Track-based alignment of the ATLAS Inner Detector: implementation and performance

Priscilla Pani on behalf of the ATLAS Collaboration
Nikhef-FOM, Amsterdam
E-mail: priscilla.pani@cern.ch

Abstract. The Large Hadron Collider (LHC) at CERN is the world’s largest particle accelerator. It collides proton beams at unprecedented centre-of-mass energies. ATLAS is a multipurpose experiment that records the products of the LHC collisions. In order to reconstruct the trajectories of charged particles produced in these collisions, ATLAS is equipped with a precision tracking system, the Inner Detector (ID). The ID alignment procedure ensures an accurate determination of the position and orientation of the detector’s sensors, such that detector mis-alignments do not degrade the physics performance. An outline of the track-based alignment approaches, their implementation within the ATLAS software framework and the resulting performance is presented.

1. Introduction
The ATLAS detector [1] is a general-purpose experiment that detects and records collisions produced at the Large Hadron Collider (LHC). In order to reconstruct the trajectories of charged particles produced in these collisions, ATLAS is equipped with a tracking system (ID) built on two different technologies: silicon planar (pixel and micro-strip, SCT) sensors and drift-tube based detectors (TRT). The ID alignment provides an accurate determination of the position and orientation of the sensors. The main goal is to assure that the degradation of momentum resolution, due to alignment, does not exceed 20% of the perfectly aligned detector, at high transverse momentum. The specific alignment requirements for each detector are shown in Table 1.

### Table 1. Requirements on alignment precision of the ID components such that the momentum performance is degraded not more than 20% over the intrinsic resolution. $(r, \phi, z)$ are cylindrical coordinates in the global ATLAS frame with the centre in the nominal interaction point and $z$ pointing along the beam axis. $x$ and $y$ are local cartesian coordinates in the plane of the silicon module with $x$ in the most sensitive direction, or $x$ in direction perpendicular to the TRT straw.

| sub-detector | Req. precision | Sensor Resolution | Align-able Objs |
|--------------|----------------|-------------------|-----------------|
|              | $r \phi$ [\(\mu m\)] $\times \ z$ [\(\mu m\)] | $x \times y$ [\(\mu m\)] | |
| Pixel Barrel | 7 $\times$ 20 | 10 $\times$ 115 | 1744 |
|              | 7 $\times$ 200 |                   | |
| SCT Barrel   | 12 $\times$ 50 | 10 $\times$ 580 | 4088 |
|              | 12 $\times$ 200 |                   | |
| TRT          | 30             | 130               | 350848 |
2. Alignment procedure and track based algorithms

The ID track-based alignment is performed at three different levels of granularity, where collections of detector elements (modules, wires), corresponding to substructures of various sizes, can be treated as rigid bodies with 6 degrees of freedom each (2 DoFs for TRT single straws).

At the first level, the sub-detector structures are aligned: all Pixel detectors are treated as a single unit and SCT and TRT are composed of 3 structures each (barrel plus 2 end-caps). At the second level, silicon barrels and end-cap disks, TRT barrel modules and end-cap wheels are considered. The number of degrees of freedom that are aligned at this level is 1260. At the third level the single modules and wires are aligned, for a total degrees of freedom of 726800.

To this purpose, three track-based algorithms have been developed and used in ATLAS:

(i) Global $\chi^2$ (Baseline) [2]
(ii) Local $\chi^2$ [3]
(iii) Robust approach [4]

The Global and Local alignment algorithms rely on the minimization of a $\chi^2$ constructed on track-hit residuals. The alignment $\chi^2$ is defined as [5]:

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

(1)

where the vector of the residual parameters $r(a, \tau)$ is defined as the distance between the measured hit position and the extrapolated track intersection in the module plane and depends on the track parameters $\tau = (d_0, z_0, \phi_0, \theta, q/p)$ and the alignment parameters $a$. The latter is determined from:

$$\frac{d\chi^2}{da} = 0 \Rightarrow \sum \left[ \left( \frac{dr}{da} \right)^T V^{-1} \left( \frac{dr}{da} \right) \right] \delta a + \sum \left( \frac{dr}{da} \right)^T V^{-1} r = 0$$

This requires solving a linear system with a number of equations equal to the number degrees of freedom (DoF).

The individual hit covariance matrix (V) does not have any correlations, i.e. all measurements including scatterings are assumed to be independent. On the other hand, correlations between the alignment modules are due alignment parameter covariance matrix of Equation (1).

The Global $\chi^2$ approach is used for problems up to the size of the entire silicon tracking system (35000 DoFs). However, it is practically impossible to solve the $\sim 7 \cdot 10^5$ DoF set of linear equations of the third level alignment without a dedicated computing hardware. For problems of this size, the Local $\chi^2$ algorithm is used, which neglects correlations between the alignment modules, and allows to solve for such a high number of DoFs at the third level of granularity. The Robust approach, a more intuitive algorithm based on histograms of residuals, was extensively used during detector commissioning.

The implementation of the track-based alignment within the ATLAS software framework unifies different alignment approaches and allows the alignment of all tracking subsystems together. The alignment specific classes derive from the track reconstruction software and provide tools for computation of necessary quantities (residuals, pulls, track derivatives, covariance matrices). Solving for the Global $\chi^2$ problem poses a computational challenge as it involves inversion or diagonalization of a large matrix that may be not sparse and not diagonal. Fast solving algorithms as well as full diagonalization have been implemented.

The alignment software also has the ability to introduce constraints on track parameters (beam spot, primary vertex, momentum from the ATLAS muon system, momentum charge...
asymmetry from calorimeter informations) or on the alignment parameters, in order to help control ”weak modes” of the solution.

Since 2012, whenever detector movements are identified (for example in case of cooling failures or when the magnetic field conditions changed), a new set of alignment constants is produced on the fly and applied to the data first reconstruction. In addition, alignment constants are re-computed for full data reprocessing campaign, approximately two or three times per year.

3. Monitoring and performance of the detector alignment

The detector alignment is monitored by means of a python-based monitoring infrastructure that that collect properties of individual tracks, the beam spot, well known resonances ($K^0_s$, $J/\Psi$, $\Upsilon$, $Z$), etc and produces O(100) plots on run-by-run basis. Both the production and the validation of alignment constants are done using the LHC Computing Grid (LCG), allowing access to all datasets, usage of thousands of CPUs and almost unlimited disk storage.

The residual plots are also used to monitor and validate the alignment sets and in order to decide if updates are needed due to considerable detector movements.

3.1. Residual distributions

Performance of the alignment is shown in Figures 1(a)-1(c), where residual distributions for Pixel, SCT and TRT barrels in 2010 proton-proton collisions are shown. The distributions are centered on zero and the resolution approaches that of a perfectly aligned MC.

![Residual distributions](image)

(a) Pixel Barrel  
(b) SCT Barrel  
(c) TRT Barrel

**Figure 1.** Residual distribution of Pixel, SCT and TRT barrel. 2010 proton-proton collisions is compared to perfectly aligned MC [5].

3.2. Correcting weak modes

The track-based algorithms guarantee that the various components of the detector are aligned in order to provide an efficient and good-quality track fit. However there are detector distortions,
referred to as "weak modes", that maintain the helical trajectory of the track unaffected while introducing a systematic bias on reconstructed parameters. Particle momentum and impact parameters are the most vulnerable and consequently may affect physics measurements. In order to eliminate weak modes, one needs to rely on additional information. In particular, vertex constraints, well-known resonances and calorimeter information are used.

Large charge-antisymmetric momentum biases ($\delta_{\text{sagitta}}$) have been removed in the 2011 data using difference of the electron and positron energy measured in the calorimeters. This type of weak mode affects the reconstructed momentum as shown in Equation 2. In the equation $q$ is the electron charge and $p_T$ it’s transverse momentum. It can be independently measured using the dependence of the reconstructed $Z \rightarrow \mu^+\mu^-$ invariant mass on the $\mu^+\mu^-$ kinematics.

$$q/p \rightarrow q/p(1 + q p_T(\delta_{\text{sagitta}})) \quad (2)$$

Figure 2(a) shows a momentum bias ($\delta_{\text{sagitta}}$) before the alignment correction. Local biases up to 8% can be observed.

The results after momentum-constrained alignment of the detector are shown in Figure 2(b). Charge-antisymmetric momentum biases have been reduced by an order of magnitude resulting in a uniform detector response.

![Figure 2](image)

(a) Original Alignment  
(b) Updated Alignment

**Figure 2.** 2011 proton-proton collisions, weak-mode bias [6]. In the plots $\eta$ is a function of the polar angle $\theta$ (pseudorapidity $\eta = -\ln \tan(\theta/2)$) and $\phi$ the azimuthal angle.

### 4. Conclusions

The alignment of the Inner Detector has been fully integrated into the ATLAS computing framework and makes use of huge resources available through the LCG. The track-based algorithm, based on the Global $\chi^2$ method, enables the alignment of the ID at different levels of granularity. The validation and performance study of the residual distributions show that the results are close to a perfectly aligned MC, although there is still room for improvement in order to reach the requirements needed by certain precision physics measurements. Further types of detector distortions that do introduce biases on reconstructed track parameters, have been identified and re-aligned using constraints such as the electron energy measured in the calorimeters or the $Z$ invariant mass. Calibration-loop alignment and sophisticated monitoring techniques can provide corrected alignment in quasi-real time for the bulk data reconstruction.

### References

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