Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Instruments and Methods in Physics Research A 539 (2005) 595–605

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.com/locate/nima

The ALTA cosmic ray experiment electronics system

W. Brouwer, W.J. Burris, B. Caron, J. Hewlett, L. Holm, A. Hamilton,
W.J. McDonald, J.L. Pinfold*, P. Price, J.R. Schaapman,
L. Sibley, R.A. Soluk, L.J. Wampler

Physics Department, University of Alberta, Edmonton, ALb, Canada T6G 2J1

Received 11 May 2004; accepted 21 October 2004
Available online 7 December 2004

Abstract

Understanding the origin and propagation of high-energy cosmic rays is a fundamental area of astroparticle physics with major unanswered questions. The study of cosmic rays with energy more than 10^{14} eV, probed only by ground-based experiments, has been restricted by the low particle flux. The Alberta Large-area Time-coincidence Array (ALTA) uses a sparse array of cosmic ray detection stations located in high schools across a large geographical area to search for non-random high-energy cosmic ray phenomena. Custom-built ALTA electronics is based on a modular board design. Its function is to control the detectors at each ALTA site allowing precise measurements of event timing and energy in the local detectors as well as time synchronization of all of the sites in the array using the global positioning system.

PACS: 96.40.Pq

Keywords: Cosmic rays; Extended air shower; Global positioning satellite system; Large area array; Readout electronics

1. Introduction

High-energy cosmic rays (HECRs), made up primarily of protons and atomic nuclei, allow one to probe much higher energies then can be reached by terrestrial accelerators and are the focus of numerous current experiments. In the last 10 years a number of projects [1] have started up using sparse arrays of cosmic ray detectors situated in local high schools and colleges to look for either extremely large showers caused by single cosmic rays, or groups of showers due to correlated cosmic ray air shower phenomena. The longest running of these projects is the Alberta Large-area Time-coincidence Array[1] (ALTA) experiment

---

*Corresponding author.
E-mail address: pinfold@phys.ualberta.ca (J.L. Pinfold).

[1] http://www.ualberta.ca/alta.

0168-9002/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2004.10.032

initiated in 1994 as a collaboration between the University of Alberta (UofA) and local high schools. The main research aim of the ALTA collaboration is to search for a non-random component in the HECR flux by looking for pointing and time coincidences between widely separated detector stations. The GPS system employed by ALTA allows precise timing between sites separated by distances ranging from a few kilometres to hundreds of kilometres. The geographical layout of the present and planned detectors forming the ALTA array is given in Fig. 1. At present 13 detector stations are operational at sites covering an area of the order of $100,000\,\mathrm{km}^2$.

It should be noted that the LAAS sparse network [2] of university/institute-based detectors in Japan has been operating for the past several years. This effort has similar physics aims to the ALTA project, without the specific educational and outreach dimensions. This network has ~10 detector stations spread over $130,000\,\mathrm{km}^2$.

2. The ALTA design

Each ALTA site consists of three weatherproof insulated enclosures mounted on a building roof at the vertices of an equilateral triangle, with approximately 10 m sides. On or near these enclosures is a GPS antenna mounted on a length of conduit to raise it above any structures on the roof. Each enclosure houses a temperature controller connected to a length of heater tape and a light tight box which contains a sheet of scintillator ($1\,\mathrm{cm} \times 60\,\mathrm{cm} \times 60\,\mathrm{cm}$) read out by a light guide and photomultiplier tube (PMT). Cables from each enclosure run through grounded metal conduit to custom electronics housed in a Eurocrate and read out by a computer (Fig. 2).

An incident shower of large enough extent, greater than $\sim 10^{14}\,\mathrm{eV}$, will cause a local coincidence between the three detectors. Comparing the local timing of the three detector hits allows the direction of the incoming shower to be measured. Each local coincidence is stamped with the GPS time and the whole event is written to the data acquisition computer. The data from each detector station is uploaded every 2 h to a central site. Using the GPS times a search is made for coincident events at different locations or bursts of events at one or more sites.

Although by involving schools ALTA has an outreach component, its primary goal is as a physics experiment and so all of its components are designed and constructed to maintain the level of quality and accuracy expected in any subatomic physics experiment. This includes the data acquisition electronics which form the heart of each ALTA detector system and is based on a modular, crate-mounted design.

3. ALTA electronics

The ALTA electronics consists of a set of seven circuit boards designed and assembled at the UofA Centre for Subatomic Research and housed in a 6U Eurocrate, as shown in Fig. 3.

A common design element of the ALTA boards is the use of a field programmable gate array (FPGA) to do most of the data handling and storage. The original boards used various Xilinx 4000 series FPGAs with code uploaded by computer via ALTAs custom data acquisition program. The current revision uses the less expensive and more powerful Xilinx Spartan FPGA loaded on power up from an EPROM located on each board.

All boards accumulate data in a FIFO located in their FPGA. The GPS 1 s pulse is used to generate an interrupt in the DAQ computer which then reads out all of the data collected in the crate once per second. Boards based on the old 4000 series FPGAs could store 43 full triple coincidence events before their FIFOs were filled. The limit of the newer Spartan-based boards has not been measured since none of the new coincidence boards have yet been assembled. The new boards are expected to be able to store 172 events. The actual rate for triple coincidence events is only 2–3 per minute, double coincidence events occur at about 2–3 per second, while in single coincidence the data rate is over one hundred counts per second.

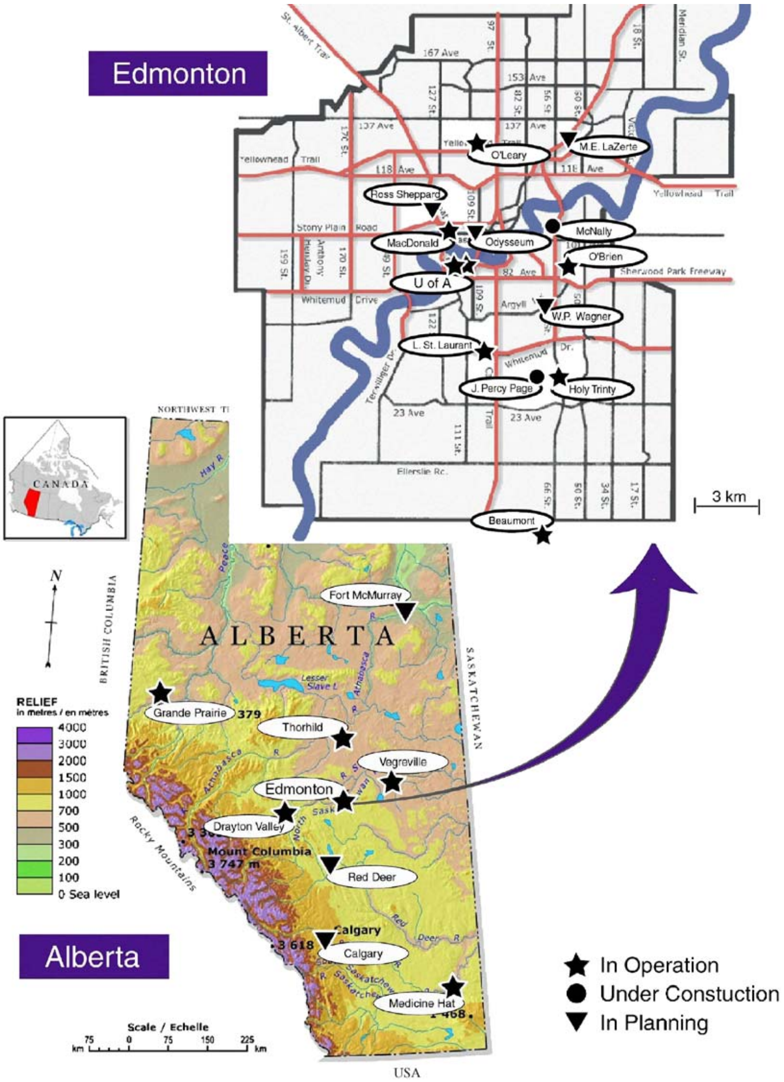


Fig. 1. The geographical distribution of detectors in the ALTA array.

The coincidence, analog, calibration, temperature and high-voltage control boards all have functions that use computer controlled numerical values. These values are set using digital-to-analog converters (DAC) then the output of the DAC is sampled by an analog to digital converter (ADC) and echoed back to the computer. In this way when you set a value you immediately have confirmation that the correct value has been received and set by that particular board.

3.1. Coincidence module

The outputs from the three photomultiplier tubes enter the coincidence module which makes the trigger decision on whether or not a 'good' event has occurred. A block diagram of the coincidence board is shown in Fig. 4. The PMT signals enter a Comlinear CLC411 amplifier with a gain of 2 and then are split into two channels, one going into constant-fraction pulse height

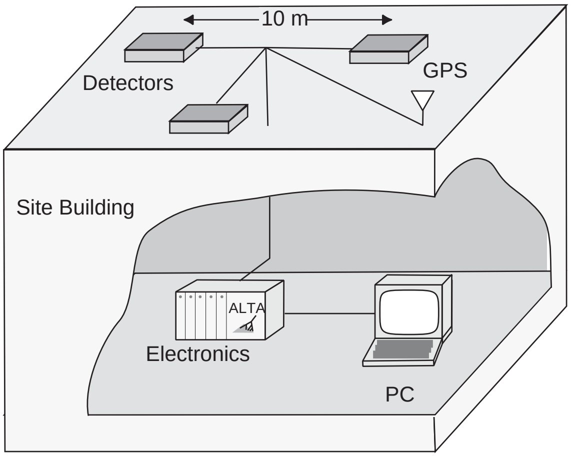


Fig. 2. Schematic depiction of an ALTA detector system (not to scale).

discriminators, the other going along the crate backplane to the analog board. The discriminators use an Analog Devices AD891 rigid disk data channel qualifier and produce a 120 ns long output pulse if the input PMT signal is above a computer adjustable threshold. An important measurement for ALTA is the local time difference between the three detectors which is used to determine the direction of the cosmic ray air shower. Constant fraction discriminators [3] were choosen because they yield a more consistent timing measurement then conventional discriminators which are much more sensitive to rise time and pulse height variations.

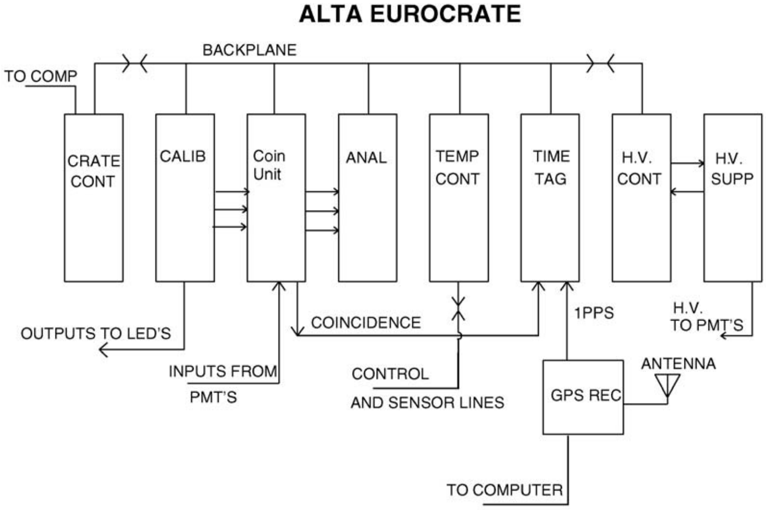
The discriminator outputs are split into two channels. One is delayed by 100 ns while the other goes to a coincidence network which makes the trigger decision on whether or not the data represents a ‘good’ event. The coincidence network can be set in software to require that only one, any two, or all three of the discriminators be simultaneously fired. The individual channels can be ‘disabled’ which sets them as always true for purposes of the coincidence logic. The coincidence threshold is set by an 8 bit DAC with a range of 0–−1 V. The input circuit is linear for inputs from 0 to −1.6 V and saturates at −2.0 V. Most PMT pulses are less then 500 mV and the normal discriminator threshold is −30 mV.

In most cases the coincidence level is set to three so that all three PMTs need to have produced pulses above threshold within a window of approximately 90 ns. The output of the coincidence network is fanned out to three ISNG 8784-011 time to amplitude converters (TACs) on the coincidence board where it provides the start time. It is also sent by the back plane to the analog board, where it triggers the PMT pulse area measurement, as well as through a front panel output to the time-tag board, where it is used to define the global event time. The stop time to the three TACs comes from the 100 ns delayed discriminator outputs and the resulting local time between the different PMT hits is read by an Analog Devices AD9220 12 bit ADC and stored in the FPGA memory. The TACs are calibrated to yield 1 ADC count per 25 ps.

The ADC values in both the coincidence and analog modules are generated with a single ADC by multiplexing all three inputs through an ADG201HS analog switch (see Fig. 4). Each input is given approximately 2.5 μs to settle before the ADC start convert is issued then an additional 1.5 μs is given for readout before the analog switch selects the next input channel. This gives an overall deadtime of 12 μs after a trigger is generated. As the low overall event rate deadtime was not considered an issue the use of a single readout ADC and switch eliminated potential crosstalk between ADC channels as well as concern that ADC noise offsets would effect the timing.

3.2. Analog module

The analog board receives the trigger decision from the coincidence board and the amplified PMT signals, via the crate backplane (Fig. 4). One of the central features of the analog board is a pair of chips designed for the Sudbury Neutrino Observatory (SNO) [4]. The trigger drives the SNO discriminator chip which is used to control gates on the SNO integrator chip. The SNO chips support four channels of inputs and two different possible gains for each input. The PMT signals are delayed by 125 ns, put through a 400 ns shaping amplifier then enter the SNO integrator which integrates the pulse area over 600 ns. As with the



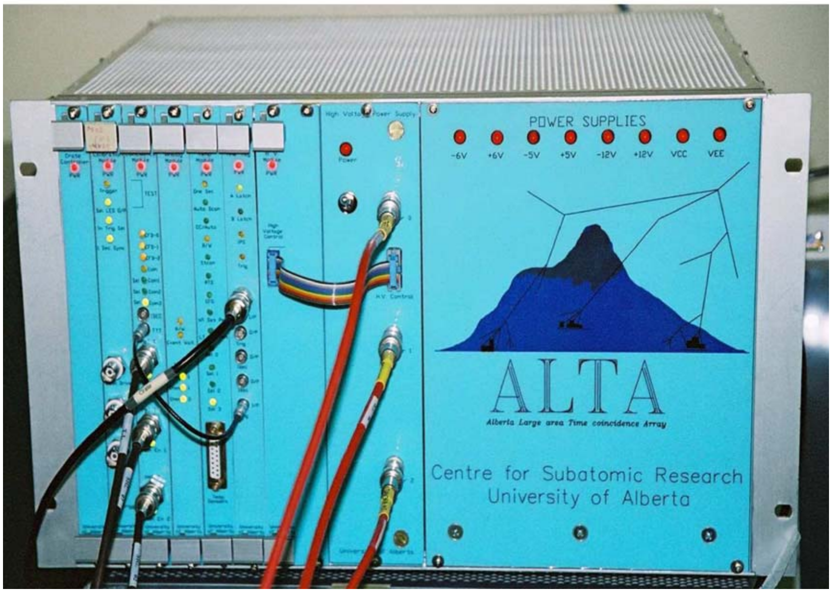


Fig. 3. The ALTA electronics crate.

coincidence board, the results of the integrator are multiplexed through an analog switch and read out with a 12 bit ADC.

3.3. Time-tag module

The coincidence board records the local timing of the three scintillation detectors relative to each other, the time-tag (TTAG) board records the global timing of one site relative to another. The first ALTA TTAG boards were computer-mounted ISA boards based on a design from Leeds [5] but they have since been redesigned to be consistent with the rest of the ALTA electronics. The TTAG board receives front panel inputs from the GPS receiver and the coincidence board (Fig. 5). It tags each good event with a number representing when the event occurred relative to

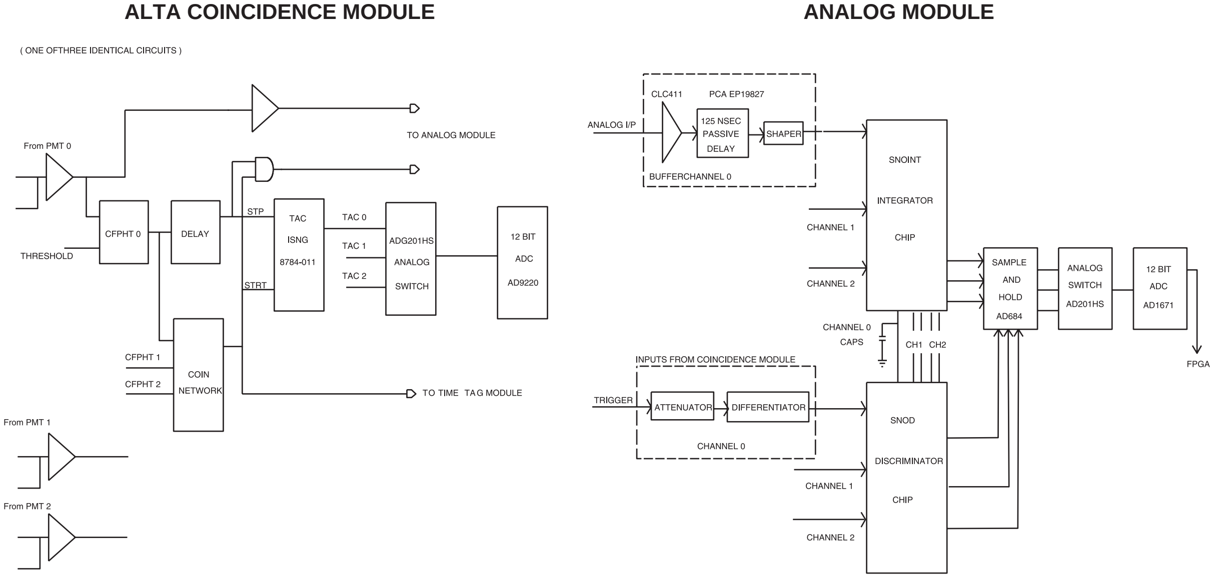


Fig. 4. Schematic view of the coincidence and analog boards.

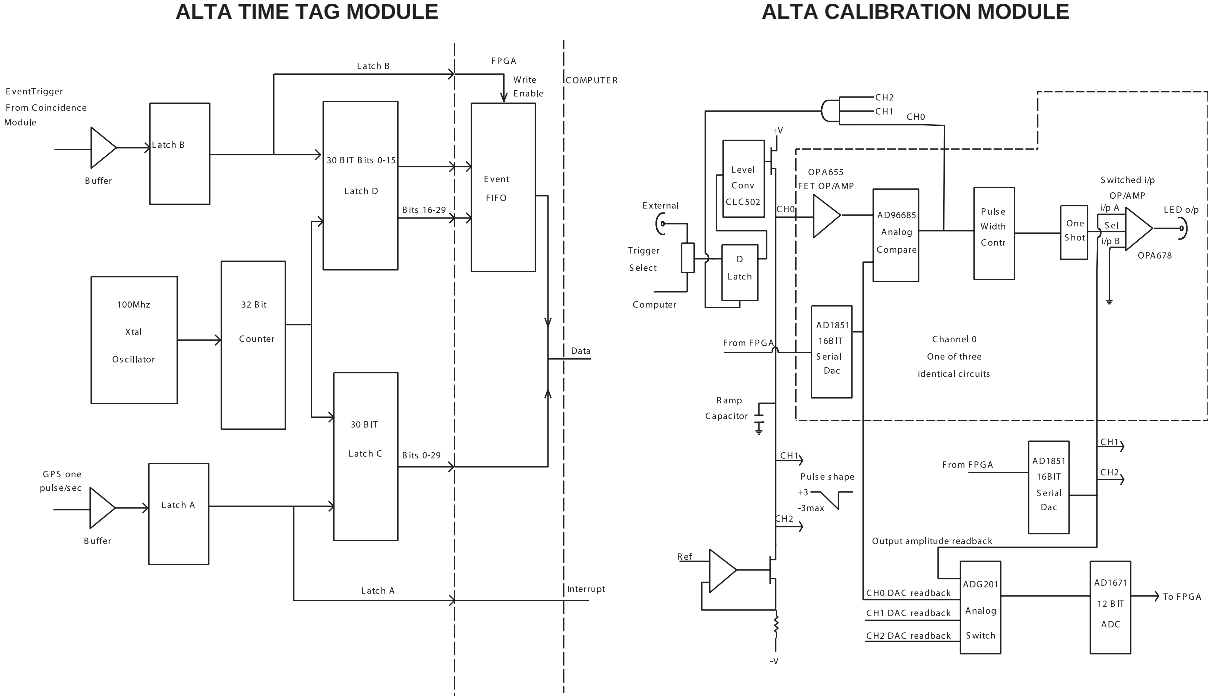


Fig. 5. Schematic view of the TTAG and calibration boards.

the previous GPS 1 s pulse and also generates the interrupt which causes the DAQ computer to read out the data stored in memory on the various boards. The heart of the TTAG board is a MTI Milliren Technologies 210-05599 100 MHz temperature-compensated oscillator connected to a 30 bit counter. The oscillator frequency drifts by a few Hertz a month but some temperature-dependent effects have been seen, so using GPS data the frequency of the oscillator is recalculated every 15 min to ensure the most accurate result possible. The 30 bit counter was a separate ECL IC on the boards based on the 4000 series FPGAs but the Spartan FPGAs are fast enough that the counter is now built directly into the FPGA. The free running counter is incremented on every 10 ns clock cycle. The value of this counter is recorded at the instant that either the GPS 1 s pulse (ALATCH) or coincidence trigger pulse (BLATCH) arrives. The difference of the ALATCH and BLATCH counter values allows the timing of the coincidence trigger, relative to the GPS second pulse, to be determined to within 10 ns. It is currently being investigated whether clock doubling in the Spartan FPGAs can be used to make this accuracy 5 ns. Detailed information on the ALTA GPS and TTAG system, as well as their performance, can be found in Ref. [6].

3.4. Calibration module

The calibration module [7] has three computer controlled outputs which drive the LEDs mounted in the scintillators (Fig. 5). This board has the largest number of user controls. How often the LEDs are pulsed can be set from once per second to once per several hundred seconds, or they can be turned off completely. They can be synchronized to the GPS second, so that the LEDs are always flashed at the same time relative to when the GPS 1 s pulse arrives, or allowed to fire randomly during the GPS second. All three LEDs are driven with the same amplitude pulse set with a software controlled range of 0–3.5 V. Pulse duration is 15 ns, but each of the three LEDs has an independent user controlled delay of 0–100 ns.

The calibration board can be used to simulate both the energy and time offsets of real cosmic hits and is normally set to fire once per minute synchronized to the GPS pulse to allow monitoring of both detector gain and timing performance of the coincidence and TTAG modules. The calibration board is very useful for trouble shooting systems and it can also be used to generate controlled data runs for testing offline analysis code.

3.4.1. Temperature module

The temperature board reads in one temperature sensor from the backplane and three from its front panel (Fig. 6). The front panel inputs are from temperature sensors in the three detector enclosures, the backplane input is from a sensor in the crate which monitors crate temperature. The sensors are Dallas Semiconductor DS1631 digital thermometer/thermostats which also act at temperature controllers and, once initially set up via the temperature board, will regulate the temperature even if the rest of the electronics is disconnected. The temperature controller turns on heat tape in each enclosure if the temperature falls below freezing. The unit mounted in the crate is used just as a temperature sensor. One temperature is read out and stored in the local FPGA on every interrupt from the TTAG board, therefore it takes 4 s to poll all 4 temperatures.

3.4.2. High-voltage control and supply modules

The PMT high-voltage supplies are Spellman model MS2.5N12/C DC to DC converters which output 0—–2500 V with 3 W of power. The high-voltage control board uses a DAC8413 quad 12 bit DAC to independently set the high-voltage values to an accuracy of 1 V (Fig. 6). In addition to the normal echoing back of the output of the DACs a voltage divider circuit is used to measure the actual output voltage of each high-voltage supply. These HV values are recorded with each event.

3.4.3. Crate controller

The crate controller allows interaction between the crate and the DAQ computer via a 16 bit parallel cable. The original crate controller connected to a custom-made ISA board located in the DAQ computer. Because the ISA bus standard is now obsolete and becoming difficult to find, the

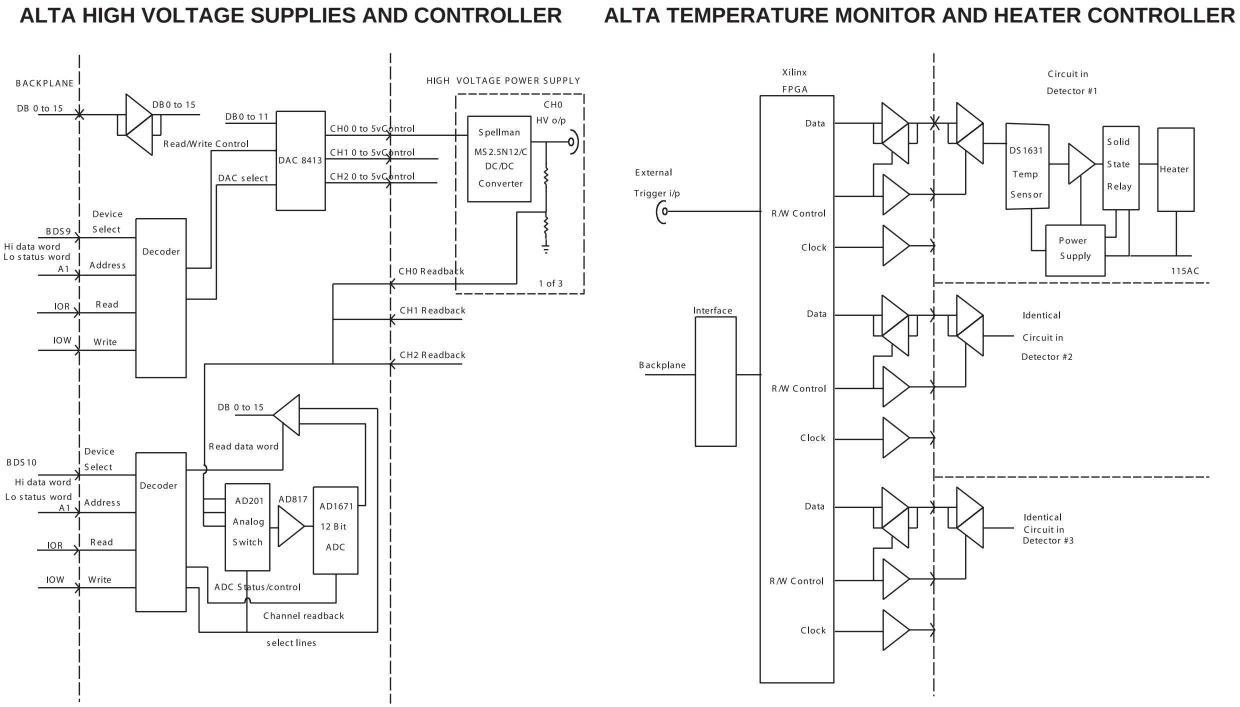


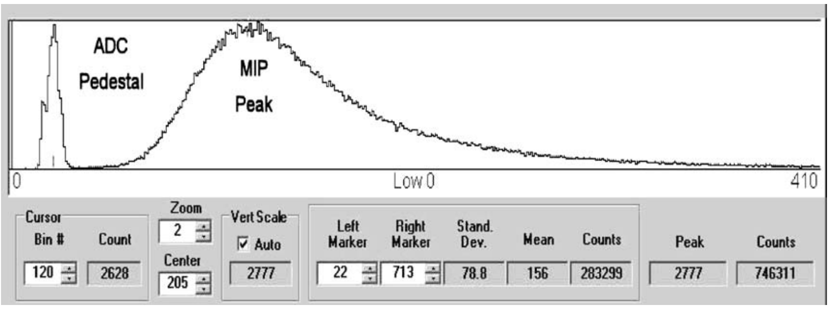
Fig. 6. Schematic view of the temperature and HV control boards.

new version of the crate controller is designed to connect to a standard off-the-shelf PCI parallel card. A crate controller which connects directly to a standard USB port is under development.

4. Electronics performance

Tests done on the GPS system indicate that for sites separated by a few hundred kilometers the relative timing between sites can be measured with an accuracy of 16 ns [6] and for sites separated by only tens of kilometers the accuracy should be within 10 ns, with the largest source of error being ionospheric variations over the area of the array.

A typical minimum ionizing particle (MIP) peak observed in the ADC spectrum of an ALTA detector is shown in Fig. 7. The MIP peak gives rise to ≈25 photoelectrons [8] and the high voltage



Cursor Bin #	Cursor Count	Zoom	Center	Vert Scale ☑ Auto	Left Marker	Right Marker	Stand. Dev.	Mean	Counts	Peak	Counts
120	2628	2	205	2777	22	713	78.8	156	283299	2777	746311

Fig. 7. A typical ADC spectrum showing the MIP peak.

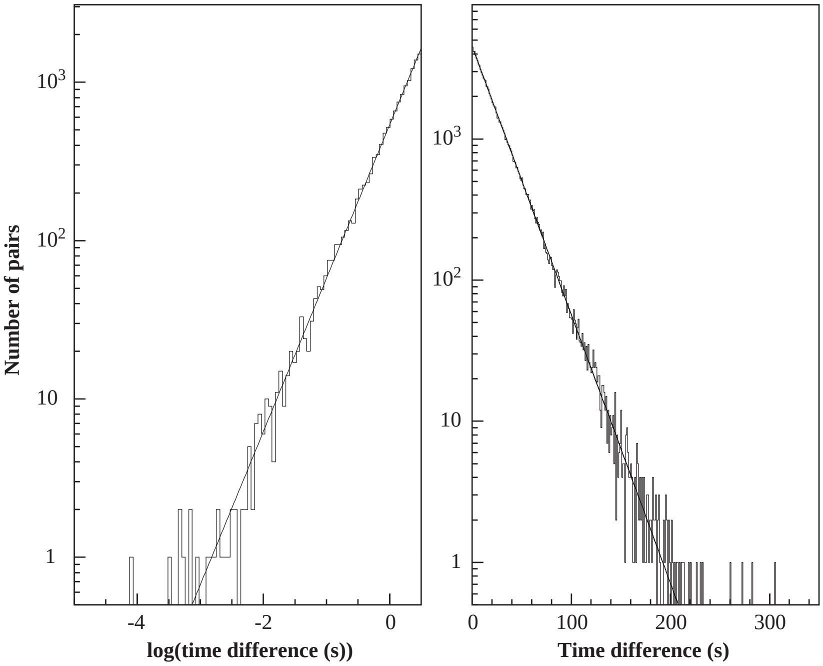


Fig. 8. A typical Δt plot for a single site. Δt is the difference in time between consecutive coincidences (or 'hits') between the three detectors forming the local detection system. The data was fit to an exponential distribution.

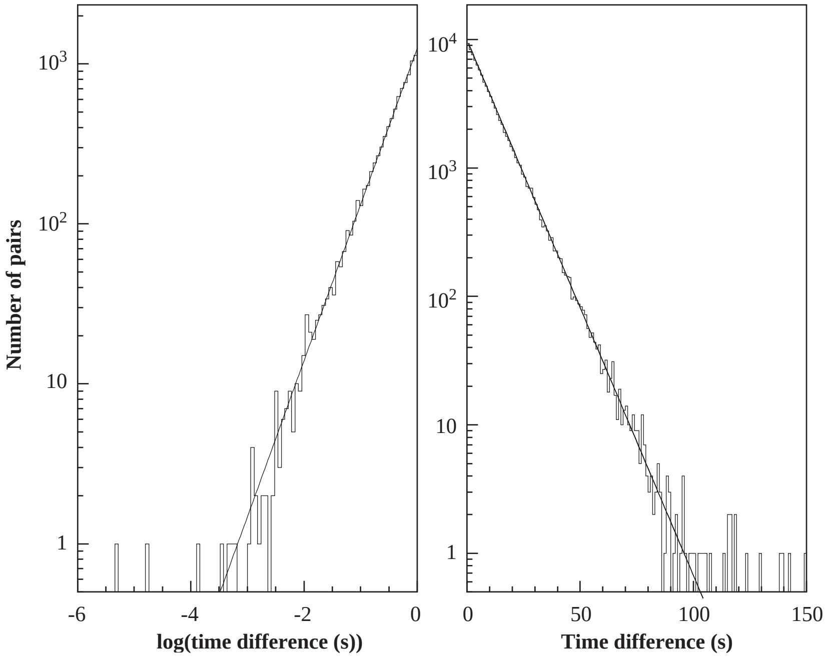


Fig. 9. A typical Δt plot between two separated sites. Δt is the minimum time difference between hit times at the two sites. The data were fit with an exponential distribution.

is tuned so that each ADC count corresponds to approximately 20 keV of energy deposited in the scintillator.

Pulser tests have shown that the coincidence board can measure local timing to an accuracy of 40 ps. Detector effects and variation in arrival times of the particles in the shower front (the 'thickness' of the incoming shower) limit the actual timing resolution to an order of 1 ns. Thus, the electronics does not contribute significantly to the timing uncertainly.

Due to a manufacturer defect in the original DS1621 temperature controllers the roof top detectors have been exposed to temperatures ranging from −30°C in the winter to +50°C in the summer. The Eurocrates have had long-term exposure to very dusty conditions and +45°C temperatures. Both the detectors and electronics have performed well even under these conditions.

Correlated cosmic ray phenomena can be revealed at a single detector site or by separated detector sites in two ways. Firstly, at a single site, by bursts of events in which the individual coincidences have a much smaller temporal separation than the 'normal' coincidences. A typical time difference plot is given in Fig. 8. In the event of a signal being seen one can also invoke the criterion that the signal events are consistent with arriving from the same direction.

Secondly, one can look for coincidences between separated detector sites. In the ALTA array this separation varies from 100 m to several hundred kilometres. A typical time difference plot is given in Fig. 9. This plot was populated by taking the minimum time difference between hit times at the two sites. In this case the two sites separated by approximately 140 km. In the event of a signal being seen, at small time difference, one can also require that the candidate events are consistent with arriving from the same direction.

5. Conclusion

The aim of the ALTA electronics development is to provide a custom-made, full function, low cost, electronics system for an ALTA detector triplet, that provides: triggering and precise event pointing via a precision coincidence measurement; readout; HV control; precision GPS time stamping; LED-based calibration; and, some environmental control. The oldest ALTA sites have now been in operation since 1998. The detector and electronics have both proved effective and robust even when operated for long periods under the harsh weather conditions experienced in central Alberta. Revisions in ALTA board design have allowed advantage to be taken of new technology and have reduced the electronics cost by roughly a factor of two, to around $5000 (US), with no loss of performance. The next series of planned revisions calls for reducing the total number of boards in the ALTA electronics crate from 7 to 4 with a reduction in low-voltage power supply size resulting in further cost savings.

Acknowledgements

We would like to acknowledge the following funding bodies without whom this work would not have been possible: The Alberta Innovation and Science Research Investment Program (ISRIP); the Imperial Oil National Centre for Math, Science and Technology Education (IONC-MASTE); Saint Gobain Crystals and Detectors (formerly Bicron); Life Members Organization of the Engineering Institute of Canada; The Centre for Math Science and Technology Education (CMASTE); and last, but not least, the Office of the Vice President (Research), the Dean of Science and the Chair of the Physics Department of the University of Alberta.

References

[1] See http://www.ualberta.ca/nalta.
[2] N. Ochi, et al., Nucl. Phys. B (Proc. Suppl.) 97 (2001) 165.
[3] M.R. Maier, et al., The sixteen channel CAMAC constant fraction discriminator for APEX, IEEE 1991 Nuclear Science Symposium and Medical Imaging Conference.
[4] F.M. Newcomer, et al., A wide dynamic range integrator discriminator timer chip set for PMT applications, IEEE Trans. Nucl. Sci. NS-42 (4) (1995).
[5] C.L. Pryke, Nucl. Instr. and Meth. A 384 (1997) 420;
C.L. Pryke, et al., Nucl. Instr. and Meth. A 352 (1995) 560.
[6] W. Brouwer, et al., Nucl. Instr. and Meth. A 493 (2002) 79.
[7] The calibration board used some ideas from: O. Sasaki, et al., A precision pulse generator for TDC calibration, IEEE 1988 Nuclear Science Symposium.
[8] Andrew Hamilton, ALTA: Alberta large area time coincidence array, M.Sc. Thesis, University of Alberta, Fall 2002.