Precision of the ATLAS muon spectrometer

Woudstra, M.J.

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Chapter 2  Muon spectrometer design

"Meaningless! Meaningless!" says the Teacher.
"Everything is meaningless!"

Ecclesiastes 12:8

As stated in the muon TDR [24], the ATLAS muon spectrometer instrumentation must meet demanding specifications:

- Operation: it must operate reliably for many years in a high rate and high background environment. This affects the operating point, notably the drift gas, in view of the performance degradation due to possible chamber ageing, and the segmentation in view of pattern recognition complexity due to a high occupancy;

- Precision: the measurement accuracy must be commensurate with the physics requirements. The large air-core toroidal magnetic field configuration and the muon chamber design provide three high precision track segments over a large volume in a moderate magnetic field, which allows a precise momentum determination;

- Realisation: muon chamber production will span a long time period and involve many different institutes. Given limited personnel and financial resources an economic and robust technology suitable to mass production is required and continuous quality assurance is a sine-qua-non.

This thesis focuses on the Monitored Drift Tube (MDT) chambers that measure the precision coordinates of the magnetically deflected muon tracks. It also covers the alignment system for the MDT chambers. The scope is limited to the barrel system.

2.1 Overview

The barrel of the muon spectrometer covers the rapidity range $-1 \leq \eta \leq 1$ and consists of three concentric stations of Monitored Drift Tube (MDT) chambers, as shown in figure 2-1 [24]. The stations are called 'Inner', 'Middle' and 'Outer' respectively for increasing radial position. Each barrel station has two types of MDT chambers, 'Large' and 'Small', which are alternating and partly overlapping in azimuth ($\phi$) to avoid holes in the acceptance. They exhibit a two times eight-fold symmetry in $\phi$. The different types of MDT chambers are labelled with a three letter name: first a B (for Barrel), then the station (I/M/O), and finally the size (L/S). Along the LHC beam axis ($z$) 6 adjacent chambers of the same type make up half a barrel, as shown in figure 2-2 [24].
Table 2-1 lists the geometrical parameters of the six main types of MDT chambers in the barrel spectrometer. Several other types exist in the barrel for special regions (ATLAS feet and rails, toroid ribs, barrel / end-cap transition) of which only few are needed. Even some of the listed main types have fewer tubes per layer to make space for the services of the inner detectors and calorimeters, and to provide access to the detector elements once ATLAS is fully assembled.

<table>
<thead>
<tr>
<th></th>
<th>BIS</th>
<th>BIL</th>
<th>BMS</th>
<th>BML</th>
<th>BOS</th>
<th>BOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>radial position (mm)</td>
<td>4525</td>
<td>4926</td>
<td>8070</td>
<td>7116</td>
<td>10544</td>
<td>9477</td>
</tr>
<tr>
<td># tubes per layer</td>
<td>30</td>
<td>36</td>
<td>48</td>
<td>56</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td># layers per multilayer</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>tube length (mm)</td>
<td>1617.5</td>
<td>2671.5</td>
<td>3071.5</td>
<td>3551.5</td>
<td>3773.3</td>
<td>4961.5</td>
</tr>
<tr>
<td>spacer height (mm)</td>
<td>6.5</td>
<td>170</td>
<td>170</td>
<td>317</td>
<td>317</td>
<td>317</td>
</tr>
</tbody>
</table>

Resistive Plate Chambers (RPCs) are installed in the middle station and the outer station and serve for muon triggering, second coordinate measurement for the MDTs (along the wire), and bunch crossing identification for the global event reference time [24]. They are indicated in figures 2-1 and 2-2.

Figure 2-3 Three dimensional view of the superconducting air-core toroid magnet system of the ATLAS muon spectrometer. The right-hand end-cap magnet is shown retracted from its operating position.
The magnetic field is supplied by three air-core toroid superconducting magnets, designed to produce a large-volume moderate magnetic field covering the rapidity range $-2.7 \leq \eta \leq 2.7$ [24]. It has an open structure that minimises the contribution of multiple scattering to the momentum resolution. The barrel toroid extends over a length of 25 m with an inner bore of 9.4 m and an outer diameter of 20.1 m, and provides a typical bending power of 3 Tm. The two end-cap toroids are inserted in the barrel at each end. Figure 2-3 shows a 3-D view of the muon magnet system.

2.2 Muon measurement principle

The muon momentum measurement is based on the measurement of three points along the track of the particle that is deflected in the magnetic field. The amount of curvature is a measure for the particle momentum. Each of the three ‘stations’ in the muon barrel system provides one measurement point along the track. It is convenient to express the curvature in terms of a ‘sagitta’, which is the distance from the point measured in the middle station to the straight line connecting the points in the inner and outer stations. The precision of the sagitta measurement is a direct measure for the precision of the muon momentum. A muon with a momentum of 1 TeV/c has a sagitta of about 500 μm, and the target momentum measurement precision of 10% translates into a sagitta precision of 50 μm. The actual precision depends not only on the local precision of the points measured in the muon chambers, but also on the relative positions of the three stations. These positions therefore need to be known with an accuracy that is comparable to the individual chamber point measurement precision. The target total contribution of the chamber point measurements to the sagitta precision is 40 μm. It is impossible to keep the geometry of the chambers stable to that precision. Permanent alignment systems are therefore needed to monitor the relative chamber positions with high accuracy, where the displacements in the sagitta direction are of prime importance. This has lead to the alignment scheme outlined in paragraph 2.5, which aims at a total contribution of the alignment to the uncertainty of the sagitta measurement of 30 μm.

Each station of muon chambers does not only provide a point in space, but also a direction. This allows an angle-angle momentum measurement in addition to the sagitta measurement. Although this is less accurate, it allows a momentum measurement in case only two out of the three stations are hit by the muon. Moreover, it improves the measurement resolution for muons with low momentum. The toroid-shaped magnetic field is perpendicular to the muon momentum direction at all rapidities. This ensures that the full bending power is still available at high rapidities.

2.3 Monitored drift tube chambers

The precision coordinate measurement in the bending direction of the muon track is performed by the Monitored Drift Tube (MDT) chambers. The precision muon momentum is therefore provided by the MDTs. With 370,000 channels they cover almost the entire area of 5500 m$^2$ which is needed for a good momentum determination of the muons with rapidities ranging from $-2.7$ to $+2.7$ [24].
2.3.1 Operating principle

The basic detection element is a cylindrical aluminium drift tube with a diameter of 30 mm, holding a 50 µm diameter W-Re wire at its centre. The tube is filled with a non-flammable drift gas at high pressure for reduced diffusion and ionisation position fluctuations. A positive high voltage is applied to the wire. When a charged particle traverses the tube, the gas is ionised and the electrons drift to the wire, generating a signal on the wire. This is illustrated in figure 2-4, where the path is curved due to the magnetic field. Close to the wire an avalanche is generated by the (locally) very high electric field, which results in a signal amplification, the ‘gas gain’. The signal on the wire propagates to the end of the tube, where a current-sensitive amplifier annex shaper (15 ns peaking time) followed by a discriminator feeds a timing pulse into the on-chamber time-to-digital converter (TDC). The MDT operating point as foreseen for ATLAS is listed in table 2-2. The Ar / CO₂ gas mixture is chosen for its excellent ageing properties. The high-voltage and the Ar / CO₂ ratio are chosen to limit the gas gain, and thereby ageing, to limit after-pulsing and to limit the maximum occupation time to 700 ns. The discriminator threshold should be as low as possible for optimal resolution and is chosen at five times the noise level to limit the number of noise hits [26].

The time between passage of the particle through the tube and arrival of the signal on the wire is a measure for the distance from the particle track to the wire. The relation between the drift time and the drift distance is shown in figure 2-5 for the operation point listed in table 2-2, in absence of a magnetic field. The precision with which the drift distance can be determined from the drift time is limited by the statistical nature of the signal generation. Figure 2-6 shows the simulated and measured resolution of the measured drift distance of an MDT (with the operating point listed in table 2-2) as a function of the radial position of the muon track [26]. The measured resolution is the r.m.s. of the residuals of the drift distances measured by the tube when they are compared to the track positions, which are measured by an external reference system. The simulations (from GARFIELD [27]) and measurements show excellent agreement. The shape of the resolution is typical for the Ar / CO₂ drift gas [28]. The relatively bad resolution near the wire (r = 0) is due to the high drift velocity and due to the geometrical distribution of the ionisation clusters in combination with the fluctuations of the ionisation cluster size and position. For increasing radius the drift velocity decreases due to the decreasing electric field, and

### Table 2-2 MDT operation point foreseen for ATLAS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas mixture</td>
<td>Ar / CO₂ 93 / 7</td>
</tr>
<tr>
<td>Pressure</td>
<td>3 bar absolute</td>
</tr>
<tr>
<td>High voltage</td>
<td>3080 V</td>
</tr>
<tr>
<td>Gas gain</td>
<td>2 x 10⁴</td>
</tr>
<tr>
<td>Discriminator threshold</td>
<td>20th electron</td>
</tr>
</tbody>
</table>
the effect of the ionisation fluctuations is reduced due to the geometrical distribution of the ionisation clusters. At high radius, diffusion starts to play a role. The average intrinsic resolution is 58 µm, which is well below the target resolution of 80 µm.

When a muon traverses an MDT chamber, it hits six (or eight) drift tubes. The measured drift times are combined to reconstruct a track segment in the chamber. Effectively two parameters are determined for a track segment: the translation perpendicular to the track direction with a resolution of 28-32 µm, and the track angle with resolution of 0.16 - 0.50 mrad, where the ranges cover the various numbers of tube layers (2 x 3 or 2 x 4) and spacer heights (6.5 mm to 317 mm).

2.3.2 Single drift tube

A single Monitored Drift Tube (MDT, see figure 2-7) consists of an industrially available aluminium tube with an outer diameter of 30 mm and a 400 µm thick wall. It holds a standard 50 µm diameter gold plated (3% by weight) W-Re (97/3) wire at its centre. The tube is closed at both ends with specially developed ‘end-plugs’ [29], which serve several purposes at the same time:

- Hold the wire in the centre of the tube with a precision of 10 µm. This is achieved by a ‘twister’ type wire locator, which is inserted into the central hole of the end-plug. The twister facilitates at the same time an automated tube wiring procedure [30];

1. This value is historical and corresponds to the average resolution achieved for the drift gas that was originally foreseen for ATLAS (Ar / N₂ / CH₄ 91 / 4 / 5) [24]. This gas has been abandoned for reasons of ageing.
• Give electrical access to the tube (ground) and to the wire (high voltage supply and signal read-out);
• Inlet and outlet of the drift gas;
• Gas tightness of the tube;
• Provide a precision reference surface to position the tubes with high accuracy during the chamber assembly.

After assembly of an MDT single tube, several tests are performed for quality control. The position of the wire in the end-plug is measured and has an r.m.s. of 7 µm in both coordinates for the BOL tubes constructed at NIKHEF (figure 2-8 a). The wire tension (figure 2-8 b) is measured by measuring the wire resonance frequency \( f \), which is required to fall in the range 27.2±1.4 Hz. The frequency is converted into a wire sag \( s \) (for horizontally installed chambers) with the formula \( s = g/(32f^2) \), where \( g \) is the gravitational acceleration (9.81 m/s \(^2\)). The measured mean value corresponds to a wire sag of 417 µm and the r.m.s. is equivalent to 7 µm. The gas leak rate (figure 2-8 c) is well below the required \( 2.5 \times 10^{-8} \) bar liter/s. The dark current with applied high-voltage (figure 2-8 d) is also better than the required 5 nA.

### 2.3.3 Full chamber

An MDT chamber (see figure 2-9) consists of two ‘multilayers’ of MDTs separated by a spacer structure of ‘cross-plates’ and longitudinal beams (‘long-beams’). Each multilayer consists of 3 or 4 layers of 30 to 72 tubes, which are 1.6 m to 5 m long. The size of a chamber depends on its location in the spectrometer.

Since a muon track position is measured relative to the wire positions, it is of prime importance to precisely know the wire positions. The precision of the positioning of the MDT wires in a chamber is determined by the precision of the wire position inside the tube and the precision of the stacking of the tubes in the chamber.

The precision of the wire position inside the tube is obtained by the precisely machined end-plug components with a reference surface on the outside that is used in the tube stacking during chamber assembly. The reference surface has a 40 µm larger diameter than the tube to prevent the tube shape and size deviations from influencing the wire position in the chamber.
The precision of the tube stacking is obtained by a mechanically precise assembly table with on-line monitoring systems for temperature and mechanical movements (with Rasnik, see paragraph 2.4). Figure 2.10 shows a photograph of the BOL assembly table in the clean-room at NIKHEF. Table 2.3 lists the BOL chamber nominal parameters, where the distance between the multilayers is given relative to their centres of gravity. The key components to obtain high mechanical precision are:

Table 2.3 BOL nominal geometrical parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>z-pitch</td>
<td>30.0353 mm</td>
</tr>
<tr>
<td>y-pitch</td>
<td>26.011 mm</td>
</tr>
<tr>
<td>y multilayer distance</td>
<td>399.032 mm</td>
</tr>
</tbody>
</table>
• The 6 x 2.5 m\(^2\) granite table that serves as a precise (±10 μm) and stable reference surface;

• The aluminium combs, in which a single tube layer is laid. The tubes are held firmly in place by vacuum suction cups, that pull the tubes onto reference surfaces. The two combs at the locations of the end-plugs are of high mechanical precision with steel reference surfaces to ensure precise stacking of the tubes in a layer. This determines the z-pitch, and individual y-deviations;

• The adjustable ‘sphere towers’, which determine the horizontal and vertical distances between the layers. They position the spheres that are temporarily mounted on the cross-plate extremities during the complete assembly of a chamber. For adjacent layers the towers are shifted vertically by the y-pitch and horizontally by half the z-pitch;

• The ‘RasAss’ towers, containing calibrated Rasnik elements (sensor and lens), which are used to monitor with a few μm precision the horizontal and vertical distances between the layers. The corresponding Rasnik masks are mounted on the mechanics that connect the spheres to the cross-plates;

• The ‘sag compensation system’, which compensates the sag of the cross-plates. Without this system the cross-plates would deform (sag) by typically 50 μm. This system reduces the sag to the order of 10 μm;

• The cross-plate Rasnik systems, which monitor the cross-plate sag with a few μm precision. These systems are removed from the chamber once it is completed.

Figure 2-10 Photograph of the BOL assembly table in the clean-room at NIKHEF.
A BOL chamber is constructed layer by layer:

1. The three cross-plates and two long-beams are glued together to form the spacer. All in-plane, cross-plate and RasAss Rasnik systems are calibrated;
2. A layer of tubes is placed in the combs on the assembly table. The vertical tube positions are verified using a laser beam and they are oriented to make the ground pin match the front-end electronics boards later on;
3. Glue is dispensed on the tubes at the locations where the spacer will be attached and in between the tubes;
4. The spacer is lowered onto the sphere towers to leave about 0.7 mm distance between the cross-plates and the tubes; this is the thickness of the glue gap between the spacer and the multilayers;
5. Points 2 - 4 are repeated for the first layer on the other side of the spacer;
6. For the layers that are glued to a layer already on the chamber, the spacer is shifted horizontally by half a pitch (by the sphere towers) and is carefully lowered to leave a distance of only 25 μm between the precision surfaces of the end-plugs of adjacent layers, and a distance of 65 μm between the tube walls (at the end-plugs).

At NIKHEF, chambers are now assembled in seven working days: one day for the spacer and one day per tube layer. The construction time is limited by the glue curing time (one night per glue step). After having finished the mechanical construction, several chamber services are mounted: ground foil, ground pins, gas manifold, hedgehog boards for high voltage distribution and front-end electronics, Faraday cage, temperature sensors, magnetic field sensors and platforms for projective and praxial alignment systems. After the gas manifold is mounted, a gas leak test is performed on the chamber as a whole. At NIKHEF series production started in summer 2001 and 96 BOL chambers will be ready in 2004. At the time of publication of this thesis, about one third of the BOL chambers have been constructed.

2.3.4 Projective tower

The widths and lengths of the MDT chambers are such that one set of BIL / BML / BOL chambers or BIS / BMS / BOS chambers form a 'projective tower' that covers part of the solid angle as viewed from the interaction point. As a consequence, most muons will traverse one tower only, and the momentum measurement is basically performed per tower. The alignment of the chambers within one tower is therefore more relevant for the precision of the momentum measurement than the alignment between towers.
2.4 Rasnik alignment monitor

2.4.1 Basic principle

The Red Alignment System NIKHEF (Rasnik) is a three-point high-precision wide range optical straightness monitor that is developed at NIKHEF. It consists of an infra-red light source which projects a coded mask via a lens onto an optical image sensor. This is schematically shown in figure 2-11. The system monitors the relative displacements of the three components: mask, lens, and sensor.

![Diagram of Rasnik alignment monitor](image)

Figure 2-11 Schematic view of the Rasnik alignment monitor, including the multiplexed read-out system for ATLAS.

Rasnik measures the following coordinates:

- The $x$ and $y$ coordinates of the mask in the mask plane;
- The magnification factor, which gives information on the relative displacement of the components along the optical axis;
- The relative rotations between the mask and the sensor around the optical axis;
- The relative rotations between the mask and the sensor around the $x$ and $y$ axes can in principle also be determined.

2.4.2 The mask, lens, sensor and read-out

The Rasnik mask has a chess-board like pattern with non-transparent ('black') and transparent ('white') squares. Figure 2-12 shows a video image of a mask and indicates the mask coordinate system, which defines at the same time the Rasnik coordinate system. To obtain a wide dynamic range (20 mm and 40 mm for ATLAS), the mask is usually much larger than the sensor and only a small part of the mask is visible by the sensor. To determine which part is visible, global position information is provided in the form of a binary number encoded on the mask. Standard high-precision (< 0.1 μm) electron-beam technology from industry is used to produce the chromium-on-glass coded mask. The high-precision measurement is provided by the many black-white transitions on the mask that are visible by the sensor. This is achieved by choosing a small square size (typically 120 μm).
A single large (100 x 100 mm²) mask is produced on a standard 5 inch glass substrate, which is cut afterwards into smaller masks according to the required dynamic range. One consequence is that the encoded binary numbers in a specific mask have an arbitrary offset and Rasnik does not give the absolute deviation from a straight line unless the system is calibrated. The calibration procedures for some of the ATLAS alignment systems are given in paragraph 2.5.4.

The ‘RasLed’ combines the mask in an aluminium die-cast housing with an array of 3 x 3 high intensity infra-red (875 nm) LEDs for illumination. A 3 mm thick Opaline glass diffuser is inserted between the LEDs and the mask for uniform overall light intensity.

The focal length of the lens should be adapted to the distances between the components to ensure a sharp image. The lens aperture should be chosen to balance the light intensity (large aperture) with the depth of field (smaller aperture gives larger dynamic range along the optical axis, the z-axis) and the financial budget (smaller lenses are cheaper). For ATLAS, the lenses are specially produced with specific focal lengths to match the geometry, and high precision of the focal length is required for the longer Rasniks to ensure a sharp image.

The ‘RasCam’ sensor was developed for ATLAS by NIKHEF and employs the commercially available radiation hard VLSI Vision VV5430 Monolithic Sensor, which is based on CMOS sensor technology. It incorporates an array of 384 x 287 pixels of 12 µm x 12 µm, and outputs a standard CCIR composite monochrome video signal. The RasCam board is mounted in an aluminium die-cast housing of 5 x 6 x 3 cm³. An infra-red pass filter in installed before the image sensor, so Rasnik can be operated under normal daylight conditions.

The video signal is digitised with a commercial framegrabber installed in a PC. For ATLAS only a few PCs are needed to control and read out several thousand Rasniks through three levels of multiplexing; RasMux (all Rasniks of one muon chamber), MasterMux (16 RasMuxs) and finally USA15Mux (48 MasterMuxs). Figure 2-11 includes this Rasnik read-out system schematically. The ‘Icaras’ control software switches on the RasLeds and the corresponding RasCams one by one, grabs the image, sends the image to the analysis package, and stores the results of the analysis to disk. The raw 8-bit grey-scale image can be stored on demand in uncompressed TIFF format. The image analysis package is supplied as a separate dynamic link library, so it can easily be exchanged or updated independently of Icaras itself.
2.4.3 Image analysis

The Rasnik image is analysed in several steps:

1. Noise filter and edge detection to find the black-white transition points. The projected black-white transitions cover several sensor pixels, making a fine interpolation of the transition possible that is an order of magnitude more accurate than the pixel size. An image typically contains several thousand black-white transitions;

2. Fit of a grid of horizontal and vertical lines to the black-white transition points, and determine the colour of each square (‘black’ or ‘white’);

3. Extraction of the code bits and code lines. Every ninth row and column of squares contains an eight bit binary code. A code square is binary one if it deviates from the regular chessboard pattern, and binary zero if it is regular;

4. Decoding of the binary global position code. The horizontal code lines contain the y position information and the vertical code lines contain the x position information. The intersection of a code row and code column is always a binary one. Within one code line the binary code is repeated every ninth square, and the code changes by one from one code line to the next;

5. Determination of the distance from the code line to the top-left corner of the sensor;

6. Convert to mm, rad and magnification.

The analysis determines the x and y coordinates of the point on the mask which is projected onto the top-left corner of the sensor. Initially this is done in units of mask squares and only in the last step the conversion to mm is made via the size of the mask squares, which is an input parameter. The x and y determination is independent of the pixel size and the relative rotation of the mask and sensor. The size of one mask square as measured on the sensor is initially expressed in units pixels. In the last step the magnification is calculated using the pixel size, which is another input parameter. The relative rotation between the mask and the sensor around the axis perpendicular to the mask (usually equal to the optical axis) is determined from the slopes of the lines of step 2. The relative rotations around the x and y axes of the mask are determined from the variation of the magnification over the image. The analysis time of one image is 3 s on a 450 MHz Pentium-II PC.

2.4.4 Performance

The performance of a single Rasnik is tested with a dedicated set-up. In this set-up one of the Rasnik components can be moved in two dimensions with a precision of 0.1 μm and rotated around one axis with a precision of 0.001 degrees. The distance from the mask (120 μm square size) to the sensor is about 225 mm and the magnification is about 0.5. The lens has a focal length of 50 mm and an aperture of 3 mm. For a range of positions and angles the Rasnik image is analysed and compared to the input movement. At each input position 16 Rasnik images are taken.

Linear scans are made in x and y by moving the mask along one of its coordinate axes. Figures 2-13 and 2-14 show the varying Rasnik measurements and the residuals as a function of the set input position for the x and y scans respectively. The residuals are taken relative to a straight line fit, because Rasnik has an arbitrary offset. Moreover, it can not be guaranteed that the direction of movement coincides exactly with one of the Rasnik axes. The width of the residual distribution is of the
order of 1 \( \mu \)m for both coordinates, which is more than adequate for ATLAS (order 10 \( \mu \)m required).

A rotational scan of the mask around the (optical) z-axis is shown in figure 2-15. The residuals are taken relative to a straight line fit, because there is an arbitrary offset. Moreover, it can not be guaranteed that the rotation axis coincides exactly with the Rasnik z-axis. The width of the residual distribution is about 20 \( \mu \)rad.

The Rasnik magnification factor is tested with a linear scan in z by moving the mask along the optical axis. Figure 2-16 shows the measured Rasnik magnification as a function of the set z-position. The residuals are shown relative to set magnification \( A_{set} \), which is calculated from the set z-position with:

\[
A_{set} = \frac{b}{v_0 - z_{set}},
\]

where \( b \) is the distance from the sensor to the lens, and \( v_0 \) is the distance from the mask to the lens at \( z_{set} = 0 \). The values of \( v_0 \) and \( b \) are determined by making a fit to the Rasnik measured magnifications, because they are not known with sufficient precision. This fitted function also absorbs any non-parallelity between the direction of movement and the rasnik z-axis. The width of the residual distribution is \( 2.5 \times 10^{-5} \).

First results of the rotations around the x and y axes reveal large systematic deviations, and a more detailed study is needed before those can be reliably used, and are therefore not included here.

We conclude that Rasnik measures with high precision (order 1 \( \mu \)m) the relative positions of three components perpendicular to its optical axis, and thereby provides exactly what is needed for the ATLAS muon spectrometer: precise relative alignment (order 30 \( \mu \)m) of three muon stations perpendicular to the direction of the particle tracks. The precision of Rasnik is best exploited if the optical axis runs parallel to the particle tracks. If more than three points need to be aligned relative to each other, the Rasnik system can be also be used, provided several Rasinks are combined.
Figure 2-13 Rasnik linear scan in x. Rasnik measurements (a) and straight line fit residuals (b) as a function of the set position. The residual distribution (c) includes a Gaussian fit.

Figure 2-14 Rasnik linear scan in y. Rasnik measurements (a) and straight line fit residual (b) as a function of the set position. The residual distribution (c) includes a Gaussian fit.
Figure 2-15 Rasnik rotational scan around z. Rasnik measurements (a) and straight line fit residuals (b) as a function of the set rotation. The residual distribution (c) includes a Gaussian fit.

Figure 2-16 Rasnik linear scan in z. Rasnik measurements (a) and magnification fit residuals (b) as a function of the set z-position. The residual distribution (c), includes a Gaussian fit.
2.5 Alignment of the chambers

In the ATLAS muon spectrometer several alignment systems can be distinguished according to the type of displacements they monitor. The in-plane systems monitor single MDT chamber deformations. The praxial systems monitor the relative movements of same type chambers within one half barrel octant. The projective system monitors the relative displacements of the three half stations. All these systems use various combinations of Rasnik monitors. Finally, the relative displacements of the large and small chambers inside the same station, and the movements relative to the magnet are monitored by BCAMs (Boston Ccd Angle Monitor, [31]). The aim of the whole of these systems is to achieve a precise sagitta correction (30 μm), and a less precise global chamber positioning (400 μm). The following paragraphs describe each of these systems in more detail and discuss their calibration.

2.5.1 In-plane system

Each MDT chamber incorporates a set of Rasniks to monitor chamber deformations: the ‘in-plane’ system. Figure 2-17 shows the four Rasniks mounted on the MDT spacer frame and indicates the local coordinate system. The main tasks of the in-plane system are to measure the chamber torque around the x-axis and to monitor the chamber sag. Installation of the in-plane alignment system is part of the chamber assembly procedure.

A chamber torque directly influences the wire positions, and needs to be accurately measured. For a BOL chamber, a precision of the order of 20 μm / 1 m = 20 μrad is needed. The torque is measured directly by the εx of the Rasniks, and indirectly by combining the four y-displacements, where the latter is more precise.

Historically, the chambers with the longer tubes were foreseen to have an additional wire locator halfway along the tubes. In that case the position of the middle cross-plate directly influences the wire positions, and needs to be known with a precision of the order of 10 μm. In the final ATLAS design, without this central wire locator, this strong requirement is replaced by a much weaker requirement (order 0.1 mm) coming from the needed concentricity of the wires and the tubes over the full area of the chamber. This concentricity requirement keeps the time-distance relation radially symmetric.

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1. Only the BIS chambers, which have a spacer with a height of less than 10 mm, have only one in-plane Rasnik mounted on the tubes on the outside of the chamber.
2.5.2 Projective system

The projective alignment system monitors the relative displacements of the three MDT barrel stations and is essential to the precision momentum measurement. To fully exploit the intrinsic precision of the Rasnik alignment monitor, i.e. the coordinates perpendicular to its optical axis, the optical axes of the projective systems point towards the interaction point (i.e. parallel to the high-momentum tracks), so the track sagitta is perpendicular to the Rasnik optical axis. Ideally, one projective Rasnik is installed at each of the four corners of each MDT projective tower. However, to minimise the number of optical path cut-outs in the MDTs and RPCs, only four pairs of projective systems are distributed over the six large chambers of half an octant, as illustrated in figure 2-18. The other chambers are aligned relative to the chambers that are equipped with projective systems. The next paragraph explains how this is implemented. The layout of the chambers and the projective alignment paths are chosen such that only some of the BMS chambers require cut-outs. The components of the projective Rasnik systems will be mounted on extension plates fixed on platforms that will be glued on the outside tube layer of the (large) MDT chambers. The extension plates and Rasnik components will be mounted on the respective chambers only after installation in ATLAS.

2.5.3 Praxial and other systems

The ‘praxial’ (proximity + axial) alignment system is installed on the chambers to interconnect the six adjacent chambers per half octant, both for the small and the large chambers. This allows the concept of logical projective towers that need not necessarily coincide with the physical MDT chamber projective towers. It is composed of the axial system and the proximity system as illustrated in figure 2-19. The Rasnik components of the two systems are combined on the same base plates at the four corners of the MDT chambers in between the two multilayers. The axial system employs long distance longitudinally overlapping Rasnik systems with the optical axes along the z-axis. Per axial Rasnik two components are mounted on the same chamber (but different base plates) and the third component is mounted on the adjacent chamber.
3D proximity sensors (praxial)

Axial ray

Figure 2-19 Schematic overview of the praxial alignment system. It shows the Rasnik sensors and optical rays of the proximity and axial system, as well as part of the global alignment system connecting the chambers to the toroid magnet using BCAMs.

The proximity system combines two short distance Rasnks at angles of $\pm 25^\circ$ to the z-axis to enable the precise measurement of the relative positions and angles of base plates of adjacent chambers. This is illustrated in figure 2-20. The base plates are mounted on platforms that are glued on the tubes during the MDT chamber assembly. The base plates are installed on the platforms only after the chamber is installed in ATLAS.

The small chambers are aligned relative to the large chambers via 'BCAMs'. A BCAM (Boston Ccd Angle Monitor, [31]) is an optical alignment system developed at Brandeis University which uses a camera + lens unit looking at several point light sources and measures angles.

Figure 2-20 Schematic close-up view of praxial base plates of two adjacent MDT chambers showing the axial and proximity Rasnik components and light paths.
A reference system based on BCAMs (some are shown in figure 2-19) measures the global alignment of the chambers relative to the toroid magnet with a precision of about 400 μm. This is needed for the pattern recognition procedure in high background environment and for magnetic field knowledge.

2.5.4 Calibration of the alignment systems

The alignment system must provide absolute corrections for the sagitta measurement and therefore needs to be calibrated. The calibration procedure for the in-plane system is fundamentally different from the calibration of the projective and praxial systems.

The calibration of the in-plane system is performed during the chamber assembly (paragraph 2.3.3). Since the Rasniks are calibrated only after the components have been mounted, the positioning of its components on the cross-plates is not subject to stringent tolerances (order 1 mm) and the only requirement is a sharp image on the sensor. After gluing of the spacer frame and mounting of the Rasnik components, but before the tubes are glued, the angles of the four masks are measured on the assembly table with a dedicated calibrated ‘Rasnik tower’ that incorporates a lens and a Rasnik sensor. After gluing of all tube layers, the Rasniks are read out while the chamber is still on the assembly table. These readings are corrected for the known deformations of the assembly table, giving the absolute calibration of the four systems to a precision of about 10 μm.

For the projective and praxial systems the situation is more complicated because the Rasnik components are only mounted after installation of the chambers in ATLAS. The Rasnik components of the projective and axial systems, embedded in their respective supports, will be calibrated on a dedicated bench with a target precision of about 10 μm before they are installed on the chambers. The proximity system will be calibrated on a dedicated bench with the Rasnik components already mounted on the base plates. Experimental tests at C.E.A. Saclay with a praxial prototype have shown that resolutions better than 10 μm and 30 μrad can be achieved [32].

The complication with the projective and praxial systems is that the mounting precision of the calibrated components on the chambers adds to the uncertainty of the effective calibration. Depending on the system, several contributions add up. For the proximity system and the axial system: the gluing of the platform on the chamber and the mounting of the base plate on the platform. The axial system has an additional mounting uncertainty of the components on the base plates. For the projective system: the gluing of the platform on the chamber, the mounting of the extension plate on the platform and the mounting of the component on the extension plate.

With the intrinsic resolution of Rasnik of the order of 1 μm and the calibration of the Rasnik components to about 10 μm, less than 30 μm is left over for the total contribution of all mechanical tolerances to the uncertainty on the sagitta measurement. It has not yet been demonstrated that this can be achieved.

There is, however, a second method foreseen for calibration of the alignment systems: after installation in ATLAS using straight tracks (magnet off). Once the calibration is finished with the magnet off, the chambers will move several mm when the magnet is switched on, but these movements will be tracked by the alignment system with a precision of a few μm and the muon sagitta can be corrected.
2.6 Muon momentum resolution

The momentum resolution of the spectrometer has been computed with an analytical method that accounts for the detailed geometry of all detectors and the distribution of material in the spectrometer [24]. The analytical approach has the advantage of minimal computing time requirements. A comparison to a full Monte Carlo simulation and reconstruction was carried out for selected cases and shows excellent agreement. The various contributions to the muon barrel momentum resolution (at the interaction point) are shown in figure 2-21 as a function of the transverse momentum [24].

Three resolution regimes clearly emerge:

- At high momentum \((p_T > 300 \text{ GeV/c})\) the resolution is dominated by the precision with which the track deflection is measured: single tube resolution and chamber alignment. The single tube resolution includes the intrinsic resolution and calibration errors. This will be covered in detail in chapter 4 for the MDT chamber cosmic ray test stand at NIKHEF. It also includes the MDT chamber mechanical precision. This contribution is aimed to be negligible compared to the intrinsic resolution and is absorbed in the calibration errors. Chapter 3 covers the X-ray tomograph that measures the mechanical precision of the MDT chambers. The chamber alignment uncertainties will be covered in detail in chapter 5 for one real size barrel projective tower using prototype MDT chambers (the 'DATCHA' set-up);

- At moderate momentum \((30 < p_T < 300 \text{ GeV/c})\), the resolution is increasingly limited by multiple scattering in the muon spectrometer for decreasing \(p_T\). The multiple scattering depends on the amount of material traversed and on the distribution of the material along the track. The effect is dominated by the material of the middle station of MDT chambers. The \(p_T\)-dependence of the multiple-scattering contribution is related to the point-and-angle measurement capability of the MDT chambers. At low \(p_T\) the track deflection is sufficiently large to allow an effective angle-angle measurement in addition to the sagitta measurement in the three MDT stations. Its sensitivity to the spatial distribution of radiative thickness between chambers is different from that of the three-point measurement, resulting in an improvement at lower \(p_T\);

- At low momentum \((p_T < 30 \text{ GeV/c})\), energy loss fluctuations in the calorimeters, which influence the extrapolation from the muon spectrometer to the interaction point, become dominant. In this momentum range the inner detector, which does not suffer from the calorimeters, provides the more precise momentum measurement.

The momentum resolution is typically 2–3% over most of the kinematic range apart from very high momenta, where it increases to reach about 11% at \(p_T = 1 \text{ TeV/c}\).
Figure 3-1 Photograph of the X-ray tomograph at CERN with the NIKHEF BOL chamber installed. Main components and the coordinate system are indicated.