}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{T}_{4\mathrm{n}_{\mathrm{tracks}}}}}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{T}_{4\mathrm{n}_{\mathrm{tracks}}}}} \end{bmatrix} \begin{bmatrix} \alpha_{\mathrm{D}_1} \\ \vdots \\ \alpha_{\mathrm{T}_{4\mathrm{n}_{\mathrm{tracks}}}} \end{bmatrix} \\ = -\begin{bmatrix} \sum_i^{n_{\mathrm{tracks}}}\sum_j^{n_{\mathrm{detectors}}}\frac{1}{\sigma_j^2}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{D}_1}}\mathrm{F}^0_{i,j} \\ \vdots \\ \sum_j^{n_{\mathrm{detectors}}}\frac{1}{\sigma_j^2}\frac{\partial \mathrm{F}_{i,j}}{\partial\alpha_{\mathrm{T}_{4\mathrm{n}_{\mathrm{tracks}}}}}\mathrm{F}^0_{i,j} \end{bmatrix}. \tag{1.15}$$

To solve Eq. 1.15, the matrix on the left side must be inverted. A normal alignment run however, results in over 200,000 tracks meaning this matrix is huge and infeasible to invert. Fortunately many of the entries in the matrix are zero which allows that this matrix inversion can be reduced to the inversion of several smaller matrices.

To perform the matrix inversion, note that Eq. 1.15 can be written

$$\left[\begin{array}{c||ccc} \sum_i \mathrm{C}_i & \dots & \mathrm{G}_i & \dots \\ \hline\hline \vdots & \ddots & 0 & 0 \\ \mathrm{G}^{\mathrm{T}} & 0 & \Gamma_i & 0 \\ \vdots & 0 & 0 & \ddots \end{array}\right] \left[\begin{array}{c} \alpha_\alpha \\ \hline\hline \vdots \\ \alpha_{\mathrm{T}_i} \\ \vdots \end{array}\right] = \left[\begin{array}{c} \sum_i b_i \\ \hline\hline \vdots \\ \beta_i \\ \vdots \end{array}\right], \tag{1.16}$$

where $\sum_i \mathrm{C}_i$ and $\sum_i \mathrm{b}_i$ include only derivatives of $\mathrm{F}_{i,j}$ with respect to alignment parameters, Γ_i and β_i include only derivatives of $\mathrm{F}_{i,j}$ with respect to track parameters and G_i includes derivatives of $\mathrm{F}_{i,j}$ with respect to both alignment and track parameters. Then reference [1] shows that Eq. 1.16 can be inverted to give the alignment parameters as

$$\alpha_\alpha = \mathrm{C}'^{-1}\mathrm{b}', \tag{1.17}$$

where

$$\mathrm{C}' = \sum_i \mathrm{C}_i - \sum_i \mathrm{G}_i\Gamma_i^{-1}\mathrm{G}_i^{\mathrm{T}}, \tag{1.18}$$

and

$$\mathrm{b}' = \sum_i \mathrm{b}_i - \sum_i \mathrm{G}_i \Gamma_i^{-1} \beta_i. \tag{1.19}$$

1.3 Results

The spectrometer alignment is performed in iterative steps. In each iteration of the alignment procedure, the matrix inversion, Eq 1.16, is performed. All alignment tracks reconstructed in the first alignment iterations are based off of two pivot detectors. That is straight track parameters were determined from these two pivot detectors and all detectors were aligned relative to these pivot detectors. In 2015 the pivot detectors were GM05 in LAS and GM08 in SAS. After each iteration the detector parameters are updated to reduce the overall χ^2 value. Each new iteration is performed using the same data set and the alignment parameters are better described with each iteration.

The procedure used in 2015 was as follows:

1. Align with magnets off data. In this stage all the spectrometer detectors except the outer regions of the straw detectors are aligned. This includes all the detectors downstream of the polarized target but does not include the beam telescope detectors. Magnets off data is used as a first iteration and therefore only alignment in the u-coordinate is performed.

2. Align the same spectrometer detectors with magnets on data. In these iterations the detectors are aligned for u-coordinate, angle and pitch.

3. Align the beam telescope detectors with magnets on data. In these iterations the previous detectors are all used as pivots. The beam telescope is therefore aligned relative to the spectrometer detectors.

4. Finally the outer region of the straws are aligned with physics data. For this alignment, the spectrometer detectors are again used as the pivot.

The quality of the alignment was monitored after each iteration and checked that the procedure was converging. In practice four iterations of each of the previous steps were found to be sufficient for convergence. To ensure the alignment data was from quality tracks, only tracks with momentum reconstructed and having reduced χ^2 less than 30 were considered.

As detectors all but the pixal detector planes only measure a coordinate in one direction, the detector positions are only updated in their measured direction. This can lead to detectors being well miss-aligned in the direction orthogonal to their measured coordinate however. To account for this, detector planes were updated to match the u-position from a detector plane measuring a different coordinate in the same detector station. For example DC04X planes had their y-coordinate determined from the DC04Y planes and DC04Y planes had their x-coordinate determined from DC04X planes.

After each alignment iteration the quality of the alignment is accessed for each individual detectors and for the spectrometer as a whole. The quality distributions to check after each iteration are described in the following list.

i) The residual distribution, Δu, of each detector. That is a distribution of

$$\Delta \mathrm{u} = \mathrm{u}_{\mathrm{track}} - \mathrm{u}_{\mathrm{detector}}, \tag{1.20}$$

where this distribution indicates if the detector is shifted along the direction of its measured coordinate. This distribution is expected to be a Gaussian with a zero mean and an RMS value comparable to the position resolution of the detector. Any deviation from a zero mean indicates the detector is shifted and a large RMS value indicates the detector is not performing as expected. It the detector is not performing as expected the most obvious reason is the calibrations used for that detector are not accurate. Fig. 1.1 shows an example of this distribution to monitor.

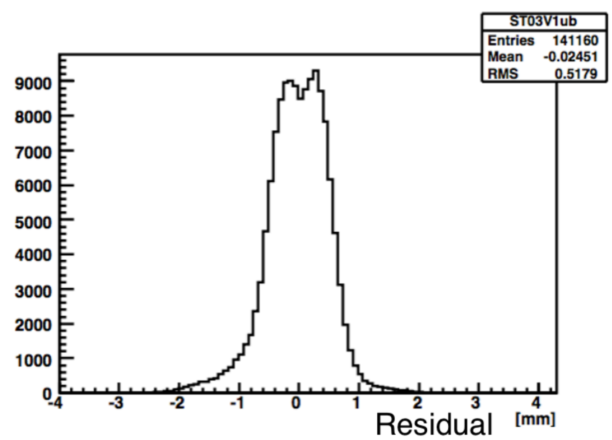

Figure 1.1: The residual distribution for a straw detector plane

ii) The change in the residual as a function of the detector's v-coordinate. In a wire detector for example, this is the change in the residual as a function of the distance along the wire. This distribution, Fig. 1.2, is expected to be uniformly zero. A slope in this distribution indicates that the detector's angle is miss-aligned.

iii) The change in the residual as a function of the detector's u-coordinate. For a wire detector, this is the change in the residual as a function of the distance perpendicular to the wire. This distribution,

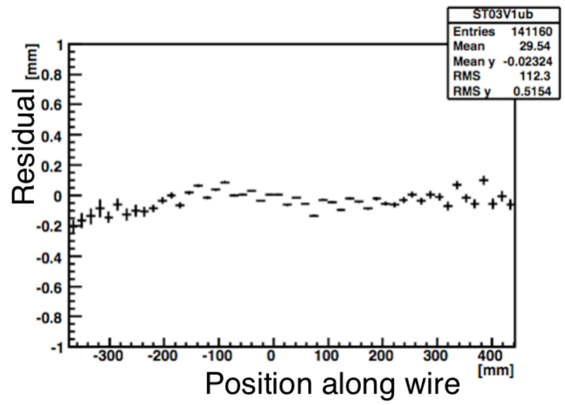

Figure 1.2: The residual as a function of the detector v-coordinate for a straw detector

Fig. 1.3, is also expected to be uniformly zero. A slope in this distribution indicates that the detector is miss-aligned in it's z-coordinate or that its pitch is not described well. Due to the fact that the alignment data is with straight tracks, the alignment in the z-coordinate has never been able to converge. For this reason the pitch of the sensors on the detector is changed to account for this effective shifts in z-position. The sensor pitch however, is never expected to be larger than the true detector pitch distance. If the detector pitch is determined to be too large after the alignment, this indicates a problem.

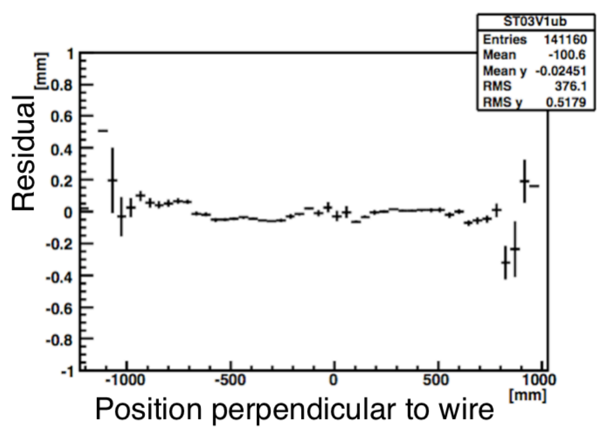

Figure 1.3: The residual as a function of the detector u-coordinate for a straw detector

iv) The reduced χ^2, Fig. 1.4, distribution of the reconstructed tracks. With better alignment the track reduced χ^2 distribution will approach a theoretical distribution of a reduced χ^2 distribution.

v) The global number of tracks reconstructed. Better alignment implies that more detectors can be

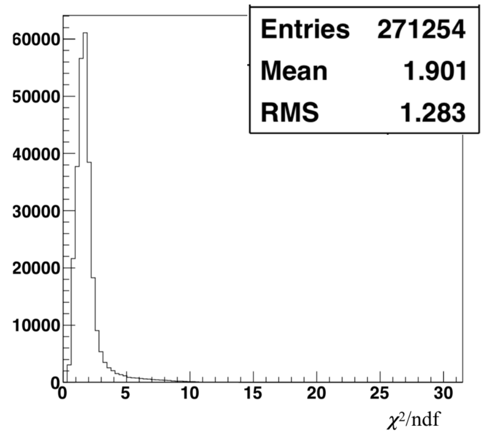

Figure 1.4: The reduced χ^2 from alignment data tracks

associated with a track and therefore more tracks will be reconstructed.

References

[1] Volker Blobel and Claus Kleinwort. A New method for the high precision alignment of track detectors. In *Advanced Statistical Techniques in Particle Physics. Proceedings, Conference, Durham, UK, March 18-22, 2002*, pages URL–STR(9), 2002.

[2] H. Pereira and J. M. Le Goff. Compass Spectrometer Alignment.