

Alignment of the ATLAS Muon Spectrometer with Muon Tracks

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Abstract—The ATLAS muon spectrometer uses three layers of precision drift-tube chambers to measure muon momenta accurately up to the TeV scale in an air-core toroid magnet system providing a field integral of 2.5 to 7 Tm. In order to achieve the required momentum resolution of better than 4% for transverse momenta below 400 GeV/c and of 10% at 1 TeV/c, the relative positions of the muon chambers must be known with $30\ \mu\text{m}$ accuracy. A system of optical alignment sensors monitors relative movements of the chambers with a few micrometers accuracy. It is capable of measuring the relative chamber positions with an accuracy better than $30\ \mu\text{m}$ after it has been calibrated with straight tracks. These will be provided by special runs with the magnets turned off. We present results of Monte-Carlo studies for the alignment with straight tracks recorded with proton-proton collisions at the LHC and cosmic muon data.

Index Terms—ATLAS detector, muon spectrometer, drift tubes, alignment, tracks, muon.

I. INTRODUCTION

THE ATLAS muon spectrometer is instrumented with three layers of so-called "Monitored Drift-Tube" (MDT) chambers for the precise measurement of muon tracks in a toroidal magnetic field of 0.4 T average field strength. The MDT chambers consist of two triple or quadruple layers of aluminium drift tubes with 30 mm diameter and 0.4 mm wall thickness mounted on either side of an aluminium space frame. The tubes are filled with argon and carbon dioxide in the mixing ratio 93:7 at 3 bar absolute pressure. Operated at 3080 V voltage, corresponding to a gas gain 20,000, the tubes provide an average single-tube resolution of $80\ \mu\text{m}$. Due to the high $20\ \mu\text{m}$ mechanical positioning accuracy of the sense wires inside a chamber the tube resolution leads to $35\ \mu\text{m}$ spatial resolution of the chambers. If the three layers of MDT chambers are aligned with an accuracy of $30\ \mu\text{m}$, a momentum resolution better than 10% is achieved up to $p_T = 1\ \text{TeV}/c$. The MDT chambers measure track positions only in the bending plane of the toroid magnet. The missing coordinate in the direction of the field is provided by so-called "Resistive Plate" (RP) and "Thin Gap" (TG) trigger chambers in the barrel and the end caps respectively [1].

The barrel part ($|\eta| < 1$) of the muon spectrometer is arranged in 16 sectors (see Figure 1). Relative movements of the chambers within a sector are monitored with $10\ \mu\text{m}$ resolution

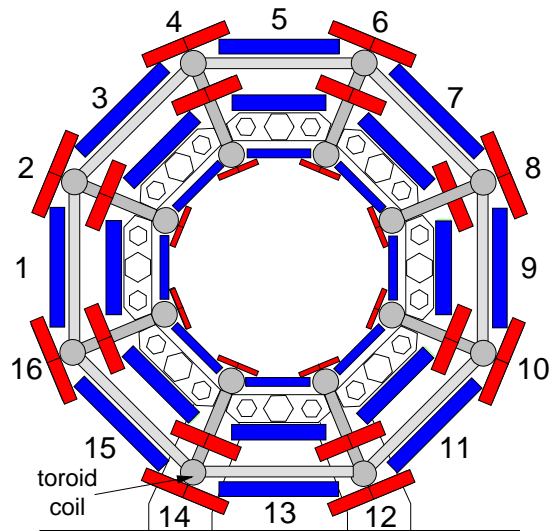


Fig. 1. Schematic of the the cross section of the ATLAS muon spectrometer. The muon chambers shown as blue and red boxes are arranged in 16 towers.

by a system of optical alignment sensors. The positions of the chambers must be determined once by means of straight muon tracks [2].

As we shall describe in this article, straight cosmic muon tracks can be used to align the top sectors (3-7) and the bottom sectors (11-15) with the required accuracy. There are not sufficient horizontal muon tracks in the other sectors in the ATLAS cavern 100 m below ground. Straight muon tracks to align the whole barrel muon spectrometer will be provided in a special run in which muons from pp collisions will be recorded with the toroid magnet turned off. Our Monte-Carlo studies for this run show that the positions of all muon chambers can be measured with the data of this special run.

II. MOMENTUM MEASUREMENT AND ALIGNMENT REQUIREMENTS

Muon tracks are measured by three layers of MDT chambers as sketched in Figure 2. These provide three track points with $35\ \mu\text{m}$ accuracy, one at the entrance of the spectrometer, one in the middle, and one at the exit. These three points are used to measure the sagitta which is defined as the deviation of

the track point in the middle from the straight interconnection of the inner and outer track points. The sagitta s is inversely proportional to the transverse momentum and about $500 \mu\text{m}$ for 1 TeV muons. As the fractional momentum resolution equals the fractional sagitta resolution, a 10% momentum resolution corresponds to 10% sagitta resolution which is $50 \mu\text{m}$ at 1 TeV. The track point resolution of $35 \mu\text{m}$ contributes $40 \mu\text{m}$ to the sagitta resolution. So the contribution from the misalignment of the three chambers should be less than $30 \mu\text{m}$.

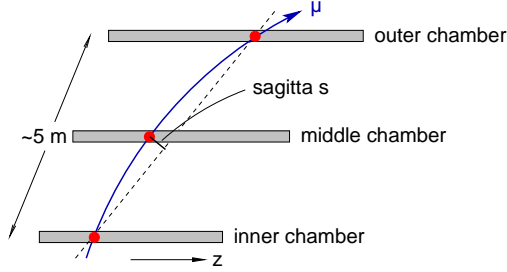


Fig. 2. Sketch of the sagitta measurement performed in the ATLAS barrel muon spectrometer

III. STRAIGHT-TRACK ALIGNMENT ALGORITHM

In this section we describe the algorithm used for the internal alignment of a barrel sector with straight muon tracks. We begin with the reconstruction of a straight muon trajectory.

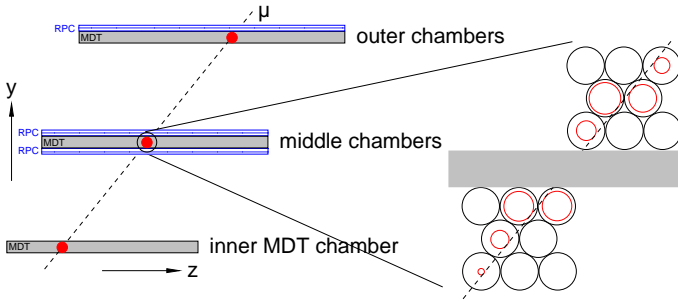


Fig. 3. Schematic drawing of a straight muon track traversing three muon chambers of a sector. On the right the drift circles in the tubes crossed by the muon are depicted.

As depicted in Figure 3 we use a coordinate system in which x is parallel to the anode wires of the tubes of the MDT chambers, y points in radial direction outwards from the pp interaction point, and z is parallel to the direction of the proton beams. The muon trajectory can be parametrized as straight lines in the xz and yz planes:

$$\begin{aligned} x &= m_x z + b_x, \\ y &= m_y z + b_y. \end{aligned}$$

The MDT chambers measure the trajectory in the yz plane. The trajectory in the xy plane is measured by the RPC trigger chambers.

m_x and b_x are determined by minimizing

$$\chi_{RPC}^2 = \sum_{h=1}^H \frac{[x_h - (m_x z_h + b_x)]^2}{\sigma_h^2}$$

where H denotes the number of hits in the RPC chambers, x_h and z_h are the x and y coordinates of the h th hit. While the RPC chambers provide cartesian hit coordinates, the MDT chambers only provide drift radii $r(t_k)$ which are measurements of the track distances with an uncertainty $\sigma(r(t_k))$. One therefore has to minimize

$$\chi_{MDT}^2 = \sum_{k=1}^K \frac{[r(t_k) - d_k(m_x, b_x, m_y, b_y)]^2}{\sigma(r(t_k))} \quad (1)$$

with $d_k(m_x, b_x, m_y, b_y)$ being the distance of the track from the anode wires of the hit tube and K being the number of hit tubes. Let w_{y_k} and w_{z_k} be the wire coordinates of the k th hit at the reconstructed hit position w_{x_k} along the wire. Then $d_k(m_x, b_x, m_y, b_y)$ is given by

$$\begin{aligned} d_k(m_x, b_x, m_y, b_y) &= \frac{|m_y w_{z_k} + b_y - w_{y_k}|}{\sqrt{1 + m_y^2}} \\ &= \text{sgn}(m_y w_{z_k} + b_y - w_{y_k}) \cdot \frac{m_y w_{z_k} + b_y - w_{y_k}}{\sqrt{1 + m_y^2}} \end{aligned} \quad (2)$$

Let $C(k)$ label the chamber to which the k th hit belongs. When the MDT chambers are displaced from their nominal positions by δ_{yC} in y direction and δ_{zC} in z direction and rotated by small angles ϕ_{xC} , ϕ_{yC} , and ϕ_{zC} around the x , y , and z axes, w_{y_k} and w_{z_k} have to be replaced by

$$\begin{aligned} w'_{y_k} &:= w_{y_k} + \delta_{yC(k)} - w_{z_k} \phi_{xC(k)} + w_{x_k} \phi_{zC(k)}, \\ w'_{z_k} &:= w_{z_k} + \delta_{zC(k)} + w_{z_k} \phi_{yC(k)} - w_{x_k} \phi_{yC(k)} \end{aligned}$$

in Equation (2).

d_k is neither linear in the track parameters nor in the alignment parameters. It can be linearized without loss of precision in the following way. Firstly as the geometry of the chambers is known, the restriction of the track fit to each chamber provides us with the sgn term. Secondly as the inner and outer muon chambers are 5 m apart, the slope is reconstructed with permille accuracy even for the limited mounting accuracy of the order of a millimeter. Let s_k denote the $\text{sgn}(m_y w_{z_k} + b_y - w_{y_k})$ as obtained from the restricted track fit and \bar{m}_y be the slope reconstructed in a first pass track fit before any alignment corrections have been applied. Then

$$\begin{aligned} d_k(m_x, b_x, m_y, b_y) &\approx s_k \frac{m_y w_{z_k} + b_y - w_{y_k}}{\sqrt{1 + \bar{m}_y^2}} \\ &+ \frac{s_k}{\sqrt{1 + \bar{m}_y^2}} [-\delta_{yC(k)} + \bar{m}_y \delta_{zC(k)} \\ &\quad + (1 + \bar{m}_y) w_{z_k} \phi_{xC(k)} \\ &\quad - \bar{m}_y w_{x_k} \phi_{yC(k)}] \\ &=: \bar{d}_k(m_x, b_x, m_y, b_y) \end{aligned}$$

to good approximation. We replace d_k by \bar{d}_k in Equation (1). In order to determine the alignment parameters we minimize the sum of the χ^2_{MDDT} s of the collected tracks in the track and alignment parameters. During the fit we impose the condition on the alignment parameters that centre of gravity of the sector is unaltered. Due to the linearization of d_k the minimization problem can be solved analytically.

IV. APPLICATION TO STRAIGHT TRACKS IN pp COLLISIONS

As mentioned in the introduction, the optical alignment system monitors chamber movements with a resolution of a few micrometers. The positions of the chambers within a sector must be determined with straight muon tracks. In order to provide straight muon tracks, ATLAS plans a dedicated run in which the toroid magnet of the spectrometer will be switched off during the operation of the LHC. The magnetic field in the inner detector will be turned on to permit the measurement of muon momenta. The transverse muon momentum spectrum is steeply falling with the transverse momentum. So most of the muon above a p_T thresholds have a momentum close to the threshold value. We chose a p_T threshold of 20 GeV/c to limit multiple scattering and simulated 100,000 single muon tracks with $p_T = 20$ GeV/c in one sector of the muon spectrometer to study our alignment algorithm.

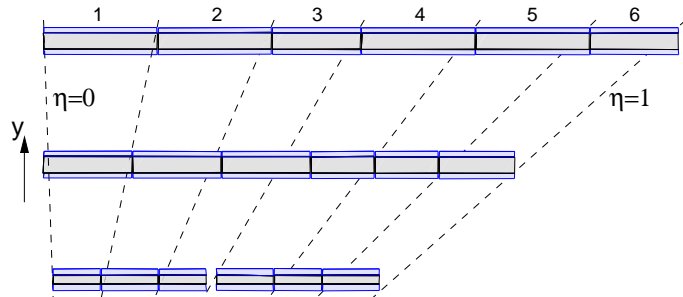


Fig. 4. Schematic of one half of a barrel sector of the muon spectrometer. The pp interaction points is in the lower left corner. The dashes lines indicate the tower structure inside a sector.

The chambers within a barrel sector of the muon spectrometer are arranged in towers of three chambers are indicated by the dashed lines in Figure 4. Most of the straight muon tracks are fully contained in a tower. But there are also straight tracks linking neighbouring towers especially at large rapidities. Our Monte-Carlo studies show that the individual towers can be aligned with the required accuracy. Yet the angular spread of the tracks linking two neighbouring towers is too small to align neighbouring towers with respect to each other with the same accuracy. This problem can be cured by imposing constraints on the movements of the chambers in y direction of the order of 200-300 μm . Such constraints will be provided by an optical alignment system monitoring the planarity of the individual chamber layers within a sector.

Figure 5 shows the accuracy of the alignment correction on the sagitta provided by our straight-track alignment algorithm with 100,000 muon tracks of $p_T=20$ GeV/c. An accuracy of

10 μm is achieved for the large sectors drawn in blue in Figure 1. The accuracy decreases to 30 μm in the small sectors drawn in red in Figure 1 due to multiple scattering of the muon in the toroid coils.

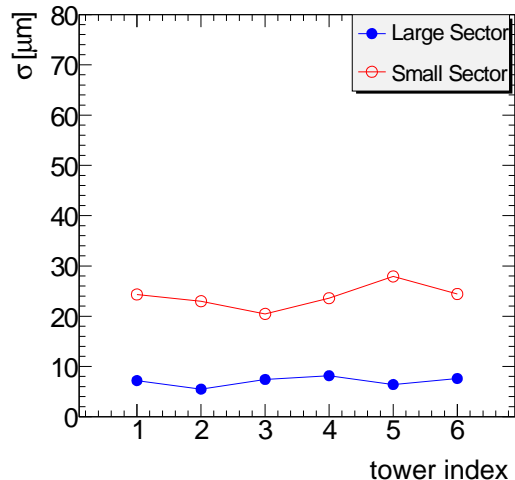


Fig. 5. Accuracy of the sagitta correction after the alignment with 100,000 straight muon tracks of $p_T=20$ GeV/c in the barrel.

V. APPLICATION TO COSMIC MUON DATA

During the past year ATLAS recorded millions of cosmic muon data. These data can be used to align the top and bottom sectors of the barrel muon spectrometer. We applied our algorithm to 400,000 muon tracks traversing the top sector 5 of the spectrometer. As the angular spread of cosmic muons is larger than that of straight muons from pp interactions, no constraints from the optical system on the vertical displacement of the chambers have to be applied. As shown in Figures 6, we were able to align the three inner towers of the sector with 30 μm resolution and better than 80 μm for the outer towers. We excluded the outermost tower from our alignment fit due to lack of statistics of muons connecting the outermost chambers with the rest of the chambers of the sector.

Two tests were performed to verify the correctness of our alignment constants. The first test is a self-consistency test in which we select cosmic muons pointing to the imaginary pp interaction point. The mean value of the residuals in the middle chamber of a tower is $\frac{2}{3}$ of the bias on the sagitta. Figure 7 shows that the bias on the reconstructed sagitta reduces from $\frac{3}{2} \cdot 0.566 \text{ mm} = 0.849 \text{ mm}$ before the track alignment to $\frac{3}{2} \cdot 0.002 \text{ mm} = 0.003 \text{ mm}$ after the track alignment. As expected the bias on the sagitta is minimized after the application of the alignment corrections provided the track alignment algorithm. In the second test we compared our measurement of the distances of the chambers within the inner and outer layer of the top sector with a measurement of the chamber distances using a feeler gauge. Figure 8 shows a clear correlation between the distances measured in the track alignment procedure and the mechanical measurements. The distances of the outer chambers agree within 85 μm , but a shift of 190 μm is observed between

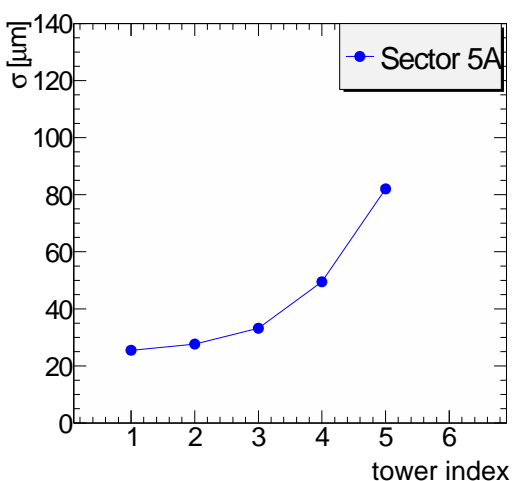


Fig. 6. Accuracy of the sagitta correction after the alignment with 400,000 straight cosmic muon tracks in the top sector 5 of the barrel muon spectrometer.

the track alignment and the mechanical measurement. The discrepancy is caused by the fact that chamber distances are measured between mounting rods of the inner chambers while distances between adjacent tubes of the outer chambers are measured. New measurements of the distances of adjacent tubes of the inner chambers are planned to verify the explanation.

VI. SUMMARY

An algorithm for the alignment of the sectors of the barrel ATLAS muon spectrometer with straight tracks has been presented in this article. Monte-Carlo studies show that the algorithm provides sagitta correction with the required accuracy of $30 \mu\text{m}$ or better for 100,000 muon tracks with $p_T \geq 20 \text{ GeV}/c$. The application to cosmic muon data recorded with the top sector of the ATLAS muon spectrometer confirms the

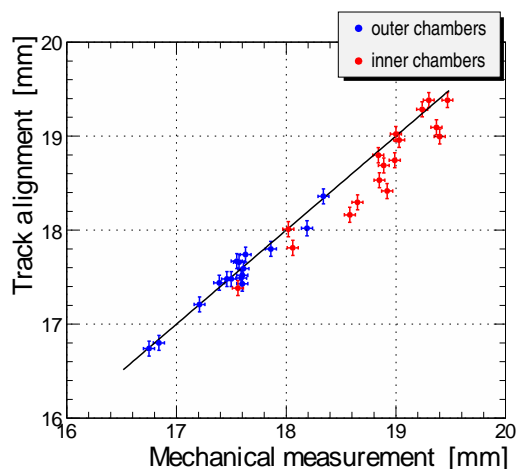


Fig. 8. Comparison of the distance of the inner and outer chambers as measured by the alignment algorithm with mechanical measurements using a feeler gauge.

accuracy of the alignment corrections provided by the described straight-track alignment procedure.

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REFERENCES

- [1] G. Aad et al. The ATLAS Experiment at the CERN Large Hadron Collider. *JINST*, 3:S08003, 2008.
- [2] C. Amelung et al. The ATLAS muon alignment system. Prepared for 1st LHC Detection Alignment Workshop, Geneva, Switzerland, 4-6 Sep 2006.

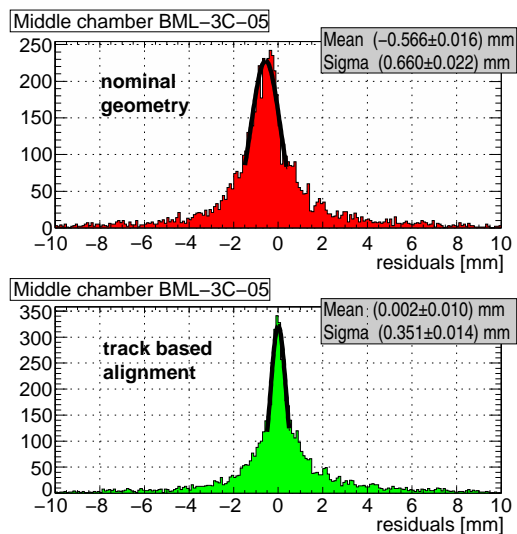


Fig. 7. Track residual in a middle chamber of the top sector before the alignment with track (top) and after the alignment with track (bottom).