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(54) Title: METHOD AND APPARATUS FOR BOREHOLE LOGGING

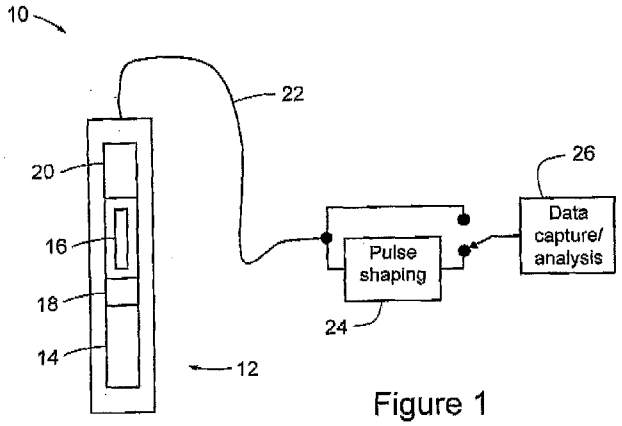


Figure 1

(57) Abstract: A method and apparatus for borehole logging, the method comprising collecting detector output data from a radiation detector of a borehole logging tool, and resolving individual signals in the detector output data by (i) determining a signal form of signals present in the data, (ii) making parameter estimates of one or more parameters of the signals, wherein the one or more parameters comprise at least a signal temporal position, and (iii) determining the energy of each of the signals from at least the signal form and the parameter estimates. The logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

METHOD AND APPARATUS FOR BOREHOLE LOGGING

elated Application

ıis application is based on and claims the benefit of the filing date of US ɔplication no. 61/041,141 filed 31 March 2008 and of US application no. l/138,879 filed 18 December 2008, the contents of which as filed are corporated herein by reference in their entirety.

eld of the Invention

ıe present invention relates generally to a method and apparatus for borehole gging, of particular but by no means exclusive application to oil well logging.

ackground of the Invention

mineral and oil exploration, borehole logging is used to determine the ıbsurface content of rocks and mineral deposits.

ıclear logging tools provide valuable data to the oil industry and have been ɜed in oil well logging for more than 30 years. Data on the porosity and ɜnsity of rock formations, which is used to help detect the presence of ɜological reservoirs and their contents (e.g. oil, gas or water), form one of the g suites used in oil well logging.

ıe existing digital pulse processing techniques employed in borehole logging ly on linear filtering methodologies. However, with increasing count rate, the gh-pass filters required to shorten pulse length and increase throughput also ɜgrade signal-to-noise ratio (SNR), and ultimately, energy resolution. This ıits the count rate that can be employed, the strength of the source, the oximity of the source and detector, or combinations of these parameters. In ıre-hole logging applications, for example, overall measurement time is very ıportant. The information lost due to the discarding of pile-up events extends ɜ collection time required to obtain sufficient accuracy in the estimation of ɜmental concentration and ultimately places an upper limit on the speed at ıich a well can be logged. US patent no. 4,883,956, for example, assesses ɜ benefits of a new radiation detection crystal, cerium-doped gadolinium thosilicate (GSO). The decay time of GSO detectors results in less pile-up for ıy particular count-rate, or accommodates a higher count-rate for a particular ɔceptable pile-up.

Summary of the Invention

According to a first aspect of the invention, therefore, there is provided a method of borehole logging, comprising:

collecting detector output data from a radiation detector of a borehole logging tool; and

resolving individual signals in the detector output data by (i) determining a signal form (or an impulse response) of signals present in the data, (ii) making parameter estimates of one or more parameters of the signals, wherein the one or more parameters comprise at least a signal temporal position, and (iii) determining the energy of each of the signals from at least the signal form and the parameter estimates;

whereby the logging tool is shorter, logging tool speed is greater, dwell time (i.e. irradiation and/or data collection time) is shorter and/or resolution is improved.

Thus, this method endeavors to characterize as much data as possible, but it will be appreciated that it may not be possible to adequately characterize some data (which hence is termed 'corrupt data'), as is described below. It will be understood that the term 'signal' is interchangeable in this context with 'pulse', as it refers to the output corresponding to individual detection events rather than the overall output signal comprising the sum of individual signals. It will also be appreciated that the temporal position (or timing) of a signal can be measured or expressed in various ways, such as according to the time (or position in the time axis) of the maximum of the signal or the leading edge of the signal. Typically this is described as the arrival time ('time of arrival') or detection time.

It will also be understood that the term 'detector data' refers to data that has originated from a detector, whether processed subsequently by associated or other electronics within or outside the detector.

The method may include constructing a model of the data from the parameter estimates, and determining the accuracy of the parameter estimates based on a comparison between the detector output data and the model.

The signal form (or impulse response) may be determined by a calibration process that involves measuring the detector's time domain response to one or more single event detections to derive from that data the signal form or impulse response. A functional form of this signal form may then be obtained by

interpolating the data with (or fitting to the data) a suitable function such as a polynomial, exponential or spline. A filter (such as an inverse filter) may then be constructed from this detector signal form. An initial estimate of signal parameters may be made by convolution of the output data from the detector with the filter. Signal parameters of particular interest include the number of signals and the temporal position (or time of arrival) of each of the signals.

The particular signal parameters of interest can then be further refined. Firstly, the estimate of the number and arrival times of signals is refined with the application of peak detection and a threshold. Secondly, knowledge of the number of signals and their arrival time, coupled with the detector impulse response (and hence signal form) makes it possible to solve for the energy parameters of the signals.

The accuracy of the parameter estimation can be determined or 'validated' by comparing a model (in effect, an estimate) of the detector data stream (constructed from the signal parameters and knowledge of the detector impulse response) and the actual detector output. Should this validation process determine that some parameters are insufficiently accurate, these parameters are discarded. In spectroscopic analysis using this method, the energy parameters deemed sufficiently accurate may be represented as a histogram.

The method may include making the estimates of signal parameters in accordance with the signal form (i.e. the impulse response of the detector used for generating the signal). The method may include determining the signal form by a calibration process including measuring the response of the detector to one or more single detections to derive a data based model of the signal form. In particular, the method may include obtaining a functional form of the model by interpolating the data with a function to generate the expected signal form. The function may be a polynomial, exponential or spline function.

The method may include designing a filter on the basis of the predetermined form of the individual signals produced by the radiation detector. The filter may be, for example, of matched filter or inverse filter form.

In one embodiment, the method includes using convolution of the detector output and filter to make an initial estimate of the signal parameters. The method may include refining the estimate of the signal parameters. The method may include refining the estimate of signal number with a peak

detection process. The method may include making or refining the estimate of signal temporal position by application of a peak detection process. The method may include refining the estimate of signal energy by solving a system of linear equations, by matrix inversion or by iterative techniques.

In an embodiment of the invention, the method includes creating a model of the detector output using the signal parameters in combination with the detector impulse response. The method may include performing error detection by, for example, comparing the actual detector output data with the model of the detector output, such as by using least-squares or some other measure of the difference between the data and the model.

The method may include discarding parameters deemed not sufficiently accurately estimated.

In one embodiment, the method includes presenting all sufficiently accurate energy parameters in a histogram.

The data may include signals of different forms. In this case, the method may include determining where possible the signal form of each of the signals.

In one embodiment, the method includes progressively subtracting from the data those signals that acceptably conform to successive signal forms of a plurality of signal forms, and rejecting those signals that do not acceptably conform to any of the plurality of signal forms.

In one embodiment, the resolving of individual signals comprises:

obtaining the detector output data as digitized detector output data in a form of a digital time series; and

forming a mathematical model based on the digital time series and as a function of at least the signal form, the temporal position of the at least one signal, and an amplitude of the at least one signal;

wherein determining the energy of each of the signals comprises determining the amplitude of the signals based on the mathematical model, the amplitude being indicative of a radiation event.

In one embodiment, the method comprises oil well logging.

The logging tool may be less than 3 m in length, and in some cases less than 2.7 m in length or even less than 2.4 m in length.

The resolving of the signals may reduce dwell time by a factor of 2 or more, and in some case by a factor of 5 or more. The resolving of the signals may increase logging tool speed by a factor of 2 or more or in some cases by a factor of 5 or more.

The method may be characterized by an incident flux on the radiation detector of gamma-rays of 500 kHz or more.

The method may be characterized by a data throughput of greater than 90% for an input count rate of 200 kHz.

The method may be characterized by a data throughput of greater than 70% for input count rates between 500 and 2000 kHz.

The method may be characterized by a data throughput of greater than 95% for an input count rate of 100 kHz.

The method may be characterized by a data throughput of greater than 95% for input count rates between 100 and 200 kHz.

The method may comprise an input count rate of greater than 750 kHz.

The method may comprise an input count rate of greater than 1 MHz.

The detector may comprise a GSO detector.

The method may include pulse shaping the output of the detector.

The method may include employing a source synchronization signal to avoid misallocation of data.

In a second aspect, the invention provides an borehole logging apparatus, comprising:

a borehole logging tool for irradiating a material surrounding the logging tool, detecting radiation emitted by the material, and for outputting detector data in response thereto; and

a processor for receiving the detector data in digitized form, and programmed to determine the signal form of each of the signals present in the data, to make parameter estimates of one or more parameters of the signals, and to determine the energy of each of the signals from at least the signal form and the parameter estimates, wherein the one or more parameters comprise at

least a signal temporal position;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter or resolution and/is improved.

The processor may be programmed to obtain the detector output data in a form of a digital time series and to form a mathematical model based on the digital time series and as a function of at least the signal form, the temporal position of the signals, and an amplitude of the signals;

wherein determining the energy of each of the signals comprises determining the amplitude of the signals based on the mathematical model, the amplitude being indicative of a radiation event.

The apparatus may be adapted for oil well logging.

The logging tool may be less than 3 m in length.

Use of the processor may allow a reduction in dwell time by a factor of 5 or more. Also, use of the processor may allow an increase in logging tool speed by a factor of 5 or more.

The apparatus may be characterized by an incident flux on the radiation detector of gamma-rays of 500 kHz or more.

The apparatus may be characterized by a data throughput of greater than 90% for an input count rate of 200 kHz.

The apparatus may be characterized by a data throughput of greater than 70% for input count rates between 500 and 2000 kHz.

The apparatus may be characterized by a data throughput of greater than 95% for an input count rate of 100 kHz.

The apparatus may be characterized by a data throughput of greater than 95% for input count rates between 100 and 200 kHz.

The apparatus may comprise an input count rate of greater than 750 kHz.

The apparatus may comprise an input count rate of greater than 1 MHz.

The detector may comprise a GSO detector.

The apparatus may include a pulse shaping module for pulse shaping the output of the logging tool.

The logging tool will typically house both a radiation source and a radiation detector in a single housing, but the logging tool may be in a distributed form with, for example, the radiation source and radiation detector in separate housings.

In a third aspect, the invention provides a method of quantifying a chemical element in a formation traversed by a borehole, comprising:

collecting detector output data from a radiation detector of a borehole logging tool; and

resolving individual signals in the detector output data by (i) determining a signal form of signals present in the data, (ii) making parameter estimates of one or more parameters of the signals, wherein the one or more parameters comprise at least a signal temporal position, and (iii) determining the energy of each of the signals from at least the signal form and the parameter estimates;

determining a quantity of the element from at least those of the signals arising from instances of the element in the formation;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

The resolving of individual signals may comprise:

obtaining the detector output data as digitized detector output data in a form of a digital time series; and

forming a mathematical model based on the digital time series and as a function of at least the signal form, the temporal position of the at least one signal, and an amplitude of the at least one signal;

wherein determining the energy of each of the signals comprises determining the amplitude of the signals based on the mathematical model, the amplitude being indicative of a radiation event.

In a fourth aspect, the invention provides a method of borehole logging, comprising:

collecting detector output data from a radiation detector of a borehole logging tool; and

resolving individual signals in the detector output data by (i) obtaining or expressing the detector output data as a digital series, (ii) obtaining or

determining a signal form of signals present in the data, (iii) forming a transformed signal form by transforming the signal form according to a mathematical transform, (iv) forming a transformed series by transforming the digital series according to the mathematical transform, the transformed series comprising transformed signals, (v) evaluating a function of at least the transformed series and the transformed signal form and thereby providing a function output, (vi) modelling the function output according to a model, (vii) determining at least one parameter of the function output based on the model, and (viii) determining a parameter of the signals from the at least one determined parameter of the function output;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

In a fifth aspect, the invention provides a borehole logging apparatus, comprising:

a borehole logging tool for irradiating a material surrounding the logging tool, detecting radiation emitted by the material, and for outputting detector data in response thereto; and

a processor for receiving the data as a digital series, and programmed to (i) obtain or determine a signal form of signals present in the data, (ii) form a transformed signal form by transforming the signal form according to a mathematical transform, (iii) form a transformed series by transforming the digital series according to the mathematical transform, the transformed series comprising transformed signals, (iv) evaluate a function of at least the transformed series and the transformed signal form and thereby provide a function output, (v) model the function output according to a model, (vi) determine at least one parameter of the function output based on the model, and (vii) determine a parameter of the signals from the at least one determined parameter of the function output;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

In a sixth aspect, the invention provides method of mineral logging, comprising:

collecting detector output data from a radiation detector of a mineral logging tool; and

resolving individual signals in the detector output data by (i) determining a signal form of signals present in the data, (ii) making parameter estimates of one or more parameters of the signals, wherein the one or more parameters

comprise at least a signal temporal position, and (iii) determining the energy of each of the signals from at least the signal form and the parameter estimates;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

Thus, the present invention may also be used to log the composition of a mineral or minerals, which may be placed adjacent to the logging tool, passed by the logging tool (such as on a conveyor belt), logged *in situ* by a mobile logging tool, or otherwise.

In a seventh aspect, the invention provides a mineral logging apparatus, comprising:

a mineral logging tool for irradiating a material, detecting radiation emitted by the material, and for outputting detector data in response thereto; and

a processor for receiving the detector data in digitized form, and programmed to determine the signal form of each of the signals present in the data, to make parameter estimates of one or more parameters of the signals, and to determine the energy of each of the signals from at least the signal form and the parameter estimates, wherein the one or more parameters comprise at least a signal temporal position;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

It should be noted that the various optional features of each aspect of the invention may be employed where suitable and desired with any of the other aspects of the invention.

Brief Description of the Drawings

In order that the invention may be more clearly ascertained, preferred embodiments will now be described, by way of example only, with reference to the accompanying drawing, in which:

Figure 1 is a view of an oil well logging apparatus according to an embodiment of the present invention;

Figure 2 is a view of the Sodium Iodide NaI(Tl) gamma-ray detector of the apparatus of Figure 1;

Figures 3a, 3b and 3c are graphs illustrating pulse pile-up;

Figure 4 is a diagram illustrating the mathematical modeling of radiation

detection used by the signal processing method embodied in the apparatus of Figure 1;

Figure 5 is a diagram detailing the mathematical model of radiation detection used by the signal processing method embodied in the apparatus of Figure 1;

Figure 6 is a schematic diagram of the functional elements of the data capture module of Figure 1;

Figures 7a, 7b and 7c are plots of unprocessed digitized data collected directly from the output of the detector of Figure 2 over time ranges of 1000 μs, 100 μs and 10 μs respectively;

Figure 8 is a schematic representation of the signal processing method for pulse pile-up recovery employed by the apparatus of Figure 1 for analyzing spectroscopic data according to this embodiment of the invention;

Figure 9 is a schematic flowchart of the signal processing method for pulse pile-up recovery employed by the apparatus of Figure 1 for analyzing spectroscopic data according to this embodiment of the invention;

Figures 10a, 10b and 10c are plots of the results at different stages of the signal processing method of Figure 9;

Figure 11 are plots of gamma-ray spectra for a 137Cs source at various input count rates, processed with the method of Figure 9;

Figure 12 is a plot of the results of a computer simulation of the signal processing method of Figure 9 prepared using a simulated data set produced by a digital nuclear pulse generator;

Figure 13 is plot of the performance of the simulation of Figure 12 for a gamma-ray source over a range of count rates;

Figures 14a, 14b, 14c and 14d depict the results of applying the signal processing method of Figure 9 to the output of a 76 mm x 76 mm NaI(Tl) gamma-ray detector;

Figures 15a, 15b, 15c and 15d depict the results of applying the signal processing method of Figure 9 to data collected with a HPGe detector;

Figures 16a, 16b, 16c and 16d depict the results of applying the signal processing method of Figure 9 to the output of a Xenon gas proportional detector;

Figure 17 is a plot of the energy spectrum collected with the apparatus of Figure 1, with the neutron source on, plotted on log-linear scale;

Figure 18 is a plot of the energy spectrum collected with the apparatus of Figure 1, with the neutron source off, plotted on log-linear scale;

Figure 19 comprises plots illustrating the different stages of data processing, showing a section of (i) the input data stream, (ii) the pulse localization output, (iii) the pulse identification output, and (iv) validation error signal;

Figure 20 is schematic, cross-section view of neutron activated gamma-ray spectroscopy well-logging tool of an embodiment of the present invention;

Figure 21 is a plot of throughput count rate as a function of input count rate, calculated for the well-logging tool of Figure 20, and of the calculated performance of the well-logging tool of Figure 20 without signal processing method for pulse pile-up recovery of the present invention;

Figures 22a and 22b are plots of percentage throughput as a function of input count rate calculated for the well-logging tool of Figure 20, and of the calculated performance of the well-logging tool of Figure 20 without signal processing method for pulse pile-up recovery of the present invention; and

Figure 23 is schematic, cross-section view of neutron activated gamma-ray spectroscopy well-logging tool according to an embodiment of the present invention.

Detailed Description of the Embodiments

Figure 1 is a schematic view of an oil well logging apparatus 10 according to an embodiment of the present invention. Apparatus 10 includes a logging tool or 'collar' 12 for lowering into an oil well bore (or other borehole). Tool 12 has a neutron source 14 in the form of a pulsed neutron generator for generating neutrons for exciting the material surrounding the bore, a detector 16, a shield 18 separating the neutron source 14 and detector 16, and a pre-amplifier 20 coupled to the output of detector 16. An output of pre-amplifier 20 is coupled to a coaxial cable 22. It will be appreciated that tool 12 may include a plurality of detectors comparable to detector 16.

Apparatus 10 includes a pulse shaping module 24 and a data capture and analysis module 26. These are arranged so that the output of pre-amplifier 20 can be transmitted by coaxial cable 22 either to pulse shaping module 24 and hence to data capture module 26, or directly to data capture and analysis module 26. It should be appreciated that data capture and analysis module 26 may comprise either a computing device configured to both collect data and analyze that data as described below, or a plurality of components such as a data collection device and a distinct data analysis device for performing these

functions. In the latter case, such data collection and data analysis devices may each comprise computing devices. In both cases, data capture and analysis module 26 includes a display.

Tool 12 is adapted to be used with a borehole of about 20 cm diameter, and of depths typical in this field (which may be as great as 10 km or more). The maximum depth into the surrounding material from which useful data may be collected is greater than with typical existing tools, owing to the ability of apparatus 10 to handle high count rates. This allows the use of stronger neutron sources that give rise to useful count rates from greater depths.

In addition, the ability of apparatus 10 to handle high count rates allows shield 18 to be thinner if desired, or the distance between source 14 and detector 16 to be reduced (or both). The overall length of tool 12 may thus be reduced. Also, the ability of apparatus 10 to extract more useful information from the output of tool 12 with effectively less pile-up (as is discussed below) allows irradiation or collection times—and hence "dwell" and total logging times—to be reduced.

Thus, at present the shortest tools are greater than 6.5 m in length. Test measurements with apparatus 10 (see below) suggest that an increase in tolerable count rate of at least a factor of 2 may be achieved, so it is envisaged that results comparable to the present state of the art may be obtained according to the present invention with a tool less than—and possibly considerably less than—6 m in length. Similarly, logging rates of about 135 m per hour (collecting two data points per 30 cm) have been reported: it is envisaged that comparable results may be obtained according to the present invention with a logging rates at least 50%—and possibly 100%—faster.

Pulse shaping module 24 performs pulse shaping of the output of pre-amplifier 20 to reduce the length of the pulses outputted by pre-amplifier 20, and is employed if necessary but may be omitted or bypassed. Whether or not pulse shaping module 24 is employed, the pre-amplifier signals are ultimately transmitted to data capture and analysis module 26.

Data capture and analysis module 26 includes a signal processing unit that comprises two parts: 1) an analog to digital converter which produces a digital output corresponding to the analog output of the detector unit, and 2) a processing unit which implements digital signal processing (DSP) routines in

accordance with the present invention. The output signals of pre-amplifier 20 are coupled connected to the signal processing unit.

Figure 2 is a schematic view of detector 16. When a gamma-ray is emitted by an atom in the material surrounding the oil well bore, having been excited by neutrons from neutron source 14, it may pass into detector 16 and, if so, its energy is transferred from the gamma-ray to electrons within the NaI(Tl) crystal 28. Upon the emission of ultra-violet photons the electrons lose this energy, promoting electrons within the crystal to excited states. Upon the emission of ultra-violet photons the electrons decay to lower energy states. The aforementioned ultra-violet photons pass through the optical window to the photocathode 36 of the photomultiplier tube 32 where they are converted into photoelectrons and subsequently multiplied by an electron multiplier 38 before arriving at the anode 40 of the photomultiplier tube 32. A further multiplication stage may be provided by an on-board pre-amplifier 42. In this manner an electrical signal, whose amplitude is proportional to the energy of the incident gamma-rays, is present at the detector output terminals 44 of detector 16. It will also be appreciated that the detector may additionally include a mu metal magnetic shield 46 located about the sides 48 of photomultiplier tube 32 and extending forwardly of the photomultiplier tube 32 sufficiently far to surround a portion of the NaI(Tl) crystal 28.

Scintillation detectors of this kind have high efficiencies, that is, exhibit a high probability of detecting an incident gamma-ray. However, they also exhibit a relatively long detector response time. The detector response time is the time required by the detector to detect an incident gamma-ray and return to a state where the next incident gamma-ray can be accurately detected. Radiation detectors with long detector response times are thus prone to pulse pile-up. That is, the output, which ideally consists of completely discrete pulses each corresponding to the incidence of a single gamma-ray, instead exhibits a waveform in which individual pulses can overlap making them difficult to characterize.

Figures 3a, 3b and 3c illustrate the effect of pulse pile-up, and show illustrative signals or pulses plotted as energy E versus time t (both in arbitrary units). Figure 3a illustrates so-called 'tail-end pile-up' where, depending on the type of pulse conditioning employed, the tail 50 of one pulse 51 can provide a significant positive or negative bias positive in the illustrated example to the

amplitude of a subsequent pulse 52. Although the time displacement between the two pulses, Δt, is relatively large when compared with the overall time interval for which the pulses prevail, the signal envelope or resultant waveform 54 is significantly above zero at the arrival of the second pulse 52.

The absence of a true zero signal state between the two pulses corrupts the pulse characterization, as the amplitude of the second pulse is falsely inflated by the tail of the first. Figure 3b illustrates another form of pulse pile-up, 'peak pile-up'. Here two pulses 56 and 58 arrive closely spaced in time i.e. the time displacement Δt between the pulses is small compared with the overall time interval over which the pulses prevail. The resultant output waveform 60 appears more or less as a single pulse of somewhat greater amplitude than either of the component pulses. In situations where the flux of gamma-rays through the detector is extreme, it is not uncommon to have multiple events arriving within the response time of the detector leading to multiple pile-up events. Such a case is illustrated by Figure 3c. Multiple signals or pulses (such as those shown at 62) arrive with random time separation Δt and sum to produce a resultant waveform 64 from which the parameters of the component signals are difficult to extract.

One component of the method of addressing pulse pile-up according to this embodiment is the estimation of certain parameters of the signals or pulses; these parameters are the number, time-of-arrival and energy of all gamma-rays in the detector data stream. These parameters are estimated, according to this embodiment, by modeling the signals in the data stream mathematically. The model employed in this embodiment includes certain assumptions about the data and the apparatus, as are discussed below.

Figure 4 is a diagram that illustrates the modeling of the radiation detection process. The radiation $g(t)$ 70 is incident on the detector 72 represented by the measurement process $m(t)$, resulting in output data from the detector $y(t)$ 74. The addition of a sampling process 76 produces the digital detector data or 'time-series' $x[n]$ 78.

It is possible to add to the above-described model some knowledge about the physical processes of radiation detection. Figure 5 illustrates a more detailed mathematical model of the detection process shown in Figure 4. The input $g(t)$ to the detector is characterized by Equation 1, in which the input $g(t)$ is

assumed to be an unknown number (N) of delta-function-like impulses of random amplitude (α) and time of arrival (τ). An illustrative example of such input is shown at 80.

$$g(t) = \sum_{i=1}^{N} \alpha_i \delta(t - \tau_i) \qquad i = 1, 2, 3, \ldots, N. \tag{1}$$

The radiation detector is assumed to have a specific response to the incoming radiation, referred to as the detector impulse response $d(t)$ (or, equivalently, the signal form of the signals in the data), which is illustrated at 82. The digitized version of the detector impulse response (i.e. signal form) is denoted $d[n]$.

The output from the detector is shown at 86 and characterized by Equation 2, in which the detector output $y(t)$ is the sum of an unknown number of signals of predetermined signal form $d(t)$, with unknown energy (α) and unknown time of arrival (τ). Sources of random noise $\omega(t)$ 84 are also considered. The digital detector data $x[n]$ 88 is produced by the analog to digital converter 76.

$$y(t) = \sum_{i=1}^{N} \alpha_i d(t - \tau_i) + \omega(t) \qquad i = 1, 2, 3, \ldots, N. \tag{2}$$

The digitized signal $x[n]$ (which constitutes a time series of data) at the output of the analog to digital converter 76, as illustrated at 88, is therefore given by

$$x[n] = \sum_{i=1}^{N} \alpha_i d[n - \Delta_i] + \omega[n], \tag{3}$$

where $d[n]$ is the discrete time form of the signal form $d(t)$, Δ_i is the delay in samples to the ith signal, and $\omega[n]$ is the discrete time form of the noise. The digitized signal $x[n]$ may also be written in matrix form as

$$\mathbf{x} = \mathbf{A}\alpha + \omega, \tag{4}$$

where $\mathbf{A}$ is an M x N matrix, the entries of which are given by

$$\mathbf{A}(n,i) = \begin{cases} d[n - \Delta_i] & \Delta_i \le n < \min(M, \Delta_i + T - 1) \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

Also, T is the length of $d[n]$ in samples, M is the total number of samples in the

digitized signal x[n], α is the vector of N signal energies, and ω is the noise vector of length M. Matrix **A** may also be depicted as follows:

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ \vdots & & & \\ 0 & \vdots & & \\ d[1] & & & \vdots \\ d[2] & 0 & & \\ \vdots & d[1] & & \\ d[T] & & & \\ 0 & \vdots & \ddots & 0 \\ & & & d[1] \\ \vdots & d[T] & & d[2] \\ & & & \vdots \\ 0 & \cdots & 0 & d[r<T] \end{bmatrix} \begin{matrix} \\ \\ \\ \leftarrow \text{row } \Delta_1 \\ \\ \leftarrow \text{row } \Delta_2 \\ \\ \\ \leftarrow \text{row } \Delta_N \\ \\ \\ \end{matrix}$$

Thus, the columns of matrix **A** contain multiple versions of the signal form. For each of the individual columns the starting point of the signal form is defined by the signal temporal position. For example, if the signals in the data arrive at positions 2, 40, 78 and 125, column 1 of matrix **A** will have '0' in the first row, the 1st datum point of the signal form in the second row, the 2nd datum point of the signal form in the 3rd row, etc. The second column will have '0' up to row 39 followed by the signal form. The third column will have '0' up to row 77; the fourth column will have '0' up to row 124 and then the signal form. Hence the size of matrix **A** is determined by the number of identified signals (which becomes the number of columns), while the number of rows depends on the number of samples in the time series.

The signal processing method of this embodiment thus endeavors to provide an accurate estimate of some unknown parameters of the detector data, including not only the number of component signals (N) in the detector output but also the energy (α) and time-of-arrival (τ) of each of the component signals.

Signal Processing Method

Figure 6 is a schematic diagram of the functional elements of data capture module 26 of Figure 1, with detector 16, and is provided to explain in more detail the signal processing method for pulse pile-up recovery employed by the

apparatus of Figure 1. Referring to Figure 6, detector 16 is connected to a pulse processing board 92 via an analog front end (AFE 94). The purpose of the AFE 94 is to digitize the signal produced by detector 16 by performing analog to digital conversion at, in this embodiment, 125 MHz with 12-bit conversion accuracy.

Figures 7a, 7b and 7c illustrate the waveform resulting from such digitization, over time ranges of 1000 microseconds, 100 microseconds and 10 microseconds respectively. The various peaks in these figures correspond to the detection of respective gamma-rays. Some peaks appear as discreet signals or pulses 110, 112 which may indicate the presence of only a single gamma-ray. Other peaks are due to the pile-up either of two peaks 116 or of three or more peaks 114.

After the output of detector 16 has been digitized by AFE 94, the signal processing method for pulse pile-up recovery is implemented. Referring again to Figure 6, the digital signal produced by AFE 94 is passed into the pulse processing Field Programmable Gate Array (FPGA) 96. The pulse processing FPGA (96) then implements the pulse processing method of this embodiment; a digital signal processing coprocessor 98 may optionally be used to assist the pulse processing FPGA 96 to implement the pulse processing method. Variables required by the pulse processing FPGA 96 and data produced at interim steps of the pulse processing method are optionally stored in memory 100. The signal processing is controlled via a Data/Control Interface 102 which, in conjunction with a Control Processor 104, can be used to modify the implementation of the signal processing. The output data from the signal processing method can be displayed on a display 106 via the Data/Control Interface 102. Display 106 is provided in a computer that may, if desired, be used to perform post-processing and system control.

Figure 8 is a schematic diagram of the signal processing method for pulse pile-up recovery of radiation signals in the detector time series of this embodiment. The digitized detector signal (from AFE 94) forms the input 120 for this signal processing method. Offline System Characterization 122 is used to determine the detector impulse response unique to the particular digitized detector signal. Characterization data generated in System Characterization phase 122 is used in a Pulse Localization phase 124. The Pulse Localization phase 124 estimates, in real-time, the number and temporal position (or time-of-arrival) of

radiation pulses within the digitized detector signal. In a Pulse Identification phase 126, the digitized detector signal, the detector impulse response and the output from the Pulse Localization phase 124 are used to determine the energy of the signals or pulses. Validation 128 involves comparing the output of the Pulse Identification phase 126 with the digitized detector signal 120. If this comparison indicates that any of the pulse parameters have been estimated inaccurately, those parameters are rejected so that only valid data is output 130. The error signal generated in the Validation phase 128 is also employed in System Characterization 122. In circumstances where the detector impulse response may change over time, such as owing to the aging of components, temperature variations or increased radiation fluxes, System Characterization 122 updates the detector impulse response online and adaptively by employing the error signal. Such updating of the detector impulse response may be performed with any suitable adaptive method, such as least mean squares adaptation, normalized least mean squares adaptation or recursive least squares adaptation as described, for example, by S. Haykin [*Adaptive Filter Theory*, 4th Ed, Prentice Hall, 2002].

Figure 9 is a flow diagram of the signal processing method of this embodiment. At step 140, calibration is performed. This involves Data Regularization or Conditioning 142, Data Selection and Fitting 144 and Optimal Filter Construction 146. In Data Regularization 142, calibration data signals recorded at a low incident radiation flux are loaded from data files, the integrity of these calibration data is checked and any bias in the baseline of the data removed. Data Selection and Fitting 144 involves selecting only that data corresponding to the detection of single radiation events and constructing a data based model of the detector impulse response. A functional form of this model is then obtained by fitting a suitable function to the data, such as a polynomial, exponential or spline function. This results in the expected impulse response of the detector $d[n]$. Optimal Filter Construction 146 employs this detector impulse response to construct a suitable filter for the detector, such as an inverse filter or a matched filter.

At step 150 data is acquired, but may be affected by significant pulse pile-up. The data may be input 152 either from a file or directly from the detector elements 16.

At step 160 signal processing routines are applied to determine the amplitude

and timing parameters of the signals in the time series. Firstly the data is conditioned 162 to remove any bias in the baseline of the data. Next, the detector data is convoluted 164 with the filter derived in step 146 to provide an initial estimate of the time-of-arrival parameters (τ) and number of pulses (N). The timing parameters and estimate of the number of pulses are then further refined 166 using a suitable peak detection process, and the energy parameter (α) is determined from τ, N and the detector impulse response $d[n]$ (such as by linear programming, matrix inversion or convolution techniques). Finally, from the number (N), energy (α), timing (Δ_i) and detector impulse response ($d[n]$), an estimate of the detector data stream ($\hat{x}[n]$) is made 168.

The parameter vector (α) may be determined by linear programming or by solving the system of linear equations defined in Equation 4 using a suitable method for solving such systems of equations, such as one of those described, for example, by G.H. Golub and C.F. Van Loan [*Matrix Computations*, 2nd Ed, Johns Hopkins University Press, 1989].

At step (170) the validation phase 128 referred to above is performed, which may be referred to as error checking as, in this embodiment, validation involves determining an error signal $e[n]$, computed successively for the set of samples corresponding to each signal i where $1 < i < N$ (N being the total number of signals in the data stream). This error signal is calculated by determining 172 the squares of the differences between the time series data $x[n]$ and the model based data-stream ($\hat{x}[n]$ from step 168); $e[n]$ is thus the square of the difference between $x[n]$ and $\hat{x}[n]$, as given in Equation 6.

$$e[n] = (x[n] - \hat{x}[n])^2 \qquad (6)$$

If $e[n]$ exceeds a predetermined threshold, these parameters are rejected 174 as this condition indicates that the signal parameters do not produce a model of the respective signal that acceptably conforms to that signal (that is, is sufficiently accurate); the relevant signal is deemed to constitute corrupted data and excluded from further spectroscopic analysis. The threshold may be varied according to the data and how closely it is desired that the data be modeled; generally, therefore, in any particular specific application, the method of validation and definition of the threshold are chosen to reflect the requirements of that application.

One example of such a threshold is the signal energy α_i multiplied by a suitable

factor, such as 0.05. Validation will, in this example, deem that the model acceptably conforms to the data constituting signal *i* when:

$$e[n] < 0.05\alpha_i \quad (7)$$

Validation may be performed by defining the error signal and threshold in any other suitable way. For example, the error signal may be set to the absolute value of the error. The threshold may be defined to be a multiple other than 0.05 of the signal amplitude. Another threshold comprises a number of noise standard deviations.

Decreasing the threshold (such as by decreasing the coefficient of α_i in Equation 7) enables improved energy resolution at lower throughput, while increasing the threshold enables improved throughput at reduced energy resolution.

At step 180 a decision is made as to whether there is sufficient data. If not, processing continues at step 150. Otherwise, the method proceeds to step 190. At step 190 a gamma-ray energy spectrum is created. The gamma-ray energy parameters determined at step 166, which were deemed to be of sufficient accuracy at step 174, are represented 192 in the form of a histogram. This is the gamma-ray energy spectrum on which spectroscopic analysis may be performed.

Results of Signal Processing Method

Figures 10a, 10b and 10c are plots of the results at various stages of processing of the digital signal processing method described above by reference to Figures 8 and 9, for digitized data collected with a scintillation gamma-ray detector. The detector data stream was digitized by an analog to digital converter at 125 MHz and 12 bit accuracy; the gamma-ray source used was a 137Cs source with a primary gamma-ray emission of 661.7 keV.

Scintillation detectors employ light generated by the detector/radiation interaction to detect and measure that incident radiation. A scintillation detector may comprise organic scintillators or inorganic scintillators. Organic scintillators include both organic crystalline scintillators and liquid organic solutions (where the scintillating material has been dissolved to form a liquid scintillator, which can then be plasticized to form a plastic scintillator. Inorganic scintillators

include crystalline scintillators such as NaI(Tl), BGO, CsI(Tl) and many others, and photo switch detectors (in which a combination of two or more dissimilar scintillators are optically coupled to a common PMT to exploit the differing decay times of the scintillators to determine where a radiation/detection interaction has occurred).

In this example the detector comprised a 76 mm × 76 mm NaI(Tl) gamma-ray scintillation detector. Figure 10a is a plot of a portion of the digitized detector data 200 prior to processing by the signal processing method plotted as energy E(keV) versus time t(μs), together with the results (for example, at 210) of the signal processing method plotted in terms of the temporal position and energy of the component signals. For example, what may appear to be a single peak 220 in the original digitized detector data 200 at approximately 75.8 μs has been resolved into two distinct signals 222, 224 at respectively 75.3 and 75.7 μs.

From the determined temporal positions, energies and forms of the signals it is possible to generate a model of the detector data. Figure 10b is a plot of the resulting data model 230, shown as energy E(keV) versus time t(μs), of that portion of the digitized detector data stream 200 shown in Figure 10a. An inverted error plot 240, comprising a plot of the squares of the differences between the detector data 200 and the data model 230, is also shown, and indicates the error in the model 230. The error signal is small where the model 230 has tracked the output of the detector accurately, but the error becomes large when there are inconsistencies between the model 230 of the detector data and the detector data 200 itself. Based on this error signal 240, a decision can be made as to whether to accept or reject the signal parameters estimated by the signal processing method.

Figure 10c is a gamma-ray energy spectrum 250 shown as a log-linear plot, produced by the signal processing method. The energy parameters that have been accepted are plotted as a histogram, where the horizontal axis represents the energy E(keV) of each signal in a respective bin, and the vertical axis represents the number of counts N of that energy determined to have been detected in the collection period (in this example, 1 s).

Figure 11 is a plot of exemplary gamma-ray energy spectra, collected using a sodium iodide NaI(Tl) gamma-ray detector. The gamma-ray energy spectra

shown in Figure 11 demonstrate the performance of the signal processing method for pulse pile-up recovery at a range of count rates. The experimental data were collected using a 76 mm × 76 mm Canberra brand NaI(Tl) gamma-ray detector (model number 802) coupled to a detector base (model number 2007); no preamplifier was used. The signal processing hardware was connected to the dynode output of the detector base via a 65 MHz 14-bit analog to digital converter.

The NaI(Tl) crystal was irradiated with a collimated gamma-ray beam, which ensured that the central portion of the detector was illuminated with an essentially parallel beam of gamma-rays; the beam diameter was 50 mm.

Two 137Cs gamma-ray sources of 0.37 GBq and 3.7 GBq, in combination with three calibrated aluminium transmission filters, were used to obtain a range of gamma-ray fluxes at the detector face. The detector to source distance remained constant during data collection.

Referring to Figure 11, the spectra 260, 262, 264, 266, 268 and 270 were collected at count rates of respectively 529 kHz, 230 kHz, 167 kHz, 124 kHz, 67 kHz and 9 kHz. As would be expected, the energy resolution of the data collected with the apparatus and processed with the method of this embodiment deteriorated as the count rate increased. Expressed as a percentage of the peak energy (i.e. 661.7 keV), the full width at half maximum (FWHM) of the peak was found to be, respectively, 9.6% 7.3%, 7.1%, 6.9%, 6.7% and 6.7%. For count rates of 9 kHz to 230 kHz, the energy resolution of the 137Cs gamma-ray energy peak at 661.7 keV remained less than 7.5%; that is, despite more than a 25 fold increase in the count rate from the NaI(Tl) detector, the energy resolution at 661.7 keV is degraded by less than 0.5%.

The performance of the signal processing method of this embodiment is also illustrated in Figure 12 and Figure 13. These two figures were generated from the results of a computer simulation, in which the input count rate could be accurately controlled hence enabling a very wide range of input count rates to be considered. Figure 12 is a log-log plot of the throughput of the signal processing method (i.e. that portion of the input count rate accurately detected) against input count rate from 0.1 to 2.5 MHz. The theoretical limit (i.e. where the throughput equals the input) is shown with a dashed line. This figure demonstrates that, over a very wide range of input count rates, the throughput

of the signal processing method remains greater than or equal to 90%.

Figure 13 is a linear-log plot comparable to Figure 12 but with percentage throughput plotted against input count rate from 0.005 to 10 MHz. In addition, Figure 13 includes plots of the energy resolution and peak position performance of the signal processing method of this embodiment. The energy resolution of the 137Cs peak degrades by less than 10% over 0 to 2.5 MHZ, and the peak position shows very little change over that range.

Figures 14a, 14b, 14c and 14d also depict the results of applying the signal processing method for pulse pile-up recovery of this embodiment to the output of a 76 mm × 76 mm NaI(Tl) gamma-ray detector. Approximately 14 μs of data was used to generate the data plotted in these figures. The figures are plots of energy E in arbitrary units against time t(μs).

Figure 14a is a plot of the output of AFE 94: an analog to digital conversion rate of 65 MHz and 14 bit resolution was used to convert the time varying voltage output of the detector to digital data. Figure 14b is a plot of the results of applying the method. The temporal positions of the signals (depicted as vertical lines) have been resolved, as have the energies of the component signal (depicted as crosses). The temporal position and the energy of the component signal were used as described above, in conjunction with the signal form, to determine a model of the gamma-ray detector output: the resulting model is plotted in Figure 14c.

The digitized output of the gamma-ray detector was compared with the model of the gamma-ray detector output to derive an estimate of the error made in characterizing the gamma-ray detector output. This error signal is plotted in Figure 14d. It is then possible, on the basis of this error signal, to determine thresholds for the exclusion of signal parameter estimates, such as the decision to accept or reject an estimate of signal energy may be determined by the magnitude or the error near the position of a signal peak.

Figures 15a, 15b, 15c and 15d depict the results of applying the signal processing method for pulse pile-up recovery of this embodiment to data collected with a semiconductor (or solid state) detector. Such detectors employ the interaction of incident radiation with the electrons in the crystalline lattice of the semiconductor, forming electron hole pairs. Examples of these detectors include High-Purity Germanium (HPGe) detectors, Silicon Diode detectors,

semiconductor drift detectors (such as Silicon Drift detectors), Cadmium Telluride (CdTe) detectors and CZT detectors.

Hence, the apparatus of Figure 1 was employed, though with a detector unit in the form of a Canberra Industries brand High Purity Germanium (HPGe) detector substituted for detector 16, and with a 57Co gamma-ray source (whose two principal gamma-rays have energies of 122.1 and 136.5 keV) rather than a neutron source and specimen. The output of the HPGe detector was fed through a pre-amplifier and then into an Ortec brand pulse shaping amplifier. Approximately 92 μs of data was collected, from which was generated the data plotted in Figures 15a, 15b, 15c and 15d as energy E in arbitrary units against time t(μs). Figure 15a is a plot of the output of AFE 94. The time varying voltage output of the detector was converted to digital data at an analog to digital conversion rate of 65 MHz with 14 bit resolution. Figure 15b is a plot of the results of applying the method. The temporal positions of the signals (depicted as vertical lines) have been resolved, as have the energies of the component signal (depicted as crosses). The temporal position, the energy of the component signal and the signal form were used to determine a model of the processed HPGe detector output, which is plotted in Figure 15c.

Figure 15d is a plot of the error signal, derived from a comparison of the digitized processed output of the HPGe detector and the model of that output. This error signal can again be used to determine thresholds for the exclusion of signal parameter estimates.

Figures 16a, 16b, 16c and 16d depict the results of applying the signal processing method for pulse pile-up recovery of this embodiment to the output of a gas proportional detector used for detecting X-rays. Gas proportional detectors are a class of detector whose behavior is similar to that of solid state detectors. Gas proportional detectors rely on the interaction of the radiation with a gas in a chamber. An electric field is created in the chamber between an axial wire and the walls of the chamber. Radiation passing through the gas ionizes the gas, which produces electrons that then collect on the wire owing to the electric field, and are output as the detector data.

Thus, a simplified form of apparatus 10 of Figure 1 was employed, with a detector in the form of a Xenon gas proportional detector substituted for detector 16, and with an X-ray generator from an X-ray diffraction apparatus

rather than neutron source 14. Approximately 300 μs of data was used to generate the data plotted in Figures 16a, 16b, 16c and 16d, which plot energy *E* in arbitrary units against time *t*(μs). A significantly longer data collection period was used compared with that of the previous examples, owing to the relatively long decay time of the xenon gas proportional detector (of the order of 50 μs or more). For this reason also the sampling rate of AFE 94 was reduced.

Figure 16a is a plot of the output of AFE 94; in this example an analog to digital conversion rate of 15 MHz and 14 bit resolution was used to convert the time varying voltage output of the detector to digital data. Figure 16b is a plot of the results of applying the method. The temporal positions of the X-ray signals (depicted as vertical lines) have been resolved, as have the energies of the component signal (depicted as crosses). The temporal position and the energy of the component signal were used as described above, in conjunction with the signal form, to determine a model of the Xenon gas proportional detector output: the resulting model is plotted in Figure 16c.

The digitized output of the Xenon gas proportional detector was compared with the model of the Xenon gas proportional detector output to derive an estimate of the error made in characterizing the Xenon gas proportional detector output. This error signal is plotted in Figure 16d. This error signal can then be used to determine thresholds for the exclusion of signal parameter estimates, such as the decision to accept or reject an estimate of signal energy may be determined by the magnitude or the error near the position of a signal peak.

Plural Signal Forms

For some detector types, such as large volume solid state detectors, the form of a given signal may be one of a plurality of possible signal forms. This may be intrinsic to the detector type, or be due to temperature or other measurement-specific factors.

For example, a CsI(Tl) detector is a scintillation detector that, depending on whether a neutron or gamma-ray is being detected, exhibits two distinct signal forms. Solid state radiation detectors can exhibit a time-varying signal form, even when detecting only one form of radiation; large volume High Purity Germanium (HPGe) detectors, for example, can produce an output signal whose form depends on the specific site of interaction between the radiation and the detector. The interaction of radiation with the Germanium crystal of a

HPGe detector produces a multitude of electron-hole pairs; radiation induced charge is carried by both the electrons and the holes. However, the electrons and holes travel through the HPGe detector at different velocities, so the charge pulse produced by the electrons generally has a different form from that produced by the holes. Thus, the pulse produced by the detector (being the sum of the charges carried by both the electrons and holes) has a form dependent on the location of interaction.

Hence, the plurality of signal forms are the result of these varied physical mechanisms. The respective signal forms may be denoted $d_1[n]$, $d_2[n]$,... , $d_Q[n]$, where Q is the total number of different signal forms that may be generated by a particular detector type. Each of the possible signal forms is characterized in the same way that the signal form of data having a single signal form is characterized. With plural signal forms, however, the calibration process must be extended for an appropriate length of time to ensure that all of the possible signal forms have been identified and characterized; the estimation of signal parameters, including temporal position and signal energy, can be performed once the form of each signal in the data stream has been identified. In order to estimate these signal parameters correctly, a number of possible extensions of the method described above (for data with a single signal form) may be employed.

1. The signal parameters, including signal temporal position and signal energy, may be estimated for each signal in the data stream by treating all signals in the data stream as having the same form, such as of the first signal, *viz.* $d_1[n]$. The parameters for those signals that do not acceptably conform to signal form $d_1[n]$ are rejected at the validation phase; signals for which the parameters have been estimated successfully and thus acceptably conform to signal form $d_1[n]$ are subtracted from the data stream. This process is repeated successively for $d_2[n]$ up to $d_Q[n]$, where at each stage signal parameters are estimated for signals that are of the signal form used at that stage. At each stage matrix Equation 4 is solved with matrix **A** constructed repeatedly using, in iteration p, the signal form $d_p[n]$. At the conclusion of the process, those signals that have not passed the validation phase for any of the plurality of signal forms are rejected as not acceptably conforming to any of the plurality of signal forms.

2. In a variation of the first approach, the signal parameters are estimated for each of the signal forms in turn, but the signal estimates are not subtracted at

each stage. Instead, the estimated signals are used in a final signal validation stage to determine the signal form and signal parameters that provide the best overall estimate of the data stream. This allows for the possibility that a signal is incorrectly estimated to be of one form, when it is actually of a form that has not yet been used to estimate the signal parameters.

3. In a further variation of the first approach, it may be possible to model each of the signal forms $d_p[n]$ as a linear combination of two signal forms, termed $d_1[n]$ and $d_2[n]$ for convenience. Hence, the *p*th signal form $d_p[n]$ is modeled as:

$$d_p[n] = (a.d_1[n] + b.d_2[n]) \qquad (8)$$

where *a* and *b* are unknown constants that can be determined directly from this equation if necessary. In order to solve the matrix equation in this case, the matrix equation is extended to be:

$$\mathbf{x} = [\mathbf{A}_1 \ \vdots \ \mathbf{A}_2] \begin{bmatrix} \gamma \\ \cdots \\ \beta \end{bmatrix} + \omega, \qquad (9)$$

where the sub-matrices $\mathbf{A}_1$ and $\mathbf{A}_2$ are formed from the signal forms $d_1[n]$ and $d_2[n]$ respectively using Equation 5. The vector of unknown signal energies α has been redefined as being made up of vectors γ and β, so that the energy of the actual signal form of signal *i* can be estimated as $\alpha_i = \gamma_i + \beta_i$. The new system of linear equations is solved using the same methods as those used to solve the earlier matrix equation, Equation 4. It should be noted that this approach allows for the possibility that the signal form may be from a continuum of possible signal forms that can be represented as a linear combination of the two signal forms $d_1[n]$ and $d_2[n]$.

Thus, this approach permits a practically unlimited number of signal forms to be represented.

4. In a further variation of approach 3, the procedure of decomposition of each of the plurality of signal forms into a linear combination of just two signal forms may be extended to the general case where the plurality of signal forms may be decomposed as a linear combination of an arbitrary number of signal forms.

The matrix **A** and the signal energy vector **α** is augmented accordingly.

EXAMPLE

An exemplary oil well logging apparatus according to the embodiment of Figure 1 was tested by lowering its tool 12 into a container of test material. The test material was illuminated with neutron source 14, observations were made with detector 16, whose output was pre-processed by pulse shaping module 24 and recorded on data capture and analysis module 26. The pre-processed detector output was captured at a sample rate of 52.5 MHz.

The procedure was repeated at different source intensities, so as to achieve different detection count rates. In this way the throughput performance and energy resolution variation with count rate of apparatus 10 could be assessed.

The objective of the analysis was to obtain radiation energy spectra for each of the source and processing electronics configurations, and to obtain spectra obtained during the periods when source 14 was on, when source 14 was off, and when the source was off for long intervals.

The analysis was performed off-line: the recorded data was subsequently 'played' into the data analysis component of data capture and analysis module 26, the output of which was used to produce energy spectra for display. The analysis process is illustrated in Figure 8, which also shows the intermediate steps of the analysis. Output 130, in this example, comprised a histogram plot of the processed data on the display of data capture and analysis module 26.

Figure 17 is a plot of energy spectra collected with source 14 on, plotted on log-linear scale, while Figure 18 is a plot of energy spectra collected with source 14 off, also plotted on log-linear scale. In both cases, the three spectra (a), (b) and (c) correspond to different currents supplied to neutron source 14, and hence different count rates. These count rates were approximately 600–700 kHz, 300 kHz and 150 kHz. The higher the current of neutron source 14, the more neutrons are generated in any given neutron pulse and therefore the more gamma-rays produced in the test material and detected. The data was collected over the same period in each case, so the higher spectra relate to higher count rates.

For each experiment, 500 data files were recorded, with each file containing

262,144 data samples, or approximately 5 ms of data at the 52.5 MHz sampling rate. Hence a total of 2.5 seconds of data was recorded for each experiment.

The different stages of the data processing are illustrated by showing the results of the analysis of a small section of the recorded data in Figure 19. Figure 19 comprises four plots; from top to bottom these are (i) the input data stream, (ii) the pulse localization output, (iii) the pulse identification output, and (iv) validation error signal. In this analysis sample, the pulse identification output is almost perfectly overlaid on the input data stream, demonstrating the ability of apparatus 10 to resolve pulses in the presence of pulse pile-up, and accurately determine the energy of each pulse in the data stream. If the estimated pulse parameters are incorrect, a high validation error signal will result, and enable data in that region to be rejected.

The following observations can be made in the light of these results.

As the source intensity is increased, so too does the count rate of the processed output. Existing approaches reject data affected by pulse pile-up, which increases sharply with count rate, so the ratio of processed output to input stream diminishes. The ratio of processed count rate in the present measurements, however, is well maintained throughput as a percentage of input count rate.

As the count rate increases, the energy resolution of the main spectral feature (at approximately bin 200) remains almost constant. This demonstrates the ability of apparatus 10 to continue to perform well and maintain energy resolution at extremely high count rates.

In the source off spectra of Figure 18, features are visible that are not evident in the source on spectra of Figure 17. It is anticipated that with the additional use of a source synchronization signal, to avoid misallocation of data, such features would be still more clearly observed.

EXAMPLE

As will be appreciated by those in the art, in oil well logging a detailed understanding of the reservoir rock formation is required in order to improve the efficiency and cost effectiveness of oil extraction from the reservoir. Neutron activation techniques (inelastic, capture and activation) can be used in a down-

hole environment for the evaluation of most of the minerals and fluids found in subsurface geological formations. These techniques can be used to distinguish between oil, gas and water and also be used to identify minerals based on their elemental composition. A detailed understanding of the reservoir rock formation is essential for improving the efficiency and cost effectiveness of oil extraction from the reservoir. Other nuclear techniques including: neutron backscatter; gamma-ray logs and natural gamma-ray logs may also be used to understand characteristics of the rock formation.

Figure 20 is a schematic diagram of neutron activated gamma-ray spectroscopy well-logging tool 280 of an embodiment of the present invention, located in a borehole 282 surrounded by rock formation 284. Tool 280 has a pressure resistant collar 286 to enclose and protect its other components from the environment encountered in use. Within collar 286, tool 280 has a chassis 288 to encase those components. Tool 280 has an overall length of approximately 3 m and a diameter of from 8 to 16 cm (according to application).

The components of tool 280 include a radiation source towards the distal end of tool 280 in the form of an electronic neutron generator (ENG) 292 (though other tools employ an isotopic source, such as AmBe). An ENG can produce a high radiation flux *in situ* without the radiation handling risk on the surface, as it can be turned on while the borehole but shut off when on the surface. ENG 292 generates neutrons by electrically accelerating deuterium ions into a tritium or deuterium target; the neutron output may be pulsed at tens of kHz. Tool 280 also has electronics 294, adapted both to control the pulsing of ENG 292 and the gating of the detected radiation and located adjacent—and distal to—ENG 292.

Tool 280 includes, proximal to ENG 292, a neuron detector 296 for tracking the actual output flux of neutrons from ENG 292, as the absolute strength of the nuclear source is often important in the calibration of detection. Proximal to neutron detector 296, tool 280 has lead or tungsten shielding 298, followed by near detectors 300 and, then—towards the proximal end of tool 280—far detectors 302. Shielding 298 reduces the flux of radiation due to ENG 292 through near detectors 300, as that flux constitutes a background in any actual measurements.

Tool 280 also includes stabilisers 304, which are used to urge tool 280 against

one side of borehole 282 in use.

In use, tool 280 is lowered down borehole 282. ENG 292 is activated, and emits neutrons isotropically into the surrounding reservoir rock formation 284 where they interact with the constituent elements of the formation. A portion of the resultant radiation flux in turn interacts with near detectors 300 and far detectors 302. Depending on the nuclear interaction being used the resultant radiation includes gamma-rays or neutrons. The signals outputted by near detectors 300 and far detectors 302 are subjected to spectroscopic analysis according to the method of the present invention described above by reference to Figure 9; in addition, the time distribution of detected neutrons and/or gamma rays can be used to further probe the constituent elements of rock formation 284.

ENG 292 can produce neutron yields in the order of $2–3\times10^8$ neutrons per second, substantially higher than isotopic sources. (Isotopic sources are limited by the requirement for safe handling, such as to 4×10^7 neutrons per second for 16 Curies of AmBe.) The flux of the neutrons from source (whether ENG or isotopic source) affects the count-rate observed in near detectors 300 and far detectors 302, but with an ENG the instantaneous count-rate can range up to several hundred thousand counts per second. At the elevated count-rates produced by ENGs the effects of detector and electronic timing resolution are very significant and dead-time corrections and pulse pile-up rejection techniques are employed to facilitate accurate elemental composition estimation.

Figure 21 is a plot of calculated throughput count rate (kHz), that is, the number of events correctly registered by one of the detectors of tool 280 and electronics 294, versus input count rate (kHz). The dashed line 310 indicates an ideal system where throughput count rate equals input count rate. The performance of tool 280 (implementing the signal processing method for pulse pile-up recovery of the embodiment of Figure 9) has been calculated and is plotted as stars in this figure at 310. The calculated throughput count rate of the GSO scintillation detector with standard detector electronics is plotted as circles at 312. It can be seen that the performance of the GSO with standard detector electronics reaches a point 314 at which further increases in input count rate (such as from an increase in the strength of the radiation source) do not produce an increase in throughput count rate. This is because the probability of

pile-up increases as the input count rate increases, and data corrupted by pulse pile-up cannot be used.

Figures 22a and 22b are plots of calculated percentage throughput versus input count rate, depict the percentage of input radiation events which will be detected without pulse pile-up. It is apparent from these plots that, at an input count rate of 200 kHz (cf. point 320), the throughput of the GSO detector with standard electronics is approximately 78%, whereas tool 280—employing a GSO detector with the signal processing method of the present embodiment—at this count rate has a throughput of approximately 98%. Hence, the time required to conduct an oil well log at any particular depth—the dwell time—using tool 280 is expected to be about 78/98 = 80% the time required using standard detector electronics.

However, as depicted in Figure 22b, the method of the present invention is able to operate at input count rates significantly above 200 kHz while maintaining good throughput statistics: at an input count rate of 2 MHz (cf. point 330) the throughput remains greater than 75%. If a source strength were employed such that the input count rate were 2 MHz it would be possible to reduce, by a factor of 9.6 (or, conservatively, by a factor of 2, or 5 in some applications), the time required to conduct an oil well log at any particular depth.

Nuclear logging tools of the background art but similar to that shown in Figure 20 may be able to conduct a standard oil well log at the rate of approximately 3600 feet per hour (~1100 m/h) and achieve an elemental accuracy of around ± 5%. Alternatively they may be able to conduct a 'high resolution' oil well log at the rate of approximately 1800 feet per hour (~550 m/h) and achieve an elemental accuracy of approximately ±2%. Using the tool of this embodiment, a standard oil well log, using a source that produced an input count rate of 200 kHz, could be run 20% faster at a rate of ~1,320 m/h (neglecting the time required to relocate tool 280 between measurements). Alternatively, if a high flux source is used, a logging rate faster than 1100 m/h may be obtained with an elemental accuracy greater than ±5%. It is thus reasonably expected that the ability to process significantly high throughput count rates should also enable the size of the nuclear well logging tool to be reduced below 3 m in length, by 10 or 20%.

The amount of shielding 298 between ENG 292 and detectors 300, 302 may

thus be reduced (or eliminated), or detectors 300, 302 may be made smaller (and hence lighter), or both, enabling a slimmer tool designed to fit into narrower boreholes. The selection of modification—and the resulting benefit—can be made according to application.

Figure 23 is thus a schematic diagram of neutron activated gamma-ray spectroscopy well-logging tool 340 according to an embodiment of the present invention, located in a borehole 282 surrounded by rock formation 284. Tool 340 is essentially identical with tool 280 of Figure 280, and like reference numerals are used to indicate like features. However, tool 340 has lead or tungsten shielding 342 that is thinner than shielding 298 of tool 280, and near and far detectors 344, 346 that are shorter than corresponding detectors 300, 302 of tool 280. Consequently, the overall length of tool 340 is significantly less than that of tool 280.

Modifications within the scope of the invention may be readily effected by those skilled in the art. It is to be understood, therefore, that this invention is not limited to the particular embodiments described by way of example hereinabove.

In the claims that follow and in the preceding description of the invention, except where the context requires otherwise owing to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

Further, any reference herein to prior art is not intended to imply that such prior art forms or formed a part of the common general knowledge.

CLAIMS:

1. A method of borehole logging, comprising:

collecting detector output data from a radiation detector of a borehole logging tool; and

resolving individual signals in the detector output data by (i) determining a signal form of signals present in said data, (ii) making parameter estimates of one or more parameters of said signals, wherein said one or more parameters comprise at least a signal temporal position, and (iii) determining the energy of each of said signals from at least said signal form and said parameter estimates;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

2. A method as claimed in claim 1, wherein said resolving of individual signals comprises:

obtaining said detector output data as digitized detector output data in a form of a digital time series; and

forming a mathematical model based on the digital time series and as a function of at least the signal form, the temporal position of the at least one signal, and an amplitude of the at least one signal;

wherein determining the energy of each of said signals comprises determining the amplitude of said signals based on said mathematical model, the amplitude being indicative of a radiation event.

3. A method as claimed in claim 1, comprising oil well logging.

4. A method as claimed in claim 1, wherein the logging tool is less than 3 m in length.

5. A method as claimed in claim 1, wherein the resolving of said signals reduces dwell time by a factor of 2 or more.

6. A method as claimed in claim 1, wherein the resolving of said signals increased logging tool speed by a factor of 2 or more.

7. A method as claimed in claim 1, characterized by an incident flux on said

radiation detector of gamma-rays of 100 kHz or more.

8. A method as claimed in claim 1, characterized by an incident flux on said radiation detector of gamma-rays of 500 kHz or more.

9. A method as claimed in claim 1, characterized by a data throughput of greater than 90% for an input count rate of 200 kHz.

10. A method as claimed in claim 1, characterized by a data throughput of greater than 70% for input count rates between 500 and 2000 kHz.

11. A method as claimed in claim 1, characterized by a data throughput of greater than 95% for an input count rate of 100 kHz.

12. A method as claimed in claim 1, characterized by a data throughput of greater than 95% for input count rates between 100 and 200 kHz.

13. A method as claimed in claim 1, comprising an input count rate of greater than 750 kHz.

14. A method as claimed in claim 1, comprising an input count rate of greater than 1 MHz.

15. A method as claimed in claim 1, wherein the detector comprises a GSO detector.

16. A method as claimed in claim 1, including pulse shaping the output of the detector.

17. A method as claimed in claim 1, including employing a source synchronization signal to avoid misallocation of data.

18. A borehole logging apparatus, comprising:

a borehole logging tool for irradiating a material surrounding the logging tool, detecting radiation emitted by the material, and for outputting detector data in response thereto; and

a processor for receiving the detector data in digitized form, and

programmed to determine the signal form of each of the signals present in the data, to make parameter estimates of one or more parameters of the signals, and to determine the energy of each of the signals from at least the signal form and the parameter estimates, wherein the one or more parameters comprise at least a signal temporal position;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

19. An apparatus as claimed in claim 18, wherein said processor is programmed to obtain said detector output data in a form of a digital time series and to form a mathematical model based on the digital time series and as a function of at least the signal form, the temporal position of said signals, and an amplitude of said signals;

wherein determining the energy of each of said signals comprises determining the amplitude of said signals based on said mathematical model, the amplitude being indicative of a radiation event.

20. An apparatus as claimed in claim 18, adapted for oil well logging.

21. An apparatus as claimed in claim 18, wherein said logging tool is less than 3 m in length.

22. An apparatus as claimed in claim 18, wherein use of the processor allows a reduction in dwell time by a factor of 2 or more.

23. An apparatus as claimed in claim 18, wherein use of the processor allows an increase in logging tool speed by a factor of 2 or more.

24. An apparatus as claimed in claim 18, including a pulse shaping module for pulse shaping the output of the logging tool.

25. A method of quantifying a chemical element in a formation traversed by a borehole, comprising:

collecting detector output data from a radiation detector of a borehole logging tool; and

resolving individual signals in the detector output data by (i) determining a signal form of signals present in said data, (ii) making parameter estimates of

one or more parameters of said signals, wherein said one or more parameters comprise at least a signal temporal position, and (iii) determining the energy of each of said signals from at least said signal form and said parameter estimates;

determining a quantity of the element from at least those of the signals arising from instances of the element in the formation;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

26. A method as claimed in claim 25, wherein said resolving of individual signals comprises:

obtaining said detector output data as digitized detector output data in a form of a digital time series; and

forming a mathematical model based on the digital time series and as a function of at least the signal form, the temporal position of the at least one signal, and an amplitude of the at least one signal;

wherein determining the energy of each of said signals comprises determining the amplitude of said signals based on said mathematical model, the amplitude being indicative of a radiation event.

27. A method of borehole logging, comprising:

collecting detector output data from a radiation detector of a borehole logging tool; and

resolving individual signals in the detector output data by (i) obtaining or expressing the detector output data as a digital series, (ii) obtaining or determining a signal form of signals present in the data, (iii) forming a transformed signal form by transforming the signal form according to a mathematical transform, (iv) forming a transformed series by transforming the digital series according to the mathematical transform, said transformed series comprising transformed signals, (v) evaluating a function of at least the transformed series and the transformed signal form and thereby providing a function output, (vi) modelling the function output according to a model, (vii) determining at least one parameter of the function output based on the model, and (viii) determining a parameter of the signals from the at least one determined parameter of the function output;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

28. A borehole logging apparatus, comprising:

a borehole logging tool for irradiating a material surrounding the logging tool, detecting radiation emitted by the material, and for outputting detector data in response thereto; and

a processor for receiving the data as a digital series, and programmed to (i) obtain or determine a signal form of signals present in the data, (ii) form a transformed signal form by transforming the signal form according to a mathematical transform, (iii) form a transformed series by transforming the digital series according to the mathematical transform, said transformed series comprising transformed signals, (iv) evaluate a function of at least the transformed series and the transformed signal form and thereby provide a function output, (v) model the function output according to a model, (vi) determine at least one parameter of the function output based on the model, and (vii) determine a parameter of the signals from the at least one determined parameter of the function output;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

29. A method of mineral logging, comprising:

collecting detector output data from a radiation detector of a mineral logging tool; and

resolving individual signals in the detector output data by (i) determining a signal form of signals present in said data, (ii) making parameter estimates of one or more parameters of said signals, wherein said one or more parameters comprise at least a signal temporal position, and (iii) determining the energy of each of said signals from at least said signal form and said parameter estimates;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

30. A mineral logging apparatus, comprising:

a mineral logging tool for irradiating a material, detecting radiation emitted by the material, and for outputting detector data in response thereto; and

a processor for receiving the detector data in digitized form, and

programmed to determine the signal form of each of the signals present in the data, to make parameter estimates of one or more parameters of the signals, and to determine the energy of each of the signals from at least the signal form and the parameter estimates, wherein the one or more parameters comprise at least a signal temporal position;

whereby the logging tool is shorter, logging tool speed is greater, dwell time is shorter and/or resolution is improved.

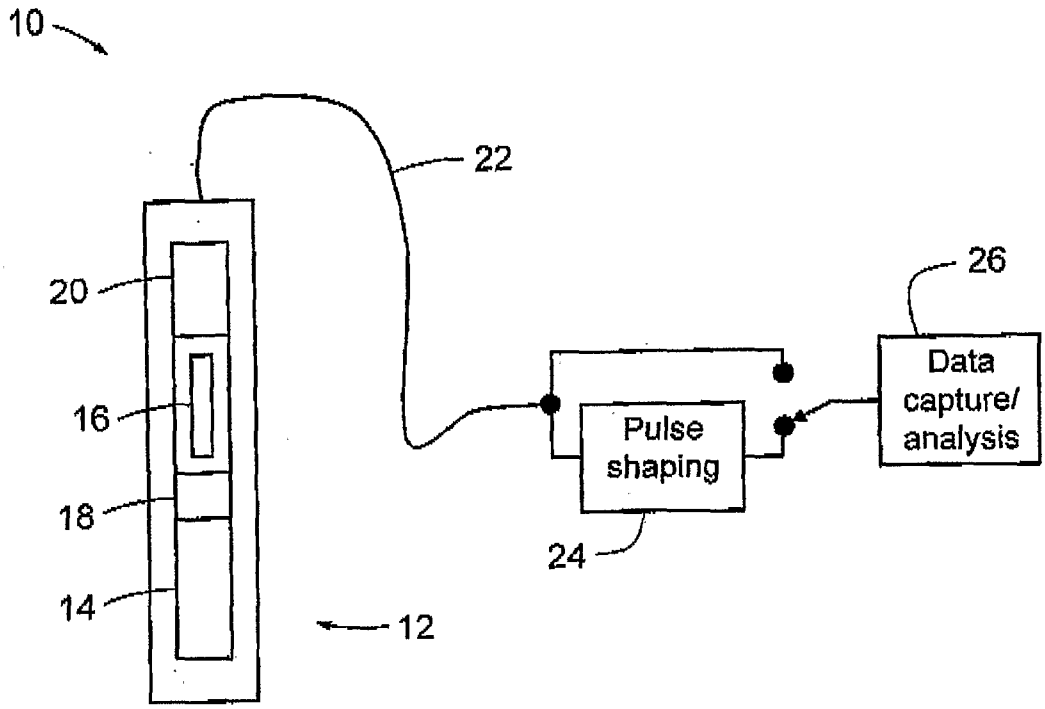


Figure 1

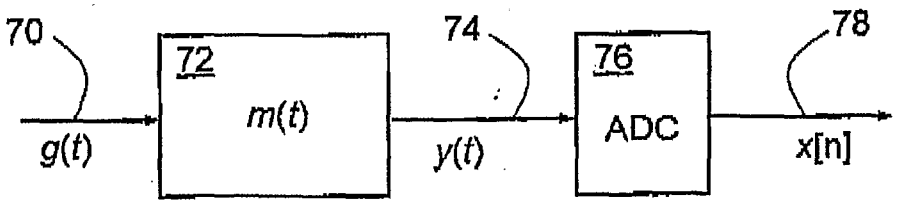


Figure 4

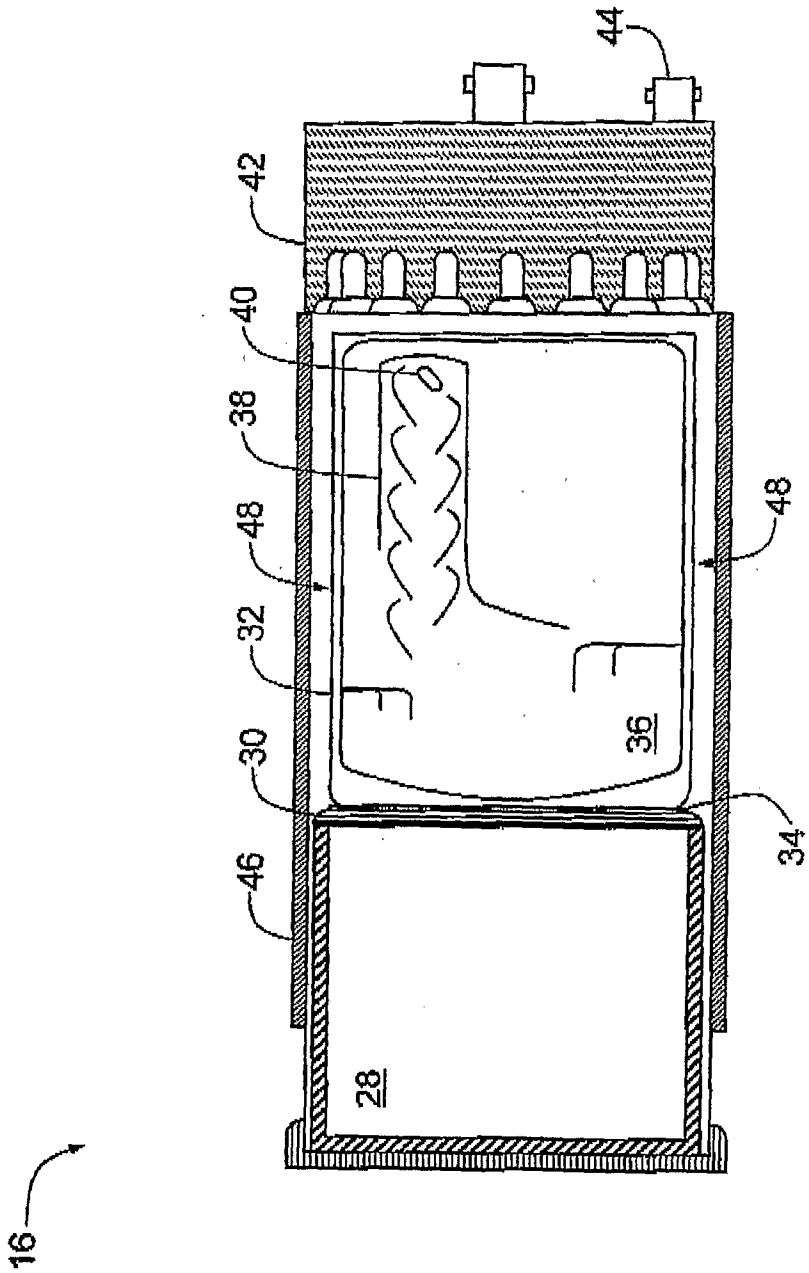


Figure 2

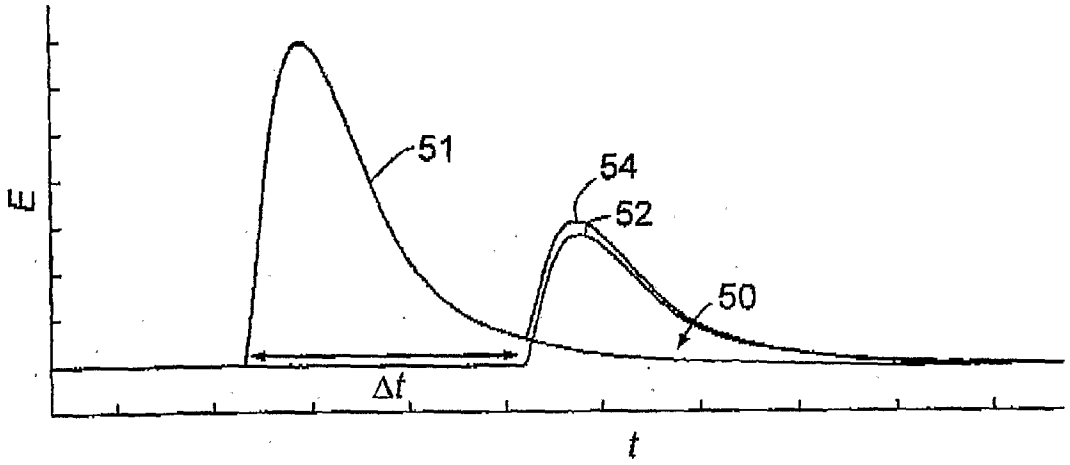


Figure 3a

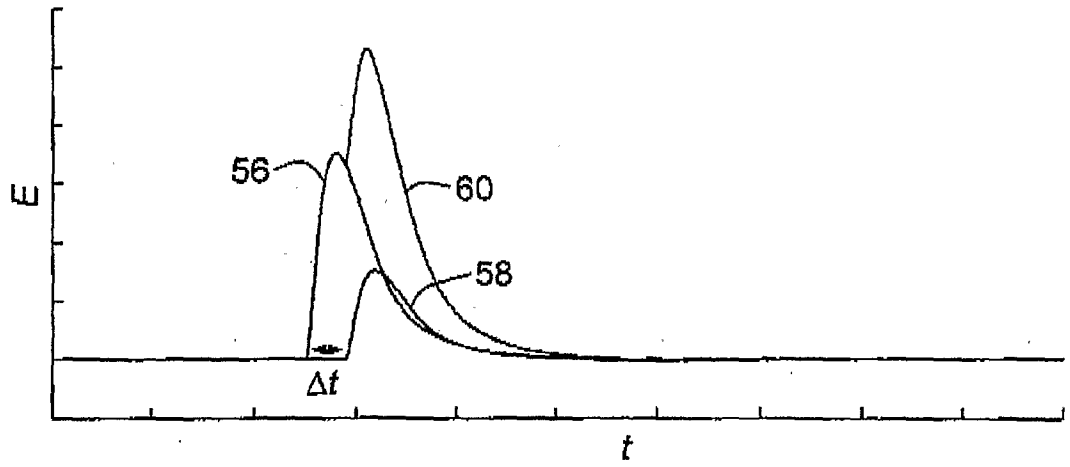


Figure 3b

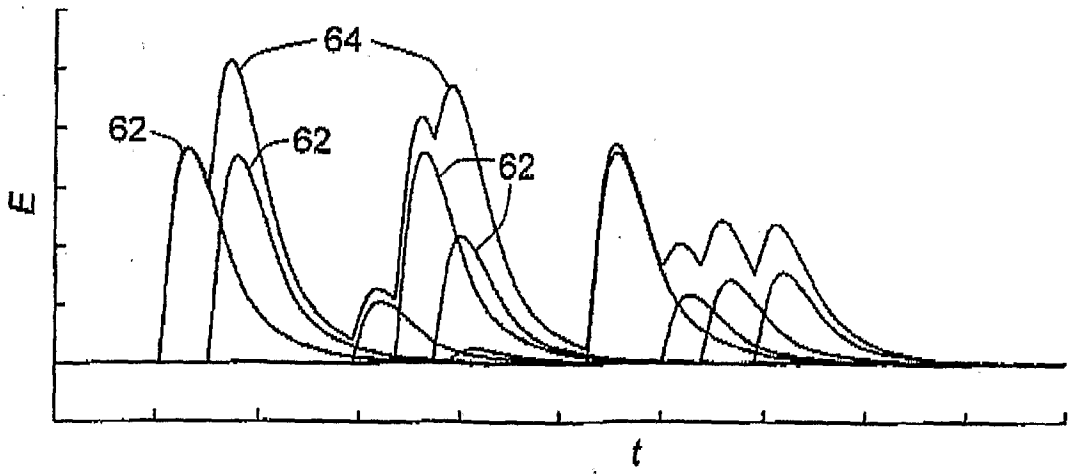


Figure 3c

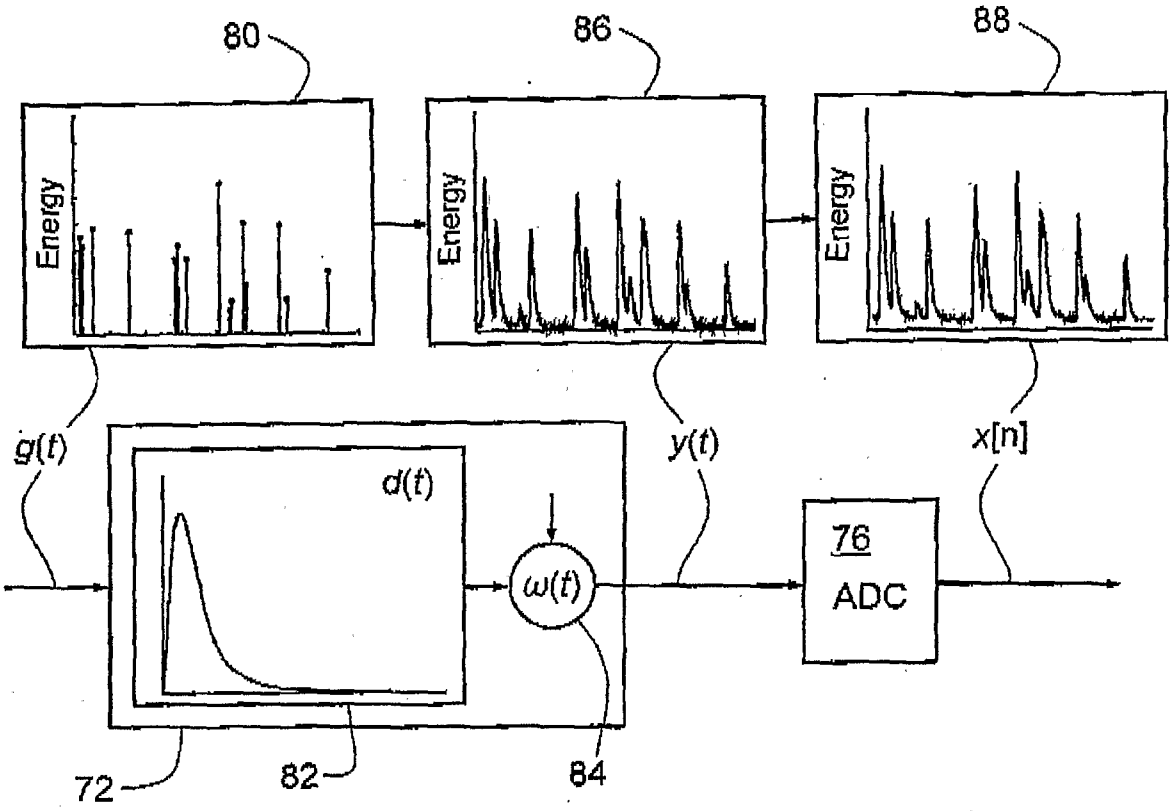


Figure 5

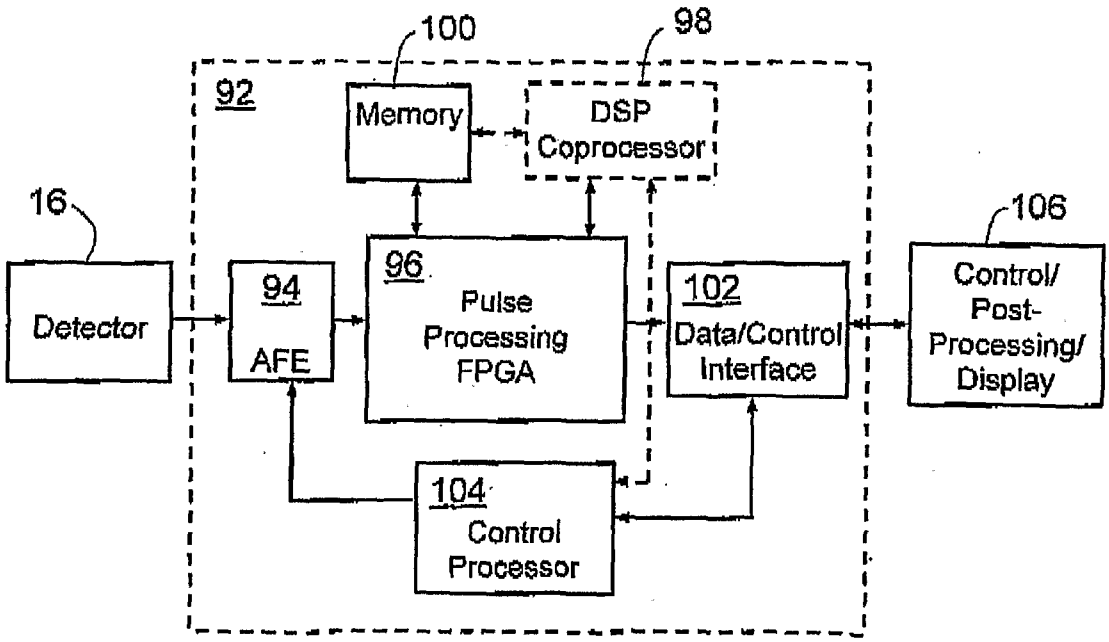


Figure 6

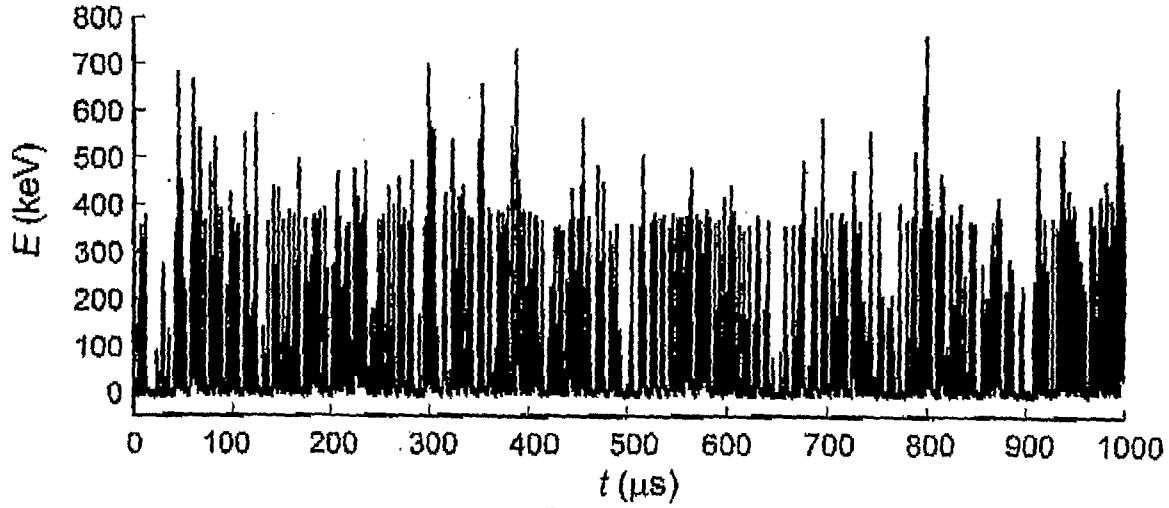


Figure 7a

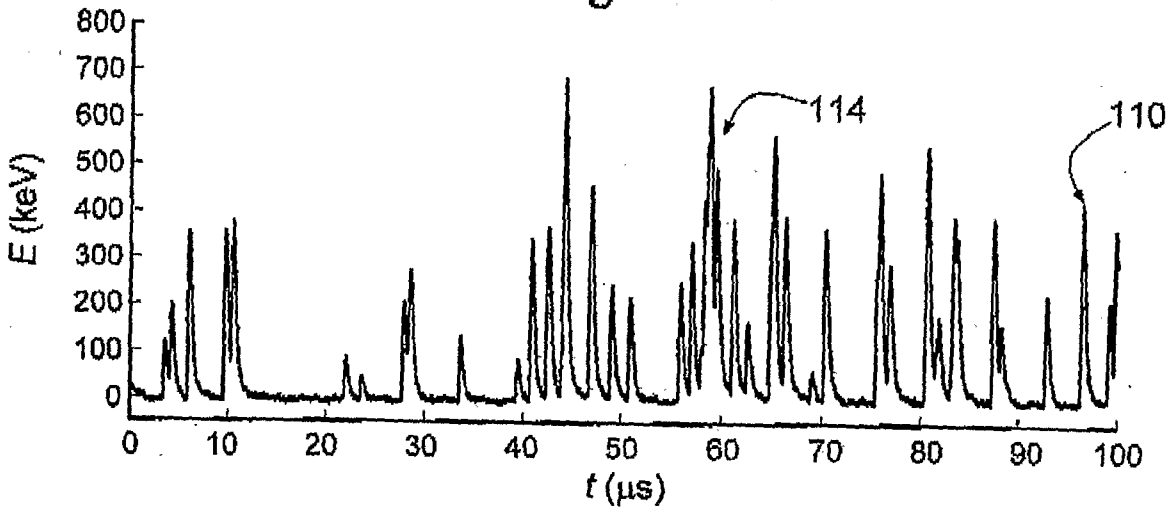


Figure 7b

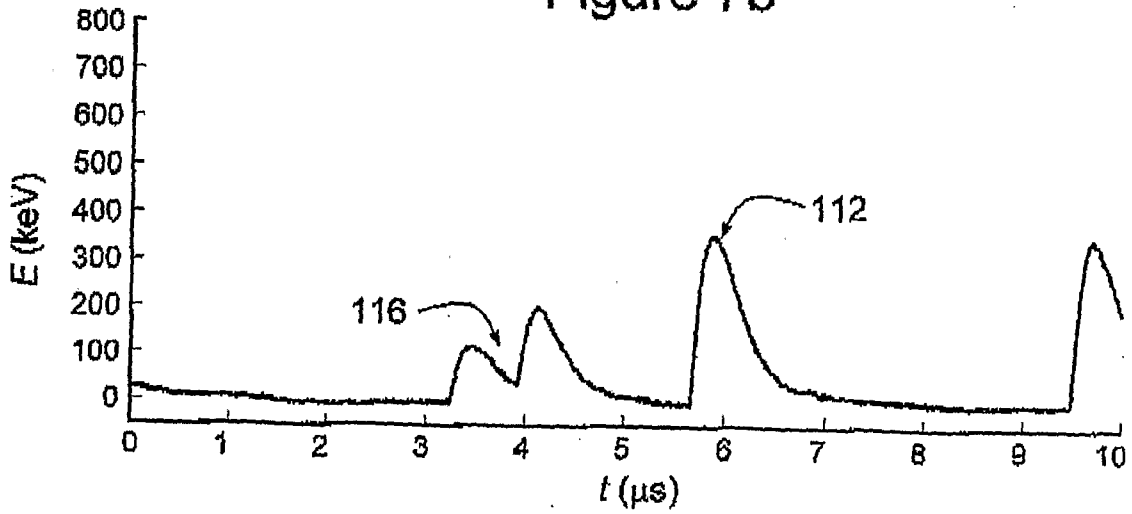


Figure 7c

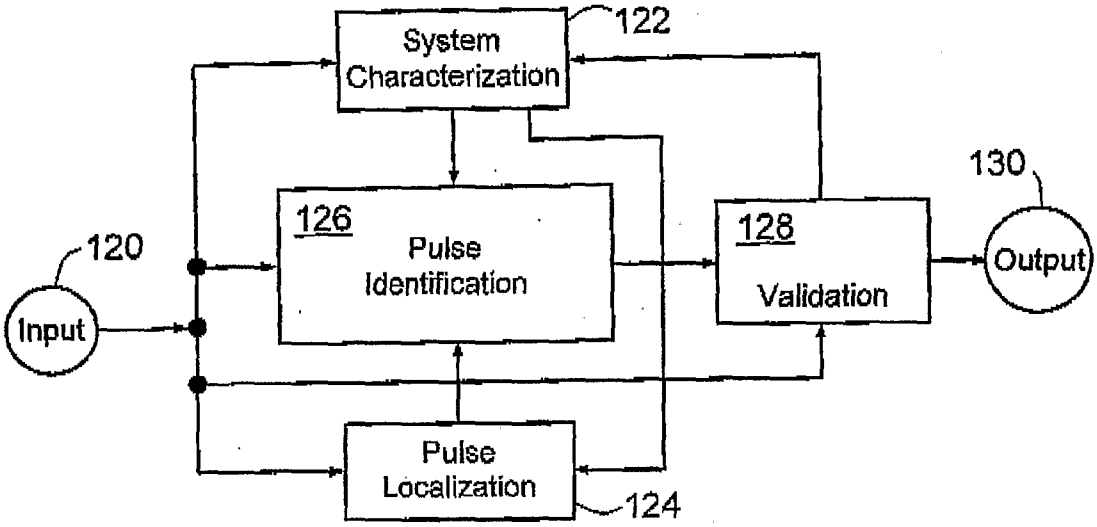


Figure 8

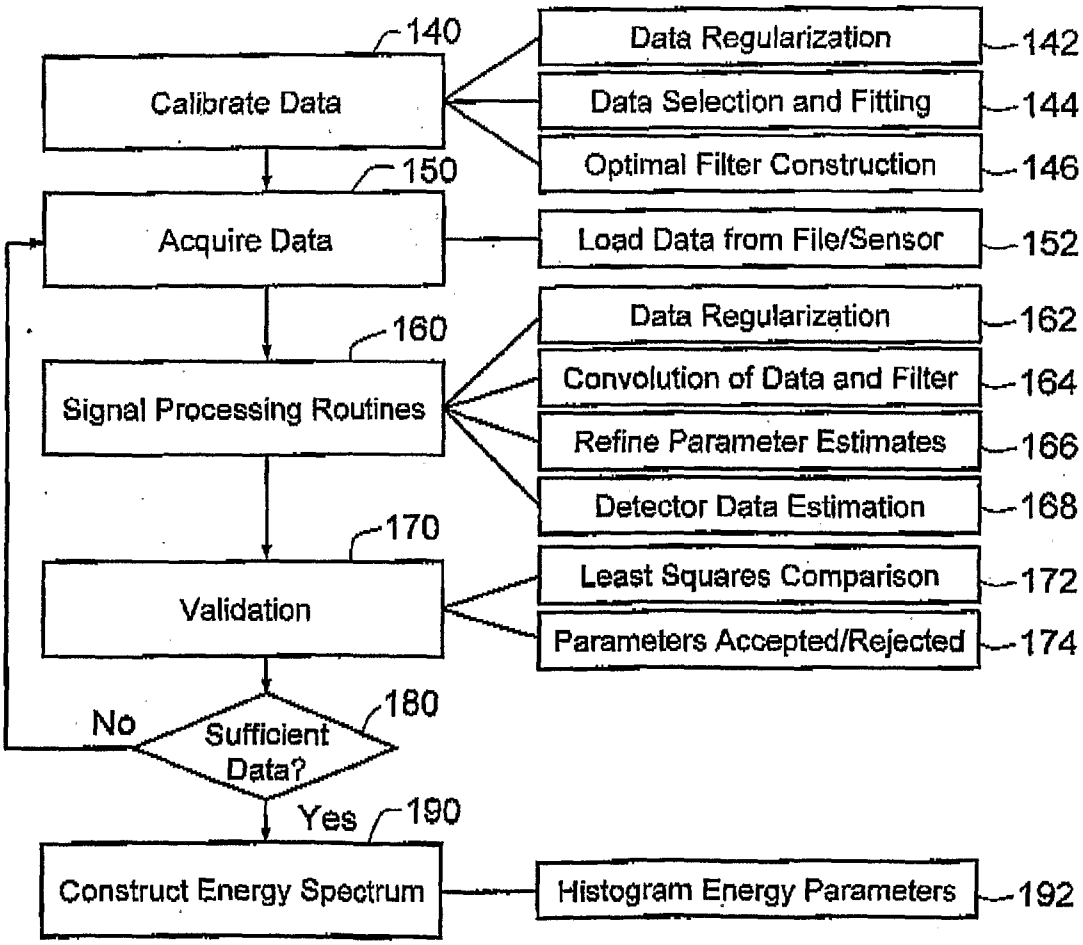


Figure 9

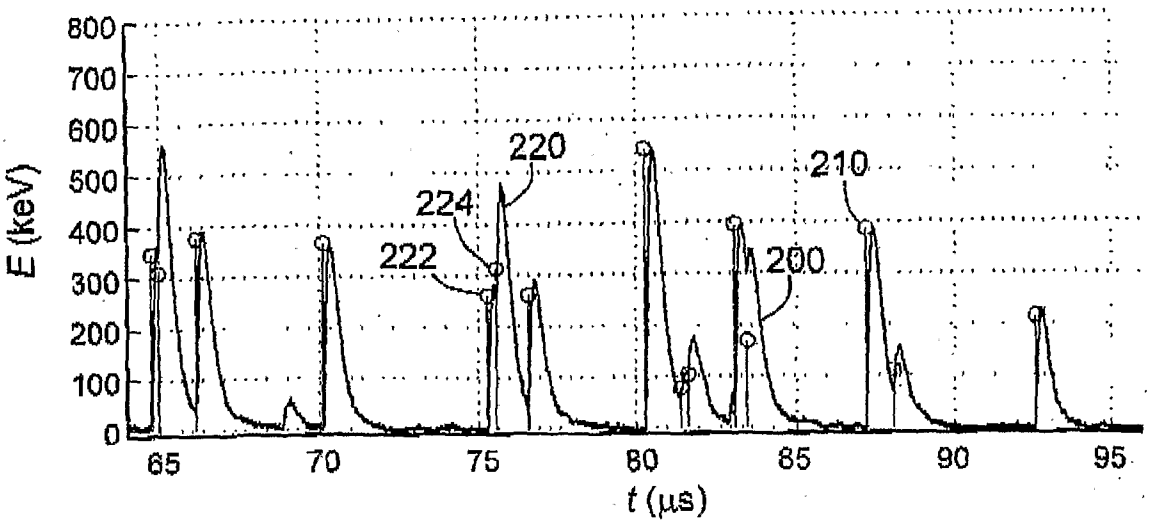


Figure 10a

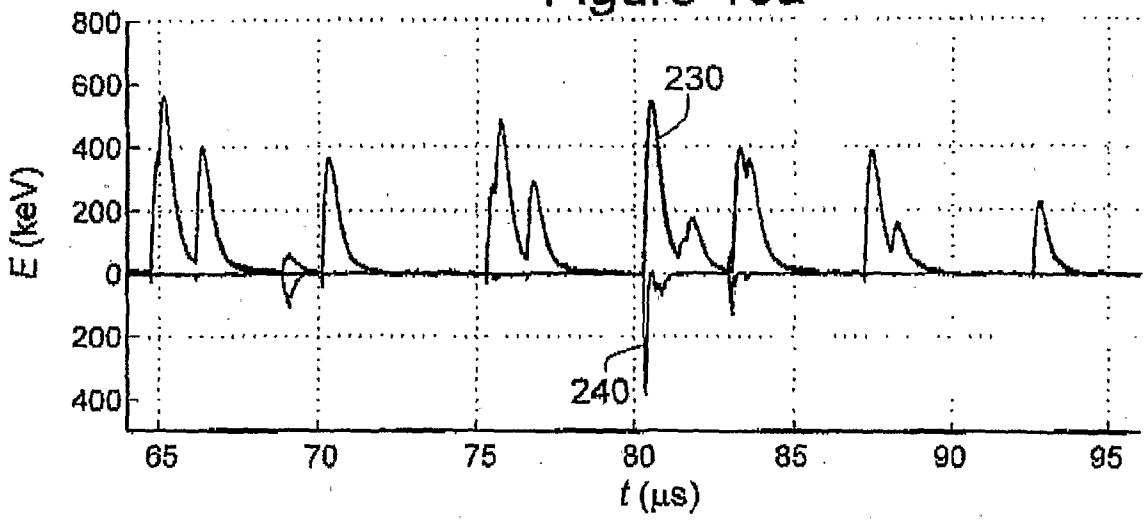


Figure 10b

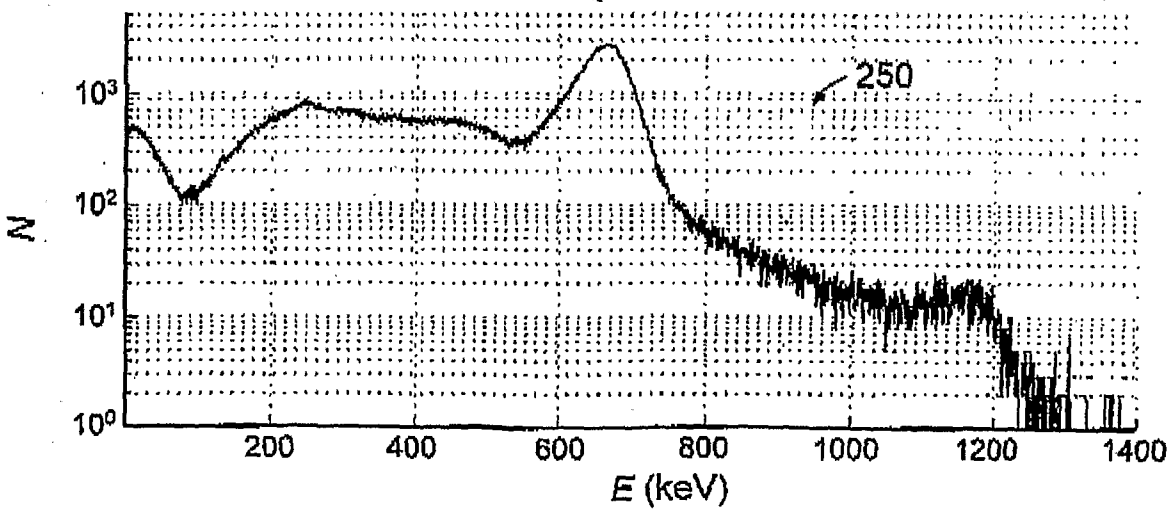


Figure 10c

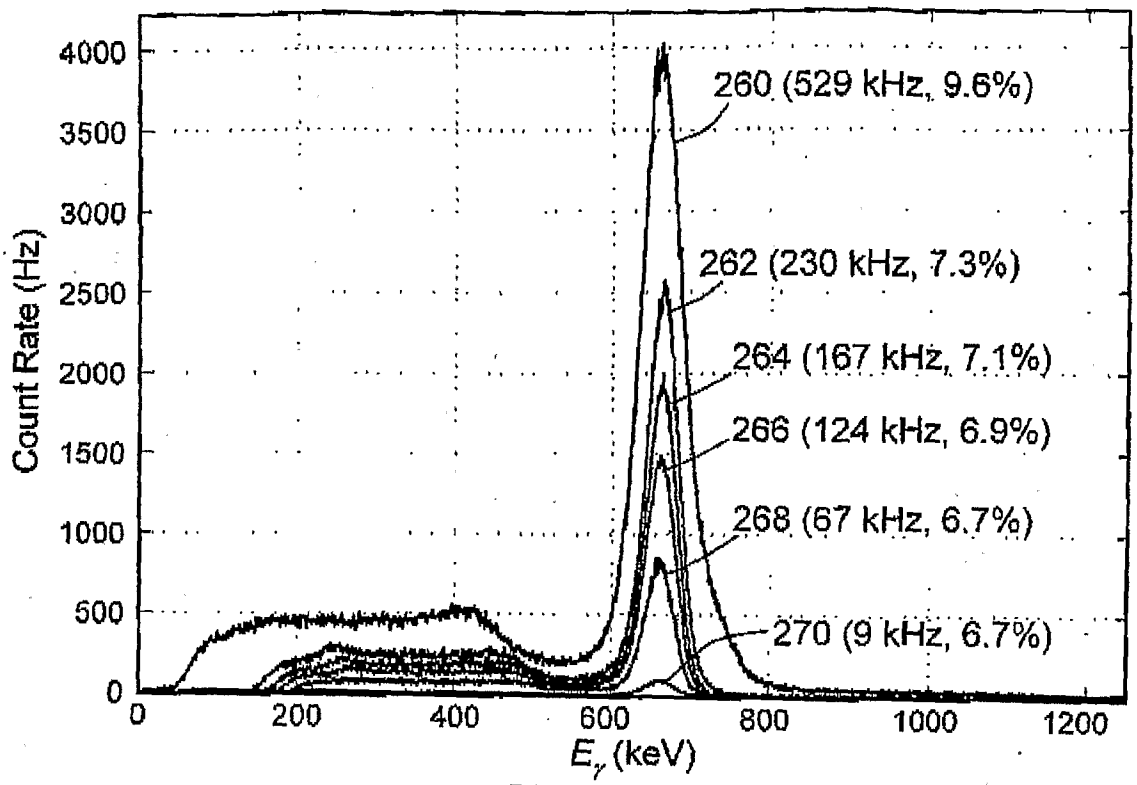


Figure 11

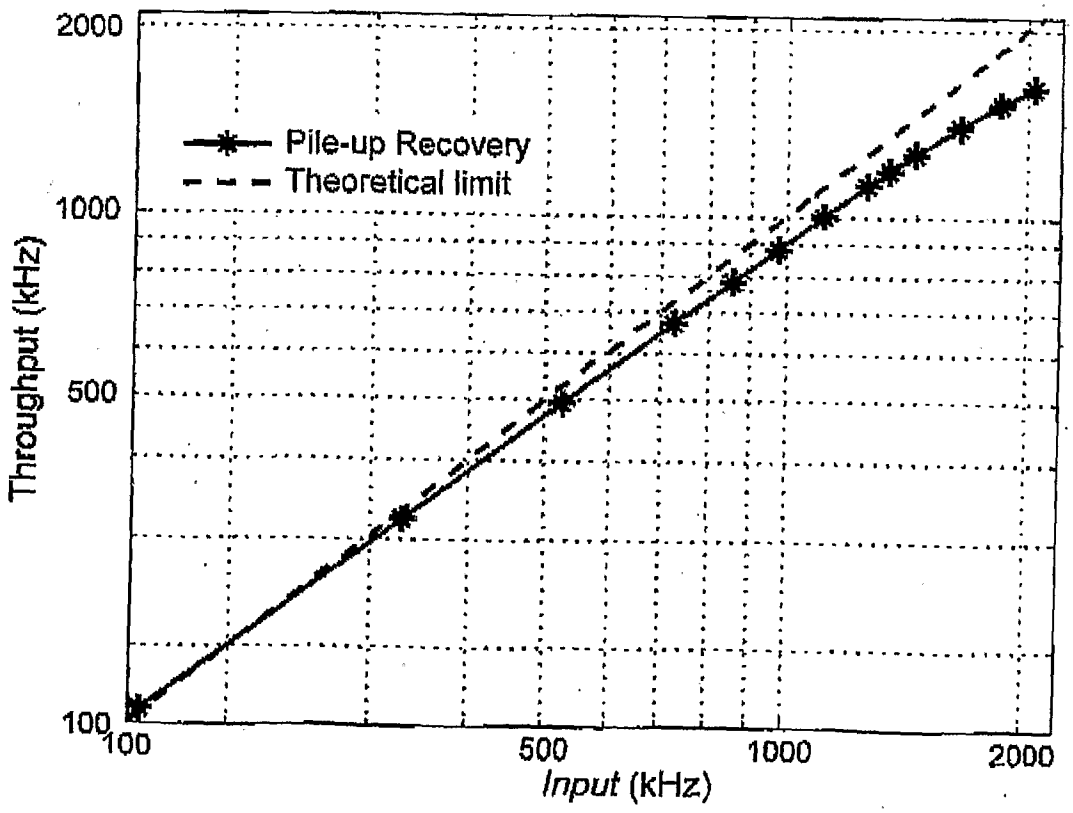


Figure 12

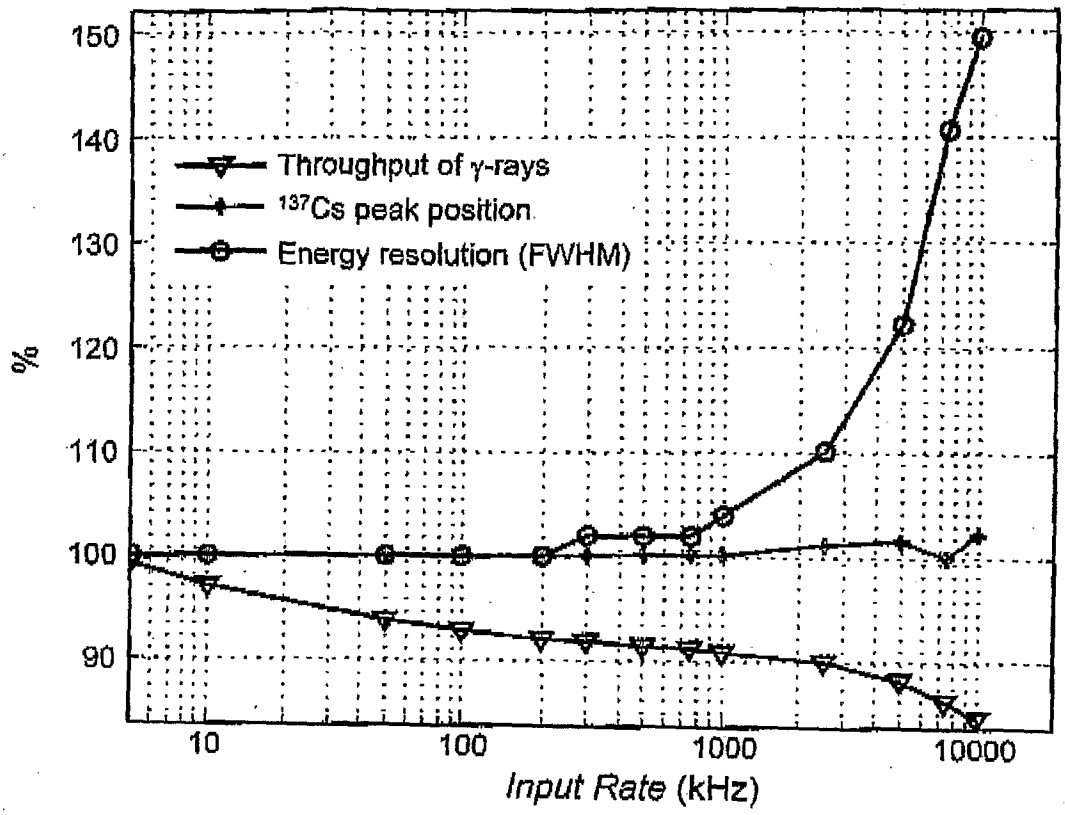

150
140
130
120
110
100
90
%
Throughput of γ-rays
137Cs peak position
Energy resolution (FWHM)
10
100
1000
10000
Input Rate (kHz)

Figure 13

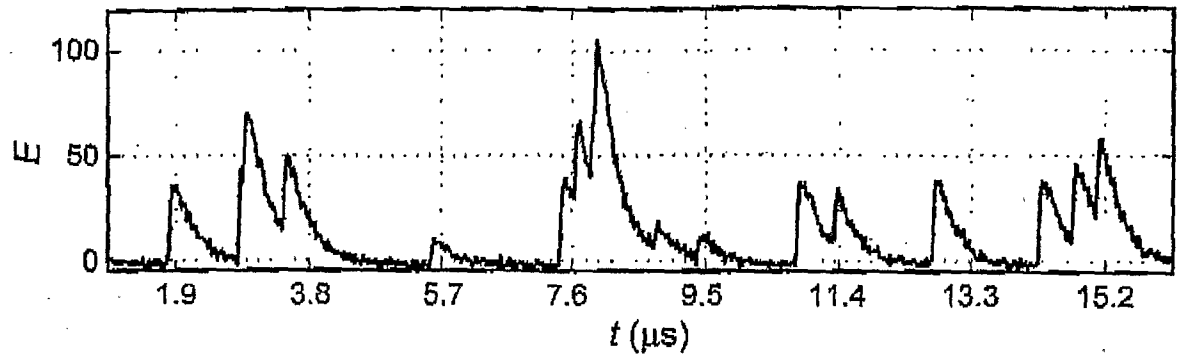


Figure 14a

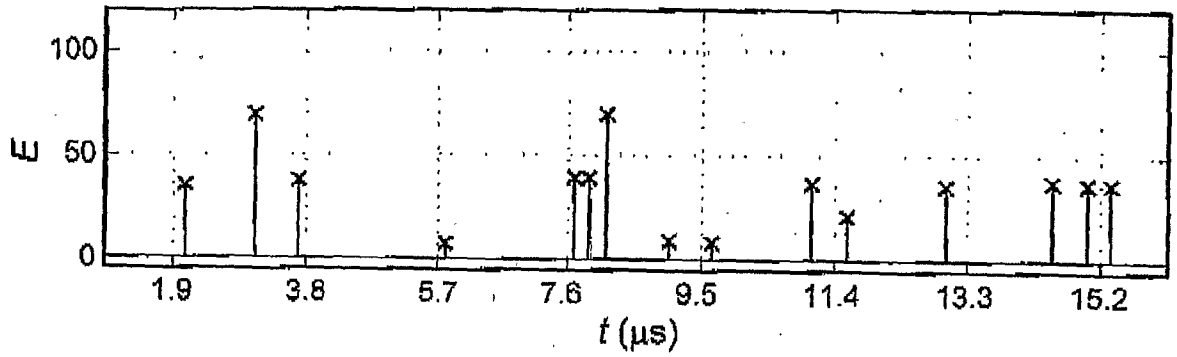


Figure 14b

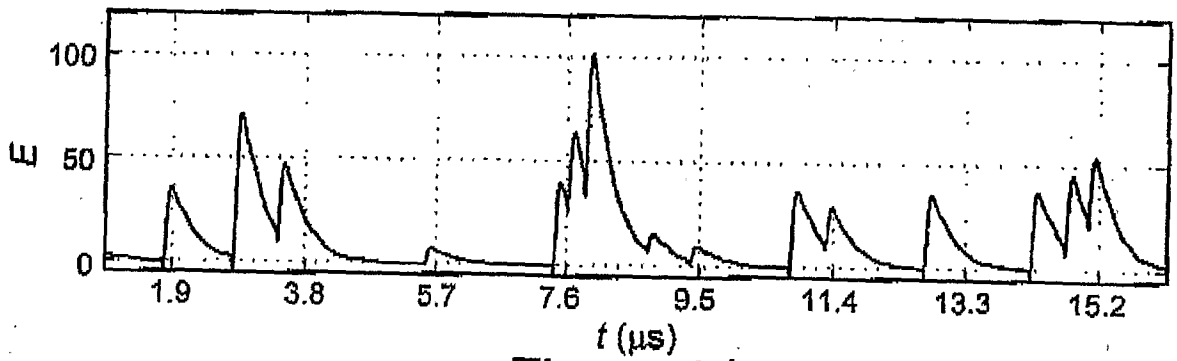


Figure 14c

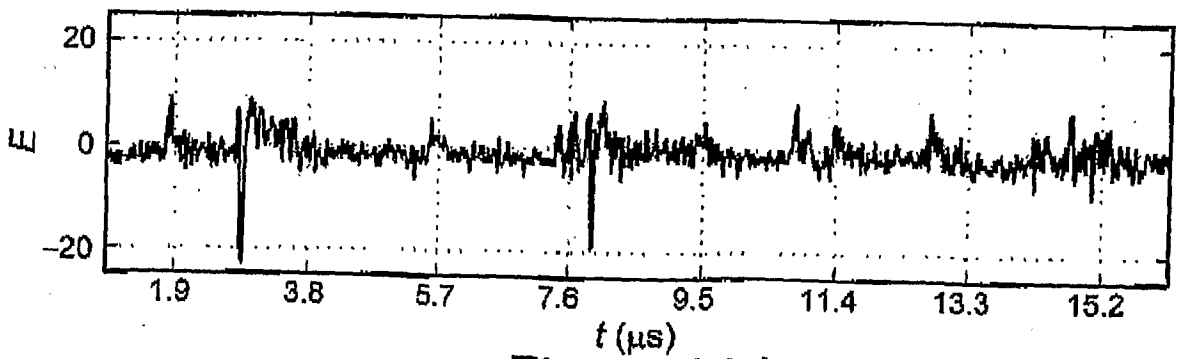


Figure 14d

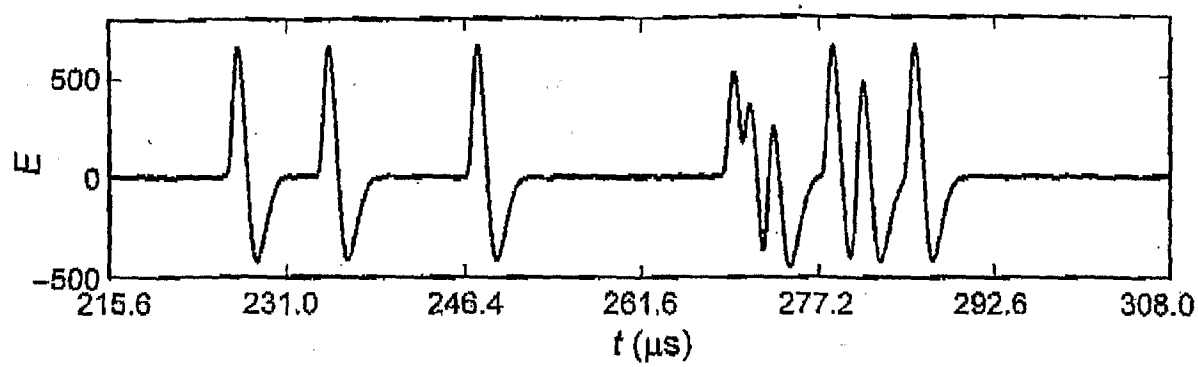


Figure 15a

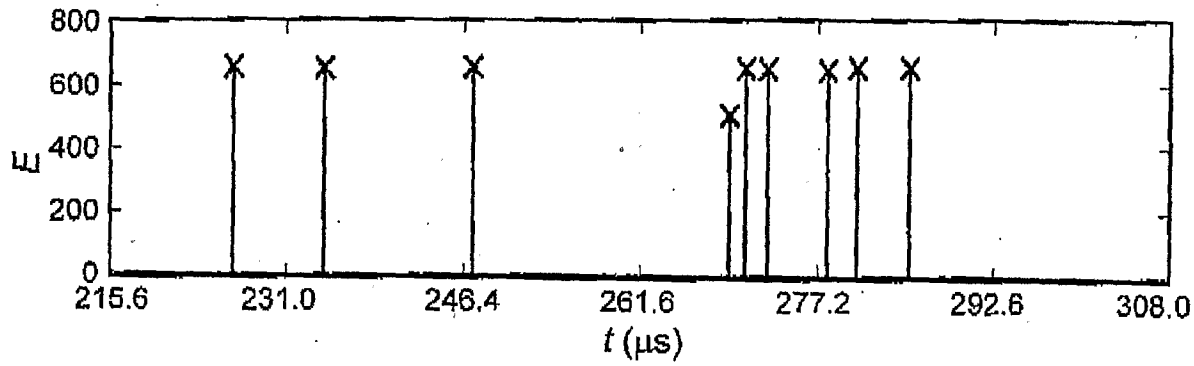


Figure 15b

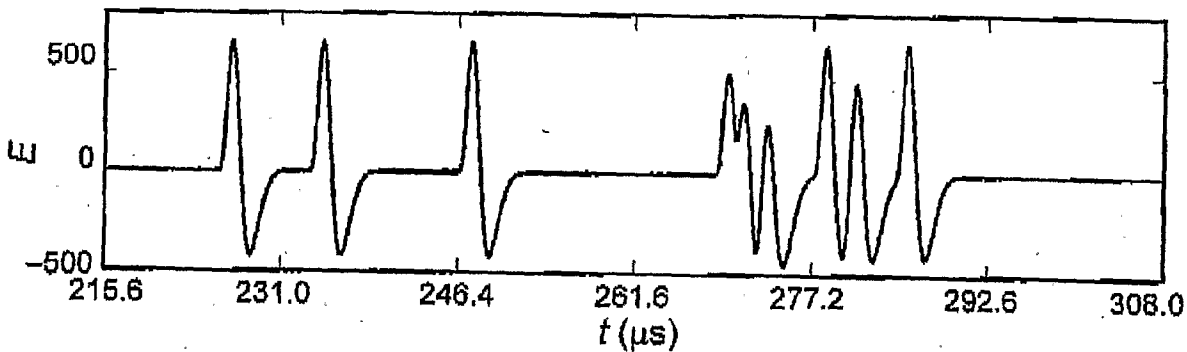


Figure 15c

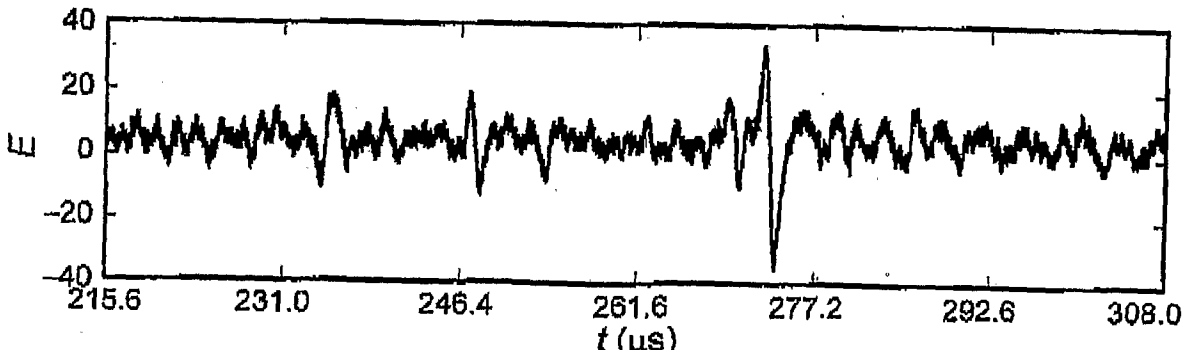


Figure 15d

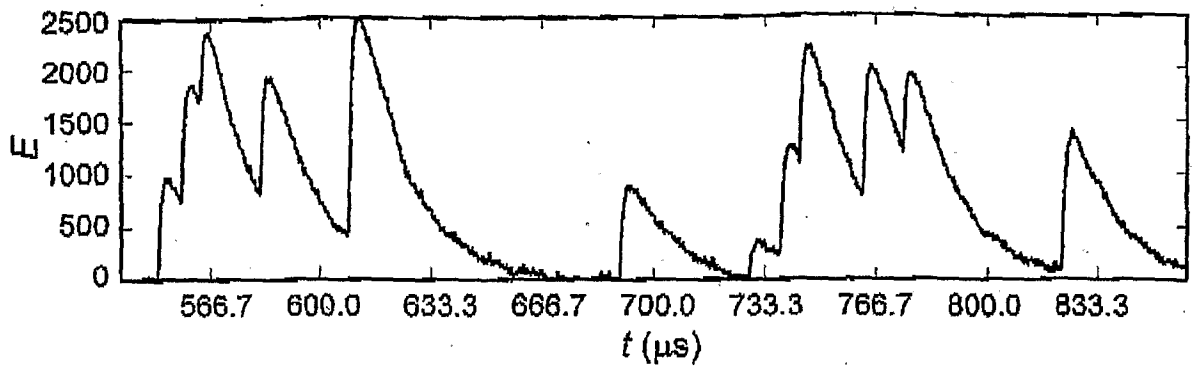


Figure 16a

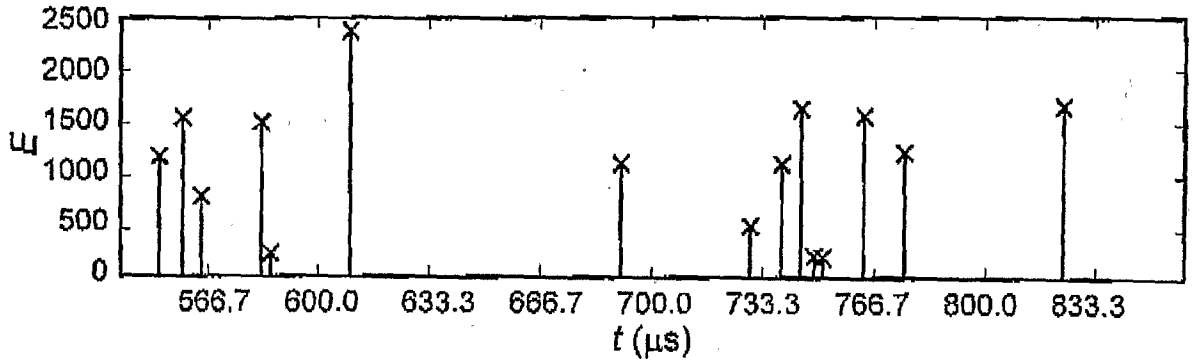


Figure 16b

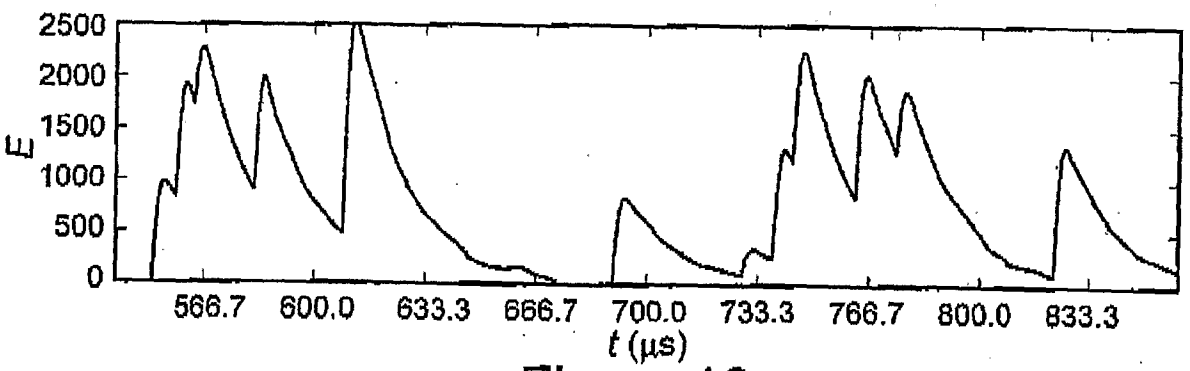


Figure 16c

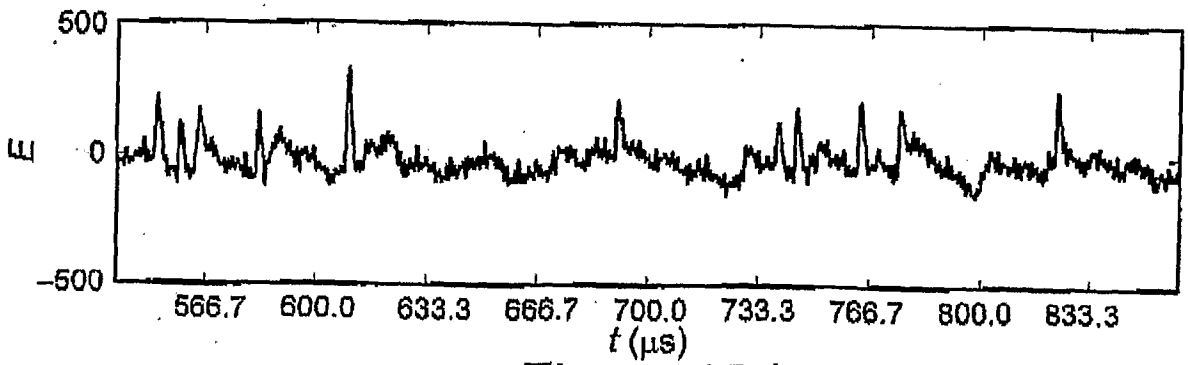


Figure 16d

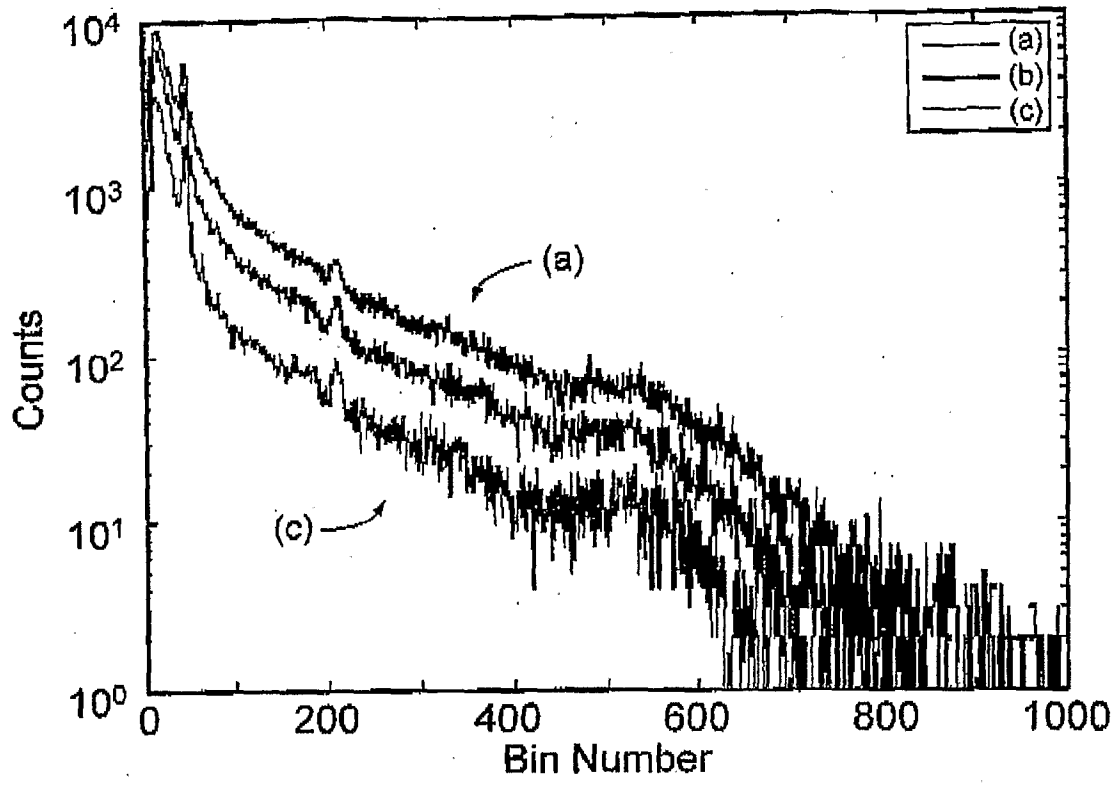


Figure 17

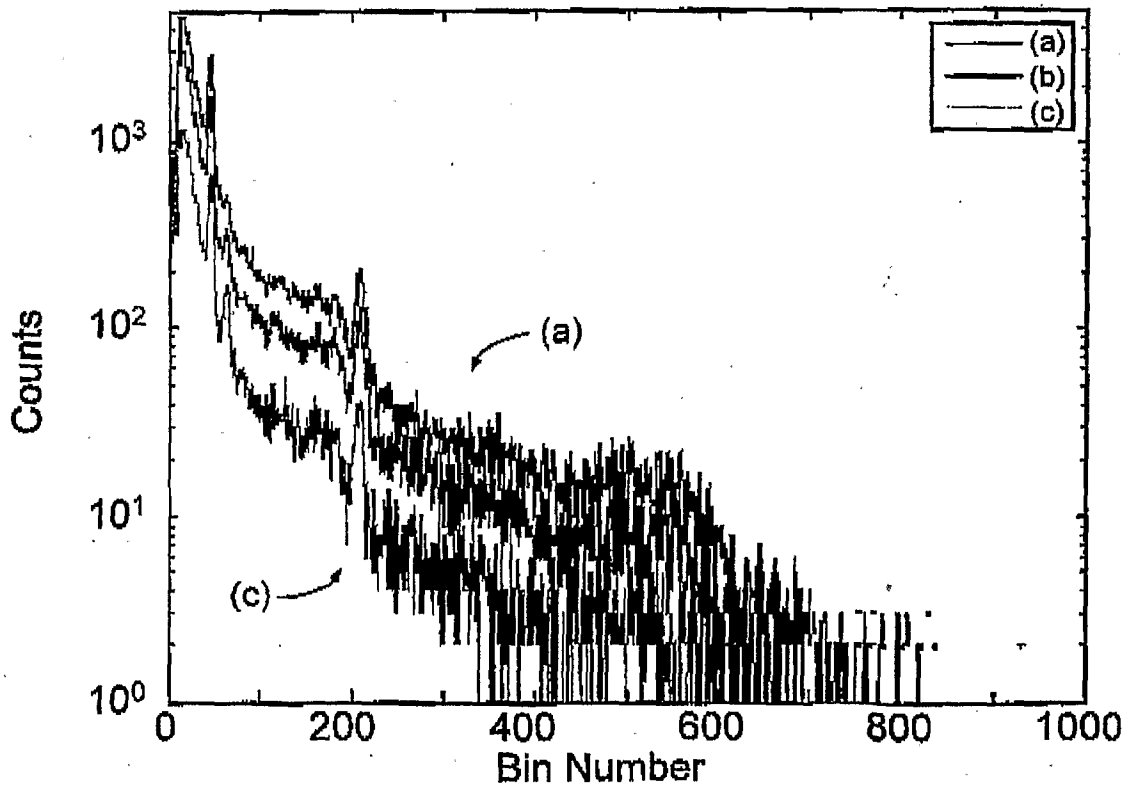


Figure 18

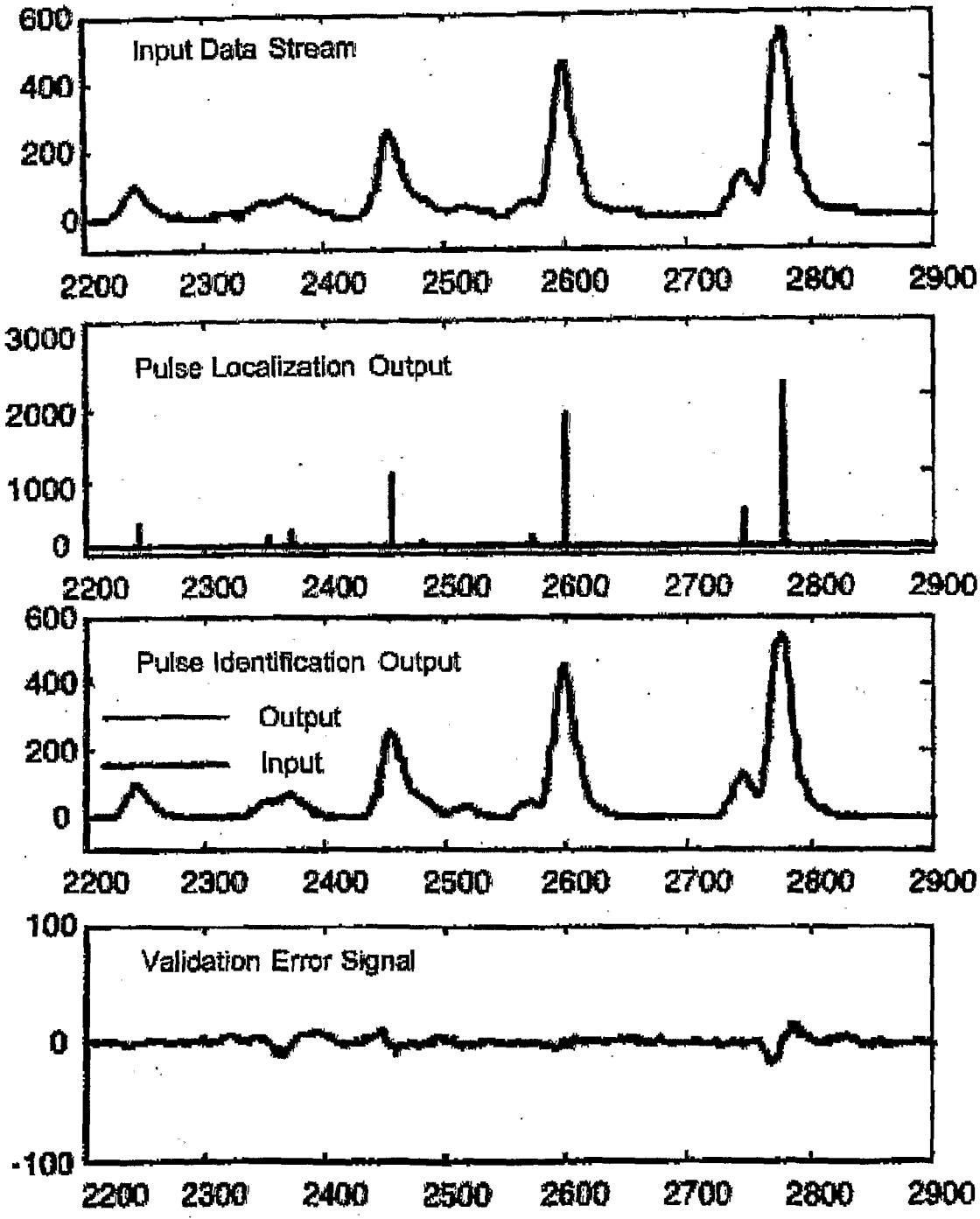

Input Data Stream
600
400
200
0
2200 2300 2400 2500 2600 2700 2800 2900
Pulse Localization Output
3000
2000
1000
0
2200 2300 2400 2500 2600 2700 2800 2900
Pulse Identification Output
Output
Input
600
400
200
0
2200 2300 2400 2500 2600 2700 2800 2900
Validation Error Signal
100
0
-100
2200 2300 2400 2500 2600 2700 2800 2900

Figure 19

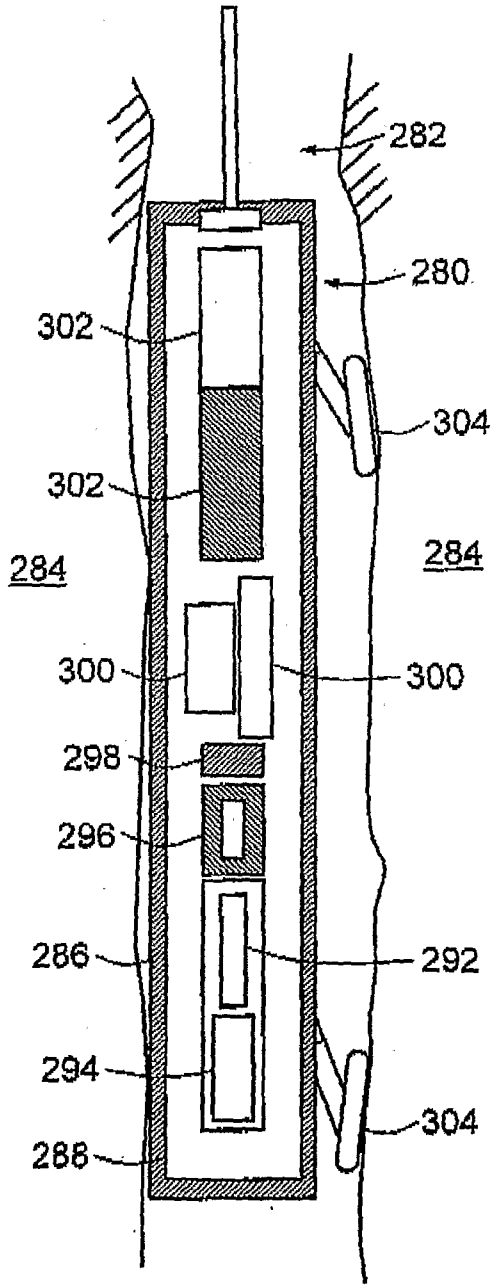


Figure 20

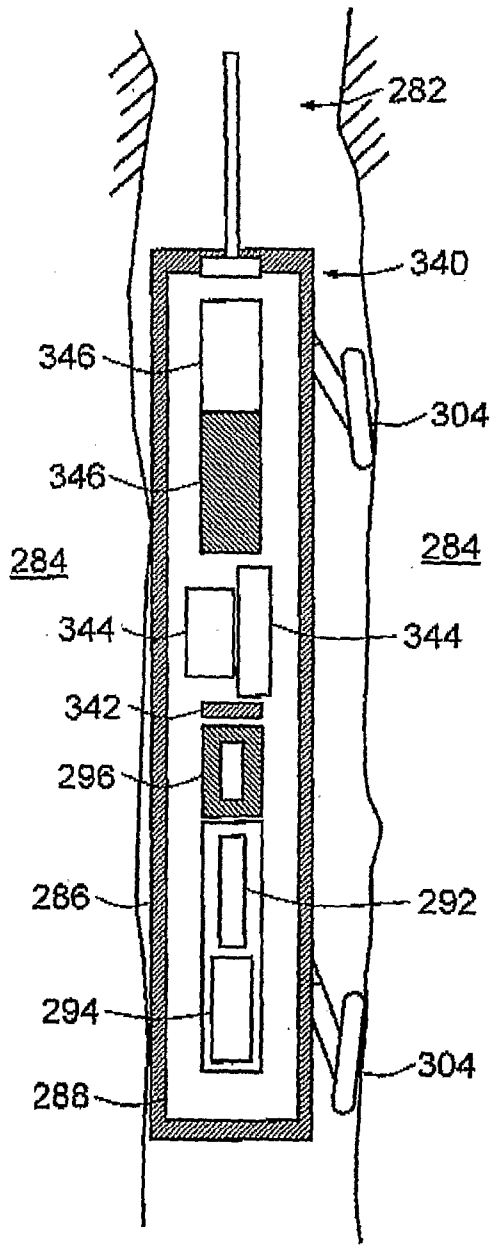


Figure 23

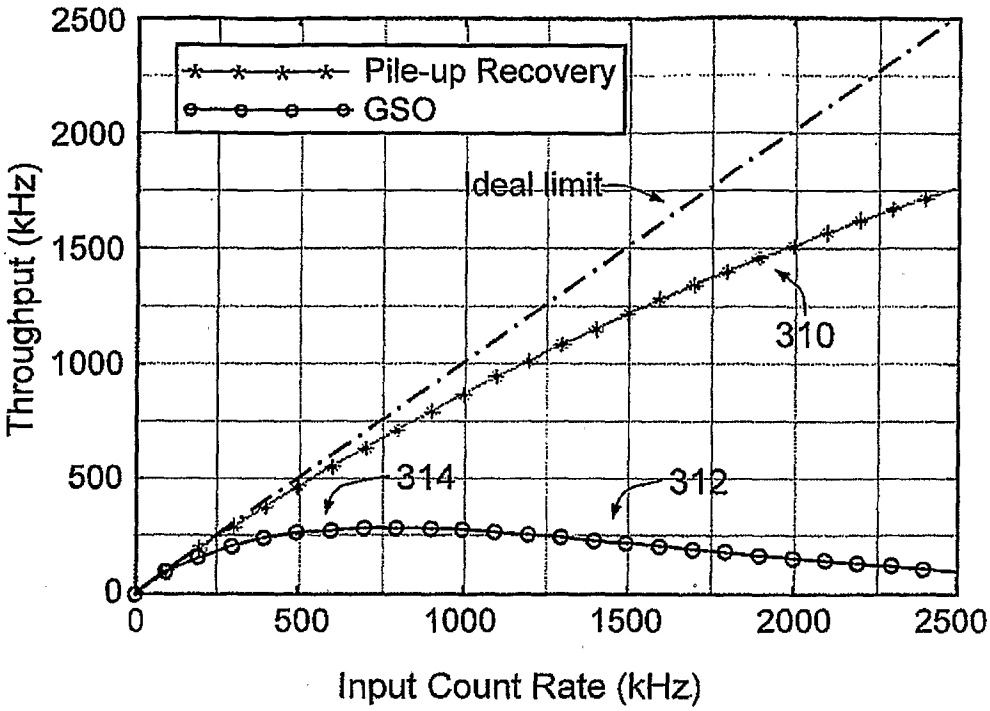


Figure 21

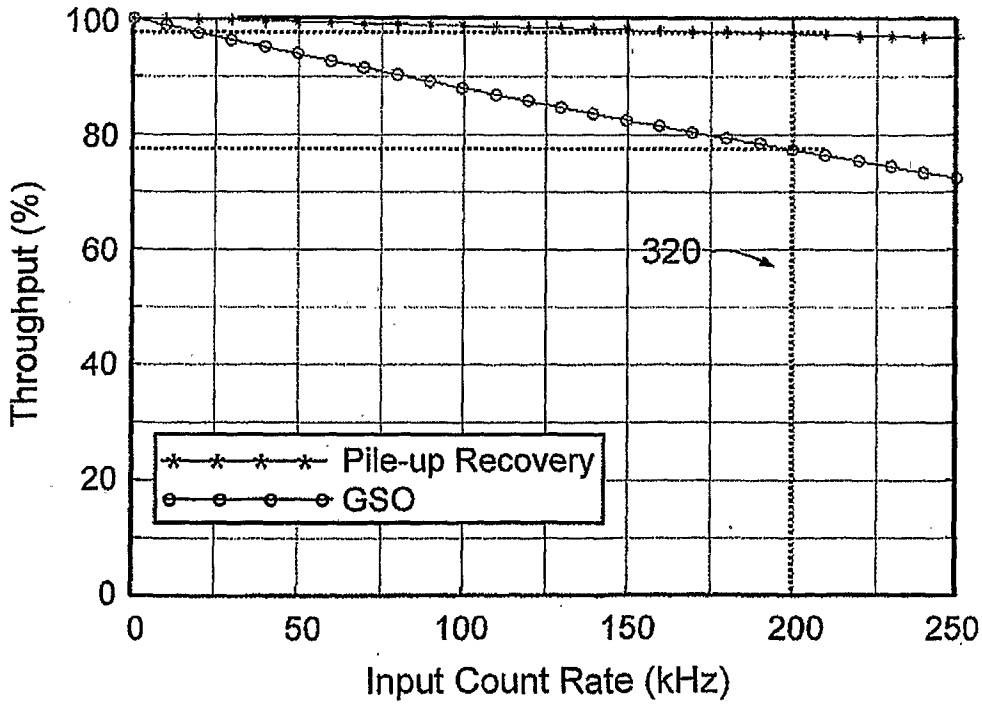


Figure 22a

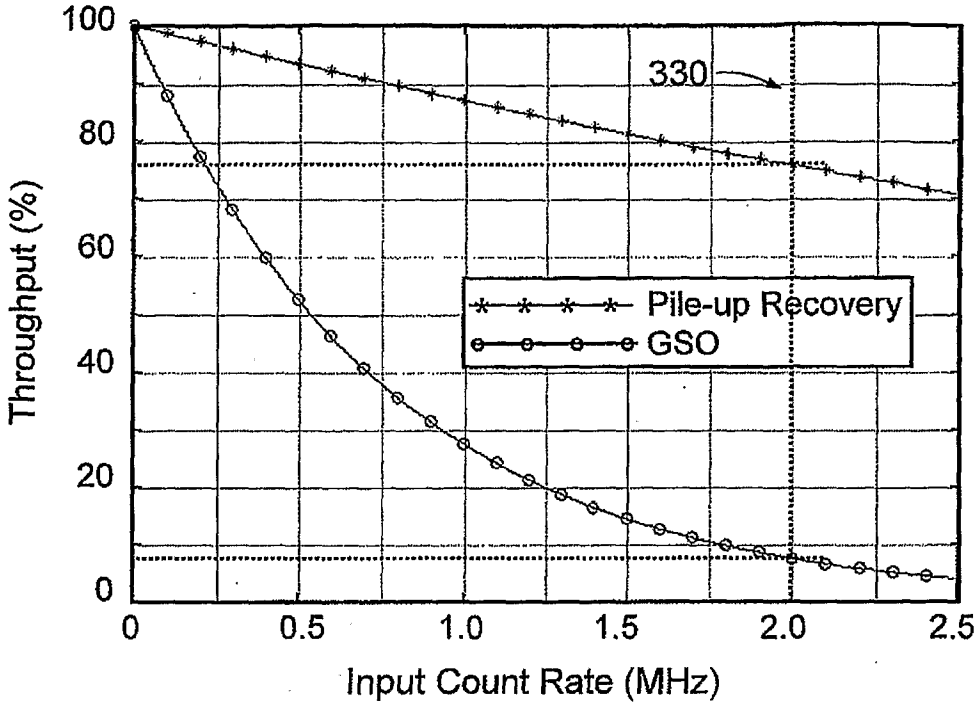

100
80
60
40
20
0
Throughput (%)
330
Pile-up Recovery
GSO
0
0.5
1.0
1.5
2.0
2.5
Input Count Rate (MHz)

Figure 22b

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000394

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

G01V 5/10 (2006.01) ***G01N 23/222*** (2006.01) ***G01T 1/202*** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
TXTUS1, TXTUS2, TXTUS3, TXTEP1, TXTGB1, TXTWO1, TXTAU1, TXTCA1, INSPEC, ESPACENET, Patentscope, Google Scholar and keywords (neutron?, gamma, x_ray, pulse?, peak?, overlap+, pile_up, time resolve?, series, spectroscopy, PHA, energies, point spread function, instrument response, transform+, convolve+, deconvolv+, borehole?, mining, prospect, element+ analysis and similar words)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	WO 2006/029475 A1 (THE UNIVERSITY OF ADELAIDE et al.) 23 March 2006	
X	Abstract; figure 1; pages 2–4, 6 and 8–16; claim 1	1–14, 16, 18–30
Y	As above	27–30
	WO 2003/040757 A2 (BOARD OF REGENTS, THE UNIVERSITY OF TEXAS SYSTEM) 15 May 2003	
X	Abstract; figures 1–2, 16–17F; page 1, lines 10–28; page 3, lines 10–18; page 15, line 19 to page 25, line 28; page 29, line 13, to page 30, line 17	1–2, 4–14, 17–19, 21–23, 27–30
Y	As above	27–30
	US 2003/0076914 A1 (TILLER et al.) 24 April 2003	
X	Abstract; figures 1, 3a–7; paragraphs 0021, 0035–0038, 0048–0050	1–2, 4–14, 18–19, 21–23, 25–30
Y	As above	27–30
	EP 0790508 A2 (ANADRILL INTERNATIONAL SA) 20 August 1997	
X	Abstract; figures 2–4; column 7, line 55, to column 10, line 57; column 13, lines 24–29	1–2, 4–14, 15–16, 18–19, 21–30
Y	As above	27–30

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 May 2009	27 MAY 2009
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. +61 2 6283 7999	Authorized officer **STEPHEN HARKER** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6283 7962

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000394

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2263767 A (SCHLUMBERGER LIMITED) 4 August 1993 Abstract; figure 1; pages 1–3	1, 4–14, 18, 21–23
Y	As above	27–30
	Meng et al., 'An inter-comparison of three spectral-deconvolution algorithms for gamma-ray spectroscopy', IEEE Transactions on Nuclear Science, Vol. 47, Issue 4, pages 1329–1336, August 2000, preprint downloaded 4 May 2009 from the internet <URL: http://www-ners.engin.umich.edu/labs/radmeas/C.pdf>	
Y	Whole document	27–30
E, A	WO 2009/043095 A1 (COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION) 9 April 2009	
	Note: Two arguments are presented for claims 27–30, the first is a novelty argument with respect to single citations, in the second Meng et al., can be combined with any one of WO 2006/029475, WO 2003/040757, US 2003/0076914, EP 0790508 OR GB 2263767.	

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000394

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

[Continued in Supplemental Box]

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000394

Supplemental Box
(To be used when the space in any of Boxes I to IV is not sufficient)

Continuation of Box No: III

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

In assessing whether there is more than one invention claimed, I have given consideration to those features which can be considered to potentially distinguish the claimed combination of features from the prior art. Where different claims have different distinguishing features they define different inventions.

This International Searching Authority has found that there are two different inventions as follows:

- Claims 1–26 are directed to methods and apparatus for borehole logging. It is considered that collecting radiation detector output, resolving individual signals, estimating parameters and determining the energy of the signalscomprises a first distinguishing feature.

- Claims 27–30 are directed to methods and apparatus for borehole logging. It is considered that collecting radiation detector output, resolving individual signals, expressing these signals as a digital series, transforming the detector signals by a mathematical transform, evaluating a function of at least the transformed series and signal form and modelling the function output to determine at least one parameter of the function output comprises a second distinguishing feature.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

The only feature common to all of the claims is collecting radiation detector output and resolving individual signals. However this concept is not novel in the light of (for example):

WO 2006/029475 A1 (THE UNIVERSITY OF ADELAIDE et al.) 23 March 2006, see abstract and claim 1.

This means that the common feature can not constitute a special technical feature within the meaning of PCT Rule 13.2, second sentence, since it makes no contribution over the prior art.

Because the common feature does not satisfy the requirement for being a special technical feature it follows that it cannot provide the necessary technical relationship between the identified inventions. Therefore the claims do not satisfy the requirement of unity of invention *a posteriori*.

Note: claim page 36 starts duplicating claim numbering of claims 10 to 18. This has been the subject of an invitation to correct defects, but the replacement sheets not received as yet. For the purposes of this report the numbering of the claim set starting from the second claim 10 has been interpreted as being to claims 19 onwards.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/AU2009/000394

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	2006029475	AU	2005284602	CA	2621736	CN	101124725
		EP	1794884	US	7383142	US	2007147702
		US	2009048795				
WO	03040757	AU	75661/98	CA	2288788	CA	2463756
		EP	1007988	EP	1444534	US	6310349
		US	6525322	US	6936822	US	2002121603
		US	2004036025	WO	9850802		
US	2003076914	US	7139350	US	2003138067		
EP	0790508	AU	12491/97	AU	36287/95	AU	56415/98
		BR	9508924	BR	9700909	BR	9802878
		CA	2196636	CA	2199726	CA	2230919
		CN	1162740	CN	1177402	EP	0781422
		EP	0864883	ID	16452	ID	20012
		JP	10311882	MX	9701047	MX	9701937
		NO	970628	NO	971202	NO	980910
		US	5539225	US	5608215	US	5804820
		WO	9608733				
GB	2263767	FR	2686982	US	5349195		
WO	2009043095	NONE					

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX