

The Online Luminosity Calculator of ATLAS

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Abstract. Online luminosity monitoring at the LHC is important for optimizing the luminosity at the experimental insertions and vital for good data taking of the LHC experiments. It is an important diagnostic tool, in particular for the normalization of trigger rates and data samples. The ATLAS experiment has several sub-detectors, which can be used for relative luminosity measurements. In order to collect all data from the variety of different sources and to process them centrally, the software application “Online Luminosity Calculator” has been developed.

1. Introduction

Measurement and constant monitoring of the luminosity is vital for good data taking of the experiments at the Large Hadron Collider (LHC) [1]. Online luminosity at the ATLAS experiment [2] is measured by several sub-detectors. Collection and central processing of this data is achieved by a software application called “Online Luminosity Calculator” (OLC). It is written in C++ and integrated into the ATLAS online software framework. There are three main tasks of this application: First, collection of data from the sub-detectors and the LHC beam instrumentation. This requires handling of online information published in various formats, by different middleware. Further, calibration of the raw luminosity information, time integration and normalization. The last step is the publication of the results in a coherent format for online usage and permanent storage in the conditions database. This contribution will give an overview of the basic concepts of the OLC, which plays a key role in the luminosity dataflow of ATLAS.

1.1. Luminosity Measurements at the LHC

The instantaneous luminosity of proton-proton collisions can be calculated as:

$$\mathcal{L} = \frac{R_{inel}}{\sigma_{inel}} \quad (1)$$

Where R_{inel} is the rate of inelastic collisions and σ_{inel} is the pp inelastic cross section. Any detector that is sensitive to inelastic pp interactions can be used as a source for relative luminosity measurements. Formula (1) can be rewritten as:

$$\mathcal{L} = \frac{\mu n_b f_r}{\sigma_{inel}} \quad (2)$$

Where f_r is the LHC revolution frequency, n_b the number of bunches colliding at the ATLAS interaction point and μ is the average number of inelastic interactions per bunch crossing. Relative luminosity measurements lack the overall normalization and need to be calibrated by absolute results. In the future, the ALFA detector [4] will provide an absolute luminosity calibration for ATLAS through

the measurement of elastic pp-scattering. In addition it may be possible to normalize cross-section measurements to electroweak processes for which precise NNLO calculations exist, for example W and Z production [5]. An alternative is to use the absolute luminosity \mathcal{L} measured from beam parameters:

$$\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \quad (3)$$

where n_1 and n_2 are the number of particles in the two colliding bunches and Σ_x and Σ_y are the horizontal and vertical beam profiles, typically measured in *van der Meer* (vdM) scans [6]. The reader is referred to [3].

1.2. Luminosity Sub-detectors of ATLAS

The ATLAS strategy to understand and control the systematic uncertainties affecting the luminosity determination is to compare the measurements of several luminosity detectors. For online measurements ATLAS uses six detectors, with big differences in performance, acceptance and efficiency:

- **LUCID**, a Cherenkov detector dedicated to relative luminosity measurements: $5.6 < |\eta| < 6$
- **FCAL**, the Forward Calorimeter: $3.2 < |\eta| < 4.9$
- **ZDC**, the Zero Degree Calorimeter: $8.3 < |\eta|$
- **BCM**, the Beam Condition Monitors, placed at the Inner Detector: $|\eta| \sim 4$
- **MBTS**, the Minimum Bias Trigger Scintillators, located at the LAr-Endcaps: $2.09 < |\eta| < 3.84$
- **HLT**, Vertex counting in the High Level Trigger ¹: $|\eta| < 2.5$

Figure 1 illustrates their position along the ATLAS interaction point. Most of the detectors use more than one counting technique, which are characterized by significantly different acceptance, pile-up response and sensitivity to instrumental effects and beam-induced backgrounds:

- *Event counting*: Counting of events satisfying a given selection requirement.
- *Hit counting*: Counting of hits (e.g. channels or clusters above threshold) per bunch crossing in a given detector.
- *Particle counting*: Counting the number of particles measured per beam crossing.

Different algorithms are built by requiring counts on either just one side of the interaction point (OR algorithms), or by requiring a coincidence on both sides (AND algorithms). The nomenclature for a given algorithm from a certain sub-detector is e.g. LUCID_EventAND or LUCID_HitOR.

Six separate sub-detectors give a total of 16 independent raw luminosity measurements, all published at their own rhythm, in different formats and to different locations. Most measurements are integrated over all bunches of an LHC orbit, some detectors are additionally capable of publishing measurements for each LHC Bunch Crossing Identifier (BCID). The OLC handles this variety of information in a coherent way.

1.3. Luminosity Blocks

The time unit in which ATLAS luminosity data is recorded is called Luminosity Block (LB). It is a roughly 2min. interval during which the luminosity is supposed to remain constant. This concept allows to time-average and thus makes comparisons between measurements of different sub-detectors possible. The Central Trigger Processor (CTP) of ATLAS issues this signal with the corresponding time stamps. All data recorded is labeled with a Luminosity Block Number (LBN) and a Run Number (RunN).

¹ not yet implemented in the OLC

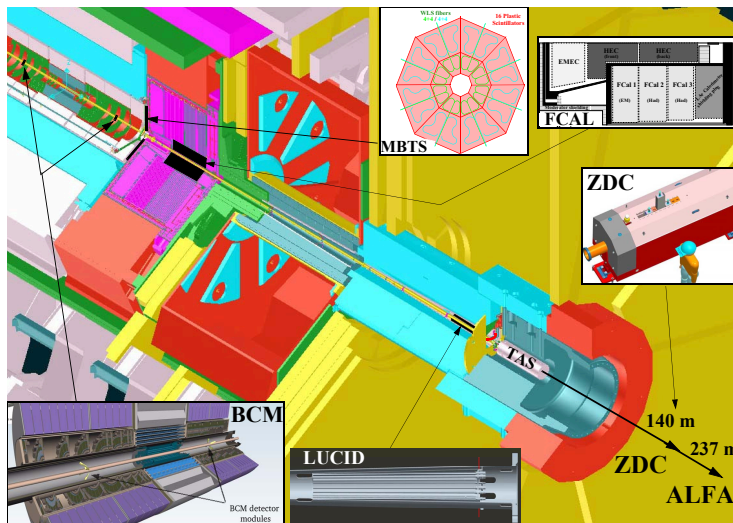


Figure 1. Positions of the ATLAS luminosity detectors and distance from the interaction point. All having different acceptances, systematic uncertainties and sensitivity to background.

2. The Online Luminosity Calculator

The OLC is a program that runs within the ATLAS TDAQ online environment and able to perform online calculations. Its algorithms can be built up by OKS² objects or have parts of their logic implemented directly in C++. A schematic view of the online data flow is given in figure 2.

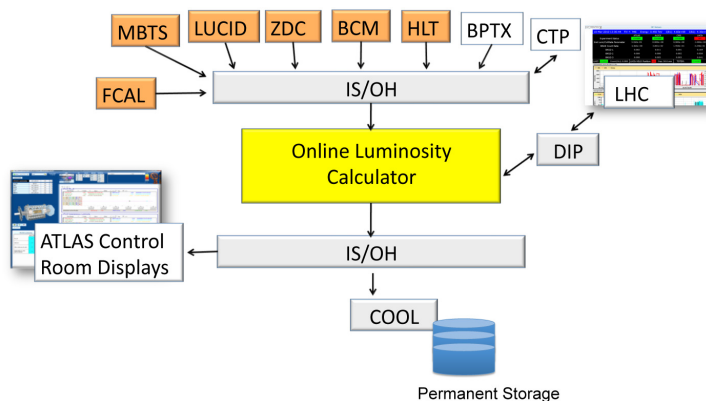


Figure 2. The online luminosity dataflow. The sub-detectors are publishing their raw counts to IS, from where they are picked up by the OLC. The OLC performs algorithms and publishes the results back to a dedicated IS server. From there the data are sent to online displays in the ACR, the LHC and for permanent storage stored to COOL [8].

The OLC runs with a frequency of 1Hz and has three main functions:

(i) Collection of data from the sub-detectors and the LHC beam instrumentation:

The six luminosity sub-detectors publish their raw luminosities to different servers on the Information Service³ (IS). Most algorithms are published multiple times, in different format and with different integration time. One has to distinguish between instantaneous and Luminosity Block averaged counts (LBAv), and “BCID blind” and “Per-Bunch” publications:

- **Instantaneous:** The counts are published roughly every second, integrated over all bunches in the ring. (Provided by all sub-detectors)
- **LBAv:** The counts are accumulated by the sub-detector per Luminosity Block, integrated over all bunches in the ring. (Provided by almost all sub-detectors)

² The object managing tool OKS [7] allows to store class definitions and their instances in XML files. It has a C++ application program interface and includes GUI applications to design class schema and to manipulate objects.

³ The Information Service is software which allows information exchange between different online application. The information is held on dedicated IS servers, to which clients can publish, read, and subscribe for information.

- LBAv “Per-Bunch”: Vector of counts per BCID, accumulated per Luminosity Block. (Provided only by LUCID and BCM)

The OLC retrieves all these publications from IS, as well as data from beam-instrumentation from the LHC via the Data Interchange Protocol⁴ (DIP).

(ii) **Calibration of the raw luminosity information, time integration and normalization:**

The measured luminosity is calculated by applying calibration constants. Necessary ingredients for this calculation, e.g. the number of colliding bunches in the ring, are retrieved from the Beam Pick-Ups (BPTX).

The OLC is also subscribed to the LB object, issued by the CTP. With this timing signal the OLC calculates Luminosity Block averages (OLCLBAvs) from instantaneous quantities. This provides a crosscheck for Luminosity Block averages done by the sub-detectors and is especially crucial for those sub-detectors that are not able to publish LBAv quantities.

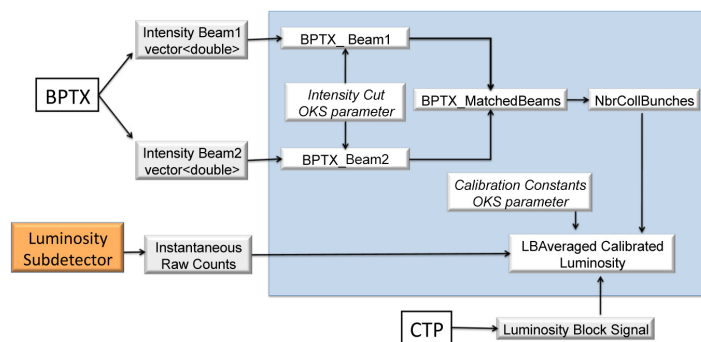


Figure 3. Steps in the OLC to calculate LB-averaged luminosity from instantaneous raw counts of a given sub-detector. See text for further details.

Most of the final OLC objects are built up with intermediate objects, all of which can be optionally published to IS as well. Figure 3 shows a simplified schema of how the OLC calculates LBAv luminosity from instantaneous raw counts.

The BPTX publish intensities for Beam 1 (B1) and Beam 2 (B2) as a vector of BCIDs to IS. The OLC creates BCID vectors from the BPTX measurements, where an optional noise cut can be applied.

From the noise-suppressed intensities a new integer vector is calculated, a mask that tells which BCIDs are colliding (value 3), empty (value 0) or unpaired, i.e. only B1 (value 1) or B2 (value 2) are filled. An example histogram is shown in figure 4. From this filling scheme an integer containing the number of colliding bunches is extracted and published. Another OLC object subscribes to the Luminosity Block signal and averages the instantaneous counts of a given algorithm over the time of two subsequent LB publications. With the number of colliding bunches and the integration time, raw counts from a sub-detector can be translated into counts per bunch crossing. By applying calibration constants, which are defined in OKS, the average luminosity in the LB is calculated. Once the next LB callback is received the object is published. It contains besides the calibrated luminosity and its statistical error also the initial raw counts, the LBN and RunN, start- and end-time of the corresponding LB and also a quality flag. This flag is composed of the quality propagated by the sub-detectors and the OLC quality for the calculation of this particular object, e.g. set to bad if the number of colliding bunches was not received properly.

(iii) **Publication of the results in a coherent format for online usage and permanent storage in the conditions database (COOL):**

Instantaneous values are published with a frequency of 1Hz. LBAv quantities corresponding to a

⁴ DIP is a simple and robust point to point, publish/subscribe system which is used LHC-wide.

specific LB are first gathered and published as soon as the next LB callback is received, i.e. published 1 LB delayed. For monitoring purposes including time trends the data is sent to slow control displays in the ATLAS control (ACR) room where it is also stored in the ATLAS online-monitoring archive. Example online diagnostic plots are shown in figures 5 and 7.

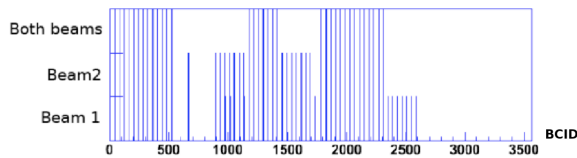


Figure 4. An example filling scheme with 50 bunches in each beam, where 30 are colliding in ATLAS.

Several luminosity values are also sent to the LHC control room via the online infrastructure DIP. This assists in collision optimization at the ATLAS interaction Point. Out of the 16 luminosity values, the luminosity community chooses a “preferred algorithm” from one preferred detector. This value is published as the “official ATLAS luminosity”, and is also displayed on the LHC Page 1 website [9]. The choice for the preferred algorithm and sub-detector depends on the performance of each sub-detector, and can change with the actual running conditions. The other 15 measurements serve as important crosschecks and as a fallback solution, in case the preferred one drops out. LBAv luminosities and beam parameters, such as the beam currents and the LHC bunch-pattern are permanently stored on the ATLAS conditions database COOL.

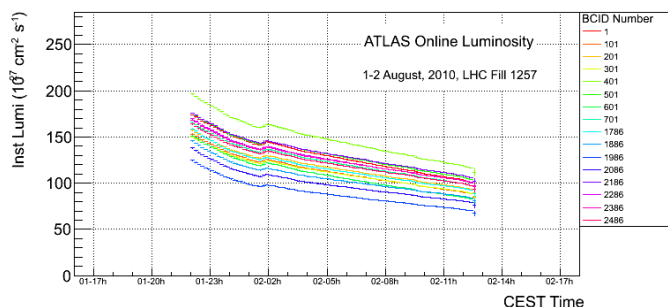


Figure 5. Time evolution of the per-bunch instantaneous luminosity for a fill with 16 bunch pairs colliding in ATLAS. The difference, at a given time, between the highest- and the lowest-luminosity bunch is a factor of about 1.6, reflecting the variation of bunch currents and emittances along the colliding-bunch trains.

3. The BunchGrouper Application

The capability of the OLC of handling per-bunch information is also useful for the ATLAS Level-1 trigger. A second instance of the OLC called “BunchGrouper” calculates the best estimate of 8 Bunch Groups, based on predefined and configurable algorithms. The 8 bunch groups are repetitive trigger conditions, which can be fully programmed for each BCID. They are typically used by requiring coincidences with the other trigger conditions, which allows triggers to be restricted to certain BCIDs. Each trigger may belong to one or more “Bunch Groups”. An example bunch group configuration is given in figure 6. The *collision* bunch group contains only paired BCIDs and is used by physics triggers. Other bunch groups, triggering on empty or unpaired BCIDs, are used for background studies or calibration purposes. Knowledge about which bunches are un-paired, empty and paired is extracted from the filling scheme. The result is then provided to the Central Trigger Processor (CTP), part of the ATLAS Level-1 Trigger. As the LHC fill scheme can vary from fill to fill, the ATLAS trigger shifter can compare the current configuration of the CTP to the new estimate of the BunchGrouper and may generate a new configuration by simply pressing a button.

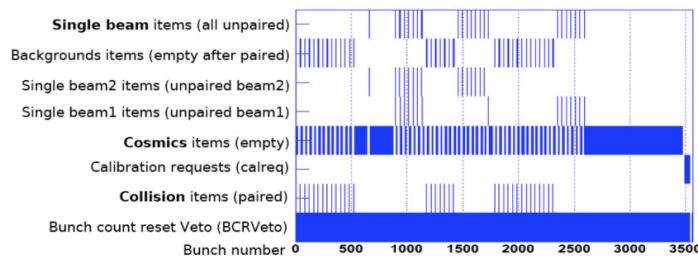


Figure 6. An example Bunch Group setting for the filling scheme shown in figure 4. The X-Axis is the LHC bunch number, the Y-Axis the 8 available Bunch Groups.

4. Conclusions

The software tool OLC is successfully providing online calibrated luminosity from five of the six foreseen sub-detectors. The output is constantly monitored in the ACR, sent to the LHC and stored to the ATLAS conditions database. Its algorithms and infrastructure are built up in a way that they can be easily adapted to new publications. Just recently, a new instance of the Online Calculator, mainly providing information on beam background, has been integrated into the ATLAS online environment.

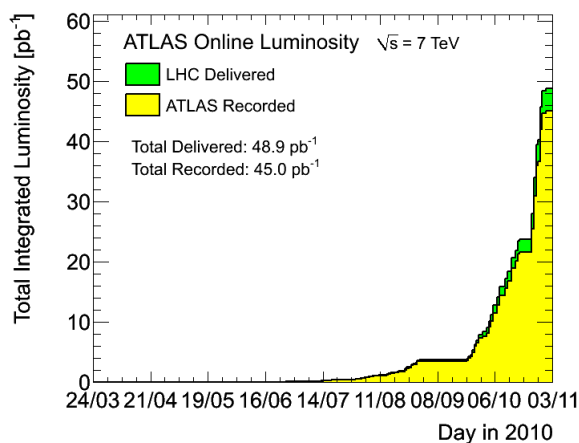


Figure 7. Total integrated luminosity with stable beams versus day. Shown is the online luminosity as determined from counting rates measured by the luminosity detectors. The detectors have been calibrated with the use of the van der Meer scan method.

5. Acknowledgments

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