Commissioning of the ATLAS detector with cosmic rays and first LHC beams

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Abstract. Looking towards first LHC collisions, the ATLAS detector is being commissioned using all types of physics data available: cosmic rays and events produced during a few days of LHC single beam operations. In addition to putting in place the trigger and data acquisition chains, commissioning of the full software chain is a main goal. This is interesting not only to ensure that the reconstruction, monitoring and simulation chains are ready to deal with LHC physics data, but also to understand the detector performance in view of achieving the physics requirements. The status of the integration of the complete software chain will be presented as well as the data analysis results.

1. Introduction
The already installed ATLAS detector [1] of the Large Hadron Collider (LHC) consists of an inner detector immersed in a solenoidal field of 2 T, calorimeters and a muon spectrometer operating inside an aire-core toroid system with a peak field in the coil windings of 4 T. A schematic view of the detector is shown in Figure 1.

Pattern recognition, momentum and vertex measurements of charged particles, and electron identification are achieved by the inner detector with a combination of discrete, high-resolution semiconductor pixel and strip detectors in the inner part of the tracking volume (Pixels and SCT), and straw-tube tracking detectors (TRT) in the outer part with the capability to generate and detect transition radiation to improve the electron identification. The electromagnetic calorimeter uses liquid argon as active medium to detect photons and electrons with excellent performance in terms of energy and position resolution. The hadronic calorimetry is provided by a scintillator-tile calorimeter (TileCal) in the central part and by a liquid argon electromagnetic and hadronic calorimeter in the endcaps. The calorimeter is surrounded by the muon spectrometer, consisting of precision tracking chambers, monitored drift tubes (MDT) and cathode strip chambers (CSC), as well as trigger chambers with excellent timing resolution made out of resistive plate (RPC) and thin gap (TGC) chambers. The CSC and TGC chambers are only in the muon endcaps.

The commissioning of the ATLAS experiment with cosmic rays started more than 3 years ago in parallel to the installation of the detector. For the inner detector, cosmic rays were in addition recorded in the CERN SR1 assembly area previous to installation in the ATLAS cavern. In the ATLAS cavern, data were taken with different detector and magnet configurations as systems were becoming available. Combined cosmic runs to integrate new systems were organized in the so-called Milestone weeks, the last one being in July 2008. From then on, ATLAS entered
in an almost continuous data taking mode to reach a stable operation for the LHC start-up on September 10th 2008. During the 3 days in which one of the two LHC beams were circulating through ATLAS, LHC beam data were also recorded. After the LHC incident on September 19th, a long global cosmic run took place in ATLAS to collect enough statistics for detailed detector performance studies.

The main motivations for commissioning the experiment with these kind of data are the following: first of all, to get experience in the operation of the detector in all aspects, from the trigger and data acquisition part up to the reconstruction software and data analysis all over the world in the Grid centers. These data could also be used to start understanding the detector performance, including providing its first alignment and calibration constants, towards reaching the very challenging physics requirements. The work presented here will be focused on the software and analysis aspects of the overall ATLAS commissioning activity.

2. Overview of the software operation chain
Focusing on the software aspects, the ATLAS operation model is as follows: The data readout by the ATLAS detector is filtered in a three-stage trigger system [2]. The recorded events are stored into different streams depending on whether they are meant for calibrations and alignment purposes or for physics studies. A sub-set of the physics events define the so-called express stream. The Tier-0 at CERN processes first the express stream in quasi real time, running the complete reconstruction and monitoring chain. The calibration centers, which include some Tier-2 Grid centers as well as the CAF (CERN Analysis Facility), perform a first pass calibration and alignment within 24 hours after the data has been taken. The obtained constants are then used for the bulk processing of the data, once they have been validated by a second re-processing of the express stream. Data are then distributed to the Tier-1 and Tier-2 centers for data analysis. Further data re-processings with improved reconstruction software and calibration constants can then take place at the Tier-1 centers. The reconstruction and monitoring chain also runs continuously online to provide an online event display and histograms monitoring the data quality during detector operations.

The reconstruction algorithms used during this first data period are in some cases exactly those that will run for collision data. However, specific adaptations to deal with particles not coming from the interaction point and, for the case of cosmic rays, not synchronized with the readout clock were needed in some algorithms.
Given the obvious differences between LHC collision data and the data recorded by ATLAS so far from cosmic rays and LHC single beam operations, LHC collisions are of course needed to make the final test of the operation chain described above. However, a very significant part of this chain has already been exercised with real data. The Tier-0 processing has reached a very stable and robust level of operation, the data quality is continuously monitored, both online and offline, data are being analyzed in detail and alignment and calibration corrections leading to very significant improvements have been provided. An example of the latter is shown in Figure 2, where the improvement obtained in the residual distributions in the silicon detectors after they have been aligned is clearly visible. A large scale re-processing of about 300 million events with improved software and detector calibration constants has also taken place successfully at the Tier-1 centers.

![Figure 2. Residual distribution in the Pixel and SCT barrel for the nominal geometry and the preliminary aligned geometry.](image)

There is nevertheless still some work ahead like for example the exercise of the 24 hours calibration loop. Up to now, all streams have been treated in the same way in what concerns the Tier-0 processing, i.e. all events have only been processed once using the latest available alignment and calibration constants which are updated with lower frequency basis.

### 3. Data analysis results

#### 3.1. Cosmic rays data

A large amount of cosmic rays have already been collected by ATLAS with different detector and magnet configurations. For instance, in 2008 ATLAS registered more than 500 million events, corresponding to a raw data volume greater than 1.2 PB and to around 700 TB of derived data, allowing for a relevant test of the computing model as well. The most interesting events are those collected during the global cosmic run already mentioned, since, with the exception of the CSC chambers, the whole detector was read out. During this period, data were collected with different magnet configurations to allow for some specific studies such as the determination of alignment constants. Figure 3 shows the accumulated statistics in the global cosmic run for the different streams (left) and how that translates into number of reconstructed tracks in the Pixel detector, the system with the smallest geometrical cross section for cosmic rays (right).

This large statistics allows us to perform detailed detector studies although it is still not enough to reach the precision required in the alignment of the tracking devices. Some examples of these studies will be given below for each sub-system: inner detector, calorimeters and muon spectrometer.

In addition to real data, a simulation of cosmic rays going through the ATLAS detector has also been provided for different magnet and detector configurations to allow for data/Monte Carlo comparisons. A Monte Carlo generator was used for simulating muons from cosmic ray
Figure 3. (Left) Number of cosmic ray events collected in ATLAS versus time since September 13, 2008 until the end of the global cosmic data taking period. (Right) Tracks reconstructed in the Pixel detector as a function of time during the global cosmic period.

Cosmic ray data have also allowed detailed studies in the calorimeters, for example validating the timing and energy calibrations. An example of the latter is illustrated in Figure 4 (right), where the measured energy loss per path length in the barrel hadronic calorimeter shown is in good agreement with the expected value for muons. The uniformity of the energy response has also been studied with these data. Figure 5 (left) shows the normalized reconstructed energy as a function of pseudo-rapidity together with the second sampling cell depth. Three cluster curves are shown: two different cluster algorithms applied to real data and the true cluster from the cosmic simulation. The data curves clearly track the cell depth as one would expect for a minimum ionizing particle and the uniformity of the response agrees with simulation at the level of 2%.

Progress in the understanding of the muon spectrometer performance has been achieved in terms of both tracking and triggering, providing first alignment and calibration corrections as...
**Figure 4.** (Left) Measured Pixel cluster width (units are number of Pixels) as a function of the track incident angle for the cases in which the solenoid magnet was turned on and off. (Right) Measured energy loss per mm in the TileCal hadronic calorimeter.

**Figure 5.** (Left) Normalized energy response in the electromagnetic calorimeter as a function of pseudo-rapidity $\eta$ for real and simulated data as well as second sampling cell depth $\eta$ dependence. (Right) Measured sagitta for tracks passing in a middle muon chamber before alignment (top) and after applying the alignment corrections obtained by the optical system (middle) and those obtained using tracks (bottom).
well as lists of problematic channels. An example of the alignment status is shown in Figure 5 (right) where the improvement of the residual distributions in one of the muon chambers thanks to the optical and track based alignment is clearly visible.

After checking the performance of the individual systems, the overall performance of the ATLAS detector can be studied with cosmic rays. For instance, the performance of combined tracking algorithms using measurements from both inner detector and the muon spectrometer or muon identification algorithms based on the calorimeters or muon system information can be verified.

Figure 6 shows the difference in the azimuthal angle $\phi_0$ and momentum obtained for tracks reconstructed in the inner detector and muon system for both real and simulated data. For the momentum measurement in the muon system, tracks coming from the bottom part were used, and therefore, due to the energy loss in the calorimeters, the values obtained are lower than for the inner detector. In spite of the fact that no alignment corrections were used, the data/MC agreement is fairly good, and indeed combined tracks are well reconstructed for cosmic rays, as can be seen in Figure 7.

**Figure 6.** Difference on the $\phi_0$ (left) and momentum (right) track parameters reconstructed in the inner detector and muon spectrometer for both real and simulated data. For the momentum measurement in the muon system, only the bottom hemisphere of the detector is used.

### 3.2. LHC single beam data

On the 10th of September 2008, the LHC managed to have the first bunch of protons at the injection energy of 450 GeV circulating around the ring and therefore going through the ATLAS detector. Previously, for safety reasons, the tertiary collimators 140 meters away from the ATLAS detector were closed and therefore for each beam injection a spray of particles was expected to go through the detector, producing the so-called splash events. Once the collimators were opened and beam was circulating through ATLAS, physics events were expected to be the machine background, so beam halo events containing mainly muons or the outcome of the interactions of the beam protons with the pipe walls or residual gas in the pipe. In the beginning, the RF capture was not yet achieved and the magnets were not all correctly adjusted. Therefore, the bunch of protons was expected to dissolve longitudinally after a few turns and the beam halo
Figure 7. An ATLAS event display showing a cosmic muon going through the whole detector.

contamination was also expected to be high. RF capture was already achieved on the second day of LHC operations and a clean beam could circulate through ATLAS until the night of September 12th, when a transformer of the machine failed.

Thanks to the previous commissioning period with cosmic rays, the ATLAS detector was ready to take data and reconstruct it successfully at the start-up of the LHC. For safety reasons, the Pixel detector was turned off and the SCT, muon chambers and the forward calorimeter were working at reduced high voltage. The first level trigger and the data acquisition were fully operational. The High Level Trigger (HLT) was available, however, since the plan was to store all events, it was decided to only use the HLT for streaming the data based on the first level trigger results.

One of the first splash events seen by the ATLAS detector is shown in Figure 8. As expected, these events are characterized by a huge number of signals in the detectors, e.g. more than 100,000 hits in the muon chambers, and a huge energy deposit in the calorimeters, more than 1000 TeV in the hadronic calorimeter and several TeV in the electromagnetic one.

Since these events produce a signal in almost all channels of the detector, as can be seen for instance in Figure 9 for the TRT, they turned out to be very useful to find dead channels and also to time in all channels with high precision with only a few of these events. For instance, for the TRT these events were used to validate the timing achieved with cosmic rays in the barrel with a precision better than 1 ns, to time in with also high precision the endcaps and to compute the time of flight corrections needed for LHC collisions.
Figure 8. One of the first LHC event seen by the ATLAS detector produced by the interaction of the beam with the closed tertiary collimators.

Once the collimators were closed and a single beam of protons was circulating in the ring, initially, before RF capture was achieved, quite a few particles crossing the detector horizontally at the same time were detected, corresponding to beam halo muons. Figure 10 (left) shows one of these events in the hadronic calorimeter, where the reconstructed clusters and horizontal tracks are displayed. These horizontal tracks were used in the hadronic calorimeter to validate the energy calibration, by computing the energy deposit per path length along the beam axis. As can be seen in Figure 10 (right), the response was checked to be uniform within 6% and the measured value ($1.9 \pm 0.2 \text{ MeV/mm}$) is in good agreement with that obtained with cosmic rays ($1.7 \pm 0.3 \text{ MeV/mm}$).

Once RF capture was achieved, the beam was much cleaner and therefore very few beam halo muons were seen in ATLAS. Unfortunately, due to the LHC transformer failure on the 12th of September, ATLAS could not record a large amount of data in these conditions. Figure 11 shows a comparison of the angle $\theta$ with respect to the beam axis of the tracks reconstructed in the muon spectrometer for cosmic rays and single beam data, where one can see that cosmic muons are mostly vertical while those recorded during LHC single beam operations were horizontal as expected for beam halo muons.

Concerning beam-gas interactions, none of these events have been observed in the ATLAS recorded data, probably because of the excellent vacuum in the pipe. Some candidates for beam hitting the beam pipe were observed. But, given that the inner detector was not fully on during this period, the identification of this kind of events is difficult.
4. Conclusions

The commissioning of the ATLAS detector with physics data started more than three years ago with cosmic rays. This has enabled us to put in place the full operation chain, from the trigger and data acquisition up to the analysis all over the world. Thanks to this intense commissioning campaign, ATLAS was ready to collect data already during the first day of LHC single beam operations on the 10th of September in 2008.

The analysis of both cosmic ray and LHC single beam data has improved our understanding
of the detector, reconstruction, monitoring and simulation software and has enabled us to obtain the first calibration and alignment corrections. ATLAS is looking forward to LHC collision data while continuing its cosmic ray data taking campaign and exploiting the data taken so far to guarantee readiness for the start of the physics programme.

References
[1] Aad G et al [ATLAS Collaboration] 2008 The ATLAS Experiment at the CERN Large Hadron Collider JINST 3 S08003
[2] ATLAS HLT/DAQ/DCS Group 2003 ATLAS High-Level Trigger, Data Acquisition and Controls Technical Design Report CERN Report CERN/LHCC/2003-022, ATLASTDR-016
[3] Allkofer O C et al 1971 The absolute cosmic ray muon spectrum at sea level Phys. Lett. B 36 425