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 spent the summer of 2015 collecting 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 relative orientation with respect to each other. For a tracking detector plane, there are four parameters the alignment procedure updates: the x central position, y central position, angle and the pitch. These parameters are described in the COMPASS lab frame and the pitch refers to a sense wire distance for wire chambers or central strip 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 each other for each tracking plane.

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. The task of simultaneously minimizing all the detector 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 [1]. 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 dedicated low intensity muon beam, $\approx 10^5 \frac{\mu^-}{\text{spill}}$, data. 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 the assumption that only one track occurs per event and a 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 turn 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 good quality alignment runs 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.

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.

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

1.2 Procedure

The starting point for alignment is a detectors.dat file with 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 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 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 vertical 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 measure coordinate of the detector, and the v-axis is perpendicular to the direction of the measure coordinate of the 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

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

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

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

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

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 effect shift in the z direction.

Residual Function

The goal of the alignment procedure is to minimize the distance of a track positions through a detector with respect to where the detector measures the track position. 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 but 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, F is the residual distance of each detector.

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. The parameters are first determined with the current detector parameters and then iteratively updated as the detector parameters are updated. 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 x^0, y^0 and z^0 refer to positions 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

$$F(\alpha_T, \alpha_D + \delta\alpha_D) = (1 + \delta p)\Big\{ \cos(\theta + \delta\theta)[x^0 + t_x^0(z - z^0)] + \sin(\theta + \delta\theta)[y^0 + t_y^0(z - z^0)]\Big\} - (u + \delta u). \quad (1.9)$$

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

$$x = x^0 + \delta x + (t_x^0 + \delta t_x)(z - z^0), \quad (1.10)$$

$$y = y^0 + \delta y + (t_y^0 + \delta t_y)(z - z^0), \quad (1.11)$$

where the δ_x, δt_x, δ_y and δt_y changes are determined from CORAL during the reconstruction. 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 the track position must also be updated in the y coordinate.

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

$$\begin{aligned} F(\alpha_T, \alpha_D + \delta\alpha_D) = (1 + \delta p)\Big\{ &\cos(\theta + \delta\theta)[x^0 + \delta x + (t_x^0 + \delta t_x)(z - z^0)] \\ &+ \sin(\theta + \delta\theta)[y^0 + \delta y + (t_y^0 + \delta t_y)(z - z^0)]\Big\} - (u + \delta u). \end{aligned} \quad (1.12)$$

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

$$\frac{1}{2}\frac{\partial\chi^2}{\partial\alpha_k} = \sum_i^{n_{\text{tracks}}} \sum_j^{n_{\text{detectors}}} \frac{1}{\sigma_j^2} \frac{\partial F_{i,j}}{\partial\alpha_k} F_{i,j} = 0. \quad (1.13)$$

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

$$F = F^0 + \sum_k \frac{\partial F}{\partial\alpha_k}\alpha_k. \quad (1.14)$$

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

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

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

$$
\begin{bmatrix}
\sum_i^{n_{\text{tracks}}} \mathrm{C}_i & \dots & \mathrm{G}_i & \dots
\end{bmatrix}
\begin{bmatrix}
\alpha_{\mathrm{D}_1} \\ \vdots \\ \alpha_{\mathrm{T}_{4\mathrm{n}_{\text{tracks}}}}
\end{bmatrix}
= -
\begin{bmatrix}
\sum_j^{n_{\text{detectors}}} \frac{1}{\sigma_j^2} \frac{\partial \mathrm{F}_j}{\partial \alpha_{\mathrm{D}_1}} \mathrm{F}^0_j \\
\vdots \\
\sum_j^{n_{\text{detectors}}} \frac{1}{\sigma_j^2} \frac{\partial \mathrm{F}_j}{\partial \alpha_{\mathrm{T}_{4\mathrm{n}_{\text{tracks}}}}} \mathrm{F}^0_j
\end{bmatrix}.
\tag{1.16}
$$

1.3 Results

In each iteration of the alignment procedure the matrix inversion in equation 1.15 is performed. All alignment tracks are reconstructed based off the starting positions of all the detectors and after each iteration the detector parameters are updated to reduce the overall χ^2 value. Several iterations of the alignment procedure are therefore required and are performed to ensure the procedure converges.

The final product of the alignment procedure is an alignment file, for each data period, that describes the location of every detector and is used in all the data analysis. For quality assurance several residual distributions are plotted after each iteration for all the detectors. The overall residual distribution is used to tell if a detector is shifted, the change in residual as a function of the distance parallel to the wires tells if a detector is rotated and the change in residual as a function of the distance perpendicular to the wires tells if a detector has been assigned the correct wire pitch in the alignment file. Examples of these residuals, to check are shown in figure **??**.

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.