The ADAQ framework: An integrated toolkit for data acquisition and analysis with real and simulated radiation detectors

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Abstract

The ADAQ framework is a collection of software tools that is designed to streamline the acquisition and analysis of radiation detector data produced in modern digital data acquisition (DAQ) systems and in Monte Carlo detector simulations. The purpose of the framework is to maximize user scientific productivity by minimizing the effort and expertise required to fully utilize radiation detectors in a variety of scientific and engineering disciplines. By using a single set of tools to span the real and simulation domains, the framework eliminates redundancy and provides an integrated workflow for high-fidelity comparison between experimental and simulated detector performance. Built on the ROOT data analysis framework, the core of the ADAQ framework is a set of C++ and Python libraries that enable high-level control of digital DAQ systems and detector simulations with data stored into standardized binary ROOT files for further analysis. Two graphical user interface programs utilize the libraries to create powerful tools: ADAQAcquisition handles control and readout of real-world DAQ systems; and ADAQAnalysis provides data

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analysis and visualization methods for experimental and simulated data. At present, the ADAQ framework supports digital DAQ hardware from CAEN S.p.A. and detector simulations performed in Geant4; however, the modular design will facilitate future extension to other manufacturers and simulation platforms.

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1. Introduction to the ADAQ framework

The relatively recent proliferation of digital data acquisition (DAQ) systems for radiation detectors has provided significant advances over traditional analog DAQ systems. In addition to the replacement of large, bulky, and expensive analog hardware with digital algorithms, advantages include preservation of unshaped detector signals, implementation of digital pulse processing (DPP) algorithms that are not possible or difficult in analog circuits, unlimited optimization of DPP algorithms in post-processing, and signal stability against gain drifts or increased noise from analog shaping circuits that are no longer needed [1]. Furthermore, due to technological advances and cost reductions, the last decade has seen a commoditization of digital DAQs from vendors such as CAEN S.p.A of Italy¹ and Struck Innovative Systeme of Germany², in which hardware previously found almost exclusively in particle or nuclear physics experiments is increasingly available to fields

¹CAEN website: <http://www.caen.it/csite>

²Struck website: <http://struck.de/>

15 such as nuclear security, nuclear fission and fusion energy, medical physics,
16 ion beam materials analysis, accelerator-based science, and undergraduate
17 education in the teaching laboratory.

18 The ability to rapidly and seamlessly integrate digital DAQ hardware into
19 the research workflow requires the availability of complementary high perfor-
20 mance software. This is particularly important for commodity users, who,
21 unlike the particle and nuclear physics communities, often have far less re-
22 sources and expertise than are necessary to implement high quality in-house
23 software. These users utilize detectors and DAQ systems as standard lab-
24 oratory tools rather than as a core component of their research. To meet
25 this need, the ADAQ framework - a set of software libraries and graphical
26 user interface (GUI) programs designed to provide production-quality acqui-
27 sition and analysis of radiation detector data with digital DAQ systems - is
28 being developed. Furthermore, ADAQ is built on top of two world-leading
29 software projects that significantly enhance its capabilities: ROOT [2], a sci-
30 entific software framework that provides data processing, statistical analysis,
31 visualization, and persistent storage; and Geant4 [3], a Monte Carlo particle
32 transport toolkit for the comprehensive simulation of particles interacting
33 with matter. The ADAQ framework is open source, cost-free, modular, and
34 extensible, providing the user with a powerful and accessible solution for
35 experimental and simulated data acquisition with radiation detectors.

36 The purpose of this paper is impart to the reader a high level description
37 of the tools in the ADAQ framework and an understanding of their perfor-
38 mance capabilities in a modern digital DAQ system. In order to do so, this
39 paper is structured as follows: Section 2 describes how the ADAQ frame-

Figure 1: Two examples of workflows that incorporate radiation detector data acquisition and analysis. (A) Without ADAQ, the real-world and simulated detector workflows are completely separate with substantial work and expertise required by the user despite tools provided by digital DAQ manufacturers. (B) With ADAQ, the workflows are integrated together to provide fidelity between experiment and simulation with substantial reduction in required user effort and expertise.

work meets some of the challenges in modern radiation detection; Section 3 describes the ADAQ software libraries and file formats; Section 4 describes ADAQAcquisition, a program for control, readout, and data storage with digital DAQs; Section 5 describes ADAQAnalysis, a program for offline analysis of experiment and simulated detector data; and finally, Section 6 presents some concluding remarks.

2. Overview of the ADAQ framework

2.1. Challenges in detector data acquisition and simulation

As described in the introduction, fully utilizing the power of digital DAQ hardware requires complementary software to acquire, readout, and analyze detector data. While high performance digital DAQ hardware is becoming

51 more affordable, widespread, and available directly from commercial ven-
52 dors (rather than developed in-house), acquisition and analysis software has
53 largely not kept pace. Most vendors of high-performance digital DAQ sys-
54 tems designed for detector applications, such as CAEN or Struck, specialize
55 in digital DAQ hardware and only offer a limited set of software develop-
56 ment and production tools that in many instances do not meet the need of
57 many users who require high quality software tools. Researchers must either
58 divert substantial effort and resources from their primary science or engi-
59 neering research into implementing their own software or in the absence of
60 software and DAQ expertise simply forego the inclusion of digital DAQs in
61 their experiments.

62 Another area where digital DAQs can be transformative is in the teaching
63 laboratory. Historically, students have used traditional analog DAQ systems,
64 which require expertise in analog circuits and electronics to understand the
65 fundamentals of pulse processing, or performed acquisition and analysis with
66 commercial “black box” software, which often obfuscates the underlying op-
67 erations on detector pulses. Digital DAQs, in contrast, alleviate both of these
68 issues. By acquiring raw, unprocessed digital waveforms and then analyzing
69 the pulses with simple digital algorithms that can be easily written by the
70 student, digital DAQs enable the student to focus on the most critical aspects
71 of detector data acquisition and analysis fundamentals while simultaneously
72 being exposed to the systems that are increasingly prevalent in the research
73 environment.

74 This primary challenge in digital DAQ is depicted graphically in Fig-
75 ure 1A. The figure shows common experiment and simulation workflows us-

76 ing available hardware and software from CAEN. The first challenge is the
77 amount of effort and expertise required of the user as indicated by the dom-
78 inance of cyan-colored boxes in the flow chart. Demands are placed on the
79 user such as implementation of data file structures, analysis codes for sim-
80 ulation and experiment, and from-scratch data acquisition software. Such
81 efforts can take substantial resources (time, money, personnel) away from
82 the scientific or engineering goals and are obvious tasks that could be com-
83 moditized for the researcher. However, while CAEN provides a GUI program
84 to control their digitizers, they are intended for demonstration purposes and
85 are not suitable for production-level experiments. CAEN provides a fairly
86 comprehensive set of low-level software libraries, but these require substantial
87 software development and data acquisition expertise to fully utilize.

88 A second challenge that is evident from the figure is the decoupling of
89 the workflows between real-world and simulated detectors. This has the
90 affect of increasing the user workload due to implementation of multiple data
91 formats and analysis codes while lowering the fidelity between experiment
92 and simulation since the data is not necessarily processed with the same set
93 of algorithms.

94 *2.2. The ADAQ framework solution*

95 As shown in Figure 1B, the ADAQ framework is composed of three pri-
96 mary tools that empower the researcher by providing a comprehensive and
97 integrated software environment that enables the high performance acquisi-
98 tion and analysis of radiation detector data and that unites the experiment
99 and simulation workflow for high-fidelity results. At the core of the frame-
100 work is the ADAQ and ASIM libraries, shown at the bottom and top, respec-

tively of the figure. The ADAQ libraries [4] are a set of C++ and Python libraries that provide a standard interface between firmware running on DAQ hardware and a computer with data stored in binary ROOT files known as ADAQ files; the ASIM libraries provide a standard interface between Geant4 simulated detectors and the computer with data stored in binary ROOT files known as ASIM files. The ADAQAcquisition [5] program utilizes the ADAQ libraries to create a GUI-based program to control digital DAQs and automatically read out data into ADAQ files. Finally, the ADAQAnalysis [6] program provides a GUI-based program for comprehensive analysis of data that is stored in ADAQ and ASIM files, giving the user a complete toolchain for the acquisition and analysis of detector data from hardware or simulation. In addition, if the expert user wishes to implement his or her own custom applications for specialized needs, the ADAQ libraries and ADAQ/ASIM file formats provide a standardized, enhanced, and more powerful starting point for development compared to vendor provided software tools.

The three ADAQ tools described above are available as open source, cost-free tools to the user for download or collaboration via GitHub under the GNU G.P.L. v3.0, which gives the user flexibility to copy, modify, and redistribute the codes to best serve his or her research needs. As of December 2015, the ADAQ framework is compatible with the most recent versions of ROOT (version 6.06.00) and Geant4 (version 10.02). The code and documentation is under active development, expanding the acquisition and analysis capabilities and the range of hardware on which the ADAQ tools can be run. The ADAQ framework is presently used in a number of experiments across several institutions, including an accelerator-based diagnostic for materials

126 inside the Alcator C-Mod tokamak at the MIT Plasma Science and Cen-
127 ter [7], a multiple monoenergetic gamma radiography experiment for nuclear
128 security involving MIT, Penn State, and Georgia Tech [8], and detector de-
129 velopment on a novel scintillator-based neutron detector at Penn State [9].
130 The ADAQ framework is also being used in teaching laboratories on radiation
131 and detectors within the Department of Nuclear Science and Engineering at
132 MIT.

133 3. The ADAQ libraries

134 The ADAQ libraries are a collection of C++ and Python libraries that
135 provide a modular software interface to digital DAQ hardware. The pur-
136 pose of these libraries is to provide a set of standardized, hardware-agnostic,
137 object-oriented libraries that not only wrap the low-level libraries provided by
138 hardware manufacturers but extend them to perform more powerful, higher-
139 level functionality. These libraries provide an excellent foundation for the
140 ADAQAcquisition (Section 4) and ADAQAnalysis (Section 5) programs but
141 also for programmers who write their own acquisition and analysis code.

142 At present, the ADAQ libraries only support digital DAQ hardware from
143 CAEN, including the following units:

- 144 • *VME bridge*: The V1718 VME-USB bridge board
- 145 • *High voltage*: The V6533 and V6534 families of VME high voltage
146 boards
- 147 • *Waveform digitizers*: The x720, x724, x725, x730, x751, both in VME
148 board and desktop form factors

149 • *High voltage + digitizer*: DT5790 desktop unit

150 The ADAQ libraries, however, have been designed such that future support
151 for hardware from other vendors is easily accommodated by adding new
152 software classes for each new piece of hardware that defines the hardware
153 register maps, integrates vendor software libraries, and implements specific
154 methods to control the hardware through the ADAQ libraries.

155 3.1. *The ADAQ and ASIM file formats*

156 The use of efficient, standardized format data files is at the core of the
157 ADAQ framework. Ensuring the data is stored in a consistent and compre-
158 hensive format streamlines the connection between data readout and data
159 analysis, provides a uniform data interface for different analysis methods,
160 and eliminates redundancy of having separate data formats for real-world
161 and simulated detectors. The ADAQ framework relies on the highly com-
162 pressed binary ROOT file to accomplish this. The ROOT file enables the
163 persistent storage of a wide range of data types, from fundamental data types
164 to complex classes, and is capable of massive and efficient data input/output.
165 Rigidly ensuring that ROOT files are written from any ADAQ tool with a
166 prescribed set of data objects guarantees a standard file format for analysis,
167 either using an ADAQ framework tool or using custom-analysis code devel-
168 oped by the user. For ROOT files storing real-world detector data, the files
169 are known as ADAQ files and indicated as such by the `.adaq.root` exten-
170 sion. Similarly, for ROOT files storing simulated detector data, the files are
171 known as ASIM files and indicated as such by the `.asim.root` extension.

172 3.2. *The ADAQControl library*

173 The **ADAQControl** library is composed of three related classes all inherit-
174 ing from the common, pure abstract **ADAQVBoard** class that provides a generic
175 set of descriptors for a DAQ device, such as hardware identifiers, VME ad-
176 dress, and connection state of the device. Each of the three derived classes -
177 **ADAQDigitizer**, **ADAQHighVoltage**, and **ADAQBridge** - provide a generic pro-
178 gramming interface to a range of hardware within the digitizer, high voltage,
179 and VME bridge device types. Each class provides methods to control all
180 aspects of the hardware, from reading/writing individual hardware register
181 values to more complex functions, such as powering high voltage channels or
182 reading out digitized waveforms.

183 3.3. *The ADAQReadout library*

184 The **ADAQReadout** library is composed of a manager class, **ADAQReadoutManager**
185 class, that provides the user with an easy way to create and populate spe-
186 cially formatted, compressed binary ROOT TFiles - known as ADAQ files
187 (See Section 3.1) - with data acquired through the digital DAQ control
188 methods contained in the **ADAQControl** library. Raw digitized waveforms
189 are stored as C++ vectors in ROOT TTree data objects within the ADAQ
190 File. Two supporting classes act as standardized containers for the data: the
191 **ADAQWaveformData** class holds event-level waveform data (baseline, pulse
192 area, pulse height, PSD integrals, time stamp, channel ID, and device ID);
193 the **ADAQReadoutInformation** holds run-level information on the DAQ hard-
194 ware and a complete record of hardware, firmware, and software settings used
195 in data acquisition.

196 3.4. The ASIM libraries

197 The ASIM libraries provide a conduit through which detector data sim-
198 ulated with Geant4 can be stored within specially formatted, compressed
199 binary ROOT TFiles - known as ASIM files (See Section 3.1) - and analyzed
200 with the ADAQAnalysis program. This gives the user convenient access to
201 the same powerful data analysis methods (*e.g.* spectra calibration, contin-
202 uum calculation, fitting, integrating) that are used in analyzing real detector
203 data stored in ADAQ files. This capability provides a streamlined and high-
204 fidelity approach to comparing real-world and simulated detectors.

205 An example is shown in Figure 2, in which ADAQAnalysis was used to
206 compare experimental and simulated 14.1 MeV detector response functions.
207 The experimental setup was a $5.1\phi \times 5.1$ cm EJ301 liquid organic scintillator
208 coupled to a 2-inch PMT and placed 1 m in front of a 14.1 MeV neutron
209 generator. The detector was read out by a CAEN V1720 VME digitizer board
210 running standard firmware. The V1720 was located in a CAEN VME8100
211 powered crate and controlled by ADAQAcquisition through the PC via the
212 CAEN V1718 USB-VME bridge board located in slot 0 of the crate. Detector
213 data was stored in an ADAQ file for offline analysis in ADAQAnalysis. The
214 Geant4 simulation setup was identical to the experimental geometry with the
215 simulated detector read out through the ASIM libraries with data stored in
216 an ASIM file for offline analysis in ADAQAnalysis.

217 Two libraries are created. The first - the `ASIMReadoutManager` library -
218 handles the readout of data from the user's Geant4 simulation. The library
219 includes a set of special Geant4-derived sensitive detector and hit classes that
220 the user can incorporate into his/her own simulation. Event-level informa-

Figure 2: A comparison between experiment and simulated detector response of an EJ301 liquid organic scintillator detector to 14.1 MeV neutrons. The experimental data was acquired with ADAQAcquisition and CAEN digitizers; the simulated data was produced with an ASIM-integrated Geant4 simulation that utilizes recent capabilities of the Geant4 toolkit to simulate photon production from nonlinear scintillators [10]. Both data sets were calibrated and histogrammed identically using ADAQAnalysis, which ensures high fidelity when comparing experimental and simulated detector data.

tion - stored in `ASIMEvent` class objects - can include total energy deposition, optical photon production, and optical photon detection in a photodetector such as a photomultiplier tube or silicon photomultiplier. Run-level information - stored in `ASIMRun` class objects - includes incident particles, detected particles, optical photons created, and optical photons detected, with a set of methods to allow the user to specify thresholds for scoring events. The library is capable of handling readout in parallel processing through the `MPIManager` class, which provides the user an easy way to parallelize a Geant4 simulation. The second library - the `ASIMStorageManager` library - handles the persistent storage to ASIM files on disk the information that is read out with the `ASIMReadoutManager` library methods.

ASIM functionality is intentionally split between two libraries in order to isolate the dependence on Geant4 headers and libraries from the `ASIMStorageManager` library. This enables users to build the `ADAQAnalysis` program and analyze ASIM files on systems without Geant4 installed. Example simulations are available within the distribution to show the user how to integrate the ASIM libraries into his or her own Geant4 simulation.

4. `ADAQAcquisition`: DAQ hardware control and readout

`ADAQAcquisition` is a GUI-based program that implements control, acquisition, readout, and persistent storage for digital DAQ systems. The program provides the user with several levels of control over the hardware, from low-level tasks such as individual register read/write operations to more complex high-level tasks such as acquiring calibrated energy spectra or pulse shape discrimination (PSD) histograms in real-time. In addition to a fully

Figure 3: ADAQAcquisition acquiring a waveform from a cosmic ray in digital oscilloscope mode. The detector was a 10.16 cm cube of NaI(Tl) scintillator read out by a 3-inch PMT and digitized with a CAEN V1725 VME board in a CAEN 8100 VME crate.

245 featured digital oscilloscope and multichannel analyzer, the program provides
 246 persistent storage of waveform data in ADAQ files for offline analysis, either
 247 with the user's own analysis code or with the ADAQAnalysis program de-
 248 scribed in Section 5. Other useful features are packaged in as well, such as an
 249 acquisition timer, checks on system dead time and data loss, and high-quality
 250 graphical output. The digital oscilloscope in ADAQAcquisition is shown in
 251 Figure 3 displaying a cosmic ray waveform from a NaI(Tl) detector.

252 As discussed in Section 3, ADAQAcquisition is at present only compati-

253 ble with the hardware from CAEN that is supported by the ADAQ libraries;
254 however, as support is added for new hardware from other vendors into the
255 ADAQ libraries as described in Section 3, the ADAQAcquisition graphical
256 interface, hardware programming, and readout methods can easily be up-
257 dated.

258 *4.1. DAQ hardware programming*

259 ADAQAcquisition is designed to provide control over three main types
260 of DAQ hardware: PC-to-VME bridge boards, high voltage units, and wave-
261 form digitizers. It enables this control through a GUI, which gives the user
262 complete high-level control of all aspects of the hardware. In addition, direct
263 reading and writing of individual hardware registers is possible for low-level
264 control, with translation and graphical display of binary, decimal, hexadeci-
265 mal numbers used in such programming enhancing usability.

266 The first type of supported hardware is the PC-to-VME bridge boards
267 that form a standard interface between the boards running in a VME enclo-
268 sure and the PC that controls them. These boards are typically located in
269 slot 0 of a VME crate and connected to the PC either via a USB cable or
270 an optical fiber. The program provides methods to interface with any digi-
271 tizer and high voltage board attached to the VME backplane via the VME
272 bridge by specifying the address in VME space; control of other features
273 found on CAEN VME bridge boards, such as digital signal generators, are
274 also provided.

275 The second type of supported hardware is high voltage units typically
276 used to power radiation detectors. Upon connection to a high voltage unit,
277 either a VME board via the VME bridge or a desktop high voltage unit, the

278 program will automatically configure the user interface for the specific unit,
279 providing the correct number of channels, proper safety limits on voltage and
280 current, and initializing the board in a safe, powered off state. The user has
281 the ability to set maximum voltage and current trip points, as well as to
282 monitor the active voltage and drawn current in real time.

283 The third type of supported hardware is waveform digitizers used to read
284 out radiation detectors signals. Upon connection to a digitizer, the ADAQAc-
285 quisition interface is automatically configured not only for the hardware but
286 also for the type of digitizer firmware. ADAQAcquisition supports standard
287 CAEN firmware for all digitizer families and desktop units as well the digital
288 pulse processing pulse shape discrimination (DPP-PSD) firmware that runs
289 on CAEN’s x720, x725, and x730 families of digitizers as well as the DT5790
290 desktop unit. The user has the ability to set all global and channel-specific
291 settings for digitizer control and readout, as well as on-board FPGA pro-
292 cessing in the case of DPP-PSD firmware. Future upgrades to the ADAQ
293 framework will include support for CAEN’s DPP-CI (charge integration) and
294 DPP-PHA (pulse height analysis) firmware on supported digitizer hardware.

295 4.2. *Waveform digitizer readout*

296 Following digitizer programming, readout of digitized information occurs
297 once the user has initiated acquisition and started to accumulate data. In
298 detector acquisition, data is usually packaged into “events”, which typically
299 contain the information acquired during a single trigger of the system. Events
300 in ADAQAcquisition can include event metadata (*e.g.* event number, trigger
301 time stamp, the organization and byte structure the event), the full digitized
302 waveform, and the results of processing the data on the digitizer FPGA (*e.g.*

baseline, pulse area, pulse height). For digitizer triggering, ADAQAcquisition provides three methods: manual triggering via a user action, automatic channel self-triggering when the digitized signal exceeds a threshold, or external triggering using a standardized TTL or NIM signal input on the digitizer front panel. In self-triggering mode, the user may set a coincidence level requirement on triggering, from requiring coincidence between two channels up to all channels on the digitizer units. The user may specify how many triggers occur (*i.e.* how many events are allowed to accumulate in digitizer memory) before the data is transferred from the digitizer to the PC for further processing.

ADAQAcquisition completely handles the transfer of events to the PC using the proprietary software protocols of the digitizer manufacturer over USB or optical cables. For example, on CAEN digitizers using standard firmware, an aggregate of events that includes the entire digitized waveform is transferred, where the proprietary structure of the events are decoded into usable data. On CAEN digitizers running advanced firmware, such as DPP-PSD, the user's may choose which information to include in the event - full waveforms, FPGA-processed data, or both - before transfer and decoding, providing the ability to optimize data format and throughput. Once the events have been transferred from the digitizer, the data can be optionally further processed on the PC CPU. These actions can include waveform analysis (*e.g.* calculating baselines, pulse areas, pulse heights, and PSD integrals), and creation of energy spectra or pulse shape analysis histograms to examine particle discrimination or pileup status using the dual charge or dual gate method.

328 4.3. *Live analysis and persistent storage*

329 ADAQAcquisition provides two primary real-time analysis methods. The
330 first is to act a full feature digital oscilloscope, providing instant graphical
331 feedback on the acquired waveforms and various acquisition settings. The
332 user has an interactive graphical display that can be zoomed for detailed
333 inspection, custom configured to best show the data, and saved in many
334 image formats. The second is to act as much more powerful digital MCA,
335 providing real-time pulse spectra with optional energy calibration as well as
336 pulse shape analysis histograms to examine particle discrimination or pileup
337 status using the dual charge or dual gate method.

338 The user has several options for saving data persistently to disk. The
339 user may store any combination of full waveforms, analyzed waveform data
340 (timestamp, baseline, pulse area, pulse height), or PSD integrals depending
341 on his/her post-processing needs in an ADAQ file; the format and contents
342 of the ADAQ file are described in Section 3.1. Data storage can be en-
343 abled/disabled automatically via an acquisition time or manually by user
344 control. An energy acceptance window from the pulse spectra can be used
345 as a filter to ensure only waveforms meeting certain criteria are stored to
346 disk. Finally, the user has the option of saving the pulse spectra and PSD
347 histograms directly to disk, either as ROOT objects in a ROOT file or as
348 raw text in an ASCII or CSV formatted file.

349 5. ADAQAnalysis: analysis of experimental and simulated detec- 350 tor data

351 ADAQAnalysis is a GUI-based program that provides powerful analysis
352 methods for experimental and simulated radiation detector data that is stored
353 in ADAQ or ASIM file formats. For real detectors, data is most easily pro-
354 duced using the ADAQAcquisition program described in detail in Section 4
355 although the user can build his or her own data acquisition application us-
356 ing the ADAQ libraries in order to utilize the standard ADAQ file format
357 required by ADAQAnalysis. For simulated detectors, such data is produced
358 by integrating the ASIM libraries into the user's Geant4 detector simulation
359 as described in Section 3.4. A screenshot of ADAQAnalysis is shown in Fig-
360 ure 4 performing PSD on waveforms from a EJ301 liquid organic scintillator
361 detector.

362 5.1. Waveform inspection and processing configuration

363 To utilize the power of waveform digitization, ADAQAnalysis provides a
364 set of waveform inspection and analysis tools that can be applied to either
365 real or simulated waveforms stored in an ADAQ or ASIM file, respectively.
366 These tools enable the user to examine waveforms in detail and then optimize
367 the full set of parameters that is used in processing the waveforms into energy
368 spectra or pulse shape discrimination histograms.

- 369 1. *Baseline calculation:* A time window can be specified in any part of
370 the waveform in which the pulse baseline will be calculated. Function-
371 ing as a digital baseline restoration circuit, this feature maximizes the
372 accuracy of pulse height and area calculation in signals with moderate

Figure 4: ADAQAnalysis performing pulse shape discrimination on neutron and gamma events induced by a 14.1 MeV fast neutron source. The detector was a $2.5\phi \times 2.5$ cm EJ301 liquid organic scintillator read out by a 1-inch PMT and digitized with a CAEN V1720 VME board in a CAEN 8100 VME crate.

373 noise of slowly drifting baselines relative to the pulse timescale. The
374 user can plot a baseline-subtracted waveform as they adjust the time
375 window to see the impact on the resulting waveform.

376 2. *Zero suppression:* Waveform samples below a user-specified threshold
377 will be removed from the waveform before processing, eliminating very
378 small amplitude data and maximizing computation efficiency without
379 sacrificing accuracy. Known as zero suppression, this technique is par-
380 ticularly useful for long waveforms in which many peaks appear in a
381 single acquisition window. The user can plot a zero-suppressed wave-
382 form as they adjust the zero-suppression threshold to see the impact
383 on the resulting waveform.

384 3. *Multipeak algorithm:* In some cases, it is either advantageous or un-
385 avoidable to acquire a single acquisition window with many peaks. Ex-
386 amples may include pulsed accelerator systems where a trigger signal
387 may be used to open an acquisition window during the beam pulse
388 or acquisition of waveforms at extremely high rates, such that post-
389 processing pileup deconvolution algorithms may be implemented. Uti-
390 lizing the sensitive nonlinear iterative peak-clipping (SNIP) algorithm
391 [11], ADAQAnalysis provides a robust, tuneable peak-finding algorithm
392 that can locate and calculate individual peak heights/areas for energy
393 spectroscopy or pulse shape rejection algorithms. A demonstration of
394 the algorithm appears in Figure 5, in the algorithm is clearly able to
395 identify all peaks in the long acquisition window.

396 4. *Pileup rejection:* Waveforms that overlap in time, or pile up, can be

397 identified and removed during waveform processing to prevent contam-
398 inating an energy spectrum or pulse shape discrimination histogram.
399 With pileup rejection enabled, the user can inspect waveforms to see
400 which peaks are accepted and rejected, an example of which is shown in
401 Figure 5. The double peak that occurs around 1000 ns is flagged by the
402 algorithm for rejection and shaded red; the remaining well-separated
403 peaks are accepted by the algorithm and shaded green.

404 Once waveform processing parameters have been set, as described in Sec-
405 tion 5.1, waveforms can be processed into either pulse spectra or PSD his-
406 tograms with two algorithms. The first - the “max/sum” algorithm - is a
407 simple but computationally fast algorithm that rapidly finds the maximum
408 pulse height or sums samples into a pulse area within a user-selected wave-
409 form time range. The second algorithm - the “peak finder” algorithm - is
410 more computationally intensive but provides greater waveform analysis ca-
411 pabilities, including identifying many peaks in a single acquisition.

412 5.2. Energy spectra creation and analysis

413 One of the primary features of ADAQAnalysis is the ability to process
414 detectors waveforms into spectra. For real detectors storing data in ADAQ
415 files, spectra can be created for any digitizer channel as either pulse height or
416 pulse area spectra. For simulated detectors storing data in ASIM files, spec-
417 tra can be created for any registered ASIM readout from energy deposited,
418 number of optical photons created per event, or number of optical photons
419 detected per event, as described in Section 3.4.

420 For uncalibrated spectra, the user can locate calibration points in two
421 ways: either locating spectral peaks - suitable for many types of detectors

Figure 5: ADAQAnalysis demonstrating its multipeak finder algorithm, which robustly identifies all peaks (red triangles) above a floor (dotted red line), filters them with a pileup rejection algorithm (shaded green peaks are accepted; shaded red peaks are rejected), and then computes pulse height and area for spectroscopy. The data is from a lanthanum-bromide scintillator coupled to a silicon avalanche photodiode and readout with a CAEN V1720 VME digitizer that is used in the AIMS diagnostic on the Alcator C-Mod magnetic fusion tokamak [7].

Figure 6: ADAQAnalysis locating the 4.44 MeV full energy peak and first and second escape peaks in a gamma spectrum from 3.0 MeV deuterons bombarding a natural boron target. The data was acquired with a $2'' \times 4'' \times 16''$ NaI(Tl) scintillator coupled to a 2-inch PMT and readout with a CAEN V1724 VME digitizer that is used in a monoenergetic gamma radiography experiment for nuclear security [8].

such as inorganic scintillators, high purity germanium, and charged particle - or by using an edge finding algorithm - suitable for detectors based on elastic scattering such as liquid organic scintillators. Once calibration points have been set, linear fits (for two or more calibration points) or quadratic fits (for three or more calibration points) can be used to create calibrated energy deposition spectra. Once a spectra is energy calibrated, energy analysis tools are available to the user, such as the escape peak finder shown locating the 4.44 MeV gamma and its escape peaks in the NaI(Tl) spectrum shown in Figure 6.

To obtain quantitative results, spectra can be further analyzed. Detailed spectra continua can be calculated using the powerful sensitive nonlinear iterative peak-clipping (SNIP) algorithm [11]. The user can tune a variety of algorithm parameters to get an excellent continuum across a complicated spectrum as shown in Figure 7, which shows a high purity germanium gamma spectrum for 1 MeV protons bombarding a lithium-fluoride target. The continuum can then be subtracted to isolate the peaks, which can then be fit with a gaussian to obtain exact parameters. An integrator is available to analyze the unfitted or gaussian peaks as well as raw or continuum subtracted spectra.

5.3. Pulse shape analysis and filtering

Another primary feature of ADAQAnalysis is the capability to analyze the shape of digitized detector waveforms and create filters for determining which events are added to pulse spectra. Two widely used applications of this technique are PSD, in which the decay pulse timing in organic scintillators can be used to identify particles, and pileup rejection, which can greatly

Figure 7: ADAQAnalysis accurately computing a gamma continuum for a high purity germanium (HPGe) detector spectrum; the inset shows a continuum-subtracted background with a gaussian fitted integral on the 6.1 MeV peak. The continuum is computed using the sensitive nonlinear iterative peak-clipping (SNIP) algorithm within ROOT's TSpectrum class [11].

447 improve spectral features at high detector count rates.

448 ADAQAnalysis employs a digital version of the pulse shape analysis
449 method known as the charge integral or dual gate method [12], in which
450 an integral of the entire pulse - the “total” or “long” integral - is compared
451 against a partial integral of the pulse, typically taken over the end of the pulse
452 - the “tail” or “short” integral. When these integrals are binned into a 2D
453 histogram, separation emerges between event groups of interest. An example
454 is shown in Figure 8, in which well-separated fast neutron and gamma events
455 from 1.1 MeV deuterons bombarding a natural boron target are measured
456 with a EJ301 liquid organic scintillator.

457 Once a 2D histogram has been created, the user can create a graphical
458 cut that will function as a filter for spectra creation, allowing the user to
459 selectively include and exclude events based on their pulse shape, as shown
460 by the magenta area surrounding the neutron events in Figure 8.

461 5.4. *Persistent storage and graphical output*

462 Finally, ADAQAnalysis is capable of saving almost all of the analysis
463 objects - waveforms, spectra, continua, calibration, pulse shape histograms
464 - as ROOT objects within a TFile or in ASCII or CSV formats for further
465 analysis. At any time during the analysis workflow, the graphical canvas can
466 be output in a variety of formats with the user able to specify a wide range
467 of graphical attributes.

468 6. Conclusion

469 The ADAQ framework provides a comprehensive set of software tools
470 that is designed to help scientists and engineers who use radiation detec-

Figure 8: ADAQAnalysis demonstrating a graphical cut (magenta shaded region) on pulse shape discrimination data that can be used to determine which events are added to energy spectra. The data is from an EJ301 liquid organic scintillator detector measuring fast neutrons (top event bunch) and gammas (bottom event bunch) produced by a 1.1 MeV deuteron beam bombarding a natural boron target.

tors in their research more easily integrate the power of digital DAQs into their workflow. The framework is intended to be useful to all levels of user - from novice to expert - and provides a range of software from low-level development libraries to high-level GUI-based programs. The ultimate goal is enable users to maximize their research productivity by enabling their use of high performance digital DAQ hardware and handling a majority of their data acquisition and analysis needs. In addition, the ADAQ framework can be a powerful tool in the teaching laboratory in two ways: first, by allowing students to focus explicitly on learning modern detector pulse processing without hardware expertise or complicated electronic circuits; and second, by easily visualizing all steps of digital DAQ programming, data acquisition, and data analysis.

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