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Standardisation of the data format for list-mode digital data acquisition: Survey results

Identifying the needs for a standard for data acquired in radiation detection and measurement

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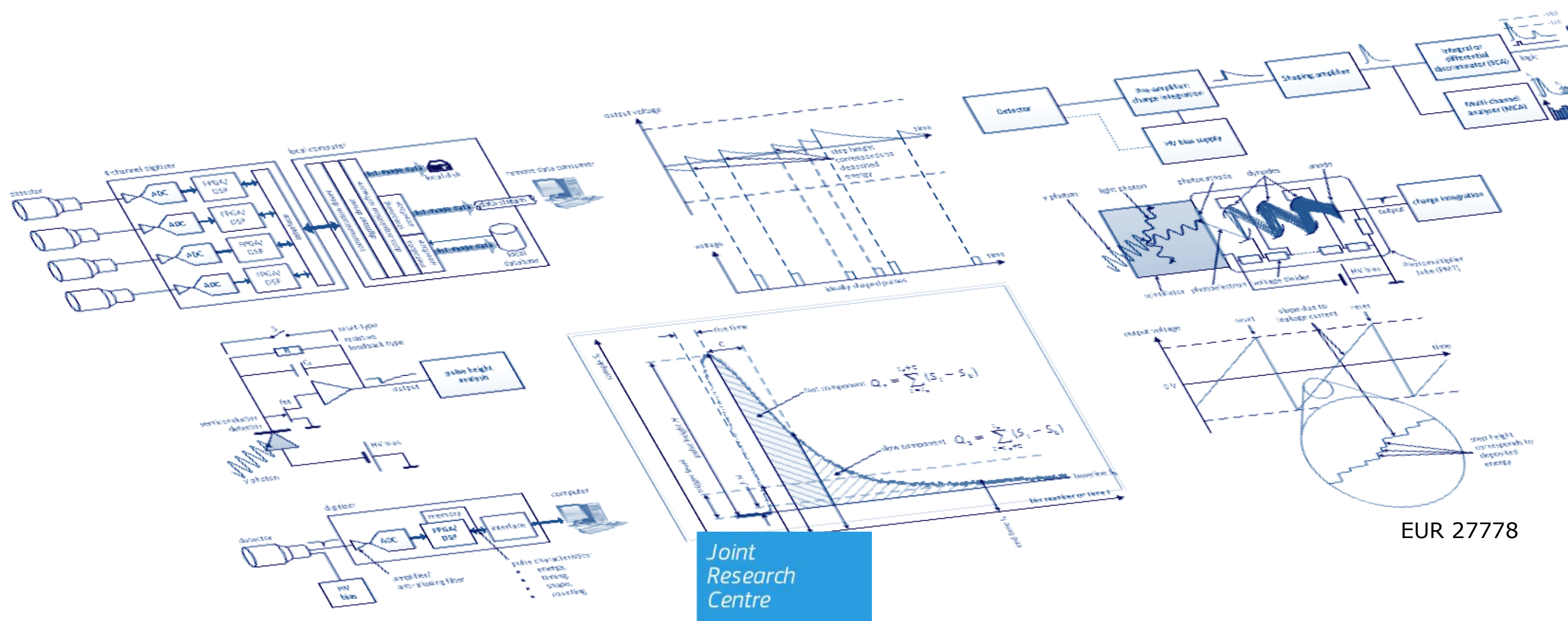

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Abstract

In the frame of Commission Mandate M/487 'Security standards', CEN/TC 391 assigned the highest priority to the standardisation of list-mode data, together with three other standardisation proposals. In response, the JRC ERNCIP Thematic Group on Radiological and Nuclear Threats to Critical Infrastructure described the state-of-the-art on list-mode data acquisition and proposed the basic elements of a standard data format. In addition, the RN Thematic Group conducted a survey addressed to users of digital data acquisition for nuclear instrumentation to investigate their needs with respect to the standardisation of the data format. This report presents the results of the survey, which will serve as an important input for the development of a preliminary draft standard that will accompany a New Work Item Proposal for a new international standard, to be submitted to the IEC in the frame of the EMPIR Project 14SIP07 'DigitalStandard', which will continue on the work initiated by the ERNCIP RN Thematic Group.

1. Introduction

1.1 Digital data acquisition

Digital data acquisition systems are high-performance instruments that sample signals from radiation detectors in order to process them in a digital manner. Their use has increased significantly over recent years, as they offer advantages over conventional data acquisition systems and allow new applications, for example in nuclear security and safeguards. At this moment, however, there is no standard data format specifying the output of these instruments, which hinders the deployment of hard- and software for data acquisition and analysis. The type of data is often called "list-mode data", and contains typically, but is not restricted to, the timestamp and the pulse height of the events associated with the interactions of radiation in the detector.

1.2 Commission Mandate M/487

In response to Commission Mandate M/487 'Security standards' to the European Standardisation Organisations, CEN/TC 391 'Societal and Citizen Security'[1], prioritised over 300 standardisation proposals from more than 200 experts in the sectors CBRNE, border security and crisis management/civil protection. The standardisation of the list-mode data was assigned the highest priority, together with three other proposals.

The Commission responded to the CEN M/487 Phase 2 report[2] by defining new priorities and standardisation activities, by means of:

- A new request to CEN proposing 9 European Standards related to Crisis Management and CBRNE;
- An Administrative Arrangement under H2020 with JRC-ERNCIP addressing 4 threats in the CBRNE area, including RN threats to critical infrastructure.

1.3 ERNCIP RN threats to critical infrastructure

One of the objectives of the ERNCIP RN Thematic Group on Radiological and Nuclear Threats to Critical Infrastructure is to develop a report/draft standard that includes the basic elements concerning list-mode data formats delivered by digital nuclear electronics, for consideration by the appropriate standardisation community.

In 2014, the Thematic Group published the following reports:

- State-of-the-art report on list-mode data acquisition based on digital electronics – EUR 26715[3] ;
- Report on critical parameters and performance tests for the evaluation of digital data acquisition hardware – EUR 26976[4].

In 2015, a survey was conducted to assess the needs of end-users of digital data acquisition systems. This report discusses the results of the survey, which will be used to develop a preliminary draft international standard.

The members of the ERNCIP RN Thematic Group that contributed to the development of the report:

Jan Paepen	Main author European Commission, Joint Research Centre
John Keightley	Lead scientist of the topic "list-mode data acquisition" National Physical Laboratory, United Kingdom
Kari Peräjärvi	RN Thematic Group coordinator Radiation and Nuclear Safety Authority (STUK), Finland
Olof Tengblad	Instituto de Estructura de La Materia – CSIC, Spain
Per Grim	Danish Emergency Management Agency, Denmark
Juha Röning	University of Oulu, Finland

1.4 New Work Item Proposal to IEC/TC 45

The International Electrotechnical Commission (IEC), Technical Committee 45 'Nuclear Instrumentation' prepares international standards relating to electrical and electronic equipment and systems for instrumentation specific to nuclear applications.

On 15 October 2015, a New Work Item Proposal for the development of a new standard has been submitted to IEC/TC 45, accompanied by a preliminary draft standard developed by the EMPIR project 'DigitalStandard'. The draft takes into account the outcome of the survey.

1.5 EMPIR SIP 'DigitalStandard'

The European Union's Horizon 2020 Euramet Support for Impact Project '14SIP07 DigitalStandard' provides funding to a consortium of four member states' laboratories, to:

- Contribute to the development of the standard;
- Stimulate the implementation of the (draft) standard by development of software tools for compliance verification, generation of test data, analysis of data and conversion of data files.

DigitalStandard is a three-year project that started on 1 June 2015, and continues on the work initiated by the ERNCIP RN Thematic Group, and the recommendations from the EMRP ENG08 MetroFission project. The IEC standard will be developed following the requirements of the ISO/IEC Directives, under the coordination of JRC.

1.6 Early involvement of industry

Through a Call for Expression of Interest, JRC will invite manufacturers of digital nuclear instrumentation to implement the draft standard and provide comments at an early stage. Eligible manufacturers will be able to test their equipment at JRC-IRMM, where they will have access to the unique EUFRAT nuclear research infrastructure dedicated to the measurement of accurate nuclear reaction and decay data.

2. About the survey

The survey was initiated by the ERNCIP RN Thematic Group. It was made publically available from 1 April until 18 September 2015 through the EUSurvey system via the URL https://ec.europa.eu/eusurvey/runner/DigitalStandard. The complete survey is attached in the annex of this report.

The survey is very technical and extensive. It is aimed at obtaining as much as possible information from potential users of the standard being developed, in order to address the needs from industry, data analysis software developers and end-users of digital data acquisition systems.

The survey has two parts: the first part is general and aims to obtain feedback on the use of digital data acquisition, list-mode data acquisition, their advantages and caveats, the need for a standard data format and software tools. The optional second part deals more with the technicalities of list-mode data acquisition and aims at optimising the standard to the needs of the future users.

The survey was publicised in the following manner:

- Invitations to respond to the survey were distributed between the members of the ERNCIP RN thematic group, who then forwarded the invitations to their experienced acquaintances.
  https://erncip-project.jrc.ec.europa.eu/news/conferences/149-2nd-erncip-conference-16-17-april-2015
- A poster was displayed and leaflets distributed at the second ERNCIP conference in Brussels, 16-17 April 2015, where 102 participants from various organisations from 20 EU member states met to discuss about critical infrastructure protection. https://erncip-project.jrc.ec.europa.eu/news/conferences/149-2nd-erncip-conference-16-17-april-2015
- To address the metrology community, who will be one of the first to benefit from a standard, a poster was displayed and leaflets distributed at the 20th International Conference on Radionuclide Metrology and its Applications (ICRM) in Vienna, 8-11 June 2015. http://icrm2015.boku.ac.at/ A presentation was made during the ICRM Radionuclide Metrology Techniques Working Group meeting.
- A poster was displayed at the 13th Nordic Meeting on Nuclear Physics, organised from 13-17 April 2015 in Saariselkä, Finland.
  https://www.jyu.fi/fysiikka/en/nmnp2015

3. Survey results

3.1 Statistics

In total, 31 replies were received over the period from 1 April to 18 September 2015. Of these, 17 chose to answer the technical part.

At the end of the survey participants had the option to enter their e-mail address:

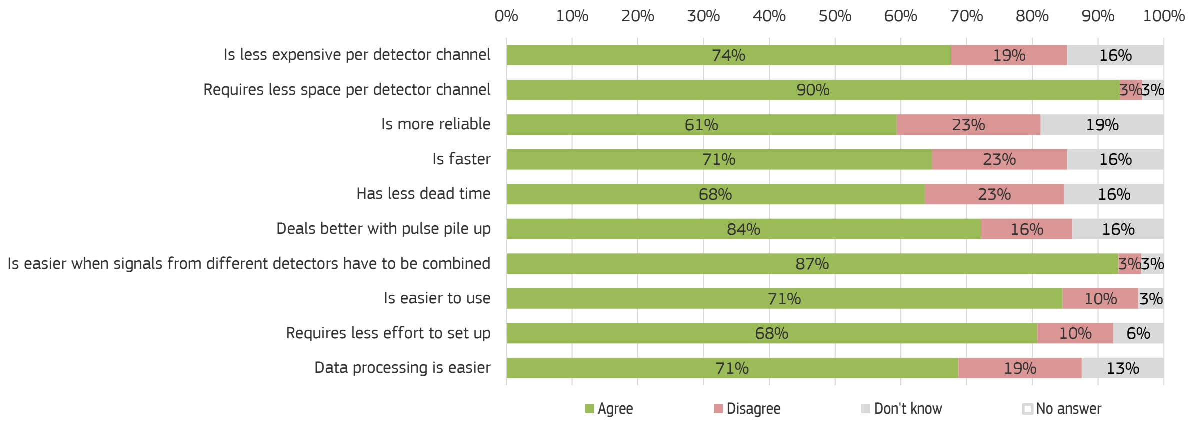
- 20 expressed their interest in receiving the results of the survey;
- 12 wanted to be kept informed on further developments;
- 11 did not provide their contact details.

Obviously, the statements below only refer to the answers of the survey and shall not be used to generalise.

3.2 Summary of results - general part

Out of the 31 replies, 97% use digital data acquisition and 90% acquire data in list-mode.

The following advantages of digital over conventional data acquisition are recognised:



The aim of the measurements where list-mode data is used varies: nuclear science, primary standardisation of radioactivity, coincidence measurements between signals coming from different detectors, liquid scintillation counting, gamma spectrometry, environmental radiation monitoring, imaging and positron emission tomography, monitoring with optimised integration time, neutron/gamma discrimination, measurement of reactor antineutrino spectra and mobile measurement with a high time resolution.

From the 27 participants that answered the question on the reasons to use list-mode data acquisition, 89% use it for off-line processing of data, 85% for re-analysis with different parameters, 70% to enable the use of advanced processing algorithms and 63% to combine data from different detectors. 26% acquire data in list mode to allow sharing of data, and 26% for quality control measures. 15% combines the list-mode data with data from other sensors such as geolocation devices.

Three participants out of 31 provided reasons not to use data acquisition in list mode; two of them do not have the appropriate equipment or software and two do not have the need for data acquisition in list-mode. One has insufficient resources to enable it.

74% of the users that answered the survey store data on the computer that runs the data acquisition, 65% copies the data to another computer for analysis. Half (partly) analyse the data during the acquisition. 19% streams the data to another computer for storage, and 16% streams to another computer for near-real time analysis (13% did not answer).

55% replied that they use only digital electronics for list-mode data acquisition, one third use both conventional and digital systems, while one user (3%) only uses conventional list-mode data acquisition (10% did not answer).

The most frequently used arguments to use digital data acquisition systems instead of conventional modular electronics are: flexibility (especially in post-processing and re-analysis) and price, compactness, performance (large pulse throughputs, dead time and pile-up reduction), ease of use (especially in combining signals from multiple detectors) and lower power consumption.

71% extract pulse height spectra or time interval distributions, 61% extract the pulse amplitude and timestamp, 39% acquire pulse waveforms (6% did not answer).

The survey asked about the origin of the software used for list-mode data acquisition and analysis.

For data acquisition, 52% use the data acquisition software provided by the manufacturer of the hardware, and 55% developed their own data acquisition software. For data analysis, 23% use publically available software and 87% use software developed in-house.

Digital data acquisition suffers from a number of issues. The issues identified are: software (48%), clock synchronisation and noise (both 39%), throughput (32%), data storage (26%), trigger issues and input dynamic range matching (both 23%), lack of timing resolution (16%), lack of amplitude resolution (13%), reliability (10%), signal connectors (6%), double triggering (3%) and power connectors (3%). 16% provided no answer to this question.

The benefits of a standard are recognised by the results of the survey. The collaborative (94%) and economic (90%) advantage of a standard, and the improved interoperability between data acquisition hardware (90%) is acknowledged. 87% believe a standard is needed and 84% that it should be global. 94% believe that a standard will stimulate developers of analysis software. Finally, about 77% would prefer a voluntary standard, while about 16% somewhat disagree with the voluntary character.

About 68% would include data streaming into a standard data format, in addition to standardisation of list-mode data files. 10% would not include streaming and 22% have no opinion.

About 74% of the survey participants recognise the need for conversion software of data acquired in list mode to a standard format. 16% do not have this need, and 10% do not know.

Of the participants, 58% invested in data conversion software in the past, and the same number foresees investment in such software in the future. 32% have not yet invested in data conversion, and 23% do not plan to do so in the future.

Software tools can help supporting the implementation of a standard. Data producers are the first users to implement a standard, they benefit from software that verifies the compliance of the data that they generate. Data consumers are developers of software for data analysis. They can benefit from a tool that generates artificial data in the standard format. Processing this data allows them to verify the validity of their analysis software. A tool that performs basic analysis of data files is valuable for end-users of digital data acquisition systems, and finally a tool to convert list-mode data files to common spectral formats can be valuable for users that want to keep their more conventional software for analysis.

Of the participants, 94% finds the (free) availability of software tools for visualisation and basic analysis of list-mode data important. 87% assign importance to the availability of software for compliance verification. 90% finds such software for generation of test data important. For 77%, list-mode conversion tools are important, but for 20% this is not very important. 81% prefers a downloadable software tool for these purposes, and 10% prefers a web application.

3.3 Summary of results - technical part

17 out of 31 answered the technical part. The percentages mentioned here refer to the 17 replies.

Nine replied that they use additional front-end electronics in between the digitiser and the detector while five do not use additional electronics. Those that use front-end electronics provided the following reasons: to match the signal with the input dynamic of the digitiser (7/9); to optimise the signal-to-noise ratio (6/9); impedance matching (5/9); anti-aliasing filtering (3/9) and high-pass filtering (2/9). Four out of nine uses off-the shelf front-end electronics; and five out of nine uses custom-made electronics.

59% of the 17 use digitisers that perform sample processing in hardware using DSP or FPGA. ADC sample rates vary from 1 MS/s to 2 GS/s. 59% use a 14-bit ADC, while the rest use 10, 12 and 16 bits ADCs in equal amounts.

Digitisers are clearly used for multiple detector systems. Only 6% of the users have one input channel on the digitiser, 24% have 2 channels, 29% have 4 input channels, 29% have 16 input channels, and 1 user (6%) even has 36 input channels on one digitiser. 41% acquires signals from 2 detectors in one setup, 12% from 6 detectors, 12% form 10 detectors, while the other five users have 48, 50, 200, 600 and even 3000 detectors in one setup.

59% require the digitiser clock to be synchronised to a master clock, but only 12% needs the master clock to be SI-traceable.

Synchronisation of the acquisition start/stop between different digitisers is realised by daisy-chaining TTL-level signals (2), PXI backplane (2), a common start trigger (1) or custom hardware (1 answer).

The required time resolution for the timestamps is in the order of nanoseconds (94%) and picoseconds (6%). Data acquisition times vary from milliseconds to days.

The following properties extracted from recorded pulses are relevant to include in the standard: pulse height (94%); timestamp (94%); single charge integration (59%); double charge integration (59%); average baseline level before the pulse (76%); pulse rise time (71%); pulse fall time (71%); pulse peaking time (59%); pulse width (65%); advanced pulse characteristics (59%); information about pulse pile up (100%) and samples integrated in the pulse tail (41%). Other features to include are: time over threshold, user-defined or application-specific parameters, system health (electronics temperature, power consumption, detector HV), logical values, pulse decay time (exponential), timestamps resulting from interpolation between samples and full waveform with possible zero suppression (the length of waveforms can vary between channels, and between events on the same channel). The standard must be flexible enough that any pulse characteristics can be added later on.

Timestamps are mainly obtained by a leading edge threshold (35%); constant fraction discriminator (29%); crossover timing (18%); and by fitting the expected pulse function (6%). 12% provided no answer to the question on how to obtain the timestamp.

The manner in which pulse rise time, fall time and pulse width shall be specified, is not clear from the answers, since only about 10 persons answered this question.

3.4 Detailed results

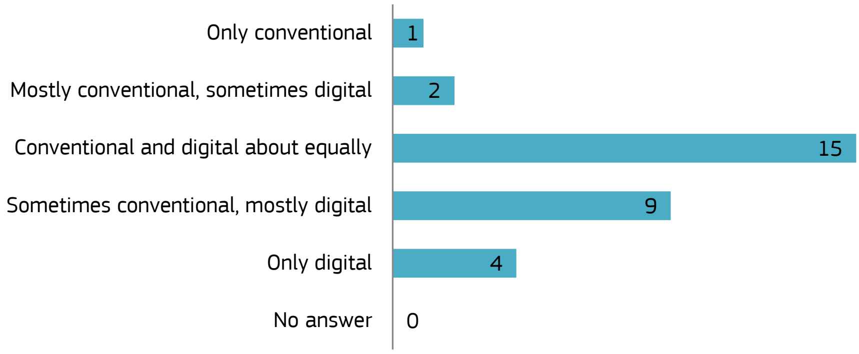
The following sections provide the complete set of answers to the survey. It is explicitly mentioned that only one selection is allowed or that more than one answer to a particular question could be selected. The questions to answer mandatory are marked with *. Some related questions are grouped: the order of the questions in this report may not correspond to the order of the questions in the survey. In the graphs, some answer phrases are truncated: the authors refer to the complete survey in chapter 5.8. The question numbers correspond with the numbers in the survey. The answers to the free text fields are provided as such.

4. Answers to the general part

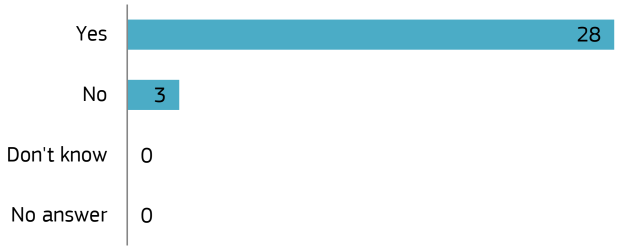
4.1 The use of digital data acquisition

The survey was aimed at users of digital data acquisition, and particularly those that acquire data in list mode. This is reflected in the answers: one user performs data acquisition with conventional electronics only and about 90% acquire data in list-mode.

2.1.1 How often do you use digital compared to conventional data acquisition? I use (select one):*



*2.2.1 Do you acquire data in list mode? (select one)**

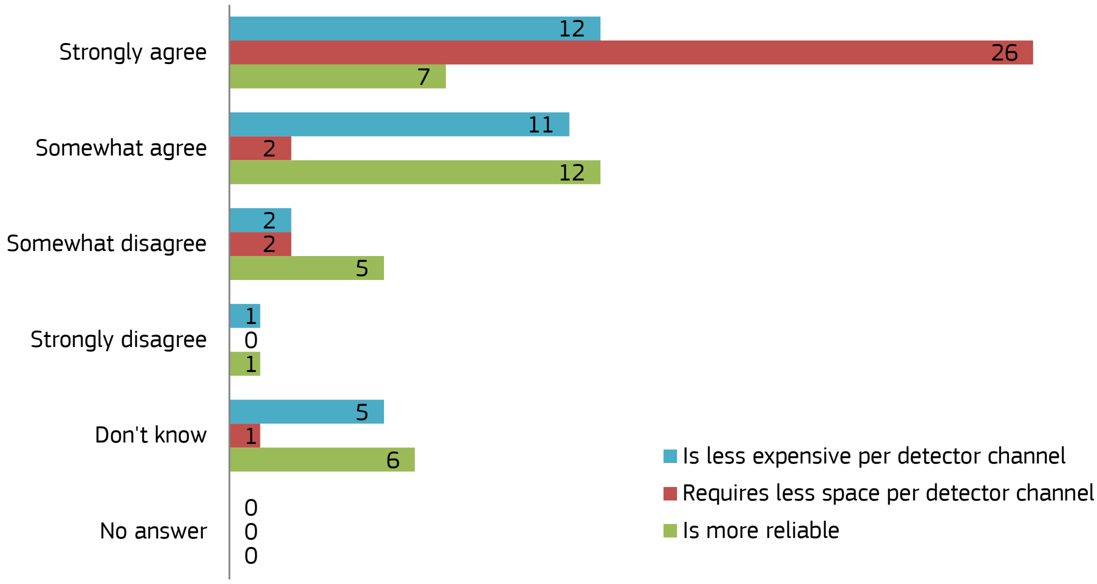


4.2 Advantages of digital data acquisition

Most of the participants agree with the statement that digital data acquisition is cost and space-saving with respect to conventional data acquisition. With respect to reliability, opinions are mixed.

2.1.2 To what extent do you agree that digital data acquisition has advantages over conventional data acquisition, with respect to the following aspects?

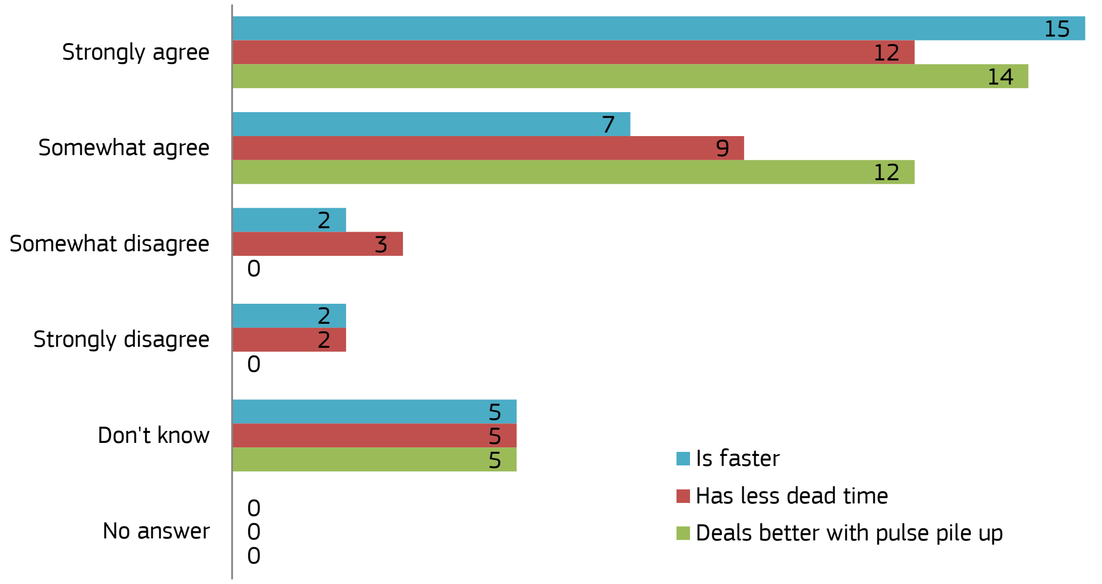
a. Cost, space and reliability:



The majority believe that digital data acquisition is faster, imposes less dead time and suffers less from pulse pile-up. Five out of twenty-nine do not know if this is the case.

2.1.2 To what extent do you agree that digital data acquisition has advantages over conventional data acquisition, with respect to the following aspects?

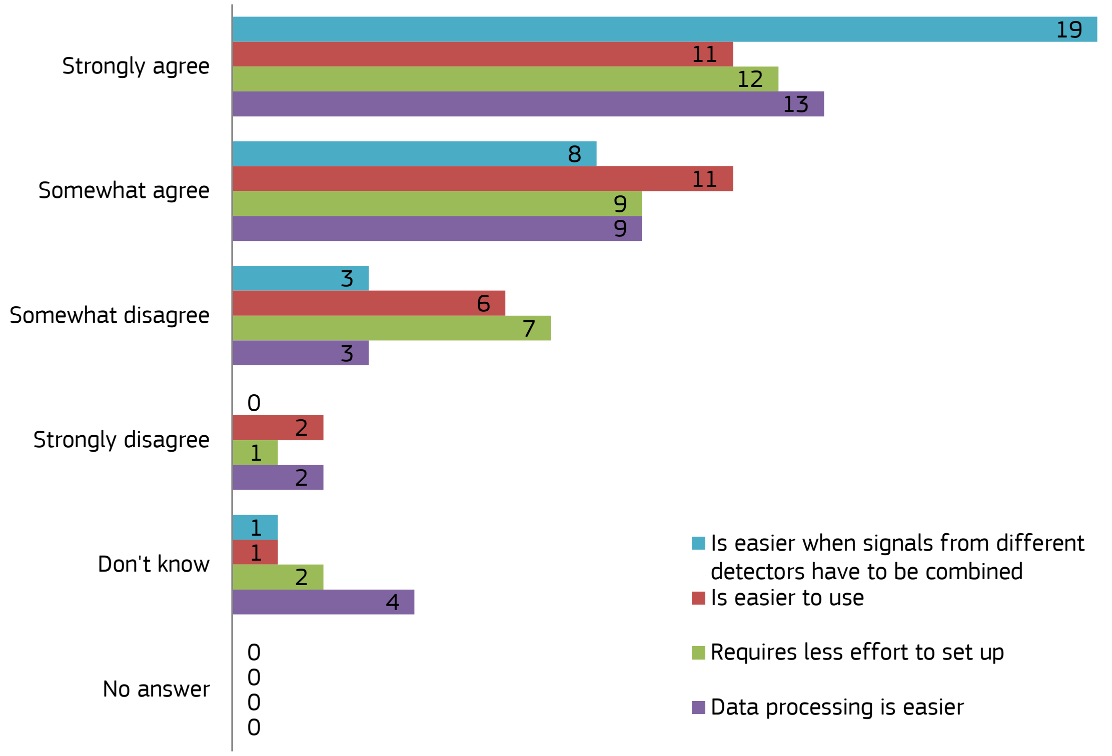
b. Performance:



One believes that with digital data acquisition, it is easier to combine signals from different detectors and it is generally easier to use and require less effort to set up than conventional data acquisition. One third disagrees or has doubts with the statement that digital data acquisition leads to easier data processing.

2.1.2 To what extent do you agree that digital data acquisition has advantages over conventional data acquisition, with respect to the following aspects?

c. Ease of use:



4.3 Application of list-mode data acquisition

An open question allowed specifying the aim of the measurement setup in which list mode-data acquisition is used.

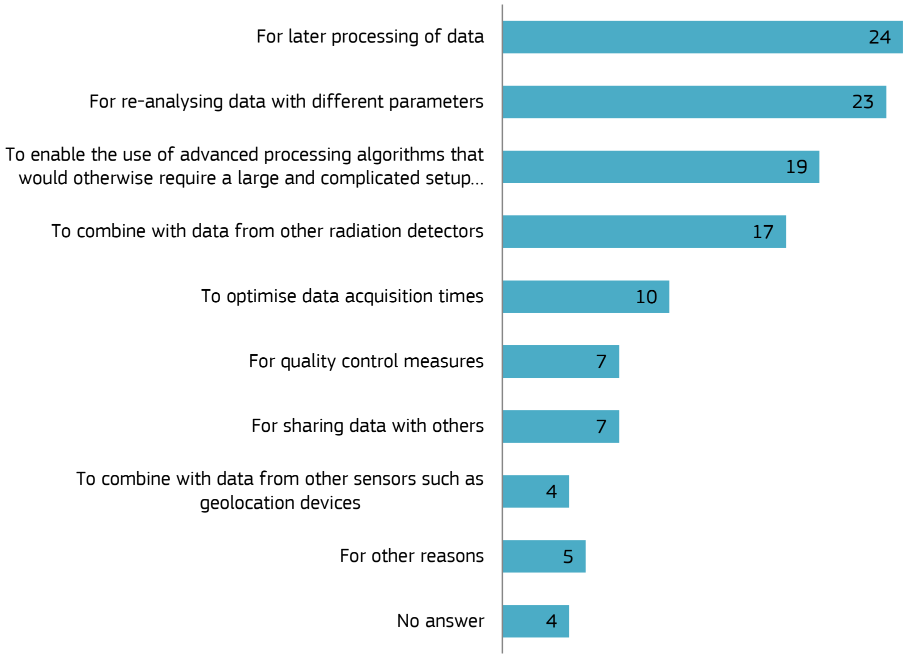
2.2.1.1 What is the aim of the measurement setup(s) in which you acquire data in list mode?

- *General experimental nuclear science; heavy ion physics. Rare isotope beam experiments.*
- *Nuclear structure research.*
- *To collect data for nuclear physics experiments. We study many different reactions involving rare isotope beams using small table-top setups to large research devices. Often people do not want to record waveforms in their list-mode data because the digitizer will produce a result from each waveform using on-board signal processing. Such results might be a peak amplitude or integral. However, when experimenters output waveforms from their digitizers during list-mode data taking, they often try to extract more detailed information concerning the shape of the waveform. For example, tracking detectors will attempt to determine the location an interaction occurred in the detector by analysing the shape of the waveform. Doing so provides position resolution that would otherwise not have existed.*
- *To measure time-of-flight and energy of elastically recoiled particles (ToF-ERDA). Coincidences between channels and detectors are built based on timestamps.*
- *Primary standards of radioactivity.*
- *Liquid scintillation measurements, photon spectrometry.*
- *Analysis of the coincidences between signals coming from different detectors.*
- *Alpha-gamma coincidence.*
- *Neutron detection, alpha-gamma, beta-gamma and gamma-gamma coincidence, imaging detectors.*
- *Simultaneous singles and coincidence counting, monitoring with optimised integration time.*
- *Neutron detection and gamma-gamma coincidence.*
- *Positron emission tomography.*
- *Measurement of Time of Flight.*
- *Environmental radiation monitoring.*
- *To determine activity concentrations of environmental gas samples.*
- *ToF-ERD measurements, energy-loss measurements, energy-loss straggling measurements.*
- *Measurement of reactor antineutrino spectrum. The currently operation detector submodule consist of 288 photosensors. I also use list-mode data for neutron/gamma -discrimination in a prototype neutron detector.*
- *To gain more information than conventional pulse height gamma ray spectrometry.*
- *Mobile measurement with a high time resolution.*
- *Low-level radioactivity measurement of environmental sample.*
- *TDCR LS counting, TAC spectra.*
- *Energy measurements.*
- *Measurement of time spectra with independent detectors against the same reference (accelerator RF) at very high detector loads (Mcps range) and very high throughput (> 500 kcps).*
- *Gamma spectrometry.*
- *Need to characterize single events (charged particle tracks, single scintillation events); sometime list mode is useful for better (off-line) noise suppression and signal-to-noise ratio improvement.*

- *Neutron and Gamma spectroscopy.*

4.4 Reasons to use list-mode data acquisition

2.2.1.2 Why do you acquire data in list mode? (more than one answer is possible)

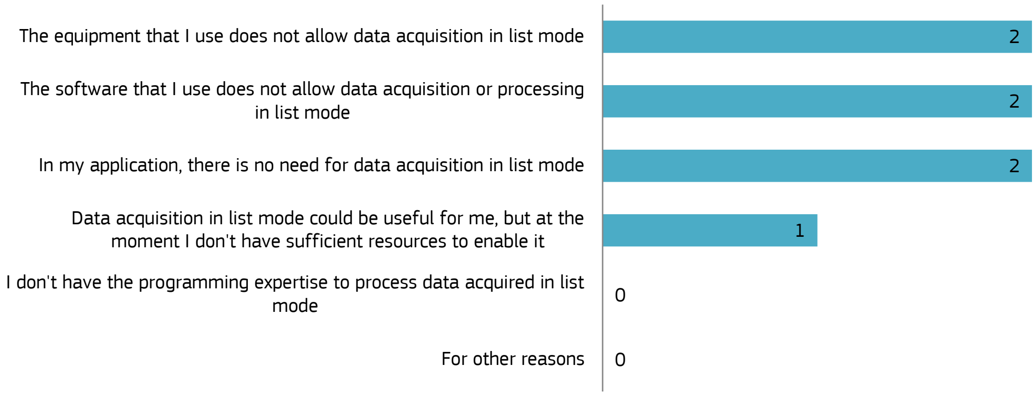


The following other reasons were mentioned (2.2.1.3):

- *Trigger-less systems, all data collected to make sure no losses are suffered.*
- *Pulse shape analysis for neutron/gamma discrimination.*
- *Also to be able to follow the evolution of a spectrum with respect to the time and to be able to make coincidence after acquisition is finished.*
- *To develop algorithms for real-time acquisitions.*
- *To synchronize spectrum accumulation with the macro time structure of the beam. Beam macro bunches ("spots" in medical treatments) of varying lengths (typically 1-10 ms) are delivered in an irregular pattern. Spectra have to be accumulated and analysed spot-by-spot.*

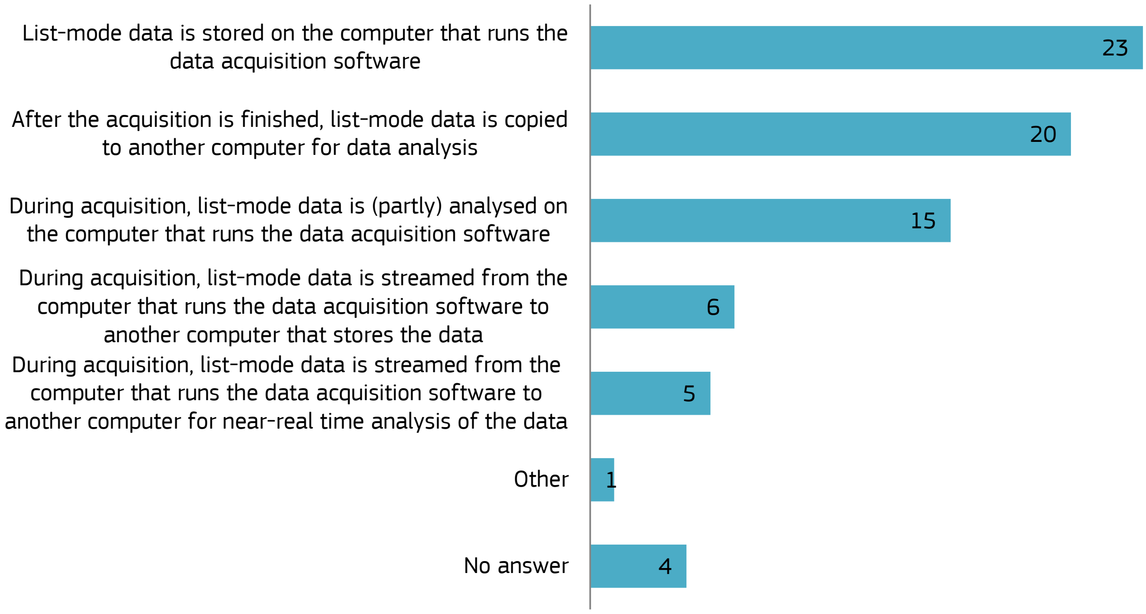
4.5 Reasons NOT to use list-mode data acquisition

2.2.2.1 Why do you not use data acquisition in list mode? (more than one answer is possible)



4.6 Streaming of data

2.2.1.4 When acquiring data in list mode, which of the following statements apply to your application? (more than one answer is possible)

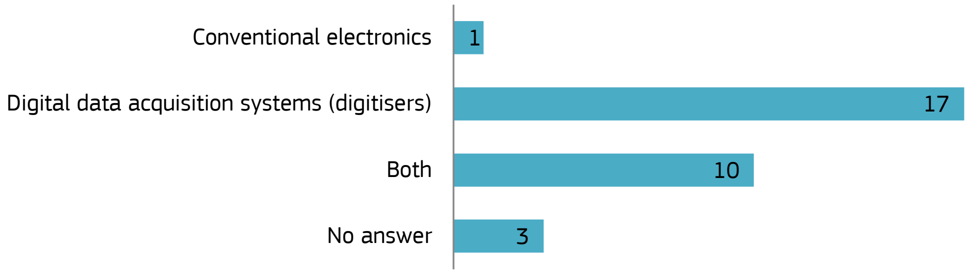


The other option noted is (2.2.1.5):

- *All data is stored on a server and analysed on local terminals.*

4.7 Type of electronics used for list-mode data acquisition

2.2.1.6 When acquiring data in list mode, do you use (select one):*



4.8 Why digital data acquisition systems are preferred

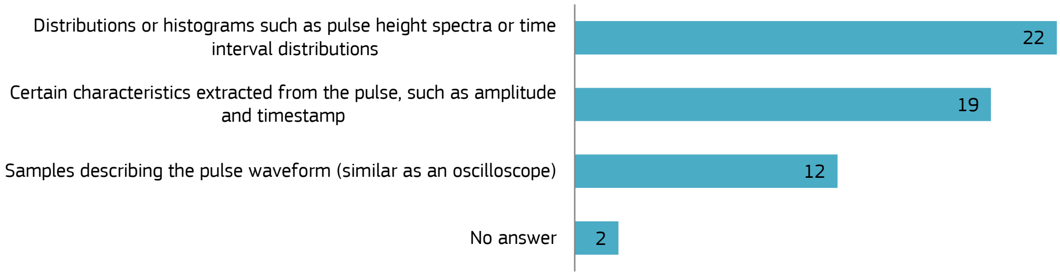
2.3.1 What are your reasons to use digital data acquisition systems instead of conventional modular electronics?

- *Digital acquisition allows for better and more in-depth post-processing of signals.*
- *Flexibility and price.*
- *Compact versatility in field use.*
- *No conventional system could provide the extreme throughput and accept the huge detector load.*
- *I use detector modules that have built-in digital data acquisition.*
- *More compact, easier to use.*
- *Digital data acquisition systems are compact and portable devices. They allow to manage problems with dead time, coincidence resolving time and pile-up of the signals by analysis of the data in off-line mode.*
- *Because it's easier and cheaper respect to conventional electronics and it permits a complete control over acquisition parameters.*

- *Ease of use to store synchronised list mode data from multiple detectors.*
- *Small size, low power consumption.*
- *The system is easier to setup, and it's also easier to combine measurement from several detectors. Too much information or time is lost in equivalent conventional modular electronics.*
- *Acquisition parameters and algorithms can be changed without operating on the hardware.*
- *Ease of setup. Lower power requirements. Smaller electronics packages.*
- *To learn how to use this rather new electronic that will become the "standard" electronic in few years.*
- *Ease of integration.*

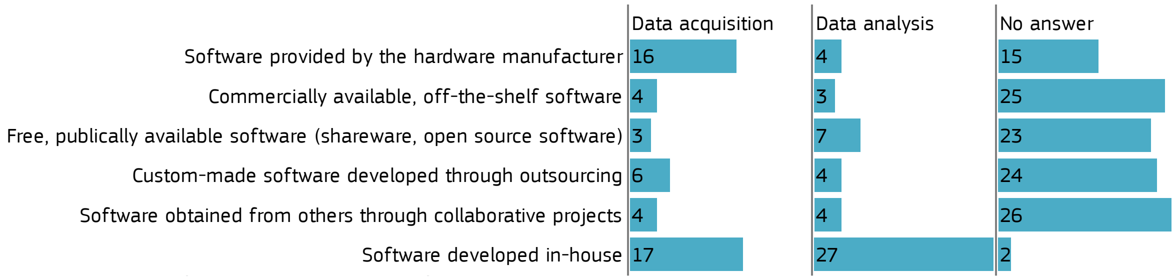
4.9 Information extracted by digital data acquisition systems

2.3.1.1 What type of information does the digital data acquisition system extract from the detector signal? (more than one answer is possible)



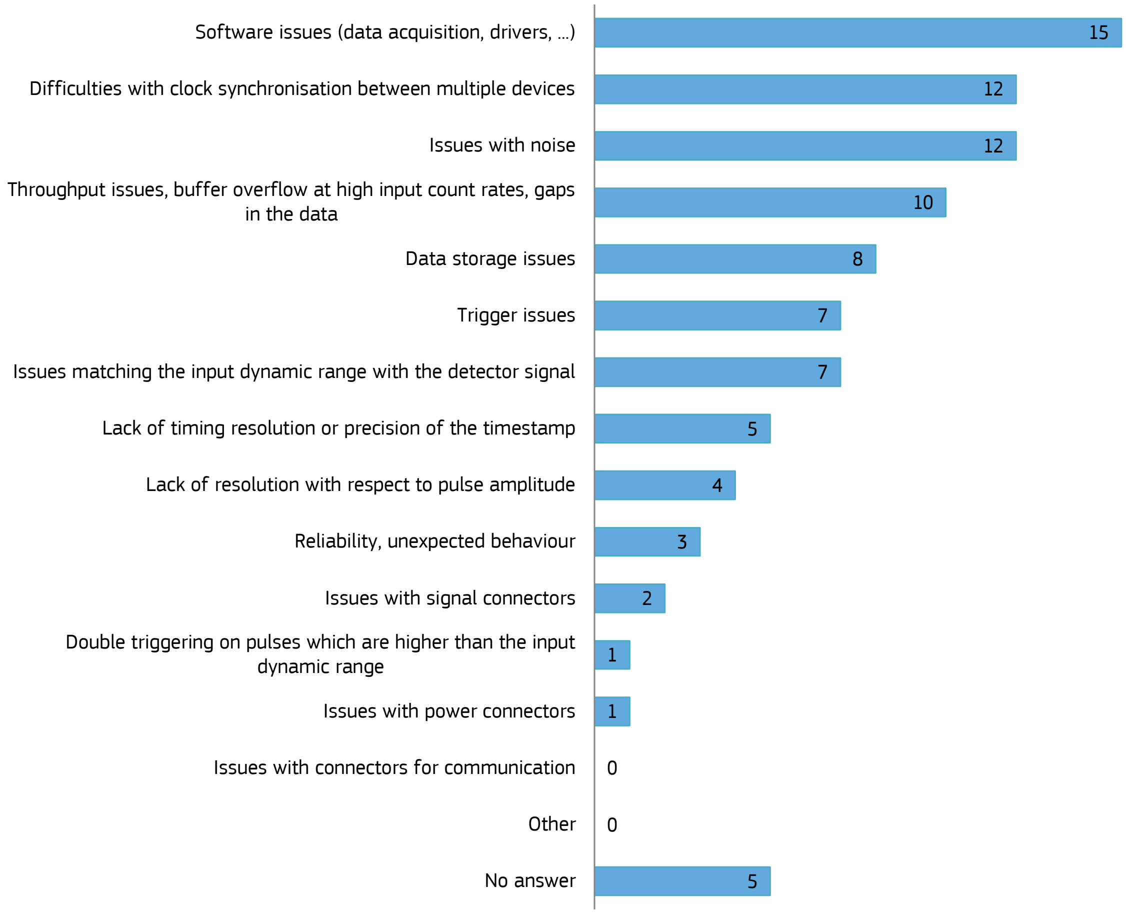
4.10 Software for list-mode data acquisition and analysis

2.3.2.1 What is the origin of the software used for list-mode data acquisition and analysis? Please select what applies (more than one answer possible).



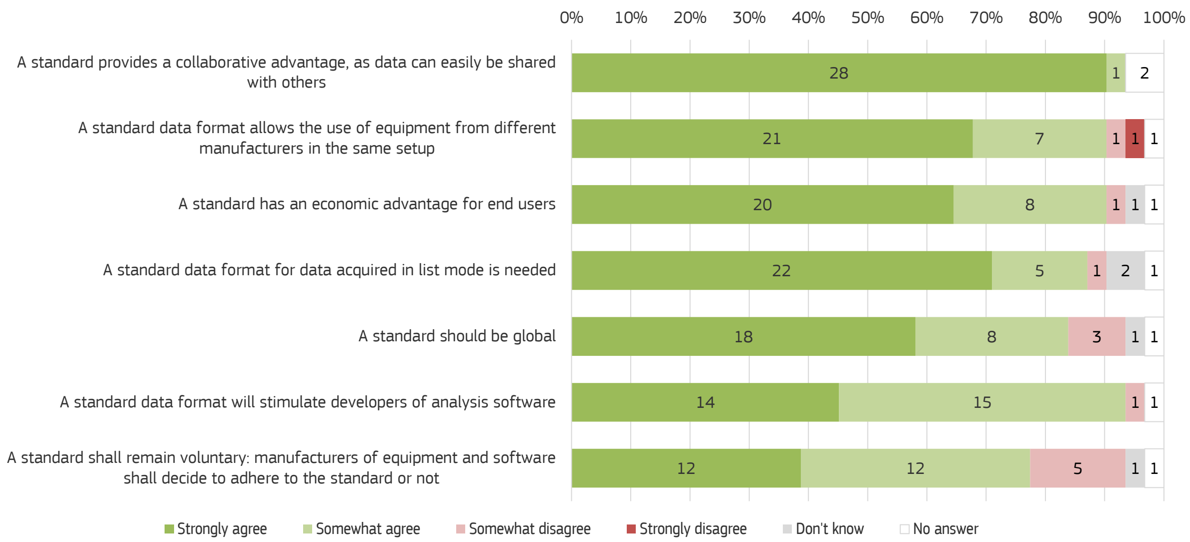
4.11 Issues with digital data acquisition

2.3.3.1 In the use of digital data acquisition, did you have issues or observed unexpected behaviour in certain conditions? (more than one answer is possible)

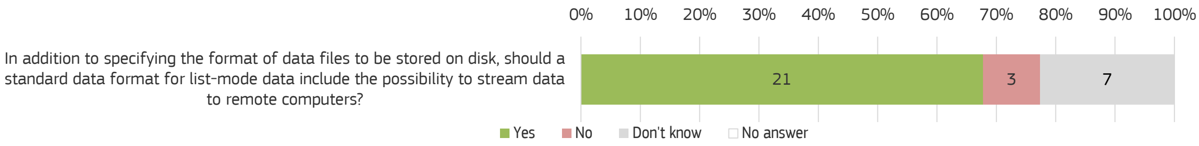


4.12 Standardisation of the list-mode data format

2.4.1 With respect to standardisation of the list-mode data format, to what extent do you agree with the following statements?

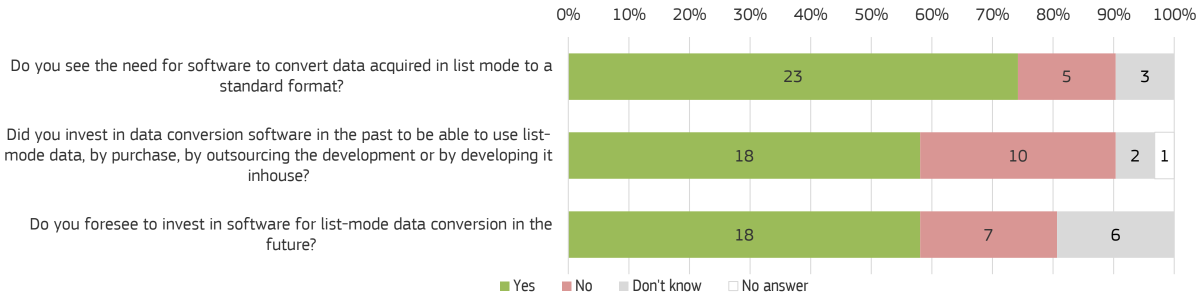


2.4.2.1 Data streaming is the transfer of data at a steady high-speed rate, sufficient to support such applications as high-definition television. Streaming of data in list-mode can be used as a way to continuously transfer data from an acquisition system to a remote computer that processes the data.



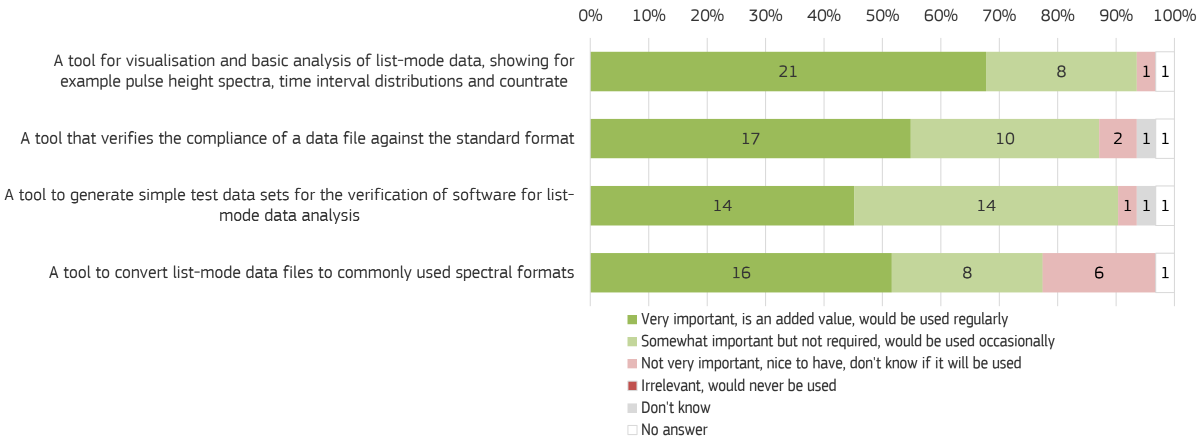
4.13 Conversion tools

2.4.1.1 Please answer the following questions concerning conversion of list-mode data to other data formats.

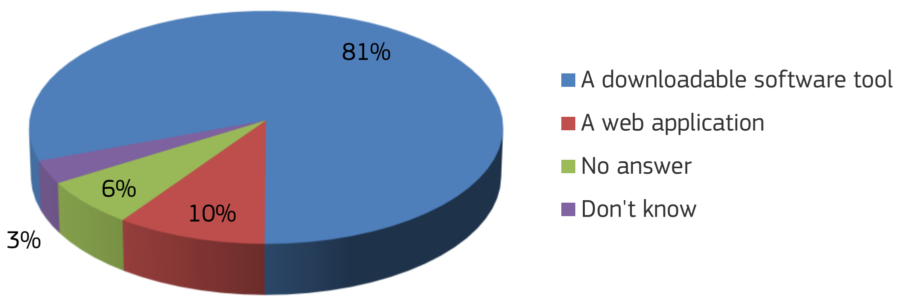


4.14 Software tools to support the implementation of a standard

2.4.3.1 The following software tools can support the implementation of the standard. How important is the (free) availability of these tools to you?



2.4.3.2 What would you prefer as software tool for these purposes?

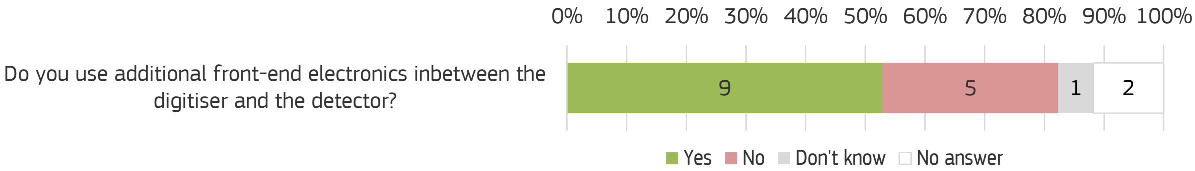


5. Answers to the technical part

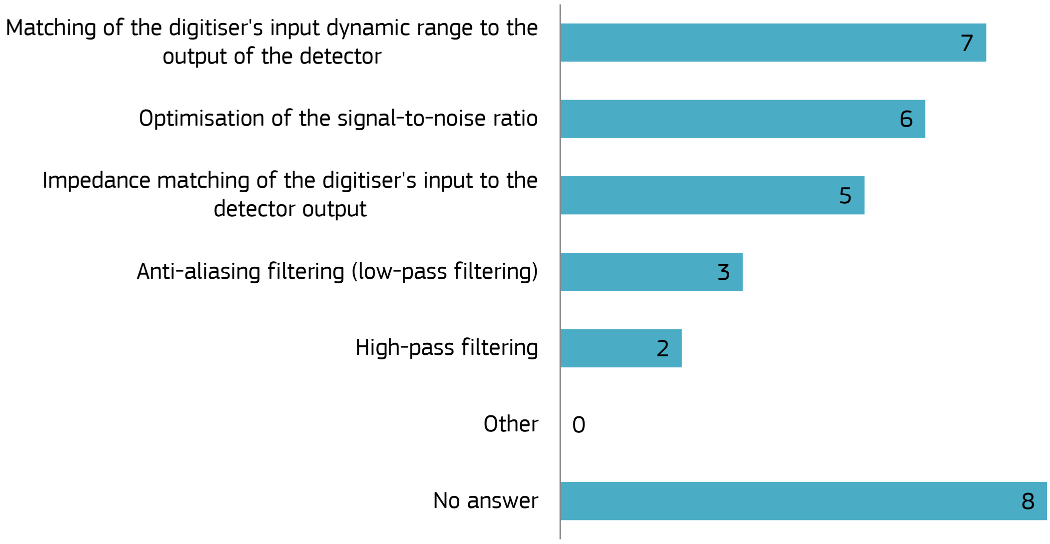
The technical part of the survey was answered by 17 out of the 31 persons who answered the first part. This response is rather low and makes it difficult to draw relevant conclusions for some of the questions. The numbers corresponding to "No answer" refer to the 17 replies that were received on the second part of the survey.

5.1 The use of front-end electronics

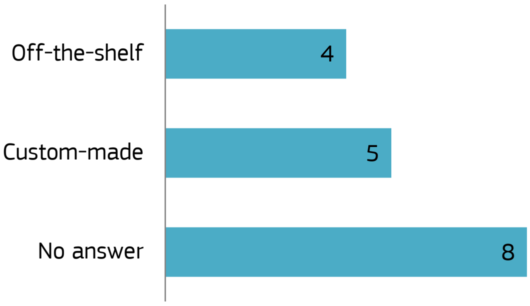
3.1.1.1 Do you use front-end electronics? (select one)



3.1.1.3 What are your reasons to use front-end electronics? (more than one answer is possible)

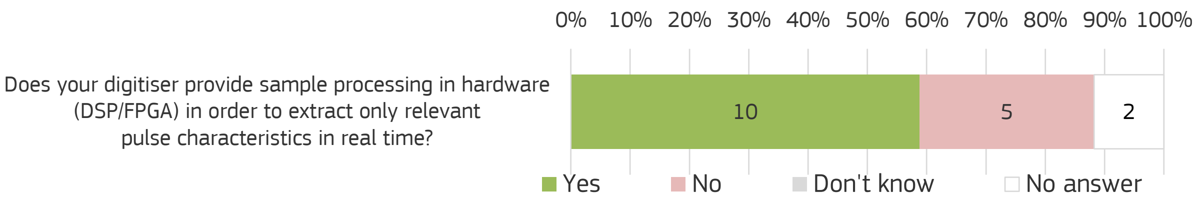


3.1.1.5 What is the origin of the front-line electronics that you use? (select one)

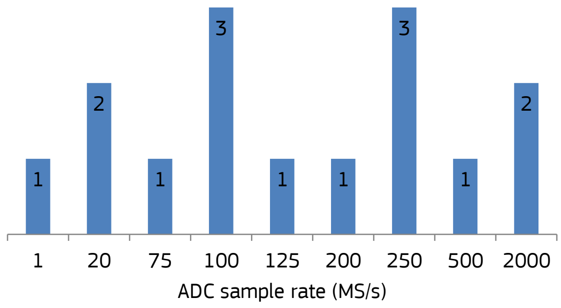


5.2 Type of digitiser

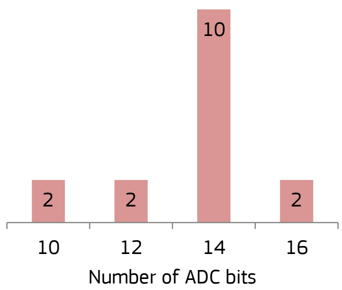
3.1.2.5 Sample processing by the digitiser's DSP/FPGA (select one)



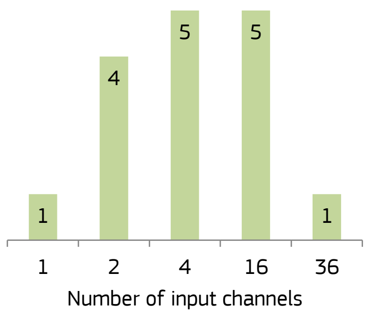
3.1.2.1 What is the sample rate of the analog-to-digital converter of the digitiser that you typically use? (specify a value in a text box)



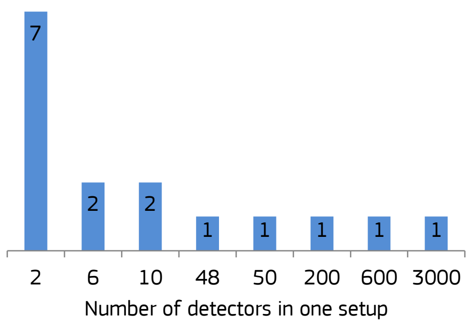
3.1.2.2 What is the number of bits provided by the analog-to-digital converter? (specify a value in a text box)



3.1.2.3 How many input channels does the digitiser(s) have? (specify a value in a text box)

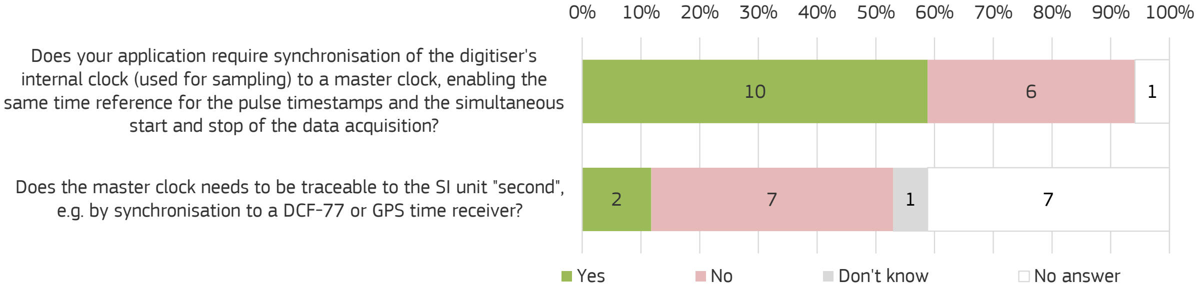


3.1.2.4 How many detectors do you have at maximum in one setup? (specify a value in a text box)



5.3 Digitiser clock synchronisation

Clock synchronisation (3.1.3.1 and 3.1.3.2) (select one)

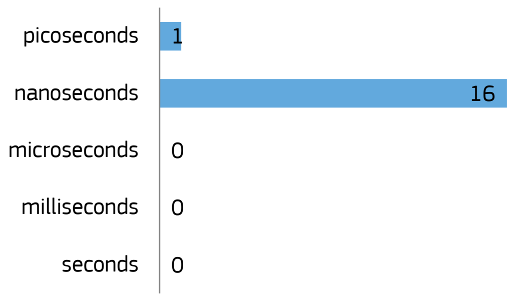


3.1.3.3 Could you describe how the start and stop of the data acquisition is synchronised between different digitisers?

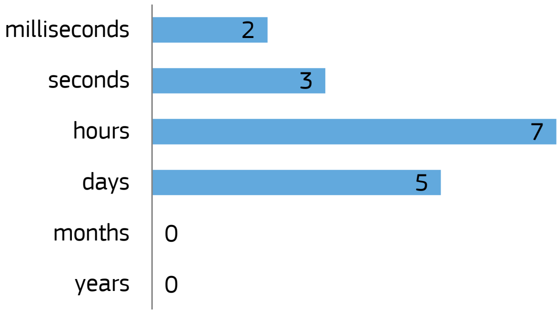
- *We use PXI16's the PXI backplane and digitizers are able to run from a single master clock with hardware near-synchronized zero. The time offsets are stable and therefore can be measured and compensated for. Typically, however waveform sample level synchronization is only required in our setup within a single PXI crate or even module with the timestamp across the crates being used for event building where tolerances are ok.*
- *Digitizers are armed, one digitizer is started by software and others receive "acquisition start" TTL-level signal from the first, in daisy chain.*
- *Custom HW.*
- *The digitizer family that is most commonly used can handle synchronization through the PXI backplane. Otherwise, we might designate a device to produce a master clock and then use its oscillator and a pulse to clear every digitizer's timestamp counters at the "same" time.*
- *So far we do not need synchronized start/stop at a level below some milliseconds. The detectors are operated independently but against the same (master) reference signal for timing. We are not (yet) looking for coincidences but measure several time spectra with independent detectors against the same reference (accelerator RF). However, clock synchronization at the ns level would be great for future applications. For the present application, the accuracy of time stamps relative to the reference signal must be of the order of 100 ps, whereas the absolute time stamps ("gross counters") of the independent detectors need not to be synchronized to better than 1 ms. In future, however, we would like to synchronize the "gross counter" as well to the level of one ADC clock cycle, i.e., a few ns, in order to allow for finding coincidences between individual detectors.*
- *By a common clock distributed to all digitizers and a common trigger for start. Stop is provided by the readout electronics.*
- *It is managed by the digitizer using the CLK_IN/CLK_OUT daisy chain.*

5.4 Required timing resolution and data acquisition time

3.1.4.1 In your application, what is the required time resolution for the timestamps (order of magnitude)? (select one)



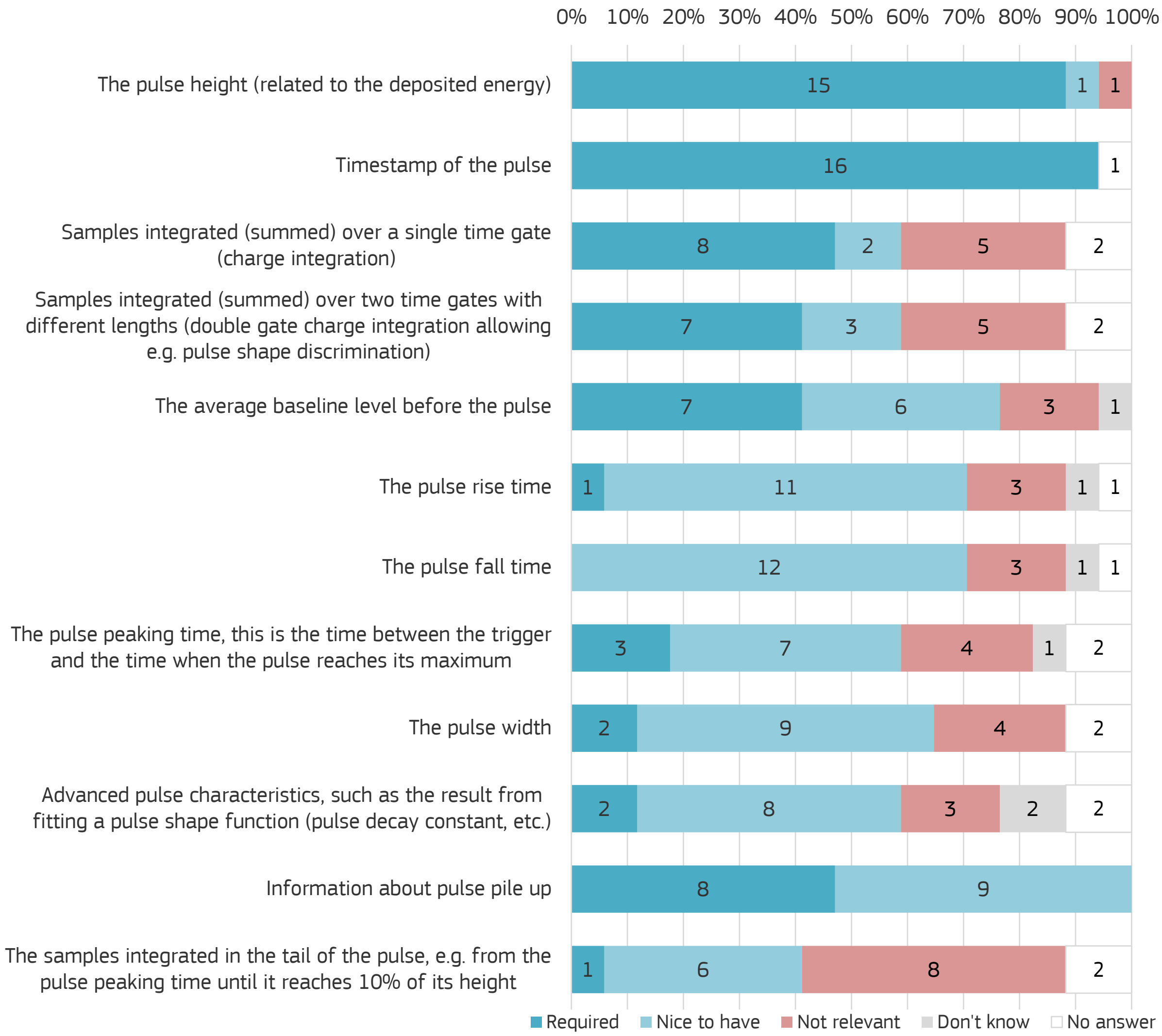
3.1.4.2 In your application, what is a typical data acquisition time? When a measurement is repeated over several acquisitions, please specify the typical length of a single acquisition. (select one)



5.5 Pulse properties extracted relevant to include in a standard

Timestamp, pulse height and information about pulse pile-up are required to include in the standard data format, as well as charge integrated over one or two gates. Some users also require pulse peaking time, pulse width, pulse tail integration and more advanced pulse characteristics.

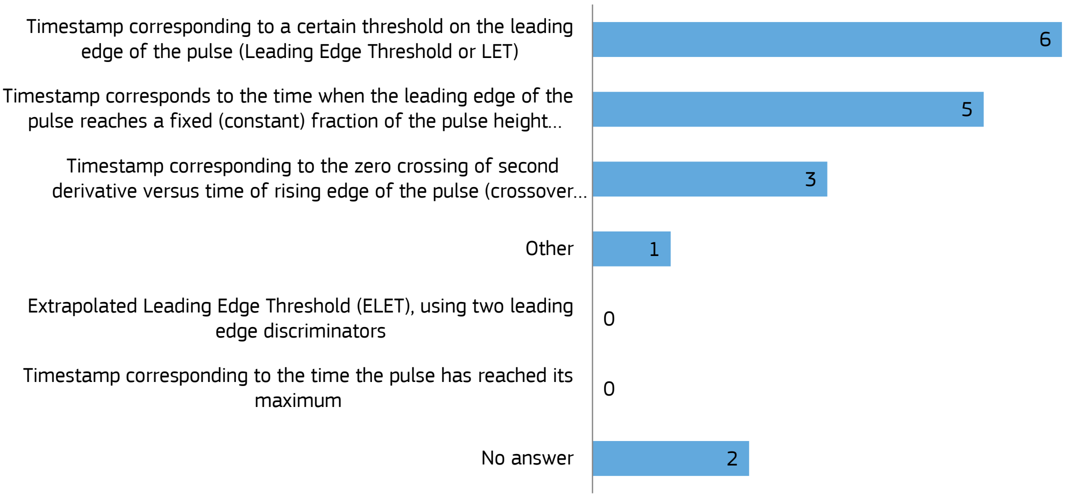
3.1.4.3 Which of the following properties extracted from pulses recorded by the hardware are relevant for you to include in the standard?



3.1.4.4 Apart from the properties mentioned in the table above, would you need other properties to be included in the data format? Please specify.

- *Besides the data stream comprising event data there should be a mechanism for submitting "system health" data (detector temperature, device or electronics temperature, power consumption, detector HV etc.) in regular intervals. Such "system health" blocks could be sent e.g. every few seconds, mixed with the event data, in the same list mode data stream.*
- *Note on the above -- The required values are a logical or over the requirements for all of the detector types we use.*
- *Full waveform with possible zero suppression.*
- *Time over threshold (signal duration over the input range).*
- *It would be useful the standard include the possibility of user defined or application specific parameters which cannot be foreseen in advance.*

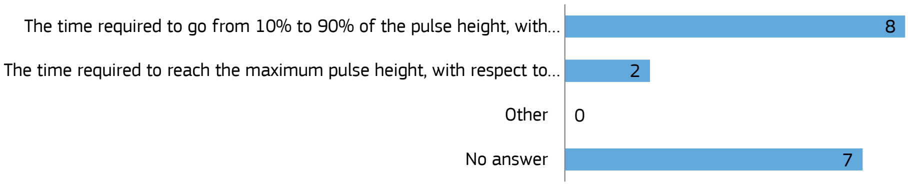
3.1.4.5 In your application, how is the timestamp typically obtained? (select one)



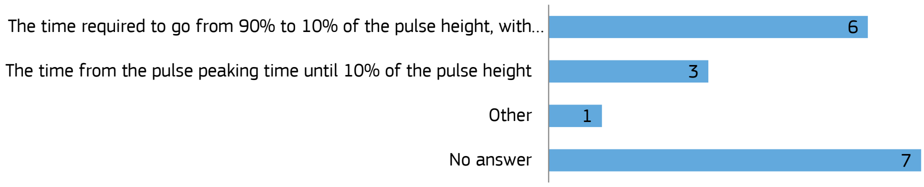
Other (3.1.4.6):

- *Fit by the expected pulse function (which contains the "start time" parameter).*

3.1.4.7 How shall the pulse rise time be specified? (select one)

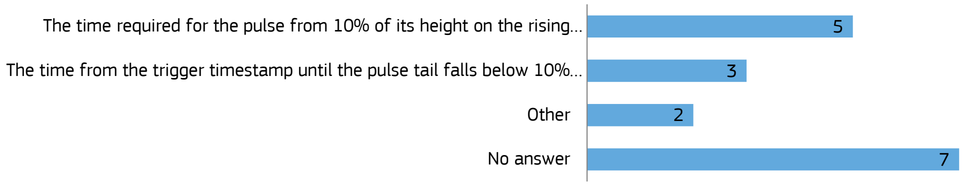


3.1.4.9 How shall the pulse fall time be specified? (select one)



Other (3.1.4.10): not specified

3.1.4.11 How shall the pulse width be specified? (select one)



Other (3.1.4.12):

- *Time from trigger to a certain level (e.g., 50%) - not to a fixed level of 10%*
- *The time over the detection threshold*

Please specify which advanced pulse characteristics you would like to see included in a standard data format.

- *The standard must be flexible enough that any pulse characteristics can be added later on.*
- *Possibility to include waveforms would be nice to have.*
- *Pulse decay time (exponent).*

5.6 Other comments

If you have any other comments with respect to the survey, you can write them here.

- *Our facility performs a very wide variety of experiments. This survey seems tuned to facilities that only use a limited set of detector types/experiment types. 3.1.4.5 - note that the timestamp can be a value interpolated between the samples (see e.g. the capabilities of a CAEN V1730 digitizer with PSD firmware. That question should have been checkboxes as well because the actual timestamp determination again is dependent on the detector and its response curve. There are cases where the firmware implements leading edge discrimination and other where a constant fraction discriminator is implemented.*
- *For further information, please contact over email.*
- *For my application, it would be crucial that the length of the stored waveform can vary between channels and event between event on the same channel.*
- *Excellent initiative. Standardization for the growing use of digitizers is very useful.*

5.7 Feedback

Would you like to receive feedback?

- *20 out of 31 would like to receive the results of the survey;*
- *12 out of 31 would like to be kept informed on further developments.*

5.8 Survey

Survey on the standardisation of the data format for the output of digital data acquisition systems used for radiation detection and measurement

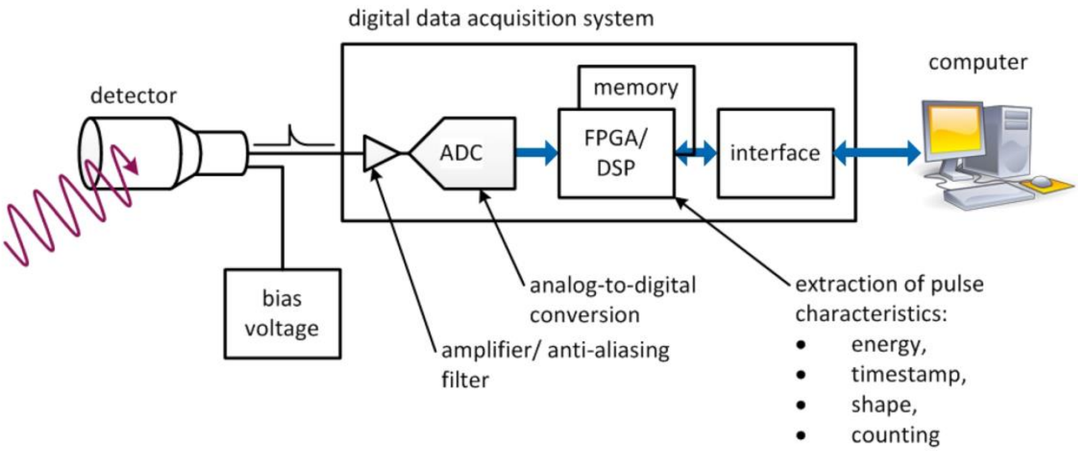
Fields marked with * are mandatory.

1 Introduction

1.1 About the survey

This survey is about the development of **a standard data format** for the output of **digital data acquisition systems** used for **radiation detection and measurement**. Such systems are commonly called "digitisers". They continuously sample the signal at the output of a radiation detector to obtain a digital representation of the pulses. The samples can be saved directly to a data file, or processed by the hardware using digital signal processing to extract only the relevant information, such as pulse height and timestamp. This way of acquiring data is also called **list-mode data acquisition**.

The schematic below represents a typical digital data acquistion setup.



More information and technical reports about list-mode data acquisition can be found on the ERNCIP RN website.

1.2
Is this for me?

This survey is addressed towards **end-users of digital data acquisition systems** (digitisers) used for radiation detection and measurement.

The first part of the survey will take about 15 minutes to complete. The optional second part will take another 5 minutes.

1.3
Goal of the survey

The goal of this survey is:

- To **gather information** on the use of digital and conventional data acquisition in list mode;
- To **assess the need for standardisation** of the format of data acquired in list mode;
- To **take** as much as reasonably possible common **needs of end-users into account** while drafting the standard.

1.4
Scope of the standard

The standard envisaged:

- Is a **voluntary** standard specifying the **format of list-mode data** acquired with modern digital data acquisition systems;
- Can also be used with **conventional** data acquisition systems that acquire data in list mode;
- Will contain data structures to represent **pulse waveform data** as well as data that contains **relevant information obtained from the pulses** such as pulse height and timestamp. The information can be obtained by the data acquisition hardware (firmware embedded in DSP/FPGA) or by software (instrument drivers or data analysis software).

1.5
Feedback

The survey is anonymous. However, if you choose, you can leave your e-mail address at the end of the survey if you want to be kept informed about the outcome of the survey and further developments.

2
General questions

2.1 Digital versus conventional data acquisition

Digital data acquisition uses a digitiser connected to a detector with minimum of electronics with the aim to convert the signal to a digital value as early as possible in the electronic chain, and to process the data using software algorithms.

Conventional data acquisition uses specific modular electronics for signal amplification, delay generation, gating, counting, analog-to-digital conversion, etc. Conversion to a digital value is performed as late as possible in the electronic chain.

2.1.1
How often do you use digital compared to conventional data acquisition?

I use:*

- Only conventional
- Mostly conventional, sometimes digital
- Conventional and digital about equally
- Sometimes conventional, mostly digital
- Only digital

2.1.2
To what extent do you agree that digital data acquisition has advantages over conventional data acquisition, with respect to the following aspects?

	Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree	Don't know
Digital data acquisition is faster	○	○	○	○	○
Per detector channel, digital data acquisition is less expensive	○	○	○	○	○
Per detector channel, digital data acquisition requires less space	○	○	○	○	○
Digital data acquisition is easier when signals from different detectors have to be combined for processing	○	○	○	○	○
Digital data acquisition systems have less dead time	○	○	○	○	○
Digital data acquisition systems are more reliable	○	○	○	○	○
Digital data acquisition systems are easier to use	○	○	○	○	○
Digital data acquisition systems require less effort to set up	○	○	○	○	○
Data processing is easier when using digital data acquisition systems	○	○	○	○	○
Digital data acquisition systems deal better with pulse pile up	○	○	○	○	○

2.2
Data acquisition in list mode

When data is acquired in list mode, relevant information is stored **event per event**. An event is the interaction of radiation in the detector which is observed as a pulse at the output of the detector. The information retrieved from the pulse could for example be the **pulse height** and the **timestamp**.

Note that data acquisition in list mode is possible with **both conventional electronics and digitial electronics**.

2.2.1

Do you acquire data in list mode?*

- ○ Yes
- ○ No
- ○ Don't know

2.2.1
For users of list-mode data acquisition

2.2.1.1
What is the aim of the measurement setup(s) in which you acquire data in list mode?

2.2.1.2 Why do you acquire data in list mode?
(more than one answer is possible)

- ☐ For later processing of data
- ☐ For sharing data with others
- ☐ For re-analysing data with different parameters
- ☐ To combine with data from other radiation detectors
- ☐ To combine with data from other sensors such as geolocation devices
- ☐ For quality control measures
- ☐ To optimise data acquisition times
- ☐ To enable the use of advanced processing algorithms that would otherwise require a large and complicated setup of conventional electronic modules
- ☐ For other reasons

2.2.1.3
Please specify other reasons why you use list-mode data acquisition:

2.2.1.4

When acquiring data in list mode, which of the following statements apply to your application?
(more than one answer is possible)

- ☐ List-mode data is stored on the computer that runs the data acquisition software
- ☐ After the acquisition is finished, list-mode data is copied to another computer for data analysis
- ☐ During acquisition, list-mode data is (partly) analysed on the computer that runs the data acquisition software
- ☐ During acquisition, list-mode data is streamed from the computer that runs the data acquisition software to another computer that stores the data
- ☐ During acquisition, list-mode data is streamed from the computer that runs the data acquisition software to another computer for near-real time analysis of the data.
- ☐ Other

2.2.1.5

Please comment

2.2.1.6

When acquiring data in list mode, do you use:*

- ○ Conventional electronics
- ○ Digital data acquisition systems (digitisers)
- ○ Both

2.2.2 For users not using list-mode data acquisition

2.2.2.1

Why do you **not** use data acquisition in list mode?
(more than one answer is possible)

- ☐ The equipment that I use does not allow data acquisition in list mode
- ☐ The software that I use does not allow data acquisition or processing in list mode
- ☐ In my application, there is no need for data acquisition in list mode
- ☐ Data acquisition in list mode could be useful for me, but at the moment I don't have sufficient resources to enable it
- ☐ I don't have the programming expertise to process data acquired in list mode
- ☐ For other reasons

2.2.2.2
Please specify other reasons why you don't use list-mode data acquisition:

2.3 For users of digital data acquisition systems or digitisers

2.3.1
What are your reasons to use digital data acquisition systems in stead of conventional modular electronics?

2.3.1 Information extracted by the digital data acquisition system

2.3.1.1 What type of information does the digital data acquisition system extract from the detector signal?
(more than one answer is possible)

- ☐ Distributions or histograms such as pulse height spectra or time interval distributions
- ☐ Samples describing the pulse waveform (similar as an oscilloscope)
- ☐ Certain characteristics extracted from the pulse, such as amplitude and timestamp

2.3.2 Software for data acquisition and analysis

2.3.2.1
What is the origin of the software used for list-mode data acquisition and analysis? Please select what applies.

	Data acquisition software	Data analysis software
Software provided by the hardware manufacturer	☐	☐
Commercially available, off-the-shelf software	☐	☐
Free, publically available software (shareware, open source software)	☐	☐
Custom-made software developed through outsourcing	☐	☐
Software obtained from others through collaborative projects	☐	☐
Software developed in-house	☐	☐

2.3.3
Issues with digital data acquisition

2.3.3.1 In the use of digital data acquisition, did you have issues or observed unexpected behaviour in certain conditions?
(more than one answer is possible)

- ☐ Double triggering on pulses which are higher than the input dynamic range
- ☐ Throughput issues, buffer overflow at high input count rates, gaps in the data
- ☐ Trigger issues
- ☐ Difficulties with clock synchronisation between multiple devices
- ☐ Issues matching the input dynamic range with the detector signal
- ☐ Lack of resolution with respect to pulse amplitude
- ☐ Lack of timing resolution or precision of the timestamp
- ☐ Issues with noise
- ☐ Software issues (data acquisition, drivers, ...)
- ☐ Reliability, unexpected behaviour
- ☐ Issues with signal connectors
- ☐ Issues with power connectors
- ☐ Issues with connectors for communication
- ☐ Data storage issues
- ☐ Other

2.3.3.2
Please explain other issues encountered

2.4
Standardisation of the data format for list-mode acquisition

2.4.1
With respect to standardisation of the list-mode data format, to what extent do you agree with the following statements?

	Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree	Don't know
A standard has an economic advantage for end users					
A standard provides a collaborative advantage, as data can easily be shared with others					
A standard data format will stimulate developers of analysis software					
A standard data format allows the use of equipment from different manufacturers in the same setup					
A standard data format for data acquired in list mode is needed					
A standard should be global					
A standard shall remain voluntary: manufacturers of equipment and software shall decide to adhere to the standard or not					

2.4.1 Data conversion software

2.4.1.1

Please answer the following questions concerning conversion of list-mode data to other data formats.

	Yes	No	Don't know
Do you see the need for software to convert data acquired in list mode to a standard format?	○	○	○
Did you invest in data conversion software in the past to be able to use list-mode data, by purchase, by outsourcing the development or by developing it inhouse?	○	○	○
Do you foresee to invest in software for list-mode data conversion in the future?	○	○	○

2.4.2
Streaming of list-mode data

2.4.2.1

Data streaming is the transfer of data at a steady high-speed rate, sufficient to support such applications as high-definition television. Streaming of data in list-mode can be used as a way to continuously transfer data from an acquisition system to a remote computer that processes the data.

In addition to specifying the format of **data files** to be stored on disk, should a standard data format for list-mode data include the possibility to **stream data** to remote computers?*

- ○ Yes
- ○ No
- ○ Don't know

2.4.3
Software tools

2.4.3.1
The following software tools can support the implementation of the standard.

How important is the (free) availability of these tools to you?

	Very important, is an added value, would be used regularly	Somewhat important but not required, would be used occasionally	Not very important, nice to have, don't know if it will be used	Irrelevant, would never be used	Don't know
A tool that **verifies the compliance** of a data file against the standard format	○	○	○	○	○
A tool to **generate simple test data** sets for the verification of software for list-mode data analysis	○	○	○	○	○
A tool for **visualisation and basic analysis** of list-mode data, showing for example pulse height spectra, time interval distributions and countrate	○	○	○	○	○
A tool to **convert** list-mode data files to commonly used spectral formats	○	○	○	○	○

2.4.3.2
What would you prefer as software tool for these purposes?

- ○ A web-application
- ○ A downloadable software tool
- ○ Don't know

2.5
End of the general questions

2.5.1
This is the end of the general survey. Thank you very much for participating.

In case you acquire data in list-mode with digital electronics, would you like also to answer additional, more advanced questions? Your answers are valuable, they will allow us to better address the content of the standard to your needs.*

- Yes, I want to answer the advanced questions.
- No, I would like to end the survey.

3
Advanced questions

3.1.1
Front-end electronics

3.1.1.1
Do you use additional front-end electronics inbetween the digitiser and the detector?

- Yes
- No
- Don't know

3.1.1.2
Why not? Please specify

3.1.1.3 What are your reason to use front-end electronics?
(more than one answer is possible)

- [ ] Impedance matching of the digitiser's input to the detector output
- [ ] Matching of the digitiser's input dynamic range to the output of the detector
- [ ] Anti-aliasing filtering (low-pass filtering)
- [ ] High-pass filtering
- [ ] Optimisation of the signal-to-noise ratio
- [ ] Other

3.1.1.4
Please specify

3.1.1.5
What is the origin of the front-line electronics that you use?

- Off-the-shelf
- Custom-made

3.1.2
On the digitisers used

3.1.2.1 What is the sample rate of the analog-to-digital converter of the digitiser that you typically use?

[ ] MS/s (million samples per second)

3.1.2.2
What is the number of bits provided by the analog-to-digital converter?

[ ] bits

3.1.2.3
How many input channels does the digitiser(s) have?

[ ] input channels

3.1.2.4
How many detectors do you have at maximum in one setup?

[ ] detectors

3.1.2.5 Does your digitiser provide sample processing in hardware (DSP/FPGA) in order to extract only relevant pulse characteristics in real time?

- Yes
- No
- Don't know

3.1.3
Clock synchronisation

3.1.3.1
Does your application require synchronisation of the digitiser's internal clock (used for sampling) to a master clock, enabling the same time reference for the pulse timestamps and the simultaneous start and stop of the data acquisition?

- Yes
- No
- I don't know

3.1.3.2

Does the master clock needs to be traceable to the SI unit "second", e.g. by synchronisation to a DCF-77 or GPS time receiver?

- Yes
- No
- Don't know

3.1.3.3

Could you describe how the start and stop of the data acquisition is synchronised between different digitisers?

3.1.4

Specific questions on a data format for list-mode acquisition

The following questions are very specific. Your answers will help us to define a draft for a standard data format.

3.1.4.1

In your application, what is the required time resolution for the timestamps (order of magnitude)?

- picoseconds
- nanoseconds
- microseconds
- milliseconds
- seconds
- not applicable

3.1.4.2

In your application, what is a typical data acquisition time? When a measurement is repeated over several acquisitions, please specify the typical length of a single acquisition.

- milliseconds
- seconds
- hours
- days
- months
- years

3.1.4.3 Which of the following properties extracted from pulses recorded by the hardware are relevant for you to include in the standard?

	Required	Nice to have	Not relevant	Don't know
The pulse height (related to the deposited energy)	○	○	○	○
Timestamp of the pulse	○	○	○	○
Samples integrated (summed) over a single time gate (charge integration)	○	○	○	○
Samples integrated (summed) over two time gates with different lengths (double gate charge integration allowing e.g. pulse shape discrimination)	○	○	○	○
The average baseline level before the pulse	○	○	○	○
The pulse rise time	○	○	○	○
The pulse fall time	○	○	○	○
The pulse peaking time, this is the time between the trigger and the time when the pulse reaches its maximum	○	○	○	○
The pulse width	○	○	○	○
Advanced pulse characteristics, such as the result from fitting a pulse shape function (pulse decay constant, etc.)	○	○	○	○
Information about pulse pile up	○	○	○	○
The samples integrated in the tail of the pulse, e.g. from the pulse peaking time until it reaches 10% of its height	○	○	○	○

3.1.4.4

Apart from the properties mentioned in the table above, would you need other properties to be included in the data format? Please specify.

3.1.4.5

You indicated that timestamp information is relevant. In your application, how is the timestamp typically obtained?

- ○ Timestamp corresponding to a certain threshold on the leading edge of the pulse (Leading Edge Threshold or LET)
- ○ Extrapolated Leading Edge Threshold (ELET), using two leading edge discriminators
- ○ Timestamp corresponds to the time when the leading edge of the pulse reaches a fixed (constant) fraction of the pulse height (Constant Fraction Discrimination or CFD)
- ○ Timestamp corresponding to the time the pulse has reached its maximum
- ○ Timestamp corresponding to the zero crossing of second derivative versus time of rising edge of the pulse (crossover timing)
- ○ Other

3.1.4.6

Please explain how the pulse timestamp shall be defined

3.1.4.7

How shall the pulse rise time be specified?

- ○ The time required to go from 10% to 90% of the pulse height, with respect to the baseline
- ○ The time required to reach the maximum pulse height, with respect to the trigger timestamp
- ○ Other

3.1.4.8

Please specify how the pulse rise time should be defined

3.1.4.9

How shall the pulse fall time be specified?

- ○ The time required to go from 90% to 10% of the pulse height, with respect to the baseline
- ○ The time from the pulse peaking time until 10% of the pulse height
- ○ Other

3.1.4.10

Please specify how the pulse fall time should be defined

3.1.4.11
How shall the pulse width be specified?

- The time required for the pulse from 10% of its height on the rising edge, to the time when the pulse tail falls below 10% of the pulse height
- The time from the trigger timestamp until the pulse tail falls below 10% of the pulse height
- Other

3.1.4.12
Please specify how the pulse width should be specified

3.1.4.13
Please specify which advanced pulse characteristics you would like to see included in a standard data format

4 Keep me informed

4.1
Would you like to receive feedback?

- I would like to receive the results of the survey.
- Please keep me informed about further developments.

4.2 Name*

4.3 Email*

4.4
If you have any other comments with respect to the survey, you can write them here.

Please complete the following CAPTCHA before submitting.

6. Conclusion

The objective of the survey was to identify the needs of end-users with respect to the standardisation of the format of the data delivered by digital data acquisition equipment used in radiation detection and measurement. Although the number of replies was rather limited (31), the survey clearly reached an audience with experience in digital data acquisition.

From the answers it is clear that a standard data format for list-mode data is wanted. Survey participants understand the importance of a standard. A lot of technical input was provided which will be used through the development process of a draft international standard. The survey also allowed setting up a community of interested end-users.

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