ATLAS muon reconstruction from a C++ perspective: a road to the Higgs
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CHAPTER 6  DATCHA

Never let reality get in the way of a good idea.

Chris Wallace

6.1 Introduction

DATCHA or Demonstration of ATLAS Chamber Alignment is an experimental setup designed to test the track detection and alignment capabilities of the ATLAS muon spectrometer [49]. It consists of three MDT chambers corresponding to a full-size barrel tower, augmented by three layers of RPCs (see figure 6.1).

The MDT chambers used in DATCHA consist of 2x3 layers in the case of the BIL and BML, and of 2x4 layers for the BOL, with the tubes extending in the x-direction (see figure 6.2). They are similar to the chambers that eventually will be used in the ATLAS detector, but due to their prototype nature they do have some imperfections. To begin with, the gas leak rate is two (BIL and BML) to three (BOL) orders of magnitude higher than the design single-tube rate of $10^{-8}$ bar.l.s$^{-1}$. This is in part caused by leaks in the gas distribution manifold. In addition, the BML

![Figure 6.1 Photo of the DATCHA setup at CERN.](image-url)
and BOL chambers also suffer from leaks in the gas connectors and cracks in the potting used to electrically insulate the passive components in the endplugs. As a consequence, the standard ATLAS gas Ar/N₂/CH₄ - 91:4:5 had to be replaced by a mixture of Argon and CO₂ in the ratio 80/20. Operated at 2 bar absolute pressure with a high voltage of 3150 V, its 1300 ns maximum drift time is much higher than the 500 ns of the standard ATLAS gas. Also, this choice of gas mixture leads to a highly non-linear r-t relation (see section 6.2.3).

A second shortcoming is that a significant fraction of the tubes in the BML and BOL chambers exhibit small discharges. However, this has for the most part been solved by adding a small amount of water (about 2500 ppm) to the gas.

The front-end electronics of a MDT chamber consist of a hedgehog preamplifier board with 32 channels serving eight tubes in each of a maximum of four tube layers. In addition they include a thick copper-clad ground plate to minimise electromagnetic interference, as well as a discriminator/multiplexer board with five outputs. Four of these are TDC outputs, one for each tube layer. This means that a TDC provides the logical OR of eight adjacent tubes within a layer. In addition, it is only capable of time stamping a maximum of eight leading and trailing edges. A typical TDC spectrum is shown in figure 6.3.
The fifth output provides the correspondence between the TDC hits and the channel numbers of the tubes in which the hits were generated, but it can only keep track of a maximum of four addresses per TDC output, i.e. per group of eight tubes.

On the other end of the tubes the high voltage is provided by Cockroft-Walton generators, one for each multilayer. They exhibit a long term stability of about 2 V at the chamber's end. The observed leak currents in the BIL chamber are about 1 μA, whereas in the other two chambers several groups of eight tubes had to be disconnected to keep the leakage below 25 μA per multilayer (see also section 6.3.1).

The MDT alignment information is provided by several RASNIK alignment systems, which operate by creating an image of a coded checkerboard mask using an infrared LED, and projecting that image onto a CCD sensor with the help of a lens [50]. In this way they are capable of measuring relative displacements perpendicular to the optical axis with an accuracy of 1 μm. Each MDT chamber is equipped with an in-plane system for monitoring possible chamber deformations. In addition, the corners of the three chambers are interconnected by projective alignment systems that record relative chamber displacements and rotations. About every ten minutes all 3x4 in-plane and four projective RASNiks are read out, their images analysed and the results stored for offline analysis.

The DATCHA RPC chambers are also similar to the trigger chambers that will be used in the ATLAS spectrometer, all be it with a much simpler layout. The two uppermost chambers, RPCs 2 and 3, contain only one layer of strips that measure the second coordinate\(^1\). Only RPC1 measures both coordinates as it has one layer of strips for each projection. Together with the scintillator hodoscope they are responsible for triggering on the cosmic muons. The hodoscope, which is positioned just below the inner MDT chamber, creates the primary signal with an overall timing resolution of 1 ns. A hit in the topmost RPC chamber is then needed to increase the chances that it was an actual muon that generated the hit in the hodoscope and that it has

\[\text{Figure 6.3 TDC spectrum of the BIL chamber after } t_0 \text{ calibration (run 2015; see section 6.1.1).}\]
traversed the whole DATCHA setup. In addition, a hit in RPC1, which lies underneath the shielding enforces a lower limit of around 3 GeV on the energy of the cosmic rays. All in all, this leads to a trigger rate of about 5 Hz.

### 6.1.1 Data Runs

The results presented in this chapter are based on a number of data runs, all taken in December 1997. For our purposes here, run 2015 serves as the reference run, while the others were taken after the BML chamber had been shifted in the y- or z-direction. Listed in table 6.1 are the number of events in each run, as well as the number of “good” muon events. This classification is based on the reconstruction of the trigger hits using a simplified version of the GD4 network described in chapter 4. In addition to the trigger definition given above, the following three requirement must be met:

1. The second and third RPC chambers must each contain only one cluster of hits, which are then used to build a trigger road. Hits in the RPC1 chamber are not used in this construction, because a cosmic-ray track can deviate significantly from a straight line due to the multiple scattering in the shielding. As a result of this requirement between 30 and 35% of the events are discarded.

2. The RPC trigger road must match to a cluster in the hodoscope, which also reduces the original sample by 30 to 35%.

3. No other clusters are allowed in the hodoscope to ensure an unambiguous determination of the trigger time. This results in a 60% rejection of the original events.

<table>
<thead>
<tr>
<th>Run</th>
<th># events</th>
<th># muon events</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>299,866</td>
<td>118,346</td>
<td>$\Delta Y_{BML} \sim -1.0 \text{ mm}$</td>
</tr>
<tr>
<td>2014</td>
<td>299,891</td>
<td>117,049</td>
<td>$\Delta Y_{BML} \sim -2.0 \text{ mm}$</td>
</tr>
<tr>
<td>2015</td>
<td>299,879</td>
<td>115,408</td>
<td>Reference run</td>
</tr>
<tr>
<td>2016</td>
<td>299,875</td>
<td>114,937</td>
<td>$\Delta Z_{BML} \sim 2.0 \text{ mm}$</td>
</tr>
<tr>
<td>2018</td>
<td>299,865</td>
<td>120,650</td>
<td>$\Delta Z_{BML} \sim -2.0 \text{ mm}$</td>
</tr>
</tbody>
</table>

Table 6.1 Summary of the DATCHA runs, which are used in this chapter.

From the quoted numbers alone it follows that these requirements can not be independent. And in fact, there is an almost 90% correlation between requirements 1 and 2. Furthermore, it turns out that the sample remaining after requirement 3 is nearly a complete subset of the requirement 2 sample. Hence the overall trigger efficiency of 38 to 40% is only slightly lower than that of requirement 3.
6.2. Calibration

6.2.1 Event Simulation

To complement the real data, simulation runs are performed using the internal simulation facility of Arve. The simulation of the MDTs is the same as described in the previous chapter, with the signal propagation velocity, r-t relations and residuals taken from the analysis of run 2015 (see section 6.2). For both the RPC chambers and the hodoscope an approximation of the support structure designed to produce the appropriate amount of multiple scattering has been implemented. Furthermore, the iron (1.6 m) and concrete (0.8 m) shielding are added to the detector description to correctly form the trigger decisions.

As a particle source, a cosmic-ray generator is used. It creates muons and anti-muons in a ratio of 4 to 5 and with their origin uniformly distributed in a plane above the detector, while their direction has an angular distribution of \( \cos^2(\theta) \), with \( \theta \) the angle between the muon and the vertical y-axis. They are given a momentum in the range of 3 to 100 GeV/c with an underlying \( p^2 \) distribution [51]. The minimum of this range is based on the shielding present in the detector, the maximum on the electromagnetic interaction tables available for the materials.

6.2 Calibration

Precise knowledge of the detector’s behaviour is needed to correctly interpret the TDC times that come out of the data acquisition system. Various corrections must be applied before these times can be converted into drift distances, which can then be used to reconstruct the tracks. These calibration aspects include:

- The time-of-flight of the muon and the response of the hodoscope;
- The relative timing between the MDT channels in the form of the \( t_0 \) (leading edge) and \( t_{\text{max}} \) (trailing edge) values of the TDCs;
- The r-t relation of the MDT gas mixture;
- The velocity with which the signal propagates along the wire;
- The relative positions of the wires;
- The chamber deformations and displacements, as well as the gravitational sag of the wires.

The first four of these corrections are explored in detail in the paragraphs that follow. The fifth effect, that of the individual wire offsets, is ignored and the design values are used in the reconstruction. To compensate for this, in the determination of the resolution of the drift tubes, an uncertainty of 20 μm r.m.s. is assumed [15].

This then leaves the last item. The chamber displacements have no effect on the MDT track segments, but only on their global matching. In contrast, the chamber deformations and

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2. The hodoscope is defined as a RPC chamber with strips the size of the scintillator tubes.
gravitational sag of the wires do effect both parts of the reconstruction. However, as they vary only moderately and continuously over the extent of the chamber, in the small region in which a track crosses that chamber they can be assumed to be constant. As a result they have no real effect on the pattern recognition, but only influence the final track segment parameters, and thereby the global matching. All these global alignment effects are folded into the sagitta measurement as described in section 6.3.4, and a more comprehensive study of the alignment systems in DATCHA can be found elsewhere [54-56].

6.2.1 Time-of-flight Correction

The first effect that has to be considered is the time it takes the cosmic muon to fly from the MDT tube in which it generates a hit to the hodoscope, which determines the trigger time. Since the muon travels at a speed close to the speed of light\(^3\) along a nearly straight path, this time-of-flight correction is only dependent on the vertical position of the hit and the direction of the particle. In principle, an initial segment fit is needed to determine these parameters. However, as it is favourable to being able to correct each individual hit before the segment reconstruction is started than to have to perform an iterative procedure, the parameters are estimated instead.

![Figure 6.4](image-url)  
**Figure 6.4** Reconstructed track angle in the yz-projection. The points represent the data from run 2015, while the shaded histogram is the result of a Monte-Carlo simulation. The reason that the Monte Carlo data has a wider distribution than the real data lies in the fact that the wall of the pit in which the detector resides is not included in the simulation.

3. At their lowest triggering energy of 3 GeV, a muon travels already at a velocity of 99.9% of the speed of light. Hence even for the BOL, the maximum effect on the time-of-flight is 0.03 ns, which can safely be ignored.
For the hit's vertical position, the location of the wire can be taken. The particle's direction is however slightly more difficult. In the xy-plane (cf. figure 6.2), it can be derived from the road created from the RPC hits. In the yz-projection no such information is available, but here the geometry of the DATCHA tower helps out: All tracks that pass the trigger requirements must have had an angle of $63 \pm 3^\circ$ (see figure 6.4). For the time-of-flight correction, this spread is ignored and the average value is taken for all hits. The error that this approximation introduces can be calculated from the yz-length $s$ of a track with an angle $\alpha$ (i.e. the real path of the muon), compared to that of a track with the average DATCHA angle of $63^\circ$ (i.e. the path assumed in the time-of-flight correction):

$$s = \frac{s_0 \cdot \tan \alpha}{\sin(\Delta \alpha) + \cos(\Delta \alpha) \cdot \tan \alpha}$$

(6.1)

with $s_0$ the track length at $63^\circ$, and $\Delta \alpha = \alpha - 63^\circ \geq 0$ the difference in angle between the two tracks. With a maximum angle of $70^\circ$ (cf. figure 6.4) the upper limits of the time-of-flight errors are equal to 0.1, 0.5 and 0.9 ns for the BIL, BML and BOL chamber respectively. For angles that are smaller than $63^\circ$ equation 6.1 must be inverted, leading to lower limits of respectively -0.2, -1.1 and -2.3 ns, which correspond to a minimum track angle of $55^\circ$.

This difference between the lower and upper limits explains the shapes of figure 6.5 in which the deviation between the reconstructed and real time-of-flight correction for 10,000 simulated events is plotted. It also shows that the errors are dominated by the approximation of the track angle in the yz-projection. Including all effects, the errors in the time-of-flight estimate are equal to 0.1, 0.4 and 0.9 ns for respectively the BIL, BML and BOL chamber.

**Figure 6.5** Difference between the reconstructed and Monte Carlo time-of-flight corrections.

### 6.2.2 Leading and Trailing Edges

The determination of the leading and trailing edges of the TDC spectrum of each individual tube is needed to factor out the behaviour of the front-end electronics, as well as the differences in length of the cables connecting the tubes to the TDCs. As its input, the procedure requires the

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4. The fact that the maximum angle in the Monte Carlo data extends to $73^\circ$ has no significant effect on the magnitude of the time-of-flight errors.
drift times corrected for the time-of-flight of the muon and for the propagation of the signal along the wire. However, the propagation velocity can only be determined after the r-t relations, and hence the leading edges, are known (see section 6.2.4). One solution would be to use only those hits that lie close to the front-end electronics, but that would lead to very poor statistics. So instead a propagation velocity equal to the speed of light is assumed, which introduces a systematic shift in the $t_0$ and $t_{\text{max}}$ values that is approximately identical to

$$\Delta t = \frac{L}{2} \left( \frac{1}{v_s} - \frac{1}{c} \right)$$

(6.2)

i.e. the difference in signal propagation time of a hit halfway down the tube as a result of the difference between the real propagation velocity $v_s$ and the assumed velocity of the speed of light. This is however only valid if this shift is small enough so that it does not influence the outcome of the pattern recognition, and thereby the r-t calibration procedure\textsuperscript{5}. These r-t relations can then be used to determine the real signal propagation velocity, after which the leading and trailing edges can be corrected for it.

The actual procedure of determining the $t_0$ values is quite straightforward: The leading edge of each individual TDC spectrum is parameterized by

$$L(t) = \alpha_1 + \frac{\alpha_2}{1 + \exp \left( \frac{\alpha_3 - t}{\alpha_4} \right)} \cdot \frac{\alpha_5 + \left[ 1 + \exp \left( \frac{t - \alpha_3}{\alpha_6} \right) \right]^{-1}}{1 + \alpha_5}$$

(6.3)

![Figure 6.6](image)

**Figure 6.6** Example of a $t_0$ (a) and a $t_{\text{max}}$ (b) fit [52, 53]. The data is represented by the dots and the fit by the solid line.

5. For the BOL, which is the largest chamber, an actual signal velocity of 75% of the speed of light corresponds to an error of 3 ns. This is much smaller than the resolution of the individual tubes and therefore causes no problems for the pattern recognition.
in the interval \( t \in -(50, 100) \) ns (see figure 6.6a), where only entries for hits that could be associated to a track segment are shown. In the first iteration all parameters are left free, while in the second iteration the slope parameters \( \alpha_4 \) and \( \alpha_5 \) as well as the plateau parameter \( \alpha_5 \) are fixed to their average value for the layer to which the tube belongs. The value of \( t_0 \) is then defined as the time at which \( L(t) \) reaches half of its maximum value. Its error depends therefore only on the slope parameter \( \alpha_4 \) and on the event statistics, and is listed in table 6.2.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>( \Delta t_0 ) (ns)</th>
<th>( \Delta t_{\text{max}} ) (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIL</td>
<td>0.5</td>
<td>2.4</td>
</tr>
<tr>
<td>BML</td>
<td>0.6</td>
<td>3.1</td>
</tr>
<tr>
<td>BOL</td>
<td>0.7</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 6.2 Errors in the leading and trailing edges.

A similar approach is used to determine the \( t_{\text{max}} \) of each channel, i.e. the time of the last hit relative to the channel’s \( t_0 \) (see figure 6.6b). These values are needed to rescale the drift times of a group of tubes to a single \( t_{\text{max}} \) value so that a common r-t relation can be used. This procedure can only be used when the gas mixture and operating conditions of those tubes are similar, and when no out-of-centre positioned wires are present. However, these are also the requirements for a single r-t relation to be valid, so the success of the r-t calibration in the next section shows that the rescaling of the drift-time spectra is a legitimate procedure.

### 6.2.3 R-T Calibration

The determination of the r-t relations is performed with the help of an auto-calibration procedure in which an initial set of relations is used to reconstruct the events. Then, based on the reconstructed track segments, the relations are recalculated by taking the fitted drift distances instead of the computed ones. The mean values of Gaussian fits to the drift times in each drift-distance bin are plotted as a function of this distance as shown in figure 6.8. The binning in the drift distance is preferred, because it leads to similar statistics in each bin. The reason for this is that because of their cosmic-ray nature the muons illuminate the tubes uniformly in radius (see also section 6.3), while the non-linearity of the r-t relations causes this uniformity to be lost in the drift times. This procedure is then repeated several times until the r-t relations are stable.

To reduce the effects of random noise and \( \delta \)-ray hits, only “good” track segments are selected as defined by:

- A segment must have at least 5 hits. In spite of the fact that the BOL consists of two more layers than the other two chambers, its many disconnected tubes prevent the application of a stricter cut;

- Of these hits, at least two must come from each multilayer;
• The chi-squared per degree of freedom of the segment fit must be equal to or less than 5.

These requirements alone are however not sufficient to always reconstruct the true track as can be seen from figure 6.7: When the hits all lie on the same side of the wires, the fit will shift the reconstructed track from the true one by any systematic error present in the r-t relations. Since the tracks used in the calibration are a mixture of type A and type B as defined in figure 6.7, this means that the calculated r-t relations lie somewhere in between the original and the true ones. Hence a larger number of iterations is needed in order for the calibration procedure to converge.

![Figure 6.7 Sketch of a MDT multilayer in which the r-t relations overestimate the drift distance of the hits. Muon track A is reconstructed almost correctly despite the systematic error, whereas the reconstructed track B shows a large deviation from the true track.](image)

To select only those tracks that cross tubes on both sides of the wires, the following criteria must also be met for each separate multilayer:

• The number of hits with the track passing the wire on the left side, and the number of right hits must both be larger than zero;

• The difference between these two types of hits must be either zero or one.

In the reconstruction of the track segments again a signal propagation velocity equal to the speed of light is assumed. This means that only for a hit in the centre of the MDT wire does the shift in the $t_0$ value cancel out against the drift time reconstruction error caused by the incorrect knowledge of this velocity. Using all hits independent of their second coordinate results in a spread in the drift times, but that does not effect the mean value in each drift-distance bin.

This leaves us with one unanswered question, viz. how many r-t relations are needed. From a theoretical standpoint it would be preferable to have a separate relation for each individual tube. However, this is neither practical nor precise due to the lack of statistics. So instead r-t relations are derived for each tube layer. Analysis has shown that the variations in
the r-t relations between different regions along the tubes’ length are much smaller than the differences between tube layers or even between individual tubes [52].

A typical r-t relation is shown in figure 6.8, and the shapes of the 19 other relations are all very similar to it. Compared to the average of each chamber they differ by less than 5 ns in the case of the BIL, and by less than 10 ns for the other two chambers (see figure 6.9). To estimate the error in the r-t relations, three different comparisons have been performed:

- The difference in r-t relations between two iterations of the calibration procedure is about 0.5 ns independent of the chamber. This is however only a measure of the stability of the algorithm, and not of the correctness of the relations for each individual tube;

- The difference between a Monte Carlo input r-t relation and the reconstructed one is found to be in the order of 2 ns for the BIL chamber and 1 ns for the other two chambers. The reason for the larger error in the inner chamber is most probably its 2x3 tube layer layout in conjunction with its small multilayer separation. These numbers are an estimate of the correctness of the r-t calibration procedure, and do not include any tube-to-tube variations;

- From the determination of the r-t relation of each individual tube, it can be deduced that the tube-to-tube variations have an r.m.s. value of 1 ns in the case of the BIL chamber, and 2 ns for the other two chambers.

In total this means that an error of 2.3 ns in the r-t relations for all chambers can be assumed.

**Figure 6.8** The r-t relation of the first layer, first multilayer of the BIL chamber (run 2015).

**Figure 6.9** Variation in the r-t relations of the three chambers relative to their average value.
6.2.4 Signal Propagation Velocity

The time it takes the signal to propagate along the wire from the point the muon crosses the tube to the front-end electronics must be subtracted from the measured time to arrive at the actual drift time. Any deviation from the real propagation velocity in applying this correction shows up as a systematic increase or decrease in the radius of all drift circles; a shift that moreover depends linearly on the hit’s second coordinate. This phenomenon can only be detected for track segments that have hits on both sides of the wires (cf. figure 6.7), which means that the same hit criteria as used in the determination of the r-t relations must be used.

The residuals of these hits, converted to drift times, can be plotted against their second coordinate as determined by the trigger roads. This is done in figure 6.10 for run 2015 with the propagation velocity set to the speed of light. Based on the slope of the fitted lines, the real velocity $v_s$ can be determined according to

\[
\frac{\Delta t_{res}}{\Delta x} = \frac{1}{v_s} - \frac{1}{c} \quad (6.4)
\]

\[
\chi^2_{ndf} = 3.063/3 \quad \Delta_0 = 0.7523 \\
\Delta_1 = 0.6266E-02
\]

\[
\chi^2_{ndf} = 13.96/3 \quad \Delta_0 = -1.309 \\
\Delta_1 = 0.7016E-02
\]

\[
\chi^2_{ndf} = 23.22/3 \quad \Delta_0 = -0.2112 \\
\Delta_1 = 0.2831E-02
\]

**Figure 6.10** Signal propagation velocity in the MDT chambers. The slope parameter $A_1$ can be converted to a velocity using equation 6.4.
which results in velocities of respectively 0.84, 0.83 and 0.92 times the speed of light. Their errors can not be determined solely based on the errors of the fits, because the slopes do depend somewhat on the binning used in the histograms. From studying various binnings an error of around 5% in \( v_s \) can be deduced. This is in fair agreement with independent signal-speed measurements performed on dedicated twin tubes\(^6\), which have determined the velocity to be 3.8 ns/m or 0.88 times the speed of light.

Based on the length of the chambers, the average errors the signal propagation induces in the times measured in DATCHA are equal to 0.3, 0.4 and 0.5 ns for the BIL, BML and BOL chambers respectively. This includes the uncertainty due to the 3 cm (0.8 cm r.m.s.) width of the trigger roads.

The errors in the drift times caused by the various calibration procedures are listed in table 6.3. The wire-offsets error corresponds to the 20 \( \mu m \) r.m.s. uncertainty in the wire position. The effect of multiple scattering on the drift times has been determined from dedicated Monte Carlo runs in which the material was selectively turned on or off. The final conversion from the drift-time errors to the corresponding errors in the drift distance is based on an average drift velocity of 11.5 \( \mu m/\text{ns} \) (cf. figure 6.8).

<table>
<thead>
<tr>
<th>Effect</th>
<th>BIL</th>
<th>BML</th>
<th>BOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger (hodoscope)</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time-of-flight</td>
<td>0.1</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>( t_0 ) calibration</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>R-T relation</td>
<td>2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal propagation</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Wire offsets</td>
<td></td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Multiple scattering</td>
<td>0.4</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.1 ns</td>
<td>3.2 ns</td>
<td>3.3 ns</td>
</tr>
<tr>
<td></td>
<td>36 ( \mu m )</td>
<td>37 ( \mu m )</td>
<td>39 ( \mu m )</td>
</tr>
</tbody>
</table>

Table 6.3 Drift-time errors in ns induced by the various calibration procedures. The last line shows the total errors in the drift distance.

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6. In a twin-tube setup the wires of pairs of MDT tubes are connected at the high-voltage side so that the signal of a hit in one of the tubes is read out in both of them.
6.3 Reconstruction

The reconstruction of DATCHA events is a three-step process. First the RPC and hodoscope hits are used to create trigger roads. This is followed by the independent reconstruction of track segments in each of the three MDT chambers. Finally, the segments are matched together to form the global muon track. The result for a typical event is shown in figure 6.11. As can be seen from the deviation between the BML segment and the global track, for the analysis described

![Diagram](image)

**Figure 6.11** Display of one of the first reconstructed events, with the inset showing the trigger road in the xy-projection. The solid circles represent the hits assigned to the track segments, and the shift of the BML chamber is clearly visible.
in this section the results of the alignment systems, i.e. possible chamber deformations and displacements, are not used in the reconstruction.

6.3.1 Single-Tube Efficiency

The single-tube or hit efficiency for the BIL chamber is shown in figure 6.12. The result of a Monte Carlo simulation of 100%-efficient tubes up to their inner radius of 14.6 mm has been included for reference. The hit efficiency is defined as the fraction of tubes crossed by the track segments that contain a hit. The good-hit efficiency requires in addition to this that the hit in question has been assigned to one of the segments. The behaviour of the other two chambers is very similar to that of the BIL, all be it with different efficiencies.

![Hit efficiency graphs](image)

**Figure 6.12** Hit efficiency (squares) and good-hit efficiency (circles) as a function of drift radius (a) and second coordinate (b) for the BIL chamber in run 2015. The shaded histograms show the results of a Monte Carlo simulation.

The highest hit efficiency is recorded in the BIL: Up to a drift radius of around 10 mm it is fairly constant at around 98%. The fact that it starts to drop for radii beyond that is explained in figure 6.13:. A track with a certain angle $\alpha$ that generates a hit with a radius above a value given by

$$r_{hit} = p \sin \alpha - r$$  \hspace{1cm} (6.5)

with $r$ the tubes’ radius and $p$ their pitch, also crosses a neighbouring tube in the same layer. In seven out of eight times these two tubes belong to the same multiplexer, and hence only the address of one of the two tubes is retained. Due to the layout of the DATCHA setup (cf. figure 6.4) $\alpha$ falls in the range between 55° and 70°, which means that this effect starts to occur for hits with a radius of 10 mm ($r = 14.6$ mm and $p = 30.1$ mm) and reaches its maximum
inefficiency of 44% at a radius of 13.7 mm. Unlike this dependence on the drift distance, there is hardly any variation visible in the hit efficiency as a function of the second coordinate (see figure 6.12b).

The small inefficiency of the BIL chamber is in part explained by its one dead tube. The remaining 1.5% inefficiency could be the result of cross talk between the tubes, which as a result of the multiplexed read-out shows up as an inefficiency. This idea is confirmed by a dedicated run with every other tube disconnected, i.e. with the multiplexing scheme in principle disabled, in which this inefficiency is fully recovered.

The much higher inefficiencies observed in the BML and BOL chambers are almost entirely due to their disconnected tubes. In fact the fractions of disconnected tubes of around 34% and 59% respectively are much higher than the observed inefficiencies of 14% and 17%, but this is because the disconnected tubes cover entire regions of the chambers in which no tracks are found to start with.

Figure 6.12 also shows the good-hit efficiency. It is in general 5% to 10% lower than the standard hit efficiency due to δ-rays and incorrect results of the pattern recognition. The additional inefficiency observed at small drift distances is in part caused by the increased chance of reconstructing the wrong track segment because of an incorrect left-right assignment of the hits, and in part by the behaviour of the front-end electronics. When a track passes close to the anode wire, and therefore leaves a long ionization trail, it can generate many discriminator level crossings. Because the TDCs are only capable of storing the last eight leading and trailing edges, when there are more, the first and most important ones are lost. This means that a hit is still registered in that tube, but that its drift time is incorrectly measured. Hence the difference between the hit and the good-hit efficiencies.

When looking at the coordinate along the wire, the hit and good-hit efficiency follow each other nicely. The loss of efficiency near the ends of the tubes is a normal phenomenon in drift-tube operation.
6.3.2 Segment Reconstruction

The segment reconstruction follows the same path as described in the previous chapter, and uses the hit requirements listed in section 6.2.3. For the BIL, the accuracy of the fit in the form of the errors in the angle and offset parameters of the reconstructed segments is shown in figure 6.14. These same quantities for all chambers are listed in table 6.4. They are slightly better than the results of the simulated data (see section 5.4), because of a higher single-tube resolution of the DATCHA chambers compared to what is expected of the future ATLAS chambers. This is most likely due to the much slower gas that is used here.

![Figure 6.14](image_url)

**Figure 6.14** Angle (a) and offset (b) errors of the track fit in the BIL chamber.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Efficiency</th>
<th>$\sigma_\alpha$ (mrad)</th>
<th>$\sigma_{\text{offset}}$ ((\mu\text{m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIL</td>
<td>61%</td>
<td>0.20</td>
<td>24.6</td>
</tr>
<tr>
<td>BML</td>
<td>42%</td>
<td>0.17</td>
<td>28.1</td>
</tr>
<tr>
<td>BOL</td>
<td>42%</td>
<td>0.15</td>
<td>35.0</td>
</tr>
</tbody>
</table>

**Table 6.4** Results of the track-segment reconstruction in the three MDT chambers.

Table 6.4 also lists the efficiencies for reconstructing a track segment in the various chambers. In the case of the BML and BOL chambers they are a direct result of the single-tube efficiencies. On the other hand, for the BIL the inefficiency has a largely geometrical origin since the muons that cross the chamber at its edges fail to generate enough hits to pass the cuts.

The corresponding hit residuals are shown in figure 6.15. To convert them to single-tube resolutions, the same approach as described in section 5.5 is used, i.e. one hit at a time is removed from the track after which the fit is repeated. The residual of the removed hit, after

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7. Based on the DATCHA results and those of ageing tests, the ATLAS MDT gas has recently been changed to an Argon-CO\(_2\) mixture with a maximum drift time of 700 ns.
Figure 6.15 Residual distributions of the BIL (a), BML (b) and BOL (c) chambers, and as a function of the hit’s drift distance (d).

it has been corrected for the finite precision of the track fit, is then used as an estimator of the resolution. After unfolding the errors of the various calibration procedures (see table 6.3), the resulting resolutions are 68, 82 and 86 μm for the BIL, BML and BOL chambers respectively.

6.3.3 Segment Matching

In the segment matching process, the information from the alignment systems is not used to correct for any chamber displacements or deformations. Therefore systematic shifts between the angles and positions of the segments from different chambers are to be expected, and the matching criteria are kept very loose to compensate for this.

As a first step, the segments in the BIL and BOL chambers are compared to form a global track (see figure 6.16). The difference in their position is determined by following the BIL segment to the BOL chamber, and reveals a shift in the relative positions of the chambers compared to the design values as used by the reconstruction. The widths of both distributions
6.3. Reconstruction

Figure 6.16 Angle (a) and offset (b) difference between the BIL and BOL track segments for run 2015.

are for the most part comparable to what can be expected from multiple scattering. The remainder is caused by misreconstructed track segments in either of the two chambers. Based on these figures, the cut on the difference in angle between the BIL and BOL segments is set at 10 mrad, while the cut on their offset difference is set to 30 mm around a mean value of 21 mm. This leads to an efficiency for finding a global track of around 28%, which means that the inefficiencies in the two chambers are almost completely uncorrelated.

The global track can then be compared to the segment found in the BML chamber. Because the BML chamber can be shifted in y and/or z, no cut on the offset difference is applied. Only a 10 mrad maximum on the difference in angle between the global track and the BML segment is enforced. The resulting efficiency then comes in at 16%.

6.3.4 Sagitta Measurement

The sagitta measured between the global track and the BML segment is converted to a horizontal, i.e. in the z-direction, shift of the BML chamber using the track’s angle. Its distribution for run 2015 is shown in figure 6.17. The mean value is not consistent with zero as the chamber positions do not coincide with the design values used in the reconstruction. Its width is almost completely brought about by the multiple scattering in the BML chamber. This is not only clear from the fact that the r.m.s. sagitta of 1.8 mm far exceeds the accuracy of around 30 μm in the reconstructed offset parameters of the track segments, but has also been confirmed by the results of a material-free Monte Carlo simulation run.

The same sagitta is also measured by the four projective RASNIK alignment systems, whose averaged value is equal to 1.005 ± 0.002 mm. But as the RASNIK systems have not been absolutely calibrated, this number can not be directly compared with the result of the cosmosics reconstruction. To circumvent this, one must look at the change in sagitta between the various runs (cf. table 6.1) as displayed in figure 6.18. This procedure has the added advantage that the
Figure 6.17 Distribution of the sagitta between the global tracks and the BML segments in run 2015.

Figure 6.18 The sagitta measured by the RASNIK systems compared to the reconstructed mean sagitta values of the cosmic muons (a), and the residuals of the straight-line fit (b).
unknown chamber deformations, rotations and displacements as discussed at the beginning of section 6.2 factor out.

Figure 6.18 clearly shows that the sagitta measurement from the cosmic muons agrees very well with that of the RASNIK systems, as the slope of the straight-line fit through the data points is equal to unity within its error. The r.m.s. deviation of 15 µm is dominated by the statistical uncertainty in the reconstructed cosmic-muon sagitta (14 µm) and can therefore be significantly reduced by using larger data samples. However even now this number is already well below the ATLAS design target of 30 µm, although it must be realised that it does not contain any absolute-calibration error, which will be one of the larger contributions to that 30 µm.

6.4 Conclusion

After the initial problems with the MDT chambers such as gas leaks, random discharges and leak currents had been solved, the chambers operated quite well. When ignoring the disconnected tubes, the single-tube efficiencies were excellent and the noise levels were low.

The reconstruction also performed admirably, giving resolutions and track-parameter accuracies comparable to what is expected of the ATLAS software. In addition, an excellent agreement between the reconstructed sagittae of the cosmic muons and the measurements of the RASNIK alignment systems was achieved.