Alignment of the ATLAS Inner Detector tracking system

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2010-01/loddenkoetter

Modern tracking systems like the ATLAS Inner Detector (ID) have intrinsic resolutions that by far exceed the assembly precision. For an accurate description of the real geometry one has to obtain corrections to the nominal positions. This alignment task is crucial for efficient track reconstruction as well as for precise momentum measurement and vertex reconstruction.

The criteria for the required alignment precision at ATLAS are that the resolutions of the track parameters should not decrease by more than 20% due to alignment effects and that the systematic error on the W mass should be below < 15 MeV [1].

The ID [1][2] consists of three sub-components: the Pixel Detector (Pixel), the Semi-Conductor Tracker (SCT) and the Transition Radiation Tracker (TRT). The Pixel is a silicon pixel detector consisting of three cylindrical barrel layers and three disks in each end-cap. Its intrinsic resolution is $10 \times 115\ \mu m^2$ ($R\phi \times z$), leading to a required alignment precision of $7 \times 100\ \mu m^2$.

The SCT is a silicon strip detector with four barrel layers and nine disks per end-cap. The intrinsic resolution of the SCT is $17 \times 580\ \mu m^2$ ($R\phi \times z$), the target precision for alignment is $12 \times 200\ \mu m^2$. Pixel and SCT together consist of about 5800 modules in total.

The TRT consists of straw-like polyamide drift tubes with a diameter of 4 mm. The barrel is divided into three rings of 32 modules each, containing in total 73 layers of straws. Each end-cap consists of 160 disks of radially oriented straws. The TRT has an intrinsic resolution of 130 µm ($R\phi$ only), the target alignment precision is 30 µm.

To achieve the alignment goals, various tools are available. Already during the detector installation, *assembly and survey measurements* were performed, yielding a precision of up to O(100 µm). These measurements serve as a starting point or external constraint for other methods [3].

The SCT is equipped with a *Frequency Scanning Interferometry (FSI)* [4] system that measures deformations of the SCT with an extremely high precision of O(1 µm). Its purpose is to monitor the stability of the alignment with time. The FSI is not fully integrated in the alignment software yet.

The tool for ultimate alignment precision is *track-based alignment* which uses particle tracks to determine the alignment by examining residuals between the reconstructed hits in the detector and the intercept of the track trajectory in the module, estimated by the track fit. Several million high-p_T tracks are needed in order to reach the desired precision.

The algorithms used by ATLAS are based on minimizing the track χ^2 or on centering residual distributions by examining their mean values.

The alignment can be performed at different levels of granularity. This *alignment level* defines the "alignable structures" i.e. the substructures of the ID to which individual alignment constants are assigned. Each alignable structure has six degrees of freedom (dof), corresponding to six alignment parameters (three translations and three orientations). For the ID alignment, several alignment levels are implemented: Level 1 treats the whole Pixel as well as SCT and TRT barrel and end-caps as alignable structures, which makes 42 dof, on level 2 all ID subcomponents are split up into their barrel layers/modules and end-cap disks/layers (1146 dof). Finally, on level 3, all single sensors are aligned individually (Pixel and SCT only, about 36000 dof). Furthermore, several intermediate levels are defined that all follow the assembly structures of the detectors. For a full ID alignment, the alignment chain is run iteratively at different levels.

The baseline algorithm for track-based alignment at ATLAS is the Global χ^2 [5]. Tracks are fitted simultaneously, minimizing a global χ^2 w.r.t. all track and alignment parameters at the same time. The χ^2 definition is given in Eq. 1, where $\mathbf{r_j}$ is the vector of residuals of a track, $\boldsymbol{\tau_j}$ and $\mathbf{a}$ denote the track and alignment parameters, respectively, and V is the covariance matrix.

$$\chi^2 = \sum_{tracks} \mathbf{r_j}^T(\boldsymbol{\tau_j}, \mathbf{a})(V^{-1})_j \mathbf{r_j}(\boldsymbol{\tau_j}, \mathbf{a}) \qquad \longrightarrow \qquad \frac{d(\chi^2)}{d(\boldsymbol{\tau_j}, \mathbf{a})} \stackrel{!}{=} 0 \tag{1}$$

For minimization, the derivatives of χ^2 w.r.t. all $\boldsymbol{\tau_j}$ and $\mathbf{a}$ are required to be 0 at the same time. This leads to a linear system of N linear equations, represented by an N×N matrix, where N is the number of dofs. This can be solved by different techniques. At low granularity, the full diagonalization of the matrix is possible. All eigenmodes of the system and their eigenvalues are then known. At full granularity, a fast solution is more suitable and can be achieved with matrix conditioning. In this case the eigenvectors and -values are unknown. Also the statistical errors on alignment parameters cannot be calculated then.

Unfortunately, the χ^2 minimization is normally not sufficient for a proper alignment. The reason are the *weak modes*, which are solutions of the alignment that leave the residuals (almost) invariant, but may bias the track parameters and therefore are a source of systematics. In the χ^2 algorithm they appear as eigenmodes with very small eigenvalues, to which the algorithm is therefore insensitive. Typically, weak modes correspond to systematic deformations of the whole detector. To deal with weak modes, various measures can be taken.

The most important is to prevent the alignment from introducing weak modes. At low granularity, when the eigenmodes are known, this can be done by cutting away those modes with the lowest eigenvalues. At high granularity, when the eigenmodes are unknown, one can apply a *soft mode cut*, i.e. constrain the system by appropriately conditioning the matrix in a way that weak modes get suppressed.

Of course, cutting away or suppressing weak modes is not enough, as the real detector may contain such deformations. Aligning these requires extra steps. As weak modes are often connected to certain track topologies, a good measure is to mix tracks with different topologies, e.g. collision tracks, cosmics and beam halos. Effectively, this reduces the number of weak modes

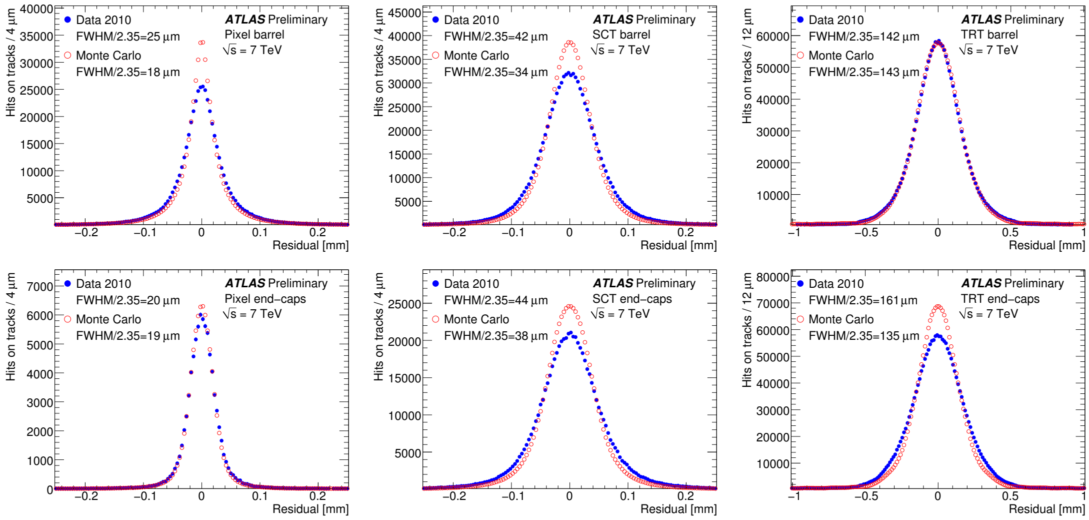

Figure 1: Unbiased residual distributions in local x coordinate for barrel and end caps of Pixel, SCT and TRT. Data points are for 7 TeV collision data from 2010 with the current alignment (dark dots) and for a simulation with perfect alignment (light circles). The simulated distributions are normalized to the number of entries in the data. The "Full Width Half-Maximum" of the distributions divided by 2.35 are quoted.

of the system. Vertex or beam spot constraints have a similar effect. Finally, one can examine quantities that *are* affected by weak modes, like invariant mass distributions of resonances etc.

Figure 1 shows the results for 7 TeV data from 2010 with the current alignment (dark dots) and for a simulation with perfect alignment (light circles). The unbiased residual distributions in the most sensitive local coordinate are presented for all sub-detectors. Tracks used for the plots were required to have $p_T > 2$ GeV and number of silicon hits ≥ 6. For these low-momentum tracks, the width of the residual distribution is larger than the intrinsic "per-hit" accuracy of the detectors due to the contribution from multiple scattering to the track parameter errors.

In the TRT end-caps the measured resolution w.r.t. the simulation is significantly worse than in the barrel. This is due to the fact that the TRT end-cap geometry did not allow for as detailed cosmic ray studies as the barrel and the Pixel and the SCT. Further commissioning of the TRT end-caps is required to achieve performance similar to that of the barrel.

References

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