Alignment of the Muon Spectrometer in ATLAS

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Abstract
The ATLAS muon spectrometer is designed to measure the momentum of a 1 TeV/c muon to an accuracy of 10%. A muon of this momentum bends, on average, 500 μm in the toroidal field of ATLAS. Therefore, the position of the muon chambers within a tower and along the precision coordinate must be known to better than 50 μm. ATLAS uses a combination of an optical and track-based alignment to achieve such a precise alignment. Several analyses to monitor and validate the alignment were undertaken in the first year of LHC operation. This report provides a brief overview of the motivation, building and commissioning of the optical system, performance, and validation of the alignment of the muon spectrometer.

Keywords: LHC, ATLAS, MDT, muons, alignment

1. Introduction
The ATLAS muon spectrometer [1] is designed to provide excellent momentum measurements of muons at the energy scales expected in new physics scenarios. The transverse momentum, $p_T$, should have a resolution of no worse than $\Delta p_T / p_T = 10\%$ for a muon with $p_T = 1$ TeV. Due to the magnetic field inside of the spectrometer, the path of a 1 TeV muon will bend by only 0.5 to 1 mm (depending on the pseudorapidity of the track). To measure the momentum to better than 10%, the error on the sagitta must be less than 50 μm. A complex alignment system, using both optical alignment and alignment with tracks, was designed to achieve this goal. In the next sections, a detailed description will be provided for the muon spectrometer (Section 2); the alignment strategy in both the barrel (Section 3) and the endcap (Section 4); the monitoring of the alignment system (Section 5); and the validation of the alignment system (Section 6).

2. Muon Spectrometer
The muon spectrometer is made up of chambers using four unique chamber technologies: drift tubes (MDT) and cathode strip chambers (CSC) are used for precision tracking and thin gap chambers (TGC) and resistive plate chambers (RPC) are used for triggering (Fig. 1). The spectrometer is approximately a cylinder with a central barrel and two endcaps. The barrel and endcaps are further segmented into three...
layers, named inner, middle, and outer, based on their proximity to the collision point. The MDT and CSC are arranged in 16 sectors in azimuth, alternating in large and small sectors.

For muons with pseudorapidity less than 2.0, the tracks are measured by 1150 MDT chambers containing over 350000 drift tubes with a diameter of 3 cm. At the highest values of \( \eta \) in the endcap, drift tubes in the inner layer cannot handle the high rates near the beam pipe; 32 CSC were installed instead. Muons in the endcap are triggered by TGC, while those in the barrel are triggered by RPC.

The magnetic field in the muon spectrometer is provided by three air-core toroidal magnets, each consisting of eight coils. The field causes a muon track to bend in \( \eta \). A muon track will usually traverse three or more MDT/CSC layers (three such chambers are referred to as a “tower”), so its bend in the field can be measured by its sagitta, the distance between the hits in the middle layer and a straight line connecting the hits in the inner and outer layers. The sagitta is the most important contribution to the momentum measurement and must be measured accurately. The alignment system is intended to keep the error on the sagitta at less than 50 \( \mu \)m. Since the barrel and endcap of the muon spectrometer were built differently and have different challenges associated with their alignment, the alignment system for each is described separately.

3. Barrel Alignment

The barrel contains 656 MDT chambers and 5817 optical sensors. The optical alignment system in the barrel [2] uses two different types of sensors: the SaCAM and the RASNIK.

Both sensor types operate under the same principle: an optical sensor (CMOS or CCD) captures the image of a target through a lens. The sensor image is analyzed and converted into four parameters: the translations in \( x \) and \( y \) with respect to the optical axis \( z \), the relative angle of rotation \( \theta_z \) between the target and the sensor, and the magnification due to the lens.

The SaCAM sensor consists of a camera, with a CMOS and lens mounted in a frame, and a target with four back-illuminated holes, covered by a light diffuser. This sensor is a two-point alignment device, where the camera and target can be placed independently.

The target of the RASNIK system [2] [3] (referred to as a mask) is a chessboard-like pattern, and the optical sensor is a CMOS. RASNIKs are three-point alignment devices, and the three optical elements can be placed independently, anywhere in the detector. Another advantage of the RASNIK mask is that the chessboard pattern contains several wrong-colored squares. This pattern allows for information about larger-scale movements to be calculated. In other words, the dynamic range and the translation resolution are decoupled.

These two different types of optical sensors are arranged throughout the barrel in seven different classes of optical lines, five of which can be seen in the left image of Fig. 2. The first class and backbone of the barrel alignment system is the projective lines which connect three chambers of one tower. The projective
system works with RASNIKs, where the mask, lens, and CMOS are in the inner, middle, and outer layers, respectively. The number of projective lines is limited to the natural openings in the nearly hermetic detector. In the current final layout, only roughly 60% of the large chamber towers are equipped with a projective system, while small chambers are not equipped with projective lines. Towers without projective lines have to be optically linked to those towers equipped with projective lines. This is done using two types of chamber to chamber connections within one plane: a small lever arm connection, called the praxial (PRoximity Axial) system, and a long lever arm connection, called the axial system. Both systems work with RASNIKs, where each MDT is equipped with a CMOS, while the neighboring chamber is equipped with a mask (the lens can be on either chamber). In addition to the axial/praxial systems, the small chambers are connected via SaCAM to the large towers. Another optical link exists which connects the barrel MDT chambers to external points mounted on the toroid structure, creating a frame of reference. The final class of sensor is the inplane system: one or more RASNIKs mounted inside the chamber monitor deformations.

A strategy of relative alignment was adopted, where alignment by tracks is used to determine an initial set of positions for all of the MDT, and optical sensors monitor changes from this initial position. Before the LHC started providing proton collisions, ATLAS was tested and calibrated by recording large numbers of cosmic rays. The initial alignment was calculated using a period of cosmic ray tracks in October 2009.

For this initial alignment, the information from the cosmic tracks was combined with information from the optical sensors. To calculate the initial positions, an ensemble of chamber positions was chosen. For this ensemble, a $\chi^2$ was calculated for the information from the optical sensors, and a separate $\chi^2$ was calculated for the tracks. The ensemble which minimized the sum of these two $\chi^2$ was assumed to be the initial position. This initial position has been used as a baseline ever since, and the optical sensors track movement from the initial position.

4. Endcap Alignment

Similar to the barrel, the optical system in the endcap [3] uses two types of sensors: the RASNIK and the BCAM. The RASNIK is identical to that used in the barrel. The BCAM sensor has two laser diodes which are flashed onto a CCD. This sensor gives the same information as the SaCAM.

The major difference between the endcap and the barrel alignment comes in the arrangement of the sensors (Fig. 3). A major component of the endcap system is the inclusion of precisely measured aluminum alignment bars. The shape of these bars is calculated by taking into account the exact position and weight of all the sensors, as well as the temperature. To determine additional strains on the bars once installed, such as external cables, there are RASNIK sensors inside of the bars to assist in the calculation of the shape.

These bars provide the same information as the axial/praxial, reference, and projective lines in the barrel. The frame of reference and the projective information are provided by optical lines between alignment bars,
as can be seen in the right image of Fig. 3. In that image, the green lines are polar between layers of the endcap, and the blue lines are azimuthal between sectors in a single layer. Optical lines between a bar and a chamber, as can be seen in the left image, determine the placement of chambers in the reference frame.

In the endcap, a strategy of absolute alignment is used for the MDT, while the CSC is aligned using the relative alignment strategy. Absolute alignment means that the positions of the chambers are determined exclusively from the information of the optical system, with no alignment-by-tracks necessary.

5. Alignment Monitoring

To ensure that the alignment system is functioning properly, a multi-stage monitoring system has been put into place. The ATLAS central control room monitors the optical hardware, notifying experts of any failures. In the case of a potentially catastrophic failure, the control room has the ability to shut off the power for the alignment system, thereby protecting the hardware.

To monitor the output of the alignment system, namely the chamber positions, experts routinely examine the results. It has been observed that the chambers are stable within approximately 200 μm over a period of several weeks, as long as the magnetic field is not turned off. Chambers can move as much as several mm when the magnet is switched on or off. In addition to looking at the movement of chambers, alignment experts can look at the information given by an individual sensor to see if it is malfunctioning. Over 99% of the sensors are working, and the alignment system is performing as expected.

6. Alignment Validation

To confirm that the chamber positions output by the alignment system are correct and to see if the alignment is reaching its goal of 50 μm accuracy, several studies are underway. One of the most important studies operates under the principle that if a truly straight track travels through the muon spectrometer, it should have zero sagitta. In reality, a muon can interact with material and undergo multiple scattering, but if a distribution of many ‘straight-track’ sagittas are plotted, the distribution should be centered at zero with a width dominated by multiple scattering.

To get a sample of straight muon tracks, ATLAS recorded 4.6 pb⁻¹ of LHC collisions with the toroids in the muon spectrometer turned off, while the solenoid in the inner detector remained on, to allow for a momentum measurement. In Fig. 4, the sagitta distributions are shown in both endcaps, both before and after the application of alignment corrections. After correction, both distributions have means of less than
Fig. 4. Sagitta distribution in magnet-off runs for both endcaps. The grey hashed distributions are before the application of alignment corrections, the yellow after. A fit to the distributions show means of less than 50 μm. The tracks included in this plot have $p > 25$ GeV.

Fig. 5. Mean sagitta in all muon spectrometer sectors by tower. The sagitta values in each sector include a 500 μm offset so that all sectors can be seen. The small sectors are denoted by empty markers and the large sectors by filled markers. The circles represent barrel towers, while the squares represent endcap towers. The points marked by blue triangles have a CSC chamber as the inner layer; those marked by pink triangles go through a partially installed layer of the endcap. 50 μm. This shows that, on average, the alignment in the endcaps is at the expected level. However, this average is over many sectors, and smaller scale issues may be hidden.

Fig. 5 shows the mean sagitta in all sector-tower combinations. The data point for each sector-tower combination is calculated by plotting the sagitta (similar to Fig. 4). An unbinned likelihood fit is performed, with each track’s weight determined by its resolution; the resolution depends on the momentum of the muon and the amount of material traversed. The mean of this fit is the sagitta for that tower, and the uncertainty of the fit determines the error bars.
The yellow bands in the plot represent a zero sagitta plus or minus 100 μm, in each sector. Most of the towers in the barrel are inside of this band, while several in the endcap are outside. There are two potential explanations for this. Tracks in the endcap pass through more material, so the uncertainty on the sagitta is larger. Also, the barrel alignment is performed with tracks, and this procedure checks tracks. Therefore, this is more of a self-consistency check in the barrel while it is a truly independent check of the alignment accuracy in the endcap. The main conclusion from this plot is that the vast majority of towers are aligned to better than 100 μm.

In addition to looking at the individual points in Fig. 5, it is possible to calculate some descriptive quantities which can provide information about the alignment quality of large regions. Instead of performing a likelihood fit for each tower, a fit of all tracks in the three regions of the detector (barrel MDT, endcap MDT, and endcap CSC) provides a single number detailing the alignment accuracy. For the three regions, these accuracies are 60 μm (barrel MDT), 110 μm (endcap MDT), and 190 μm (endcap CSC). Combining the mean track sagitta in Fig. 5 with detailed knowledge of the magnetic field map, it is possible to calculate the contribution from the alignment to the $p_T$ resolution. For the same three regions, these contributions are (in TeV$^{-1}$): 0.14 (barrel MDT), 0.18 (endcap MDT), and 0.29 (endcap CSC).

7. Summary

The ATLAS muon alignment system is performing very well. The hardware is installed and working with less than a 1% failure rate. There are multiple methods in place to monitor and validate the alignment. While the goal of 50 μm alignment in the entire detector is not yet reached, with the barrel being close to this goal and the endcap at approximately 100 μm, work is underway to close the gap.

8. Acknowledgments

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References