Commissioning of the muon track reconstruction in the ATLAS experiment

M J Woudstra, on behalf of the ATLAS Muon collaboration

Department of Physics, University of Massachusetts, 710 North Pleasant Street, Amherst, MA 01003, United States of America

Martin.Woudstra@cern.ch

Abstract. The Muon Spectrometer for the ATLAS experiment at the LHC is designed to identify muons with transverse momentum greater than 3 GeV/c and measure muon momenta with high precision up to the highest momenta expected at the LHC. The 50 µm sagitta resolution translates into a transverse momentum resolution of 10% for muons with transverse momenta of 1 TeV/c. The target muon momentum resolution requires an accurate knowledge of the positions and orientations of the muon chambers, as well as their internal deformations. The optical and track based alignment are shown to perform as expected. Accurate calibration of the time to distance relation in the Monitored Drift Tubes (MDTs) is also required to reach design performance. The software chain that implements corrections for the alignment and calibration of the chambers is described, as well as the algorithms implemented to perform muon identification and measurement in ATLAS. The performance of the complete software chain is covered in the context of first single-beam LHC running as well as ATLAS cosmics data taking. The software is robust and reconstructs local track segments with high (> 99%) efficiency.

1. Introduction

ATLAS [1] is one of the two multi-purpose detectors at the LHC accelerator at CERN. Figure 1 shows the various sub detectors, magnets and shielding of the detector. ATLAS consists of an Inner Detector to precisely measure the transverse momentum of charged particles, a Calorimeter to identify and measure electrons, photons and hadrons, and a Muon Spectrometer to identify and measure muons. The outer size of the detector is determined by the Muon Spectrometer, which is approx. 22 m in diameter and approx. 45 m in length.
Figure 1. Overview of the ATLAS detector showing the various subdetectors, magnets and shielding.

The Muon Spectrometer (Figure 2) is build around air core toroid magnets to minimize multiple scattering. The magnetic field is 0.5 T on average but is inhomogeneous and ranges from 0.15 to 3.5 T. Three layers (inner, middle and outer) of precision chambers determine the position of the curved track to measure its transverse momentum with a precision of a few percent, degrading to ~12% at 1 TeV/c. In combination with the Inner Detector, it can identify muons down to 3 GeV/c. Fast trigger chambers are used to provide muon triggers. Four different detector technologies are used, and their locations in the detector are indicated in Figure 2. Most of the precision chambers are Monitored Drift Tube chambers (MDTs), while Cathode Strip Chambers (CSCs) are used in the inner most part of the inner end-caps, where the occupancy is expected to be highest. For the trigger, Resistive Plate Chambers (RPCs) are used in the barrel and Thin Gap Chambers (TGCs) in the end-caps.

Figure 2. Longitudinal cut view of one quarter of the Muon Spectrometer. BIL, BML, BOL, EIL, EEL, EML and EOL are MDT chambers. BML has in addition two RPC chambers (one above and one below the MDT), and BOL has in addition one RPC chamber (above the MDT). CSCs and TGCs are indicated directly.

The Muon Spectrometer provides a large rapidity coverage ($|\eta| < 2.7$) and extends beyond the coverage of the Inner Detector ($|\eta| < 2.5$). The so-called EE chambers (“End-cap Extended”) help cover the incomplete coverage of the EO chambers (“End-cap Outer”). At startup, only ~20% of the EE chambers are installed, which results in a temporary lower acceptance around $1.0 < |\eta| < 1.4$. 

17th International Conference on Computing in High Energy and Nuclear Physics (CHEP09) IOP Publishing
Journal of Physics: Conference Series 219 (2010) 032026
doi:10.1088/1742-6596/219/3/032026
2. Muon reconstruction in the ATLAS detector

ATLAS identifies muons using four different types of algorithms. The standalone reconstruction uses only the muon spectrometer. The combined reconstruction combines the standalone track with an Inner Detector track. The so-called muon taggers start from the Inner Detector tracks and look for matching muon signals in either the calorimeter or the muon spectrometer.

2.1. Muon reconstruction algorithms

The muon standalone reconstruction is illustrated in Figure 3. It starts by defining regions of activity by looking at the hits in the muon spectrometer. Within those regions it reconstructs precise local track segments in the chambers. The segments of the three spectrometer layers are then matched to form track candidates. These candidates are fit using the full information of the hits, magnetic field and material. In the last step the tracks are extrapolated to the interaction point taking into account the energy loss in the calorimeter.

Figure 3. A muon track reconstructed in the barrel of the Muon Spectrometer. The inset shows the projection of a local track segment fitted to 6 MDT hits (represented by solid drift circles).

The combined reconstruction matches the muon standalone tracks to the Inner Detector tracks and determines the track parameters by combined the two tracks. The advantage over standalone tracks is a better momentum resolution at lower \( p_T \) as shown in Figure 4, as well as a higher fake rejection rate. The disadvantage is a lower acceptance in \( \eta \), as shown in Figure 5, because the Inner Detector acceptance is smaller than the Muon Spectrometer acceptance.

Figure 4. Expected resolution for single muons as a function of transverse momentum for Muon Standalone and Combined reconstruction (barrel only).

Figure 5. Reconstruction efficiency for single muons with \( p_T = 100 \) GeV/c as a function of pseudo-rapidity. ‘All’ includes stand-alone, combined and segment taggers. The calorimeter taggers are not included.
The so-called segment taggers start from the Inner Detector tracks and extrapolate them to the Muon Spectrometer to find matching segments in the muon chambers. These segments are either the ones found by the standalone algorithm, or the segments are reconstructed in the regions of activity defined by the Inner Detector tracks. The Inner Detector tracks are then tagged as muons. If sufficient segments match an Inner Detector track, the full track can be refit to obtain a better momentum resolution. The advantage of the segment taggers compared to the standalone and combined algorithms is in the area where less than three muon layers are traversed by the muon. This holds for the very low p_T muons, which are bent too much to reach the outer stations. In the region of the missing EE chambers (End-cap Extended, see Figure 2) around \( \eta = 1.2 \) they compensate for the lower efficiency of the other two algorithms, as seen in Figure 5, which assumes that the EE chambers are not yet installed.

The calorimeter taggers also start from the Inner Detector tracks and extrapolate them outward to find matching muon signals in the Calorimeter. The Inner Detector tracks are then tagged as muons. The main advantage over the other algorithms is their acceptance at \( \eta = 0 \), where the muon spectrometer has an acceptance gap because of services, resulting in a lower efficiency in all algorithms that use the Muon Spectrometer (see Figure 5).

The reconstruction software had to be adapted to cope with cosmic muons, which have a very different signature in the detector. The most important change is the relaxation of the pointing constraint, because most of the cosmic muons do not pass near the interaction point.

2.2. Resolution of the standalone reconstruction

The design of the Muon Spectrometer is driven by the requirement of having order 10% resolution on muons with \( p_T = 1 \text{ TeV}/c \). Figure 6 shows the various components, determined from simulation, that contribute to the total resolution of the standalone muons when extrapolated to the interaction point. For low \( p_T \) (< 20 \text{ GeV}/c) the resolution is dominated by the uncertainty of the energy loss in the Calorimeter. For intermediate \( p_T \) the resolution is dominated by the multiple scattering due to the material in the Muon Spectrometer itself. For high \( p_T \) (> 300 \text{ GeV}/c), the resolution is dominated by the intrinsic resolution of the precision chambers and their alignment. The resolution at 1 \text{ TeV}/c is somewhat worse here than in Figure 4 because the latter does not include the effects of misalignment.

![Figure 6. Breakdown of the contributions to the resolution of the muon standalone reconstruction.](image)
The sagitta of a 10 GeV/c muon is about 500 µm, and a 10% resolution translates into a precision of 50 µm on the sagitta. This is split into a contribution of 40 µm from the resolution of the precision chambers and a contribution of 30 µm due to the precision of the alignment. These two contributions are the topic of the next two sections.

3. Calibration of the MDT chambers
To exploit fully the intrinsic resolution of the MDT tubes, its calibration is essential. The calibration consists of the relationship between the drift distance and the measured drift time (the r-t relationship). A dedicated data stream is sent to dedicated off-site calibration centers, where the r-t relationship and the r-dependent resolution are determined. This calibration is then stored in a conditions database. During reconstruction, the calibration is retrieved from the conditions database and applied to the measured MDT hit times to convert them into drift radii, which are used in the reconstruction. Several drift circles are shown in the inset of Figure 3.

4. Alignment of the muon chambers
The target muon momentum resolution requires an accurate knowledge of the positions and orientations of the muon chambers, as well as their internal deformations, which are induced by mechanical stress and thermal gradients during the experiment operation.

4.1. Optical alignment
The muon precision chambers are equipped with a total of more than 12k optical alignment sensors, designed to track changes in the geometry with a precision of better than 30 µm on the track sagitta. Every 15 minutes all alignment sensors are read out. Using the sensor data as input, an offline program reconstructs the individual chamber positions, rotations and deformations, which are stored in a conditions database. During track reconstruction the values are read back from the database and used to correct the geometry. Due to different geometrical constraints, the alignment strategies are somewhat different in the barrel and end-cap regions.

In the barrel, the optical alignment systems (Figure 7) are able to reliably detect relative changes in chamber position at the 20 µm level. However, the absolute chamber positions can be determined only to an accuracy of a few hundred microns, which will yield a systematic uncertainty of 100-200 µm on the residual sagitta. The mechanical positioning uncertainties of some optical sensors limit the precision of the absolute reference point. Track-based alignment algorithms must therefore be used in combination with the optical system to achieve the desired sagitta accuracy in the barrel. For a more detailed description see [2].

In the end-caps, the toroid cryostat vessels are blocking the optical path between the inner and middle stations. The end-cap alignment system (Figure 8) therefore uses an intermediate reference grid of alignment bars, which are interlinked with optical alignment systems. The chambers are aligned with respect to the bars using optical systems. First the positions and deformations of the alignment bars are reconstructed. Then the chamber positions are reconstructed relative to the alignment bars. Simulations have demonstrated that this network is sufficiently precise and to determine absolute chamber positions within each end-cap region to a 300 µm accuracy, and relative chamber positions along muon trajectories to 40 µm accuracy on the sagitta. Track-based alignment is not needed to reach this precision. For a more detailed description see [3].
4.2. Track based alignment
The alignment of the precision chambers is also determined using muon tracks. It is used in two different modes, for different purposes: with and without magnetic field.

In a special running mode without magnetic field the initial reference geometry can be determined using straight tracks. This serves as a crosscheck for the optical alignment systems and provides a precise absolute calibration for the barrel optical system. As for the optical systems, an offline program reconstructs the chamber displacements, rotations and deformations, which are stored in and read back from a conditions database.

In the normal running mode with magnetic field, the track based alignment is used to complement the optical alignment systems. In the barrel it is used, for example, to precisely determine the positions of the so-called small chambers (50% of the chambers), which lack projective alignment systems. The track based alignment is also needed to determine the global positions of the barrel and end-cap muon systems with respect to each other, and with respect to the Inner Detector. The information from optical and track-based alignment needs to be combined to reconstruct the final precise geometry. How this combination will be done is still under study.

5. Results from commissioning
The ATLAS detector has been commissioning mainly with cosmic muons. Many millions of cosmic muons have been recorded and analyzed. A small number of events have been recorded and reconstructed during the first LHC single beam running in September 2008.

5.1. Examples of reconstructed muons
On September 10, 2008 the first LHC single proton beam passed through the ATLAS detector. The beam hit the collimators in front of the detector, which caused a splash of muons to pass through the detector. This event was recorded and the many hits resulted in thousands of reconstructed local track segments in the Muon Spectrometer, as shown in Figure 9. This event was a good robustness test for the muon reconstruction software.

Figure 10 shows several beam halo muons reconstructed while one of the first proton beams was circulating through the LHC (without hitting the collimators).
Figure 9. The first LHC beam event in ATLAS.

Figure 10. Several reconstructed LHC beam halo muons.

Figure 11 shows a (rather rare) cosmic muon passing almost horizontally through the detector. It traverses both end-caps of the Muon Spectrometer and leaves a clear signal in the electromagnetic calorimeter. Most muons come in almost vertically through the access shafts, as visible in Figure 12, which shows the distribution of the muons at the surface, 80 m above the interaction point. Here, the muons were reconstructed using only the RPC chambers.

Figure 11. A nearly horizontal cosmic muon traversing ATLAS.

Figure 12. Distribution of the impact point at the surface of the muons reconstructed in the Muon Spectrometer (using RPCs only). The circles indicate the access shafts for material and personnel.

5.2. Segment reconstruction efficiency

The efficiency of reconstructing local track segments in ATLAS has been determined using cosmic muons. Tracks are selected that have at least a segment in two out of the three layers of muon chambers (inner/middle/outer). The third layer is then tested for presence of a segment, which is not required to be laying on the track. For the barrel, the resulting efficiencies are shown as a function of $\eta$ and $\phi$ for the three layers in Figure 13. For most chambers the efficiency is very high, as expected (> 99%). The middle layer has the higher average efficiency (99.4%) because it has only a few chambers with lower efficiency. The inner layer has the worst average (94.6%), because there are several chambers with an efficiency of ~75-95%. The outer layer average is somewhere in between (97.7%). The reasons for the lower efficiency of some of the chambers are not clear yet.
5.3. Performance of the alignment systems

Cosmic muons of runs without magnetic field were used to check the precision of the alignment. The tracks are straight (apart from multiple scattering) and the average sagitta of the tracks should be zero. The sagitta here is defined as the distance from the segment in the middle layer to the line connecting the segments in the inner and outer layer.

For one barrel tower, Figure 14 shows the distribution of the sagitta with the nominal geometry, with corrections from the optical alignment systems, and with corrections from the track based alignment. For the nominal geometry, the average sagitta of ~2 mm is the result of the precision of the installation of the chambers (few mm). Using the optical alignment systems, the average is ~130 µm, which is still not consistent with zero. Looking at several towers, the typical average values are 200-300 µm, consistent with what is expected taking into account the uncertainties of the positions of some alignment sensors. After corrections from track based alignment, the average sagitta is within the 30 µm goal. This confirms that the track based alignment is needed, and sufficiently precise to provide an absolute reference for the optical systems.

For the end-caps, Figure 15 shows the distribution of the track sagitta before and after the corrections of the optical alignment systems. The distribution before the corrections is very wide because the distribution for one the end-caps is significantly shifted, as shown in the two bottom plots of the same figure. This is because the middle station of the end-cap on side A is significantly displaced along the beam axis. After optical alignment corrections the average sagitta is 48±54 µm, which is consistent with zero. More statistics is needed to determine if the goal of 30 µm has been reached.

The width of the sagitta distributions after alignment corrections is consistent with multiple scattering of the cosmic muons.
Figure 14. Distribution of the track sagitta of one barrel tower with nominal geometry, after corrections from optical alignment systems and after corrections from track based alignment.

Figure 15. Distribution of the track sagitta for the end-caps. The top plot shows both end-caps superimposed, while the bottom two plots show them separately.

6. Conclusions
The muon reconstruction software has been successfully commissioned using millions of cosmic muons, beam halo muons and muons from a splash caused by a proton beam hitting collimators. The software was adapted to cope with the muons not pointing to the interaction point.

The splash of muons from the first proton beam in the LHC has demonstrated the robustness of the muon reconstruction against busy events.

The storage in and retrieval from the conditions database has been demonstrated to work both for the MDT calibration and for the geometrical corrections from alignment.

The efficiency of reconstructing local track segments is shown to be high (> 99%), as expected, for most chambers. The reasons for lower efficiency in some chambers are not clear yet.

The optical alignment systems are shown to correct the geometry according to expectations. For the end-caps, the average sagitta is shown to be consistent with zero after corrections from the optical alignment systems, although more statistics is needed to check whether it is within the 30 µm goal. For the barrel, the average sagitta per tower is 200-300 µm when using only corrections from the optical alignment systems. When the geometry is reconstructed using straight tracks, the average sagitta is within the 30 µm goal, so it can be used to provide an absolute reference for the optical systems.
Acknowledgements
The results presented in this paper are the result of the work of many ATLAS collaborators. The author would like to thank several of them, who helped in preparing this paper: Florian Bauer, Kevin Black, Laurent Chevalier, Thomas Kittelmann, Oliver Kortner, Rosy Nikolaidou, Igor Potrap, David Rousseau and Stephane Willocq.

References
[1] ATLAS collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, 2008 JINST 3 S08003, http://www.iop.org/EJ/toc/1748-0221/3/08
[2] C. Guyot et al., The alignment of the barrel part of the ATLAS muon spectrometer, ATLAS Note ATL-MUON-PUB-2008-007, http://cdsweb.cern.ch/record/1081769.
[3] C. Amelung et al., The Optical Alignment System of the ATLAS Muon Spectrometer Endcaps, ATLAS Note, ATL-MUON-PUB-2008-003, http://cdsweb.cern.ch/record/1089861.