Alignment of the ATLAS Inner Detector

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Abstract—The performance of the ATLAS Inner Detector (ID) is crucially dependent on how accurately one can determine the position and orientation of the thousands of detector modules that it is comprised of. In order not to degrade performance significantly, module positions must be known to $O(10\mu m)$ precision. Here we describe the track-based alignment algorithms used to provide alignment at this level and how they are implemented within the ATLAS data taking framework. We present results of alignment tests on simulated data, the results of aligning with the first cosmic ray events taken with the full ID, and some of the systematic problems that can arise with track-based alignment approaches.

I. INTRODUCTION

THE ATLAS detector is a large multi-purpose particle physics detector that is designed to analyse the high energy proton-proton collisions produced by the Large Hadron Collider (LHC) at CERN. ATLAS comprises of four major subsystems, the Inner Detector [1][2], Electromagnetic Calorimeter, Hadronic Calorimeter and Muon Spectrometer. The ID is the innermost detector subsystem, occupying a cylindrical volume 2.1m in diameter and 6.2m in length that immediately surrounds the beampipe. This volume is permeated by a 2T solenoidal magnetic field with field lines parallel to the beamlime. The primary role of the ID is to accurately and efficiently reconstruct the helical trajectory of charged particles in this volume. This enables a determination of the charge and momentum of the particle and also the reconstruction of primary and secondary vertices within the event. Figure 1 shows a 3-D view of the ATLAS ID. Visible are the three subdetectors of the ID; the Pixel, Semiconductor Tracker (SCT) detector and Transition Radiation Tracker (TRT). Each subdetector contains two kinds of detector modules, barrel modules which are arranged in cylindrical layers and the endcap modules which are arranged on the disk-like structures of the endcaps. Table I reports the type of each subdetector, the number of modules and their resolutions [2].

The accuracy with which the particle tracks can be reconstructed is limited by how precisely we know the individual module positions and orientations. The baseline goal is that the resolution of the track parameters not be degraded by more than 20% by imperfect knowledge of the alignment of the ID. This translates into a requirement on the alignment precision of $O(10\mu m)$ in the sensitive $r\phi$ direction and $O(100\mu m)$ in the $z$ direction. Eventually, in order to get to the precision necessary for a measurement such as the W boson mass, we will need alignment to $1\mu m$ precision. In addition, the alignment should be free of systematics which can bias track reconstruction (see section V).

The initial as-built precision of the ID module positions is $O(100\mu m)$. The barrel layer and endcap disk structures themselves have been installed with a precision of 100-1000$\mu m$. In order to get to the required alignment precision we require track-based alignment algorithms.

II. TRACK-BASED ALIGNMENT

The alignment of the ID is specified by a set of alignment constants, six for each individual ID module, which correspond to the six degrees-of-freedom (DOF) of a rigid body (three translational and three rotational). Track-based alignment algorithms make use of the information that is contained in the residual distributions of the inner detector modules to determine these constants. A residual is defined as the distance (in the $r\phi$ or $z$ direction) between the position of the measurement or “hit” on the module, and the intersection of the fitted track with that module. If the positions and orientations of all the ID modules are precisely known, then all the residual distributions should be centred on zero with a width that is determined by the intrinsic resolution of the detector elements, the effect of multiple scattering and
the track extrapolation error. However, if, for example, a particular module is displaced in the $r\phi$ direction, then its $r\phi$ residual distribution will be biased and the size of this bias will be proportional to the size of the displacement. Thus by translating and/or rotating modules until all residuals are minimised we should be able to determine the complete set of alignment constants for the ID. This can be achieved via a minimization of the following $\chi^2$ function:

$$\chi^2 = \sum_{\text{tracks}} r^T V^{-1} r$$

(1)

Where the sum is over all tracks in a given event sample, $r$ is the vector of residuals for a given track and $V$ is the covariance matrix of $r$. In general $r$ is a function of both the parameters of the track fit, $\pi$, and of the alignment constants for the modules contributing hits to the track fit $a$. Therefore, by simultaneously minimising this $\chi^2$ with respect to $\pi$ and $a$ we can determine the alignment constants. Using a number of simplifying assumptions the solution can be defined by a set of coupled linear equations:

$$\left( \sum_{\text{tracks}} \frac{dr^T}{da_0} V^{-1}\frac{dr}{da_0} \right) \delta a + \sum_{\text{tracks}} \frac{dr^T}{da_0} V^{-1} r(\pi_0, a_0) = 0$$

(2)

where $a_0$ and $\pi_0$ are the initial values of the alignment constant and track parameters respectively, and $\delta a$ is the correction to $a_0$ which we are trying to find. Performing a minimization of the $\chi^2$ in this way is known as the Global $\chi^2$ Algorithm [3]. In practice, due to the simplifying assumptions made, a number of iterations are required to converge on an alignment solution. The advantage of this approach is that it accounts fully for the correlations between modules. However, to solve for every DOF of every module in the Pixel and SCT requires solving a system of $5832 \times 6 = 34992$ coupled linear equations. This is computationally an extremely expensive exercise and in practice various preconditioning and fast solving techniques have to be used to make the problem tenable.

The alignment results for the Pixel and SCT subdetectors reported here have been produced with the Global $\chi^2$ Algorithm. However, there are also other track-based alignment approaches that are in use at ATLAS. The Local $\chi^2$ Algorithm [4] also works on a principle of $\chi^2$ minimization, but simplifies the problem by assuming that the track parameters are constant and just minimizing with respect to the alignment DOF. By executing a number of iterations of the Global $\chi^2$ Algorithm, local module alignments can be accounted for to a limited extent. The TRT alignment results reported here are achieved using a Local $\chi^2$ approach (hereafter referred to as the TRT $\chi^2$ approach). Finally, the Robust Algorithm [5] does not use a $\chi^2$ minimization approach, but calculates alignment corrections in the local module plane directly from the size of the residual bias, in particular making use of the difference

![Flow diagram showing the production of ID alignment constants during ATLAS operational running.](image)

**III. TECHNICAL IMPLEMENTATION**

A flow diagram illustrating the various stages that are executed to produce updated alignment constants during ATLAS collisions data taking is shown in Figure 2:

1) A dedicated data stream, the alignment stream, provides the input of isolated tracks to the alignment procedure.
2) The current position of the beamspot is determined by examining the correlations in track perigee parameters $d_0, z_0, \phi_0$ and $\eta_0$. This beamspot position is then used as an additional soft constraint in the track fitting.
3) A number of iterations of the Global $\chi^2$ Algorithm are made to align the Pixel and SCT subdetectors. The DOF used in the minimization are progressively increased, such that first the gross misalignments between the Pixel and SCT subdetectors are removed, then the barrel/disks within the subdetectors are aligned, and finally the individual module alignments are determined. Due to the large DOF involved in aligning every silicon module this is the most computationally intensive stage, involving $O(100)$ CPUs processing in parallel.
4) The TRT is aligned using the TRT $\chi^2$ approach. Alignment with respect to the Pixel and SCT subdetectors is first performed, followed by the internal alignment of the TRT modules.
5) Coherent global translations and rotations of the entire ID that may have been introduced by the alignment procedure are removed via a centre-of-gravity (CoG) transform to a reference geometry.
6) The beamspot position is re-determined using the new alignment constants.
These stages are executed automatically, running on a dedicated batch queue system at CERN and controlled by a series of scripts. Clearly the new alignment constants that result should only be used for the processing of the bulk trigger streams if they are an improvement on the alignment constants that were previously in the database. This is determined by reconstructing a small but representative subset of the available data using the new constants and monitoring a number of different distributions which are dependent on alignment quality. These range from basic distributions such as the tracking residuals and hit efficiencies, to more complex physics signatures such as reconstructed J/ψ, K^0_S and Z boson masses. It is anticipated that the alignment constants will be monitored in this way every 24 hours.

IV. TESTS OF ALIGNMENT APPROACH USING SIMULATED DATA

In order to test the performance of the ID alignment a large set of Monte Carlo samples were produced that have been simulated with the ID in a misaligned geometry. In this CSC (Computer System Commissioning) geometry, the following misalignments are introduced relative to the nominal geometry:

- Relative misalignment of the Pixel, SCT and TRT detectors of O(1 mm) in translation and O(mrad) in rotation.
- Relative misalignment of the Pixel and SCT barrel layer and endcap disk structures of O(100 μm) in translation and O(mrad) in rotation. Internal misalignment of the TRT barrel modules of O(100 μm).
- Internal module-to-module misalignment of the Pixel and SCT barrel and endcap modules of O(100 μm) in translation and O(mrad) in rotation.

The magnitude of the misalignments reflect the expected build precision of the ID. Using Monte Carlo samples simulated with this geometry as input, but starting from the nominal geometry, one can test the ability of the alignment procedure to remove these misalignments. In the “CSC exercise” [2][6], a Global $\chi^2$ alignment of the Pixel and SCT and subsequent TRT $\chi^2$ alignment of the TRT was performed using all available DOF on two such samples:

- A large sample of CSC simulated “multimuon” events; 10 muons per event with a common event vertex and a flat distribution in $\eta$, $\phi$ and $P_T$ ($2<P_T<50$ GeV).
- A sample of CSC simulated cosmic ray events.

Figure 3 shows the results of reconstructing the invariant mass of the two muon legs of a CSC simulated $Z \rightarrow \mu\mu$ Monte Carlo sample using the nominal geometry (black points), perfect knowledge of the misaligned geometry (red curve) and using the alignment constants determined from the alignment procedure (blue curve). The point of view, were intended to develop and test the full alignment procedure of Figure 2 in ATLAS operational conditions. Over the course of one week the alignment procedure was run on a daily basis on a CSC simulated alignment stream, and, following an improvement in the alignment quality evident from the alignment monitoring distributions, the database updated and the constants used for bulk reconstruction. The initial FDR exercises facilitated the development of the computing tools required to implement the alignment procedure smoothly, such that by the end of the final FDR exercise in August 2008 alignment results compatible with the “offline” CSC exercise had been achieved.

V. WEAK MODES

It is known that certain global deformations can be applied to a perfectly aligned detector that leave the residual distributions and hence the fitted tracks $\chi^2$/DOF unchanged. Such deformations are known as “weak modes”. It is possible that the Global $\chi^2$ minimization may not fully remove the misalignments, but instead settle on a geometry where residual weak mode deformations remain. Where these weak modes result in biases in the parameters of the reconstructed tracks they clearly present a serious threat to the physics potential of the ID. Four such weak mode deformations, considered the most likely and dangerous, have been generated such that we may investigate how to detect and remove them:

- “Curl” mode: global phi rotation of modules which increases as a function of radius. Produces a track curvature bias.
- “Twist” mode: global phi rotation of modules which increases as a function of global Z. Produces a $\theta$ dependent curvature bias.

$^1\theta$ is the angle the track makes with the beamline.
Fig. 4. Curvature bias (the difference in curvature between the ID reconstructed track and the truth track) for simulated tracks reconstructed with ideal (black), curl weak mode (red) and curl aligned (blue) geometries.

- “Elliptical” mode: radial distortion which varies as a function of global phi. Biases the mass of reconstructed vertices.
- “Telescope” mode: translation in global Z of modules which increases as a function of radius. Produces a track $\theta$ bias.

It has been demonstrated that, although the Curl deformation is a weak mode to tracks produced in beam collisions, it is not a weak mode to cosmic ray tracks, and hence these events can be used to effectively remove the curl deformation in the barrel. Figure 4 shows the resultant curvature bias when simulated beam collisions tracks are reconstructed with the curl geometry (red curve) and with the same geometry but after alignment corrections have been applied (blue curve). After alignment the curvature bias is compatible with zero.

However, it is known that cosmic tracks will not eliminate every weak mode, and they are of course only useful in the barrel. Beam halo events, produced when the proton beam interacts with LHC components further upstream, result in tracks that are primarily parallel to the beamline and so may fulfil a similar role in the endcaps. Several other strategies to remove weak modes are under investigation, such as using constraints derived from energy measurements in the calorimeter or from the reconstructed mass of $J/\Psi \rightarrow \mu\mu$ events.

VI. ALIGNMENT USING 2008 COSMIC RAY DATA

September 2008 saw ATLAS take the first cosmic ray data with the Pixel, SCT and TRT fully integrated. At the time of writing, around 300,000 cosmic ray tracks with at least one measurement in the Pixel detector have been collected. Using these tracks as input the Global $\chi^2$ algorithm has been run to determine a set of alignment constants for the Pixel and SCT barrels, progressively increasing the allowed degrees of freedom:

1) Pixel and SCT barrel rigid bodies - 12 DOF.
2) 6 Pixel barrel layer-halfshells and 4 SCT barrel layers - 60 DOF.
3) 112 Pixel barrel ladders and 48 SCT barrel rings - 960 DOF.

Figures 5 and 6 show the $r\phi$ residual distributions that are obtained for one layer in the Pixel barrel and one layer in the SCT barrel respectively (characteristic of the performance in the other layers), where the cosmic tracks are reconstructed with hits in the silicon detectors only. The residual distributions shown here are biased; the track fit includes the hit on the module for which the residual is being calculated. The red curve shows the result of reconstructing with the modules in their nominal positions, whereas the black curve is the result of reconstructing with modules in their aligned positions.

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improvement in the relative alignment of the TRT with respect to the silicon.

An unavoidable limitation of cosmic ray data is that, since they primarily pass vertically through the detector, the illumination of the endcap detector elements is poor. There are insufficient tracks with hits in the endcap to attempt an internal alignment, although enough tracks with hits in both the SCT barrel and endcap have been collected to enable the removal of gross SCT Barrel-Endcap misalignments.

VII. Conclusions and Outlook

Alignment of the modules of the ATLAS Inner Detector to a precision of better than 10 \( \mu m \) is required, and to achieve this goal a number of track-based alignment approaches have been developed. Currently the Global \( \chi^2 \) Algorithm (for the Pixel and SCT) and TRT \( \chi^2 \) Algorithm have been integrated into an automated alignment procedure to run on computer nodes at CERN. This procedure has been extensively tested on Monte Carlo samples simulated with realistic misalignments.

In recent months, the first cosmic ray data taken with the full ID operational have enabled the first attempts to determine the relative alignments of the Pixel, SCT and TRT barrel components, and in addition to perform some internal alignments of the Pixel and SCT barrel layer structures. Increased cosmic statistics may allow for a determination of module-to-module alignments in the Pixel, SCT and TRT barrels, and possibly a determination of the distortions of individual TRT straws within modules. However, in the end cosmic events can only take us so far. LHC beam collision events are needed to provide sufficient illumination of the endcap for alignment, and ultimately to provide the statistical power required to get to micron level alignment precision of individual modules. In addition, until we can examine physics signatures, such as how well we can reconstruct J/Psi and Z boson masses, the actual quality of the alignment, whether, for example, we have avoided a weak mode deformation, remains unknown. The observed improvements in the cosmic residual distributions indicate that the alignment so far has resulted in improved track fits, but this is of course the expected result from a Global \( \chi^2 \) minimization procedure.

References