Novel time-dependent alignment of the ATLAS Inner Detector in the LHC Run 2

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ABSTRACT: ATLAS is a multipurpose experiment at the LHC proton-proton collider. Its physics goals require an unbiased and high resolution measurement of the charged particle kinematic parameters. These critically depend on the layout and performance of the tracking system and the quality of the alignment of its components. For the LHC Run 2, the system has been upgraded with the installation of a new pixel layer, the Insertable B-layer (IBL). 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 μm and a vertical displacement of the Pixel detector of $\sim 6 \mu\text{m}$ have been observed during data-taking. The techniques used to correct for these effects and to match the required Inner Detector performance will be presented.

KEYWORDS: Alignment; IBL; Bowing; Pixel; Tracking; ATLAS.

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1. Introduction

The Inner Detector (ID) of the ATLAS experiment [1] comprises its tracking system, used for the reconstruction of the charged particles trajectories. The accuracy of the trajectory reconstruction is determined by the intrinsic precision of the detector elements, the amount of material in the detector and the precision of the alignment of the detector elements. Misalignments of the detector modules can lead to systematic biases in the measured trajectories and to a degraded resolution of the measured track parameters. A precise alignment of the Inner Detector is therefore essential. The Inner Detector is composed of IBL, Pixel, SCT and TRT subdetectors.

Unlike in the LHC Run 1, in which the Inner Detector was relatively stable for long periods of time, during Run 2, some subdetectors of the Inner Detector have undergone time-dependent deformations or movements that required to introduce a new dynamic alignment scheme. The Inner Detector alignment corrections are updated promptly after the data is collected using a new fully automated system.

2. Calculation of the alignment corrections

Track based alignment algorithms rely on track-hit residual minimization [2, 3]. Residuals are defined as the distance between the measured hit location and its extrapolated position in the reconstructed track. The residuals χ^2 function and its minimization condition are built as follows:

$$\chi^2 = \sum_{\text{Tracks}} |\mathbf{r}(\mathbf{a}, \boldsymbol{\tau})|^T \mathbf{V}^{-1} |\mathbf{r}(\mathbf{a}, \boldsymbol{\tau})| \quad ; \quad \frac{d\chi^2}{d\mathbf{a}} = 0$$

where $\mathbf{r}(\mathbf{a}, \boldsymbol{\tau})$ is the vector of track-to-hit-distance, $\boldsymbol{\tau}$ are the track parameters, $\mathbf{a}$ are the alignment parameters or degrees of freedom (DOF) and $\mathbf{V}$ is the covariance matrix of the detector measurements. Alignment corrections are obtained from the minimization set of equations. Figure 1 shows how the position of misaligned module is updated by minimizing the residuals.

The alignment correction is derived iteratively by increasing detector elements granularity, following the structure of the ID. Starting with the largest physical structures (level 1), the

detector subsystems are aligned separating 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. Level 3 corresponds to individual modules alignment. The levels are addressed iteratively and consecutively during the alignment procedure.

Figure 1. Alignment procedure based on residuals χ^2 function minimization. On the left, the central module position is wrongly determined, biasing its hits and the reconstructed track parameters. On the right, the misalignment is detected by minimizing the residual distributions and the position of the detector is updated.

3. IBL bowing

3.1 Temperature-dependent IBL distortion

During the commissioning phase with cosmic data in 2015, the IBL staves were found to bow in plane depending on their temperature [4]. In order to study the temperature correlation to the size of the IBL distortion, during March 2015, commissioning cosmic-ray runs were collected with different set points temperatures of the IBL. Those changed from -20 to +15 °C. Figure 2 (left) shows the x-residual mean along the staves at each temperature point. Figure 2 (right) is a visualization of the distorted stove with magnified distortion size. In order to describe and correct the bowing distortion of the IBL, a new DOF was introduced.

Figure 2. Left plot shows the track-to-hit residual mean in the local-x direction. The residual mean is averaged over all hits of modules at the same global-z position and they are calculated with respect alignment corrections derived with data at -20°C. Right plot shows a 3D Finite Elements Analysis simulation of the distorted IBL. Its size is magnified for visualization. [4]

3.2 Time-dependent IBL distortion

During collisions data taking, the staves were seen to bow even within a run. This was caused by an increased power consumption of the modules induced by irradiation, known as *total ionization dose effect* [5]. The distortion varies with the integrated radiation dose and as a function of the LHC luminosity within a fill. Figure 3 (left) shows how the IBL distortion

magnitude changes within a run and that it can be corrected by the alignment. A time-dependent alignment correction was introduced and now it is automatically calculated for each run immediately after the data taking [6, 7] at the calibration loop. The new procedure completely mitigates the impact on the track parameter resolution. The impact of the IBL distortion on the x-residuals and the improvement achieved with time-dependent alignment corrections is shown in Figure 3 (right).

Figure 3. Left plot shows the IBL distortion magnitude in the transverse plane per luminosity block range for three different alignment corrections: Without bowing correction (blue), with a fill-averaged correction (red) and with additional time dependent alignment correction (black). The IBL local x unbiased residual distributions for the same three collections are shown at right plot. [7]

4. Pixel Drift

During Run 1, the Pixel detector was observed to rapidly move vertically a few microns at the start of each run before stabilising. This effect is attributed to the change of mass of the cooling fluid in the detector caused by increased cooling required after enabling the sensor preamplifiers.

A slow movement in the opposite direction to the initial one has become significant in 2016 data. Both movements can be seen in Figure 4: Pixel fastly lifts $\sim 6 \mu\text{m}$ during the first hour of the run, followed with a gentle descend afterwards. Figure 5 shows that the movement speed is correlated to the peak luminosity of the fill [8]. The alignment software infrastructure has been updated to correct for this movements and has been deployed in the automatic calibration of the data since mid September 2016. The ID geometry database has been restructured in increasing levels of complexity, resembling the alignment levels, in order to allow more frequent updates.

Figure 4. Correction in the horizontal (left) and vertical (right) direction for the inner detector components as a function of time. Corrections are relative to SCT position, that was fixed as reference. For first ~ 60 minutes of collisions, the ID is aligned each ~ 20 minutes. Later on, the frequency of the alignment is decreased to once each ~ 2 hours. [8]

Figure 5. Vertical speed of the Pixel package as a function of the peak luminosity of the fill extract from the alignment corrections. The vertical speed is determined as the average speed of the Pixel package excluding the first one hour after the start of the data taking. [8]

5. Summary and Conclusions

The Inner Detector alignment framework has been successfully upgraded to cope with Run 2 requirements. A new developed time-dependent scheme has been implemented to correct for IBL and Pixel rapid movements. A fully automatized process aligns and updates the geometry database just after the recording of a new run stops. This has allowed us to achieve alignment of the same quality as in 2015 despite the more challenging operating conditions.

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