List-mode data acquisition based on digital electronics

State-of-the-art report

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List-mode data acquisition based on digital electronics State-of-the-art report

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Related Documents:
"Critical parameters and performance tests for the evaluation of digital data acquisition hardware" : in preparation.
"Critical parameters and performance tests for the evaluation of list mode data files and analysis software" : in preparation .

1 Executive summary

This report deals with digital radiation detection systems employing list-mode data collection, which improves data analysis capabilities. Future data acquisition systems shall also ultimately enable the movement of detection data from first responders electronically to analysis centres rather than the costly and time consuming process of moving experts and/or samples. This new technology is especially useful in crisis events, when time and resources are sparse and increased analysis capacity is required. In order to utilise the opportunities opened by these new technologies, the systems have to be interoperable, so that the data from each type of detector can easily be analysed by different analysis centres. Successful interoperability of the systems requires that European and/or international standards are devised for the digitised data format. The basis of such a format is a list of registered events detailing an estimate of the energy of the detected radiation, along with an accurate time-stamp for recorded events (and optionally other parameters describing each event).

The need for standardisation of list-mode data has been recognised by CEN/TC 391, which executes the Commission mandate M/487 to establish European security standards. In their final Phase 2 report addressed to the Commission, CEN/TC 391 assigned a high priority to the standardisation of list-mode data.

This report proposes a draft list-mode data format for further discussion within the standardisation community, and is therefore directly supporting a number of EU priorities as articulated in relevant policy documents, covering two interrelated goals: enhancing the EU's internal security, and facilitating the development of a single market for European security industry. Details are given in section 2.

List-mode data acquisition using digital electronics offers many advantages over traditional acquisition methods for the detection and assay of radioactivity. Recently, high-performance digital data acquisition systems have become available which provide a sufficiently high sampling rate, allowing direct digitisation of the signal, even from very fast radiation detectors. These digitisers are equipped with sophisticated firmware running real-time data reduction algorithms that extract only the relevant information contained in a detection pulse, e.g. its timestamp, pulse height and/or pulse shape properties. Without such data reduction, all signal samples need to be transferred which requires a data connection with a large throughput, and ultimately limits the maximum permissible count rate.

Even though list-mode data acquisition based on digital electronics is rapidly increasing in popularity, at present, there are no suitable standards related to list-mode data formats. This is a hindrance to enabling efficient interoperability and the "pooling of resources" to provide a rapid and robust means of analysing list-mode data sets. Some emerging radiation detector technologies actually require data to be stored in list-mode in order to optimise functionality.

There are many advantages of digital list mode data acquisition in radiation detection, which are detailed in section 2.2, including:

1. Improved radiation detection systems can be developed for nuclear security.
2. Border monitoring of nuclear materials will result in less false alarms.
3. Novel detection systems can be built based on active interrogation of the material.
4. Cross-disciplinary applications become possible.
5. Improved data analysis capabilities are possible.
6. Detection sensitivity is improved by optimizing data acquisition time .
7. Source localization in a mobile environment is more effective.

8. More robust, transparent and efficient calibration standards can be provided.
9. Quality control of the digitised data is improved.
10. Data security is improved.
11. New techniques become available for nuclear safeguards.
12. Medical Physics and basic research benefit from a standardised data management system.

This report not only provides background information on the state of the art in digital radiation detection systems employing list-mode data collection techniques, but also proposes a draft list-mode data format, providing enough information for the first steps towards its adoption as a European and International standard.

Two further reports from this ERNCIP Thematic Group will follow to provide guidelines on the testing of operational systems and instrumentation utilising list-mode data acquisition with digital electronics.

2 Introduction

ERNCIP (the European Reference Network for Critical Infrastructure Protection) has established a Thematic Group on the Protection of Critical Infrastructure from Radiological and Nuclear Threats, looking at issues such as certification of radiation detectors, standardization of deployment protocols, response procedures and communication to the public, e.g. in the event of a radioactive object being found. This report has been produced by this ERNCIP thematic group, and deals with digital radiation detection systems employing 'list-mode' data collection. In short, the question is about standardising the format that is used in saving and sending the collected data to enable further analysis. The issue is closely related to the opportunity, opened by the current developments in technology, of utilising remote support of field teams (”reachback”) in radiation detection.

Traditionally, front line officers or first responders have operated detection instruments, and if anomalous radioactivity has been detected, specialists have been invited to the field with more sophisticated equipment and know-how, or the sample has been sent off-site for further analysis.

Today it is possible for first responders to be equipped with much more elaborate spectrometers with the gathered data sent wirelessly to the analysis centre, where the experts follow the measurements in-real time and give advice accordingly. So, data moves instead of people and samples, guaranteeing a faster high quality response with less people.

Besides “normal” RN detection situations, this new technology is especially useful in crisis events, when time and resources are sparse and greater analysis capacity is required. Indeed, in principle list-mode data acquisition allows a smooth cross-border cooperation and resource pooling in radiation detection. In order to utilise the opportunities opened by new technologies, however, the systems have to be interoperable, so that the data of each type of detector can easily be analysed in different analysis centres. The interoperability of the systems requires European/international standards for the digitalised data format, along with protocols enabling efficient data exchange.

This report not only discusses the issue and provides background information, but it is also proposing a draft list-mode data format for further discussion within the standardisation community, directly supporting priorities of the EU as articulated in policy documents, covering two interrelated goals: enhancing the EU's internal security, and facilitating the development of a single market for European security industry. The first goal is most notably expressed in the EU Internal Security Strategy in Action, which gives attention to the need to enhance capabilities against CBRNE (chemical, biological, radiological, nuclear, explosives) threats, including developing minimum detection and sampling standards [COM(2010) 673 final: Action 2], and more explicitly elaborated in the CBRN Action Plan which details detection as one of the priorities [COM(2009) 273 final: Section 4.5]. The latter goal in turn is expressed in the EU Security Industrial Policy Action Plan [COM/2012/0417 final: Section 4.1.1. Action 1], which concludes that the European security industry suffers from market fragmentation, and in order to overcome this and move closer to a single market it necessitates European-wide standardisation of, and certification scheme for, security products. To this effect, the work underway in the framework of the European Standardisation Organisations (ESOs), under the banner of DG Enterprise and Industry's Mandate 487 (M487), is aimed at leading towards more harmonised European security standards. In the preparatory work under the Phase 2 and its CBRNE part, the task to standardise the data format for list-mode data acquisition is highly prioritised.

The European Commission's "Action Plan for an innovative and competitive Security Industry" [COM/2012/0417] is aimed at strengthening CBRN security in the European Union by reducing the threat of and damage from CBRN incidents of accidental, natural or intentional origin, including acts of terrorism. The Action Plan identified that one of the main issues facing the EU security industry is its highly fragmented nature, exhibiting a lack of standardization and harmonised certification procedures.

As a direct response, a new ERNCIP Thematic Group on the Protection of Critical Infrastructure from Radiological and Nuclear Threats (RN TG) was instigated to identify and work on currently unaddressed Critical Infrastructure Protection (CIP) issues, such as certification of radiation detectors, standardization of deployment protocols and response procedures.

Given the short time-frame for this work, and after consultation with ERNCIP, the RN TG is focussing on three subjects, with dedicated tasks related to each. Full details of the remit and tasks of the RN TG are available in the Work Programme of the RN TG.

Task 1 : List-mode data acquisition based on digital electronics
Task 2 : Remote expert support of field teams
Task 3 : Remote controlled radiation measurements and sampling using unmanned vehicles

The current report addresses the first of these tasks, related to list-mode data acquisition, and analyses the state of the art for digital data acquisition devices for radiation detection systems, particularly those used in list-mode. Digitised pulses from radiation detectors are analysed to provide spectral information for radionuclide identification purposes, as well as temporal information (time-stamps) and optional parameters describing each pulse. Such a scheme enables the development and enhancement of a variety of novel techniques for the accurate assay of radionuclides and nuclear material. A series of critical parameters enabling cost-effective and efficient implementation of analysis of list-mode data records are identified.

As incorrect decisions based on collected data could prove costly in many ways, data collection in list-mode (with suitable data compression in a "standardised" data format) facilitates more robust and "transparent" assay: i.e.: the data may be readily exported electronically, allowing analysis to be scrutinised and confirmed by "off-site" experts, providing "near real-time" decisions away from the site of measurement. Such remote expert support of field teams in being addressed in the second task of the RN TG and the current report provides critical information required to be addressed therein.

Finally, the RN TG will incorporate the information collated from Tasks 1 and 2 in order to realise Task 3.

This report also provides information for the provision of a possible future standardization of such data formats, and a preliminary draft standard data format is proposed. The content and detailed structure of the data headers and data blocks are defined and documented. This draft data format aims to not only address the requirements of CIP related radiological and nuclear threats, but to contain suitable information so the standard format may also be adopted in a variety of interdisciplinary applications, including: nuclear security, border monitoring of nuclear materials, active interrogation of suspected nuclear material, source localisation measurements, provision of radioactive calibration standards, nuclear safeguards and medical physics.

2.1 History of list-mode data acquisition

Acquisition of data in list mode has been performed since the mid-1980s (e.g. [ACH, 1985], [NAG, 1985], [GOL, 1986], [HOL, 1985]). For many years list mode data has been acquired using conventional analog electronic modules: i.e.: values from analog to digital converters (ADCs) are stored together with a timestamp of the event (or time-of-flight of the particle), obtained (for example) by using time-to-amplitude converters and additional ADCs.

Around the year 2000, digitiser systems were introduced on the market with the ability to sample the signals directly from the output of the detector (pre-amplifier or photo-multiplier), albeit at a rather limited sampling rate of a few tens of MHz, making them unsuitable for direct use with fast detectors such as liquid scintillators. Even today, conventional analog electronics are used in roughly 90% of publications related to applications citing list-mode data acquisition. However, a rapid increase in the use of digitisers is being initiated, as can be observed from Figure 1.

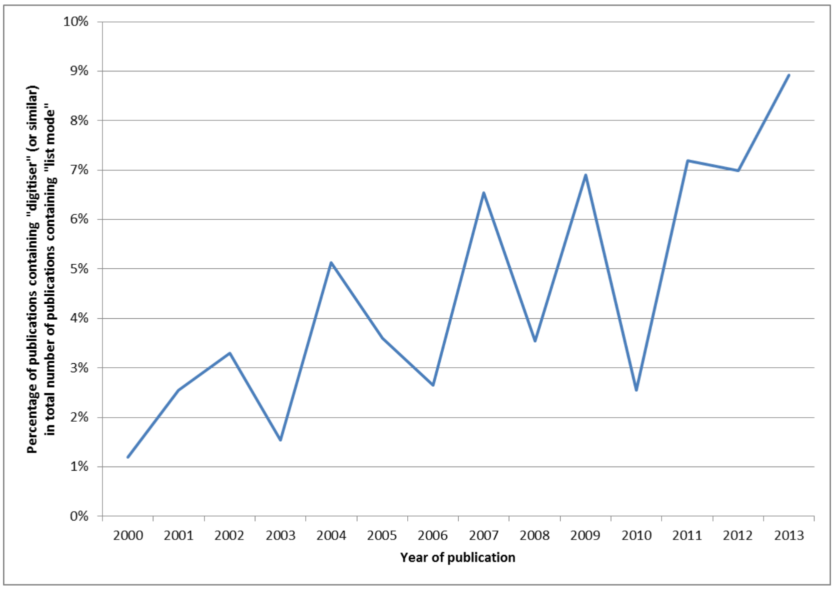

Figure 1: Number of publications on ScienceDirect with the search term "list mode" AND (digitiser OR digitizer OR FPGA OR DSP) with respect to number of publications found with search terms "list mode" alone.

The reason for this rapid increase is that it is only in recent years that digitisers exhibiting sampling rates from 500 MS/s up to about 5 GS/s have become available. To improve the effective information throughput to the host computer, recent digitisers use Digital Signal Processors (DSPs) and Field Programmable Gate Arrays (FPGAs) equipped with algorithms for data reduction which are embedded in the digitiser's firmware (software describing logic operations and embedded in hardware). Different types of data reduction algorithms can be utilised, depending on the type of radiation detector being used. The algorithms are designed to retain only the valuable information contained in a pulse acquired when a particle or photon is detected, and rejecting the uninteresting voltage signals between recorded events, thereby dramatically increasing the pulse rate that the detector system can cope with, up to over 1 million pulses per second [PAE, 2014].

2.2 Applications and advantages of list-mode data

The power of appropriate data storage in "list-mode" cannot be underestimated, as not only does this facilitate easier (and more time-efficient) data collection, but it provides a mechanism for enabling more robust and transparent detection and measurement of radioactivity: where not only the estimate of the activity is provided, but also the data-set employed in the construction of this estimate. This allows external and independent verification of the calculations employed.

Timestamp based digital data acquisition also paves the way for designing novel data acquisition equipment. These new detection systems can be much simpler and smaller than traditional hardware solutions (without a loss of precision) and are thus well-suited for both laboratory services and in-field applications. The small footprint, and thus portability, of timestamp-based digital data acquisition systems make them ideal candidates for use in a variety of radiation measurement methods in the nuclear security sector, ranging from the deployment of large detector arrays for in-situ sample measurements to the screening of vehicles at major public events.

Some recent developments and advantages of the digital list-mode approach are listed below:

2.2.1 Improved radiation detection systems can be developed for nuclear security

In nuclear security, the detection of illicit trafficking of nuclear material (particularly plutonium) is at present based on the use of ^{3}He detectors for the detection of the characteristic neutron emanations in radiation portal monitoring systems. The recent significant increase in the demand for instrumentation related to nuclear security, coupled to the reduced production of nuclear weapons, has created an issue with ^{3}He detector supply from manufacturers, leading to an associated exponential price increase. Recent research into alternative detection systems based on technologies different to ^{3}He [PER, 2013] has given preliminary indications that some novel and promising alternatives to the use of ^{3}He may be employed to guarantee the availability of detection systems for nuclear security.

Furthermore, the European FP7-SECURITY project 'SCINTILLA' (Scintillation Detectors And New Technologies For Nuclear Security) [SCI], [PAE, 2014], is compiling a comprehensive toolbox of innovative radiation detection technologies to improve upon the capabilities of ^{3}He devices in order to develop reliable, portable, mobile and cost-effective solutions to the ^{3}He supply issue, as well as addressing the challenges associated with masked/shielded nuclear materials. The following technologies are being investigated: neutron detectors based on plastic scintillators with pulse shape discrimination, $^{6}LiZnS$, Gd-lined plastic detectors, gamma detectors based on scintillating plastic, NaI crystals, Miniature CZT semiconductors and CZT Imaging arrays. An important aspect of the SCINTILLA project is the proposal of a communication protocol to enable the detectors and detection systems to be rapidly integrated into sub-systems in real-life conditions.

The feasibility of gamma-ray Compton imaging with a segmented coaxial high purity germanium (HPGe) detector has been demonstrated by [NIE, 2005]. Critical to the operation of this system is the employment of digital pulse-shape analysis, which enables the imaging of gamma-rays in 4π steradians without employing a collimator system. In addition to the 4π imaging capability, such a system is characterized by its excellent energy resolution and can be implemented in any size possible for Ge detectors to achieve high efficiency.

In the last 10 years a large number of new high light-yield scintillator materials have been discovered. The first and the most famous among them, the Lanthanum Halides, were already the target of an intense R&D, which provided the starting point for the design and development of several new high performance LaBr3:Ce/LaCl3:Ce based detector arrays. A suite of 'new' detector technologies and systems are currently emerging: Within the ERA-NET project GANAS one is investigating a series of new materials and ideas for gamma and particle detection.
http://www.iem.cfmac.csic.es/departamentos/nuclear/GANASwebpage/html/

- $CeBr_3$, for room temperature, high resolution gamma-ray spectrometry which features an energy resolution slightly worse than that of LaBr3:Ce, but has no internal activity [GUS, 2010];
- SrI_2, as a high performance (linearity and brightness) scintillator material for radiation detection with better energy resolution than $LaBr_3$:Ce detectors [CHE, 2009];
- CLYC crystals, with a high cross section for neutrons, where pulse shape discrimination techniques can identify gamma radiation, fast and slow neutrons and determine an estimate of the neutron kinetic energy.

Many high light-yield materials are currently being investigated for use in the homeland security sector (among others), but require intense R&D activities in order to fully characterise their properties. These include: elpasolite scintillators: CLLB ($Cs_2LiLaBr_6$:Ce) and CLYC (Cs_2LiYCl_6:Ce). And especially CYGAG:Ce, a transparent ceramic material exhibiting promising scintillation properties and offering the advantages in terms of chemical stability and robustness that a ceramic can offer with respect to an inorganic crystal.

By combining two or more scintillator materials (Phoswich configuration) in a single compact detector, new features may be obtained. For example, direct digitisation of the signals from the scintillators, and storage of appropriate information in list-mode, enables an off-line pulse-shape analysis regime to fully identify the incoming radiation, based on either a *total to tail* or a *total to pulse height* method [TEN, 2013]. Furthermore, the combination of two materials of different characteristics can be a cost effective way of detecting gamma, particles and neutron radiation with the same detector. The combination of materials and segmentation of the crystals gives also new imaging features that can help in detecting the angle of impact and thus the direction of the source relative to the detector

In general the use of digital signal processing (and associated list-mode data storage) fin combination to these novel detectors is a critical component to fully take advantage of the sensitivity to both gamma and neutron radiation as well as to take advantage of the imaging possibilities combining different materials in one detector.

For example, CLYC is sensitive to both neutrons and gamma rays, and exhibits improved energy resolution for gamma-rays than conventional NaI detectors. For optimal operation, CLYC requires the use of pulse shape discrimination algorithms, and storage of the data as trace/wave forms is not feasible due to the vast amounts of data to be logged. On-line analysis algorithms are planned to be implemented into FPGAs, and in order to adequately describe the incoming detector signal.

Due to the "atmosphere of silence" surrounding security applications, a comprehensive list of publications related to the use of list-mode data acquisition is difficult to compile. However, it is expected that the application of list-mode in nuclear security will only increase in the near future, as novel detector systems are developed and their capabilities investigated.

2.2.2 Border monitoring of nuclear materials will result in less false alarms

Current neutron counting systems exhibit an inherent problem of yielding too many (costly) false alarms. The reason for these ‘spikes’ in count-rate is well understood (due to the effects of cosmic ray showers on the detector systems and surrounding materials, where many counts are recorded in a short time interval of ~ 0.1 seconds). In existing systems, where an integral count over a larger time period is recorded, the observed average count rate is thus elevated yielding a “false alarm”. These artefacts can be readily identified, and consequently rejected, by list mode data acquisition systems, without compromising the remaining valid data set.

2.2.3 Novel detection systems can be built based on active interrogation of the material

Shielded Special Nuclear Materials (SNM) are a challenge to detect via passive means, where detection is based on the radioactive emanations from the material itself. Using an external source of radiation, typically a compact, commercial off-the-shelf electronic neutron generator, to interrogate such targets, fission may be induced if fissile material is present. These fission signatures, for example prompt or delayed fission gammas, or prompt or delayed fission neutrons, may be then detected by appropriate detector systems capable of discerning the fission signature from the interrogating radiation and other backgrounds [GEN, 2012]. For the optimal performance of such devices data will need to be collected in list-mode [YAN, 2009]. Note that such active techniques can also be used for the detection drugs, explosives etc.

Active neutron interrogation systems can detect small targets (< 1 kg) of special nuclear material contraband, such as highly enriched uranium (HEU) or Pu in cargo containers, even when well shielded by thick cargo. These systems utilise the stimulated high-energy (3-10 MeV) γ-ray emissions which are well separated from the normal background radiation γ-ray emissions, and readily penetrate a thick mixture of low-Z and high-Z cargo [SLA, 2003].

2.2.4 Cross disciplinary applications become possible

Different sensors, for example optical and nuclear detectors can work together in coincidence mode which provides new possibilities to build enhanced security systems. The list-mode approach provides a technical means to build simpler data acquisition systems, with the burden transferred from equipment to software.

2.2.5 Improved data analysis capabilities are possible

For reachback (remote support) centres to provide effective support to field teams and first responders, efficient and well-defined data communication protocols are mandatory, in order to provide the data in a timely and transparent fashion. A comprehensive reachback system can provide automatic data analysis on a large amount of data, with human intervention and analysis of the data also possible. Such a scheme can provide timely feedback to the first responders for correct response, including a graded approach based on consequence analysis [SNI, 2013].

Present in-field measurements are based on analysis of spectra gathered in short time intervals, on the order of a few seconds. However, a much more efficient system can be created if the basic product is a list of events rather than a spectrum acquired at certain intervals. Remote analysis of the acquired list-mode data removes analysis burden from the field personnel and has several other advantages:

- False data can be removed (acoustic disturbances);
- Different dead times can be imposed (assess the effect);
- Delays between signals from different detectors can be taken into account;
- Effect of different coincidence resolving times can be assessed;
- Coincidence and anticoincidence measurements on same data can be performed.

2.2.6 Detection sensitivity is improved by optimizing data acquisition time

The present in-field systems exhibit a serious operational problem – the selection of suitable data acquisition times. To achieve adequate precision based on counting statistics, data collection times must be sufficiently long. However, in the field, rapidly changing levels of radioactive contamination are to be expected, yielding a requirement for short counting intervals to enable effective localisation of the target. As the exact location of the target and associated count rates are unknown prior to the detection process, it is impossible to set the optimal data acquisition time beforehand.

The application of the list-mode approach to data acquisition essentially solves this dilemma, with the optimized detection capability now possible via employment of advanced on-line and off-line analysis algorithms, employing parallel data analysis routines with differing data acquisition times.

2.2.7 Source localization in a mobile environment is more effective

Source localization is a difficult problem in nuclear security. In the presence of elevated count rates, the detector may give an alarm but it gives no hint from which direction the signal emanated. The problem is particularly difficult, if the detection system or the target, or both, are moving fast. The list mode data acquisition approach provides data in a format which will enable a solution to the problem.

2.2.8 More robust, transparent and efficient calibration standards can be provided

The primary standardisation of radioactivity, and associated nuclear data measurements, benefits greatly from data acquired in list-mode. Acquired data can be verified against theoretical models, improving the reliability of the measurement result [KEI, 2002]. From the analysis of time-interval distributions, perturbations from the random (or Poisson) nature of the inter-arrival times of events due to effects like detector dead times and 'nuisance' effects like detector 'after-pulsing' can be verified and corrected for. Digital coincidence counting has been employed for precision activity measurements employing the $4\pi\beta-\gamma$ coincidence technique since 1998 [BUC, 1998] and [BUT, 2000], and is rapidly becoming commonplace: for example [KEI, 2007], [BOB, 2012], [KAW, 2012], [KAW, 2013] and [MIN, 2013].

In the different applications of digital coincidence counting (and its variants), processing of data acquired in list mode allows the assessment of the effects of imposition of different types and lengths of dead time. Data from the different detectors can be readily aligned in time, and the coincidence resolving time can be optimised. In addition, many conditions can be imposed e.g. efficiency monitoring for various decay paths via imposition of multiple energy windows, without requiring data re-collection.

In nuclear data measurements, list-mode data makes is easier to determine half-lives and emission probabilities of short lived nuclides, in particular when there is a complex decay scheme.

2.2.9 Quality control of the digitised data is improved

List-mode data acquisition provides an easy way to check that the data has arrived as expected. Sometimes, particularly in mobile systems, the acquired spectra are corrupted by noise caused by acoustic disturbances (for example, in HPGe detector systems). These false counts can be easily filtered out from the list-mode data. In gamma and alpha spectrometry, list-mode data is used for coincidence measurements, for correcting gain drifts [POM, 2004], [TOR, 2005] and for improvement of spectral quality via Compton suppression.

2.2.10 Data security is improved

Some laboratories perform high-security tasks for national or international purposes. It is utmost important to protect their counting systems against any tampering. List mode data acquisition is inherently more secure than traditional data acquisition based on spectral collection only; the data themselves (and associated inter-event arrival time distributions) reveal any short-term 'spoofing'.

2.2.11 New techniques become available for nuclear safeguards

In nuclear safeguards, several tens of ^{3}He neutron detectors are typically placed around the object to be measured (fuel element, waste drum, etc. emitting a group of fast neutrons for every fission). ^{3}He detectors are placed in moderators as they are only sensitive to thermalized neutrons. Typically, every detector's pre-amplifier has only one digital output (e.g. TTL or NIM pulse). Signals from all detectors are logically OR-ed to one digital pulse train. Dedicated hardware based on shift-register logic is being used already for decades. There is a tendency to sample the signals from the individual outputs of the preamplifiers, so that a timestamp can be associated with a detector number. When a neutron has been detected, the detector number and timestamp is stored in a list-mode format for processing, offering many advantages [RID, 2014], [WEN, 2013], [HEN, 2012], [BAG, 2009]. Another tendency is the replacement of ^{3}He detectors by less scarce alternatives, e.g. plastic or liquid scintillators which are made sensitive to neutrons. These detectors are then sensitive to both gamma and neutron radiation. A discrimination technique is required to separate the signals from gammas and neutrons. Recent, fast digitisers with on-board pulse processing have embedded firmware for pulse shape discrimination. The recorded information for each event contains the timestamp and the type of radiation, or some kind of characteristic of the shape of the pulse waveform that allows discrimination. The gamma energy and sometimes information about the neutron energy is also stored.

It is foreseen that in future safeguards instrumentation, e.g. in the neutron multiplicity counting and passive tomography of spent nuclear fuel, list-mode data acquisition will also play a major role.

2.2.12 Medical Physics and basic research benefit from a standardised data management system

For PET (positron emission tomography), list-mode data is extensively being used for image reconstruction. Typical detectors used are fast scintillators, placed in a ring with a diameter of about 1 m. Main issues are the high count rate and dead-time losses due to pile-up, requiring the use of more detectors (even several hundreds). The use of photomultiplier tubes is still dominant but is expected to be gradually phased out in favour of APD (avalanche photodiodes) and SiPM (silicon photomultiplier) devices. The list-mode data typically contains energy, timestamp and the detector channel number.

In ion beam analysis techniques, like PIXE, the X and Y coordinates of the beam are recorded, together with the pulse height of the detected X-ray, photon or particle, allowing reconstruction of the elemental map of the sample.

In basic research (especially nuclear and particle physics) the combination of different detectors, often of very high segmentation leads to a vast number of read out channels. The physics events and especially coincidences between detector of interest are not known in advance why the data has to be stored for off-line analysis. The data rate is generally very high and the amount of data to be stored is enormous. Many groups from different countries and institutes are collaborating and everyone wants to take part in the analysis of the data. The data thus has to be available over the borders. This leads to that a standardized data handling and management system is of outmost importance. The CERN solution for the global data handling is the GRID (http://wlcg.web.cern.ch/).

2.2.13 List mode data acquisition provides substantial technological advantages over conventional detection systems

Recent advances in digital signal processing capabilities enables significant progress in the development of robust radiation detection systems, with a multitude of advantages over conventional systems, including:

- Reduction of the amount of equipment (and cost) in a detector system.
- Increased portability of detector systems.
- Less maintenance and setup-time required, enabling end users to rapidly setup complicated radiation detection systems.
- Storage of data acquired at an earlier stage in the detector chain for later referral.
- Diagnostic tools to check the quality of the data, e.g. pickup of repetitive signals or after pulses can be easily detected by means of time interval distribution.
- Corrections for detector drift during measurement periods are possible, leading to improved energy resolution in spectral analyses [POM, 2004].
- Calibration exercises with carefully prepared reference standards are expensive and time-consuming. If the calibration data are recorded in list-mode, it is possible to create, retrospectively, the calibration curve for any combination of detector channels [BAG, 2009].
- More reliable. Dead-time losses on singles, doubles and triples in passive neutron coincidence counting can be estimated better.
- Allows precise time synchronization of multiple detectors enabling, for example, simultaneous singles and coincidence spectrometry.

3 Challenges for digital data acquisition in list mode

Although the advantages of data collection in list mode are numerous, there are a few issues which have hindered the universal adoption of the technique.

3.1 High count rates create data throughput and storage issues

Even with data reduction algorithms, the amount of data to be transferred from the data acquisition system to the analysis or storage system can be large, limiting the maximum count rate the system can cope with. This could be an issue for security applications, where large detectors are used and large count rates can be expected. The performance and achievable data throughput of digital data acquisition systems is increasing, but nevertheless they should be equipped with a system that detects and indicates full-memory conditions in case data throughput limits are reached.

3.2 More efforts in software development are required for data analysis

The use of digital list-mode data acquisition opens up new applications and provides better use of the available information acquired. These advantages require essential additional effort in providing analysis software and routines.

3.3 There is no standard format for data acquired in list mode

The lack of a standard list-mode data format is hindering the development of data acquisition and analysis software, as well as the exchange of data and the development of data acquisition hardware. The development of such a standard data format will benefit all measurement laboratories immensely, as analysis code re-use and data sharing will be facilitated, as will international efforts to collaborate on pulse characterisation algorithms.

4 State-of-the-art of knowledge and critical parameters

The analog to digital conversion process always contains imperfections, with errors introduced by the sampling frequency and the number of bits of ADC resolution. As mentioned before, continuous storage of the entire ADC data stream is impractical, and above certain count-rates even impossible. Currently used state-of-the-art digitisers employing list-mode data storage are capable of on-line signal processing, greatly reducing data stream sizes and increasing data throughput rates. Such processing is typically performed via programmable FPGAs (Field-Programmable Gate Arrays) which can provide on-line and real time data compression (by only recording certain parameters of interest for each event) as well as digital filtration of the input signals to improve estimates of pulse heights, pulse arrival times, and pulse shape parameters. Algorithms are also employed to provide recognition of piled-up events, automatic baseline subtraction etc., and pulse shape discrimination. The FPGA may also impose some band-pass filtration to remove artefacts of certain frequencies.

Several algorithms for such data reduction are currently in use, and the development of new algorithms is a growing field. Some commonly used digital filter designs [CAE, 2011] include:

- Charge Integration

  When the (pre) amplification of pulses prior to digitisation is such that the shape of the detector signal is unchanged, the energy information may be represented by the area below the pulse. Charge integration requires a gate signal to define the integrating window. In some applications the expected arrival time of events is known in advance (most likely in beam experiments) and the gate is readily provided by the system. In radioactivity measurements, with exponentially distributed random pulse inter-arrivals, this is not the case, and it is necessary to generate the gate from the detector signals themselves. This involves splitting the signal, with one branch sent to a discriminator to provide a logic gate, the original signal is delayed to align the timing of the gate and the signal pulse. The use of coincidence logic provides the pulse integration.

- Double gate charge integration

  If the signal is the convolution of two exponentially decaying components, with different time constants, then the ratio between the fast and the slow components gives information about the type of the particle that produced the pulse. Such a technique is commonly used for gamma-ray and neutron discrimination in certain detector types, and is effectively a form of pulse shape discrimination.

- Pulse height analysis

  Such a digital filter is the digital equivalent of a pulse shaping amplifier and peak sensing ADC. A commonly used approach to estimating the pulse height is the trapezoidal filter [JOR, 1994], where the input exponentially decaying signal is transformed into a trapezoid that presents a flat top whose height is proportional to the energy released by the particle in the detector. A long trapezoidal shaping time gives better energy resolution but increases the probability of pulse pile-up. The digitiser is AC-coupled with respect to the output of the preamplifier, thus removing any input “baseline”.

- Zero length encoding

  The zero length encoding algorithm provides a means to transfer only the waveforms of pulses of interest. The algorithm continuously calculates the signal baseline and evaluates given trigger conditions, (signal thresholds and timing conditions). When trigger conditions are fulfilled, all samples describing the pulse of interest, but also some samples before and after the pulse, are transferred to the host PC.

- Time stamp generation by cross-over timing

  The input pulse is transformed into a bipolar signal (by effectively differentiating the signal) and the zero crossing determines the arrival time, which is independent by the pulse amplitude. The timing resolution is affected by the sampling rate of the ADC, by the number of bits and the slope near the zero crossing point. In order to increase the timing resolution beyond the granularity given by the sampling clock of the ADC, it is necessary to use two or more samples around the zero crossing and perform an interpolation.

Some manufactures provide list mode data files in an ASCII text format, while others provide a more compact binary format. However, the superiority of the binary format relies not only on the (typically) smaller data size, but on the fact that each data record has a pre-defined byte-size, thus facilitating an efficient means of reading large “chunks” of data into memory buffers using optimised low-level read routines from a suitable programming language. Experiments performed within the RN TG demonstrated that reading and analysis of large ASCII data files can take an order of magnitude longer to process than for a well-defined binary file containing exactly the same information.

4.1 Critical parameters related to the digitisation process

4.1.1 ADC sampling rate

An ideal digitiser will operate as close as possible to the detector, with minimal distortions to the input signal. The ADC sampling frequency must be large enough to provide an accurate representation of the input pulse. Sampling frequencies of the order of one or two GS/s are adequate for pulses from photomultiplier tubes (PMTs) used with liquid or plastic scintillators, which have pulse rise-times of a few nanoseconds, typically. However, the pulse rise-time of newly developed alternatives for PMTs, like avalanche photodiodes (APDs) or silicon photomultipliers (SiPM, an array of APDs on common silicon substrate) are shorter, requiring a higher sampling rate. Current state-of-the art digitizers are available with sampling rates up to 5 GS/s.

4.1.2 Data throughput

Depending on the application, different types of detectors with different volumes are used, resulting in a large variation of input event rates, from a few events per second to millions of events per second. The limitations on data throughput of digitizers can be an issue for large event rates. The data throughput can be limited by pre-processing the pulse in hardware/firmware, and by only transferring the values of interest characterising the pulse, e.g. the timestamp associated to the detected event, and the pulse height. For non-integrating detector electronics, firmware providing charge integration in one or more gates can be used, as described above. Two gates are used to perform real-time pulse shape discrimination on detectors that produce a different pulse shape for different types of radiation, e.g. neutron and gamma. More advanced pre-processing could also yield the pulse rise-time, pulse height, fall-time (short and long component), baseline before the pulse, total pulse area, tail area, etc. Rudimentary (and unpublished) tests on a commercially available digitiser system performed as part of this RN TG task revealed that the maximum throughput of the proprietary optical connection was lower than was achieved via a USB 2 interface. Although this observation needs further investigation, it highlights the need to be careful with the interpretation of the manufacturers claimed maximum data throughputs. The required throughput should be evaluated in the function of the application.

4.1.3 Full buffer

The rate at which the digital acquisition (DAQ) software reads data from the digitizer buffer shall always be larger than the rate at which the buffer is filled. In the event that the DAQ software cannot empty the digitizer buffer in time, data will be lost or the acquisition will be stopped. If the user chooses to continue acquiring data, a special flag should be set and written to the list-mode file to indicate that there will be a gap in the data acquisition. During the gap, the clock used for time-stamping the events shall continue to run, so that time information of pulses after the gap is not lost.

4.1.4 Synchronization

Synchronization of clocks between different digitizers is required in case of multiple detectors or other synchronized equipment such as pulsed neutron or gamma generators. The required precision of the clock synchronization depends on the application (e.g. type of detector) and the way the data will be processed. Apart from the synchronization of the clocks, all timestamps should relate to the same absolute time.

4.1.5 Recording logic signals

In some applications, it is necessary to record the timestamps associated with transitions of logic signals from an external source. Signals could be TTL, NIM, (or others) and originate from equipment used in the measurement setup, like measurement enable signals, signals from occupancy sensors, beam on/off signals, trigger signals, etc. For these applications, the digitizer shall be able to record these transitions, e.g. detect the rising and/or falling edges of a TTL signal, or the rising edge and the pulse duration.

4.1.6 Deadtime

A clear description is required of how the digitizer deals with deadtime (the time that the system is busy processing the event), or how it achieves "deadtime-less" acquisition. For deadtime-less systems, the elimination of dead-time should not influence other parameters.

4.1.7 Timestamps

It shall be clearly described how the timestamp is derived from the pulse. The information shall be included in the recorded file header. Several options are possible, e.g.:

- corresponding to a certain threshold on the pulse
- corresponding to the time the pulse has reached its maximum
- corresponding to zero-crossing of second derivative versus time of rising edge of the pulse
- corresponding to time obtained via constant fraction discrimination algorithms

4.1.8 Pulse pile-up

It shall be clearly described how the hardware deals with pulse pile-up, along with any limitations of the algorithms used. Depending on the time between the pulses, different cases can occur (for two pulses):

- Both pulses can be processed correctly (second pulse residing on the tail of the first). All information can be obtained, but some characteristics might not be reliable, such as the height of the second pulse, due to the fact that it is sitting on a tail, and due to the changing baseline.
- Correct processing is not possible, but the pile-up can still be detected.
- In all cases, a special pile-up flag shall indicate what type of pile-up has been detected so that data processing algorithms can properly deal with pulse pile-up.

4.1.9 Reliability

Data and power connections are preferably realised with connectors that can be secured with one or more screws to avoid accidental loss of the connection. Pulling a cable should not result in loss of communication nor power. A reliable connection is especially important (for safety reasons) in modules that have a build-in high voltage generator to bias the detector or photomultiplier.

4.1.10 Operation in the field

The performance of digitizers in rough environmental conditions is an important parameter to be evaluated. This includes shock resistance, relative humidity, extreme temperature and barometric pressure conditions. In addition, low power consumption and the possibility to run the equipment on battery power is essential for applications using remotely controlled vehicles. It is important for in-field applications (particularly related to data transfer to remote locations for detailed analysis, or *reachback*) that the digitiser can provide measurement files in intervals of (say) one second. In addition, such data must contain supporting relevant information related to the sampling conditions.

This system of data storage will be discussed in detail in a subsequent report from the ERNCIP RN TG, under Task 2 “Remote Expert Support of Field Teams”.

4.1.11 User friendliness

Although difficult to define, the operation of digitizers and the data acquisition software, including the ease of data exchange between data acquisition and analysis software shall be addressed.

4.1.12 Built-in quality control and quality assurance

Apart from the above mentioned requirements related to performance and reliability, it shall be possible to link the generated list-mode data file to quality management tools. A convenient solution is to include one unique identifier in the list-file header, coming from a management tool database. Quality management tools should be sufficiently flexible to generate these identifiers and to include tables that link the list-file to other tables describing the measurement setup, detectors used, measurement conditions, calibration data, and other "metadata". Further information is available in Appendix 1 of this report.

4.1.13 Cost

The cost per channel versus size, weight and performance is a useful property for the evaluation of digitizers, and should always be kept in mind.

4.2 Critical parameters related to the data format

The header shall include a field with variable length that can be used freely to store any user-defined information. The format of the content of this field will not be standardised. The header format itself should be allowed to evolve in future incarnations.

Note that some metadata may change during the course of the data analysis (such as the location of a detector via GPS coordinate logging). The sampling rate of the radiation detector is typically of the order of (say) 100 MSPS to 1 GSPS. However, the logging of detector location/s may be only required at an interval of (say) 1 per second.

In security arrangements, gamma spectra would probably be automatically generated and analyzed approximately once per second together with appropriate QA/QC measures, and the data formats required would need to facilitate an easy means of fetching or directly outputting such data sets.

Concerning the event data format (data block part of the file) it was concluded that recording entire pulse traces is too memory-consuming for such a scheme to be currently recommended for CIP routine use. Therefore, developing on-line analysis and data reduction in FPGA firmware is important. Such parameterized information would then be streamed to computer memory, as noted earlier.

Possible (but not compulsory) parameters that should preferably be extracted on-line by the FPGA are (16 bit/param):

1. pulse height
2. risetime

3. fall time fast
4. fall time slow
5. baseline
6. total area
7. tail area

5 Standardisation of list-mode data formats

At the expense of the advantages of digital data acquisition in list mode is the increased need for data analysis software. Many users currently develop their own software or use open-source software. There is a clear need for software tools capable of handling large list-mode data files. However, list-mode data is stored in different manufacturer and user specific formats, hindering data sharing between users and processing by different software packages. A standardised format for list-mode data would reduce these limitations and stimulate manufacturers of data acquisition systems and analysis software. The RN TG has discussed at length (both internally and externally) the relative merits of liaising with the European and/or international standardisation bodies, in order to facilitate the rapid introduction of an appropriate European standard to address these issues.

5.1 The European and international scene

On the global scale, IEC/SC 45B is the main provider of standards that address instrumentation used for the measurement of ionizing radiation in the workplace, to the public, and in the environment for radiation protection purposes; for illicit trafficking detection and identification of radionuclides and for radiation-based security screening [IEC].

ISO is more related to standardisation of methods, while IEC is more focussed on equipment. The complementing committee to IEC/SC 45B is ISO/TC 85 - Nuclear energy, nuclear technologies, and radiological protection. In 2012, IEC/SC 45B published IEC 62755 "Data format for radiation instruments used in the detection of illicit trafficking of radioactive materials". This is a standard based on the XML format, and already widely used, especially within the U.S. due to the fact that this standard is identical to the ANSI N42.42. However, also in Europe this standard gains importance. For example, it has been picked up by manufacturers of digitizers, who now make their software compatible with this standard.

On the European scale, CENELEC/TC 45B adopts IEC/SC 45B standards as European Standards on a case by case basis, with or without common modifications, that address instrumentation used for [CEN]:

- the measurement of ionizing radiation in the workplace, to the public, and in the environment for radiation protection purposes;
- illicit trafficking detection and identification of radionuclides;
- ionizing radiation-based security screening;
- industrial and commercial uses of ionizing radiation nuclear technology.

The scopes of IEC/SC 45B and CENELEC/TC 45B are almost identical and in line with most of the fields of applications of list-mode data, excluding medical physics. For this reason it is deemed reasonable to leave the PET application (Section 2.2.12) of list-mode data out of the scope. The remaining scope fits well with the needs identified by CEN TC/391'Societal and Citizen Security' in mandate M/487 [M487].

CEN/CENELEC will not normally start the development of a new standard when there is an international standard (ISO/IEC) that addresses the need of the European market. In order to create impact at European scale, the development of a standard for list-mode data should be considered at the level of the IEC, automatically resulting in a global impact and a European impact when CEN/CENELEC later endorses the standard as European Standard.

5.2 How to proceed

The development of a standard for list-mode data has already been informally discussed at the preliminary stage with the IEC/SC 45B secretary and chairman, the IEC/SB 45B/WG B15 convenor and the IEC/TC 45/WG 9 convenor during the TC 45 meetings in Moscow, June 2013. Since the scope of the standard is more related to the scope of WG 9 than to WG B15, a proposal for standardisation was presented to WG 9, whose national representatives were in favour. It should be made clear that this is only a preliminary and unofficial agreement. Nevertheless, the chances are high that an official voting will yield at least the required 5 positive votes by the committee P-members.

To initiate the development of a new IEC standard, a "new work item proposal" should be submitted to the IEC by a national body or a liaison organisation. Preferably, the proposal should be accompanied by a working draft, giving the P-members sufficient information for voting. Once the new work item proposal has been submitted, the development process starts. This process has a strict schedule.

APENDIX 1

Draft list-mode data format.

The draft data format has two parts:
- *List-mode data in binary format*
- *Control data in XML format*

The binary file contains the list-mode data but it also contains a header that links the binary file with an XML file containing static data necessary for the measurement, such as links to calibrations and sample properties (Figure 1).

The list-mode data are saved in binary format because of performance reasons. The standard should include different binary formats (see Tables 1-3). The least significant byte of the word is stored in the smallest address given and the most significant byte is stored in the largest (little endian). Character strings are terminated with null character ('\0', NUL). The standard shall not include encryption and authentication, as this can be implemented at a higher level.

The XML file can be a stand-alone solution or it can be merged to other data formats such the IEC 62755 (Radiation protection instrumentation - Data format for radiation instruments used in the detection of illicit trafficking of radioactive materials). The user is free to add data fields to the XML file when deemed necessary.

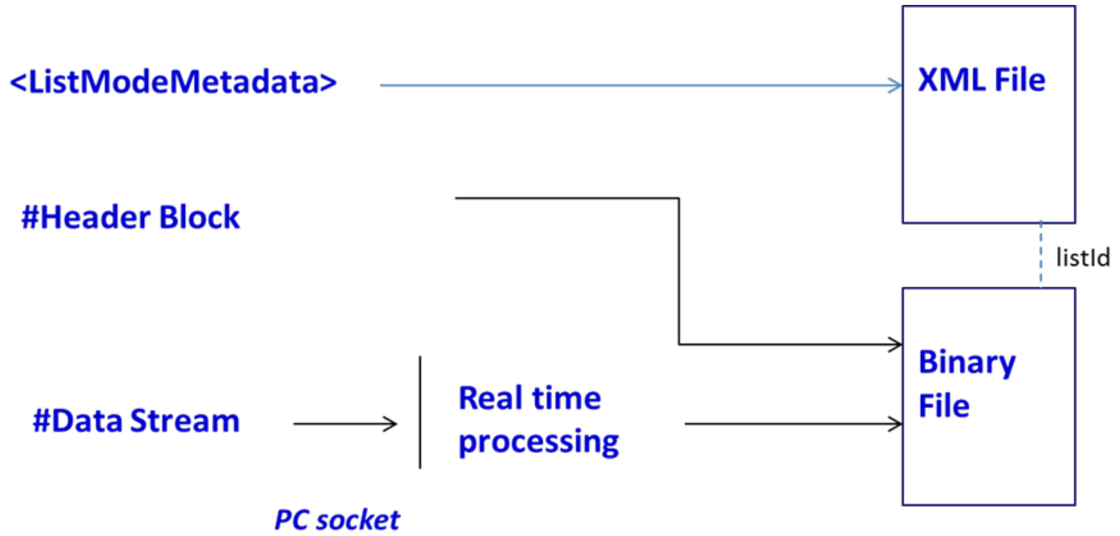

Figure 1. Data acquisition process. **listModeMetadata** and **Data Stream** have to be separated in the acquisition system. However, they are linked with *listId* which is a unique key in both files. **listModeMetadata** is created when the measurement is started and thereafter the data stream flows continuously to a socket where an application software takes over. The simplest functionality is just saving the files. Note that this approach works also for several separate data streams. i.e. there could be several DAQs with synchronized timing.

Table 1. Header of the list mode binary file. The beginning of the binary file is reserved for the application. However, the first nine items are defined unequivocally.

# List-Mode Header	
Field name	**Field contents**
listModeIdentifier	"LISTMODE" type declaration in the beginning of the binary file (8 bytes)
standardVersionNum	Standard update number at each revision (2 bytes)
headerLength	Number of header bytes in the present list-mode binary file (2 bytes) Useful to skip the complete header.
listId	Unique key identifying the file, e.g. master DAQ name +timestamp in ns; should be written also to the header of the list-mode binary file (40 bytes); Stop character "Space"
listFormat	Reserved word "simple"," basic", "shape", "cat1", "cat2", "full", "any" (20 bytes); Stop character "Space"
eventLength	Length of a single event (4 bytes)
listStartTick	Tick number (8 bytes); could be 0 at the clock reset time
listStopTick	Tick number (8 bytes); provided by the master clock at the end of data acquisition (use is optional, presence is required).
timeStampMethod	Name of the method utilised to provide the time stamp (40 bytes), such as: • pulseThreshold • pulseMaximum • secondDerivative • constantFractionDiscriminator
clockStartTime	Date and time of the clock initialization (reset). Date, hours, minutes, seconds and a decimal fraction of a second (ISO 8601): YYYY-MM-DDThh:mm:ss.sTZD (eg 2014-03-04T15:05:30.45+01:00) where: YYYY = four-digit year MM = two-digit month (01=January, etc.) DD = two-digit day of month (01 through 31) hh = two digits of hour (00 through 23) (am/pm NOT allowed) mm = two digits of minute (00 through 59) ss = two digits of second (00 through 59) s = one or more digits representing a decimal fraction of a second TZD = time zone designator (Z or +hh:mm or -hh:mm)
User or Vendor Specific Field	Up to 64 kbytes (total header length)

Table 2. Event structures in the list mode binary file.

#Data Stream			
listFormat	**Structure [Field list]**	**Size (Byte)**	
simple	[i, flag, tick, 0x00]	12	(2+1+8+1)
basic	[i, flag, tick, pulseHeight, 0x0000]	16	(2+1+8+3+2)
shape	[i, flag, tick, pulseHeight, p1..p6, 0x0000]	40	(2+1+8+3+24+2)
cat1	[i, flag, tick, pulseHeight, x, 0x00]	16	(2+1+8+3+1+1)
cat2	[i, flag, tick, pulseHeight, x, p1..p6, 0x00]	40	(2+1+8+3+1+24+1)
pulse	[i, flag, tick, n, y1… yn]	-	
full	[i, flag, tick, pulseHeight, x, p1..p6, n, y1,.., yn]	-	
any	[vendor-specific structure]	-	

Field	Byte	Field explanation
i	2	Channel pointer
flag *	1	Each bit (8) has an application-specific meaning
tick	8	Tick number
pulseHeight	3	Energy (MCA channel)
x	1	FPGA categorization result: G (photon), n, (thermal neutron) N (fast neutron), A (alpha particle, B (beta particle), F (false), P (pile-up)
p1..p6	24	(6*4 bytes) – pulse shape parameters provided by FPGA; have to be floating point numbers (6*32 bits)
n	4	Number of samples in a full pulse record
y1,…,yn		ADC sample values (n*2 bytes).

If option *any* is chosen, then without external information the user cannot know what is the data structure. However, if **listModeMetadata** follows the standard, the data management process is still possible.

* At the time of writing this report, the use of the 8-bit *flag* field is still under discussion. A possible use of is to handle the case of logic pulses described in section 4.1.5. A preliminary suggestion is to use the first 2 bits of this field as follows:

00 is a “normal” pulse
01 for a TTL rising transition
10 for a TTL falling transition
11 a “corrupted” pulse.

This leave another 6 bits for other uses, which can be discussed later, when thus draft format is sent to interested parties for review.

Table 3. Minimum data set of the XML file to support list mode data management**.** The file could contain optional blocks, such as company-specific information on the measurement system.

<listModeMetadata>		
Field name	**Field contents**	
listId	As in Binary File	
measSetupId	Pointer to the unique key identifying the measurement setup (detector configuration, sources etc.) (user input required)	
masterClockId	Pointer to the unique identifier of the DAQ (daqId) used as the master clock (synchronization)	
daqs	DAQ specific information. One entry for each DAQ.	
	daqId	Unique identifier of the DAQ
	company	DAQ manufacturer
	instrument	DAQ instrument name
	serialNumber	DAQ serial number
	adcFrequency	Frequency of the ADC in MHz
	clockFrequency	Time base in MHz
	adcResolution	10, 12, 16, 24 bit
	comments	Free text to describe the DAQ
channels	Channel specific information. One entry for each channel.	
	channelId	Unique identifier of the data input channel
	daqId	Pointer to the unique identifier of the DAQ
	detectorId	Pointer to the unique identifier of the detector attached (user input required)
	comments	Free text to describe the channel
clockStartTime	As in Binary File	
listStartTick	As in Binary File	
listStopTick	As in Binary File	
listFormat	As in Binary File	
comments	Free text to describe the measurement	
</listModeMetadata>		

Appendix 2

Manufacturers of digitizers

This information is taken from the websites of the manufacturers that the members of the RN TG are aware of, and is not considered as being a complete representation of current digitiser manufacturers.

- Aimil Ltd. offers e.g. 12-bit up to 2 GS/s http://www.aimil.com
- Agilent (previously Acqiris), offers digitisers up to 14-bit resolution and up to 8 GS/s. http://www.agilent.com
- Berkely Nucleonics Corporation (BNC) offers digitisers up to 13-bit resolution and 7 GHz sampling rate http://www.bncscientific.com
- CAEN offers digitisers up to 14-bit resolution and up to 5 GS/s. http://www.caen.it
- Canberra provides measurement solutions for nuclear safety, security and the environment. They offer 4 products with DSP: The Lynx and DSA-LX digital signal analyser, the OSPREY universal digital MCA tube base for scintillation spectrometry and the InSpector 2000 DSP portable spectroscopy workstation. http://www.canberra.com
- FAST ComTec provides multi parameter systems with time tagging of events http://www.fastcomtec.com
- Nutaq (previously Lyrtech) provides multichannel acquisition systems, e.g. VHS-ADC http://www.nutaq.com
- National Instruments provides digitisers as part of modular instrumentation http://www.ni.com
- Ortec offers DigiBASE, all-in-a-PMT-Base Digital Gamma Spectrometer, providing an all-in-one solution in a 14-pin tube base, suitable for most 10-stage PMTs. In addition, Ortec offers the DSPEC 50 and DSPEC 502 Advanced, Fourth-Generation ORTEC DSP-Based Gamma Ray Spectrometers. http://www.ortec-online.com
- SP Devices provides digitizers with various interfaces, e.g. 14-bit 1.6 GS/s, 12-bit 4 GS/s, 8-bit 7 GS/s http://spdevices.com
- Struck provides modular digitisers, e.g. 16-bit/14-bit resolution 16 channel 125/250 MS/s model SIS3316 http://www.struck.de/
- SkuTek, e.g. ten channels of low-noise, 14-bit digitization up to 125 MS/s http://www.skutek.com
- Teledyne Lecroy http://teledynelecroy.com/
- XIA provides several digital DSP/FPGA based multichannel analysers for end-use and OEM http://www.xia.com/

Some systems require the knowledge of software development for analysis of the sampled waveform, or knowledge of firmware development for real-time processing in the on-board FPGA or DSP.

Appendix 3

Summary of publications

The appendix summarises an incomplete selection of publications about list mode data acquisition.

Nuclear safeguards

[PAE, 2014] reports on the performance of a CAEN digitiser for safeguards and security applications.

[RID, 2014] Neutron multiplicity counting is rapidly changing from traditional shift-register electronics to fully digital list-mode acquisition, offering e.g. the possibility to include dead time losses on singles, doubles and triples rate. By artificially enforcing a growing dead time on the measurement results, one can describe the multiplicity moments as a function of the dead time. Then, by extrapolating back to a zero dead time, one obtains an approximation of the theoretical dead-time less rate. With shift-register electronics, dead time corrections are performed with a calibration procedure requiring a set of sources (such as ^{252}Cf) with different activities. Backwards extrapolation performed on data acquired in digital list-mode does not require this calibration and is less prone to bias due to differences in response for californium and plutonium. In addition, bootstrap analysis enables reliable uncertainty estimations for statistical quantities such as the three multiplicity moments and the fissile material mass. The authors recognise that the presented approach remains to be demonstrated for the measurements of large masses of fissile material.

[WEN, 2013] Photon-induced fission has been investigated as a method to detect and identify nuclear materials. Although high-energy delayed-fission γ-rays have been considered as a reliable signature for detection of fissionable materials, interference from γ-rays produced as secondary effects from other photonuclear reactions is inevitable. This effect has been studied in distinguishing fissionable materials from non-fissionable materials based on differential delayed γ-ray yields via both simulation and measurements. The energy spectra of delayed-photofission γ-rays carry isotopic information of the target materials. Three systems were used to acquire data from the HPGe detector: a list-mode system from FAST ComTec, a PXIe-5122 digitiser from National Instruments (14 bit, 5 MS/s sampling rate, offline signal processing in Matlab based on trapezoid shaping filters) and a Canberra LYNX (trapezoidal shaping filter embedded in firmware). The authors observed that the energy resolution achieved using the customized spectrometry system is similar to the results obtained with the commercial MCA systems.

[HEN, 2012] compares different analysis techniques on neutron pulse train data to extract correlated count rates from the detected neutron arrival times using list mode data acquired from a series of ^{252}Cf sources. The authors conclude that "as the use of the list mode data acquisition becomes more common, the most appropriate analysis technique based on the sample size, dead-time and/or precision requirements could be selected. A universal software package for acquisition and analysis of neutron pulse trains in the context of the PNMC (Passive neutron multiplicity counting) that will allow the user to choose among the different pulse train analysis techniques is currently under development at Los Alamos National Laboratory."

[BAG, 2009] reports on the development of pulse acquisition electronics that provide a timestamp (list-mode acquisition) for every digital pulse. The timestamp data can be processed directly during acquisition or saved on a hard disk. The latter method has the advantage that measurement data can be analysed with different values for parameters like pre delay and gate width, without repeating the acquisition. One particular advantage of list mode appears when instruments are calibrated. Calibration exercises with carefully prepared reference standards are expensive and time-consuming for inspectors and operators of nuclear facilities. If the calibration data are recorded in list mode, it is possible to create, retrospectively, the calibration curve for any combination of detector channels, provided that individual outputs are available for each channel. (There are typically several tens of neutron detectors in a neutron coincidence counter) If, during operation, one detector channel fails, it is possible to re-compute, from the original calibration data, the calibration curve for the remaining channels. This is not possible for the data from most conventional neutron detectors, because the data from the individual channels of these detectors are usually OR-ed together before they are processed in the shift register.

[RAO, 2008] writes about the use of a new generation list mode data acquisition card in a method that allows to correct for matrix effects in low-level radioactive waste neutronic assay (active prompt neutron coincidence measurements).

Nuclear security

[PER, 2013] (abstract) Detection of illicit trafficking of nuclear material relies on the detection of the radiation emitted. In the case of plutonium, one of the characteristic signatures derives from neutron emission. For this reason, neutron detectors cover an important role in detection systems.
Most current neutron detection systems used for nuclear security are based on the ^{3}He technology. Unfortunately, in the last few years the market of ^{3}He has encountered huge problems in matching the supply and the demand. The need has grown significantly due to the increasing demand of instrumentation for security. This has caused an exponential increase of the price from one side and on the other side a serious strategic problem of resources. In order to guarantee the availability of detection systems for nuclear security, it is necessary to develop alternative detection systems based on technologies different from ^{3}He. Many research projects have been devoted for the development of novel neutron detectors both by research organisations and by industries. Scientists from the PERLA laboratory of the Joint Research Centre (JRC) in Ispra, Italy, and their collaborators have tested several of these novel concepts in the last couple of years. This paper describes the detector systems tested at JRC and preliminary results on detectors that can be considered as promising alternatives to ^{3}He.

[GEN, 2012] (abstract) Measurement results of active detection of 19.5% enriched uranium are presented, obtained using He-4 scintillation detectors to detect prompt fission neutrons induced by the 2.5 MeV neutrons from an off the shelf electronic neutron generator used as interrogating means. Measurements were carried out with continuous as well as pulsed neutron interrogation schemes. The fission signature was clearly detected and discerned both from the background of interrogating neutrons as well as from photons backgrounds, without requiring any shielding. Based on these results, a performance prediction was made, suggesting that at 2 m standoff a 1 kg quantity of ^{235}U can reliably be detected within 10 seconds.

[YAN, 2009] (abstract) Pulsed accelerators are being used for radiographic inspections in homeland security applications. Adding spectroscopic detection capability enables additional information to be extracted but challenges signal processing hardware. This work compares two approaches to cost-effective digital spectroscopy systems designed to handle these high rate scenarios. In the first system, the signal from a PMT is directly digitized and then deconvolved on a PC using standard techniques. Bypassing the preamplifier, this system can handle high count rates (> 10^{6} cps) from an LaCl3 detector with no dead-time and an energy resolution of 5% at 1.33MeV. Spectra acquired from fission product gamma rays between interrogation pulses are shown. At higher rates, this approach is limited by the DAQ transfer rate to the PC. Instead, we tested a fast ADC (125MSPS) and an FPGA that performed on board, real-time digital signal processing (DSP). The energy spectrum is generated on the FPGA board during the measurement and transferred later. This system was tested in nuclear resonance fluorescence (NRF) experiments. Resonance peaks from NRF reactions are shown.

[NIE, 2005] (abstract) We report on the first experimental demonstration of Compton imaging of gamma-rays with a single coaxial high purity germanium (HPGe) detector. This imaging capability is realized by two-dimensional segmentation of the outside contact in combination with digital pulse-shape analysis, which enables to image gamma-rays in 4π without employing a collimator. We are able to demonstrate the ability to image the 662 keV gamma-ray from a ^{137}Cs source with preliminary event selection, with an angular resolution of 5° and a relative efficiency of 0.3%. This efficiency expresses the fraction of gamma-rays that can be imaged, out of the total gamma-ray flux which is emitted into the solid angle of the detector. In addition to the 4π imaging capability, such a system is characterized by its excellent energy resolution and can be implemented in any size possible for Ge detectors to achieve high efficiency.

[SLA, 2003] A viable concept for cargo active neutron interrogation has been presented and its components have been evaluated experimentally. Utilization of the new γ-ray signature for Special Nuclear Materials (SNM) appears to promise a dramatic improvement in sensitivity for those cases where thick intervening cargo shields a target of interest or where the material is shielded with intentionally placed high-Z materials. Experiments and simulations are reported to quantitatively determine the effects of cargo or intentional shielding to reduce and/or interfere with the SNM signature. These experiments will then be used to establish the scanning intervals required to reduce the error rates, i.e. false-positive and false negatives, to acceptable levels.

Gamma and alpha spectrometry

[ZHA, 2014] reported about the development of a gamma-gamma coincidence spectrometer which allows a more selective measurement of ^{22}Na with a significant background reduction. Hence, the system provides a more sensitive (by one order of magnitude) way to quantify trace amounts of ^{22}Na than normal high resolution gamma spectrometry providing a critical limit of 3 mBq within a 20 h count. The use of a list-mode data acquisition technique enabled simultaneous determination of ^{22}Na and ^{7}Be activity concentrations using a single measurement by coincidence and anticoincidence mode respectively.

[LAV, 2013] studied the linearity and internal background for a $LaBr_3$(Ce) γ-ray scintillation detector. A good use of $LaBr_3$(Ce) needs an accurate determination of the self-activity, particularly when low background is required or when events are collected at very low trigger rates. Data was collected in list mode using a VME data acquisition system including CAEN ADCV879.

[MARR, 2013] reports about the improvement of alpha-particle spectrometry using digital instrumentation (CAEN N1728B). For efficient storage, the data are stored as binary files. A specific data processing computer program has been developed to decode and then analyse the data by creating time and energy histograms, correcting for dead time, and carrying out a coincidence analysis of the registered signals.

[ZHA, 2013] et al. compared the performance of an analog timing and a digital list-mode data acquisition system for a Compton suppression spectrometer. The digitiser used was the Pixie-4 from XIA LLC. It has 4 input channels, and a sampling rate of 75 MHz. The pulse height is determined with a 16-bit resolution by a trapezoidal shaping algorithm embedded in FPGA. The associated timestamp of the pulse has a resolution of 13.3 ns. The authors compared conventional and anticoincidence gamma-ray spectra of ^{60}Co and ^{137}Cs sources, acquired on a HPGe detector. The list-mode system allows the spectrometer to be more flexible for coincidence/anticoincidence measurements compared to NIM analog Compton suppression system and it allows simultaneous acquisition of gamma-gamma coincidence and anticoincidence spectra. The authors indicate several possible improvements to the performance of the digital spectrometer, e.g. improved energy and timing resolution and peak-to-Compton background ratio. They also indicate the need for interactive software tools capable of handling large list-mode data files.

Primary standardisation of radioactivity and nuclear data measurements

[YUN, 2013] describes the standardisation of electron capture nuclides followed by γ-transitions using the 4π(e, X)–γ coincidence counting method. Conventional analog modules are used in the two parameter data acquisition system, as described in [KAW, 2012].

[KAW, 2013] clarifies the γ-efficiency dependency of 4πβ-γ efficiency functions by a series of 4πβ-γ efficiency extrapolation measurements of a ^{134}Cs source using a 4πβ(PS)-4πγ detector configuration. The data acquisition system is the one described in [KAW, 2012].

[SUL, 2013] deduced the half-lives of ^{217}At and ^{213}Po from delayed coincidence measurements on weak ^{225}Ac sources using digital data acquisition in list mode, and obtained 32.8 (3) ms and 3.708 (8) µs respectively.

[MARO, 2013] measured the half-life of ^{213}Bi using a planar Si detector and a digital data acquisition system based on a CAEN N1728B digitiser storing data in list-mode.

[MIN, 2013] applied a new totally digital approach for processing pulses delivered by three photomultipliers in a TDCR system in which for the first time at ENEA-INMRI the CAEN digitizers belonging to the family of desktop digitizers DT57XX were used to link directly the PMTs of home-made TDCR counters to these new front-end electronics devices. New very interesting perspectives were then opened in the TCDR acquisition and analysis by using new software codes that take into account the digitized information recorded by compact digitizer modules directly linked to the detector. Deeper investigations are still in progress to meet the required metrological accuracy in the results obtained also taking into account different parameters involved in these complex measurements.

[CAP, 2013] describes the construction of a new 4π (LS) TDCR system at ENEA-INMRI. Three photomultiplier tubes, arranged in a planar 120° geometry around a spherical optical chamber, were directly linked to a CAEN Desktop Digitizer DT5720. This module, based on the Field Programmable Gate Array (FPGA) technology for real time Digital Pulse Processing (DPP), allowed to replace all the classical TDCR electronics by only one device [MIN, 2013]. The activity of ^{3}H and ^{63}Ni standard sources were successfully measured by the new detector. Data is stored in list-mode and processed off-line.

[BOB, 2012] describes the renewal and improvement of the instrumentation in National Metrology Institutes, via the employment of adopt digital boards, which present numerous advantages over the standard electronics. The feasibility of an on-line fulfillment of nuclear-instrumentation functionalities using a commercial FPGA-based (Field-Programmable Gate Array) board was validated in the case of TDCR primary measurements (Triple to Double Coincidence Ratio method based on liquid scintillation). The applications presented in this paper allow either an on-line processing of the information or collection of list-mode data for 'off-line' treatment. Developed as a complementary tool for TDCR counting, a time-to-digital converter specifically designed for this technique is described. In addition, the description is given of a spectrometry channel based on the connection between conventional shaping amplifiers and the analog-to-digital converter (ADC) input available on the same digital board. First results are presented in the case of α- and γ-counting related to, respectively, the defined solid angle and well-type NaI(Tl) primary activity techniques. The combination of two different channels (liquid scintillation and γ-spectrometry) implementing the live-time anticoincidence processing is also described for the application of the 4πβ–γ coincidence method. The need for an optimized coupling between the analog chain and the ADC stage is emphasized. The straight processing of the signals delivered by the preamplifier connected to a HPGe detector is also presented along with the first development of digital filtering.

[KAW, 2012] describes a simple and versatile data acquisition system for software coincidence and pulse-height discrimination in 4πβ-γ coincidence experiments, build using two fast ADCs (16 bits, 25 MHz), variable delay circuits, pulse-height stretchers, pulse-height discriminators, and a dead-time controller. Data is saved in list-mode and processed in Microsoft Excel. Although data is not acquired with digital electronics, the paper shows the power of list-mode data for coincidence counting (one of the primary methods used to standardise radioactivity).

[POM, 2012] eliminated the contribution of long-lived progenies and possible impurities in the measurement of the ^{230}U half-life using data acquisition with a CAEN N1728B digitiser in list mode, allowing off-line data analysis with flexible energy selection. The data analysis was performed on the count rates in the ^{218}Rn and ^{214}Po peaks only, which were assumed to be in equilibrium with ^{230}U.

[SUL, 2012] measured the half-lives of ^{218}Rn and ^{214}Po using digital electronics and data stored in list mode. The resulting half-lives are 33.75 (15) ms for ^{218}Rn and 164.2 (6) ms for ^{214}Po, both in agree ment with some of the literature values, and obtained with higher precision.

[SZE, 2010] reports on the determination of partial gamma-ray production cross sections (σ_γ) and k_0-factors of 12 short- and medium-lived radionuclides using a chopped beam of cold neutrons, in combination with list-mode data acquisition using a XIA Polaris digital spectrometer.

[KEI, 2007] reviews the progress in the development of 'digital coincidence counting' systems used in the field of radionuclide metrology. The 4πβ–γ coincidence method for the absolute determination of nuclear disintegration rates has for decades been successfully applied to a variety of radionuclides, via the use of suites of dedicated analogue electronic modules. The high cost of procurement and maintenance of such systems, as well as the requirement for highly experienced technicians to perform the data collection have prompted the design of more flexible data collection techniques. Recent advances in digital signal acquisition technology have facilitated the possibility of storing pulse information from multiple detector systems along with a time stamp for each recorded event, allowing various radionuclide standardization techniques (based on the concept of 4πβ–γ coincidence counting) to be implemented 'offline' via the use of dedicated software routines.

[TOR, 2005] determined the α-particle emission probabilities of ^{235}U in the frame of the EURAMET 591 project. Data was stored in list mode to facilitate numerical gain stabilisation.

[POM, 2004] presented conceptual ideas for an off-line gain stabilisation method for spectrometry, in particular for alpha-particle spectrometry, at low count rates. The method involves list mode storage of individual energy and time stamp data pairs. The 'Stieltjes integral' of measured spectra with respect to a reference spectrum is proposed as an indicator for gain instability. 'Exponentially moving averages' of the latter show the gain shift as a function of time. With this information, the data are relocated stochastically on a point-by-point basis.

Ion beam analysis

[PIC, 2014] The New AGLAE external beam line provides analytical data for the understanding of the structure of archaeological and artistic objects, their composition, properties, and changes over time. One of the objectives of this project is to design and set up a new non-invasive acquisition system increasing the quality of the X-ray spectra and reducing the beam current on sensitive materials from work of art. To that end, the surface and the number of PIXE detectors have been increased from 2 Si(Li) detectors to a cluster of 5 SDD detectors. During the mapping, a multi-parameter system saves each event from X-ray, gamma and particle detectors, simultaneously with the X and Y positions of the beam on the sample. Data was acquired with DXP Mercury-4 from XIA LLC. 5 input channels are required for the X-ray detectors, and an additional two for a gamma ray detector and a charged particle detector. To process the data, different software routines have been developed or updated. Data formats used are the ESRF Data Format (EDF) and the open source format called HDF5 (Hierarchical Data Format) is planned to be used in order to decrease the data size and mitigate many problems associated with large datasets. The homemade software will be upgraded to take in charge this new file format.

[DU, 2013] described the development of a compact data acquisition and beam control system to perform routine irradiation and spatial analysis using ion microbeam. The system comprises a PXI-6115 multifunction DAQ card, a PXI-5153 digitization card (two 8-bit inputs with 2 GS/s) and a PXI-6528 DIO card from National Instruments. Together with the in-house developed Cell Exposure and Nuclear Application (CENA) software using LabVIEW, the system implements beam scanning, single ion targeting, ion counting, energy spectrum measurement, spectrum mapping and sample irradiation. Data is stored in TDMS format in list mode (a proprietary format from National Instruments).

[UDA, 2013] (abstract) The suit of techniques (RBS, STIM, ERDS, PIXE, IL, IF,. . .) available in ion beam analysis yields a variety of rich information. Typically, after the initial challenge of acquiring data we are then faced with the task of having to extract relevant information or to present the data in a format with the greatest impact.
This process sometimes requires developing new software tools. When faced with such situations the usual practice at the Centre for Ion Beam Applications (CIBA) in Singapore has been to use our computational expertise to develop ad hoc software tools as and when we need them. It then became apparent that the whole ion beam community can benefit from such tools; specifically from a common software toolset that can be developed and maintained by everyone with freedom to use and allowance to modify. In addition to the benefits of readymade tools and sharing the onus of development, this also opens up the possibility for collaborators to access and analyse ion beam data without having to depend on an ion beam lab. This has the virtue of making the ion beam techniques more accessible to a broader scientific community.
We have identified ImageJ as an appropriate software base to develop such a common toolset. In addition to being in the public domain and been setup for collaborative tool development, ImageJ is accompanied by hundreds of modules (plugins) that allow great breadth in analysis. The present work is the first step towards integrating ion beam analysis into ImageJ. Some of the features of the current version of the ImageJ 'ion beam' plugin are: (1) reading list mode or event-by-event files, (2) energy gates/sorts, (3) sort stacks, (4) colour function, (5) real time map updating, (6) real time colour updating and (7) median & average map creation.

[THI, 2011] developed an ASIC for pixel readout of an APD based 2D X-ray hybrid pixel detector, capable of operating in counting mode and list mode. In list mode the system allows to timestamp individual photon hits by driving out the hit signals towards external TDCs with sub-nanosecond resolution.

[MIG, 2008] reports on the PIXE analysis operated in scanning mode and writing data in list mode.

[BER, 2006] reports on a not very common method, developed for hydrogen measurements in thin samples using $^{1}H(p,p)^{1}H$ elastic recoil coincidence spectrometry (ERCS). Data is stored in list mode for off-line processing.

[RYA, 2004] uses data acquired in list mode to solve the issue of reproducing the spatial variation in energy-dispersive PIXE analysis.

[SJÖ, 1999] improved the accuracy of PIXE analysis with respect to the pile-up problem using data collected in list mode.

Other

[LOH, 2013] Describe a new setup that combines large volume $LaBr_3$:Ce detectors and high resolution HPGe detectors in a very close geometry to offer high efficiency, high energy resolution as well as high count rate capabilities at the same time. The combination of a highly efficient γ-ray spectroscopy setup with the mono-energetic high-intensity photon beam of HIγS provides a worldwide unique experimental facility to investigate the γ-decay pattern of dipole excitations in atomic nuclei. Data is acquired using the GSI Multi Branch System (MBS), which operates on a VME single-slot PowerPC of type CES RIO4. The secondary outputs of the HPGe detectors are directly connected to a 16 bit Struck SIS3302 flash ADC operated at a frequency of 100 MHz, with the specialized Gamma-Firmware (V1412).

[ZOG, 2011] designed an image reconstruction tool for the Medium-Energy Gamma-ray Astronomy library MEGAlib, a toolset to simulate and analyse data from gamma-ray detectors. The tool performs list-mode-likelihood image deconvolution.

[MUR, 2013] describes the construction of a charged particle detector array consisting of fourteen fast-slow plastic phoswich detectors coupled to photomultiplier tubes. The authors use analog electronic modules and classic ADCs. Data is acquired in list mode using a custom made data acquisition programme, and analysed using coincidence techniques.

[VOL, 2013] evaluated the resonance parameters for neutron induced reactions in cadmium. The time-of-flight and pulse height of each detected event were recorded in list mode, using conventional electronics.

[BUR, 2011] uses analog electronics in a bismuth activation counter, but stores data in list mode.

[PUZ, 2007] reports on a method for off-line correction of amplitude walk in leading-edge timing. The method uses analog modules, but three-parameter data from ADCs is stored in listmode to allow correction in software.

[SKU, 2001] developed an algorithm for particle identification and embedded it in the digitiser's on-board FPGA and DSP. The method is based on difference in response (slow and fast component) of different types of radiation. The CsI(Tl) crystal was coupled to a photodiode. The negative output pulses from the preamplifier were digitised at a rate of 40 MHz with 12-bit precision using the XIA's DGF-4C digital spectrometer and waveform digitiser. Data was stored in list mode, but the timestamp information was not used as it was irrelevant for this experiment.

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Title: List-mode data acquisition based on digital electronics - State-of-the-art report

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Abstract

This report deals with digital radiation detection systems employing list-mode data collection, which improves data analysis capabilities. Future data acquisition systems shall also ultimately enable the movement of detection data from first responders electronically to analysis centres rather than the costly and time consuming process of moving experts and/or samples. This new technology is especially useful in crisis events, when time and resources are sparse and increased analysis capacity is required. In order to utilise the opportunities opened by these new technologies, the systems have to be interoperable, so that the data from each type of detector can easily be analysed by different analysis centres. Successful interoperability of the systems requires that European and/or international standards are devised for the digitised data format. The basis of such a format is a list of registered events detailing an estimate of the energy of the detected radiation, along with an accurate time-stamp for recorded events (and optionally other parameters describing each event).

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