ATLAS Muon Spectrometer Simulation and its Validation Algorithms

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Abstract. The ATLAS detector, currently being installed at CERN, is designed to make precise measurements of 14 TeV proton-proton collisions at the LHC, starting in 2007. Arguably the clearest signatures for new physics, including the Higgs boson and supersymmetry, will involve the production of isolated final-state muons. The identification and precise reconstruction of muons are performed using a combination of detector components, including the Inner Detector, comprising a silicon tracker, pixel detector, and transition radiation tracker, housed in a uniform solenoidal field, and the precision standalone Muon Spectrometer, comprising monitored drift tubes and cathode strip chambers, triggered by resistive plate chambers and thin-gap chambers, and housed in a toroidal field. In order to manage the complexity and to understand the performance of the ATLAS Muon Spectrometer, a detailed full detector simulation is required and it should be kept under control by means of automatic validation procedures.

We describe the implementation and the functionalities of the recently developed MuonValidation package, which has been developed as a dedicated tool to monitor and validate the performance of the Full simulation and digitization of the Muon System. Its flexible design allows comparisons between different Muon Spectrometer geometrical layouts and different software releases. Validation results based on fully simulated GEANT4 events, using the complete detailed geometrical description of the detector, are shown.
1. Introduction
The ATLAS detector[1], currently being installed at CERN, is designed to make precise measurements of 14 TeV proton-proton collisions at the LHC, starting in 2008. The apparatus, one of the biggest and most complex ever designed, requires a detailed and flexible simulation to deal with layouts used for the Commissioning phases, deformations and alignment corrections, enabling detailed physics studies which will lay the basis for the first physics discoveries.

The full simulation[2] of the ATLAS detector consists of a collection of independent modules developed by the different teams of each subdetector (Inner Detector, Calorimeters, Muon Spectrometer and Magnet System). Dynamic loading and the organization of the detector simulation in the form of plug-in modules make the implementation extremely simple, as no modification of the framework code is required. The reference simulation tool adopted by all the detector component applications is the GEANT4 package[3]. It describes the new physics environment and tests the apparatus prototypes extensively, validating against results from real data from the ATLAS Combined Test-Beam (CTB).

The ATLAS detector geometry is described in the Software using a set of geometry primitives, called GeoModel[4], which construct a transient model from primary parameters stored in the DD database. This implementation works as a common geometry source for the simulation, the digitization and the reconstruction programs, and consequently has been adopted by the Muon Spectrometer software.

The Muon Detector Description and Simulation programs model several detector technologies. They comprise five different subsystems: two for the precision chamber description, two for the trigger system and the toroids, which support many of the chambers and provide the magnetic field. New code to emulate the digitization response of all four Muon detector technologies and a new Event Data Model (EDM) have been put in place to cope with the GEANT4 simulation input.

In this note, after summarizing the main components of the ATLAS Muon Spectrometer and their functionality (Section 2), we present the Muon Validation tools developed to test internal consistency on the global Muon simulation, digitization and reconstruction performance (Section 5). The current status of the Muon simulation and digitization is also shortly presented (Sections 3 and 4).

2. The ATLAS Muon Spectrometer
The ATLAS Muon Spectrometer[5] has been designed to provide a three-point measurement of tracks in large superconducting air-core toroid magnets. Its momentum measurement capability combines the highest possible efficiency with a momentum resolution of 2-3% at 10-100 GeV/c and 10% at 1 TeV, taking into account the high-level background environment, the inhomogeneous magnetic field, and the large size of the apparatus (24 m diameter by 44m length). An optical alignment system controls the relative positioning of muon chambers at the 30 micron level.

The Muon Spectrometer dominates the size of the ATLAS experiment with its outer diameter of 22 m. Its functioning is based on the magnetic deflection of muon tracks in the system of three superconducting air-core toroid magnets, instrumented with separate trigger and high precision tracking chambers. Over the pseudorapidity range $|\eta| < 1.0$ (barrel region), magnetic bending is provided by the large barrel toroid. For $1.4 < |\eta| < 2.7$ (endcap region), muon tracks are bent by two smaller end-cap magnets inserted into both ends of the barrel toroid. Each toroid consists of eight flat coils that are assembled radially and uniformly around the beamline. The toroids provide $3T \times m$ bending power in the barrel region and $6T \times m$ in the endcap region. Over $1.0 < |\eta| < 1.4$, usually referred to as the transition region, magnetic deflection is provided by a combination of barrel and endcap fields. This magnet configuration provides a field that is mostly orthogonal to the muon trajectories. The Muon Chambers are positioned such as to...
take maximum use of the effective bending power of the magnetic field.

In the barrel region the precision measurement of the muon tracks in the main bending direction of the magnetic field is performed by Monitored Drift Tube chambers (MDTs). The trigger function, the bunch-crossing identification and the second coordinate measurements are provided by three stations of Resistive Plate Chambers (RPCs). They are located on both sides of the middle MDT station, and directly above or directly below the outer MDT station. Chambers in the barrel are placed at three different radii with respect to the beam line.

The strategy chosen for the muon endcaps differs from that of the muon barrel, because the cryostat is a closed structure which makes it impossible to position chambers inside. In order to profit most from the magnetic field, the inner station EI (Endcap Inner) and the middle station EM (Endcap Middle) are placed as close as possible to the endcap cryostats. Using a third measurement station, it becomes possible to measure the angle under which the muon leaves the middle station. Placing the outer station EO (Endcap Outer) further away from the interaction point improves the precision on this measurement. All trigger chambers for the endcap region, TGC (Thin Gap Chambers) technology, are placed behind the magnets.

Since the occupancy for an MDT chamber would be too high for chambers close to the beam pipe, and to withstand the demanding particles rates and background conditions, Cathode Strip Chambers (CSCs) with higher granularity are placed in the innermost ring of the endcap stations.

3. Muon Spectrometer Detector Description and Simulation

The simulation program for the ATLAS Muon Spectrometer is currently in a full operational mode and integrated into the common offline software framework of ATLAS, called ATHENA[6]. The GEANT4-based muon detector simulation program (G4Atlas) is based on criteria like dynamic loading and action-on-demand, and all user-requested functionality has been added by means of plug-in modules.

3.1. Muon Databases and Detector Description

The description of the ATLAS detector (and so the Muon Spectrometer) relies on two main software components:

(i) a relational database which implements a schema capable of hierarchical version control
(ii) a set of geometrical primitives and classes providing all the necessary volume and material description, in terms of which the ATLAS detector is described.

The detector description parameters are made available to the detector description packages through the Oracle Detector Description Database[7], which is common to all ATLAS subsystems (calorimeters, inner detectors) and supports versioning or tagging in which geometries are ‘frozen’ periodically.

An ATLAS-wide Detector Description software package, GEOModel, has been fully deployed in the Muon System as the single source of geometry information for both the simulation and the reconstruction. The main purpose of GEOModel is to support a central store for a unique detector description information that can be accessed by many clients: The simulation, the digitization and reconstruction programs. MUnGEOModel, the implementation for the Muon Spectrometer in GEOModel, provides a scheme for accessing the raw geometry of a detector and subsystem-specific services synchronized to the raw geometry, while incorporating time-dependent alignments (see Figure 1). Here only the main points of the Muon Spectrometer Detector Description will be outlined, referring to dedicated documents[8] for a complete discussion.

The procedure, however, requires a detailed description of all the active and inert material in the Spectrometer. It includes an entire material geometry (the part which is seen directly by the simulation engine, GEANT4) in addition to the readout geometry. The geometry model currently
AMDB → DDDDB (Oracle DB) → GeoModel

Figure 1. Dataflow of GEOMODEL: The AMDB detector description file, which contains the primary Muon Spectrometer description parameters, gives is converted into an Oracle Database (Detector Description Database). GEOMODEL itself depends on this file and provides geometry information for track reconstruction and the full ATLAS GEANT4 simulation.

implemented in ATHENA describes the size, shape, position and materials of all the subdetectors. A precise description of passive materials, including shields and toroidal magnet systems, has recently been implemented in MUONGEOMODEL to account for the multiple Coulomb scattering and for energy losses. A single implementation of MUONGEOMODEL package is able to run on various layouts of the Muon Spectrometer.

3.1.1. Detection of Geometry Clashes The Muon Spectrometer Detector Description system has undergone specific visual debugging during the past year, addressed to the detection of geometrical conflicts among the volumes. The detection of the overlaps is complicated by the complexity of the geometry. However their removal has been especially crucial to allow, where possible, tolerance between components in view of the chamber misalignment inclusion. Chamber conflicts can cause unpredictable behavior by the simulation, from job crashes to subtle changes to particle multiplicity and physics effects.

The volume clashes can be classified into three different types (see Figure 2):

- **Overshootings**: when a given volume (A in Figure 2) sticks outside its mother volume;
- **Overlappings**: when two daughter volumes overlap (A and B, or C and D);
- **Solids**: when a solid volume has one or more null dimension(s).

Figure 2. Representation of the two different types of clashes between volumes. Overlapping errors: between A and the mother volume. Overshooting errors: between the two daughter volumes A and B, or C and D. Solid errors are not represented here, they correspond to the situation when one or more dimension(s) defining the solid volumes happen to be null.
GEANT4 has a dedicated tool, the **recursive.test**, which recursively loops over the full volume tree detecting the overlaps, and dumps a list of the conflicts and their positions in different systems of reference. The GEANT4 visualization tools then help to check the clashes, once it is clear where and between which volumes they occur. A GEOMODEL specific tool for the clash detection, based on the v-atlas code, has also been used[9]. In the following, some of the solved overlaps are shown. A few remaining unsolved clashes are strictly related to GEOMODEL functionality. They, anyway, can been proven not to spoil the robustness of the simulation.

### 3.2. Muon Hits

The information coming from the interaction of the simulated tracks with the sensitive part of the detector at a step of the simulation is encapsulated as a hit objects. Muon hits are generated by GEANT4 when charged particles cross the sensitive part of the Muon chambers.

Simulated Muon Spectrometer hits have a very light content, due to the fact that all the geometrical information is encapsulated in the specific simulation identifiers. In addition to the hit identifier, Muon hits contain information required by the digitization and pile-up procedures. A detailed description of the Muon hits content is given in [10].

### 4. Muon Spectrometer Digitization

The goal of the Muon digitization is to simulate the output signal of the ATLAS Muon Detector, starting from the output of the GEANT4 Simulation, the hit objects. The Muon digitization consists of four algorithms, one for each muon technology (MDT, RPC, CSC and TGC), which produce collections of simulated Raw Data Objects (RDOs). The Muon digitization has been designed to be independent from the GEANT4 simulation. It relies only on the read-out geometry (provided by MUONGEOMODEL) and on the detector-specific Muon Spectrometer Offline Identifiers (OIDs) scheme[11]. A detailed description of the Muon digitization is discussed in a dedicated document[10]. Here only the main steps of the general procedure are summarized.

Muon Digits are the output of the first step of the digitization procedure and resemble the detector output. They are labelled by OIDs which contain the digit geometry information packed according to a given scheme[11]. The OIDs in principle do not coincide with the Simulation Identifiers (SimIDs) associated to the hit objects. The design idea is to keep the event simulation disentangled from the digitization/reconstruction. The geometrical description of the detector elements is obtained from read-out geometry methods of MUONGEOMODEL. They allow to get information (e.g. the hit distance from the chamber read-out side) needed by the digitizers to construct the digit parameters. In a subsequent step, the Muon digits are converted to Muon RDOs, i.e., the transient representation of the byte-stream (electronics output). Any reference to the Monte-Carlo information is therefore lost after the digitisation; that is, the Muon digits or RDOs do not carry any link to the original simulated particles. To establish the MC truth of tracks and for validation purposes, a separate object, a map, is produced at the digitization level, in order to maintain the link to the original simulated particles at digit or RDO level[10].

In addition to being capable of handling hits coming from a single bunch-crossing, Muon digitization is able to handle “piled-up” collisions. Before performing the digitization, hits from several bunch-crossings are overlaid, taking into account the global time of the hit which is defined as the GEANT4 hit time plus the time of the respective bunch-crossing with respect to the main crossing. Simulated GEANT4 hits of a signal event can be read in together with hits of previously simulated background events (both minimum-bias and cavern background) and the digitization proceeds afterwards.

### 5. The MuonValidation Package

The aim of the MuonValidation package is threefold:
• to ensure the compatibility and reproducibility of data samples produced at different sites (site validation)
• to monitor the changes and the improvements of the ATLAS detector geometry and simulation by means of a detailed check on an event by event basis, for each step in the muon software chain;
• to check the physics content of the generated samples (physics validation), the top priority for the ATLAS Computing system commissioning phase.

The structure of the MuonValidation applications is shown in Figure 3. The package is part of the ATLAS offline software, it is located in the CVS repository under the offline/MuonSpectrometer/MuonValidation container.

The quality of the simulation and digitization procedures can be monitored by histogramming various characteristic and properties of the hit and digits objects. The MuonHitTest and MuonDigitTest algorithms, have been designed to perform checks and validation of the Muon Hits and Digits, for each muon technology. The two packages implement a common output format. At the end a summary for all compared histograms is dumped. The validation test suite consists of a modular analysis structure based on ROOT, which runs off an N-tuple from the MuonValidation package.

The analysis procedure consists of two steps. First, an open-ended list of sub-detector-specific macros is run from a master process to produce the two sets of validation histograms (this is done by MuonHitTest and MuonDigitTest). In a second step, an histogram-by-histogram comparison is performed between two sets of validation histograms, providing a bin-by-bin significance plot.

The MuonEvtValidator algorithm has been designed as an interface to easily compare the outcome information of MuonHitTest and MuonDigitTest. The main advantage of this interface structure is its flexibility, being independent from the original format of the input information. This allows not only the validation of simulation and digitization, but also the validation of different ATHENA releases or/and Muon Spectrometer geometries and, in future, the validation...
of cosmic data or collisions data. MuonEvtValidator compares the contents of two input files, using relevant variables:

- the total number of hits/digits per station; this allows to identify inefficiencies when assuming the same number of events in each input collection.
- the average number of hits/digits per station and per event; this allows also to detect these inefficiencies but is independent from the number of events in each input collection.

The validation variables are calculated at station level. The main part of the whole package is represented therefore by the class MVCommonStationData which represents the station unique parameters (e.g. $\eta$, $\phi$, StationNameID identifier), together with its hit and digit information on an event by event basis.

The underlying ATHENA algorithm of the MuonEvtValidator package is the MVCombined class. In a first step, the input information of the packagesMuonHitTest and MuonDigitTest is read and distributed in the corresponding MVCommonStationData objects. In a second step all validation plots are created by various loops over the station identifiers using the MVCommonStationData methods to retrieve the necessary validation information. The overall structure of this algorithm allows also an easy way to compare to hits or digits distributions for different versions, since the internal representation of hits and digits is identical.

MuonValidation uses the features of the Run Time Tester (RTT) framework\footnote{RTT} to monitor the basic functionality of the package and the most meaningful comparisons. The RTT allows one to define a series of tests to be performed automatically at each nightly build of the ATLAS offline software. This series of tests is standardized and rapidly applicable on every new release. It is a powerful automatic tool to identify and detect bugs and problems.

6. Outcome of the Muon Simulation Validation Package

Some control plots for the simulation and the digitization using a single muon sample\footnote{Single muons with $p_T = 50$ GeV/c, ATHENA-Release 12.0.3} are shown in Figures from 4 to 7. These plots can be generated by running the MuonEvtValidator package inside the ATHENA software framework.

![Figure 4. Comparison of the overall number of MDT hits and digits versus $\eta$-identifier.](image1)

![Figure 5. Comparison of the average number of MDT hits and digits per event versus $\eta$-identifier.](image2)
expected for MDT chambers, since muons interact with the gas inside one MDT tube several times when passing through. Only one hit per tube and event is thus accepted for the validation step at the MDT level and secondary hits are neglected. These quantities are calculated for each station separately as well as for all stations with the same $\eta$, $\phi$ and StationNameId. The latter choice is done since the number of stations is too large to be compared one by one effectively. Not only the hits/digits multiplicity comparison might be used as a validation quantity. The absolute value of the average number of digits per event for a given station type is also of interest: e.g. Barrel Outer Stations (BOS) stations consist of two multilayers with three tubes each. We expect roughly six digits per muon passing through one BOS station, which is perfectly consistent with the average value shown in Figure 5 (The station name identifier for BOS stations is 5).

The validation procedure of RPC, TGC and CSC chambers is more complicated, since their structure implies that one hit in a simulation step can lead to several digits. This explains the large excess of digits shown in Figure 7. A more detailed validation of these chambers can be achieved by comparing the results of different ATHENA software releases.

With the variables defined so far, only inefficiencies on the station but not on lower levels, e.g. on the tube level for MDT stations, can be detected. The package MuonEvtValidator provides also important check plots at lower levels, which is described in the following by the example of MDT chambers. If no inefficiencies at the MDT tube level are assumed, it is expected that each digit has a parent hit at simulation level. The inverse association is not that trivial since some hits might not be digitized for different reasons. Figures 8 and 9 show the association-probability for the above sample.

It can clearly be seen here that the association probability for digits to hits is 100% as expected. The inverse association probability is less than 100%, which is a hint that not all hits get digitalized. This explains the small excess of hits seen in Figure 4.

The MuonEvtValidator package provides not only a comparison functionality of the simulated and digitized data, but also the validation of the hit or digit information throughout different ATHENA releases and Muon Spectrometer geometries.

7. Conclusions
In this paper we present several ATHENA algorithms which have been implemented to perform an automatic validation of the Muon Detector Description, simulation, digitization and Reconstruction steps. They are part of the ATLAS offline software.
The MuonHitTest and MuonDigitTest run on the output of the simulation or of the digitization respectively, producing ntuples which can be used to directly monitor the Muon hit or digit parameters, or can be fed to the MuonEvtValidator algorithm. MuonEvtValidator can perform flexible comparisons between hits from different releases or muon databases or between hits and digits for the same database, etc., according to the input file types.

The MuonValidation package offers a set of user-friendly algorithms inside the Athena framework to evaluate the performance of several steps of the offline full chain. This performance evaluations allows a basic validation of the muon software using the RunTimeTest mechanisms for each new software release.

Acknowledgments
We thank Steve Goldfarb, Jean-Francois Laporte, Laurent Chevalier, Ahmimed Ouraou and Stephane Willocq for the fruitful discussions regarding this work.

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