J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

PULSE HEIGHT ANALYZERS

The pulse height analyzer (*PHA*) was originally developed to measure the amplitude of pulses from nuclear radiation detectors. It is therefore an important part of most systems that are used for analyzing event energies from alpha, beta, gamma, and X rays, for analyzing the time between events (from a time-to-pulse-height converter), and for ensuring orderly storage of count information in sequential time periods. PHAs are ideally suitable in system configurations for experimental and production applications in nuclear, chemical, medical, and materials analyses. PHAs are an outgrowth of the single-channel analyzer, which counted amplified electrical signals of a given pulse height created by nuclear events occurring within a detector. The amplitude was accepted by a peak voltage within a "window" or channel defined by two discriminators—referred to as a differential discriminator. Some of the first PHAs stacked 10 or 20 of these discriminators to form a multichannel PHA (1). (Reference 1 is one of the first articles addressing the need for PHAs that process fast pulses required in nuclear spectroscopy.) These early PHAs were commonly referred to as kicksorters. By 1956 Schumann and McMahon (2) had developed a 256-channel PHA by using a Wilkinson analog-to-digital converter (*ADC*) and a random access magnetic core memory. This PHA was very successful and led to the first commercial design of this type (manufactured by RIDL—Radiation Instrumentation Development Lab).

Pulse Processing with the PHA

The input signals to the PHA must be optimally processed to achieve the best signal-to-noise ratio (3). Pulse-processing electronics convert the burst of charge, produced when a radiation particle or photon is absorbed by the detector, to a shaped pulse (usually Gaussian). The quantity of charge produced is related to the energy of the incident radiation. A charge-sensitive preamplifier/voltage amplifier combination serves to amplify and shape the charge into a pulse with an amplitude (peak voltage) proportional to this charge, hence to the energy lost in the detector. The pulses, which are random in both time and amplitude, are fed to an ADC. The pulses are digitized and recorded in an address register and their number stored in a memory. The ADC produces this number, informs the memory, and the memory selects the address and tallies one count. This process occurs each time an event is recorded. The pulse from the detector, created by each random event, is digitized with one count added to the channel corresponding to the digitized value. This is the basis of the PHA and pulse height analysis. This process really lends itself to a computer, therefore, special-purpose computer systems that provide a variety of functions for the acquisition, storage, display, and interpretation of information from random events are referred to as multichannel analyzers (*MCA*s). The terms PHA and MCA are often used interchangeably; however, MCA is a broader term signifying a computer system that can be configured in a number of ways (including operation in the PHA mode). The term spectrometer refers to a detector, pulse conditioning electronics, and the MCA that is capable of rendering a spectrum describing the detected source and having the capability of performing analyses.

In the early 1960s, ADCs (e.g., the 4096 channel successive approximation ADC) (4) were used with Digital Equipment's (*DEC*) minicomputer, the PDP-1 (5) and later the more familiar PDP-8 (6). Pulse-height

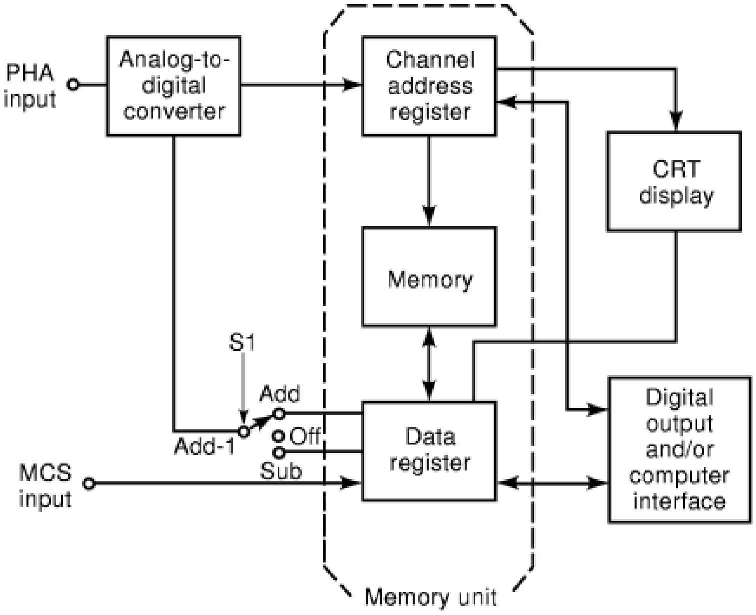

Fig. 1. This simplified MCA block diagram illustrates the use of an analog-to-digital converter to digitize the analog signal from PHA to generate the spectrum channel number. The spectrum is displayed on the CRT or transferred to the computer.

analyzer technology and computer technology merged in a major way during the 1970s. With the advent of DEC's minicomputer, the PDP-11, and later DEC's microcomputer, the LSI-11, data acquisition and analysis systems using MCAs were well on their way. The earliest MCAs came shortly after the development of the ADC but did not become sophisticated until the 1970s. The major components of the MCA are the CPU, memory, control program, acquisition interface, display controller, keyboard, display, and input/output (I/O) interface. Many early designs and references are given in the text by Robert Chase (7).

Principles of Operation

A block diagram of a typical firmware-controlled MCA system is shown in Fig. 1. In the PHA mode the ADC provides a channel address proportional to the input pulse amplitude and transfers the digitized peak voltage information to the channel address register. The count information in that channel is placed in the data register and updated by one count. The updated data are then placed in memory. The CRT display shows that a pulse has been processed by flashing the channel (horizontal) and count (vertical) information in the appropriate location. The time required by the ADC to digitize the pulse height is called the conversion time and the time required to store the data in memory is called the memory cycle time. A typical gamma-ray energy spectrum is shown in Fig. 2.

The ADC. The ADC must be capable of processing the pulses rapidly without erroneous measurements in the pulse height. The Wilkinson method (8) has been the most popular over the years because of its excellent combination of linearity, temperature stability, and speed. Successive approximation ADCs are fast (typical conversion time of about 1 μs), however, steps must be taken to improve the differential nonlinearity (see discussion below). The fastest conversion time is accomplished today with the Flash ADC (typically 200 ps

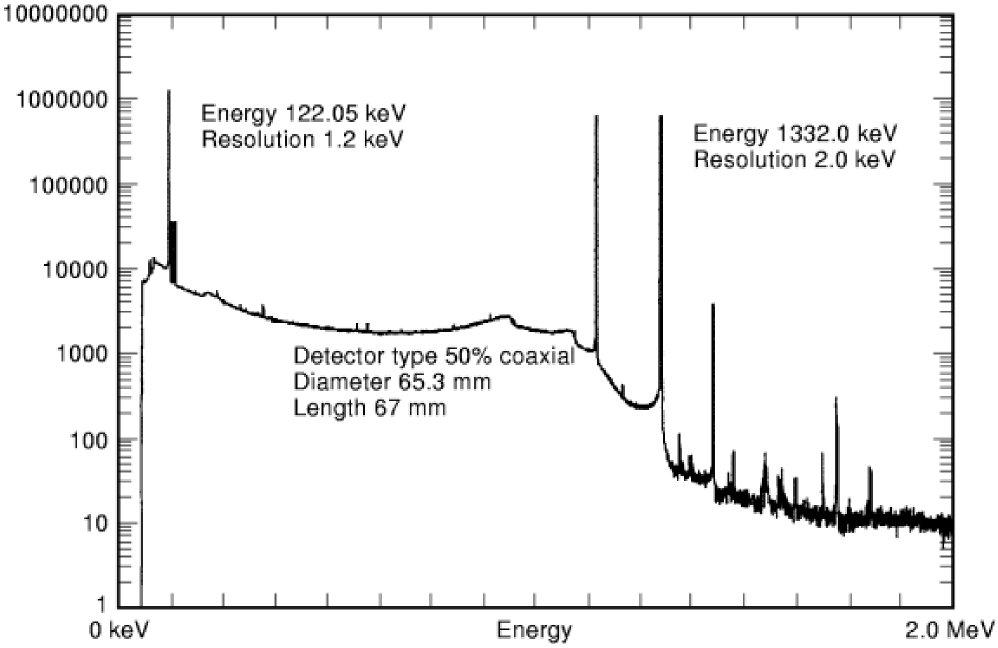

Fig. 2. Cobalt 60 (^{60}Co) spectrum, including background radiation, taken with a 50% relative efficiency COAX high purity germanium (HPGe) detector. The high energy resolution typical of HPGe detectors allows for accurate identification of individual energy peaks.

for a 256-channel unit). This design is similar to a stack of single-channel analyzers but also requires steps to improve the linearity. One of the fastest PHAs reported in the early 1980s used a Flash ADC with a postexperiment, differential nonlinearity correction scheme (9). This method used a bin correction table and had the capability of histogramming the data at 15 MHz.

One of the most important specifications of an ADC (and likewise the PHA) is its linearity. There are two terms used in describing linearity or, more precisely stated, its nonlinearity: (1) integral and (2) differential.

Integral nonlinearity can be described as the maximum deviation of any address from its nominal position described by a straight-line plot of address versus input pulse amplitude, and is shown graphically in Fig. 3. The address with the maximum deviation is identified by N; the pulse amplitude that is converted to the address N is identified as V_N; and the nominal voltage corresponding to N is V_{nom}. The integral nonlinearity is then given by the expression

$$\%\ \text{integral nonlinearity} = V_{\text{nom}} - V_N / V_{\text{max}} \times 100 \qquad (1)$$

where V_{max} is the maximum value of the input voltage.

Since the slope of the straight line has a zero intercept of voltage and address this definition may be more conservative than definitions that define the slope and the intercept by the best fit to actual values. Integral nonlinearities should be less than 0.05% in an ADC so that the centroid position of spectral peaks will not be significantly displaced.

Differential nonlinearity describes the nonuniformity of address widths over the entire number of addresses in the ADC. Therefore, differential nonlinearity is the percent deviation of the maximum and minimum

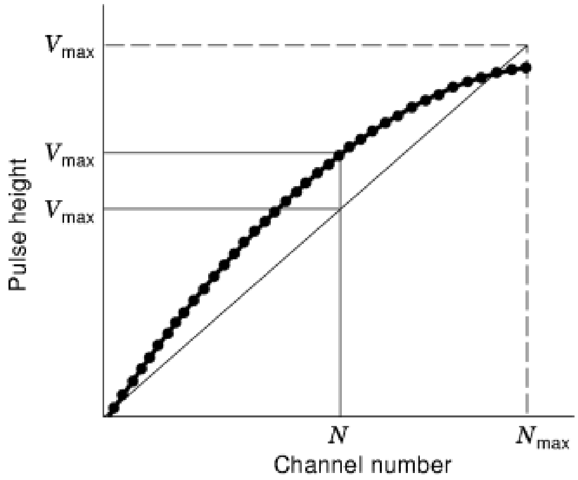

Fig. 3. Integral nonlinearity spectral distortion function. Note the significant difference between the idea and actual performance. Integral nonlinearity results in spectral distortion and energy calibration and spectral analysis problems.

address widths (W_{max} and W_{min}) to the average width (W_{avg}) of all addresses, as shown in Eq. (2).

$$\%\text{ differential nonlinearity} = \frac{1}{2} \times W_{max} - W_{min}/W_{avg} \times 100 \tag{2}$$

The factor $\frac{1}{2}$ is used in Eq. (2) so that the differential nonlinearity may be expressed as a plus or minus deviation. For good performance differential nonlinearity should be less than ± 1% over the top 99% of full scale.

Steps to improve linearity began in the 1950s with improvements by a randomizing method in the 1960s and 1970s (10,11). Today there are linearization and integrated circuitry techniques that allow performance, economy, and small size. Further discussion on improvement of linearity is presented by Knoll (12).

A typical ADC operation (Wilkinson) is briefly described using the timing diagram of Fig. 4. An input pulse, with an amplitude exceeding the lower-level discriminator threshold, charges a capacitor with a constant-current source. The capacitor voltage is directly proportional to the pulse height as shown in Fig. 4. When the peak of the pulse is sensed the capacitor is discharged by a constant-current. The time required to discharge the capacitor to the baseline, called the rundown time, is proportional to the pulse height. When the discharge is begun a gate is opened to allow the address scaler to count clock pulses from an oscillator (typically 100 MHz clock). The number of clock pulses counted during the rundown time represents the desired address or channel. At the end of the rundown time the address in the scaler is strobed into the memory address register. An input gate prevents the acceptance of additional input pulses from the start of rundown until the address transfer is complete.

The resolution of the ADC is typically equivalent to the conversion gain which is the number of channels over which the full input voltage will be spread. For example, a 12 bit ADC is normally subdivided into 4096 channels for an input voltage range of 0 V to 10 V. In this example the resolution and conversion gain is 4096. The ADC busy time or dead time is shown in the timing diagram as the total processing time of the input pulse. These pulses can provide a percent dead-time indication and therefore a live-time determination of the MCA. The dead time of the MCA has two components: (1) the processing time of the ADC and (2) the memory storage time. A clock in the MCA that records elapsed time of an analysis is gated off by the busy signal so

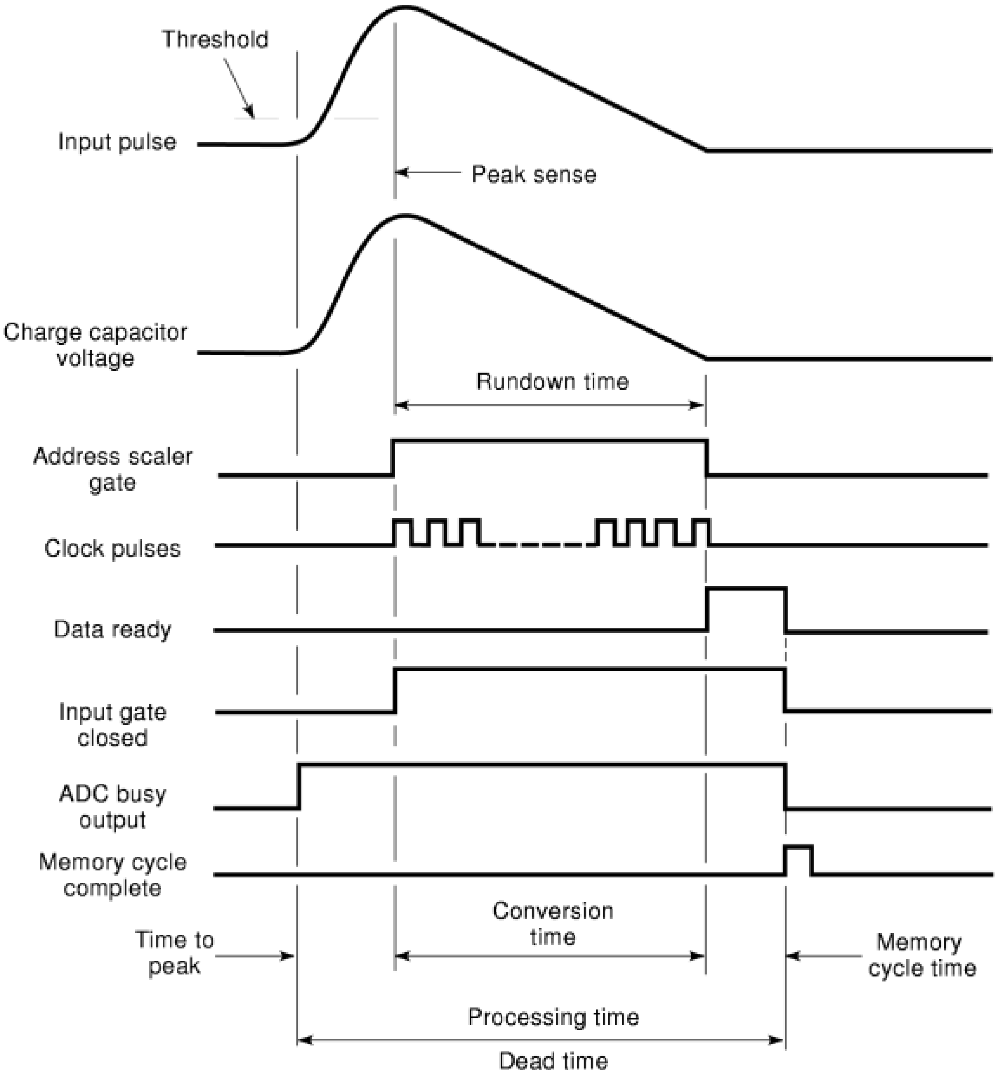

Fig. 4. Typical ADC timing sequence. The charge capacitor follows the input pulse until the peak is sensed. The capacitor then discharges during a clocked period to determine the peak amplitude.

that the analysis time will not include the time that is spent processing pulses. Accurate dead-time correction (providing accurate live-time) is very important for the analysis of some data. This subject is given further detail by Knoll (13).

The Computer-Controlled MCA. The strong growth of the personal computer has had a major impact on the MCA. Many of the functions of a traditional MCA can be performed as well as or better by a PC. These include spectral display, data analysis, and control functions. Some features of an MCA are unique, including the need for high-speed conversion and excellent linearity. By coupling the unique features of an MCA to a PC, the power of MCAs has dramatically increased as the power of PCs has increased.

The block diagram of a typical PC-based MCA is shown in Fig. 5. A microprocessor controls the ADC functions and communicates with the PC. The microprocessor is controlled by an internal program memory

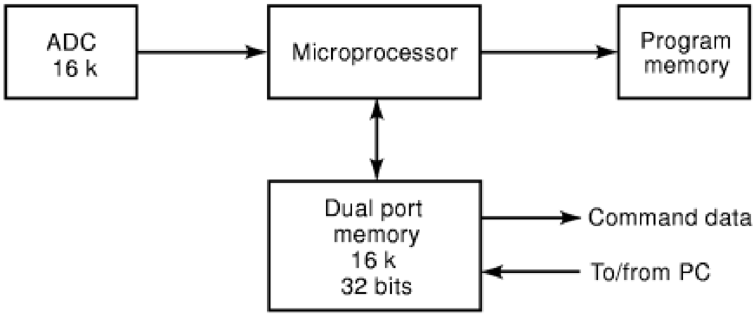

Fig. 5. A typical PC-based MCA architecture requires an ADC of appropriate bit length (resolution dependent), a microprocessor, sufficient program memory to store the MCA program, and data memory to store the acquired spectrum.

stored in firmware. The output of the ADC is stored in the data memory, which can be accessed both by the ADC and the PC. A modern data memory can store as many as 2^{32}-1 counts per channel, or over two billion counts per channel. Commands and data are sent from and to the PC using a variety of protocols including serial port, parallel port, dedicated link and, most recently, via Ethernet. Mass storage of the spectrum files is controlled from the PC using either its internal hard drive or floppy disks. One advantage of the PC-based MCA is that data can be collected and stored in the data memory while the PC is used to analyze a previously collected spectrum.

The hardware of a PC-based MCA takes many forms. One popular format is a plug-in card containing the ADC, microprocessor, data memory and control memory. Communication with the PC is via its internal bus. Other formats include NIM modules, especially for very-high-performance systems. Stand-alone boxes are also available, which combine the MCA function with other parts of the spectroscopy chain including the spectroscopy amplifier and detector bias supply. Many modern PC-based MCAs are available with this general architecture. Other useful variations include the segmentation of the data memory. This allows spectra to be stored from multiple ADCs and is especially useful in alpha spectroscopy, where there are often many detectors requiring relatively low conversion gains (64 to 1024 channels each). Another variation is to precede the ADC with an analog *FIFO* (first-in first-out) memory to enhance the data conversion rate.

Preset controls are used during PHA operations to terminate an accumulation period automatically. This provides a convenient method of normalizing the data collection of individual accumulation periods. Additionally, one or more sections of the spectrum, each defined as a region of interest (*ROI*), can be analyzed for specific information. Some common presets include real time, live time, ROI peak count, ROI integral count, data overflow, and required statistical accuracy on a peak net area.

Integrated Spectrometers. A recent trend has been the integration of all components of a spectrometer into a single package. In addition to the ADC program, and data memory, these integrated spectrometers include a spectroscopy amplifier and detector bias supply. These integrated spectrometers can be general purpose and support a variety of detectors including germanium, silicon, and NaI(Tl). Alternately, they may be designed for a single detector such as NaI(Tl) to reduce cost and size. Some systems include a spectrum stabilizer and additional data memory to store multiple spectra. Spectrum stabilization is a useful feature when making long term, high-precision measurements with detectors that exhibit characteristic energy peak drift over time. Peak drift can be the result of various factors including temperature fluctuations and component aging. Stabilization is a process by which the system gain and a user-defined energy peak in the spectrum are continuously monitored for channel location. The system gain is adjusted if the energy peak varies from the user-defined channel location. Many implementations of spectrum stabilization include the permanent insertion of a weak, non-interfering radioactive source (typically ^{241}Am in the case of NaI) to provide a continuous, stable, and reliable calibration peak. All major functions of the spectrometer are set via the computer including the amplifier gain, shaping time, and pole-zero; bias supply control; and spectrum stabilizer parameters.

A special form of the integrated spectrometer is the portable spectrometer. These portable versions can be as powerful as their line-powered counterparts, except that they are battery powered. The world-wide need to control special nuclear material has been a strong driver in the development of portable systems. A high-end system will feature a 16 k channel ADC with <10 μs conversion time, an amplifier with multiple shaping times, bias supply to support both solid-state and scintillation detectors, data memory to store multiple spectra, multiple computer interfaces, and operate on internal batteries for over eight hours. The portable spectrometers are most often operated with the new portable PCs to form a fully portable spectrometer. Because of requirements for light weight, small size, and long battery life, some portable spectrometers are specialized and support a limited number of detectors and applications. Examples include systems developed for the International Atomic Energy Agency.

Future Trends. The future power of the MCA is linked to the future power of the PC. Indications are that PCs will continue to enhance their performance in speed, size, and computational capability, resulting in improved MCA performance. The uniquely nuclear portion of the MCA will also show improvement as integrated circuits continue to become more complex and dense, resulting in increased speed and reduced size. Portable spectrometers should benefit from advances in battery technology driven by other industries such as cellular phones.

Perhaps the most exciting prospect for the future of MCAs is the advent of digital signal processing, or DSP. In a DSP-based MCA, the signal from the detector is converted to a digital word early in the signal processing. Digital filters replace the traditional analog filters and are capable of optimum filter functions that are not realizable with analog circuits. DSP-based MCAs can better match the signal processing electronics to the charge-collection properties of the detector. System throughput and resolution are both enhanced as well as temperature stability. The first DSP-based integrated spectrometers show this promise (14).

DSP technology offers additional promise. The shape of the signal from the detector contains information about the type and location of the interaction in the detector. As DSP-based systems improve, it may be possible to extract this shape information from the detector signal to improve the overall performance of the spectrometer.

Acknowledgement

The authors would like to thank Gary T. Mattesich for his exceptional assistance and generous contributions of time and expertise.

BIBLIOGRAPHY

1. G. G. Kelley *Nucleonics*, **10** (4): 34, 1952.
2. R. Schumann J. McMahon Argonne 256 channel pulse-height-analyzer, *Rev. Sci. Instr.*, **27**: 675, 1956.
3. G. F. Knoll *Radiation Detection and Measurement*, 2nd ed., New York: Wiley, 1989, pp. 607–610.
4. C. Cottini *et al. Nuc. Instrum. Methods*, **24**: 1963.
5. J. Leng Instrumentation Techniques in Nuclear Pulse Analysis, Report No. 40, National Academy of Sciences, 1963, p. 23.
6. G. T. Mattesich *CUBE Symp. Proc.*, CONF-741001, 1974, pp. 188–194.
7. R. Chase *Nuclear Pulse Spectroscopy*, New York: McGraw-Hill, 1961, p. 74.
8. D. H. Wilkinson *Proc. Cambridge Philos. Soc.*, 46: Pt. 3, 1950, p. 508.
9. H. P. Spracklen 7 MHz particle identifying PHA, *IEEE Trans. Nucl. Sci.*, **NS-29**: 896–899, 1982.

10. S. G. Gobbur D. A. Landis F. S. Goulding Fast successive approximation analog-to-digital converter, *Nucl. Instrum. Methods*, **140**: 405, 1977.
11. C. Cottini E. Gatti V. Svelto *Nucl. Instrum. Methods*, **24**: 241, 1963.
12. G. F. Knoll *Radiation Detection and Measurement*, 2nd ed., New York: Wiley, 1989, pp. 665–666.
13. G. F. Knoll *Radiation Detection and Measurement*, 2nd ed., New York: Wiley, 1989, pp. 669–670.
14. EG&G ORTEC Model DSPec Digital Gamma-Ray Spectrometer.

JAMES H. MCQUAID
ANTHONY D. LAVIETES
WAYNE D. RUHTER
Lawrence Livermore National Laboratory
THOMAS J. PAULUS
EG&G ORTEC