Testing and calibrating analogue inputs to the ATLAS Level-1 Calorimeter Trigger

R. Achenbach[b], P. Adragna[d], M. Aharrouche[c], V. Andrei[b], B. Åsman[f], B.M. Barnett[e], B. Bauss[c], M. Bendel[c], C. Bohm[f], J.R.A. Booth[a], J. Bracinik[a], I.P. Brawn[e], D.G. Charlton[a], J.T. Childers[b], N.J. Collins[a], C.J. Curtis[a], A.O. Davis[e], S. Eckweiler[c], E. Eisenhandler[d], P.J.W. Faulkner[a], J. Fleckner[c], F. Föhlisch[b], C.N.P. Gee[e], A.R. Gillman[e], C. Göringer[c], M. Groll[c], D.R. Hadley[a], P. Hanke[b], S. Hellman[f], A. Hidvégi[f], S.J. Hillier[a], M. Johansen[f], E.-E. Kluge[b], T. Kuhl[c], M. Landon[d], V. Lendermann[b], J.N. Lilley[a], K. Mahboubi[b], G. Mahout[a], K. Meier[b], R.P. Middleton[e], T. Moa[f], J.D. Morris[d], F. Müller[b], A. Neusiedl[c], C. Ohm[f], B. Oltmann[c], V.J.O. Perera[e], D.P.F. Prieur[e], W. Qian[e], S. Rieke[c], F. Rühr[b], D.P.C. Sankey[e], U. Schäfer[c], K. Schmitt[b], H.-C. Schultz-Coulon[b], P. Seidler[b], S. Silverstein[f], J. Sjölin[f], R.J. Staley[a], R. Stamen[b], M.C. Stockton[a], C.L.A. Tan[a], S. Tapprogge[c], J.P. Thomas[a], P.D. Thompson[a], P.M. Watkins[a], A. Watson[a], P. Weber[b], M. Wessels[b], M. Wildt[c]

[a] School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK
[b] Kirchhoff-Institut für Physik, University of Heidelberg, D-69120 Heidelberg, Germany
[c] Institut für Physik, University of Mainz, D-55099 Mainz, Germany
[d] Physics Department, Queen Mary, University of London, London E1 4NS, UK
[e] STFC Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot, Oxon OX11 0QX, UK
[f] Fysikum, Stockholm University, SE-106 91 Stockholm, Sweden

stamen@kip.uni-heidelberg.de

Abstract

The ATLAS Level-1 Calorimeter Trigger is a hardware-based system which aims to identify objects with high transverse momentum within an overall latency of $2.5\,\mu$s. It is composed of a PreProcessor system (PPr) which digitises 7200 analogue input channels, determines the bunch crossing of the interaction, applies a digital noise filter, and provides a fine calibration; and two subsequent digital processors. The PreProcessor system needs various channel dependent parameters to be set in order to provide digital signals which are aligned in time and have proper energy calibration. The different techniques which are used to derive these parameters are described along with the quality tests of the analogue input signals.

I. Introduction

The enormous rate of proton-proton interactions provided by the LHC machine and the limited readout bandwidth pose strong requirements on the online event selection process. The ATLAS Trigger system is therefore composed of three levels with the first level being entirely realised in programmable hardware. The two subsequent levels are implemented as large computer farms with up to around 2000 nodes divided between the two trigger levels.

The LHC machine collides bunches of protons every 25 ns with about 23 inelastic interactions per bunch crossing at the design luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The purpose of the first-level trigger is a rate reduction from the bunch crossing rate of 40 MHz to a maximum of 75 kHz using a strategy based on the search for high p_T objects such as electrons, jets, muons, etc. The calorimeter trigger combined with the muon trigger and the Central Trigger Processor form the first-level trigger of the ATLAS experiment [1]. The calorimeter trigger [1, 2, 3] is itself composed of a PreProcessor system (PPr) which feeds data into two parallel digital processor systems. The PreProcessor system digitises about 7200 analogue calorimeter signals and determines the bunch crossing of the corresponding primary interaction. The Cluster Processor (CP) searches for electron, photon and tau candidates. The Jet/Energy-sum Processor (JEP) searches for jets and determines the missing transverse energy and the total transverse energy. In addition to the main building blocks there are several additional components satisfying various infrastructural purposes which are used in the system for clock distribution, configuration and monitoring etc.

II. PreProcessor system

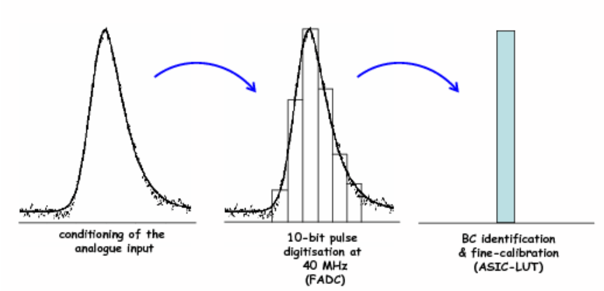

Figure 1: The signal processing chain consists of three steps: digitisation of the analogue signals, determination of the corresponding bunch crossing and finally a fine calibration of the transverse energy measurement.

The main purposes of the PreProcessor system are the digitisation of the analogue input signals, the determination of the bunch crossing of the primary interaction and a precisely calibrated transverse energy measurement. These three logical steps as indicated in figure 1 are the basis for the hardware design of the PreProcessor system. The complete system consists of 124 9U VME boards in 8 crates which cover the full calorimeter area with about 7200 trigger channels. Each PreProcessor Module (PPM) processes 64 channels in parallel. It consists of a main board with a total of 23 daughter boards as can be seen in figure 2. The real-time signal processing is performed entirely on the daughter cards.

The Analogue Input Cards (the four daughter boards seen on the left side of figure 2) condition the signals and pass them to 16 Multi Chip Modules (MCMs) which each process four channels. These MCMs (shown in figure 3) [4] form the core of the PPM processing consisting of digitisation and the subsequent bunch crossing identification using a digital filter. A noise cut and the fine calibration are performed using a programmable look-up table (LUT). The digital signal processing is performed by a custom-designed application-specific integrated circuit (ASIC) which holds additional functionality for debugging and system tests (e.g. monitoring, playback memories, etc.).

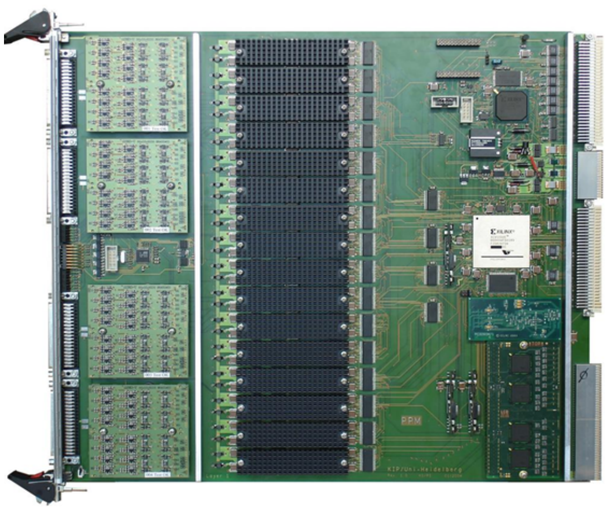

Figure 2: The PreProcessor Module consists of a main board which, apart from infrastructure, carries 23 daughter boards for signal processing, clock distribution, voltage and temperature control.

After some further processing (e.g. pre-summing of channels for the JEP system which works at lower granularity than the CP system) also performed in the ASIC, the information is serialised and sent using a further daughter card to the Processor systems (CP and JEP) in the form of LVDS signals. The main board also carries a FPGA for configuration of the signal conditioning, the various parameters of the ASIC and the timing chip on the MCM. It manages the readout of data and monitoring information and can be accessed through a CPLD by the VME bus which is present in the crate. Various components for processing of trigger and timing signals and monitoring of temperatures and voltages are implemented on further daughter cards.

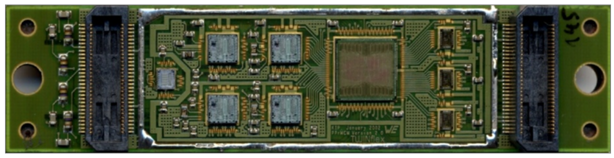

Figure 3: Photograph of the PreProcessor MCM without protection. The single chip on the left side is the timing chip with the four FADCs next to it. The large chip in the centre part is the ASIC and the three chips right of it are the serialiser chips.

III. THE ANALOGUE SIGNAL CHAIN

The ATLAS electromagnetic calorimeter is based on liquid argon (LAr), whereas the hadronic calorimeter consists of a scintillator Tile calorimeter for the central barrel and LAr for the endcap. The signals produced by ionisation in the LAr calorimeter are already preamplified in the cryostat and passed to a signal shaper located in the front end electronics of the calorimeter. An analogue sum is built from up to 60 cells (depending on the position within the compartment). The photomultiplier signals of the Tile calorimeter also pass through several shaping and amplification stages, and analogue sums of signals from typically five and sometimes six PMTs are built. These are sent to the trigger electronics situated in the electronics cavern near the experiment. The cells and photomultipliers which are added mostly cover a region of 0.1×0.1 in η - ϕ space and are called trigger towers. The Calorimeter Trigger processes signals from about 7200 of these trigger towers. Both calorimeters have pulser systems which are able to inject charge into the electronic chain with high signal accuracy and time stability. This is of paramount importance for the timing and energy calibration procedures.

The analogue trigger signals from the calorimeters are routed through $30 - 80\,\mathrm{m}$ long cables to a separate receiver system [5], situated next to the calorimeter trigger electronics, where they are conditioned. The trigger is designed to process transverse energies; e.m. calorimeter signals arrive in that form, but the gains of hadronic calorimeter signals must be adjusted. The receivers include variable-gain amplifiers that also provide precise gain calibration. A system of patch panels before and after the receiver system provides correct signal distribution to the corresponding PreProcessor Modules.

The differential signals are routed using stiff analogue cables carrying 16 channels each to the front panels of the PPMs. The signals are transformed to single-ended signals and shifted into the appropriate voltage window for the FADC. This processing takes place on Analog Input Cards which handle 16 channels each. Figure 4 shows the two parts of the differential pair for one channel of an LAr calorimeter pulse (double pulse) which was recorded with an oscilloscope at the input to the PPr.

The single-ended signals are then directed to 16 Multi Chip Modules (MCMs) which each process four channels. On the MCMs 10 bit FADCs perform the digitisation using a strobe adjustable in $1\,\mathrm{ns}$ steps under control of a special timing chip on the MCM. Subsequently, the bunch-crossing identification is done using a Finite-Impulse-Response (FIR) filter, and the fine calibration and compensation for possible non-linearities is performed using a look-up table.

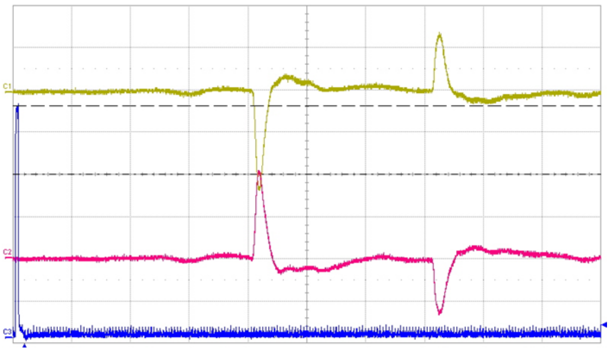

Figure 4: The two parts of the differential pair of a LAr pulser signal. Two consecutive pulses with inverted polarity are shown.

The digital processing is entirely done within the custom designed ASIC. After digitisation the data are stored in a pipeline memory from which they can be read out after receipt of an L1 Accept signal from the central trigger processor. Figure 5 shows a complete pipeline readout with signals from the LAr and the Tile calorimeter.

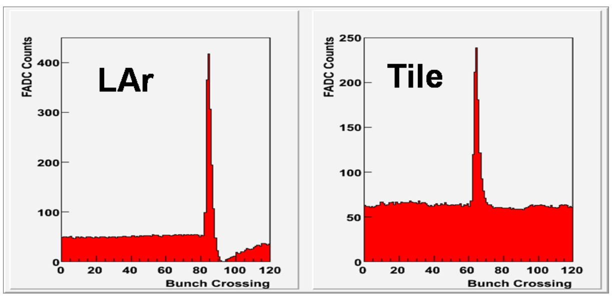

Figure 5: Digitised Pulses from the LAr- and Tile-Calorimeter as seen in the PPr system. The bipolar (LAr) and unipolar (Tile) shapes are due to properties of the pulser systems which aim to emulate real pulses as precisely as possible.

IV. The Calibration Parameters and Strategy

A large set of channel dependent and global parameters have to be adjusted in order to align all channels in time at the output stage of the PreProcessor with proper energy calibration. The input timing needs to be adjusted in order to compensate for different signal delays due to different cable lengths from the detector to the PPr. It can be done with steps of $25\,\mathrm{ns}$ corresponding to the time between two LHC bunch crossings (BC) by adjusting input pipeline delays as indicated in figure 6. This is important for the overall timing of the trigger and a correct trigger decision since the processors expect the signals which they receive to all belong to the same LHC bunch crossing.

The timing of the FADCs can be further adjusted with an accuracy of $1\,\mathrm{ns}$ in order to sample the analogue pulse at its maximum, which is needed in order to guarantee a proper energy measurement. A sampling accuracy of $5\,\mathrm{ns}$ leads to an energy measurement with a variation of $2\,\%$. Whereas a timing with a variation of $10\,\mathrm{ns}$ deteriorates the energy measurement to $10\,\%$. It should be noted that this effect not only worsens the resolution but also leads to a systematic underestimation of the energy.

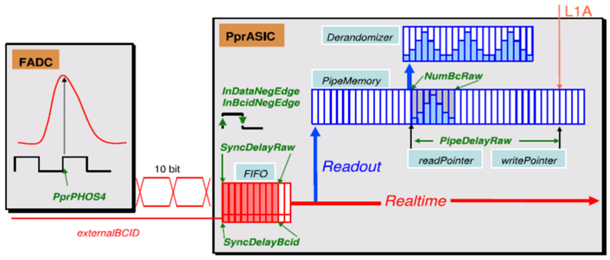

Figure 6: Dataflow scheme for the processing on the PPr MCMs. The adjustable timing parameters are indicated. (Sampling timing for the FADC (PPrPhos4), Input timing delay (SyncDelayRaw) and the readout pointer for the pipeline memory (PipeDelayRaw).)

In addition to these timing parameters which influence the real time data path a further important parameter needs to be adjusted, the readout pointer which determines the position in the pipeline memory where data have to be read upon receipt of an L1 Accept signal. The data readout itself is not essential for the trigger functionality. However it is needed for verification of the trigger decision and monitoring its performance. It is in addition involved in various calibration procedures and therefore essential for the operation of the system. In standard running condition for each channel 5 FADC slices are read with the slice corresponding to the bunch crossing in the center together with the final LUT output value.

The ASIC implements a Finite-Impulse-Response (FIR) filter for noise suppression which, together with peak-finding logic, is used to determine the bunch crossing of the interaction. Five consecutive samplings from the FADCs contribute to the input of the filter. The coefficients of the filter, which depend on the pulse shape of the signals from the calorimeter, need to be determined in order to increase the efficiency for detecting low energy objects in particular.

The noise cut needs to be determined and implemented in the look-up table to suppress positive trigger decisions due to statistical fluctuations. The energy calibration can be performed using two systems, the variable gain amplifiers of the receiver system and with somewhat less accuracy the LUT of the PreProcessor system. The LUT is however able to compensate for possible non-linearities.

Since the number of parameters fed into the system is quite large, and due to the fact that some are interdependent, a proper strategy needs to be in place in order to determine all parameters. This should be in place prior to colliding beams to guarantee a timely startup and availability of the system. The strategy consists of several steps which sometimes need iterations in order to check and refine the chosen settings.

- The readout and input timing needs to be determined in a first step in order to align all channels to the same BC and to be able to read out correct data for the further steps of the calibration procedure.
- The fine timing needs to be set correctly before any calibration can be applied in order to avoid a systematic bias from not sampling the pulses at their maximum value.
- The next step consists in a determination of the FIR filter settings to suppress noise.
- After a proper study of the channel dependent noise behaviour a noise cut can be chosen.
- At the last stage the energy calibration constants need to be determined and set at the Receiver level with possible corrections for non-linearities in the LUT.

V. The timing Calibration

A. *Readout and Coarse Input Timing*

The readout pointer, i.e. the position in the pipeline memory which holds the data for a certain BC corresponding to a L1 Accept signal, can be determined with a pulser run where parts of the system are enabled for triggering. It depends only on the time needed for the processing by the CP and JEP systems, signal transmission to the CTP and the signal transmission of the L1 Accept signal back from the CTP to the PPr. A scan subsequently reads out all parts of the pipeline memory and a fast data analysis determines the exact pulse position which produced the positive trigger decision. The readout timing is independent of the incoming signals and solely depends on the signal propagation downstream from the PPr. It can therefore be determined with a pulser run and keeps its validity also for collision data.

The coarse input timing is meant to compensate for different cable delays from the detector. As for the readout timing it can be determined with a pulser run. In practice all the input delays are set to the same value. A Readout Pointer Scan is performed which results in different readout pointers for different channels. After that all Readout pointers are set to the same value and the input delays are corrected accordingly. In order to minimize the latency of the system, the combination of the global readout pointers and channel dependent input delays is chosen such that the input delay of the channel with the largest cable length is set to zero. This choice determines unambiguously the readout pointer and the input delays of the other channels.

In contrast to the readout pointer, the input delays measured by this method are only approximately valid for collision data since the timing between channels is not necessarily the same for the pulser system and collision data. Therefore small changes of the input timing (about 1 BC for some channels) might be necessary for future collision data.

B. *Fine Timing*

The goal is to set the proper fine timing with an accuracy of a few ns in order to guarantee a proper energy measurement. Using a pulser run these settings can be found rather easily with a timing scan where all 25 different settings are applied and for each setting a certain number of events are taken. For each step the mean values of the sampled data are then calculated for the 5 FADC slices. This results in a ns accuracy sampling over $125\,\mathrm{ns}$ and therefore covers the main part of the pulses. A proper fit to these data determines the position of the maximum of the pulses. An example of such a scan (here with 20 samples read out instead of 5) is shown in the upper left plot of figure 7.

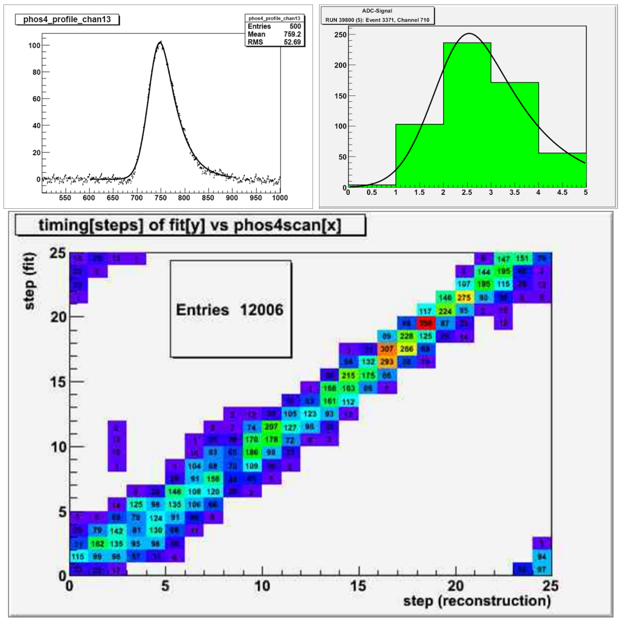

Figure 7: Fine timing studies: upper left - fine timing scan of a pulser run with ns accuracy overlaid with a fit, upper right: 5 FADC samples overlaid with a fit (after pedestal subtraction), lower: correlation of results from a fine timing scan with fits to individual signals.

However this method applies only for pulser runs, while for collision data all pulses have different pulse height which makes it nearly impossible to combine data from different events and to reconstruct the pulse shape. Therefore a method has been developed where single pulses are fitted with the position of the maximum being one of the free parameters of the fit. The upper right plot of figure 7 shows an example of such a fit where the fitted function consists of a gaussian part for the rising edge and a landau function for the falling part of the signal. Both functions are matched at the maximum and the widths of both function has been determined from a fine timing scan performed before thus leading to two free parameters in the fit being the signal height and the position of the maximum.

The lower plot of figure 7 shows the correlation of the fine timing scan and the fitting results of single pulses. Since the correlation is very good this method proves to be a promising technique for analysing collision data. However it involves a detailed understanding of the pulse shapes which is not a priori given for real pulses. However it might be possible to study the pulse shape from large samples of real data. Currently further systematic studies are being performed in order to test the reliability and robustness of the method.

VI. The Pedestal Calibration and Noise Determination

The first step towards a proper energy calibration consists in the determination of the DAC value which conditions the signals on the AnIn boards by shifting the signal in the appropriate voltage window for the FADC. This effectively determines the pedestal value of the FADC. In order to achieve this a scan of the possible 8-bit DAC values is performed and the output of the FADC is recorded. A fast data analysis determines automatically the DAC value which corresponds to the chosen pedestal value. Currently a pedestal value of 40 is chosen in order to capture the full signal amplitude even with its negative undershoot in case of the bipolar LAr pulses. Figure 8 shows a DAC-scan for a single channel and the corresponding pedestal distribution for a large number of events after adjusting the DAC values based on the scan results. The RMS of the pedestal distribution is used for the determination of the noise cut which is subsequently implemented in the LUT.

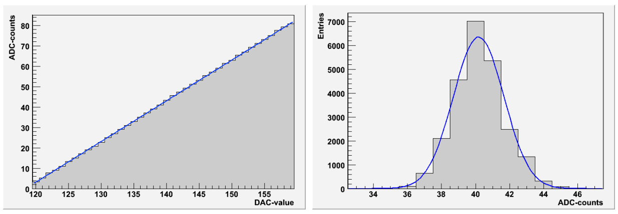

Figure 8: left: measured pedestal w.r.t. the DAC value for a single channel, right: pedestal distribution after adjustment of the DAC value with a gaussian fit overlaid.

VII. The energy calibration

A proper energy calibration is needed in order to achieve steep turn-on curves for the trigger items being used. The baseline of our calibration is the energy being measured through the standard calorimeter readout. In the circumstance that various corrections (e.g. dead material, crack losses, etc.) are used the calorimeter calibration, they will directly enter the trigger calibration as well. Currently an electronic calibration is performed which aims to shift the energy measured by the trigger to the values measured by the calorimeter. The left plot in figure 9 shows the FADC distribution for the maximum within a pulse. It should be noted that the width of the distribution is much smaller than for real calorimeter signals since it originates from charge injection into the electronic chain neglecting any calorimeter sampling effects. The right plot compares the energies of the trigger (red) with the calorimeter (black). The essentially uncalibrated trigger agrees already very well with the calorimeter measurement and this is also confirmed by studies using cosmic muons [3]. Before the restart of the LHC in early spring 2009 a detailed analysis of pulser runs will help to achieve further substantial improvements.

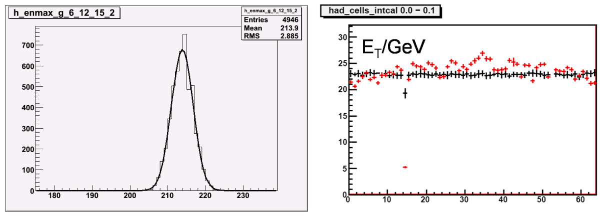

Figure 9: left: ADC distribution for the maximum of a constant pulse measured in the PPr, right: comparison of measured transverse energies for a collection of channels (red – PPr measurement, black – calorimeter readout)

VIII. Summary

After a successful installation and early commissioning phase of the ATLAS Level-1 Calorimeter trigger, the focus has shifted towards the calibration of the various timing and energy determination settings and a strategy has been set up. The first step consists in the determination of various timing settings, which is largely done using pulser runs and cosmic data taking and only small modifications expected for collision data taking. A study of the fine timing settings based on fitting individual pulses has been performed and seems to be applicable for colliding beam data. Currently detailed studies on energy calibration are being done with the aim to further improve the already reasonable energy calibration.

Acknowledgements

We wish to acknowledge the work of the ATLAS TDAQ community in providing the underlying online software and infrastructure for triggering, read-out and dataflow. We would also like to thank the ATLAS calorimeter communities, in particular those working on the trigger tower builders and receivers, for their efforts to provide genuine input signals to the trigger. Finally the successful installation of the infrastructure and cabling would have been impossible without the careful work of many technicians connected to the institutes involved. We are grateful to Björn Gosdzik, who produced figure 7(upper left) .

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