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# Advanced alignment of the ATLAS tracking system

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**Abstract**

In order to reconstruct the trajectories of charged particles, the ATLAS experiment exploits a tracking system built using different technologies, silicon pixel modules or microstrips and gaseous drift tubes, all embedded in a 2T axial magnetic field. Misalignments of the active detector elements and deformations of the structures (which can lead to *Weak Modes*) deteriorate resolution of the track reconstruction and lead to systematic biases on the measured track parameters. The applied alignment procedures exploit various advanced techniques in order to minimise track-hit residuals and remove detector deformations. For the LHC Run II, the Pixel detector has been refurbished and upgraded with the installation of a new pixel layer, the Insertable B-layer.

*Keywords:* ATLAS Inner Detector, Alignment, IBL

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## 1. Introduction

The ATLAS detector [1] is a general purpose experiment at CERN's Large Hadron Collider, performing highly precise measurements of Standard Model processes and searches for new physics phenomena. The ATLAS detector is equipped with a central tracking system, the Inner Detector (ID), in order to reconstruct the trajectories of charged particles and to estimate their kinematic parameters. The accuracy of this process is limited by the finite resolution of the sensitive devices, therefore misalignments of the active detector elements as well as geometrical distortions, lead to a deterioration of the resolution on reconstructed tracks and biases in the measured parameters. The ID has been aligned using a track-based technique [2] allowing the alignment of all tracking subsystems together. However any generic track-based alignment is exposed to a class of deformations, the so called weak-modes, against which this procedure has very low or no sensitivity. A number of updates have been applied to the ID alignment to correct for weak modes deformations. The alignment framework has also been updated to account for the presence of the new pixel detector, the Insertable B-layer (IBL) and has been tested on new Monte Carlo simulations for recovering a simple misalignment.

## 2. ATLAS Inner Detector

The ATLAS Inner Detector consists of three sub detectors, the Pixel detector , the Semiconductor Tracker (SCT) and Transition Radiation Tracker (TRT), all embedded in a 2T axial magnetic field and designed to track charged particles within a pseudo rapidity range $|\eta| < 2.5$. The Pixel detector consists of 1744 silicon pixel modules arranged in three barrel layers and two end caps with three disks each. The expected hit resolution is 10 $\mu$m in the $r-\phi$ [1] (local $x$ direction) and 115 $\mu$m in $z$ (local $y$ direction). Each module is alignable in all six degrees of freedom (DoF), leading to a total of 10464 alignment parameters. The SCT consists of 4088 silicon strip modules, arranged in four barrel layers and two end caps with nine wheels. The intrinsic resolution is $\sim 17$ $\mu$m and $\sim 580$ $\mu$m in $r-\phi$ and $z$ respectively. Each module is alignable in all its 6 DoF. The TRT is the outermost of the ID sub-detectors and is

[1] The resolution in $r-\phi$ is improved to $\sim 5$ $\mu$m using neural network clustering [4]

made of 350848 gas-filled straw tubes with a single hit resolution of $\sim 130\,\mu$m along $r-\phi$. Each TRT straw is aligned with 2 DoF. For Run II, the IBL has been added as a fourth layer to the Pixel detector, reducing the distance from the interaction point to 3.27 cm. The IBL consists of a cylindrical layer formed by 14 staves, each one formed of 12 two-chip planar modules covering the region of $|\eta| < 2$ and 4 single 3D chips located at both ends. The expected hit resolution is $\sim 8\,\mu$m in $r-\phi$ and $\sim 40\,\mu$m in $z$ [3].

## 3. Alignment Procedure

The ATLAS physics goals require high resolution and unbiased measurements of all charged particle kinematic parameters. This translates into the requirements of reducing the degradation of the track parameters due to misalignment of the active modules to less than 20% of the intrinsic tracker resolution. The alignment of the ID is performed using a track-based technique, which minimises the track-to-hit residuals, and obtains the corrections to the module positions in order to describe accurately the real geometry of the detector. The offline alignment algorithms construct a $\chi^2$:

$$\chi^2 = \sum_{trk} \left[ \mathbf{r}^T(\tau, \mathbf{a}) V^{-1} \mathbf{r}(\tau, \mathbf{a}) \right] \quad (1)$$

where $V$ is the covariance matrix of the detector measurements, $\mathbf{r}$ are the track-to-hits residuals depending on the alignment parameters $\mathbf{a}$ and the track parameters $\tau = (d_0, z_0, \theta, \phi_0, q/p)$. The angle $\phi_0$ is the azimuthal angle of the track at the perigee, $d_0$ and $z_0$ are respectively the transverse and longitudinal impact parameters, $\theta$ is the polar angle and $q/p$ is the ratio of the track charge over its momentum. Then a minimisation is performed:

$$\frac{d\chi^2}{d\mathbf{a}} = 0 \rightarrow \sum_{trk} \left[ \mathbf{r}^T V^{-1} \left( \frac{\partial \mathbf{r}}{\partial \tau} \frac{d\tau}{d\mathbf{a}} + \frac{\partial \mathbf{r}}{\partial \mathbf{a}} \right) \right] = 0 \quad (2)$$

In order to cope with a large number of degrees of freedom, the ID alignment is performed in three hierarchical *Levels*: at *Level 1* seven physical structures are aligned, the Pixel as a whole, the SCT barrel and the two end caps, the TRT barrel and, finally, the two TRT end caps. The *Level 2* treats the silicon barrel layers and end cap disks and TRT barrel modules and end caps wheels as separate objects. The *Level 3* aligns all the silicon modules and the individual wires of the TRT. For different alignment levels, some DoFs are fixed during the procedure.

## 4. Run1 Alignment Results

During the 2012 alignment campaign [5] Level 1 alignment constant were determined on per-run basis in

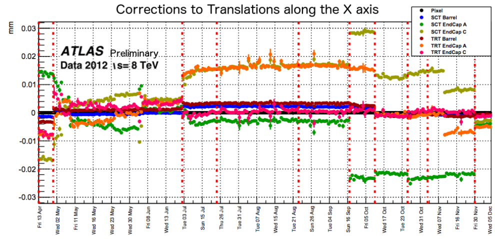


Figure 1: Level 1 translations corrections in the global x direction versus data acquisition time

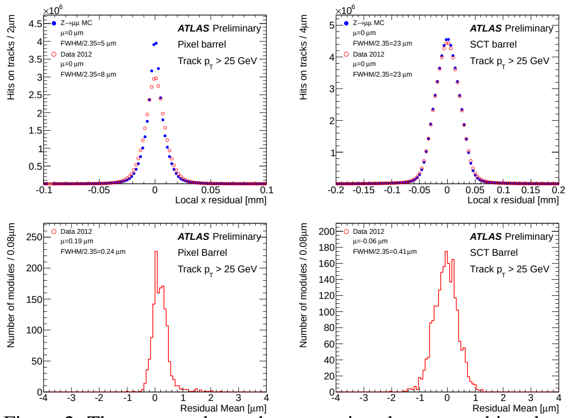


Figure 2: The top row shows the comparison between unbiased residuals of perfectly aligned MC and Level 3 realigned data in the Pixel and SCT barrel. The bottom row shows the distribution of the mean of the residual distributions for each barrel silicon module.

order to account for sizeable movements of large detector structures due to environmental changes (cooling failures, changes in magnetic field) as it is shown in Fig. 1.

The minimisation of the track-to-hit residuals is the cornerstone of the track-based alignment. Consequently, a measure of the performance of the alignment procedure is given by the comparison between residuals in data to those of perfectly aligned Monte Carlo simulation. For this purpose, all hits from each detector module are removed from the track fit prior to constructing the residuals for the module under test. Residuals defined this way are referred as unbiased. Fig. 2 shows that the silicon modules have been aligned at $\mu$m level.

A $\chi^2$ alignment cannot correct for all possible detector misalignments due to the presence of weak modes, but track parameter biases can be corrected by using external information. Orthogonal displacements of the reconstructed hits in the detector result in a shift of the measured transverse momentum according to

$$p_T \rightarrow p_T(1 + q p_T \delta_{sagitta})^{-1} \quad (3)$$

where $\delta_{sagitta}$ is an universal bias parameter for all measured momenta.

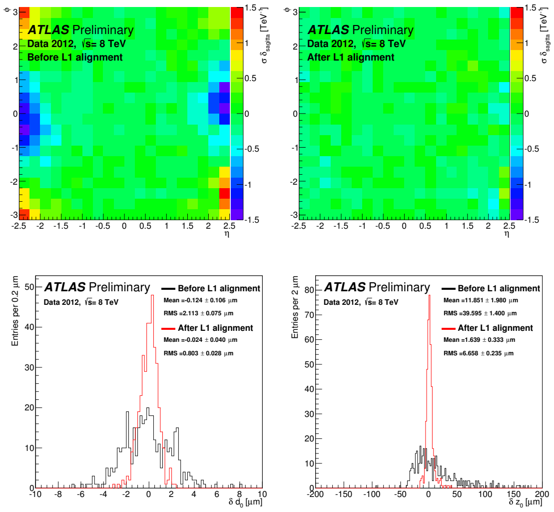


Figure 3: Top: Momentum bias before and after the constrained alignment using the $Z \to \mu\mu$ method. Bottom: Transverse and longitudinal track impact parameters bias before and after alignment

Fig. 3 shows how the sagitta bias is corrected using the reconstructed $Z$ mass in $Z \to \mu^+\mu^-$ decays, together with the reduction of the transverse ($\delta_{d_0}$) and longitudinal ($\delta_{z_0}$) track impact parameters biases, defined as the difference between the impact parameters of muon tracks originating from a $Z$ boson decay.

## 5. Integration of the IBL in the alignment framework

In preparation for Run II, the alignment framework has been extensively updated in order to cope with the integration of the new IBL sub detector in the ID tracking system. The first alignment test considers the IBL as an independent structure integrated into the Pixel detector. The first alignment test with the IBL inserted in the newest ATLAS simulated geometry has been performed using a Multi Muon Monte Carlo simulated sample. Each event is composed of muons with fixed $p_T$ of [5,15,50,100] GeV and $|\eta| < 2.5$. In order to fake a realistic initial misalignment of the ID structure, a simulated misaligned geometry has been generated assuming a shift of the IBL with respect to the nominal position of 20 $\mu$m along $x$ and $y$ directions and 200 $\mu$m parallel to the beam axis, along $z$ direction. The Multi Muon generated sample has been reconstructed both with perfect and misaligned geometry. A new alignment procedure *Level* has been defined: *Level 11* is composed by seven alignable structures, the IBL detector, the Pixel detector as a whole, two SCT end caps, the TRT barrel and, finally, the two TRT encaps. Inner Detector Alignment has been applied in this configuration keeping the SCT barrel fixed as reference in order to remove global translations of the detector that would lead to weak modes.

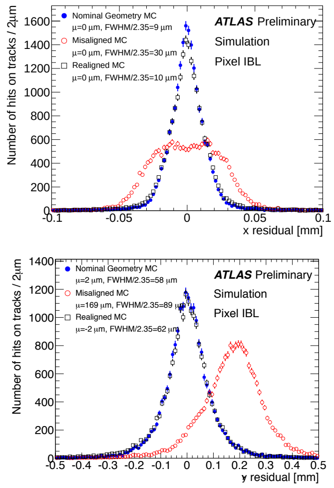


Figure 4: In blue circles the residuals for the perfectly aligned MC sample compared with the misaligned (red circles) and the realigned (white squares) samples.

In Fig. 4 the comparison between the realigned, misaligned and perfect geometry reconstructed samples is shown. The results show that the alignment framework is able to recover, after few iterations, the misalignment introduced and improve substantially the resolution of the reconstructed tracks.

## 6. Conclusions

The 2012 alignment campaign resulted in development of advanced techniques resulting in improved tracking resolution and reduction of track parameter biases. The physical movements of the ID tracking system have been tracked down run by run and understood during 2012 data taking, preventing degradation of reconstructed track parameters. The alignment framework has been successfully updated to include the newly installed IBL layer.

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