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Alignment of the ATLAS Inner Detector in the LHC Run 2

LAURA BARRANCO NAVARRO

Instituto de Físca Corpuscular, Universitat de València and CSIC, Valencia, Spain

laura.barranco.navarro@cern.ch

On behalf of the ATLAS Collaboration

Abstract. ATLAS physics goals require excellent resolution and unbiased measurement of all charged particle kinematic parameters. These critically depend on the layout and performance of the tracking system and on the quality of its offline alignment. ATLAS is equipped with a tracking system built using different technologies, silicon planar sensors (pixel and micro-strip) and gaseous drift- tubes, all embedded in a 2 T solenoidal magnetic field. For the Run 2 of the LHC, the system was upgraded with the installation of a new pixel layer, the Insertable B-layer (IBL). An outline of the track based alignment approach and its implementation within the ATLAS software will be presented. Special attention will be paid to integration of the IBL into the alignment framework, techniques allowing to identify and eliminate tracking systematics as well as strategies to deal with time-dependent alignment. Performance from the commissioning of cosmic data and potentially early LHC Run 2 proton-proton collisions will be discussed.

INTRODUCTION

Between the Run 1 and the Run 2 of the LHC a long technical stop, known as the Long Shutdown I (LS1), took place. During this LS1 several maintenance works were performed in the ATLAS [1] Inner Detector (ID) [2], together with the installation of new detectors such as the new Insertable B-Layer (IBL) [3]. To deal with these new features, the ID software has been updated.

In order to get the detector ready for the stable beams, alignment has become a major task during the cosmic ray data taking and first 13 TeV collisions, since there were expected large inicial misalignments due the maintenance works performed in the ID and the instalation of the IBL, a new pixel layer attached to the beam pipe.

ATLAS Inner Detector

The ATLAS Inner Detector consists of three subdetectors, the Pixel detector which includes the IBL, the Semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT), all embedded in a superconducting solenoid which produces a 2 T axial magnetic field. Figure 1 shows a schematic representation of the barrel region. The ID has been designed to reconstruct the trajectories of the charged particles within a pseudorapidity range of $|\eta| < 2.5$. 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 μm in $r-\phi$ coordinates and 115 μm in z 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. The IBL is composed of 280 modules, mixing planar and 3D technology, arranged in 14 azimuthal carbon fiber staves and it is placed at 3.3 cm radius. The expected hit resolution is 8 μm in $r-\phi$ and 40 μm in z. In order to simplify the notation throughout the remainder of the text, the term Pixel will be used to refer only to the three outer Pixel layers and the end cap Pixel disks and IBL to the new layer. 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 and 580 μm in $r-\phi$ and z, respectively. The TRT is the outermost detector of the ID subdetectors and is made of 350848 Argon-filled straw tubes with a single hit resolution of 130 μm along $r-\phi$.

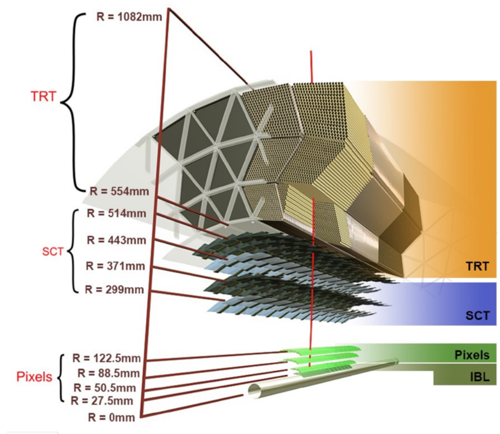

FIGURE 1. A 3D visualisation of the structure of the barrel of the ID. The beam pipe, the IBL, the three Pixel layers, the four cylindrical layers of the SCT and the 72 straw layers of the TRT are shown. System span from 27.5 mm to 1082 mm

Alignment Procedure

The alignment of the ATLAS Inner Detector is performed using a track-based technique [4][5], which minimises the track-to-hit residuals via the following χ^2:

$$\chi^2 = \sum_{tracks} [\mathbf{r}(\mathbf{a}, \boldsymbol{\tau})]^T \, \mathbf{V}^{-1} \, [\mathbf{r}(\mathbf{a}, \boldsymbol{\tau})] \,, \tag{1}$$

where $\mathbf{r}(\mathbf{a}, \boldsymbol{\tau})$ are the track-to-hit residuals, $\boldsymbol{\tau}$ the track parameters, $\mathbf{a}$ the alignment parameters (degrees of freedom, DOF) and $\mathbf{V}$ the covariance matrix of the detector measurements. Each module or sub-detector can be treated as an alignable structure. Each structure has six DOF corresponding to thethree translations (T_x, T_y and T_z) ant three rotations rotations (R_x, R_y and R_z) that define its position and orientation in space. The translations are measured with respect to the origin of the reference frame while the rotations are defined around the cartesian axes. Two types of reference frame are defined. The ATLAS reference frame is a right-handed Cartesian coordinate system, where the origin is at the nominal proton-proton interaction point, corresponding to the centre of the detector. The reference frame describing the position and orientation of individual detector modules of the ID is a right-handed reference frame with the origin in the geometrical centre of each device. Figure 2 shows a schematic view of how the position of misaligned module is updated by minimizing the χ^2 function.

The alignment procedure is split into three levels, in order to cope with the large number of alignable DoFs and to mimic the detector assembly structures. In this way, at level 1 the detector subsystems are aligned separating into endcaps 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. A new L11 has been defined to align IBL indepently from the old pixel.

TABLE 1. Number of DOFs by detector and level of alignment

Levels	IBL	Pixel	SCT	TRT
L1 (structure)	6	6	18	17
L2 (layer/disk)	6	54	132	960
L3 (module)	1680	10464	25528	701696

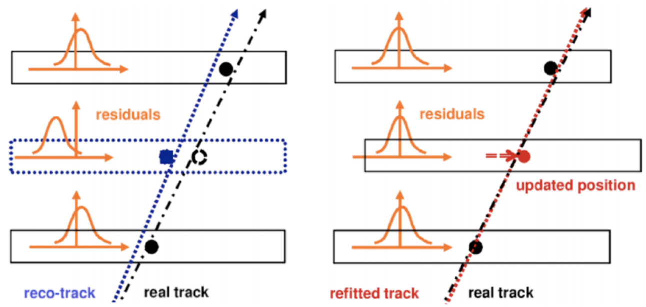

FIGURE 2. Alignment procedure based on residuals χ^2 function minimization. On the left, the central module position is wrongly determined, thus biasing the reconstructed track parameters. On the right, the misalignment is detected by minimizing the residual distributions and the position of the detector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

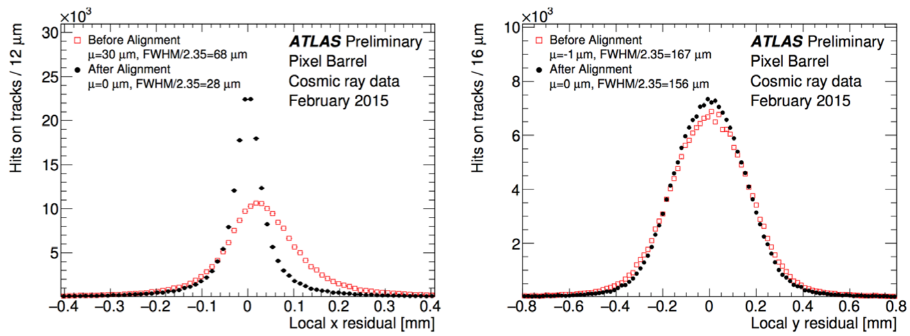

FIGURE 3. The Pixel local x (left) and local y (right) residual distribution for the cosmic-ray data sample reconstructed before (red) and after (black) alignment. The distributions are integrated over all hits associated to tracks (hits-on-tracks) in the barrel modules of Pixel layers one, two and three. Taken from Ref. [6]

Cosmic Ray Data Campaign

Data recorded by ATLAS during the 2014 and 2015 cosmic-ray campaigns were used to perform a first alignment of the ID after the LS1 and to test the performance of the new IBL detector. Results shown here were obtained using 1.1 M events recorded during February 2015. These data include $3x10^5$ ID tracks, which are used for alignment. The data were taken in a configuration with the toroid field off and solenoid field on. After the track selection requirements, 50000 tracks were used in alignment. More details about the track selection and the obtained results can be found elsewhere [6].

During LS1, the Pixel detector was removed from ATLAS for the performance of maintenance and put back in place with a precision from the survey of $100\,\mu$m. The IBL was installed during LS1 for the first time, so there was no previous experience from Run 1. The SCT and TRT barrels were not moved during LS1, so they were expected to occupy the same position as at the end of Run 1. Thus, the alignment was focused on the Pixel and the IBL. They were both aligned up to module level alignment (level 3). The SCT barrel was aligned up to level 2 and the TRT was fixed as a reference point. Figure 3 shows the improvement achieved by the alignment on local x (left) and local y (right) residual distributions for the Pixel. A bias of $30(-1)\,\mu$m in the Pixel barrel local x (local y) direction has been corrected while the width of the distribution has been reduced from $68(167)\,\mu$m to $28(156)\,\mu$m in x (y).

To test the goodness of the alignment the half-track method is used. Since cosmic tracks traverse the whole detector, they are divided into upper and lower parts, and each part is reconstructed independently as shown in Fig. 4 (left). The perigee parameters τ_{up} and τ_{down} of each half track pair are compared to each other and their difference, $\Delta(\tau_{up} - \tau_{down})$, is compared before and after the alignment. The resolution of a track parameter is obtained by the width of the distribution of $\Delta(\tau_{up} - \tau_{down})$ divided by $\sqrt{2}$.

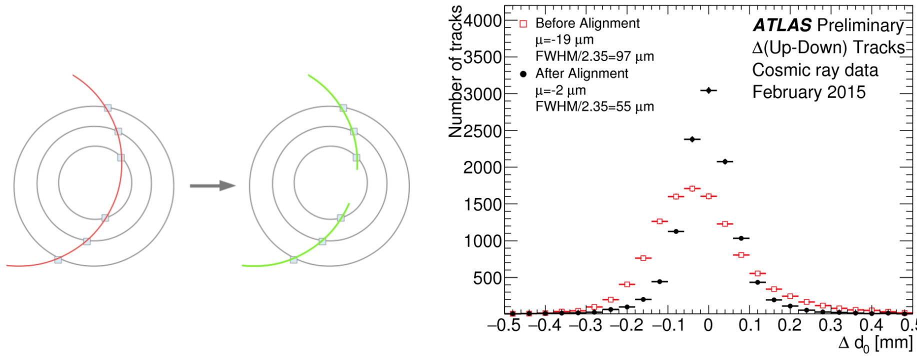

FIGURE 4. (left) Diagram illustrating the half-track parameter study. In red is shown a full track reconstructed in the inner detector, while in green are shown the two half-tracks reconstructed in the top and bottom parts. (right) Distribution of the difference of the reconstructed track transverse impact parameter Δd_0 using tracks reconstructed in the top part of the inner detector with respect to track reconstructed in the bottom part. Taken from Ref. [6]

Using this technique, biases of 19 μm in Δd_0 and of 9.4 TeV^{-1} in $\Delta(q/p_T)$ have been corrected, with the traverse impact parameter resolution being reduced from 69 to 39 μm and 3.5 to 1.4 TeV^{-1}, respectively. In the same way, the longitudinal impact parameter resolution was reduced from 160 to 134 μm. An example of the transverse impact parameter (d_0) distribution is shown in Fig. 4 (right).

First 13 TeV Collision Data

The data used for this alignment were collected by the ATLAS detector during the first 13 TeV collision run, in June 2015. The integrated luminosity is 7.9 pb^{-1} and after applying the selection criteria the final sample used for performance validation consisted of about 1.4 million tracks. More details about the track selection and the obtained results can be found elsewhere [8].

Two passes of the alignment chain were performed. During Run 1 it was observed that when the system conditions changed, for instance due to magnet power cycling, detector cooling system or high voltage being switched on/off, some relative movements of the big structures were introduced. A first pass was thus performed in order to correct for such relative movements. After this first chain, a second pass alignment was performed with the aim of improving the resolution on the transverse impact parameter of the tracks.

Figure 5 shows the improvement achieved by the alignment in the residual distributions of the TRT barrel (left) and the SCT barrel (right), where the alignment results are compared to the perfect aligned simulation (red) and results from the cosmic campaign (March Alignment, in green). A bias of 1(1) μm in the SCT(TRT) barrel has been corrected while the width of the distribution has been reduced from 123(33) μm to 123(27) μm in SCT and TRT, respectively.

June 2015 data have also been used to study the stability of the alignment between runs. For this study, the Pixel detector was fixed as a reference, while the rest of the subdetectors were aligned at Level 1 with respect to it using the June alignment constants. Figure 6 shows the run by run corrections (T_X) found for IBL, SCT and TRT with respect to the baseline constants (June alignment).

Temperature Distortion of the IBL

During the Cosmic Campaign it was discovered that the IBL shows an in-plane deformation (stave bowing) in the negative local x direction, with respect to the nominal geometry, that can be seen clearly in the local x-residuals. This observed distortion turned out to depend on the operation temperature of the IBL. Detailed investigations of the characteristic of this distortion are reported in [7].

Using cosmic ray data collected in March 2015 the dependance of the size of the IBL distortion on the operation temperature has been quantified. For this purpose, the mean of the track-to-hit residual distributions has been determined as a function of the module position in global z and integrated over the 14 staves. The cosmic ray data

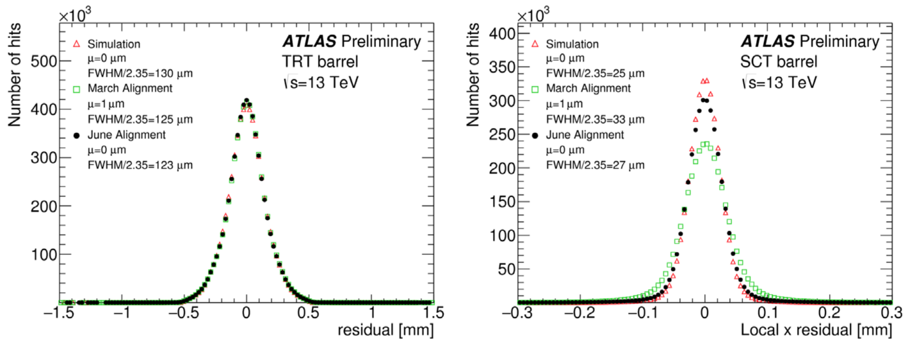

FIGURE 5. The TRT Barrel (left) and SCT Barrel (right) residual distribution for the 13 TeV collision data sample reconstructed with the June alignment (black) and March alignment (green) as well as observed in the perfectly aligned simulation (red). The distributions are integrated over all hits assigned to tracks in the respective TRT regions. Taken from Ref.[8]

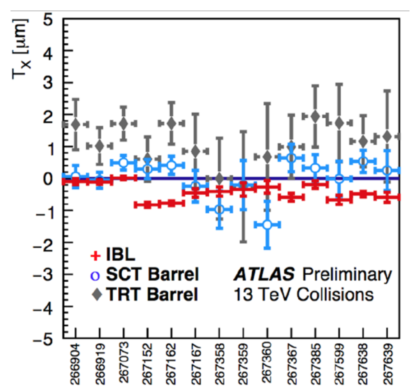

FIGURE 6. The T_X global alignment corrections of all IBL, SCT Barrel and TRT Barrel sub-detectors (with respect to the Pixel detector) as a function of the 2015 13 TeV run. Errors shown are statistical uncertainties on the determined alignment parameters and vary according to the duration of the run. Taken from Ref.[8]

have been collected at different IBL operating points and the resulting distributions are shown in Fig. 7 (left). The track-to-hit residual distributions have been fit using a parabolic formula

$$\Delta_{x_L}(z) = B - \frac{M}{z_0^2}(z^2 - z_0^2), \tag{2}$$

where Δ_{x_L} is the in-plane module displacement as a function of the global z position, B is the fit baseline, M is a free parameter that represent the bowing magnitude and $z_0 = 366.5$ mm is the fixing point of the stave at both ends. The magnitude of the distortion as function of the operating temperature is shown in Fig. 7 (right).

Alignment in the Calibration Loop

Data collected by the ATLAS experiment are promptly processed to provide fast access to high quality data for physics analysis. The high quality of the data is achieved by a so-called ”calibration loop” that relies on the detector calibrations becoming available within 48 hours based on a selected subset of the data designed to allow detailed data investigations of the detector response.

Inner detector alignment was one of the tasks included in the calibration loop during the Run 1. The implementation of the alignment in the calibration loop allows the detection of ”on the fly” movements or deformations of the different subdetectors so that these can be corrected as soon as possible. The calibration loop alignment procedure has

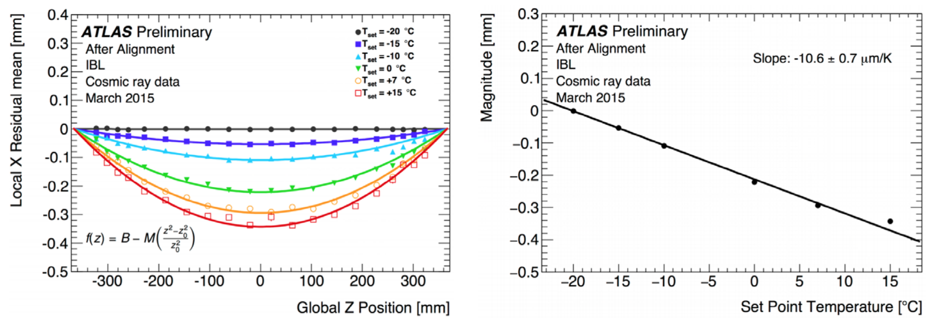

FIGURE 7. (left) The track-to-hit residual mean in the local x direction. The residual mean is averaged over all hits of modules at the same global-z position. Each data set is fitted to a parabola which is constrained to match to the baseline $B = 0$ at $z = \pm z_0 = \pm 366.5$ mm. (right) The magnitude of the distortion as a function of the temperature set point. Each data point is a best fit of a parabola to the local x residual mean as function of the global-z of the module position. Taken from Ref.[7]

been updated to include the latest changes introduced in the alignment procedure and has been extended to perform a more detailed alignment. It has been successfully tested during the Cosmic Campaign and first collisions. In order to allow for a fast reaction, a web display has been developed to monitor online the results of the alignment.

Conclusions

During the LS1 a number of upgrades have been performed on the ATLAS ID, including the addition of the IBL. In order to determine the positions of all ID systems, a first trackbased alignment was performed using cosmic-ray events recorded with the ATLAS detector. The initial 7.9 pb^{-1} of the 13 TeV proton-proton collisions from LHC have been used to align the ID. A special focus on the new IBL detector was necessary as this was the first time this system operated in real LHC conditions. An important part of the alignment work consists on knowing in real time if there is a movement or deformation of the ID in order to correct it as soon as possible. For this reason, a first alignment has been implemented in the Calibration Loop.

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