The ATLAS jet trigger performance in LHC Run I and Run II updates

Shima Shimizu
on behalf of the ATLAS collaboration
Kobe University, Rokkodai-cho 1-1, Nada-ku, Kobe 657-8501, Japan
E-mail: shima.shimizu@cern.ch

Abstract. The Large Hadron Collider (LHC) provides proton-proton collisions with a nominal rate of 40 MHz, and the ATLAS trigger performs the first event selections online during data-taking. The ATLAS jet trigger is an important element of the ATLAS trigger system, selecting collision events containing high transverse energy jets, to provide data samples for studies ranging from Standard Model physics to searches for new physics at the LHC. During LHC Run I, the first LHC operation period from 2010 to 2012, the ATLAS jet trigger system improved as experience developed with triggering in a high luminosity and high event pileup environment. For the next LHC operation period, Run II, the system is being updated for further improved performance and stability. In this contribution, performance and improvements of the ATLAS jet trigger in Run I are presented. Updates for Run II are also shown.

1. Introduction
A jet is a collimated spray of hadrons. It is produced by a scattered quark or gluon with high transverse energy ($E_T$) and is an important signature in collider physics. The LHC provided proton-proton collisions at centre-of-mass energies of 7 TeV with a luminosity up to $3.65 \times 10^{33}$ cm$^{-2}$s$^{-1}$ in 2010-2011 and of 8 TeV with a luminosity up to $7.73 \times 10^{33}$ cm$^{-2}$s$^{-1}$ in 2012, with a beam crossing rate of 20 MHz. In the operation of the ATLAS detector [1], the ATLAS jet trigger performs the first selection of interesting collision events at the LHC. The ATLAS jet trigger [2] is designed to tag events containing jets with high flexibility, to adapt to the changing LHC beam conditions and to allow a large variety of physics analyses using the ATLAS data.

2. Overview of the ATLAS jet trigger system in Run I
In Run I, the ATLAS trigger system consisted of three levels, Level 1 (L1), Level 2 (L2) and Event Filter (EF), where L1 was hardware-based and L2 and EF were software-based. The system was designed to handle a maximum event rate of 40 MHz. L1 was designed to give a trigger rate of 75 kHz (70 kHz was the actual peak value in 2012) with a fixed latency of less than 2.5 $\mu$s, L2 was designed to give 3.5 kHz with an average processing time of 40 ms (5 kHz in 75 ms in 2012), and EF to have an output rate of 200 Hz within around 4 s (700 Hz in about 1 s in 2012). The ATLAS jet trigger was allocated about 20 % of the total bandwidth of the ATLAS trigger.
Figure 1. Efficiencies of single-jet triggers at L1, L2 and EF are shown for anti-$k_t$ jets with a jet size of $R = 0.4$ in the central region of $|\eta| < 2.8$ as a function of the offline jet $E_T$. For L2 and EF, efficiencies with and without noise suppression are compared by full markers (with suppression) and open markers (without suppression). [7].

At L1, jet finding was performed with a sliding window algorithm applied on L1 calorimeter towers, which had a granularity of $0.2 \times 0.2$ in pseudo-rapidity $\eta$ and azimuthal angle $\phi$. The algorithm looked for local energy maxima in the ATLAS calorimeter. The detector region where a maximum is located was called a Region of Interest (RoI) and the information of the RoI location and of which L1 thresholds were satisfied were passed to L2. In the L2 system, jets were reconstructed within the RoIs found by L1 using an iterative cone algorithm. An algorithm called L2 Full Scan (L2FS) was introduced in 2011. It can perform reconstruction of anti-$k_t$ [3] jets (as implemented in the FastJet package [4]) using L1 calorimeter towers with a granularity of $0.1 \times 0.1$ in $\eta \times \phi$, across the entire ATLAS detector. In this algorithm, electromagnetic energies of jets can be corrected to compensate for calorimeter response to hadrons and for energy loss in dead materials. The reconstructed jets at this layer are called L2FS jets. Both L2FS jets and L1 RoIs could be used as inputs at L2 for further jet reconstruction with the cone algorithm using calorimeter cells. At EF, topological clusters [5] were created from calorimeter cells and the reconstruction of anti-$k_t$ jets was done using topological clusters across the entire detector. All the offline jet algorithms and calibrations can be applied at EF.

3. Pileup and noise suppression

Due to the high instant luminosity provided by the LHC, calorimeter energy deposits in an interesting event can be affected by other additional interactions (called pileup) in the same bunch crossing or in neighbouring bunch crossings. In the 2012 operation, the average number of interactions per bunch crossing was 20.7 [6]. A noise suppression tool was implemented at L2 and EF in 2011 such that only calorimeter cells with energy depositions above a certain threshold were considered in the jet reconstruction at L2 and EF. Figure 1 shows efficiencies of single-jet triggers at L1, L2 and EF measured using 2011 data. For the latter two, efficiencies with and without noise suppression are compared. Noise suppression improves the jet energy resolution and hence steepens the turn-on curves of the efficiencies.

4. L2 Full Scan in the 2012 operation

The L2FS algorithm was implemented in 2011 and was in use in the 2012 operation. It provides L2FS jets with quite improved jet angular resolution compared to the L1 RoIs. Hadronic calibration can be applied on L2FS jets, giving better energy resolution. This results in a rate reduction of 18% for the L2FS single-jet triggers which have efficiencies higher than 99% for jets with an offline transverse momentum $p_T > 60$ GeV. The L2FS algorithm was used in lead-lead collisions at the LHC, where multiplicity in the ATLAS detector is extremely high. The total event processing time was found to be within the nominal time limit at L2 of about 40 ms.
Figure 2. Efficiencies of multijet triggers requiring six jets at L1 (L1 6j10) and L2FS (L2FS 6j10) measured in events with six offline anti-\( k_T \) jets for a jet size of \( R = 0.4 \) with \( E_T > 30 \) GeV and \( |\eta| < 2.8 \), as a function of the offline \( E_T \) of the sixth jet. The events are preselected using a trigger with four-jets requirement. [7].

Figure 3. Transverse energy resolution of EF jets as a function of the offline jet \( \eta \), for anti-\( k_T \) jets with a jet size of \( R=0.4 \) with offline \( E_T > 100 \) GeV. Resolution in data is shown together with those in the simulation using PYTHIA [10] and HERWIG [11, 12] Monte Carlos. [7].

Figure 2 shows the efficiencies of multijet triggers requiring six jets, at L1 and L2FS. The efficiencies are measured against events with six offline anti-\( k_T \) jets with a jet size of \( R = 0.4 \), where each jet should have \( E_T > 30 \) GeV and \( |\eta| < 2.8 \) after the offline calibration. These events are preselected using a trigger requiring four jets. While the L1 multijet trigger has an inefficiency of more than 5 % even at \( E_T = 100 \) GeV of the sixth jet due to the different geometry between L1 sliding windows and offline jets, the efficiency is recovered in the L2FS multijet trigger. This shows one of the advantages of L2FS, which performs jet reconstruction across the entire detector, not only in RoIs with poor angular resolution given by L1.

5. Performance of the ATLAS EF jet trigger in Run I

Transverse energy resolution of EF jets is shown in Figure 3 for jets with offline \( E_T > 100 \) GeV in Run I data and in simulation.\(^1\) Its \( \eta \) dependence is generally described by the simulation with only minor differences between data and simulation. Figure 4 shows efficiencies of EF single-jet triggers during Run I for data and simulations. Triggers may be suppressed by recording only a pre-defined fraction of events to cope with high trigger rates. Single-jet triggers with a range of \( E_T \) thresholds are prepared to fulfill physics demands while keeping trigger rates manageable by artificially suppressing the rates of those with low \( E_T \) thresholds. Triggers with highest \( E_T \) thresholds are unsuppressed. The triggers with low-\( E_T \) thresholds, EF-j10, EF-j15 and EF-j20, run in events accepted by L1 random triggers, while other single-jet triggers are seeded by L1 and L2 jet triggers which are fully efficient at the \( E_T \) thresholds of considered EF single-jet triggers. Although the turn-on curves are steeper in simulation especially for triggers with low \( E_T \) thresholds, all the curves reach an efficiency of 100%. In physics analyses, data collected

\(^1\) The ATLAS detector simulation is performed using GEANT4 [8] in the ATLAS simulation infrastructure [9].
Figure 4. Efficiencies of EF single-jet triggers in Run I for anti-$k_t$ jets with a jet size of $R=0.4$ with $|\eta| < 2.8$, as a function of the offline jet $E_T$. They are shown for data and PYTHIA and HERWIG Monte Carlo simulation. Efficiencies of EF triggers seeded by L1 random triggers are shown on the left and those seeded by L1 and L2 jet triggers on the right. [7].

by these triggers can be easily combined to obtain samples covering a wide range of the jet $E_T$, without any complicated trigger-efficiency corrections.

6. Updates for Run II
In LHC Run II, EF and L2 systems have been merged into a single High Level Trigger (HLT) system. At the HLT, the jet trigger system performs the full scan of calorimeter cells at the Level 1 output rate. Offline jet reconstruction and calibration software are used at HLT, including the pileup suppression.

An additional read-out scheme is implemented to increase the flexibility of the HLT jet trigger system. The scheme is called Partial Scan, where only calorimeter cells in a $\eta \times \phi$ window around each RoI are read out. Topological clusters are created using cells read out in Partial Scan instead of performing a full scan of the ATLAS calorimeter cells. Partial Scan is expected to largely reduce the time for cell clustering, the most CPU time consuming step, as the simulated results show in Figure 5. Jets will be created from these topological clusters using the anti-$k_t$ algorithm. Figure 6 shows the comparison of the transverse energies of jets reconstructed from Partial Scan and those from the full scan readout system. Only a negligible difference is seen for jets with $E_T > 40$ GeV.

7. Summary
The ATLAS jet trigger was designed to tag events containing high transverse energy jets in proton-proton collisions provided by the LHC, which is operated with high instantaneous luminosity and collision rates up to 40 MHz. During the first operation period of the LHC, Run I, the ATLAS jet trigger had several improvements, such as noise suppression and the addition of the L2FS system, and this achieved excellent performance in the ATLAS operation. In the next operation period just started, Run II, the trigger system have been further updated. Software-based trigger levels in Run I have been merged as HLT which will perform the full scan of calorimeter cells to reconstruct jets at the Level 1 output rate. In addition, Partial Scan is implemented to increase the flexitility of the HLT system, with faster online jet reconstruction.

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Figure 5. Simulated processing time for topological cluster reconstruction from cells read-out by Partial Scan and the full scan. Two cases of Partial Scan are shown, with a window of $\eta \times \phi = 1 \times 1$ and that of $1.5 \times 1.5$ around the L1 RoI positions. The simulation was done using QCD dijet events with the leading jet transverse momentum $p_T > 20$ GeV at a centre-of-mass energy of 14 TeV. The simulation includes 40 simultaneous interactions per bunch-crossing. [7].

Figure 6. Simulated difference of transverse energies of EF jets from Partial Scan read-out and the full scan read-out. Two cases of Partial Scan are shown, with a window of $\eta \times \phi = 1 \times 1$ and that of $1.5 \times 1.5$ around the L1 RoI positions. The simulation was done using QCD dijet events with the leading jet transverse momentum $p_T > 20$ GeV at a centre-of-mass energy of 14 TeV. The simulation includes 40 simultaneous interactions per bunch-crossing. [7].

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