Alignment of the Inner Detector of the ATLAS Experiment

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***Abstract*— The ATLAS Experiment is one of the four detectors located at the Large Hadron Collider at CERN in Geneva, Switzerland. Data taking of ATLAS is expected to start in 2007. The reconstruction of particle tracks is performed by silicon and drift tube based subdetectors. In order not to degenerate the track measurements, the position of the silicon detector elements have to be known to a precision better than about 10 micrometers. This precision can be achieved by track based alignment algorithms combined with measurements from hardware based alignment techniques. The proposed alignment algorithms for the ATLAS inner detector and their implementation into the common ATLAS software framework are presented. First results from a testbeam setup and from cosmic ray data are shown and discussed.**

***Index Terms*— ATLAS, silicon detectors, Inner Detector, alignment.**

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I. INTRODUCTION

THE ATLAS detector is a multi-purpose experiment at the 14 TeV proton-proton Large Hadron Collider (LHC) expected to start taking data at the end of 2007. Its Inner Detector (ID) consists of a silicon-based subdetectors, PIXELs and SemiConductor Tracker (SCT), and a Transition Radiation Tracker (TRT) with drift tubes [1]. About 6000 modules are in its Silicon Tracker, where each of these module determines the position of passing particle tracks with a precision of about 20 μm. However, the position of the devices is only known to about 100 μm and therefore a track based alignment procedure has to be applied to determine the absolute position of the sensitive devices to a better precision. The position precision required by the physics goals of ATLAS has to be better than 10 μm. In 2004, a fraction of modules of the ID were tested in a Combined Test Beam (CTB), results of alignment of this sector is presented in this paper. In early 2006, the barrel sector of the SCT was integrated in the TRT barrel and the system was fully tested at the surface. A fraction of the system was equiped to record cosmic data. The alignment performance of this system is shown in this paper. Nowadays, the barrel TRT+SCT is now fully integrated with the rest of the ATLAS detector in the pit.

A. The Challenge

The ATLAS ID is a large and complicated system with 3.2 million readout channels. To achieve the physics goals, ATLAS tracking requires the position of the modules of the Silicon Tracker to be known to a precision better than 10 μm. The alignment of the ID will need to meet these requirements.

The Silicon Tracker has 3568 modules in the Barrel region (1456 PIXELs + 2112 SCT) [2] and 2264 modules in the EndCap region (288 PIXELs + 1976 SCT) [3]. These modules are distributed in 3+4 cylindrical PIXELs+SCT barrel layers and 2x(3+9) disc PIXELs+SCT EndCaps (see figure 1).

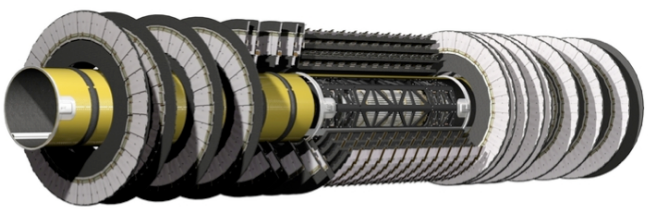

Fig. 1. ATLAS Silicon Tracker (PIXELs + SCT)

PIXELs are 50x400 μm resulting in 14x115 μm intrinsic resolution with a direct 2D readout. SCT barrel modules are single-sided back-to-back strip detectors (1D readout per side), with each strip pitch of 80 μm giving 23 μm intrinsic resolution in rϕ direction. A stereo angle of 40 mrad between sides provides 580 μm resolution in the rz direction. Details on the tracking elements of the ID can be found elsewhere.

B. The Strategy

The objective of the alignment strategy is to meet the physics requirements in time for LHC data-taking. The leading idea is to align first the Silicon Tracker and then align the TRT with repest the Silicon Tracker. For the alignment of the Silicon Tracker, the current strategy is to use a combination of a monitoring system (hardware) and track-based algorithms (software). The information gained from simple tracks is not sufficient to solve the complicated system, leading to undetermined degrees of freedom (DoF). For this reason additional constraints need to be added to the system, like track pairs originating from resonance decays, common vertex fits, etc. Additional information, as that coming from the monitoring system, can either be added directly to the equation or by enriching the number of dedicated tracks. Also, information from interferometry based alignment systems will enter in the determination of the alignment constants. Futhermore, the simultaneus combined alignment of the Silicon Tracker and TRT is being consider. This can be particularly be useful for correcting misalignment modes, such as sagitta distortions.

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II. ALIGNMENT ALGORITHMS

Currently, several alignment approaches are being developed and tested. All algorithms are implemented within the ATLAS software framework, called Athena, and use common framework tools, such as tracking, databases, etc. The algorithms align using track residuals and are iterated to re-reconstruct tracks. Upon convergence, final alignment constants are stored. The different approaches are envisaged and they can be, basically, divided into global and local fit method:

- In local methods, the position of a single module is determined iteratively by repeating a local χ^2 minimization and refitting tracks at each step.
- In global methods, the changes in the alignment constants and tracks parameters are handled together in the minimization procedure.

Both methods have been used successfully in previous experiments. The ATLAS experiment follows both approaches with different algorithms. A brief description and the main advantages and disadvantages of each algorithm used are:

1) **Global** χ^2: Minimizes the χ^2 from a simultaneous fit to all particle tracks and alignment parameters [4]. It takes into account 6 DoF per module and manages module correlations and also takes into account Multiple Coulomb Scattering (MCS) effects. It converges after a small number of iterations. The main disadvantge is that it involves handling and solving large matrices due to the many DoF (35k x 35k for the full Silicon Tracker). This poses inherent computing challenges.
2) **Local** χ^2: is similar in principle to Global χ^2, but is limited to inversion of a 6x6 matrix per module. The matrix can represent 6 DoF, but not module correlation or MCS effects are taken in account. Because of that, it may require large number of iterations to converge and to handle correlations.
3) **Robust**: uses weighted mean residuals, z and rϕ overlap residuals of neighboring modules. It can handle 2 or 3 DoF per module and needs many iterations.
4) **Kalman**: it is a novel technique never used before in a running experiment. It is a local approach where each module is aligned separately. This algorithm takes correlations in account in each track and therefore in principle no iterations are needed.
5) **Numerical** χ^2 **(Valencia)**: was only used for CTB alignment. It handles 6 DoF per module and needs iterations.

The determination of the alignment constants is closely related to the solution of a system with a large number of DoF. Considering the 5832 modules that the Silicon Tracker has and giving three translational and three rotational DoF for each module, tracker alignment has to deal with 34992 DoF. To help with this challenge, functionalities exists to add constraints from physics and external data. For example, common vertex fits or assembly survey constraints are implemented in Global and Local χ^2 algorithms. Constraints such as using a vertex and/or mass of a resonance have been tested with the Global χ^2 algorithm using simulated events.

Also, some online alignment information , such as Frequency Scanned Interferometry (FSI), was tested in the Global χ^2 algorithm in a proof of principle study. The FSI uses on-detector geodetic grids measuring lengths between nodes on the SCT. Grid shape changes can be determined to < 10 μm 3D, on a time scale of 10 min. FSI is sensitive to low spatial frequency eigenmodes, complementing track-based alignment which has a time scale of 24 hours and sensitivitiy to high spatial eigenmodes [5].

III. THE PERFORMANCE

A. *Full Silicon Detector alignment*

It is important to validate and debug the alignment algorithms using the GEANT simulation of the ATLAS detector. For this purpose, a nominal detector description or a description where misalignments introduced either at reconstruction and simulation level are used. Most recent tests were performed on a non-physics sample where each event has on average 10 muons, especially produced for alignment studies. Using the Local χ^2 all the Silicon Tracker was tested, which involve almost 35k DoF, as a proof of algorithm potencial. The Global χ^2 algorithm was run over a subsample of such events (8 million tracks) within $|\eta| < 1.0$. The choice of detector coverage was mainly to assure only the barrel region with high enough occupancy per module was examined. The alignment was, thus, performed on 2172 barrel silicon modules, including PIXELs and SCT modules, which corresponds to a 13032 DoF. Due to the large size of the matrix to be inverted, the solution was obtained using ScaLAPACK on an AMD Opteron 64 bit parallel cluster [7]. The process took under half an hour using 16 CPUs .

Some global systematic effects were observed in the PIXEL detector, which were not apparent in an earlier study on a smaller sample using earlier version of the ATLAS software. The effects are of order 40 μm in 2 of the module DoF which are large compared with typical expected errors ($\sim$10 μm). Studies are under way to understand if this is a software artifact or a real effect that was hidden by low statistics.

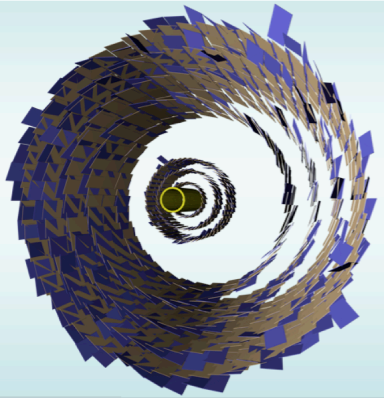

Fig. 2. Misaligned Silicon Tracker. Nominal module position (brown) are displayed together with real module position (blue) where the 3 translations and the 3 rotations are amplify by a factor of 100, to see the desviations.

Work is also ongoing on the data sample with deliberate misalignments at the module, layers/disks and subsystems levels introduced using knowledge from survey data and build tolerance specifications. In figure 2 shows how the misaligned Silicon Tracker detector looks.

B. Combined Test Beam

The first real data from ID came from the CTB 2004 data. Almost all the alignment algorithms have been used to align the ID setup with this data. Different sets of beams of e+/e-, μ+/μ-, γ and pions with energies varying from 2 to 180 GeV and with/without magnetic field runs gave abundant statistics of data (O(10^5) tracks per module and per energy run). The Silicon Tracker setup consists of 6 PIXEL and 8 SCT endcap modules configured such that the beam would cross radially as it would in actual configuration (simulating an ATLAS slice) [6]. Although the layout presented some systematic effects due to its limitations, the CTB proved to be a good start to test algorithms for upcoming data and allowed to test the software reconstruction chain and to tune the alignment algorithms.

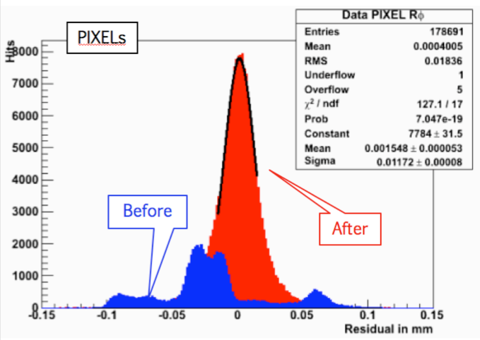

Fig. 3. PIXELs Residuals before and after Robust alignment algorithm is run over CTB2004 data

Individual algorithms use different approaches (e.g., biased or unbiased residuals) and subsets of data to extract the alignment constants, but all of them improve residuals and quality of track parameters. The results have been found to be consistent with slight differences likely to be attributed to global transformations of the layout. Before the alignment, the residuals RMS were 50-100 μm. After alignment, the overall PIXEL rϕ residual RMS are 10-15 μm and SCT residuals are 20-25 μm, depending on the algorithm [5]. Figure 3 shows the PIXEL rϕ results with the Robust algorithm where clear structures of the module configurations before alignment are visible. Figure 4 shows the mean and RMS residuals convergence, also using the Robust algorithm. The alignment reached a level with CTB data sensitive to effects at a few μm and comparison of the results are an ongoing effort.

C. SR1 Cosmic Run

In spring 2006, the first large scale test of the barrel SCT+TRT was the SR1 cosmic run on the surface. Tracks from cosmic rays are being used to align parts of the ATLAS

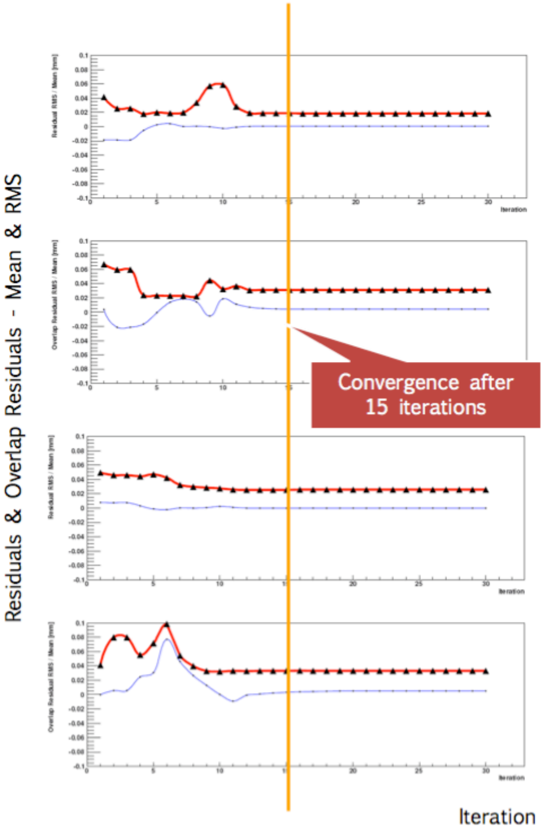

Fig. 4. Mean and RMS residuals/overlap residuals evolution using the Robust algorithm for the CTB

Inner Detector. One of the goals of these tests is to confirm the measurement provided by the optical survey. About 400k events were recorded using a partially instrumented region of the fully integrated detector. 467 SCT barrel modules (22% of the barrel) and 13% TRT were read out, in a conical section of a 20 degrees tilted geometry covering about 30 degrees of the azimuthal ϕ slice (see figure 5). Two scintillators, with 0.5 ns of time resolution, were used for triggering and together with the roof material provided an intrinsic 0.4 GeV momentum cut-off. Data were taken without a B-field, therefore no track momentum measurements were possible. As most triggered events were below 10 GeV, where MCS is important, the residuals were larger and the algorithms were adjusted to take this into account. A third scintillator was introduced under the floor to use the Time of Flight (TOF) in order to cut the momentum [8].

The Global χ^2 algorithm analyzed a dataset with 250k tracks using about half the available physics mode runs. The sample size is large enough such that statistical errors on the corrections are small with respect to the systematical errors. The RMS residuals before the alignment are about 50 μm, which are better than specified SCT assembly tolerances, indicating a very good assembly precision. If corrections are obtained using refitted tracks, the rϕ (x direction in module local frame) residual resolution is about 30 μm, after 2 iterations [5].

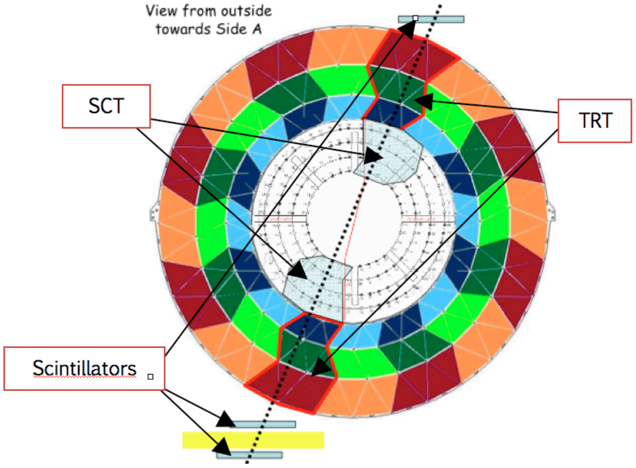

Fig. 5. SR1 setup. Just 22% SCT and 13 % TRT were read out. Trigger was perform with two scintillators, while the third one (under the floor) allows to use the TOF to cut the momentum

The cosmic ray data are also analyzed using Local χ^2 and Robust alignment algorithms. The Local χ^2 algorithm iterates more than 10 times on a limited 36k cosmic track sample for converging alignment corrections to obtain improved (unbiased) residuals. The improvements in RMS with this dataset is about 25% when averaged over four barrels. The robust alignment method was shown to work on the cosmic configuration, where initial studies with 80k tracks were performed.

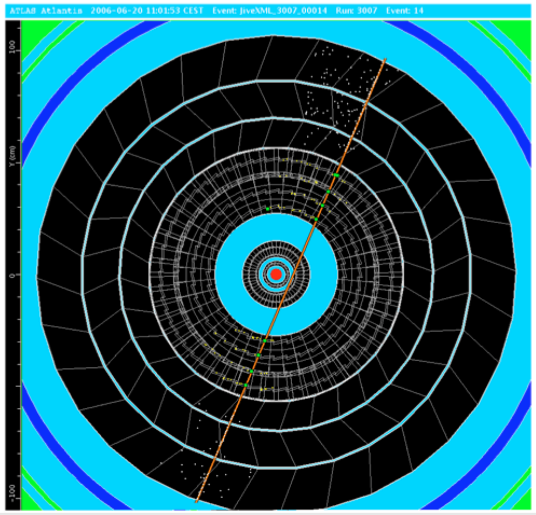

Fig. 6. Reconstructed cosmic muon from the SR1 cosmic run 2006 (Atlantis event display).

IV. Conclusion

Many algorithms have been adopted to align the ATLAS Silicon Detector within the ATLAS software framework. All methods have been used with simulated or real data and extensive validation tests are being performed. Although algorithms use different approaches in extracting alignment constants (various DoF, unbiased/biased residuals, etc...) all of them improve residuals and quality of the track parameters significantly. The alignment team have been looking at real data since 2004 in the combined test beam and now, in 2006, with the SR1 Cosmic run. The CTB analysis is almost finalized and cosmic alignment analysis is progressing very rapidly. This will allow us to validate the alignment algorithms and to get some pre-alignment of the barrel Silicon Tracker before the pit installation. The infrastructure for full scale tests using nominal and misaligned detector simulation is in place and tests are being performed. Work is in progress to understand important systematic issues both in real data and simulation, upstream and downstream of alignment algorithms. Online monitoring is getting ready for PIXELs insertion in the ATLAS cavern. New cosmic runs are being prepared at the surface and in the pit before the first LHC data will be available (late 2007).

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