Commissioning of the ATLAS Inner Detector with cosmic rays

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Abstract. The inner detector of the ATLAS experiment is in the process of being commissioned using cosmic ray events. First tests were performed in the SR1 assembly hall at CERN with both barrel and endcaps for all different detector technologies (pixels and microstrips silicon detectors as well as straw tubes with additional transition radiation detection). Integration with the rest of the ATLAS sub-detectors is now being done in the ATLAS cavern.

The full software chain has been set up in order to reconstruct and analyse this kind of events. Final detector decoders have been developed, different pattern recognition algorithms and track fitters have been validated as well as the various alignment and calibration methods. The infrastructure to deal with conditional data coming from the data acquisition, detector control system and calibration runs has been put in place, allowing also to apply alignment and calibration constants.

The software has also been essential to monitor the detector performance during data taking. Detector efficiencies, noise occupancies and resolutions have been studied in detail and compared with those obtained from simulation.

1. Introduction
The commissioning of the ATLAS inner detector is a vital activity to ensure that both the detector itself and the software infrastructure are ready for proton-proton collisions at the LHC next year. The commissioning tests are real data trials of the inner detector as the different subcomponents are integrated. Tests occur in the SR1 assembly hall and then in the ATLAS cavern itself, as the inner detector is integrated into the rest of the ATLAS detector.

The ATLAS inner detector[1] comprises of three different subdetectors, each using different detector technologies, with a central barrel section and two endcaps in the forward regions. Located closest to the interaction point is a 50-400 µm Pixel detector, which has 3 layers in the barrel region and 3 disks in each endcap. Outside of the Pixel detector is a microstrip silicon detector (SCT) (with 80 µm pitch in the barrel and 57-90 µm pitch in the endcaps). The SCT has 4 barrel layers and 9 disks in each endcap. Exterior to the SCT lies the transition radiation tracker (TRT) which consists of 4 mm diameter straw tubes with additional transition radiation detection for particle identification. The barrel section contains 73 straw layers while each TRT endcap contains 160.

The installation and commissioning of the inner detector itself and the software required to process the data is a long process, whose time table must work in conjunction with the overall
installation time table of the ATLAS detector.

In February 2006 the barrel section of the SCT was inserted into the barrel section of the TRT at the SR1 assembly area at CERN, as shown in figure 1a. Later in June 2006, this barrel section was used for the first commissioning test, before being lowered into position in the cavern in August 2006. In a similar fashion each SCT endcap was inserted into the corresponding TRT endcap in SR1, figure 1b. The first of these to be assembled (endcap C) was used in the second commissioning test in the autumn of 2006. The third commissioning test in SR1 involved one of the pixel endcaps (autumn 2006). The first of the SCT-TRT endcap sections was installed in the ATLAS cavern in May 2007. In June the second SCT-TRT section and the pixel detector were installed.

The entire Inner detector is now installed in the pit. The current commissioning activity is to integrate it into the combined DAQ.

2. Commissioning Setups.
As the various sections of the inner detector, such as the SCT and TRT barrel system, are assembled in SR1, they are tested to check their performance before they are installed in the ATLAS cavern. For these tests, runs of data were collected using both random and cosmic triggers. For the SCT-TRT barrel test, data was recorded for approximately 25% of the SCT and 13% of the TRT. The SCT-TRT endcap test involved using approximately 25% of the SCT and 6% of the TRT. The pixel test involved one whole pixel endcap.

The cosmic data was collected using scintillator triggers. For the SCT-TRT endcap test, the TRT was also used as a trigger.

After installation in the ATLAS cavern, cosmic ray data is collected with the other ATLAS detectors as they are being installed. In these runs, an internal ATLAS trigger is used, given either by the muon trigger chambers or by the hadronic calorimeter. No magnetic field was available for any of these commissioning tests.

To date, runs have been taken with 1/3 of the TRT barrel, in conjunction with the calorimeter and muon systems. The SCT has also been integrated in the combined data acquisition but is only sending noise corresponding to four SCT module prototypes.

3. Reconstruction software
The commissioning tests on the surface were a test not only of the detector itself but of the software infrastructure which will be used for actual physics data collecting, when the LHC begins collision next year. The software chain needed to reconstruct the data collected from the
Figure 2. Schematic diagram of the setup used for the cosmic simulation used the tests in the ATLAS cavern.

detector can also be applied to simulated data. The data given by the different sub-detector readout drivers (RODs) is in byte stream format which must be decoded to provide the raw data objects (RDOs), such as hits on SCT strips or pixels or TRT drift times. These RDOs are required as input to the reconstruction. These byte stream decoders need access to information from the conditions database in order to get the cabling maps (i.e. which detector element is connected to which link of the ROD). In order to translate these raw data objects into geometrical position in space (silicon clusters, spacepoints or TRT drift circles), a detector description of the setup used (commissioning or final) is required. This description includes full geometry information, plus information such as alignment corrections and masked channels, retrieved from the conditions database.

The resultant calibrated objects are then used as the input to the pattern recognition algorithms and fitting tools to obtain a list of reconstructed tracks per event. These tests with cosmic rays have specific challenges as compared to tracks from LHC collisions. First of all they occur at random intervals so hence will not be synchronized with the detector readout clock. This has implications for both the calibration of the TRT and the requirement of a specific readout for the SCT. Secondly, the cosmic rays do not originate from neither the centre of the ATLAS detector, or any given co-ordinates. This means that no vertex constraint can be used in either the pattern recognition or the SCT space point creation algorithms.

4. Simulation software
A simulation of the different cosmic setups has also been provided to first setup and validate the full reconstruction chain and then to allow for data/Monte Carlo comparisons which could lead to improvements on the current simulation. A principle of the simulation chain is as follows. A single muon is generated at a given surface. The muons are then filtered by the requirement that they initially point to a given distance from the detectors centre, as shown in figure 2. Those passing this requirement are then passed through to Geant4 simulation to produce a list of hits in the detector. A second round of filtering requires that the muons must exist within a given volume. The surviving hits are passed through to a digitization and trigger emulator in order to finally produce the raw data objects and trigger information.
5. Monitoring

The commissioning tests provide a test-bed for the development of the ATLAS inner detector monitoring tools in a real data taking environment. Different monitoring tools run at different online levels, up to the Event Filter (third trigger level) where the full reconstruction chain is run. These tools provide checks on detector performance and the quality of the data collected before events are written to disk.

Histograms are produced of different reconstructed objects such as raw data information, silicon clusters, space points, TRT drift circles and tracks. These histograms are then sent to the Online Histogram Server and are collected by an interactive graphical interface called the Online Histogram Presenter at a frequency chosen by the user[2].

Two examples of monitoring histograms taken from data collected in the SCT and TRT barrel setup on the surface are shown in figures 3 and 4. Figure 3 illustrates the detection of the loss of synchronization between the SCT and TRT detectors. By plotting the difference in the direction of tracks, in $\phi$, between the SCT and TRT detectors per event for a cosmic run, it can clearly be seen that synchronicity is lost after approximately 8000 events. Figure 4 shows the noise occupancy measured in one of the TRT endcaps as a function of the event number. A jump in the noise occupancy can clearly be seen at around 1300 events. In this example, the increase of the noise occupancy from around 2% to 6% was due to a trip of the analogue low voltage regulators.

The ATLAS event display (ATLANTIS) can be run both online and offline to provide a detailed visual check of a single event. Figures 5 and 6 show two examples of event displays taken during the combined SCT and TRT barrel on the surface and from a cosmic run in the ATLAS cavern.

6. Data analysis results
6.1. Tests with random triggers

In each of the three commissioning setups on the surface, random triggers were used to measure the noise occupancy of the subdetectors involved. Noise was observed to be within specifications.
Figure 4. TRT endcap C noise occupancy as a function of the event number.

Figure 5. An Atlantis event display taken during the combined SCT and TRT barrel cosmic run in SR1.
Figure 6. An Atlantis event display during a run with the SCT and TRT barrel installed in the ATLAS cavern. Only 1/6 of the TRT was integrated in to the combined ATLAS DAQ for this event.

and in agreement with production tests. No increase of noise was observed in any tested configuration (e.g. varying the trigger rate from 5Hz to 50Hz, different grounding schemes pickup noise from another subdetector, running with heaters on and off.) Figures 7(a) and 7(b) show the noise occupancies for the SCT modules and pixels. The straw noise occupancy for the TRT detector was measured in all cases around 2%.

6.2. Tests with cosmic rays triggers
Reconstructed tracks from cosmic ray data can be used to measure the efficiency and resolution of the inner detector. In order to measure these quantities accurately, the detector must first be correctly aligned and calibrated. This was successfully achieved for the SCT and TRT barrel cosmic test which had a large amount of tracks with a sufficient number of measurements. Figure 8(a) shows the improvement of the measured SCT residual distribution after alignment.

The residual distributions can be used to extract an estimate for the detector resolution. One complication that arises from the cosmic tests is that no magnetic field was used for either the commissioning tests in SR1 or in the cavern. This means that the momentum of the cosmic rays is not known and the effects of multiple scattering can not be taken into account in the tracking algorithms. The result of this is that the track uncertainties are not correctly estimated. These track uncertainties will also contribute to the residual distribution.
Figure 7. Noise occupancies for the different SCT wafers and for different pixels. Data collected from commissioning tests at SR1.
Figure 8. Residuals measured in the SCT and TRT during the SCT-TRT barrel cosmic test.

Figure 9. The unbiased hit efficiency measured for different layers in the barrel SCT, for the nominal and aligned detector.

The approach followed in order to get an estimate of the detector resolution was to look at the $\sigma$ of the residual distribution as a function of the unbiased $\chi^2$ for each given hit (i.e. the $\chi^2$ of the track removing the contribution of the hit under evaluation). This dependence is shown in figure 8(b) for the TRT barrel. A small $\chi^2$ corresponds to tracks with a high momentum and hence minimal multiple scattering. From figure 8(b) a $\sigma$ of about 170 $\mu$m is obtained when $\chi^2$ tends to 0, consistent with the expected detector resolution.

Efficiencies have also been computed for each sub-detector. Figure 9 shows the measured efficiency of all SCT layers is greater than 99% after detector alignment.

7. Conclusions
The ATLAS inner detector is being commissioned with cosmic rays taken first above ground with the different assembled structures and then underground in the ATLAS cavern together with the calorimeters and muon chambers. This commissioning activity is ongoing with more and more of the inner detector being integrated into the combined DAQ for the ATLAS detector.

The reconstruction, alignment, calibration and monitoring chains have been successfully
tested with real data and cosmic rays events and are providing prompt feedback to the detector performance. Results show that the detector is within specifications in terms of noise, efficiency and resolution. A simulation of the different setups has also been provided to allow for a tuning of the Monte Carlo and to prepare the full chain before dealing with real data.

References
[1] ATLAS Inner Detector Technical Design Report, Volume 2: ATLAS TDR 5, CERN/LHCC/97-17, ISBN 92-9083-103-0
[2] A.Dotti, proceedings of Computing in High Energy and Nuclear Physics 2006.