First Results from the ATLAS Muon Spectrometer Optical Alignment System

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Abstract

The muon spectrometer of the ATLAS detector at the Large Hadron Collider (LHC) at CERN consists of 1182 muon chambers for precision track measurements, arranged in three concentric cylinders of up to 25 m length in the central (barrel) region, and in four wheels of up to 25 m diameter in each of the two endcaps. They are located between 5 m and 22 m from the interaction point, and each muon track is detected in three equally spaced chambers. The muon chambers are equipped with a complex high-precision optical alignment system to monitor their positions and deformations during ATLAS data-taking with an accuracy of 30–40 \( \mu \text{m} \), ultimately required for reconstructing high-momentum final-state muons with the desired momentum resolution of 10% at 1 TeV. The alignment system, the sensors, and the readout and reconstruction software are described. The installation and commissioning of the more than 12000 sensors in the ATLAS cavern has been completed in 2008, and first data from the full system are presented.

Key words: LHC, ATLAS, MDT, muons, alignment

1. Introduction

The ATLAS muon spectrometer \cite{1} has been designed to provide an excellent stand-alone momentum measurement of muons up to the highest expected energies: the transverse momentum \( p_T \) should be measured with a resolution of \( \Delta p_T/p_T = 10\% \) at \( p_T = 1 \text{ TeV} \). Four different technologies of muon chambers are used, two for precision measurements, two for triggering. The precision measurement of muon tracks is performed in most of the spectrometer by monitored high-pressure drift tube (MDT) chambers, composed of six or eight layers of cylindrical aluminum drift tubes glued onto a spacer frame. In the very forward region, cathode strip chambers (CSCs) are used instead. The MDT and CSC chambers are together referred to as precision chambers. They are complemented by trigger chambers – resistive plate chambers (RPCs) in the barrel, and thin gap chambers (TGCs) in the endcaps. Precision chambers are arranged in 16 sectors in azimuth, covering 28° (large) or 17° (small sectors), respectively.

The spectrometer employs an air-core toroidal magnetic field, which has the advantage of causing only minimal multiple scattering due to the small amount of material present between chambers. A consequence of this design is the relatively low magnetic field strength that can be reached: the bending of a 1 TeV muon track in the magnetic field is such that the track sagitta varies between 0.5 mm at pseudorapidity \( \eta = 0 \) and 1 mm at \( \eta = 2 \). Consequently, in order to measure the momentum of a 1 TeV muon to 10% at all angles, the error on the sagitta measurement must be less than 50 \( \mu \text{m} \) in the bending direction of the magnetic field, transverse to the MDT tubes and wires. Muon tracks are detected in three equally spaced layers of chambers. The intrinsic resolution of the MDTs results in a sagitta error of 40 \( \mu \text{m} \), and the additional error from the chamber alignment should not exceed that value.

2. Optical alignment system

As long-term mechanical stability in a large structure such as ATLAS cannot be guaranteed at this level, a continuously running alignment monitoring system \cite{2,3} is required in order to fully exploit the intrinsic resolution of the spectrometer. This system is based on optical and temperature sensors, and is designed to detect slow chamber displacements, occurring at a timescale of hours or more. The information from the alignment system is used in the offline track reconstruction to correct for the chamber misalignment – no physical adjustments are made to the chamber positions after the initial positioning.

There is a large variety of optical sensors in the alignment system, all sharing the same principle: a source of light is imaged through a lens onto an electronic image sensor acting as a screen. The source of light is either a back-illuminated coded chessboard pattern (RASNIK mask), or one or several pairs of point-like light sources (BCAM and SaCam systems). In addition to optical position measurements it is also vital to determine the thermal expansion of chambers, by measuring their temperature. In total, there are about 12000 optical sensors and a similar number of

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temperature sensors in the system. They are mounted on chambers and on auxiliary reference objects, forming a complex network (Fig. 1), the layout [2, 3] of which was validated and optimized by Monte-Carlo simulations.

Optical and temperature sensors are calibrated, meaning that they can be used to make absolute measurements of muon chamber positions in space, rather than only following their movements with time, relative to some initial positions. It is therefore possible to determine the spectrometer alignment without making any use of muon tracks, and straight tracks from runs without magnetic field can instead be used for independent cross-checks of the optical system. This is of the essence, given the stringent accuracy requirement and the large number of systematic effects that need to be kept under control.

Calibrating alignment sensors at the required level of accuracy (typically 20 µm and 50 µrad) is performed by a series of measurements on a calibration stand, the geometry of which is accurately known e.g. from measurements with a coordinate-measuring machine. Sensor mounts on chambers and on auxiliary objects also have to be calibrated. In total, there are of the order of 10^5 calibration constants defining the alignment system geometry.

During ATLAS running, sensor data are acquired in an optimized combination of sequential and parallel operations. Images are analyzed on-line, and only the analysis result (i.e. the spot position for BCAM/SaCam images, and the decoded position of the mask for RASNIKs) plus some diagnostic information is stored in a database (about 0.1 KB/image); some fraction of the raw images (100 KB/image) is retained for debugging purposes. One readout cycle, yielding one image from each sensor, takes about 30–60 minutes. The alignment data acquisition is integrated with the ATLAS detector control system.

3. Alignment system performance

The muon spectrometer and its alignment system were installed and commissioned in the ATLAS cavern during the years 2005–2008, and continuous alignment data-taking with the completed system started in summer 2008. The commissioning of the alignment system was a time-consuming and labor-intensive process, and included the positioning of the chambers with an accuracy of about 5 mm, clearing obstacles like cables and pipes from optical lines, and repairing or replacing damaged sensors. The latter two items were an issue particularly in the crowded barrel region. After commissioning, more than 99% of all relevant alignment sensors were functioning, and only very few failed during the several months of data-taking in 2008.

The alignment, i.e. the position coordinates, rotation angles, and deformation parameters of the precision chambers, is reconstructed by a global χ^2 minimization procedure. The total χ^2, as well as the contributions of the individual sensor measurements to χ^2, i.e. the pulls, can be used to estimate the alignment quality from the internal consistency of the fit: if the observed sensor resolutions agree with the assumed ones, one expects approximately χ^2/ndf = 1 and a pull distribution with zero mean and unit width. As an example, Fig. 2 shows the observed and expected pull distributions in the endcaps.

The assumed sensor resolutions are adjusted until the observed pull distributions, broken down by sensor type, agree with the expected width. This yields the observed sensor resolutions, which are used as input to a Monte-Carlo simulation of the alignment system. The simulation predicts a sagitta accuracy of about 45 µm in the endcaps, and 200 µm/1 mm in the large/small sectors of the barrel. The design accuracies are 40 µm and 30 µm/300 µm, respectively (in small barrel sectors, the optical system is used, by design, only as a starting point for a track-based alignment procedure). Judging by this method, the design performance is nearly reached in the endcaps, and the absolute alignment of the large barrel sectors works at least at a level that is sufficient for many applications. The performance of the barrel system is limited by several known problems with the calibrations of sensors and sensor mounts, and is not expected to improve significantly by further analysis of the data. The final absolute alignment of the barrel will thus have to rely on straight tracks.
4. Validation of the alignment

Validating the alignment as reconstructed from the optical sensor measurements requires an external reference. During chamber installation, surveys of the completed endcap wheels were performed using photogrammetry, and positions from the alignment system agreed with the survey results within 500 μm, the quoted accuracy of the survey. For barrel chambers, tools were designed to measure distances and shifts between chambers, and measurements agreed with the alignment system results within 100–200 μm, the estimated accuracy of the tools. While establishing confidence in the optical system, these checks are limited in scope and accuracy, and the full validation of the alignment can only be done with muon tracks.

In the fall of 2008, about $10^8$ muon-triggered cosmic events were recorded during magnet-off running of the ATLAS detector. These events were used to cross-check the alignment provided by the optical system. For a perfect alignment, the reconstructed sagitta of straight muon tracks should be zero on average. The observed width of the sagitta distribution is, for cosmic muons, dominated by multiple scattering. A shifted and/or broadened distribution would indicate imperfections of the alignment.

In the barrel, the collected sample contains a sufficient number of reconstructed cosmic muons, and thus it was possible to break down the alignment checks to the level of towers, i.e. triplets of MDT chambers, which gives the best sensitivity to the alignment. The endcap analysis is statistics-limited at this point (with about 10% of the full 2008 data analyzed), and breaking it down to the chamber-triplet level will require a significant increase in statistics. Figures 3 and 4 show observed sagitta distributions, before and after applying alignment corrections, for the two endcaps and for one example tower in the barrel, as well as a summary of barrel results. The improvement is clearly visible, and the mean values of the corrected distributions are compatible with zero within the r.m.s. errors estimated above from the internal consistency of the alignment fit – 45 μm for the endcaps, and 200 μm for the barrel. The widths of the corrected distributions agree approximately with expectations for the typical energies of cosmic muons in ATLAS (from the distances between MDT chambers one expects the width in the endcaps to be about 2–3 times larger than in the barrel).

5. Summary

The ATLAS muon spectrometer optical alignment system has been designed to provide muon chamber positions with a sagitta accuracy of 30–40 μm. After three years of installation and commissioning, the system was completed in 2008. The analysis of the data is well advanced, and performance estimates indicate a sagitta accuracy of 45 μm (endcap) and 200 μm/1 mm (barrel-large/small sectors). Using straight tracks as a cross-check confirms the chamber positions within the estimated sagitta errors, showing that the optical alignment system works, and that the design accuracy has nearly been reached in the endcaps. It also shows that the system produces reliable estimates of the uncertainty of the alignment corrections it provides.

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