Data acquisition system for segmented reactor antineutrino detector

Z. Hons\textsuperscript{a,b,1} and J. Vlášek\textsuperscript{a,c,d}

\textsuperscript{a}Joint Institute for Nuclear Research, Moscow Region, Dubna, Russian Federation
\textsuperscript{b}NPI — Nuclear Physics Institute, Rež, Czech Republic
\textsuperscript{c}IEAP — Institute of Experimental and Applied Physics, CTU Prague, Prague, Czech Republic
\textsuperscript{d}UWB — University of West Bohemia in Pilsen, Pilsen, Czech Republic

E-mail: hons@ujf.cas.cz

Abstract: This paper describes the data acquisition system used for data readout from the PMT channels of a segmented detector of reactor antineutrinos with active shielding. Theoretical approach to the data acquisition is described and two possible solutions using QDCs and digitizers are discussed. Also described are the results of the DAQ performance during routine data taking operation of DANSS. DANSS (Detector of the reactor AntiNeutrino based on Solid Scintillator) is a project aiming to measure a spectrum of reactor antineutrinos using inverse beta decay (IBD) in a plastic scintillator. The detector is located close to an industrial nuclear reactor core and is covered by passive and active shielding. It is expected to have about 15000 IBD interactions per day. Light from the detector is sensed by PMT and SiPM.

Keywords: Data acquisition concepts; Detector control systems (detector and experiment monitoring and slow-control systems, architecture, hardware, algorithms, databases); Neutrino detectors

ArXiv ePrint: 1605.03983

\textsuperscript{1}Corresponding author.
1 Introduction

The DANSS project [1] aims to measure the spectrum of reactor electron antineutrinos using detection of inverse beta-decay in a plastic scintillator. Its non-flammability allows it to be located closely under a 3 GWth industrial nuclear power plant reactor in Kalinin, Russian Federation where the antineutrino flux is about $10^{21}$ per second. The detector assembly has 1 m$^3$ of active volume and is covered by passive and active shielding (figure 1). To measure the variance of antineutrino spectrum based on the distance from the reactor, the entire assembly including acquisition electronics is mounted on a lifting mechanism.

![Figure 1. Design and location of the DANSS detector.](image)
The detector is constructed from 2500 scintillating strips with dimensions of $4 \times 1 \times 100$ cm. Each strip is coated by a reflective layer containing Gadolinium (figure 2) and contains wavelength shifting fibers for light collection.

Each successive layer of the detector is built perpendicularly to the previous one. Ten parallel layers of 5 neighboring strips form one detector section (module — figure 3). The X and Y sections are intercrossing so that the positional information of the interaction can be extracted. Every detector section is connected to one PMT.

The light is collected through wavelength shifting fibers by PMT and MPPCs. Each bundle of 100 WLS fibers from 50 strips is connected to one PMT. The average yield from single strip of is about 35 photoelectrons per 1 MeV [2].

![Figure 2. Scintillating strip.](image)

![Figure 3. Detector internal layout.](image)

Every PMT is connected to an analog frontend (AFE) containing high voltage power supply, pulse shaper, analog comparator and controlling MCU with a DAC (figure 4). All AFEs are controlled from the acquisition PC via RS-485 bus. The output pulse from the pulse shaper is about 100 ns long and is accompanied with above-set-threshold digital pulse.

The MPPCs are connected to a separate data acquisition system which is not a subject of this paper.

![Figure 4. PMT signal path.](image)

An oscilloscope capture of multiple cosmic ray hits from one DANSS detector section is shown in figure 5.
Figure 5. Capture of cosmic background pulses from detector section.

The DANSS detector uses the inverse beta decay as its detection principle (figure 6). The electron antineutrino coming from the reactor core interacts with a proton inside the scintillator and produces positron and a neutron. The positron annihilates and creates a characteristic pair of 511 KeV gamma rays — “prompt signal”. After 2 to 20 µs the neutron moderates and is captured by Gadolinium. The resulting gamma rays have a total energy of 8 MeV and should be detected within a sphere of about 20 cm from the original neutrino interaction — “delayed signal”. This method of detection was verified by small scale DANSS detector demonstrator DANSSino [3].

Figure 6. Inverse beta decay detection.
Thanks to the segmented nature of the detector and the way the strips are placed, the IBD produces a characteristic signature which can be searched for. Therefore, the data acquisition system must be able to register a coincidence of two events separated by few microseconds. Generally, both prompt and delayed signals can come from the same PMT channel. The DAQ must be sufficiently responsive so that the delayed signal does not fall within its dead time.

Additionally, the DANSS detector is using cosmic muons with vertical tracks for calibration purposes and the DAQ must also record them.

Detailed description of the detector location, radiation background, detection idea, scintillator yields, final construction, calibration, shielding, lifting mechanism and estimates of sensitivity is available in [2].

2 Event structure

The physics goals of the experiment and the characteristic pulse response of the detector define content and structure of relevant data event. Coincidence measurement can be done either classically when the coincidence is detected by hardware and other pulses are ignored or all detector events are registered (“event by event”) and coincidences are searched for by software in the data stream based on event time stamps. Since the pulse response of the detector to particle interaction can generally create hits in multiple PMT channels (multiple Section Pulses — SP), the resulting group of individual pulses is defined as DANSS Pulse — DP. Given that the registration of the SP might not be exactly simultaneous, the first SP opens a DANSS Window and all SPs for configured duration (about 50 ns) are treated as one DP. Therefore, one DP should contain all detector events related to one individual particle interaction.

In the “event by event” DAQ, the event structure contains:

- Event Timestamp
- DANSS Pulse DP
  - SP₀ [charge, PMT identifier]
  - ...
  - SP₄₉ [charge, PMT identifier]

In the hardware coincidence mode, one event contains

- Event time stamp
- List of SPs composing prompt DANSS Pulse DP₀
  - SP₀ [charge, PMT identifier]
  - ...
  - SP₄₉ [charge, PMT identifier]
  - Prompt DP timestamp relative to Event start time
- List of SPs composing prompt DANSS Delayed DP1
  - SP_0 [charge, PMT identifier]
  - ... 
  - SP_49 [charge, PMT identifier]
  - Delayed DP timestamp relative to Event start time

The DAQ also records events detected in the active shielding scintillators. That allows to identify events where, for example, cosmic muon interacted with passive shielding and caused secondary IBD like interaction cascade. The active shielding events are registered only if they occurred within a programmable window around a DANSS event. The timestamps are relative to the end of the coincidence window.

Active shielding event structure:

- Event time stamp
  - [inner time stamp, shielding PMT identifier map]_0
  - ... 
  - [inner time stamp, shielding PMT identifier map]_n

A reduced channel example of captured coincidence event with two DANSS pulses and three veto pulses is shown on figure 7.

![Diagram](image)

**Figure 7.** DAQ crate event structure.
3 Hardware

Conversion of electrical PMT pulse output to a number representing energy can be accomplished either using classical charge to digital converters (QDC) or using a digitizer (FADC). Both solutions have their advantages and disadvantages and since they complement each other the DANSS experiment has decided to use both approaches. Digitizers, working almost without a dead time allow easy “event by event” measurement, whereas QDCs provide easily processable compact data. The problem with QDCs is that they have an inherent dead-time during which the collected charge is converted to a number and since the time between prompt and delayed signals of the IBD ranges from 2 to 20\(\mu\)s, it is possible that the delayed signal will arrive during the dead time. In order to acquire such events, the analog signal has to be doubled and connected to a pair of QDCs and there has to be some hardware logic to route the GATE signal to a free QDC [3]. Therefore, a group of prompt QDCs and a parallel group of delayed QDCs must be used. Given the number of input channels and the necessity of add timestamps to the events a programmable logic array (FPGA) is used to route the signals.

Based on the experience of the people on the team, economic conditions and previously existing solutions, it was decided to build the data acquisition system using CAEN VME modules [4]. The spectrometer is built from VME8010 crate with V2718 VME Controller optically connected to a Linux PC hosting the A2818 adapter card (figure 8).

The QDC spectrometer is based on eight 16-input V965 QDCs (4 prompt, 4 delayed). These QDCs have a common gate and two internally amplified readout ranges (1× and 8×). The V965 QDCs support VME CBLT mode for significantly reduced readout time. The controlling logic is implemented in the V1495 FPGA board with 64 ECL inputs and 26 NIM outputs. The firmware generates GATE and RESET signals to appropriate QDCs. RESET is used to clear the output buffer of the QDCs when the delayed signal was not received in time. The V1495 also generates an IRQ after a coincidence condition was met — both prompt and delayed pulses were observed. Above threshold logic pulses from the active shielding are registered by another V1495.

![Figure 8. Hardware schematics.](image-url)
The Digitizer spectrometer is based on the 62.5 MSPS 64-input CAEN V1740. The sampling frequency is barely adequate to sample pulses from the DANSS analog frontend, however the obtained results are sufficient. The V1740 is configured to capture 18 samples (288 ns) from each channel. The final version of the spectrometer will contain four V1730 modules, with 500 MSPS sampling rate and also have an optional firmware to calculate pulse integrals, reducing the recorded data volume.

The Digitizer can be operated with either external or internal trigger. External edge sensitive trigger, which is currently used, is generated from the QDC gates. It is also possible to move the FADC to a different crate to improve readout speed. The internal trigger starts the capture of all channels whenever any channel is above defined threshold and is then independent on the QDC spectrometer. The V1740 is able to store up to 192k samples per channel organized in 1024 event buffers.

4 FPGA firmware

Charge to digital converters (QDCs) require that the gate signal comes before the analog pulse to be converted and this defines very strict timing requirements. As it is impossible to assure nanosecond timing using a PC, we chose to develop a custom firmware for a field programmable gate array FPGA. The CAEN V1495 is a VME generic input/output card with an empty user FPGA, 64 ECL inputs, 32 ECL outputs and 3 connectors for additional I/O modules (32 × ECL, 32 × LVDS, or 8 × NIM). The presented system uses three NIM card configured for output.

A custom firmware samples digital output from analog frontends using its 200 MHz system clock. Once an edge is detected on any of the 64 inputs, a short (~ 50 ns) window is opened which collects all the section Pulses forming one DANSS Pulse. This DP in turn opens a much longer main coincidence window during which the system waits for configured number of additional DPs. The main coincidence window can operate in two modes — fixed duration with minimum and maximum number of pulses and dynamic duration with minimum number of DP modes. Additionally, any coincidence window with a DANSS Pulse with sufficient number of section pulses present can be deemed as successful (used for detector calibration using cosmic muon spectra). If the coincidence window does not meet configured criteria, a FAILURE pulse is generated. In case of a successful coincidence window an event is transferred to V1495 system BLT FIFO and the DAQ is informed by asserting VME IRQ line.

The Gate generator routes GATE signals of configured duration to appropriate QDC and blocks further gates on the same line during a hold-off period. The window failure pulse is sent to the RESET inputs of the QDCs to clear their output buffers.

Since the V1495 does not support VME multicast addressing, the asynchronous TIMESYNC input can be used to reset the system clock to synchronize multiple V1495 cards in the crate.

The active shielding V1495 firmware continuously samples logical outputs from active shielding AFEs and also uses the same DANSS pulse logic. The detected DANSS pulses are stored in a circular buffer with configured maximum age and count. If the master V1495 detects a successful coincidence window a command is sent via the serial protocol and the shielding V1495 generates an event to be read by the PC. Communication between the master V1495 and Active Shielding V1495 is done via serial pulse length encoded protocol. Table 1 shows currently used critical settings on both variants of the firmware.
Figure 9. FPGA firmware block diagram.

Table 1. V1495 operational settings.

| Master V1495         | Active Shielding V1495 |
|---------------------|------------------------|
| DANSS Pulse length  | 100 ns                 |
| Coincidence window  | max 80 μs              |
| Coincidence condition | 2 pulses or ≥ 8 active PMT |
| QDC gate length     | 200 ns                 |
|                     | DANSS Pulse length     | 100 ns |
|                     | Pre-trigger buffer     | 80 μs  |
|                     | Post-trigger buffer    | 20 μs  |
|                     | Max Pulses             | 15     |

Figure 10 shows typical inputs and outputs of the master V1495. There are two DANSS Pulses inside the coincidence window with two active PMTs each. First DP generates a GATE signal for Prompt QDC and trigger for FADC, second DP generates GATE for the Delay QDC and a trigger for FADC. The FADC trigger is edge-sensitive. After the window is evaluated as successful, a trigger command is sent to the second Active shielding V1495 to generate an event.

The firmware logic which forms DANSS Pulses is always active, even during data readout, allowing the total number of DPs in the detector to be counted.

5 Software

The spectrometer data are collected, monitored and partially on-line processed by a system described in detail in [5]. It is a system running on a Linux PC. An interesting feature of the system is that not only the vendor-specific raw data from the VME modules are written to the disk, the system also translates them into a u-data format formed by a tuple (channel_id; value) hiding the complexity and variability of the specific hardware. It also allows on-line calculation of areas (charges) of pulses.
That allows creation of data processing programs universally usable for differently configured crates. Both raw and u-data are available for remote access via TCP/IP and so is program control. Figure 11 shows the overall DAQ schematics.

Another important feature of the system is that the data acquisition algorithm is described using a simple programming language and is loaded from an XML configuration file. The file contains sections which relate to individual phases of data acquisition process (such as crate configuration, start of the run, IRQ handling, end of block, etc.).

The DAQ monitoring and data processing has a very similar philosophy. The monitoring application can either receive data on-line via TCP/IP or offline from files generated by the acquisition program. The configuration file allows a simple language to define various data processing, filtering, conditional operations and finally the way how the data are presented using ROOT [6]. The system philosophy is shown in figure 12.
6 System performance results

The final arrangement of the data acquisition system is shown in figure 13. The detector, front end electronics, measurement crates and acquisition PC is located inside a technological room underneath the reactor. An Ethernet connection from this location to a monitoring room located outside the restricted access zone allows easy on-line monitoring of the performance and data retrieval.

6.1 QDC DAQ system performance

The measurement is done in coincidence mode controlled by the V1495. Events from active shielding are collected by second V1495 controlled via serial protocol. Due to parasitic pulses which sometimes occur approximately 500 ns after a pulse, the controlling V1495 is set to ignore any pulse closer than 2 µs. The main coincidence window lasts up to 80 µs. Data are written to disk both in the RAW and translated unified u-data formats by blocks (1 block = 1 file). Every 24 hours the detector is moved into a new position. Statistical data from a single run is shown in table 2.
Table 2. DAQ Statistics for one run with QDC only.

|                |                  |
|----------------|------------------|
| Run length     | 88 020 s         |
| Number of blocks (files) | 1467            |
| Block length   | 60 s             |
| Crate events   | 18 398 866       |
| Average time between IRQs | 4.8 ms        |
| Average IRQ handling duration | 112 us        |
| Total handling time | 2068 s        |
| Total handling time [%] | 2.4%          |

Figure 14 shows the distribution of number of events per second, the discrete nature of the graph is due to the way this statistics is collected by the DAQ system.

![Event Count Per 1s](image)

**Figure 14.** Average number of events per second in one run.

Time required for crate readout are shown in figure 15. The average time to service an IRQ is 115 µs. First, the source of the interrupt is checked and appropriate VME board status registers are read. Depending on the source, either data are read from QDCs using CBLT and the control V1495, or from active shielding V1495. Because the QDC event does not contain a timestamp, the acquisition process is blocked during the readout process to assure that only related data are put into the crate event. Despite that, it can be seen that the system has been blocked only for 2.4% of the run duration.

Figure 16 and figure 17 show typical spectra of randomly selected PMT prompt and delayed channels during the 24-hour run. Both spectra show the cosmic muon peak and have a range of about 56 MeV. The sharp peak at the beginning is the result of all detector channels being converted when any channel triggers the DAQ and is therefore a peak of a zero charge.
Figure 15. IRQ handling time with QDCs only.

Figure 16. Prompt PMT channel spectrum.

Figure 17. Delayed PMT channel spectrum.

Distribution of multiplicities of section pulses in prompt and delayed DANSS pulses and their correlation are shown in figure 18. Both axes contain the number of active detector sections in the DANSS pulses.

The spatial correlation of prompt DP and delayed DP are shown in figure 19. X and Y axes contain the PMT channel number. These data are collected from hardware triggers by the V1495 which allows up to 64 logical inputs and only 50 PMTs are connected, explaining the gaps in the data. The figure also shows a hardware problem which was detected in channel 34 analog frontend causing ringing and higher-than-normal coincidence rate. Generally, the dispersion of the parameters are caused by non-uniformity of the shielding (mechanical, position on the lifting mechanism), dispersion of strip parameters, trigger threshold levels and differences in noise levels [2].
6.2 Digitizer performance results

Another spectrometer based on the V1740 digitizer is connected to the detector in parallel. Many tests were performed on a small part of the detector in the laboratory. The digitizer capture length is set to 288 ns, or 18 samples. Figure 20 and figure 21 show the results of pulse digitization capturing interaction of a testing scintillator connected to a DANSS AFE with cosmic muons in laboratory setting.

Figure 22 shows spectrum of natural background in the laboratory which was obtained by online charge integration of the digitized window converted into the u-data format.

The digitizer is configured with all of its 64 input channels enabled. In this case 64 * 18 samples have to be read during each IRQ. The average readout time is about 120 µs (figure 23), thanks to the digitizer’s compact event structure and support for VME block read (BLT). Like in
the QDC spectrometer case it is calculated as a difference between Linux system timestamp just after the acquisition process is woken up by IRQ and a call to wait for further interrupts. The peak around 20 µs is caused when V1740 asserts its interrupt line but the queried status register reports no available event prepared to be read out.

To ensure practically zero dead time the V1740 is configured to work with 8 FIFO buffers for each channel. When the digitizer internally triggers and captures samples, it generates an interrupt
and immediately is ready to capture next event. Given the average count rate of DANSS detector and its active shielding is about 2500 pulses per second and the average time it takes to read one event is about 120 $\mu$s, it is clear that it is indeed possible to capture all events in the "event by event" mode.

The V1740 is configured to not allow interleaving triggers. That means, that as soon as any channel triggers internal acquisition, other triggers are ignored and samples from all channels are
recorded relative to start of the acquisition window. Pulses which arrive later can be sampled incompletely, however the 288 ns long sampling window and associated 50 ns DANSS window provides for correct sampling of all PMT pulses forming the DANSS Pulse and compatibility of charge integration.

6.3 Combined spectrometer results

The configuration of the DANSS DAQ operating as of fall 2016 contains both the QDC and Digitizer spectrometers operating together in a single crate. Both the QDC and Digitizer are controlled by one V1495 (figure 8).

Figure 24 and figure 25 show comparisons of a DANSS channel spectra obtained by QDC (black) and the Digitizer (red and green). The FADC energy is calculated as a sum of all samples within the window scaled by a constant.

![Figure 24. Prompt QDC and FADC spectra.](image1)

![Figure 25. Delayed QDC and FADC spectra.](image2)

Figure 24 shows the total required interrupt handling time to read data from all 8 QDC, one V1740 digitizer, controlling V1495 and active shielding V1495. The required time varies with event complexity.

Table 3 shows the statistics of a 28 hour run.

7 Summary and conclusion

The presented system is currently routinely taking data in the Kalinin Nuclear Power Plant. It was built using commercial VME modules. Pairs of QDCs are used to reduce system dead time. We developed a custom FPGA firmware and we use our own data acquisition, monitoring and processing system. The DAQ network architecture enables us to operate the system from outside of the Power plant’s radiation control zone. Fine tuning of acquisition is possible thanks to configurable FPGA firmware and user friendly XML configuration files.

The characteristic interrupt handling time is around 120 µs without Digitizer active and 487 µs with the Digitizer and active shielding active, which meets the requirements of the maximally observed rate of 1000 events per second.
Figure 26. IRQ handling time QDC+FADC+active shielding.

Table 3. DAQ statistics for one run with QDC, digitizer and active shielding.

| Statistic                                      | Value          |
|-----------------------------------------------|----------------|
| Run length                                    | 102 780 s      |
| Number of blocks (files)                      | 1713           |
| Block length                                  | 60 s           |
| Average IRQ per second                        | 86.70          |
| Average IRQ handling duration                 | 494 us         |
| Total handling time                           | 4398 s         |
| Total handling time [%]                       | 4.28%          |
| Detector DANSS Pulses                         | 101 544 038    |
| Detector DANSS Pulses per second              | 988            |
| Total active Shielding DANSS Pulses           | 238 883 876    |
| IRQs                                          | 8 911 093      |
| IRQs with one pulse events (≥ 8 active PMTs)  | 2 277 876      |

A parallel digitizer based DAQ is being installed in the KNPP and will start data taking during the next technological break.

Acknowledgments

The authors would like to thank V. Brudanin, V. Egorov, I. Zhitnikov and other colleagues participating in the DANSS project for their many consultations and continuous support.

This work is supported by the Czech Technological Agency TE 01020445, Czech Ministry of Education Youth and Sports INGO II-LG14004.
References

[1] V. Egorov and A. Starostin, Solid scintillator detector of the reactor antineutrino DANSS, talk at 12th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2011), Munich, Germany (2011).

[2] I. Alekseev et al., DANSS: Detector of the reactor AntiNeutrino based on Solid Scintillator, 2016 JINST 11 P11011 [arXiv:1606.02896].

[3] I. Alekseev et al., DANSSino: a pilot version of the DANSS neutrino detector, Phys. Part. Nucl. Lett. 11 (2014) 473 [arXiv:1305.3350].

[4] CAEN, Digital Pulse Processing for the Pulse Shape Discrimination, available: http://www.caen.it/csite/CaenProd.jsp?parent=39&idmod=770.

[5] Z. Hons, A versatile DAQ, monitoring and data processing system for nuclear experiments in CAMAC and VME standards, arXiv:1508.01379.

[6] CERN, ROOT Data Analysis Framework, available: http://root.cern.ch.

[7] CAEN, CAEN VME Product page, available: http://www.caen.it/csite/Product.jsp?parent=11&Type=Product.