ATLAS Tile Calorimeter Data Preparation for LHC first beam data taking and commissioning data

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Abstract. The Tile Calorimeter (TileCal) is the barrel hadronic calorimeter of the ATLAS experiment presently in an advanced state of commissioning with cosmic and single beam data at the LHC collider. The complexity of the detector, the number of electronics channels and the high rate of acquired events requires a systematic strategy of the System Preparation for the Data Taking. This is done through a precise calibration of the detector, prompt update of the Database reconstruction constants, validation of the Data Processing and assessment of quality of the data both with calibration signals as well as data obtained with cosmic muons and the first LHC beam. This article will present the developed strategies and tools to calibrate the calorimeter and to monitor the variations of the extracted calibration constants as a function of time; the present plan and future upgrades to deploy and update the detector constants used in reconstruction; the techniques employed to validate the reconstruction software; the set of tools of the present TileCal data quality system and its integration in ATLAS online and offline frameworks.

1. Introduction
ATLAS is one of the four main experiments installed at Large Hadron Collider (LHC) at CERN. The synchrotron has been inaugurated in 2008 and it will provide proton-proton collisions at the unprecedented center-of-mass energy of 14 TeV.

The Tile Calorimeter [1] is the barrel hadronic calorimeter of ATLAS. In 2008 it was fully integrated with the other ATLAS sub-detectors and it underwent an intense phase of commissioning with cosmic rays and LHC first proton beams. Its main purposes are to contribute to the jet energy measurement and Missing ET reconstruction and to the identification of muon particles. Fig. 1 shows that TileCal is located in the barrel region of the ATLAS detector [2], $|\eta| < 1.7$, extending from an inner radius of 2.28 m to an outer radius of 4.25 m. It is divided into three cylindrical sectors along the beam axis, called Long Barrel (LB) and Extended Barrels (EBs). The LB covers the region $-1.0 < \eta < 1.0$, and the EBs cover the region $0.8 < |\eta| < 1.7$. The LB is further divided in two parts, the middle being at $\eta = 0$. The symbols A and C are used to identify them depending on the side they are with respect to the interaction point. Therefore, the four partitions are called LBA, LBC, EBA and EBC. Each one of them is divided in 64
modules equally staggered in $\phi$.

TileCal is a sampling calorimeter, made of steel as absorber and scintillating tiles as active material. Its total weight is of 2300 tons. Fig. 2 shows the structure of a TileCal module and the geometry of the calorimeter cells, that is defined by arranging the fibre readout in space, creating a quasi-projective tower structure, where the deviations from a perfect projectivity are small compared to the typical angular extent of hadronic jets. The cells are organized in three radial layers of granularity $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ for the first two layers and $\Delta \eta \times \Delta \phi = 0.2 \times 0.1$ for the last layer.

The readout is performed at the two sides of each scintillating tile of a cell by two separated photo-multipliers (PMTs). This guarantees a sufficient light yield and aims for redundancy in the read-out. In the PMTs, light produced by particles crossing the tiles is transformed into an analog signal, that is sampled and digitized by the TileCal digitizer system. There are 2 ADCs per read-out channel, one with signal low gain and one with high gain amplification. The ratio of the 2 ADCs amplification is of 64, allowing to cover a dynamic range spanning from 12 MeV (1 ADC count in high gain) to 850 GeV (1023 counts in low gain) for each individual channel. The total number of read-out channels is 10746.

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**Figure 1.** Detail of ATLAS Calorimetric system. TileCal is divided in 1 Long Barrel side A and C and two Extended Barrels side A and C.

**Figure 2.** Structure of a TileCal drawer.

The Data Preparation is intended to group all the processes preparing the data for the Physics Analysis. It covers all the activities responsible for the quality assessment and validation of the data, calibration and understanding of the detector, maintenance of the detector conditions database (DB) and study of its performance.

### 2. Tile Calorimeter Calibration

The main purpose of the Tile Calorimeter calibration system is to deliver TileCal cells calibrated at the electromagnetic scale. For what concerns the calibration, the signal path can be divided in three parts shown in Fig. 3:

- the optical part, from the cell scintillating tiles to the photomultipliers (PMTs) input;
- the PMTs converting the light into an electric signal;
- the read-out electronics that shapes, amplifies and digitizes the signal.

The calibration system has a specific entry point before each one of these components: the Cesium radioactive source system for the optical part, the Laser system for the PMTs gain and the Charge Injection System for the digital system.

**Figure 3.** Diagram of the TileCal calibration systems and signal path. The interaction of particles crossing the calorimeter produces ionization in the scintillating tiles, that transform it into a light signal. This is transported by wavelength shifting fibers to the PMT read-out. The light signal is transformed into a charge signal at the PMT anode. The signal is finally read-out and digitized.

**Charge Injection System**
The Charge Injection System (CIS) is designed for the calibration of the Digitizer Analog to Digital converters (ADCs). The Charge Injection System is composed of 2 calibration capacitors for each electronic channel, controlled by a 3-in-1 card. The capacitor charge is discharged into the read-out electronics, creating a signal which pulse shape is similar to the one measured in physics events. Differences between the physics pulse and the CIS pulse are taken into account in the signal reconstruction. The capacitors can exercise the full ADC dynamic range in both gains and the CIS constants are extracted by the ADC response as a function of the injected charge. The CIS constants allow to convert the amplitude of the reconstructed signal from ADC counts to charge, in units of pC. The constants are calculated for each individual channel: the measured Digital ADC counts to pC calibration accuracy is of 0.7%, while its variation in a period of 6 months is of 0.1%, as shown in Fig. 4.

**Laser System**
The main purpose of the Laser System is to monitor the PMTs response as a function of time. The goal is to follow the PMT gain with a relative precision of 0.5% by measuring the input laser light intensity pulse by pulse. It will provide calibration constants for the gain non-linearity and stability in time of the PMTs. Currently it is used for a precise timing synchronization of the read-out channels.

**Cesium System**
The Cesium system has the goal of equalizing the channel to channel variation in the light budget by adjusting the PMTs high voltage. The system is based on the response of the calorimeter
to a $^{137}$Cs $\gamma$ source, that is pushed by a hydraulic system through a pipe in the calorimeter, irradiating the steel plates as well as the scintillating tiles. Figure 5 shows the measured response of one TileCal PMT to the passage of a Cs source. The periodic dome shape of the response is due to the passage of the source close to the steel plate (minimum of the response) and to the edges of the scintillating tiles (maximum of the response). The source radiation (gamma rays) penetrates the calorimeter cell up to a depth of 10-15 cm depth, illuminating a few tiles at the time. Thus when the source passes through a number of tiles (row), the resulting curve has a "dome" shape, regular and symmetrical if all the tiles responses are equal/alike.

The HV of the PMTs is set to produce an uniform response of the first radial sample to electrons at 20 degrees. Residual corrections below the 1% level cannot be set by adjusting the PMT HV, but are achieved by applying a correction factor in the reconstruction software.

The minimum bias monitoring system exploits the energy released by inelastic p-p collisions of low momentum transfer to monitor the equalization of the cells response. It will become an useful verification of the Cs calibration system when p-p collisions will begin.

![Figure 4](image1.png)

**Figure 4.** Variation of the CIS constants as a function of time and their deviation from the nominal value. The time variation is 0.1% in a 6 months period for a typical channel.

![Figure 5](image2.png)

**Figure 5.** Example of response of a TileCal PMT and cell to a Cs source moving along its path. The measured current on the y-axis, expressed in ADC counts, is plotted versus the source position, expressed in cm. The peaks correspond to the Cs source passing through the individual tiles. The dot points represent the fitted amplitudes of the individual tile responses. The response of a cell is known with a typical precision of 0.3%.

Electromagnetic Scale

The absolute energy scale of TileCal is derived by the results of electron testbeam data analysis. The response of a TileCal module is defined as the ratio of the charge collected in the calorimeter cell divided by the electron beam energy. Fig. 6 shows the electromagnetic scale constant obtained during testbeam from 8 TileCal modules at 5 different energies. More than 200 cells
of the first radial sample were analyzed and the average energy scale is of 1.05 pC/GeV with an RMS of 2.4%.

Figure 6. Cell response of electrons at the angle $\theta = \pm 20^\circ$. Data is taken from testbeams at 20, 50, 100 and 180 GeV. Each entry corresponds to a cell of the first radial sample. The average value of the energy scale is 1.05 pC/GeV with an RMS of 2.4%.

Figure 7. TileCal electronic noise as a function of the pseudo-rapidity as it has been measured during the first LHC beam period and stored in the Condition Database for cluster reconstruction.

**Noise Description**

Besides the constants needed to calibrate the calorimeter at the electromagnetic scale, there are other quantities necessary to reconstruct correctly the signals in the analysis process. One of them is the electronic noise of the detector, that is evaluated from the analysis of Random triggers runs and used in the reconstruction of calorimetric clusters to estimate the significance of the cells signal. Fig. 7 shows the noise profile for TileCal as a function of $\eta$. The average noise of the cells is of the order of 40 MeV [7], well below the typical energy released by mip-like particles like cosmic muons, which is around 300 MeV per cell.

**Calibration procedure**

The process of providing precise and up to date calibration constants begins with the data of the calibration runs taken regularly twice per week. Cs scans are taken with less frequency, because they require a special radio-protection procedure and the Cs source capsule needs several hours to pass through all the barrel cells.

On a shorter time scale, the time stability is verified from calibration events taken in LHC empty bunches during physics runs every 3 LHC orbits.

Calibration runs and calibration events in physics runs are reconstructed with CERN Analysis Facility (CAF) and the output data is analyzed by the calibration experts.

The calibration constants are stored in the Conditions DB with a minimal read-out granularity of the single ADCs and time granularity of the single run (few hours at most). The process allows to keep the calibration constants up-to-date during the data taking period and to review them for the reprocessing campaigns.
3. Tile Calorimeter Monitoring and Data Quality

The Data Quality Assessment process (DQA) is responsible for the validation of the quality of the data acquired. Its goal is to ensure, in the shortest possible time, that the data is suitable for physics analysis and that the status of the detector is well determined before the bulk reconstruction of the collected data starts. The process usually ends with a go/no-go decision on the data bulk reconstruction at Tier0.

TileCal DQA [8] can be divided in Online and Offline DQA: the online DQA verifies the coarse behavior of TileCal during the data taking, allowing an immediate intervention of the shift crew in case of problems. The offline DQA is performed during the Tier0 reconstruction of the express stream of the physics events and the CAF reconstruction of the calibration runs. Both guarantee the effective Data Quality Assessment of the data before the first bulk processing (within 24-48 hours from data taking).

TileCal DQA is responsible for the prompt detection of changes in the calorimeter conditions, like the appearance of new bad or noisy channels, for the update of the detector read-out channel conditions in Condition Database used for the data reconstruction and for the monitoring of the stability of the detector conditions and performances.

TileCal Online Monitoring and Data Quality

TileCal online monitoring relies on a series of software tools sampling data from different points of the data stream: from the Read-Out Devices, the back-end system of the read-out electronics, from the Read-Out Servers, each of them collecting 1/8 of TileCal data and from the Event Filter input, where the monitoring system has access to the full event data. The online monitoring is the input for the TileCal online DQA. To produce the DQA results on the detector status and data taking, the online DQA relies on the ATLAS Data Quality Monitoring Framework (DQMF) automatic checks, the ATLAS event displays and the ATLAS histograms presenter OHP Nexus (with specific TileCal plugins), shown in Fig. 8.

Figure 8. Example of Online Data Quality Assessment: the electronic noise of the TileCal channels is tested against a threshold and a DQ result is produced accordingly.

TileCal Offline Data Quality

The offline DQ of the physics data is based on the prompt reconstruction of the express stream at Tier0 and focuses on the physics performance of the detector. TileCal Tier0 monitoring is integrated in the common ATLAS reconstruction software. The DQA is based on the ATLAS offline DQMF software and its goals are to provide feedbacks on the data taken and to update the detector conditions before the bulk reconstruction starts. The monitoring histograms and the DQ results are archived on the web, as shown in Fig. 9.
The monitoring of the calibration data is performed at the CAF facility, running detailed monitoring tools. The tools report the presence of digital errors and the response of the detector to input signals known a priori. Data Quality checks are used to assess the status of each single channel with calibration events.

The results of the DQA process are used to draft an updated version of the channel status list. Specific tools are in place to quickly summarize the results of the DQA and validate their correctness, as illustrated in Fig. 10.

4. Tile Calorimeter Performance with Cosmic and LHC single beam data
During 2008, the Tile Calorimeter was extensively commissioned in a series of integration tests with the other ATLAS sub-detectors, trigger and DAQ systems, called Milestone weeks and several cosmic rays events were recorded during these tests. Figure 11 illustrates a cosmic shower recorded by the ATLAS DAQ system and displayed by the 3D Calorimeter Viewer.

The commissioning of the detector culminated in September 2008 when the Large Hadronic Collider (LHC) circulated proton beams at the energy of 450 GeV/c in both beam pipes for the first time. ATLAS successfully recorded the first circulating beam traversing the experiment.
The data recorded in the available 30 hours of beam time were used to study the time and energy response of the Tile calorimeter. Two different types of beam events were recorded: the so-called splash events and scraping events. Splash events originate from the LHC proton beam interaction with a LHC tertiary collimator positioned 140 m up-stream of the detector, when the collimator is closed. They are characterised by millions of high energy particles reaching simultaneously the ATLAS detector. Scraping events originate from the natural defocusing of the protons bunch during the period in which the radio frequency capture (RF-capture) of the protons spill was not performed. The interaction of the defocused protons with the edge of the collimators produce a small number of high energy particles moving parallel to the beam axis and in time with the proton bunch. Fig. 12 illustrates a scraping event recorded by ATLAS during September 2008.

The beam time available to ATLAS in 2008 has been of the order of 30 hours and the data acquisition system recorded runs with clockwise beam 1 and counter clockwise beam 2.

![Figure 11. Example of a cosmic shower recorded by ATLAS read-out system and displayed by the Calorimeter Cosmic Viewer.](image)

![Figure 12. Example of a first beam event recorded by ATLAS read-out system. It is displayed by the ATLAS Virtual Point 1 event display.](image)

Cosmic and Single beam data allow to study the performance of the detector in-situ. Cosmic data was analyzed to verify the Data Preparation of the Tile Calorimeter, in particular to check the timing synchronization of the read-out channels. Figure 13 shows the module to module time difference measured from cosmic muon events, after accounting for the time of flight of the muon crossing the detector.

The data provided by the first circulating beams in the LHC collider was used to verify both the calorimeter timing synchronization and energy intercalibration.

Figure 14 shows the channel to channel synchronization of the detector for the three TileCal radial samples as measured in beam splash events. In the analysis, the time of flight of the muons travelling from a side of the detector to the other has been taken into account. Within each read-out partition, the channel to channel difference is below 2 ns, while a larger difference can observed between the partitions. The difference between partitions is not corrected for in the time calibration process with laser pulses. The analysis demonstrates the good time equalization performed with the laser system and is in agreement with the timing studies performed with cosmic events.

Scraping events were analyzed to measure the response of the calorimeter to ionizing particles and to study the uniformity of the detector as a function of the radial sample and of the modules.
Figure 13. The figure shows the time difference between measured and expected time of flight. Laser time calibration was applied to the measured time, the analysis proves that the inter-calibration of TileCal channels of the same partition during 2008 commissioning was of the order of 2 ns.

Figure 14. The average time over all cells with the same phi (azimuthal) coordinate is shown as a function of the cell Z coordinate (along beam axis) for all three radial samplings (represented with different symbols). Timing corrections based on laser data had been applied, as well as the particle time of flight correction. Within each partition, the time spread is within 2 ns.

Figure 15. Most Probable Value of dE/dx signals recorded by TileCal with horizontal muons from single beam data. This data provided the opportunity to verify the intercalibration of Tile calorimeter cylinders, already calibrated with Cs γ sources, down to the 4% precision level. The red lines represent the TileCal average MPV value of the 4 barrels and its 4% uncertainty.

Figure 16. Average Most Probable Value of dE/dx over all cells within a given radial sample response to horizontal muons is shown as function of the radial sample. This analysis verifies the per sample corrections of the EM scale, previously derived from dedicated test beam measurements and special Sr radioactive source scans. The colours represent the calorimeter response before (blue) and after (red) the per sample corrections to EM scale were applied.

Fig. 15 shows the response of the calorimeter cylinders to horizontal muons. The analysis verifies with a 4% precision, the intercalibration of the calorimeter barrels performed with $^{137}$Cs γ sources. Fig. 16 shows the response of the calorimeter as a function of the calorimeter radial
samples with and without the EM scale corrections derived from testbeam and from special Sr radioactive source scan. The purpose of the Sr scans was to quantify the difference in the tile response due to distance between the crossing radioactive source and center of the tile. The figure shows that the sample corrections improve the uniformity of the calorimeter response in single beam data.

5. Conclusions
The Data Preparation process of the Tile Calorimeter has been presented. The calibration processes have the main goal of providing a uniform calibration of the detector at the electromagnetic scale. The residual disuniformity in the intercalibration should be below 1%. The variation in time of the calibration constants are also monitored and corrected for. The noise level of the detector is small compared to the typical signal of minimum ionizing particles and is described for each individual cell.

The Data Quality process of the TileCal detector has the goal of providing a quick assessment of the detector conditions within 24-48 hours of the data taking, in time to provide feedbacks for the Tier0 bulk reconstruction. The online Data Quality process provides real time feedbacks allowing the shift crew to assess the detector conditions during the data taking. Offline Data Quality performed during Tier0 reconstruction allow to assess the performance of the detector in the reconstruction of objects. The data quality assessment of calibration runs allows to provide a detailed status of the detector by studying the response of the calorimeter under conditions known a priori.

The study of the commissioning of the detector with cosmic rays and single beam data allowed to improve the knowledge of the detector. The time calibration of the calorimeter has been validated with cosmic rays events and single beam data. Single beam events allowed also to verify the uniformity of the electromagnetic scale calibration of the calorimeter and to verify the validity of the radial sample corrections calculated from testbeam data.

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