Commissioning of the ATLAS Inner Detector Software Infrastructure with Cosmic Rays

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Abstract. Several million cosmic events were recorded during the combined ATLAS runs in autumn 2008. Using these cosmic ray events, the software infrastructure of the ATLAS Inner Detector is being commissioned. The full software chain has been set up in order to reconstruct and analyse these kind of events. Different pattern recognition algorithms, track fitters and various calibration methods have been developed and validated. The infrastructure to deal with conditions data coming from the data acquisition and detector control system as well as calibration runs has been put in place, allowing to apply alignment and calibration constants. Stable software is essential to ensure the continuous monitoring of the detector performance during data taking. Detector efficiencies, noise occupancies and resolutions are studied in detail as well as the performance of the track reconstruction itself.

1. Introduction
The commissioning of the ATLAS Inner Detector software infrastructure will be described in the following. Two approaches are used to make sure that the software will be working as expected once first collision events will be recorded by ATLAS. The first approach exercises the software infrastructure with simulated collision data to execute the whole physics chain in a stress test. The second one uses data from the continuous data taking of cosmic ray events in autumn 2008. The first approach makes sure that the algorithms can be run with the required physics and technical performance. A set of Full Dress Rehearsal tests have been carried out to assess the software performance within timing constrains and to carry out the prompt reconstruction, calibration and alignment within 20 hours after data taking. The second approach concentrates more on distinctive features present in real data like noisy modules and uncalibrated or incomplete data from the detector. It ensures that the software reconstruction can deal with all these kinds of imperfect data.

After giving a very brief introduction into the detector layout and the software infrastructure in sections 2 and 3, the two commissioning approaches will be described in more detail. First results from the autumn 2008 cosmic ray data take will be discussed in section 6.

2. The ATLAS Inner Detector Tracking System
The ATLAS (A Toróïdal LHC AparatuS) experiment is one of the four main experiments at the Large Hadron Collider (LHC) in Geneva, Switzerland. The LHC is a proton-proton collider with 14 TeV centre of mass energy and design luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. ATLAS is designed
as a general purpose detector and is sensitive to a large number of Standard Model and new physics signatures.

The ATLAS Inner Detector (ID) is a high precision tracking detector. It is contained within a solenoidal magnetic field of 2 T and consists of three sub-detectors (see figure 1): the Pixel detector, the Semi-Conductor Tracker (SCT) and the Transition-Radiation-Tracker (TRT) [1]. The Pixel and SCT detectors use semi-conductor technology and have an excellent resolution. Typically three Pixel layers and eight strip layers (or four spacepoints) in the SCT are crossed by a track in the barrel region. The TRT is consists of straw tubes and provides information in the R\(\phi\) direction only. The TRT typically contributes with 30 hits per track.

![Figure 1. The ATLAS Inner Detector tracking system.](image)

The combination of the three different detectors provides ATLAS with a very robust pattern recognition and excellent resolution. The straw hits in the TRT on the outer radius contribute significantly to the momentum measurement and resolution.

3. Software Infrastructure for Offline Track Reconstruction

A schematic view of the ATLAS software infrastructure for offline track reconstruction is shown in figure 2. The reconstruction consists of three major steps: the preparation, the track finding and the postprocessing step.

In the preparation step, the hit information from the Pixel and SCT detector is used to form first clusters and then Spacepoints. For the TRT detector, drift circles are created. The next step in the reconstruction is the track finding. Different tracking algorithms can be used to reconstruct tracks in the Inner Detector. The default track reconstruction is called NewTracking [2]. NewTracking is a modular track reconstruction chain that combines global and local pattern recognition methods. In the last reconstruction step, the postprocessing, the primary vertex is calculated and photon conversions reconstructed.
Figure 2. Schematic modeling of the ATLAS track reconstruction software.

During all three reconstruction steps common services and tools like the Detector Geometry, the Track Fitter, the Track Extrapolator or the Vertex Fitter are used by all algorithms.

4. First Test of the Software Infrastructure
A series of Full Dress Rehearsal (FDR) tests of the whole offline reconstruction infrastructure took place in spring and summer 2008. A Monte Carlo simulation of the full detector response and online data taking with an event mixing mimicking the expected composition of triggered events was produced and then reconstructed by the offline software in the ATLAS Tier0. The reconstruction was done in two steps: In the first step, only a small fraction of the data from a dedicated express stream was reconstructed. From this data calibration and alignment constants were calculated, which were used in the second step 24 hours later for the reconstruction of the physics streams. This exercise allowed a stress test of the 24 hours loop for prompt reconstruction, calibration and alignment.

5. Commissioning with Real Data
As of summer 2008, muons from cosmic ray events became the main source of data for the commissioning of the Inner Detector software infrastructure. These muons traverse ATLAS, are detected and can be reconstructed by the software. The general structure of the software as shown in figure 2 stayed the same, but some adjustments or special algorithms needed to be developed. They will be described in the following.

Cosmic ray particles enter the ATLAS detector from above instead of originating from the interaction point in the centre. Thus adjustments were made in the data preparation step to account for the different timing in the upper and lower part of the detector. For the creation of clusters and drift circles the information from the conditions service was used. The conditions service provides information about module voltages, calibration constants or as to whether a certain module was included in the data taking or not. This information was used to mask out
data from noisy modules and apply alignment and calibration constants. Some key features of the conditions service like the module voltages and the information about the participation of a module in the data taking were used for the first time in the 2008 cosmic data take.

In the track finding step, two different track reconstruction algorithms were used: a special version of NewTracking and the dedicated Cosmic and Testbeam (CTB) tracking [3]. For NewTracking the pattern recognition had been adjusted. The most important changes include removing the restriction of the track to the interaction point and combining hits from the upper and lower part of the detector. The CTB Tracking had been developed initially for tests on the surface and uses the same common code base as NewTracking (event data model, fitter, extrapolator). In the commissioning of the software the CTB tracking is used as a reference for the performance of NewTracking on cosmic ray events.

In the postprocessing step, no primary vertex is calculated and photon conversions reconstructed.

6. Results from the Cosmic Ray Data Taking
In autumn 2008, several weeks of combined cosmic ray data taking involving the whole ATLAS detector took place. Several million tracks with and without solenoid field were reconstructed from these datasets. Two reprocessing campaigns followed in December and March to account for improvements in the software and the understanding of the detector. They have shown that the reconstruction software and the two tracking algorithms NewTracking and CTB tracking reconstructed very reliably several million Inner Detector tracks in over two-hundred million events. The difference between the two numbers comes from the fact that the majority of cosmic ray particles do not traverse the Inner Detector.

Validation of the Track Reconstruction
The validation of the adjusted NewTracking track reconstruction chain uses the specialised Combined Testbeam and Cosmics (CTB) tracking. Figure 3 shows the $p_t$ and $\eta$ spectrum for tracks reconstructed with these two track reconstruction algorithms for run 91885 from the 2008 cosmic ray data take. The two maxima in the $\eta$-distribution at $\eta \approx -0.2$ and $\eta \approx 0.2$ are due to the construction shafts in the ATLAS cavern. The cosmic ray spectrum is dominated by particles reaching the ATLAS detector through these shafts. The two plots show that the adjusted NewTracking and the specialised CTB tracking have reconstructed the same cosmic ray spectra.

![Figure 3. $p_t$ and $\eta$ spectrum for tracks reconstructed with NewTracking and CTB tracking for run 91885.](image-url)
Detector Performance
The results from the offline data reconstruction can be used to determine the performance of the detector. Figure 4 shows the occupancy in the Pixel and SCT detector. The left plot shows the occupancy for each Pixel barrel layer. For this measurement a sample with no tracks was used and the noisiest pixels (less than 0.02% of all channels) were masked out. After this, the noise occupancy is about $10^{-10}$. This value stays well below the design value of $10^{-4}$ for pile-up events [4]. On the right the noise occupancy measured in the SCT Barrel and End-Cap modules is shown. These measurements were made in December 2008 at the end of the cosmic ray run. The noise occupancy is measured at 150V bias voltage and is significantly below the TDR specification of $5 \cdot 10^{-4}$ (right edge of plot).

Figure 4. Noise occupancy in the Pixel and SCT detectors.

The hit efficiency from cosmic ray tracks in the Pixel and SCT detector is shown in figure 5. It is defined for expected hits only, taking into account that a few percent of modules were inactive for the data taking period\(^1\). The hit efficiency for each of the three Pixel barrel layers as shown in the left plot is about 99.8%. For the SCT barrel an efficiency above 99.5% is obtained for each side of its four layers (right plot). The hit efficiencies in both Pixel and SCT detector exceed significantly the design value of 97% [4].

Figure 5. Hit efficiency in the Pixel and SCT detectors.

\(^1\) For the Pixel detector approx. 2% of barrel modules (72 out of 1755 in total) and for the SCT 1% of the barrel modules (73 out of 4088 in total) were disabled for the 2008 data taking period. These modules are not considered for the efficiency measurement. Some of them are expected to be repaired for the data taking period in 2009.
**Calibration and Alignment**

The cosmic ray data take provided sufficient statistics to calibrate and align the ATLAS detector down to module level in the barrel region. Figure 6 shows the residual distributions for the x- and y-coordinate in the Pixel barrel. The resolutions obtained by the present alignment ($\sigma_x = 24 \, \mu m$ and $\sigma_y = 131 \, \mu m$) have reached now the same order of magnitude as those found in Monte Carlo simulation for a fully aligned detector ($\sigma_x = 16 \, \mu m$ and $\sigma_y = 127 \, \mu m$). These results already show an excellent understanding of the detector and its alignment.

![Residual distributions for x and y coordinate in the Pixel barrel.](image)

**Figure 6.** Residual distributions for x and y coordinate in the Pixel barrel.

### 7. Conclusions

The ATLAS Inner Detector software infrastructure has been commissioned using Monte Carlo simulation and real data from cosmic ray events. A Full Dress Rehearsal allowed a test of the 24 hours loop for prompt reconstruction, calibration and alignment with simulated data. The reconstruction of cosmic ray events in several reprocessing campaigns show the improvements in the software and the understanding of the detector. Conditions data from the online data taking have been used for the first time in the offline reconstruction to mask out malfunctioning modules, calculate hit efficiencies and noise occupancies. The resolutions obtained with the cosmic ray data are already approaching the ones in perfect Monte Carlo simulation.

This shows that the ATLAS Inner Detector software infrastructure is in an excellent shape and ready for first collision events in autumn 2009.

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