Alignment of the ATLAS Inner Detector Tracking System

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The position and orientation of the modules of the ATLAS Inner Detector tracking system must be known to $O(10)\mu m$ precision in order to not degrade the tracking performance significantly. Here we briefly describe the track-based approach that is used to determine the ID alignment, and present the results of aligning the Inner Detector using the cosmic ray data collected in the final months of 2008.

Keywords: ATLAS; Inner Detector; Alignment.

1. 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\(^1\) (ID), Electromagnetic Calorimeter, Hadronic Calorimeter and Muon Spectrometer. The ID is the innermost detector subsystem, contained within a 2T solenoidal magnetic field which has field lines parallel to the beamline. The primary role of the ID is to accurately and efficiently reconstruct the helical trajectory of charged particles emerging from the interaction point. Figure 1 shows a 3-D view of the ATLAS ID. Visible are the three subdetectors of the ID; the Pixel detector, Semiconductor Tracker (SCT) and Transition Radiation Tracker (TRT). Table 1 reports the type of each subdetector, the number of modules and their resolutions.\(^1\)

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 modules. 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 longitudinal $z$ (radial $R$) direction in the barrel (endcaps).\(^2\) To perform a precision
Table 1. Components of the ATLAS Inner Detector.

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Pixel</th>
<th>SCT</th>
<th>TRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Layers/Disks</td>
<td>3 ( \times ) 2</td>
<td>4 ( \times ) 2</td>
<td>3 ( \times ) 2</td>
</tr>
<tr>
<td>No. of Modules</td>
<td>1456</td>
<td>2112</td>
<td>96</td>
</tr>
<tr>
<td>Type</td>
<td>silicon pixel</td>
<td>silicon strip</td>
<td>gaseous drift tube</td>
</tr>
<tr>
<td>Resolutions</td>
<td>10( \mu )m ((R\phi))</td>
<td>17( \mu )m ((R\phi))</td>
<td>130( \mu )m</td>
</tr>
<tr>
<td></td>
<td>115( \mu )m ((z/R))</td>
<td>580( \mu )m ((z/R))</td>
<td></td>
</tr>
</tbody>
</table>

measurement, such as the \(W\) boson mass, will likely require alignment to \(O(1)\mu m\) precision. The initial as-built precision of the ID module positions is \(O(100)\mu m\).

2. Track-Based Alignment

The alignment of the ID is specified by a set of alignment constants, six for each individual ID module, corresponding to the six degrees-of-freedom (DoF) of a rigid body. Track-based alignment algorithms use the tracking residuals of the ID modules to determine these constants. A residual is defined as the distance (in the \(R\phi\) or \(z/R\) direction) between the position of the measurement on the module, and the intersection of the fitted track with that module. The global \(\chi^2\) approach determines the alignment constants.
via the minimization of the following $\chi^2$ function:

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

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 measurements to the track fit, $a$. Therefore, by simultaneously minimising this $\chi^2$ with respect to $\pi$ and $a$ the alignment constants can be determined. This approach forms the basis of the algorithms\textsuperscript{3,4} that are used to produce the baseline ID alignment constants at ATLAS.

3. Alignment using 2008 Cosmic Ray Data

Between September 13th and December 1st 2008 the ATLAS ID took cosmic ray data, the first such data where all ID subdetectors were fully integrated. During this period the ID reconstructed $\sim 7.6$ million tracks, 5 million (2.6 million) with the solenoid magnetic field off (on), of which $\sim 230000$ (190000) contained at least one pixel measurement. The cosmic ray tracks produce measurements primarily in the modules in the top and bottom quadrants of the ID barrel, and produce significantly fewer measurements in the endcaps. This data has been used to align the following Pixel and SCT structures in sequence as follows:

(1) Pixel detector, SCT barrel and SCT endcap (24 DoF).
(2) 6 Pixel barrel half-shells, 4 SCT barrel layers, 2 Pixel endcaps and 2 SCT endcaps (84 DoF).
(3) 112 Pixel barrel staves, 176 SCT barrel staves, 2 Pixel endcaps and 2 SCT endcaps (1752 DoF).
(4) Individual Pixel and SCT barrel modules (7136 DoF). Only two degrees-of-freedom are used in this alignment: translations in the sensitive $R\phi$ direction and rotation in the module plane.

Figure 2 shows the improvement in the residual distribution for Pixel and SCT barrel modules after the alignment sequence: the distribution is centred on zero, with a width that is approaching that observed in a cosmic ray simulation using perfect ID alignment. One can gain an insight into the impact of the alignment on tracking resolutions by splitting reconstructed cosmic ray tracks in half, independently refitting the two halves, and then comparing the track parameters of the resulting upper and lower cosmic
Fig. 2. Pixel (a) and SCT (b) barrel residual distributions in the sensitive $R\phi$ direction.

Fig. 3. Difference in impact parameter (a) and azimuthal angle (b) between the upper and lower cosmic ray half-tracks fitted using measurements in the Pixel detector and SCT only.

Ray half-tracks. Figure 3 shows the distribution of the difference in the reconstructed impact parameter and azimuthal angle for the upper and lower half-tracks fitted using measurements in the Pixel and SCT modules only, and which are required to have $p_T > 2$ GeV and to intersect the innermost Pixel layer. The performance is approaching that obtained using a perfectly aligned cosmic ray simulation.

The 2008 cosmic ray data has also been used to perform a TRT barrel alignment. The TRT barrel is first aligned with respect to the Pixel detector and SCT using 5 DoF (excluding translations in $z$), and subsequently an
internal alignment of the TRT barrel modules is performed (again using only 5 DoF). Figure 4(a) shows the improvement in the matching of cosmic ray half-tracks after the relative alignment of the TRT with respect to the SCT. Figure 4(b) shows the improvement in the residual distribution for TRT barrel modules after the full TRT alignment.

4. Summary and Conclusions

Cosmic ray tracks collected in the final months of 2008 have been used to align the ATLAS Pixel, SCT and TRT subdetectors, determining both the relative alignment of these subdetectors and, in the case of the barrel, the alignment of individual modules. This is the first time a coherent alignment of these subdetectors has been attempted post-installation in the ATLAS cavern, and the results presented here demonstrate that this alignment has achieved considerable success.

References