Novel methods in track-based alignment to correct for time-dependent distortions of the ATLAS Inner Detector

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Abstract. ATLAS is a multipurpose experiment at the LHC proton-proton collider. Its physics goals require high resolution and unbiased measurement of all charged particle kinematic parameters. These critically depend on the layout and performance of the tracking system and the quality of its alignment. For the LHC Run-II, the system has been upgraded with the installation of a new pixel layer, the Insertable B-layer (IBL). The offline track alignment of the ATLAS tracking system has to deal with about 700,000 degrees of freedom defining its geometrical parameters, representing a considerable numerical challenge in terms of both CPU time and precision. An outline of the track based alignment approach and its implementation within the ATLAS software is presented. Special attention is paid to describe the techniques allowing to pinpoint and eliminate track parameter biases. During Run-II, the ATLAS Inner Detector Alignment framework has been adapted and upgraded to correct very short time scale movements of the sub-detectors. In particular, a mechanical distortion of the IBL staves up to 20 $\mu$m has been observed during data-taking. The techniques used to correct for this effect and to match the required Inner Detector performance are presented.

1. Introduction

The ATLAS detector \cite{1} is a general purpose detector located at the Large Hadron Collider (LHC) at CERN. The first proton-proton collisions registered at the LHC took place in 2009 at a center of mass energy of 900 GeV. In 2010, the center of mass energy was set to 7 TeV and raised to 8 TeV in the final campaign of Run-I. A long shutdown stop (LS1) took place before Run-II started to raise the center of mass energy to 13 TeV and thus beating all the records. During this stop ATLAS upgraded the pixel detectors, adding the Insertable B-Layer (IBL), and thus becoming the closest detector to the beampipe.

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 degradation of the resolution on reconstructed tracks and may lead to biases in the measured parameters.

Alignment is concerned with determining the actual geometry of the tracking system and its eventual changes in time. The aim is to compute the alignment parameters that result in
the best description of all active detector modules. To do so, the ID has been aligned using a track-based technique [2], however any generic track-based alignment is exposed to a class of geometry deformations, the so called weak-modes, against which this procedure has very low or no sensitivity.

2. ATLAS Inner Detector
The ATLAS Inner Detector consists of three subdetectors, the Pixel detector (including the IBL), the Semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT), where all are embedded in a 2 T axial magnetic field. The ID has been designed to reconstruct the charged particles trajectories within a pseudorapidity range of $|\eta| < 2.5$ (see Figure 1 for a schematic view of the barrel region). 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 µm in $r\phi$ coordinates and 115 µm in the longitudinal coordinate. During LS1, the IBL was added as an additional layer to the Pixel detector, reducing the distance from the interaction point to the first tracking layer, as IBL is placed at 33.25 mm radius while the inner layer of the rest of the Pixel is placed at 50.5 mm, becoming the nearest sub-detector to the beampipe. The IBL is composed of 280 modules, mixing planar and 3D technology. The expected hit resolution is 8 µm in $r\phi$ coordinates and 40 µm in the longitudinal coordinate [3]. The SCT consists of 4088 silicon strip modules, arranged in four barrel layers and two end caps with nine wheels each. The intrinsic resolution is 17 µm in $r\phi$ coordinates and 580 µm in the longitudinal coordinate. The TRT is the outermost detector of the ID subdetectors and is made of 350848 straw tubes filled with Argon gas with a single hit resolution of 130 µm along $r\phi$.

![Figure 1](image.png)

Figure 1. Schematic view of the ID barrel. The ID barrel is arranged in sub-detector layers. From innermost to outermost sub-detectors: IBL, Pixels, SCT and TRT.

3. Alignment procedure
The alignment procedure is based on the minimisation of the track-to-hit residuals for each module. Every sensor or mechanical assembly part is then considered as an alignable structure, which is treated as a rigid body with six degrees of freedom (DoF) that uniquely define its position and orientation in space. These six DoF are three translations $(T_x, T_y, T_z)$ of the centre
of the object and three rotations \((R_x, R_y, R_z)\) around the Cartesian axes and will be referred to as the alignment parameters. Residuals are defined as the distance between the hit position as measured by the sensor and as computed in the track extrapolation. The minimisation of the \(\chi^2\) function, which is referred in equation (1), is used to find the alignment parameters that correct the module positions in order to describe accurately the real geometry of the detector:

\[
\chi^2 = \sum_{\text{tracks}} \sum_{\text{hits}} \left( \frac{\vec{r}_h(\pi, a)}{\sigma_h} \right)^2 = \sum_{\text{tracks}} \vec{r}(\pi, a)^T V^{-1} \vec{r}(\pi, a)
\]

where \(V\) is the covariance matrix of the detector measurements, \(r\) are the track-to-hit residuals depending on the alignment parameters, \(a\) the alignment parameters and \(\pi\) the track parameters.

One of the big successes of the alignment procedure is that it is performed in hierarchical levels starting from the biggest structure and finishing at the module level, mimicking the mechanical assembly. Starting with the largest physical structures at level 1, the detector subsystems are aligned separating the whole detector into end-caps and barrel regions in order to correct for collective movements. Level 2 treats individual barrel layers and end-cap disks as physical structures (barrel modules and end-cap wheels in case of the TRT). Level 3 corresponds to a silicon module and TRT wire level alignment. The levels are addressed consecutively during the alignment procedure. Table 1 shows the number of DoFs for each detector and level of alignment.

**Table 1.** Number of DoFs by detector and level of alignment. Assembly structures and silicon modules use 6 DoF. TRT wires use just 2 DoF.

| Levels          | Structures | DoFs  |
|-----------------|------------|-------|
| L1 (large structure) | 8          | 48    |
| L2 (Si layers/disks, TRT modules and wheels) | 208        | 792   |
| L3 (Si modules)   | 6112       | 36672 |
| L3 (TRT wires)    | 350848     | 701696|

**4. Time-dependent deformations**

During the LHC Run-I data taking campaign, the ATLAS Inner Detector was found to be stable for long periods of time, except for some "seismic" events (magnet ramp, power-cut, cooling failure,...), as Figure 2 shows.

However, in Run-II some sub-detectors have shown time-dependent deformations or movements, even within a single run, which required to introduce a new dynamic alignment scheme. Currently, two movements are known:

- Vertical movements of pixel sub-detector at the beginning of each run.
- IBL mechanical instabilities with temperature.

**4.1. Pixel movements**

Vertical movements of the pixel detector at the beginning of each run are registered due to change in the mass of the cooling liquid after the detector is switched on until an equilibrium between vapor and liquid is reached. Previously in Run-I no correction was applied, because only a small fraction of data was affected. During Run-II, an additional slow drift has also been observed. It takes places during all the run, in the opposite direction to the initial movement. The velocity
of this slow drift depends on the peak luminosity of LHC, which was increased during 2016. Figure 3 shows that Pixel quickly lifts 6 $\mu$m during the first hour of the run, followed by a gentle descent afterwards. A new dynamic alignment procedure was introduced in August 2016 which corrects for both these effects using time-dependent alignment. This required the introduction of an improved alignment database, in which the ID geometry database was restructured. Prompt alignment updates are computed currently within a run in 20-minute intervals and are running automatically inside the calibration loop process (updated within 24 hours after run is finished).

Figure 3. Correction in the Y vertical direction for the inner detector components as a function of time. Bands indicate statistical uncertainty. End-caps on the positive and negative side of the detector are shown separately. SCT barrel is kept fixed as a reference during the derivation of the alignment constants. While good stability was observed for all ID components in the X direction, the figure shows a fast movement of 6 $\mu$m for the Pixel sub-detector in the Y direction.

4.2. IBL mechanical instabilities
During collision data taking, the IBL staves were seen to bow even within a run. This was caused by an increased power consumption of the modules induced by irradiation, due to total ionization dose effect. Figure 4 (left) shows that the IBL staves bend depending on the different operating temperature conditions, while Figure 4 (right) shows that distortion magnitude changes in the same run, since the distortion varies with the integrated radiation dose and as a function of the LHC luminosity within a fill.
Figure 4. Left figure shows IBL local-X correction in the transverse plane averaged over all 14 IBL staves for 2015 data (red open squares), and for 2016 data using different temperature (+15, solid blue circles; +5, solid green triangles). No error bars associated with data are shown. Lines are presented just to highlight that trend. Right figure shows the relative bowing magnitude of the IBL staves, averaged over its 14 staves and computed with the default alignment (blue dots) and with respect to the aligned geometry (red open circles). The IBL operation temperature ($T_{set}$) for each period is also shown.

5. Run-II alignment results

The alignment performance is checked by evaluating the track-to-hit residuals. A comparison between residuals in data to those of perfectly aligned Monte Carlo simulation is also crucial. Figure 5 shows that the modules have been aligned at $\mathcal{O}(\mu m)$ level in both final 2016 data and initial 2017 data.
Nevertheless, track-based alignment is blind to deformations that preserves the helicoidal paths of the tracks. Additional constraints, such as beam spot, mass resonances \((Z, J/\psi, K_s)\) or external detector constraints \((E/p)\), are needed to detect and correct such deformations or weak modes. Orthogonal displacements of the reconstructed hits in the detector affect the measured momentum and the measured impact parameter (the distance of closest approach to the primary vertex) according to:

\[
p_{\text{reco}}^T = p_{\text{true}}^T \left( 1 + q p_{\text{true}}^T \delta_{\text{sagitta}} \right)^{-1}
\]

where \(\delta_{\text{sagitta}}\) is a universal bias parameter for all measured momenta.

Figure 6. Prompt (left) and reprocessed (right) biases maps for the sagitta and impact parameters. For the reprocessed alignment the complete 30.4 fb\(^{-1}\) of proton-proton data taken after Technical Stop 1 are used, while for the prompt alignment only 20.3 fb\(^{-1}\) of data are used. Significant improvements in average biases are seen after the reprocessing with the updated alignment.

Momentum biases can be monitored using \(Z \rightarrow \mu^+\mu^-\) events and an independent method based on electrons from \(E/p\). While \(Z \rightarrow \mu^+\mu^-\) events have been used to derive corrections for the impact parameters (i.e. \(d_0\) and \(z_0\)) and sagitta biases, the \(E/p\) method is used as a cross-check for the sagitta biases, following the methods described in Ref. [4].
The first Inner Detector (ID) alignment constants for 2017 data-taking were derived using 82 pb$^{-1}$ of proton-proton collision data delivered by the LHC in June 2017. The alignment was performed in several steps, considering different sub-detectors at increasing levels of detail, as explained in Section 3.

Figure 6 (left) shows weak modes maps using prompt alignment corrections (alignment constants derived shortly after the run has finished) and Figure 6 (right) shows corrections using reprocessed alignment (whose constants were derived after applying weak modes constraints and realigned). A clear improvement is observed for the sagitta and the impact parameters (i.e. $d_0$ and $z_0$) using reprocessed data.

6. Conclusions
The Inner Detector alignment framework has been successfully upgraded to cope with time-dependent deformations observed in Run-II. New techniques have been introduced to correct for IBL and Pixel rapid movements. In spite of the very challenging conditions, the alignment has been able to reach very precise results in a fully automatized process. Weak modes misalignments were identified and corrected for 2016 data. Initial 2017 data residuals look excellent already, being among the best that ATLAS recorded.

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