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## AugerPrime implementation in the DAQ systems of the Pierre Auger Observatory

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The AugerPrime upgrade of the Pierre Auger Observatory converts the existing surface detector, consisting of an array of 1660 water-Cherenkov detectors (WCDs), into a multi-hybrid instrument. This upgrade required improved surface detector electronics and acquisition software to accommodate the new detection channels corresponding to the scintillator surface detectors, radio detector antennas, and the underground muon detectors as well as the additional, small area photo-multiplier in the WCDs. In this work, we present an overview of the data acquisition software, both at the level of individual detector stations and the central data acquisition system. We highlight the modifications performed to handle the new multi-hybrid data of AugerPrime and cope with surface detector stations with different hardware configurations operating simultaneously in the array during the transition phase.

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## 1. Introduction

The Pierre Auger Observatory [1] comprises two main detectors: the Surface Detector (SD), which observes the particles of extensive air showers (EASs) at the ground level, and the Fluorescence Detector (FD), which detects the fluorescence light emitted by nitrogen molecules excited by charged particles of the EASs as they pass through the atmosphere. The SD (or SD-1500) is an approximately  $3000 \text{ km}^2$  array of 1600 Water Cherenkov Detectors (WCDs) distributed in an isometric triangular grid with 1500 m spacing. About 60 additional WCDs are installed in a denser region, where the distances are 750 m (comprising the SD-750) and 433 m (comprising the SD-433). Each WCD consists of a tank with a cylindrical volume of purified water with an area of  $10 \text{ m}^2$  and a height of 1.2 m viewed by three 9 inch photomultiplier tubes. The FD comprises 24 telescopes distributed between four sites overlooking the SD array. Each telescope is instrumented with 440 photomultiplier tubes and field of view approximately  $30^\circ \times 30^\circ$ . The telescopes are organized at each site to view  $30^\circ$  in elevation and  $180^\circ$  in azimuth. Additionally, at one of the sites, three additional telescopes were installed with the objective of being able to observe lower-energy EASs, which develop higher in the atmosphere. The elevation of these telescopes ranges from  $30^\circ$  to  $60^\circ$ .

The AugerPrime upgrade [2] improves the capabilities of the SD with respect to discriminating between cosmic rays of different composition. This is accomplished with the addition of two detectors operating together with the original WCD: an  $\sim 3.8 \text{ m}^2$  Scintillator Surface Detector (SSD) [3] and a Radio Detector (RD) [4]. Both are installed on top of the WCD. In addition, a small area photomultiplier (sPMT) [5] is installed in each WCD to extend its dynamic range. The stations have been instrumented with an Upgrade Unified Board (UUB) [6], which has additional inputs to service all detectors and a higher sampling rate (120 MS/s) and improved resolution (12 bits) compared to the original Unified Board (UB). In the SD-750 and SD-433,  $30 \text{ m}^2$  scintillator counters buried at a depth of 2.3 m next to each WCD comprise the Underground Muon Detector (UMD) [7].

In this work, we give an overview of the acquisition processes that run on each UUB, which we will refer as Local Station Data Acquisition (LSDAQ), and which handle the timing, calibration, triggering, and other auxiliary functions required in measuring and transmitting the signals of air showers. We also discuss the Central Data Acquisition System (CDAS), which receives and processes the data of all the individual electronics units. However, before discussing each of these acquisition systems, we give a general view of the communications system linking the LSDAQ of the stations of the array with CDAS, which significantly impacts on how these acquisition systems have been designed.

## 2. Communication between LSDAQ and CDAS

The communication between the LSDAQ of each detector station and CDAS is performed primarily by two communication systems. One is a commercial communication device, which provides the connection between the towers next to each FD building and the tower at the Central Campus. The other is a custom-made wireless communication system, which maintains the link between each SD station and its assigned tower. From the point of view of the acquisition software, the first system appears as a set of ethernet routers and switches. The traffic between towers is

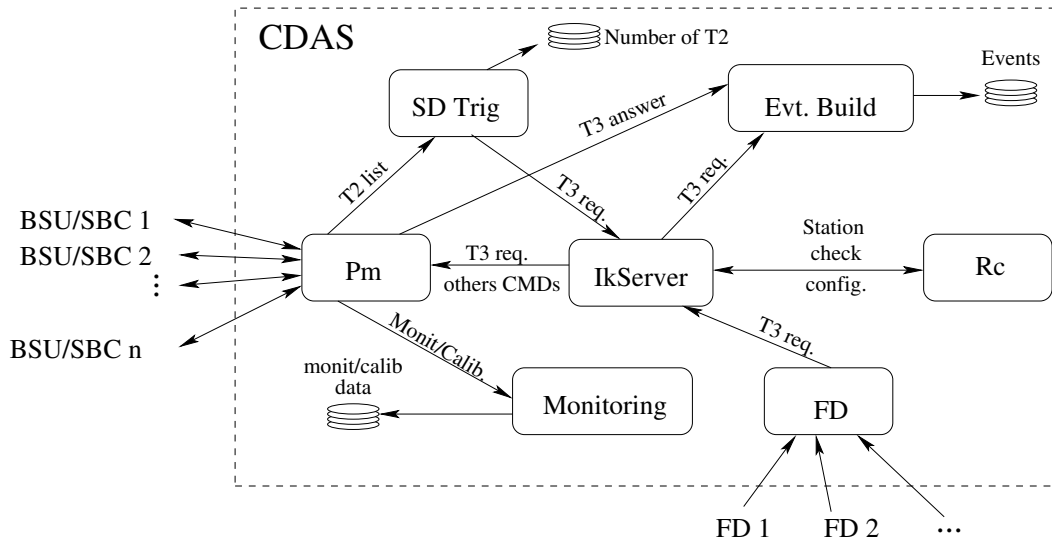
significantly below the available bandwidth provided by this first system. It is therefore not the limiting factor for the acquisition of SD data. The custom-made wireless communication system allows up to 68 stations, referred to as subscribed units (SU) which sits next to the UUB, to be connected in a single base station unit (BSU) which is installed at the tower, and it is possible to operate up to 51 BSUs simultaneously, which is more than enough to support communication with all SD stations. This system, however, imposes important bandwidth limitations: 149 bytes per second for the transmission from stations to tower and 129 bytes per second from tower to stations. Therefore, it was necessary to develop strategies on how to optimally approach the transmission of data. As described in [8], each station continually sends the type and timestamp of triggers to be considered in event identification, i.e. level 2 (T2) triggers, to CDAS. In the event-level trigger algorithm implemented in CDAS, the T2 lists are used to identify temporal and geometric coincidences between the T2 triggers reported by all the stations in the SD array. Such coincidences result in event-level triggers, i.e. level 3 (T3) triggers. In case a T3 is formed, the complete data pertaining to the event stored in any stations with any trigger at a compatible time are requested by CDAS. Aside from the T2 and T3 data, monitoring and calibration data are periodically sent from each station to CDAS. To manage the transmission of all these data, the messages are organized in priority, and the high priority messages are sent first. T2 data has the highest priority, followed by T3 data, monitoring, control data like a user request command answer.

The algorithms that send data from stations to CDAS look at how much of the highest priority message can be sent (one slice) in each given communication package. If the highest priority message has been or may be completely sent with space to spare, the algorithms consider the messages with the next highest priority and send as much of or as many as the remaining space permits. This algorithm is repeated until there are no available message to be sent. Typically, a T2 message is sent every second and uses about half of the package memory. The T3 data is about 15 KB and there are normally few tens a day in most of the array. At CDAS, all the slices of a message are joined to reconstruct the message content for subsequent interpretation and storage.

### 3. Central Data Acquisition System

A Linux operating system (OS) has been used for the development of the central data acquisition system due to the stability of the OS, the community supporting it, and the developer demographic, among others factors. To divide the computational load across multiple machines as well as the maintenance reasons, CDAS has been designed in multiple processes, each one dedicated to few specific tasks. In Figure 1, we show a block diagram of the CDAS architecture. All the communication between CDAS processes as well as the communication with external devices such as the BSUs and FD DAQ is performed with TPC/IP protocols. Data from stations is received by the BSUs and passed to the Single Board Computer (SBC) at their respective towers and sent to the Post Master (“Pm”) process of the CDAS DAQ from there.

The “Pm” interprets the packages and reconstructs the messages from the slices, and when the message is completely received, it is sent to corresponding clients. Handling of T2s is slightly different in that a list of all T2s corresponding to a given second is built from T2s reported from all stations. The “Pm” continues to collect T2s corresponding to a given second for 5 seconds after which, the T2 list is sent all at once to the “SD Trig” process. The 5 second waiting period allows



**Figure 1:** Block diagram of CDAS. The processes are represented in the rectangles with rounded corners.

the communication system to try to recover erroneous messages and ensures even T2s arriving at the “Pm” with a delay are properly considered in building event-level T3 triggers by the algorithms of the “SD Trig” process.

The “SD trig” process looks for temporal and geometric coincidences in the list of T2 triggers reported by all stations for a given second [8]. When such a coincidence is found, i.e. the conditions for an event-level T3 trigger are satisfied, a T3 request is sent to internal kernel server (“IkServer”). The request includes the time of the identified event, the list of stations involved in satisfying the trigger conditions, as well as other nearby stations. With this information, stations receiving the request can identify if they possess a trigger compatible with the T3 request and if so, respond by transmitting event data to CDAS.

The “IkServer” is primarily a process to receive and deliver messages according to the message destination and type. Messages have the following fields: message source (i.e. the name of the process that generated the message), destination (i.e. the name of process which should receive the message), message type and content. Clients of the “IkServer” receive messages if they are specified in the message destination. They can also receive messages based on the message type. Given the existence of the “IkServer”, other processes do not need to manage the list of processes that should receive a particular message since this is already taken care of. An example of this is a T3 request, which is delivered by the “SD Trig” process with “Pm” specified as the destination. The “Pm” process will receive the T3 request message and the event builder (“Evt. Build”) process will also get the request, since it requests T3-request messages by type. When the “Pm” receives a request from the “IkServer”, it determines the list of BSUs/SBCs that should receive the message. It then creates new messages for each BSU, including only the information relevant for that specific BSU. These messages are then divided based on the size of a single communication package, stored in order of priority, and equipped with communication system protocols. Finally, the packages are sent to the corresponding BSUs.

Another process which can also send a T3 request is the “FD”. If it receives a trigger from

the Fluorescence Detector DAQ, it emits a T3 request to the “Pm”. The idea is to read out SD shower measurements for the air shower in question even if insufficient stations triggered in the SD to generate an independent T3. This can occur frequently for very low energy showers. Even if the SD data is insufficient to independently reconstruct shower parameters, it often provides useful constraints for the Fluorescence Detector reconstruction.

The Event Builder (“Evt. Build”) receives T3 requests and the T3 event data sent by each station in response to the T3 requests. The process stores all the data of a single event together in a single data structure to simplify downstream processing. It is similar to the “Monitoring” process which periodically (with an interval of ~6 min) collects and stores primarily monitoring data from each station.

The “Rc” process primarily configures the LSDAQ with corresponding station identification in cases where the LSDAQ is newly deployed or restarted. It performs this task based on the position reported by the GPS Receivers in the electronics board at station.

### 3.1 Changes due to AugerPrime

It was not necessary to make extensive changes to the design of the CDAS DAQ for the AugerPrime upgrade with the exception of including the additional data of the new detectors and considering the different data format of the new electronics. Changes were performed almost exclusively in the “Evt. Build” and “Monitoring” processes. To simplify data handling with various formats, the processes simply invoke different functions based on the data version. The version number directly corresponds to either the UB or UUB electronics. As a result, CDAS can distinguish and function with both types of electronics. This allowed the entire SD array to operate as a unified system without the need to divide it into two parts during the installation of the updated electronics.

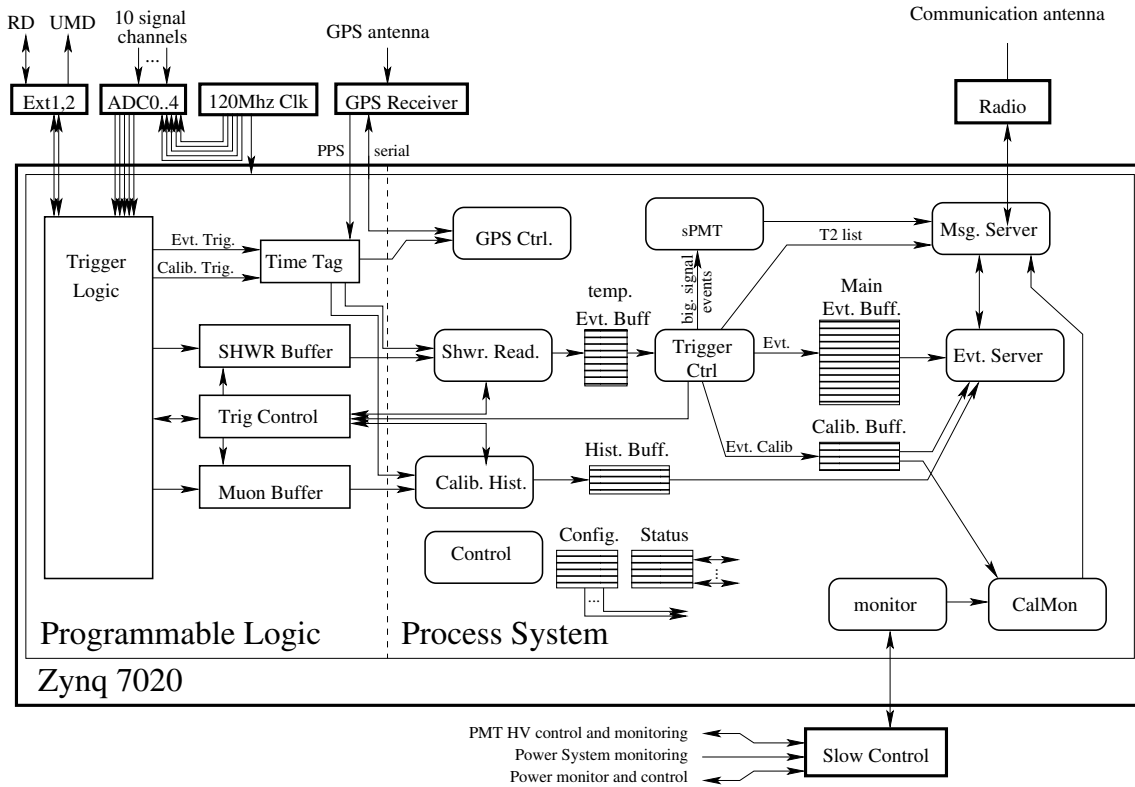
With the UUB a T3 message are sent as a single message, but internally it is divided into smaller logical data blocks, each containing data related to a particular aspect of a T3 event. This feature makes the incorporation of additional data easier and less error prone. Blocks not recognized by the readers in the “Evt. Build” process are stored in separate files, since the current data format does not allow appending unrecognized data. This approach makes testing and augmentation of the T3 data to be sent by stations significantly easier as it does not require synchronized changes in the LSDAQ, CDAS, and downstream programs that further process or analyze the data.

With the UUB, calibration and monitoring data are sent in a way analogous to how T3 data is sent to the “Evt. Build” process. The data are structured in a single message with multiple blocks. This structuring made addition of the “RD” monitoring data as simple as adding a further logical block.

## 4. Local Station DAQ (LSDAQ)

The main controller in the UUB is the Zynq 7020, which has incorporated the FPGA (Programmable Logic) and two cores ARM cortex A9 processors (Process System) in a single component. It runs the Linux operating system, where the LSDAQ is implemented.

To ease development and maintenance, the LSDAQ has been divided in multiple processes, each one dedicated to a handful of specific tasks. This is analogous to the division of the CDAS



**Figure 2:** Block diagram of the Local Station DAQ in the new electronics. On the left side, the “Programmable Logic,” implemented on an FPGA is depicted. On the right side, the “Process System” is depicted and includes processes (rounded corner blocs) which run on the operating system running in the CPUs. The the blocks filled with horizontal lines are shared memory (memory blocks which can be read by and written to by different processes).

into several processes. In the Figure 2 we show a block diagram indicating relationships between the processes. In the following, we discuss the most relevant processes of this diagram, beginning with the analog signals of the PMTs and subsequently following the data flow through the different processes.

The “Programmable Logic” reads signal traces, which have been digitized at 120 MHz by the 10 ADCs channels of 12 bits resolution. Internally, the signal traces are passed to two different modules: one which looks for air shower events and another that is used primarily for the calibration of the PMTs. The former acquires and stores triggered traces of about  $17 \mu\text{s}$  in length in the “SHWR Buffer” (see Figure 2). The latter acquires signal traces of the high gain channels of the photomultipliers with a very low trigger threshold. These data are stored in the “Muon Buffer” (see Figure 2).

The “Trig Control” in the “Programmable Logic” (Figure 2) is a set of registers used to manage the trigger settings (i.e. which triggers are enabled, trigger conditions, thresholds, etc.) and the readout process of the “SHWR Buffer” and “Muon Buffer”. The LSDAQ manipulates these buffers and registers primarily by reading and writing data to specific memory addresses.

The “Calib. Hist.” process reads and analyzes the short signal traces from “Muon Buffer”. It

calculates parameters including the signal amplitude and integral, and fills these data into corresponding histograms. As very low trigger thresholds are used, the signals generated by the abundant muons of low energy showers will be visible in the generated histograms. These histograms are used to estimate the signal generated by vertical muons (VEMs) in each WCD and minimum ionizing particles (MIPs) in the SSD. The generated histograms are stored in the “Hist. Buff.” as depicted in Figure 2.

The “SHWR Buffer” has space to store up to 4 first level trigger events (T1). If this buffer is full, the Programmable Logic does not have a way to write additional events, which equates to dead time. Therefore, the read and primary event processing from this buffer have been implemented in two different processes: “Shwr. Read.” which extracts the events from the “SHWR Buffer”, releasing space for new events, and stores them in “temp. Evt. Buff” as quickly as possible. Further processing is then performed in the “Trigger Ctrl” process.

The “Trigger Ctrl” is the key process related with the triggering and online calibration as described in [8] and in [9]. Aside from moving the events from the “temp. Evt. Buff” to the “Main Evt. Buff.”, it performs two principal tasks. The first is it generates the list of timestamps for a given second of all the events which pass the second level trigger (T2) condition (i.e. the “T2 list”) and sends it to the “Msg. Server” process. This list is later sent to CDAS, which uses it to search for coincidences between stations (i.e. to form T3 triggers). The second looks for the features of the events such as the trigger rate, and signal amplitude and integral. Using these features, it provides an “online” estimate of the VEM [9]. Based on the estimated VEM, it sets the trigger conditions in the “Trig Control” of the “Programmable Logic”.

The T3 request sent by CDAS is received by the “Evt. Server”, which searches the “Main Evt. Buff.” for events matching the request. In case no event matches the request, a flag indicating no event is returned. Otherwise the event is joined with calibration data from the “Calib. Buff.”, histograms from the “Hist. Buff.” and some additional timing information from the “Status” buffer (which is actually collected by the “GPS Ctrl.”). This data is then sent back to CDAS.

The “CalMon” process acquires calibration data from the “Calib. Buff.” and monitoring data (e.g. power system parameters, HV settings applied to the PMTs, and so on) through the “monitor” process. These data are packed and sent to the “Msg. Server” for transmission to CDAS.

In the UUB, the “Msg. Server” is capable of handling two different communication protocols and recognizing which one is available. One of these protocols is compatible with the communication radio (SU) with which the vast majority of stations in the array are equipped; the other, with TCP/IP. As the communication through TCP/IP has much higher bandwidth, the stations running with this communication system can transfer data much faster. This is important in the SD-750 and SD-433 regions of the array where the rate of T3 events exceeds the capacity of the usual communications system<sup>1</sup>.

The communication of processes in the LSDAQ with the “Msg. Server” is implemented with local named socket and the messages to be transmitted are ordered in priority in an internal “Msg. Server” buffer of 1 MB (which would be enough for more than 50 T3 events). These features allow a process to send messages with differing priority and also permits the straightforward implementation

<sup>1</sup>As the stations are much closer to each other in SD-750 and SD-433, the efficiency of forming T3s for lower energy events is significantly higher, hence the T3 rate in these regions is much higher due to the power law cosmic ray energy spectrum.



of additional processes communicating with the “Msg. Server” since the communication is mostly writing and reading data to and from an established connection.

#### 4.1 Additional detectors

The new detectors of AugerPrime that are included as part of or communicating through the SD stations are the SSD [3] and RD [4] as well as the sPMT [5]. The SSD and sPMT are just additional channels in the UUB which are treated similarly to the usual WCD PMTs. Although the acquisition of the RD is implemented in external electronics, the “Programmable Logic” makes most of its data available to the LSDAQ in form similar to additional PMTs channels.

For the calibration of the sPMT (i.e. determination of its gain relative to the other WCD PMTs), a selection of the events which are seen by the sPMT and WCD PMTs has been implemented in “Trigger Ctrl” process. These events are received by the “sPMT” process, which extracts the signal amplitude and total charge of all PMTs and sends this data to CDAS. In CDAS these data are stored by a dedicated process for posterior processing to determine the calibration constants for the sPMT.

The UMD [7] is installed in many stations in the SD-750 and SD-433. This detector has its own acquisition; however, readout is triggered by the SD station. The T1 signal from the SD electronics is sent through the external connector with an event identification. This identification is also stored in the “Main Evt. Buff” with each event. When the “Evt. Server” process find an event matching a T3 request, the event identification is send to the UMD through the local network. With this identification, it is possible to find which UMD event corresponded to the SD event in question.

#### 5. Conclusions

In this contribution, we gave a general overview of the SD DAQ system within the context of the infrastructure for communication between SD stations and CDAS. AugerPrime necessitated modifications in the existing DAQ. The majority of modifications in CDAS were to support the differing format of UUB data and of the new detectors while simultaneously maintaining the functionality to handle the data of the original UB electronics. This made for a smooth transition from UBs to UUBs possible in the SD array. The LSDAQ has been equipped to manage the additional detectors of AugerPrime. Moreover this includes modifications to make testing and augmentations to the data sent to CDAS significantly less cumbersome and error prone.

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