

**GAMMA RAY SPECTROMETRIC METHODS IN URANIUM EXPLORATION-
AIRBORNE INSTRUMENTATION**

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Abstract

Gamma ray spectrometry is used in uranium exploration to determine as precisely as possible the crustal distributions of potassium, uranium and thorium by quantitative measurements of the gamma radiation from the natural radioisotopes associated with these elements. This applies to airborne and ground surveys and to borehole logging.

In recent years and particularly since 1972, the commercially available instrumentation for such surveys has achieved a level of sophistication found only in research laboratories. Technical specifications generated by various national agencies involved in uranium resource assessment programs have hastened this process in the case of airborne surveys by requiring multichannel analysis using analogue-to-digital converters, complete spectral recording, atmospheric radon monitoring and by setting sensitivity and overall detector performance standards for the equipment.

The advent of 4 x 4 x 16 inch (100 x 100 x 406 mm) prismatic-shaped sodium iodide detectors, with a volume equivalent to a conventional 9 x 4 inch (230 x 100 mm) detector, but with only one photomultiplier tube, has greatly simplified the packaging of multidetector arrays and associated electronics, allowing lighter and more compact spectrometers with lower power consumption. It is now possible, for example, to operate a system with a 2000 cubic inch (32.8 L) volume, complete with full spectral recording using a helicopter.

Most airborne gamma ray spectrometry instrumentation is now designed as one component of multisensor integrated data-acquisition systems based on microprocessors or minicomputers. This new found flexibility has encouraged the development of a variety of features such as real-time on-line corrections for Compton scatter, background radiation, detector gain shift and verification of taped data by read-back-and-compare, all of which can be implemented by software.

Electromechanical methods of mass storage such as magnetic tapes and discs are the most failure-prone components of any field system. Recent advances in memory technology may bring solid state equivalents such as bubble memories, into use as practical and economically viable replacements before 1985.

Résumé

Dans la recherche de l'uranium, la spectrométrie de détection de rayons gamma permet de déterminer de façon aussi précise que possible la répartition de potassium, d'uranium et de thorium dans la croûte terrestre par des mesures quantitatives de la radiation gamma émise par les radioisotopes naturels de ces éléments. Cette technique s'applique aux levés aériens et terrestres ainsi qu'à la diagraphie par trou de sonde.

Au cours des dernières années, particulièrement depuis cinq ans, les instruments que l'on trouve sur le marché pour de tels levés ont atteint des niveaux de perfectionnement que l'on retrouve seulement dans les laboratoires de recherche. Les spécifications techniques exigées par divers organismes nationaux qui s'occupent de programme d'évaluation des ressources en uranium ont accéléré ce processus dans le cas des levés aériens, en exigeant l'utilisation d'analyses multi canal faites au moyen de convertisseurs numériques-analogiques, des techniques complètes d'enregistrement spectral, le contrôle du radon atmosphérique et l'établissement des normes de sensibilité et de rendement global des détecteurs pour le matériel.

La mise au point de détecteurs prismatiques à iodure de sodium, de 4 x 4 x 16 po (100 x 100 x 406 mm), d'un volume équivalent à celui d'un détecteur classique de 9 x 4 po (230 x 100 mm), mais avec un seul tube multiplicateur, a grandement simplifié l'assemblage d'ensembles de multi détecteurs et des composantes connexes, permettant ainsi l'utilisation de spectromètres plus légers et plus compacts, d'une consommation énergétique moindre. Il est maintenant possible, par exemple, de faire fonctionner un réseau complet de 2 000 po cubes (32,8 litres), avec tout l'enregistrement spectral, à bord d'un hélicoptère.

La plupart des instruments aéroportés de spectrométrie à rayons gamma se retrouvent maintenant sous forme de composantes de systèmes intégrés de saisie de données à multicapteurs basés sur des microprocesseurs ou des miniordinateurs. Ce nouvel apport de flexibilité a favorisé l'élaboration d'un ensemble de particularités comme les corrections en direct et en temps réel pour la diffusion Compton, le rayonnement de la zone de fond, le décalage de rendement du détecteur et la vérification des données sur bandes par relecture/comparaison, opérations qui peuvent toutes être effectuées par logiciel.

Les méthodes électromécaniques de mémoires de grandes capacités comme les bandes et les disques magnétiques constituent les composantes les plus sujettes au défailances de tout système d'exploration sur place. Des progrès récents dans les techniques de mise en mémoire peuvent favoriser l'utilisation, avant 1985, d'équivalents transistorisés comme les mémoires à bulles, comme moyen de remplacement pratique et économiquement rentable.

HISTORICAL DEVELOPMENT OF AIRBORNE GAMMA RAY SPECTROMETRY

There are three radioelements in the terrestrial crust which are readily detectable by the gamma radiation emitted by the natural radioisotopes associated with them, potassium, uranium and thorium. However, until the early 1950s there was no method of distinguishing between different gamma radiation energies. The standard radiation detector, the Geiger-Müller counter, provided only a total count indication. Thus it was not possible to distinguish between potassium, uranium and thorium. The advent of the thallium-activated sodium iodide scintillation detector was a major advance for two reasons, it had a stopping power (i.e. detection efficiency) several hundred times that of the Geiger-Müller counter for the energy range of interest in this application and the output pulses it produced had amplitudes proportional to the energy of the gamma radiation which caused them. By adding electronic circuitry capable of sorting and counting pulses according to their amplitudes it was possible to separate the contributions from the three radioelements according to their energies, which is by definition gamma ray spectrometry.

The essential details of a scintillation counter and its method of operation can be understood by reference to Figure 10A.1. Gamma rays which interact in the crystal cause tiny flashes of light (scintillations) the intensities of which are proportional to the energy deposited in the crystal by the gamma rays. The photomultiplier tube which is optically coupled to the crystal, usually with transparent grease, converts the scintillations to corresponding electrical signals which can be amplified and sorted in the subsequent electronic circuitry.

The technique of sorting pulses according to their amplitudes is known as pulse height analysis. The most elementary method is to use a single discriminator circuit which allows all pulses above a certain preset amplitude (i.e. energy) to be counted and rejects all others, or vice versa. A slightly more sophisticated arrangement uses two such discriminators which can be preset to different levels. Pulses having amplitudes which fall between the two levels are counted while all others are rejected. This arrangement is known as a Single Channel Analyser (SCA) and is shown in Figure 10A.2.

Until the mid 1960s airborne gamma radiation surveys were largely confined to "total count" measurements. The first gamma ray spectrometry systems for airborne use which became available at that time consisted broadly speaking of the following items:-

- Scintillation detector, usually one 150 x 100 mm (6 x 4 inch).
- 4 counting channels, each with a single channel analyzer and analogue rate meter
- 4 channel strip chart recorder

The block diagram is shown in Figure 10A.3. Three of the single channel analyzers were set to cover the pulse amplitudes (i.e. energy bands) corresponding to those of potassium, uranium and thorium, while the fourth was set to cover an energy range encompassing all three, the "total count".

Various systems based on the above concept were produced in the years following and they found wide acceptance in the exploration industry. A lack of standards, and in many cases a lack of understanding of the principles of the new technique, caused difficulties in the collection and interpretation of spectrometric data. It also became evident that a gap had developed between the level of instrumental technology in the equipment used for uranium prospecting and similar equipment which was available in the laboratory at that time.

Since then and particularly during the last five years the situation has changed dramatically with the dissemination of more information and the development of more sophisticated techniques and instrumentation, the latter being covered in some detail below.

No attempt is made in this article to describe available commercial instrumentation. For this information the reader is referred to an excellent annual review which appears in the Canadian Mining Journal (P.J. Hood, 1967, et seq). The purpose here is to acquaint the reader with currently used techniques, their advantages and their limitations.

FUNDAMENTAL CONSIDERATIONS

While the radiation physics aspects of gamma ray spectrometry are covered in detail elsewhere in this three part article, the spectrum from a standard calibration pad (Fig. 10A.4) is included here as a convenient aid for discussing the instrumental aspects of the technique.

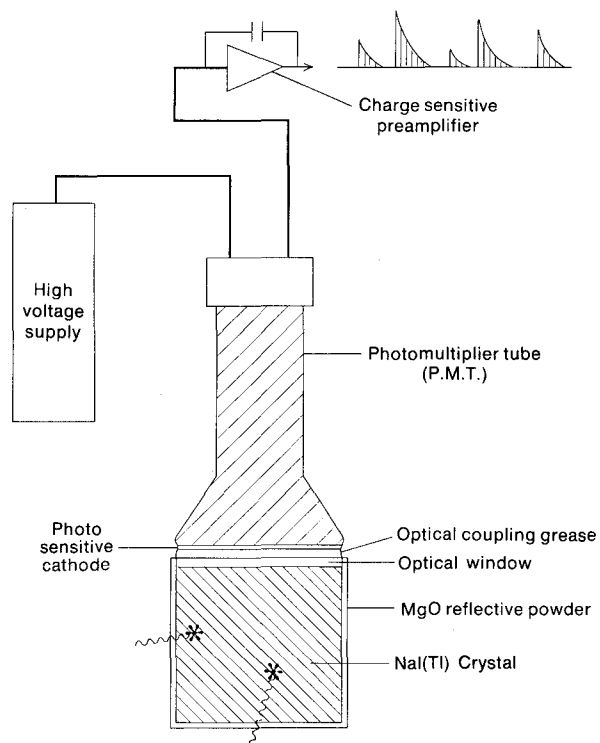


Figure 10A.1. Gamma ray scintillation detector.

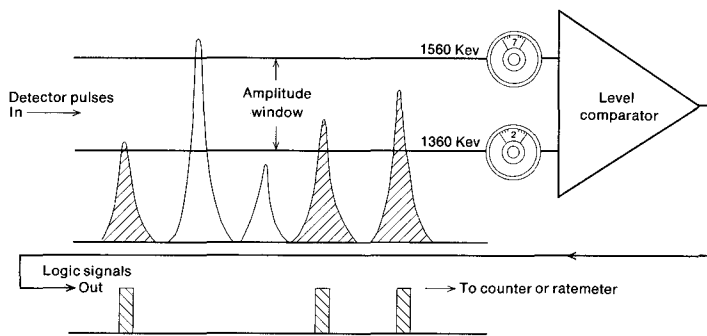


Figure 10A.2. Single channel analyzer.

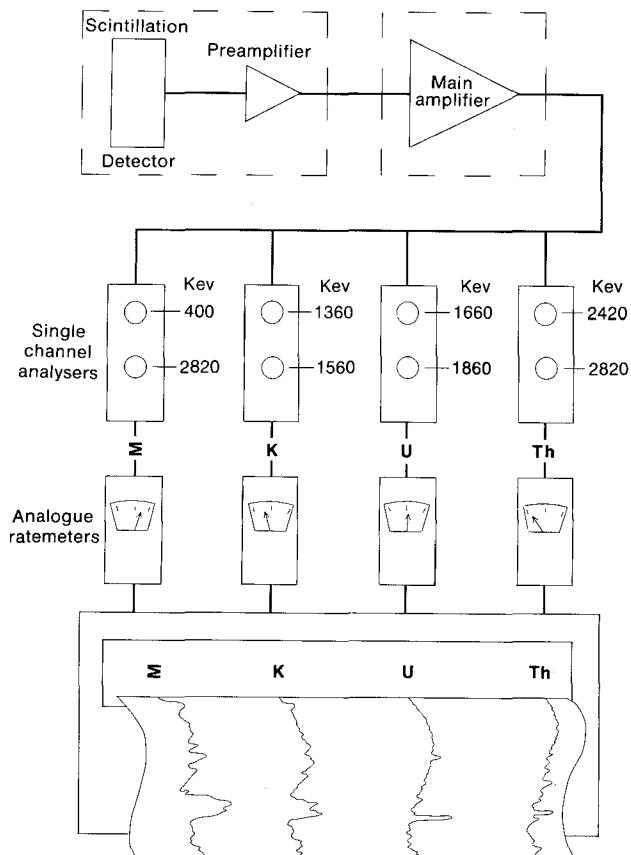


Figure 10A.3. Simple four-channel spectrometer, widely used for airborne surveys until about 1975.

From the strictly instrumental point of view the purpose of a radiometric survey is to record accurately the radiation intensities (count rates) at the detector in predetermined energy bands or "windows". Instrumental factors which degrade or cause errors in this process can be summarized as follows: -

- Inadequate counting statistics for reliable quantitative data.
- Inadequate detector resolution (i.e. inability to resolve energy peaks sufficiently well for satisfactory pulse height analysis) due to poor quality crystals or defective assembly.
- Detector gain drift, i.e. systematic variations in the pulse height corresponding to scintillations generated by a given energy.

- Inaccurate or varying window width settings.
- Excessive noise in the pulse amplifying and shaping chain causing an additional statistical variation in pulse heights.
- Spectrum distortion at high counting rates.
- Pulse height distortion due to detector overload by high energy events from cosmic sources.

It should be noted that even if these pitfalls are avoided and the objective indicated above is achieved, the measurements still require correction for the following factors: -

- Spectral interferences; due to the physical processes involved in the interaction of gamma radiation with the detector material and to the introduction of statistical noise by the photomultiplier tube, there is a mutual overspill or crosstalk between the closely adjacent potassium (^{40}K) and uranium (^{214}Bi) windows and a contribution to both of them from the thorium (^{208}Tl) window. "Stripping ratios" are experimentally determined and applied to recorded data to correct for this.
- Background radiation due to sources other than the crustal radioelement content. These include atmospheric radon, cosmic sources and radioactive material in either the equipment itself or the aircraft used to carry it.
- Atmospheric attenuation.

The theory behind these corrections and the methods of applying them are dealt with in more detail elsewhere in this article.

CURRENT LEVEL OF TECHNOLOGY FOR GAMMA RAY SPECTROMETERS

The instrumental techniques and hardware which are now coming into use in modern exploration gamma ray spectrometers are discussed here with reference to the fundamental considerations outlined above. For convenience they are separated into groups as follows: -

- Detectors
- Signal-conditioning electronics
- Pulse height analysis
- Spectrum stabilization
- Data display and recording

Detectors

The scintillation detector is still the most widely used type for airborne and ground follow-up equipment and appears likely to remain so for some time. Figure 10A.1 shows the crystal material labelled as NaI(Tl), which is an abbreviation for sodium iodide (thallium-activated). While this is the material most commonly used in scintillation detectors designed for uranium exploration applications, it is by no means the only one. Other inorganic crystals sometimes used in borehole logging applications are cesium iodide, activated with either sodium or thallium [$\text{Cs}(\text{Na})$, $\text{Cs}(\text{Tl})$] and bismuth germinate ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$). The cesium iodide crystals have a density which is approximately 25 per cent greater than that of sodium iodide with a correspondingly higher efficiency or stopping power for sensing gamma radiation; however the ability to resolve spectral peaks (resolution) is somewhat less than for sodium iodide. Bismuth germinate has a density very nearly double that of sodium iodide, but the resolution of detectors made from this material is barely adequate at present for spectrometry. An entirely different class of scintillators is that based on the use of organic plastics. These materials have low atomic numbers and hence very low efficiencies for the complete absorption of gamma rays in the

0.5-3.0 MeV region which is the useful range in uranium exploration applications. While they are widely used in laboratory work as active shields and in related applications where the requirement is for detecting and timing radiation events as opposed to energy measurements of such events, their very limited ability to resolve spectral peaks coupled with their poor efficiency renders them unsuitable for use in uranium survey work. Detectors made from plastic scintillators are much less costly than their inorganic crystal counterparts and some workers have conducted experiments to evaluate them as a less expensive alternative for airborne gamma radiation surveys (see e.g. Duval et al., 1972).

Experiments and studies have been conducted to evaluate the potential for airborne work of intrinsic germanium solid state detectors which have a resolution far superior to that of scintillation detectors. These indicate that the advantage of high resolution does not offset the cost of an array of sufficient volume to match the detection sensitivity of currently used scintillation detectors. The requirement for cryogenic operation with liquid nitrogen also presents an operational problem with solid state detectors. It seems probable however that solid state detectors will be used in borehole gamma ray spectrometry. In this application the detector volume is limited by the borehole tool diameter which in turn severely limits detector stopping power or efficiency for energies much above 1.0 Mev. Consequently it would be an advantage to have a detector capable of resolving the closely spaced lower energy peaks also associated with uranium and thorium.

For portable spectrometers single scintillation detectors with one photomultiplier tube (PMT) and a 76 x 76 mm (3x3 inch) crystal are still the standard unit. In airborne systems arrays of large detectors are in common use, and usually these are offered as add-on-modules of 16.4 L (1000 cu. in.) pre-packaged with suitable thermal insulation and shock mounting. Until recently the individual detectors have been of the traditional cylindrical type 100 to 130 mm thick by 150, 179, 203, 229 or 279 mm in diameter (4 or 5 inches thick by 6, 7, 8, 9 or 11 inches in diameter). The number of PMTs per crystal vary from three on the smaller ones to four on the 9 x 4 inch to seven on the 11 x 4 inch crystal. The reason for having more than one PMT on large crystals is to ensure more nearly constant light collection no matter where in the crystal a scintillation of given intensity occurs. This requires that each PMT be fitted with a separate gain control and that they be equalized by experiment to optimize the detector resolution, a tedious and time consuming task.

During the last three years a detector has become available in a prismatic configuration with a 100 x 100 mm (4 x 4 inch) square cross-section by 406 mm (16 inch) long with a single PMT mounted on one end. This has become very popular for airborne systems as it lends itself to compact packaging with an array of four or six side by side forming a "slab". Figure 10A.5 is a photograph showing such an arrangement.

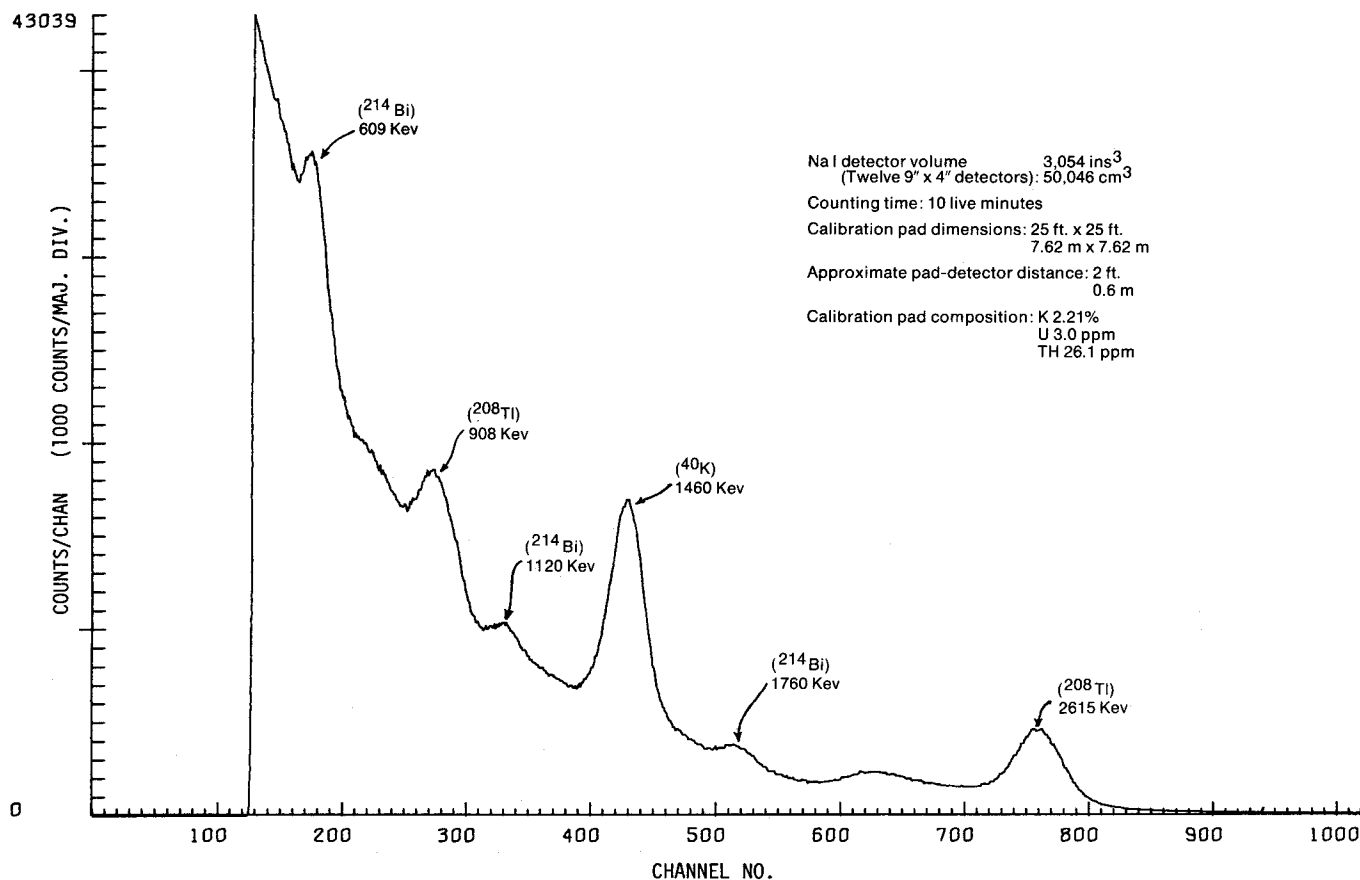


Figure 10A.4. Typical natural radioactivity spectrum.

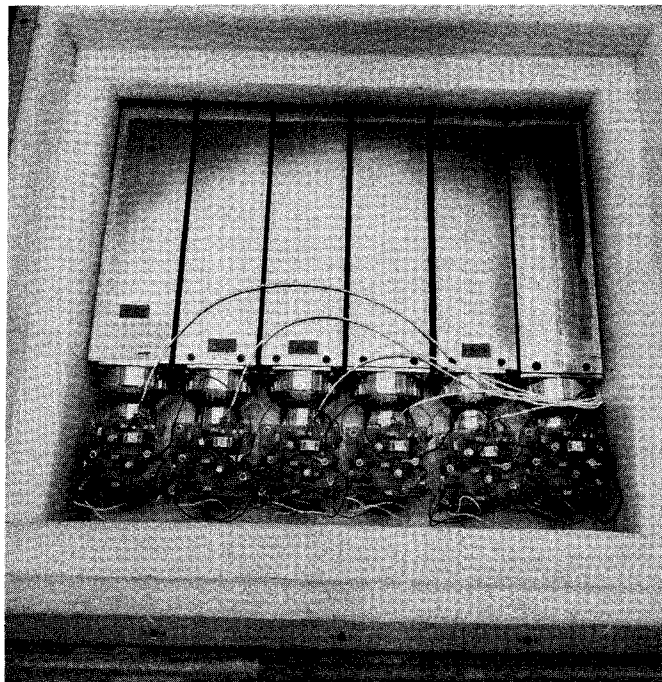


Figure 10A.5. Typical array of six 100 x 100 x 406 mm (4 x 4 x 16 inch) NaI detectors installed in a container designed to provide both thermal and electrical shielding. GSC 203492-K

More recently an actually slab-shaped detector has appeared measuring 279 x 279 mm by 100 mm (11 x 11 x 4 inches) thick with four PMTs mounted on the upper surface. It remains to be seen how widely this type will be used.

One of the standard measures of performance of a scintillation detector is the resolution of the 661KeV single energy peak of the isotope ¹³⁷Cs. This is a measure of the sharpness of the photo peak and is by implication a measure of the ability of the detector to resolve two closely spaced peaks. Figure 10A.6 illustrates the way that detector resolution is calculated and specified as a percentage. Individual detectors used in an airborne array such as the 100 x 100 x 406 mm (4 x 4 x 16 inch) size and others of comparable volume should have resolutions of 9.5 per cent or better (i.e. less).

A gamma ray in the 0.5 – 3.0 MeV range interacts with sodium iodide by a series of interactions with electrons in the material, during which most of the energy is converted to a series of virtually simultaneous scintillations. If all of the energy of an incident gamma ray is absorbed by the detector in this way then the resulting composite scintillation will produce a pulse height corresponding to the full energy. However if after a number of energy absorbing collisions the gamma ray, now reduced in energy, escapes from the detector, then the pulse height produced by the event will be identified as being of a lower energy and will not be counted in the proper energy window. The process is analogous to dropping a bead of mercury into a beaker; it shatters into a large number of small droplets which if all remain in the beaker will add up to the mass of the original bead. If some are "scattered" over the top then the mass will be less than that of the original bead.

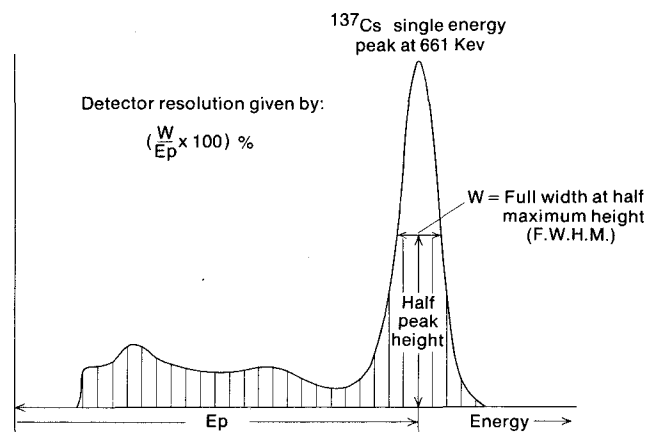


Figure 10A.6. Standard method of measuring detector resolution.

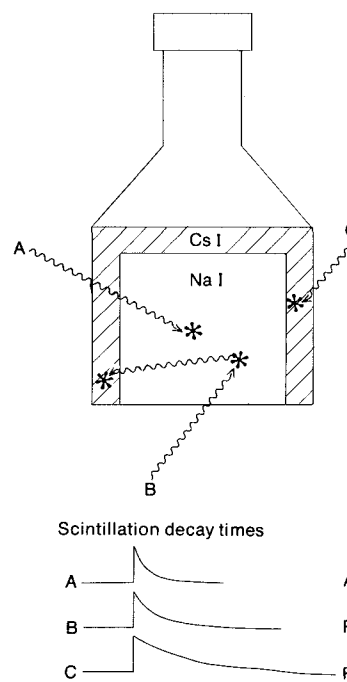


Figure 10A.7. The PHOSWICH (phosphor-sandwich) Detector. Different scintillation decay times in CsI and NaI enable only gamma rays which are absorbed in the NaI core (A in figure) to be recognized and accepted on basis of pulse shape. This greatly reduces the Compton Scatter interference normally generated by analyzing and counting partially absorbed gamma rays.

The partially absorbed photons which appear in lower energy windows after the pulse sorting process, are reduced in a new type of detector known as the "Phoswich" detector, the name being a mnemonic for "phosphor-sandwich". The principle is illustrated in Figure 10A.7. The crystal is in a form similar to that of an iced cake with the "cake" being made from sodium iodide and the "icing" from cesium iodide. The decay time for scintillations in the two materials is different by about 4:1, so that it is possible to differentiate between photons which have been completely absorbed in the sodium iodide central portion, (the active part of the detector) and those which have been absorbed by both parts, i.e. those which have been partially absorbed and scattered.

Pulse shape discrimination circuitry is used in the subsequent electronics to reject all events which have occurred either wholly or partly in the caesium iodide "icing" and accept only those which have been completely absorbed in the sodium iodide. The "Phoswich" detector is still in the experimental stage and it remains to be seen whether the advantages will offset the additional complication and expense.

A new type of photomultiplier tube, presently at an early stage of development, makes use of a silicon diode to replace the dynodes used in the conventional photo multiplier tube. Scintillations liberate photoelectrons from a photocathode deposited on glass in the usual way. These are then accelerated by a potential of the order of 10 kilovolts and focused onto a silicon photodiode which produces charge at an effective rate of approximately one electron per 3.3 eV (electron volts) of energy of each of the accelerated electrons from the photocathode. Since each of these has an energy of about 10 keV, approximately 3000 times as much charge is produced by the silicon diode as was liberated from the photocathode. This effective multiplication, while nowhere near as large as with a conventional multidynode arrangement, is sufficient and is produced in one step compared to the ten or more steps using a conventional tube. Consequently the statistical variation in the number of electrons produced per photoelectron liberated from the photocathode is less, offering the potential of improved energy resolution. However a high-gain low-noise charge preamplifier is then required to boost the signal to the level normally produced by a conventional photomultiplier tube. Early indications are that this technique is capable of providing a useful improvement in scintillation detector resolution over what can now be obtained with ordinary photomultiplier tubes. Additional advantages are a reduced dependence of the overall detector gain on high voltage and ambient temperature variations.

Signal-Conditioning Electronics Circuitry

This is the term generally used to describe the process of extracting, filtering or amplifying analogue signals so that the information they contain can either be digitized or fed directly to some form of visual or audio device with the minimum of unwanted noise. Examples would be the demodulation of stereo or colour TV signals, or the removal of d.c. levels from strain gauge signals to obtain an output suitable for driving a strip chart recorder. In this case the object is to convert the tiny charge signals which appear at the anode of the PMT of a scintillation detector into voltage pulses whose amplitudes are proportional to the energies of the gamma ray events which caused them.

Well-designed systems have a charge sensitive pre-amplifier for each detector, usually located in the detector package, which converts the charge pulses to voltage pulses capable of driving a reasonable length of line. This is followed by a main amplifier containing special filter circuits which shape the pulses to give an optimum signal to noise ratio. Figure 10A.8 shows the arrangement and how the zero level or base line between pulses following the preamplifier is poorly defined and noisy, but is considerably improved after the filtering and pulse shaping in the main amplifier. There are a number of excellent main amplifiers available in the popular "NIM" (Nuclear Instrument Module) package from laboratory instrumentation manufacturers. The generally preferred kind are those which produce Gaussian-shaped pulses. Most main amplifiers designed for laboratory work in the NIM package are more than adequate for exploration spectrometers and have provision for "base line restoration", an important feature when moderately high counting rates (greater than 20 000 c/s) are likely to be involved.

The need for base line restoration can be understood by reference to Figure 10A.9. At some point in the signal conditioning chain the pulse train will be passed through a capacitor to remove a d.c. level, following which the average d.c. level will always be zero. This means that at high count rates with a large number of pulses causing a net positive shift, the base line between pulses settles down to a slightly negative level to maintain the overall average at zero. The subsequent pulse-height analysis circuitry however does not recognize the negative shift of the base line, but sees all the pulses apparently reduced in amplitude and sorts them into lower energy slots than they should be. In other words at high count rates the entire spectrum is shifted to the left causing peaks to move out of their windows by an amount which is dependent on the count rate—a very undesirable effect indeed.

This effect can be compensated for in a variety of ways which are collectively termed base line restoration and as indicated earlier most good quality main amplifiers now have this feature incorporated.

The multidetector arrays used for airborne surveys require that the pulse signals from each of the individual detectors be adjusted so that the pulse amplitudes for a given energy are the same from each one. The outputs from all the detectors are then summed together at some point between the preamplifiers and the main amplifier. The circuitry for this is normally in a separate module with separate gain controls and switches for each detector to facilitate gain matching.

A modern airborne survey system with a detector volume of 50 L (3000 cu. in.) should have an overall resolution at the ^{137}Cs energy of at least 12 per cent (FWHM); although with good quality detectors and carefully designed signal conditioning electronics much better resolution is achievable.

Pulse-Height Analysis

The simplest form of pulse height measurement device, the Single Channel Analyzer (SCA) described earlier, accepts detector pulses from the main amplifier and puts out a logic signal whenever a detector pulse falls between amplitude limits set on two front panel controls. The most serious problem with SCAs is the difficulty in determining what energy limits the calibrated front panel controls actually correspond to. In the case of portable four-channel spectrometers for exploration work, a fifth channel is usually incorporated preset to cover the energy peak from an isotope such as the 661 KeV peak of ^{137}Cs , to allow for manual calibration. The other window limits also have preset controls not accessible on the instrument front panel. Initial settings of these is virtually a factory adjustment, requiring a reliable nuclear pulse generator with calibrated controls and provision for varying the pulse shape to match that of the detector being used. Most SCA discriminator circuits are sensitive to pulse shape to some degree as well as pulse height, so that initial pulse generator calibrations by the manufacturer can be in error if this point is not appreciated.

Once the initial calibration is done the accuracy of the subsequent measurements by the user (perhaps over many seasons), depends entirely on all of these preset controls maintaining their relative positions corresponding to the required window limits.

For many years so called "multichannel analyzers" have been available for making much more accurate pulse height measurements. These require an analogue-to-digital converter (ADC) which is similar to a very high speed digital voltmeter but with no visual display of the numbers it produces. The amplitude of each incoming detector pulse is

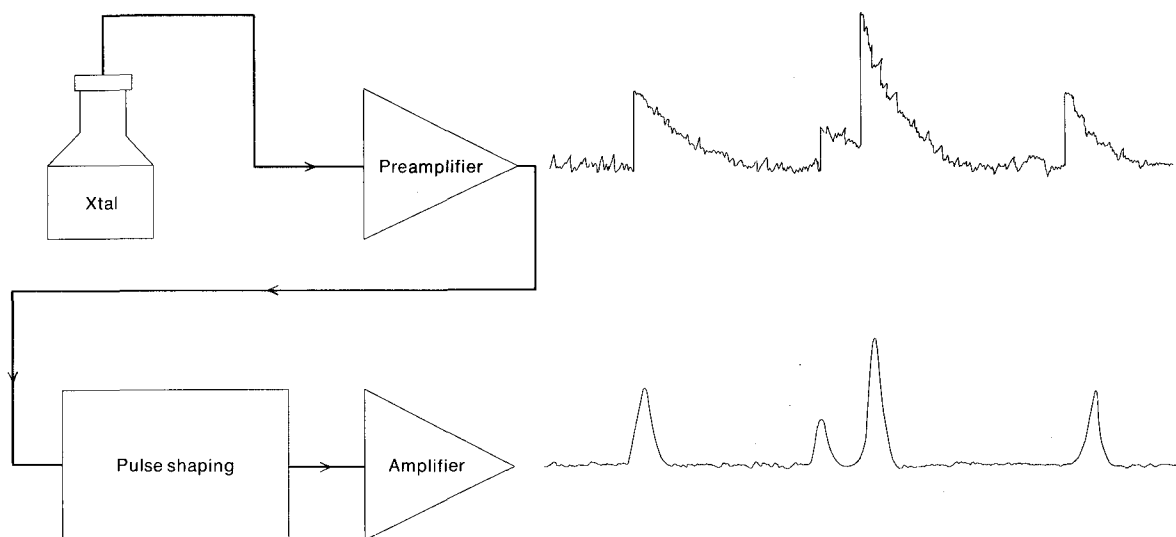


Figure 10A.8. Signal conditioning.
Well-designed signal conditioning electronics are essential for accurate pulse-height analysis.

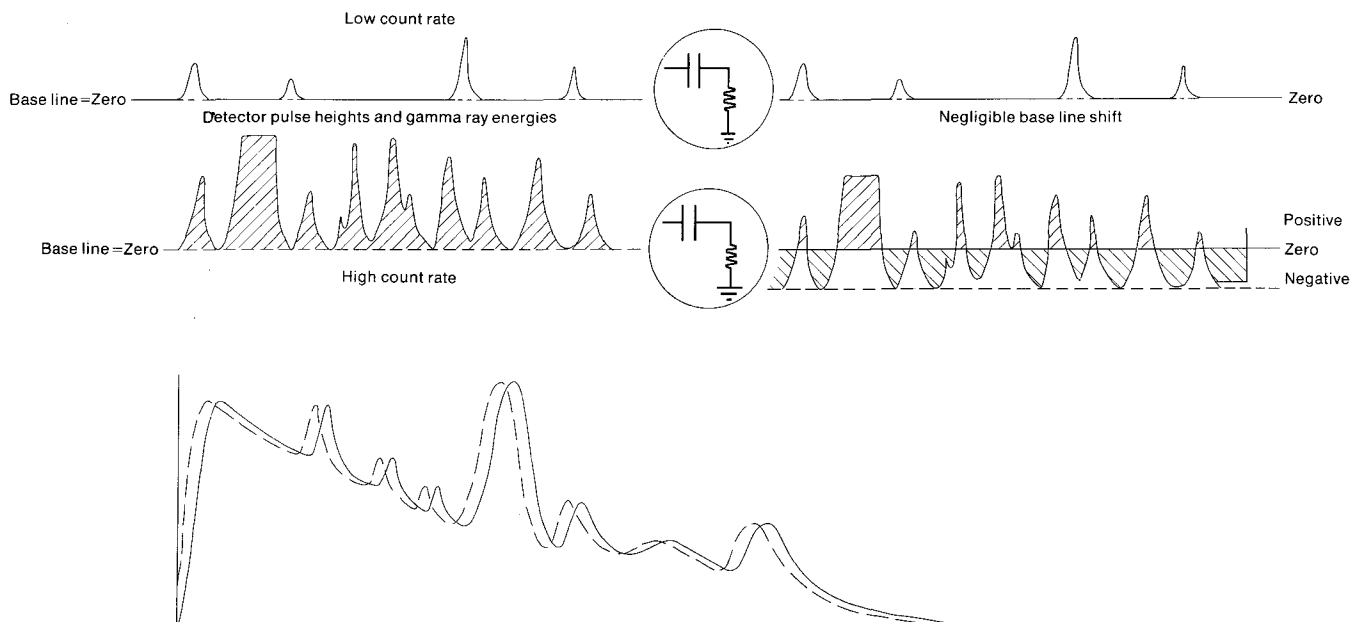
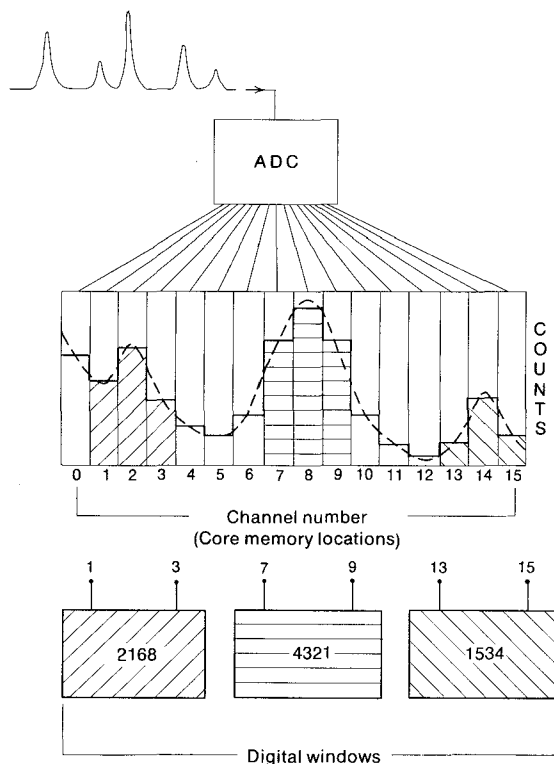


Figure 10A.9. Baseline shift.
If the detector pulse train is passed through a resistor-capacitor network (centre), the baseline shifts downward to maintain equal areas above and below the true zero level. Since pulse heights are measured from the true zero, this shift can cause serious errors at high count rates causing the entire spectrum to be shifted to the dashed line position (bottom).

measured by the ADC which assigns it a number between 1 and some maximum. In laboratory systems this could be as high as 8192 if high resolution solid-state detectors are being used; in airborne survey systems 256 is usually the maximum. The ADC thus has the capability of grading or sorting incoming detector pulses according to amplitude (i.e. energy), into one of 256 or more slots or channels. This is equivalent to 256 Single Channel Analysers in one box, except that to make use of all this information we now need 256 counters to keep track of the number of detector pulses that are accumulating in each channel. From this point there are two alternative methods for handling these data as indicated in Figure 10A.10.

- Use 256 locations of a minicomputer memory or equivalent device and increment each location when its number is "called" by the ADC
- Use digital circuitry that will increment a single counter for all numbers generated by the ADC between certain preset limits corresponding to a desired energy window.

The first method produces a representation of the gamma ray energy spectrum in the memory which is simply a histogram of energy divided into 256 discrete steps, showing the number of gamma photons which fell into each channel during the counting period. This can be displayed on a CRT,



ADC measures height of each incoming pulse, in this case on a scale of 16 and increments contents of corresponding memory locations by one to build up a 16 channel spectrum or histogram. By using more channels a smoother curve can be obtained corresponding to the dotted line. If only counting windows are required then counters can be connected to the ADC via a simple interface and arranged to count all pulses in preset ranges of channel numbers - no computer or memory is required.

Figure 10A.10. Advantages of an Analogue/Digital Converter (ADC).

or plotted on hard copy and provides complete information on the sources of radiation which were detected (within the limits of the detector resolution).

The second method is fairly straightforward and can be implemented without any memory, with the necessary circuitry being duplicated to produce as many "digital windows" as required. The advantage over the equivalent Single Channel Analyser arrangement is that all the window limits are set by specifying channel numbers generated by the ADC, and these have a fixed and predictable relationship with each other, since each channel spans a known energy increment.

As to the ADCs themselves there are two distinct principles of operation for converting the pulse height into a number proportional to it. One is known as the "Wilkinson Ramp" method and the other as the method of "Successive Approximations". Since there has been some controversy as to which is most suitable, their relative merits are worth some discussion.

The Wilkinson ramp principle is illustrated in Figure 10A.11 and is analogous to the "hour glass" principle. Imagine an hour glass being filled with sand to a level which is equal to the height of a detector pulse. If the hour glass is then inverted, the time the sand takes to run out is then proportional to the pulse height. The number of seconds of elapsed time could be interpreted as the channel number for that pulse height (gamma photon energy). Note that if a second pulse arrives during the time the hour glass is running for the first one, the second one is ignored and neither analyzed nor counted. This is the ADC "dead time" and in the Wilkinson ramp type it is proportional to the height of the pulse being analyzed, plus a fixed time for some logical operations in the ADC.

In electrical terms a capacitor is charged to the height of each detector pulse and then discharged linearly to zero while pulses from a high frequency oscillator (50 to 200 MHz) are counted. The number in the counter at the end of this process is then taken as the channel number of that detector pulse.

The successive approximations method can be understood by reference to Figure 10A.12. Essentially it works by comparing the incoming detector pulse height to a series of yardsticks of varying lengths on a trial-and-error basis starting with the longest yardstick. If the pulse amplitude is greater than this then an amount equal to this yardstick is subtracted and the next shortest one is compared to the remainder; if this is too long the next shortest is tried. The process continues until a match is found. The circuitry then infers from the particular yardsticks which were used to subtract pieces from the incoming pulse, what the channel number is.

By way of example suppose that it was only required to sort the incoming detector pulse into one of sixteen channels rather than 256. Suppose further the particular pulse being analyzed had an amplitude of 13 on this scale. The ADC requires only four yardsticks to sort any pulse into one of sixteen channels, their lengths (in arbitrary units) being 1, 2, 4 and 8 units. Beginning with the longest (8 units) it would find that the pulse was larger and subtract the equivalent of 8 units. It would then compare the remainder with the 4 unit yardstick and still find a mismatch. Having subtracted off 4 more units it would test the remainder against the 2 yardstick which would be too large. Finally the 1 yardstick would be used to find a match. The height of the pulse would thus be computed as $8 + 4 + 1 = 13$ units.

This is a much quicker process than the clock pulse counting required by the Wilkinson ramp type. For example in order to sort a pulse into one of 256 slots, (including zero) only 8 yardsticks are required with at most only 8 comparisons. The difficulty arises in making accurate comparisons and subtractions of the yardsticks, (voltages developed across precision resistors in fact) with and from the incoming detector pulses.

In the case of a 256 channel successive approximations ADC, a detector pulse having a channel number of 128 will be analyzed after applying the very first yardstick, although the remaining seven comparisons will be made anyway because the logic is simplified by so doing, but one having a value of 127 will require the successive subtraction of voltages corresponding to all of the 8 yardsticks before it is determined. This places very stringent conditions on the accuracy of both the yardsticks and the subtraction/comparison circuitry used if the effective widths in terms of energy increments for the pairs of channels which occur at "yardstick change" points are to be equal.

The advantages and disadvantages of the two types of analogue-to-digital converter can be summarized as follows: -

Successive Approximations Type

- rapid conversion time which is the same for all detector pulses regardless of amplitude
- high probability of sharp discontinuities in adjacent channel widths particularly at 1/4, 1/2 and 3/4 of full scale due to the nature of the conversion process

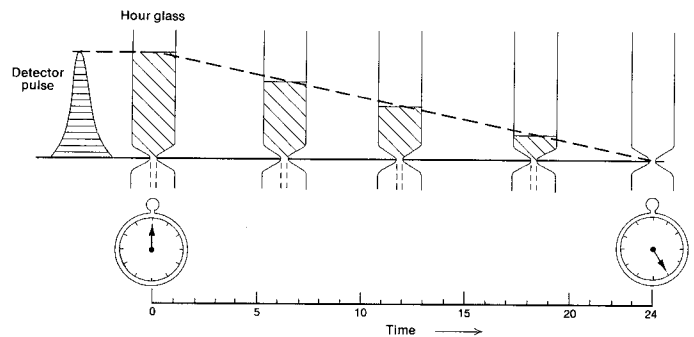
Wilkinson Ramp Type

- Conversion time which is proportional to the amplitude of the pulse being analyzed plus a small constant and which is of the order of twice as long as for the successive approximations ADC at full scale.
- Differential nonlinearity, i.e. variation in channel widths across the range, far less than for the successive approximations type due to the inherently linear "hour glass" principle of conversion.
- Universally used by nuclear laboratories where high precision is required and where the constraints of high count rate and limited available counting time are not a problem.
- As a result of many years of refinement, well-designed ADCs of this type are available off-the-shelf in one or two width NIM (Nuclear Instrument Module) packages at relatively modest cost from a number of sources.

So long as the scintillation detector with its comparatively poor resolution is being used with only 256 channels to cover the spectral region of interest, then there is probably little to choose between the two types unless the data are to be used for very precise spectral analysis. However if solid-state detectors come into vogue as they probably will for borehole logging, requiring 2048 or 4096 channels for adequate spectral information, then the successive approximations ADC will require considerably more development to achieve the necessary differential linearity.

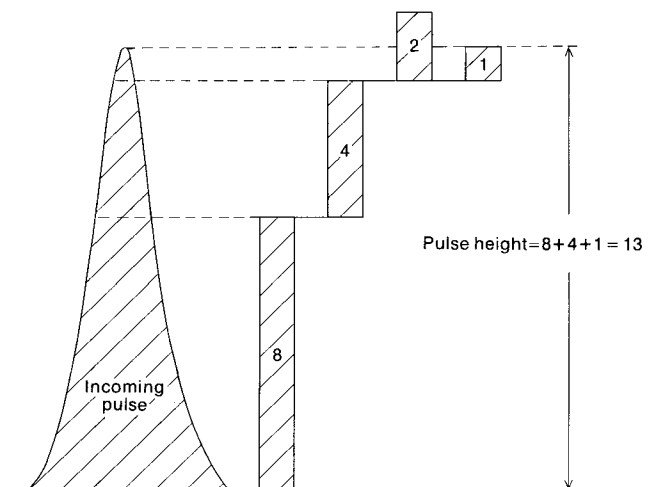
ADC "dead time" is a factor which requires some form of correction no matter which type is used. The dead time is the interval during which the ADC is making a conversion and is unable to accept any other detector pulses. In the case of

the successive approximations type the dead time is a fixed length, whereas it is proportional to the amplitude of the pulse being analyzed for the Wilkinson-ramp type. A correction can be made in the former case by multiplying the total number of pulses counted in say one second by the known conversion time (a few microseconds) and increasing the contents of all channels pro rata to compensate for the lost time. A hardware method applicable to both fixed and variable dead time ADCs involves two time counters, one of which is interrupted for all intervals when the ADC is busy (i.e. "dead"). At the end of each sample time the difference between the contents of the two counters is a measure of the dead time for that record and can be used to make an on-line correction to the data just acquired, or simply recorded on tape along with other data for use in off-line data processing.



Imagine an hour glass filled to the height of an incoming detector pulse. The time for the sand to run out would then be proportional to the energy of the corresponding gamma ray. A measurement of the time in appropriate units (microseconds in practice) is then a digital representation of the energy.

Figure 10A.11. Principle of the Wilkinson Ramp type ADC.



The amplitude of an incoming pulse is digitized by comparing it with a series of precision voltage "yardsticks". In the case shown four comparisons only are required to determine the amplitude as a number on a scale of 1-15. A more precise determination on a scale of 0-255 would require eight yardsticks with relative values 1:2:4:8:16:32:64:128.

Figure 10A.12. Principle of Successive Approximation ADC.

Spectrum Stabilization

All spectrometers are vulnerable to spectrum drift, i.e. the possibility that the detector pulse height corresponding to a given energy changes over a period of some hours. This manifests itself as a uniform scale change on the horizontal axis of the spectrum. Figure 10A.13 shows the effect of a reduction in pulse height causing the spectral peaks to shift to the left and off the centres of the counting windows.

The major sources of spectrum drift are the gains of the PMTs which are notoriously temperature dependent and not particularly stable even at constant temperature, and changes in the high voltage supply. A change of 0.1 per cent in the high voltage applied to the PMTs changes the pulse heights by about 1 per cent. Modern high voltage supplies designed specifically for this purpose are now more than adequate to reduce this source of spectrum drift to negligible proportions. The PMT gain variation can be reduced to manageable limits by packaging the detectors in a thermally controlled environment. Virtually all airborne spectrometers currently on the market have heated detector packages for this reason.

There are some spectrometers available which incorporate active spectrum stabilization. This involves monitoring detector pulses which are known to be due to scintillations of a certain energy generated in the detector either by a specially implanted radioisotope, or an artificial light source. The principle is illustrated in Figure 10A.14. Two adjacent counting windows are set up to centre on the spectral peak generated by the implanted source. The circuitry is so arranged that when their counting rates are equal no output is obtained, but when they differ a suitable analogue error signal is generated, positive say if the peak is off centre to the left and negative if it is off centre to the right. This error signal can then be used to change the gain of the system somewhere in the chain to restore the proper relation between spectral peaks and counting windows. The usual technique for applying corrective action is through the high voltage supply, although changing the conversion gain of the ADC or the gain of the main amplifier (more difficult) would achieve the same result.

Spectrum stabilization is not difficult to implement and many variations on the general technique have been utilized at one time or another, particularly in portable spectrometers. The problem is to avoid interfering with the spectral information which is being sought in the first place. This constraint means that the implanted source should not generate a peak in the region of interest i.e. approx. 0.5-3.0 MeV. In the case of an implanted light source such as a PIN diode, it can be pulsed on during predetermined short intervals when data acquisition is disabled to avoid any such interference. However a radioisotope cannot be so controlled other than by a mechanical shutter which is cumbersome.

To avoid interference with the data and the uncertainties of the PIN diode light source (still in the experimental stage), some manufacturers use low energy sources such as ^{133}Ba which generates a peak at 356 KeV. At this low energy even a small base-line shift at high count rates equivalent to say 20 KeV, would be interpreted by a spectrum stabilized using ^{133}Ba as a reduction in gain of 20/356 or about 6 per cent. It would then call for an overall gain increase of 6 per cent to correct for a minor offset which would not of itself have caused a significant error in the results. The 6 per cent gain increase would however in this case result in a very significant error.

The problem can be circumvented in airborne systems with arrays of large detectors by using the potassium ^{40}K peak itself as the reference, since it is a reliably prominent one under most conditions. In a mini-computer-based experimental system designed by the author

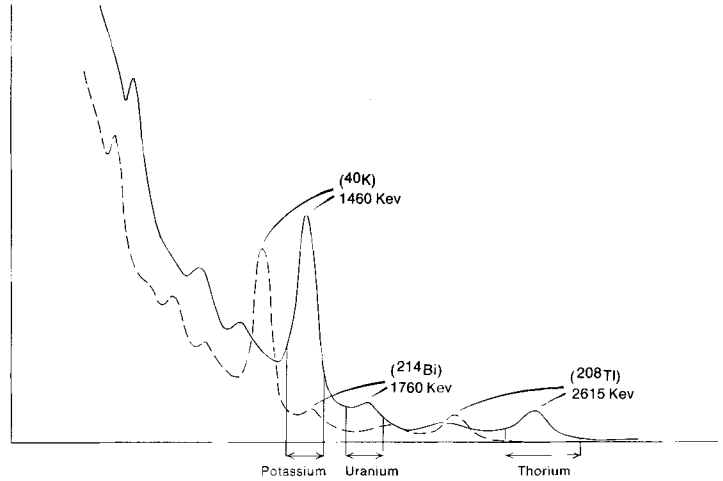
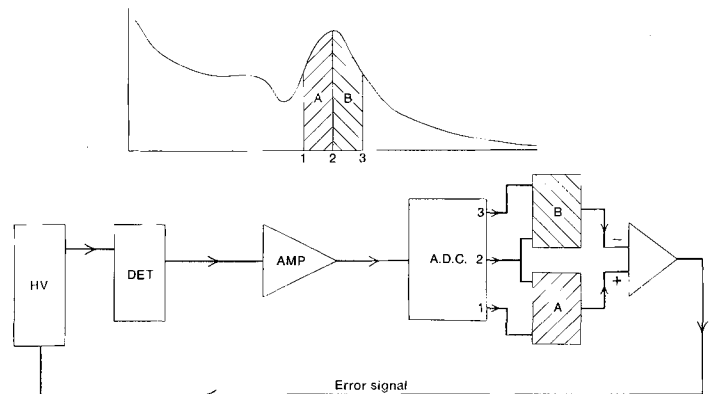


Figure 10A.13. The dashed line shows what happens to the spectrum if the detector gain or subsequent amplifier gains drop. In this extreme case the ^{214}Bi peak has moved into the ^{40}K window. Unless drifts of this sort are quickly spotted by the equipment operator, useless and misleading data may be used in good faith to complete radiometric maps or make exploration decisions.



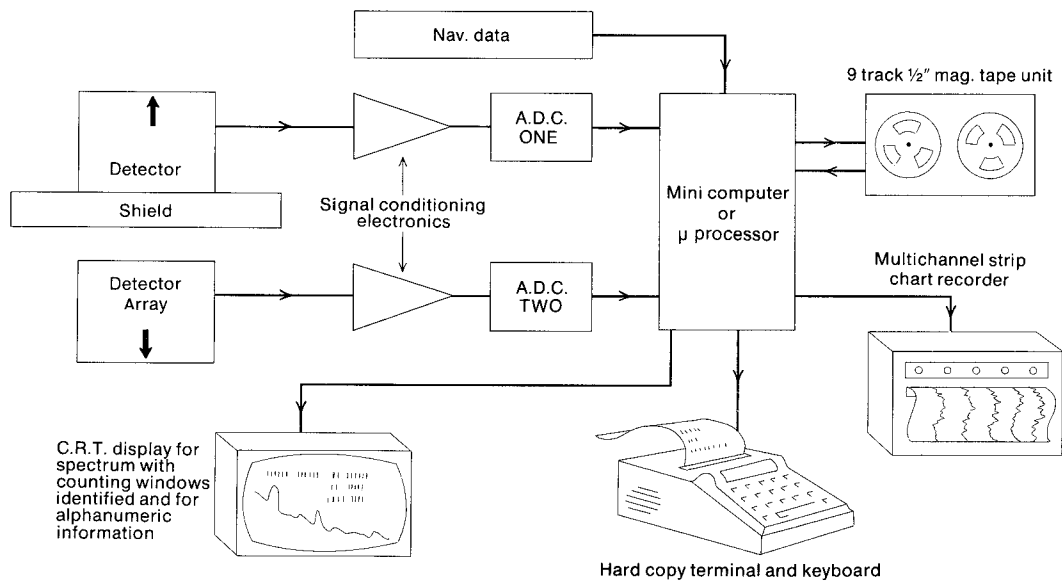
When count rates in windows A and B are equal the error signal is zero. When the count rates differ a positive or negative error signal is generated according as $A > B$ or $A < B$ which alters the high voltage in such a way as to move the peak back and restore symmetry. A stabilizing peak must always be present for such an arrangement and can be generated by a pulsed light source or radioisotope implanted in the detector, or by using an external source.

Figure 10A.14. Spectrum Stabilization.

(description to be published), the ^{40}K peak position is monitored and the counting window positions are recomputed periodically to correct for any drift.

Data Acquisition: Display and Recording

More often than not the gamma ray spectrometer is but one component of a multiparameter system in airborne applications and some complexity is necessary in handling the incoming data in order to display and or record it in an orderly manner. Until recently this function was performed by hardwired logic controllers with operator entries being made via thumbwheel switches.



Such a system will have full spectral recording, means for atmospheric radon correction, a spectrum display with windows identified and a strip chart recorder on which a variety of profiles can be plotted. Such a system would normally be minicomputer or microprocessor based.

Figure 10A.15. Modern airborne gamma-ray spectrometer

Most equipment now incorporates programmable hardware based on minicomputers or their microprocessor equivalents. The advent of this technology in a form suitable for field and airborne instrumentation has suddenly opened up the possibility for sophisticated on-line data correction, CRT displays, keyboard entry of commands etc., to an extent limited only by the imagination of the designers.

Manufacturers have been understandably cautious in exploiting these possibilities, however most have the capability for storing complete gamma ray spectra and most either have or are adding CRTs for displaying the full spectrum with provision for identifying the counting windows. This is a well high indispensable feature in the author's view for detector gain matching and other performance checks. Window counts and other alphanumeric data are displayed either on CRT terminals or LED readouts; some manufacturers offer hard copy terminals rather than CRT displays.

Multichannel strip chart recorders are still universally used to display inflight profiles of window counts and other data such as ratios and radar altimeter readings. Some systems also use the same recorder for generating plots of complete spectra for system performance records.

Digital recording of airborne survey data was for many years done on 0.5 inch magnetic tape at a density of 200 or 300 bits per inch (bpi), using incremental seven-track tape transports. The years 1976 and 1977 saw an almost universal change over to the newer nine-track tape transports which are compatible with data centres all over the world and with 16 bit minicomputer systems. They also offer much higher recording rates than the older seven-track systems and more economical information storage as the bit density is 800 bpi, about three times that of the older standard. One disadvantage is that this high bit density makes factors such as tape condition, cleanliness of the recording heads and capstan drive etc., very much more critical than they were with the older systems, so that more attention must be paid to tape storage and handling practices and preventive maintenance schedules for the tape transports during survey operations.

The higher recording rates now available make it possible to record complete gamma ray spectra at the end of each counting period if they are stored in a suitable memory by the ADC as described earlier. Several survey specifications drawn up by national agencies now call for complete spectral recording from two separate detector arrays, one with a downward field of view and a smaller one shielded from direct terrestrial radiation which is used to monitor atmospheric radon. The recorded spectra extend to 6.0 MeV, allowing cosmic background to be monitored so that corrections can be made continuously for this contribution to the potassium, uranium and thorium derived signals. The arrangement is fairly elaborate and requires two ADCs and buffer memories, so that one pair of spectra can be acquired while the previous ones are being written to tape. Figure 10A.15 shows the block diagram of a typical modern airborne spectrometer.

FUTURE TRENDS IN AIRBORNE GAMMA RAY SPECTROMETRY

One thing which has bedevilled electronic data processing in general and field recording systems in particular has been the need for electromechanical mass storage systems such as magnetic discs, drums, and tapes large and small. It now seems likely that "magnetic bubble" memories and similar technology will replace these devices in the foreseeable future. Bubble memories can be considered (very broadly indeed) as the solid state analogue of the magnetic disc memory. Instead of the disc physically rotating past a sensing head, the tiny magnetic anomalies (bubbles) in a piece of otherwise uniform material are moved in the material itself. Storage and readout are not yet as fast as with core or solid state memory devices, but even now are orders of magnitude faster than for a disc. There seems little doubt that by 1985 or even sooner, the cost and the development will have reached the point where bubble memories could replace magnetic tape for in-flight storage of survey data.

As microprocessors become faster and more sophisticated there will be no reason not to do on-line data processing, including the deconvolution of spectra to correct for the known and imperfect response of detectors to the gamma radiation they receive.

Analogue-to-digital converters are already available in single width Nuclear Instrument Modules (e.g. Nuclear Data model 575). As large scale integration becomes more sophisticated, their sizes will shrink to the point where it would be possible to consider having one ADC for each detector in an airborne array. If at the same time the PIN, diode light source or an implanted alpha emitter such as ^{241}Am becomes a reliable method of providing a reference source, then the necessary signal conditioning electronics circuitry an ADC and a high voltage power supply could be designed to be integral with the detector as a single package. The detector "output" would then be a digital address rather than an analogue pulse height, with the energy and address relation internally stabilized by the reference scintillation source using appropriate windows on the ADC as described earlier. This would avoid the analogue problems which develop at high count rates since the detector "outputs" would be "summed" digitally. The superimposition of analogue pulses from different detectors would also be avoided by pushing the digital processing one stage farther back in this way.

Detectors with internally stabilized digital outputs could then be assembled in very large arrays indeed without any loss in overall resolution, thereby allowing higher survey speeds.

REFERENCES

The literature cited below is a selected bibliography where additional discussions of the instrumental aspects of gamma ray spectrometry can be found. These are not necessarily in the context of uranium exploration as this represents a fairly limited and specialized application of the science. For references to earlier work in this field the reader is referred to the proceedings of the Symposium on Mining and Groundwater Geophysics held at Niagara Falls, Ontario 1967 (see below for citation).

- Breiner, S., Lindow, J.T., and Kaltenbach, R.J.
1976: Gamma-ray measurement and data reduction considerations for airborne radiometric surveys; *in* I.A.E.A. Proc., International Symposium Exploration of Uranium ore deposits, Vienna 1976.
- Bristow, Q.
1974: Gamma-Ray; sensors; *in* geoscience instrumentation; E.A. Wolff, E.P. Mercanti, ed., John Wiley & Sons, New York.
1975: Gamma-ray spectrometry instrumentation; *in* Report of Activities, Part C, Geol. Surv. Can., Paper 75-1C, p. 213-219.
1977: A system for the offline processing of borehole gamma-ray spectrometry data on a NOVA mini-computer; *in* Report of Activities, Part A, Geol. Surv. Can., Paper 77-1A, p. 87-89.
1978: The application of airborne gamma-ray spectrometry in the search for radioactive debris from the Russian satellite COSMOS 954 (Operation "Morning Light"); *in* Current Research, Part B, Geol. Surv. Can., Paper 78-1B, p. 151-162.
- Chase, R.L.
1961: Nuclear pulse spectrometry, McGraw Hill, New York, 221 p.
- Crouthamel, C.E.
1960: Applied gamma-ray spectrometry, Pergamon Press, New York, 443 p.
- Duval, J.S., Worden, J.M., Clarke, R.B., and Adams, J.A.S.
1972: Experimental comparison of Na(Tl) and solid organic scintillation detectors for use in remote sensing of terrestrial gamma-rays; *Geophysics*, v. 37(5), p. 879-888.
- Fairstein, E. and Hahn, J.
1965/
1966: Nuclear pulse amplifiers - fundamentals and design practice, Parts 1-5, *Nucleonics*: v. 23(7), p. 56 (July 1965); v. 23(9), p. 81, (Sept. 1965) v. 23(11), p. 50 (Nov. 1965); v. 24(1), p. 54 (Jan. 1966); v. 24(3), p. 68 (Mar. 1966).
- Foote, R.S.
1970: Radioactive methods in mineral exploration; *in* Mining and Groundwater Geophysics, ed., L.W. Morley; Geol. Surv. Can., Econ. Geol. Rept. No. 26, p. 177-190.
- I.A.E.A.
1974: Recommended instrumentation for uranium and thorium exploration; I.A.E.A. Technical Rept. No. 158, Vienna.
- Killeen, P.G. and Bristow, Q.
1975: Uranium exploration by borehole gamma-ray spectrometry using off-the-shelf instrumentation; I.A.E.A. Proc. International Symposium on Exploration of Uranium Ore Deposits, Vienna.
- Nicholson, P.W.
1974: Nuclear electronics; John Wiley & Sons, London.
- Reed, J.H. and Reynolds, G.M.
1977: Gamma-ray spectrum enhancement; U.S., E.R.D.A. Rept. No. GJBX-25(77).
- Orphan, V., Polichar, R., and Ginaven, R.
1978: A "solid state" photomultiplier tube for improved gamma counting techniques; Uranium Exploration Technology Ann. Amer. Nucl. Soc. Meet., San Diego, Calif, June, 1978. (Abs.)
- Pemberton, R.H.
1970: Airborne radiometric surveying of mineral deposits; *in* Mining and Groundwater Geophysics, ed., L.W. Morley; Geol. Surv. Can., Econ. Geol. Rept. No. 26, p. 416-424.
- Schneid, E.J., Swanson, F.R., Kamykowski, E.A., and Mendelsohn, A.
1977: Airborne detector improvement; U.S. E.R.D.A. report No. GJBX-40(77).