Design and Performance of the ATLAS Muon Detector Control System

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Abstract. Muon detection plays a key role at the Large Hadron Collider. The ATLAS Muon Spectrometer includes Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC) for precision momentum measurement in the toroidal magnetic field. Resistive Plate Chambers (RPC) in the barrel region, and Thin Gap Chambers (TGC) in the end-caps, provide the level-1 trigger and a second coordinate used for tracking in conjunction with the MDT.

The Detector Control System of each subdetector is required to monitor and safely operate tens of thousand of channels, which are distributed on several subsystems, including low and high voltage power supplies, trigger and front-end electronics, currents and thresholds monitoring, alignment and environmental sensors, gas and electronic infrastructure. The system is also required to provide a level of abstraction for ease of operation as well as expert level actions and detailed analysis of archived data.

The hardware architecture and software solutions adopted are shown along with results from the commissioning phase and the routine operation with colliding beams at 3.5 × 3.5 TeV. Design peculiarities of each subsystem and their use to monitor the detector and the accelerator performance are discussed along with the effort for a simple and coherent operation in a running experiment. The material presented can be a base to future test facilities and projects.

1. Introduction

ATLAS is one of two general-purpose detectors for the Large Hadron Collider (LHC) at CERN. The ATLAS muon spectrometer is designed to measure the transverse momentum ($p_T$) of muons with $p_T > 3$ GeV with a resolution of 3% for $p_T < 250$ GeV and of 10% at $p_T$ of 1 TeV. For this it relies on large air-core toroidal magnets in the barrel and in the endcap with a typical field of 1 Tesla, and four types of trigger and precision tracking detectors: Monitored Drift Tubes (MDT) for precision tracking in the spectrometer bending plane, Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC) for triggering in barrel and endcap, respectively, and Cathode Strip Chambers (CSC) for precision measurements in the high-rate endcap inner layer where MDTs would have occupancy problems. In the following sections, after a brief illustration of the ATLAS Detector Control System (DCS), the muon spectrometer DCS is presented. Due to the space limitation only a few selected subsystems are described in more detail.

2. The ATLAS Detector Control System

The ATLAS DCS is organized as a large distributed system following a hierarchical structure. A Finite State Machine (FSM) provides the translation from the infinite conditions the detector and its thousands of analog and digital devices might be, to a limited set of known states. At the lowest level of the hierarchy are the Local Control Stations (LCS), computing nodes which have a direct connection to hardware devices such the as low and high voltage (LV,
HV) channels, environment sensors, services, etc. Above this level, each subdetector has a **Subdetector Control Station** (SCS) which owns the subdetector top FSM node and provides access for subdetector user interfaces. At the highest level is the **Global Control Station** (GCS) which connects the whole experiment and summarizes the ATLAS state. The various phases of data taking preparation and running are described by states (**SHUTDOWN**, **TRANSITION**, **STANDBY**, **READY**, ...), their transition commands (**GOTO_SHUTDOWN**, **GOTO_STANDBY**, **GOTO_READY**, ...) and alarm severity conditions (**OK**, **WARNING**, **ERROR**, **FATAL**). The commands, sent from the central DCS or the Subdetector Control Station, are propagated through the FSM tree down to the hardware devices. The commercial supervisory control and data acquisition software **PVSS**[1] (now version 3.8 SP2) with custom extensions by the CERN **Joint Control Project (JCOP)** framework components [2] has been chosen as software environment. This environment provides the required scalability, a structured and hierarchical organization and a very flexible user interface. It supports the most common standards to connect to hardware devices and to external databases, like **ORACLE** [3], which are in use at CERN.

3. The DCS of the Muon Spectrometer

Given the different characteristics and requirements of the 4 detectors used, the muon DCS is naturally composed of 4 independent subsystems although, wherever possible, an effort was made to keep design choices and the infrastructure organization similar. Some characteristics of the ATLAS Muon Spectrometer are summarized in table 1. More details can be found in [4].

| Technology | η Range | #Readout Ch. | Nominal HV | Gas Mixture | #Chambers |
|------------|---------|-------------|------------|-------------|-----------|
| MDT        | | | 340 k      | 3080 V      | Ar:CO₂ (93.7% at 3 bar) | 1150 |
| RPC        | | | 360 k      | 9600 V      | C₂H₄F₂ iso-C₄H₁₀ SF₆ (94.7:5.0:0.3%) | 544 |
| TGC        | 1.1 < |η| < 2.4  | 320 k      | 2800 V      | CO₂ n-Pentane (55.45%) at 17°C | 3588 |
| CSC        | 2.0 < |η| < 2.7  | 31 k       | 1800 V      | Ar:CO₂ (80:20%) | 32 |

Table 1. A few numbers relative to the four detector technologies used in the ATLAS Muon Spectrometer are here summarized. Indicated are, among others, the coverage in pseudorapidity (η), the number of readout channels, the nominal HV setting used during Physics collisions and the gas mixture.

The Muon DCS system is in charge of:
- Operate and monitor the detector power system including the detector HV and LV supply.
- Read and archive all environmental and detector condition data.
- Control which actions are allowed under what conditions to prevent configurations potentially harmful for the detector.
- Adjust working point parameters (HV, front-end thresholds etc.) to ensure efficient data taking and synchronized operation with ATLAS and the LHC.
- Control and archive data from the alignment system and the environmental sensors.
- Configure the front-end electronics (MDT).
- Provide coherent shift and expert tools for detector monitoring and maintenance.

Given the large size of the system, the load of the control and monitoring tasks is distributed over a farm of more than 40 multiple-core computers to allow reliable performance in terms of stability and speed. The four FSM top nodes are connected to the ATLAS central DCS and are used to communicate and exchange states, commands and severity flags. Information from external systems (LHC beam conditions, rack monitoring, central gas system, etc.) is distributed and used to verify the proper detector conditions or to trigger automatic safety actions in case of failures. Several detector specific panels and expert tools are provided to study the detector performance and help during maintenance periods.
4. The Power System

With the exception of the CSC LV, which adopted a different solution \(^1\), the complete HV and LV supply for the muon spectrometer is based on the commercial CAEN EASY (Embedded Assembly SYstem) solution\(^5\). EASY consists of components made of radiation and magnetic field tolerant electronics (up to 2 kG) and is based on a master-slave architecture. **Branch controllers**, hosted in a CAEN mainframe, act as master boards, allowing the control and monitoring of electronics in up to 6 remote EASY crates. Fig. 1 shows such a setup along with the list of components connected to the DCS required to operate the detector. The mainframes (SY-1527) and the branch controllers (A-1676) are located in the ATLAS counting rooms. The radiation and magnetic field tolerant electronics, including power supplies, HV, LV boards, are located in the experimental cavern. Several of the boards delivering HV and LV or additional services were developed or adapted to specific ATLAS needs in collaboration with the manufacturing company. While the remote hardware placed in the experimental cavern was allocated from the beginning, the infrastructure of CAEN mainframes and controlling computers was adapted and upgraded during the commissioning phase. In particular the number of mainframes was upgraded from two to four for the the RPCs, and from one to two for the MDTs for more efficient operation and faster data retrieval. Further optimization was done by fine tuning the **OPC groups** in **Polling Mode** for the MDTs or by running the CAEN mainframes in **Event Driven Mode**. This hardware configuration (using the latest firmware version 3.0) has shown over the last year of running a satisfactory stability. Although PVSS is available both on Linux and Windows platforms, the need for a communication based on OPC \(^6\) with the CAEN mainframes (as most of the common off-the-shelf solutions) biased the choice toward Windows at least for the systems connected via OPC to some hardware.

![Figure 1. The CAEN EASY Power System architecture. A total of 8 Mainframes (2 for MDT+CSC, 4 for RPC, 2 for TGC) are located in the counting room. On the right, the CAEN EASY hardware located in the experimental hall is listed.](image)

### Detector Board Items Channels Use

| Detector | Board | Items | Channels | Use      |
|----------|-------|-------|----------|----------|
| CSC      | A3540AP | 12    | 144 ch.  | HV       |
| MDT      | A3016  | 32    | 192 ch.  | LV       |
|          | A3025  | 113   | 452 ch.  | LV       |
|          | A3540AP | 204   | 2448 ch. | HV       |
| RPC      | A3009  | 80    | 1280 ch. | LV       |
|          | A3025  | 160   | 4000 ch. | LV       |
|          | A3486  | 35    | 70 ch.   | AC/DC    |
|          | A3512AP | 49    | 294 ch.  | LV       |
|          | A34801 | 50    | 6400 ch. | ADC      |
|          | A34802 | 24    | 3072 ch. | DAC      |
|          | A3025  | 74    | 296 ch.  | LV       |
|          | A365010D | 24  | 48 ch.   | LV       |
|          | A31100 | 74    | 74 ch.   | LV       |
|          | A3486  | 26    | 52 ch.   | AC/DC    |
|          | A3535AP | 126   | 4032 ch. | HV       |

5. Environmental Monitoring and Front-End Initialization

MDT and TGC communicate with the front-end electronics and read out a manifold of environmental sensors using Embedded Local Monitor Boards (ELMBs). The ELMB\(^7\), which is a custom ATLAS radiation and magnetic field tolerant plug-on board, has an on-board CAN-interface and is fully programmable, either via an on-board connector or via CAN. There are 18 general purpose I/O lines, 8 digital inputs and 8 digital outputs. Optionally, a 16-bit ADC and multiplexing for 64 analogue inputs is provided. Within the Muon Spectrometer the ELMBs are used for the readout of temperature sensors (~12000 sensors), chamber displacements (TGC ~3700), dynamic magnetic field map (~1800 sensors), monitoring of voltages and temperatures of the front-end electronics. Most of the MDT chambers are equipped with up to 30 temperature

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\(^1\) WIENER Marathon [http://www.wiener-d.com/](http://www.wiener-d.com/)
sensors. About half of the MDT chambers is equipped with up to four B-sensor modules each, that can measure B-field values in three dimensions with a precision of $10^{-4}$ up to a maximum field of 1.4 Tesla[8].

The MDT front-end electronics initialization is done via JTAG, programming frontend shift registers from the ELMB digital outputs. A sophisticated mechanism and interplay of the DCS and the DAQ has been put in place to allow stop-less removal or recovery of detector modules which have encountered an error. The ELMBs are controlled by the DCS via OPC server clients structure by means of a commercial CAN interface located on the DCS computers.

6. The Barrel and Endcap Alignment System
Two alignment systems[9, 10] are provided for the barrel and the endcap chambers, respectively. In the barrel region the alignment is performed via custom RASNIK optical modules, each one containing a camera, a light source, a coded mask and a lens. Three layers of multiplexing are applied, controlled and monitored by eight PCs, each one equipped with a frame-grabber, which grabs the pictures to be analyzed. Analyzed results are stored into a database for off-line corrections of the muon tracks. In the endcaps, RASNIK modules are complemented by BCAM modules for alignment measurements between neighbouring chambers or layers. The data is readout and processed on embedded VME systems. Both systems are controlled and integrated in the DCS project using the PVSS software environment and FSM architecture. The alignment system allowed, already after the commissioning phases, to reach the design accuracy of track sagitta: $< 40 \mu m$.

7. The TGC Chamber Charge Measuring Circuit
The main building block of the TGC on-detector DCS is a custom, radiation tolerant DCS-PS board[11]. Its functionality includes setting and reading the front-end thresholds, measuring chamber charge in response to minimum ionizing particles, configuring programmable parameters of front-end ASICs, reading temperature and alignment sensors. Each of these boards is mounted on the TGC trigger electronics and hosts an ELMB with custom firmware. A dedicated Chamber Charge Measurement Circuit (CCMC) integrates, over a given time window, the charge delivered by the TGC chambers single analog output channel. It verifies whether a corresponding chamber produced a coinciding hit, and if so, the integrated analog charge is delivered to the ELMB. The CCMC readout mechanism is implemented entirely within the ELMB. It was designed to supply the CCMC with a set of requested operation parameters, and collects the integrated charges in a histogram. The complete histogram is sent to the LCS, where it is analyzed offline. The primary aim of the CCMC mechanism is to supply information concerning the TGC chambers and electronics performance. Abnormal counting rates or changes in histograms shape may indicate malfunction of a chamber or of the electronics. It allows estimating the loss of trigger events by a high threshold cut, and estimating the level of noise from random digital triggers. Thus, it provides the TGC DCS with a powerful diagnostic tool.

8. RPC Gas Gap Currents and Peak Measurements
For the RPC the front-end threshold settings and the monitoring of the detector are performed within the CAEN Power System using DAC (A-3802) and ADC (A-3801) modules[12]. The individual gas-gap currents along with environmental parameters and front-end electronics current draw are monitored with high granularity giving a detailed picture of the detector performance. In addition a special feature, requested to CAEN when designing the DCS, was for the ADC channels (6500 in total) to be capable both of averaged and peak sensitive readout. The first allows monitoring of the average current corresponding to the ionization rate and the chamber dark current. The peak readout, which is tunable with threshold and gate parameters,

2 KVASER http://www.kvaser.com/
can be used to spot HV noise and study events with large multiplicities as cosmic shower events or beam background effects which would saturate the digital path of the DAQ system. On November 21st 2009, the DCS precisely measured the LHC splash events intentionally generated for detector and timing studies by colliding one proton beam bunch against a closed collimator upstream of ATLAS. The firmware of the ADCs has been recently upgraded with the capability of per channel threshold setting and absolute clock counter/time stamp measurement so that the DCS will be able to deliver peak information with a precision of 20 ms.

9. Online Data Quality through the DCS
Collecting all relevant information from the detector, its HV and LV settings, the current draw, the status of the front-end initialization, the trigger rates, the DCS of each muon subdetector is able to automatically deliver Data Quality flags. This information, calculated online with a fine granularity and archived in the central ORACLE database, provides a good estimate of the detector conditions during data taking and is used to flag the offline reconstruction and data selection. A subset of this information specially formatted (COOL) is also accessible by the standard ATLAS offline analysis environment with minimal overhead.

Figure 2. a) Layout of the Muon Top Panel embedded into the ATLAS DCS FSM. A synoptic view of the four muon technologies along with summary MUON and ATLAS/LHC information. The navigation through the FSM tree discloses many monitor panels and expert tools. b) The network of the muon DCS computing nodes. At the top of the hierarchy is the muon GCS which connects to the 4 independent muon SCS and the common muon infrastructure.

10. Muon Project Unification and DCS Performance
During the 2010 data taking a common muon project with the scope of unifying and simplifying the detector operation and the shift load was added. This project is connected to the top node of the 4 subdetector systems allowing common operation to all four systems and is the ideal placeholder for devices which are common for all components. One such system handles the Stable Beams Flag from the LHC and confirms the safe state of the detector for beam adjustments or physics data taking. In Fig. 2 the FSM top panel of the muon DCS is shown with a synoptic view of the four detector technologies along with a summary of the main infrastructure blocks (power, front-end initialization, DAQ, gas, data quality, LHC status etc).

The 2010 data taking has been a success for ATLAS and the muon detectors and the effort of integration and unification has allowed the gradual reduction of the shift personnel to two people in 2010 with the aim of a single shifter for the 2011 data taking phase. Since August 2010 automatic high voltage ramping from safe settings to nominal voltage triggered by the LHC Stable Beams Flag was introduced reducing further the load to the shift personnel.
11. Background Maps and Luminosity Measurement
The size and high granularity of the information read out and archived by the DCS is a valuable source of data for detector physics. The currents in the gas-gaps of the RPCs, measured by the DCS with a sensitivity of 2nA, allow for a precise estimation of background and beam effects. The monitored currents, environmental variables corrected and pedestals subtracted are used to estimate average currents per surface unit to study beam background and activation effects. Fig. 3 shows the distributions over the longitudinal coordinate $z$ of the currents as measured and normalized by the detector surface for the 3 double layers of RPC chambers. Higher currents are observed at larger $\pm z$, as expected from the cracks between the barrel and endcap calorimeters. A good correlation of the total instantaneous RPC HV currents versus the luminosity is observed. The obtained distributions are in agreement with Monte Carlo simulations and provide a good means to estimate background and detector occupancies when running at nominal LHC or upgrade luminosities.

![Figure 3](image.jpg)

**Figure 3.** DCS online plots displaying the pedestal subtracted gas-gap currents for the 3 layers of RPC chambers (a). The normalized sum is shown together with the instantaneous luminosity and proton beam currents in b. A linear fit of the currents from runs with different instantaneous luminosities is shown in c.

12. Conclusions
The design and performance of the ATLAS Muon Spectrometer DCS have been remarkably successful. The use of commercial solutions complemented by custom developments and a distributed and scalable design has proven its benefits in terms of stability and maintenance. The system, operating steadily since the first data taking phases has shown to be extremely flexible and powerful allowing shifter (FSM) as well as expert operation and analysis. The open design, the online analysis and the data already collected allow for detector specific studies extending the original scope of the DCS.

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