Developments in the Standardization and Analysis of Airborne Gamma-Ray Data

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ABSTRACT

In the last ten years, the use of gamma-ray spectrometry for geological mapping and mineral exploration has shown considerable growth. With this growth, standardized procedures have been developed for the calibration and processing of the airborne measurements so that they will be independent of survey parameters. This paper describes some of the new developments to convert airborne data to ground concentrations of potassium, uranium and thorium. There are now accepted procedures for removing atmospheric background variations using upward-looking detectors and through spectral analysis. Recently, more reliable measurements of the ground concentration of potassium, uranium and thorium have been achieved through analysis of the 256 channel spectrum.

INTRODUCTION

Airborne gamma-ray spectrometry is increasingly being used by the exploration industry for geological mapping and for locating mineral deposits. Its use also extends to environmental geophysics, where the regional mapping of natural radiation levels assists in the estimation of health risks and provides a baseline against which man-made radioactive contamination can be measured. But the full potential of the method can only be realized if common standards for the measurement of the natural radiation environment are adopted. Specifically, measuring units should be independent of the instrumentation and survey parameters. This allows the data from many different surveys to be combined into coherent large scale compilations which will enhance their value for regional interpretations. It also provides more stringent control of spectrometer performance resulting in the early detection of malfunctions.

Procedures for standardizing airborne and ground gamma-ray measurements were developed in the mid 1970s as a result of large government uranium exploration programs such as those carried out in the United States and Canada (Duval, 1991; Darnley *et al.*, 1975). The International Atomic Energy Agency (IAEA) has dealt with the calibration and processing procedures to convert the airborne measurements to ground concentrations of potassium, uranium and thorium (IAEA, 1991). More recently, the Australian Geological Survey Organisation (Grasty and Minty, 1995a) produced a guide to the specifications for airborne gamma-ray surveys which explains in more detail the technical and practical reasons for the specifications.

This paper first gives a brief account of the current status of instrumentation. The main body of the text concentrates on several important aspects of standardization, particularly in relation to calibration facilities. This is followed by a discussion on the determination of atmospheric background which is one of the main problems in airborne gamma ray spectrometry. This is followed by a discussion on the standardization of old gamma ray survey data.

The final part of this paper describes some of the procedures that have recently been developed for the analysis of the full spectrum. One of these techniques, described in the current proceedings (Hovgaard and Grasty, 1997) appears to be a major breakthrough in the analysis of multi-spectral gamma-ray data.

INSTRUMENTATION

Modern spectrometers record at least 256 channels of data in the range 0 keV–3000 keV. They were used as early as the 1970s for the large United States National Uranium Resource Evaluation (NURE) program (Duval, 1991). At that time the spectrometers were temperature stabilized to minimize spectral drift and required skilled operators. However, these systems sometimes drifted by 2–4 channels per day at the 2615 keV thorium photopeak. Grasty and Minty (1995a) have shown that a gain drift of 4 channels can introduce errors exceeding 5% in the measurement of both uranium and thorium. In some instances, subsequent analysis of the spectral data has found that the photopeaks had drifted

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completely outside the window of interest (Smith, 1996). Cumulative spectral plots for each flight line serve to monitor any spectral drift. Those flight lines exhibiting significant drift should be energy calibrated prior to integrating over the conventional windows.

The Geological Survey of Canada (GSC) developed the first gamma-ray spectrometer which corrected for spectral drift in real time (Bristow, 1979). This was achieved by monitoring the position of the potassium photopeak from an accumulated spectrum of all detectors and computing new potassium, uranium and thorium windows. The current generation of commercially available spectrometers employ an on-line, self-stabilizing technique which uses the centre of the prominent potassium or thorium photopeaks to maintain proper alignment of each individual detector. These self-stabilizing spectrometers normally maintain the correct positions of the photopeaks to within ±0.5 channels and no post-flight adjustments are required to extract the correct window count rates. In many cases, self-stabilzation and automatic monitoring of system performance has reduced survey costs, since a spectrometer operator is no longer necessary.

Some of the new spectrometers can record up to 2048 channels of spectral data but typically only 256 channels would be recorded. For normal surveying there is little advantage in recording any more than 256 channels due to the wide photopeak widths of NaI detectors at high energies. However, for environmental surveying of man-made low energy radiation, this may not be the case.

Spectrometers require a finite time to process each pulse from the detectors and any pulse that arrives while another is being processed is automatically rejected. The total counting time available is thus reduced by the time taken for all pulses to be detected. This "dead-time" effect has been considerably reduced by some manufacturers by using a separate analogue-to-digital converter for each crystal.

The International Atomic Energy Agency (IAEA, 1991) have recommended fixed window boundaries for airborne gamma ray spectrometry (Table 1). It has been established that these windows are near optimum for normal crustal material (Minty and Kennett, 1995; Grasty *et al.*, 1991) and there are a number of advantages in conforming to this standard. For example, meaningful comparisons can be made between the calibration constants from various systems, and the monitoring of system constants over time can help detect potential malfunctions of the equipment.

CALIBRATION PADS

Proper calibration of the gamma ray spectrometer system is a critical component and is required to determine parameters for the various correction stages which lead to ground level radioelement concentrations. In general, it is not practical to calculate these parameters due to the complexity of the processes involved and consequently special calibration facilities are required. Calibration pads have two purposes:

1. to determine the various stripping ratios of the airborne system; and
2. to calibrate the ground spectrometer used to measure the ground concentration of the airborne calibration range.

The GSC has been involved with the calibration of ground and airborne gamma ray spectrometers since it constructed the first calibration facility for airborne spectrometers in 1968 (Grasty and Darnley, 1971). Similar calibration facilities have now been constructed in many countries throughout the world. These facilities are usually four or five large concrete slabs or pads about 8 m × 8 m × 0.5 m thick with known concentrations of potassium, uranium and thorium. Most of these calibration facilities have been studied by Løvborg (1984) through a research contract with the IAEA.

Large calibration pads are expensive to build. It is also difficult to distribute small amounts of uranium and thorium ores uniformly through the concrete. If the pads are inhomogeneous, then the calibration constants derived from measurements on the pads will be unreliable (Corner and Smit, 1983). Many of the uranium pads have also been found to lose some of their radon with a resultant loss in gamma ray activity (Grasty, 1987; Stromswold, 1978 and Løvborg *et al.*, 1978). This loss of radon is recognised as a common problem in the construction of calibration pads.

In 1988, the GSC experimented with small transportable pads 1 m× 1 m × 30 cm. weighing approximately 700 kg. The concentrations of the four pads were constructed to conform with those recommended by the IAEA (1989). The uranium and thorium pads were constructed using Canadian uranium and thorium materials distributed by the IAEA as laboratory gamma ray counting standards. However, within a few months of their construction, the uranium pads had lost from 9–15% of their gamma-ray activity. Apparently, the alkalis in the cement had broken down the uranium grains allowing a partial loss of radon to occur. This was somewhat surprising considering that the uranium ore was known to be a low emanator of radon. Subsequently, a uranium-rich calcium silicate slag from a phosphorus processing plant was used for the construction of the uranium pads. Measurements one year later confirmed that there was no radon loss from the pads.

Table 1: ***Recommended windows for natural radioelement mapping (IAEA,1991).***

Window name	Isotope used	Gamma-ray energy (keV)	Energy window (keV)
Potassium	^{40}K	1460	1370–1570
Uranium	^{214}Bi	1760	1660–1860
Thorium	^{208}Tl	2615	2410–2810
Total count	–	–	410–2810
Cosmic	–	–	3000 – ∞

The results of the GSC studies have shown that because these pads are small, it is easier to make them uniformly radioactive and as a result their radioelement concentrations can also be accurately determined. Consequently, in using these pads, the calibration constants can be measured reliably. Experiments have also shown that these small pads give the same calibration constants as the much larger and more expensive aircraft calibration pads. Small transportable pads appear to be an effective and inexpensive way of calibrating both ground and airborne gamma ray spectrometers. Sets of these transportable calibration pads are now being used in many countries throughout the world.

CALIBRATION RANGES

Calibration ranges are used to calculate height attenuation coefficient for each window and to calculate sensitivity coefficients at the nominal survey altitude. Following the IAEA guidelines (IAEA, 1991), an airborne calibration range should have the following features. It should:

1. be relatively flat;
2. have uniform concentrations of K, U and Th;
3. be close to a body of water for the measurement of background;
4. be free of flight restrictions;
5. be readily accessible for surface measurements;
6. be easy to navigate;
7. be about 8 km long, equivalent to about 150 s flying time at 50 m/s;
8. have no hills within about 1 km of the flight line.

These guidelines were proposed for both practical and technical reasons. Uniform concentrations of the radioelements ensure that navigation, both in the air and along the ground, is not crucial to the estimation of the height attenuation and sensitivity coefficients. The uniform concentrations also ensure that at all altitudes the airborne and ground measurements are effectively sampling the same source. Over-water backgrounds give an absolute background correction and remove any uncertainties associated with other methods of removing background. A calibration range along a power line, road or fence is easy to navigate and usually provides good access for ground measurements.

A major source of errors in gamma-ray spectrometry is due to Poisson counting statistics. These errors depend on the concentrations of potassium, uranium and thorium in the ground, the sampling time and number of measurements, as well as on the various calibration parameters of the detection systems such as background count rates, sensitivities and stripping ratios. The higher the concentration of the calibration range, the more reliable will be the individual ground and airborne measurements. However, the IAEA (1991) guidelines do not specify any minimum concentrations for a calibration range. Grasty and Minty (1995b) have recommended that the calibration range should have minimum concentrations of approximately 1% potassium, 3 ppm uranium and 6 ppm thorium to reduce the errors in the sensitivity coefficients to acceptable levels.

There are difficulties in meeting the ideal requirements for a calibration range. Two airborne calibration ranges in Australia lack many of the desirable features of a calibration range. In particular the two ranges are inhomogeneous which has made the calibration task difficult (Grasty and Minty, 1995b). In Canada, the GSC has developed a calibration range near Ottawa (Grasty and Charbonneau, 1974). However, its relatively low uranium concentration limits the accuracy of the uranium calibrations. The United States calibration range near Lake Mead, Nevada (Foote, 1978) is reported to have problems with landowner permission for ground accessibility, a common problem in the development of a calibration range. Two recently developed calibration ranges in Namibia and Australia are reported to meet the desired characteristics, but there is clearly a need for more acceptable calibration ranges for fixed-wing aircraft.

Calibration of a helicopter system can be achieved by hovering at a fixed location. Ground measurements are much easier to perform since the airborne system is viewing a limited area and therefore a much smaller area need be sampled on the ground. It is also easier to find a small area with uniform concentrations of the radio-elements than it is for a calibration range for a fixed wing aircraft which would normally extend up to 8 km in length. This procedure has now become an accepted method for calibrating helicopter systems.

At the same time as the airborne calibration flights are being performed, the ground concentration of the range must be measured. There are several reasons why these measurements should be made with a calibrated portable spectrometer rather than by the geochemical analysis of soil samples. For example, variations in soil moisture affect the radiation output from the ground but not the geochemical analyses. More importantly, there may be large radon changes in the soil between sample collection and analysis (Grasty, 1997).

Another reason why geochemical sampling is not recommended relates to the response of a gamma-ray spectrometer to sources at various depths. Sources near the surface have a greater influence on the airborne measurement than sources at depth. Since the radioactivity of soils can vary with depth, soil sampling is not a reliable means of comparing ground concentrations with the airborne response.

BACKGROUND ESTIMATION

Aircraft and cosmic component

The counts recorded in any window have three background components. These background components originate from:

1. the radioactivity of the aircraft and its equipment;
2. high energy cosmic ray particles that interact with the air, the aircraft and the detector;
3. radon decay products in the air.

The count rates due to cosmic radiation increase exponentially with height above mean sea level in all spectral windows. This cosmic ray component can be removed through the use of the cosmic ray window that records all crystal interactions above 3 MeV (Table 1). The advantage of the cosmic-ray window is that it is not influenced by gamma radiation from the ground since no terrestrial gamma rays have energies above 3 MeV. Therefore, through an appropriate calibration procedure, this window can serve to monitor increases in the cosmic-ray background in all windows (IAEA, 1991).

The calibration of the cosmic ray window is performed by flying at different barometric altitudes over the sea or a large lake. In the past, every possible effort has been made to avoid radon contributions to the various windows. This has resulted in flights being carried out at altitudes as high as 4500 m. Previous contracts have often specified that these flights should be made over the sea when there is an on-shore breeze so that radon problems are minimized. Recommended flights were from 1500 m to 3000 or 3500 m at 300 m intervals with a 10-minute measurement time.

The requirement to fly at high altitude was designed to minimize any effects due to radon, in the belief that it was necessary to separate the aircraft and cosmic background contributions in each window from the variable radon contribution. This can only be achieved provided there is no radon present at the altitudes flown. Figure 1 shows an example where there is significant radon at lower elevations. By fitting a straight line, as shown, to the values at high cosmic counts, it would be assumed that there was no radon contribution in the various windows. However,

there may still be a uniform distribution of radon at the higher elevations. Some contractors have found quite different linear relationships depending on when they fly the cosmic calibrations.

However, Grasty and Minty (1995a) have shown that it is not necessary to carry out the cosmic calibration flights when there is no radon present in the atmosphere. The unknown radon component appears as part of the aircraft background and cosmic stripping ratio and is removed during the normal processing procedures. Accordingly they recommend that aircraft and cosmic calibration measurements be taken over the sea at only two barometric altitudes covering the range of altitudes that will be encountered during the course of the survey. In Australia they recommend flying over the sea at 250 m and 2250 m. The lower limit is based on the fact that the sea has a small potassium concentration which can be detected at normal survey altitude. By flying 250 m above the sea, this contribution will be exceedingly small and virtually undetectable. The higher altitude of 2250 m was based on the height of Mt. Kosciusko, the highest mountain in Australia.

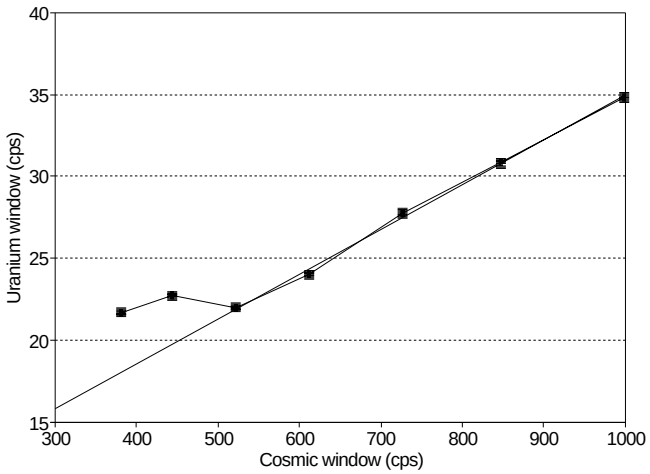

Figure 1: *The variation of the uranium and cosmic windows showing the effects of radon at the lower elevations.*

This recommended procedure eliminates the necessity of extrapolating the high altitude cosmic ray measurements to the survey altitude. The cosmic and aircraft background components are simply removed in one step, by monitoring the cosmic ray window during the course of the survey and linearly interpolating the two calibration measurements over the sea. There is also the added advantage that flights at altitudes in excess of 3000 m are no longer necessary, thereby saving valuable time and money.

Radon component

One of the daughter radionuclides in the uranium decay series is the radioactive gas, radon (^{222}Rn), which has a relatively long half-life (3.8 days), and can diffuse from the ground into the atmosphere. Unfortunately, one of the decay products of radon is ^{214}Bi, which is the nuclide used to measure the uranium content of the ground. It is therefore essential to correct for the effects of atmospheric radon.

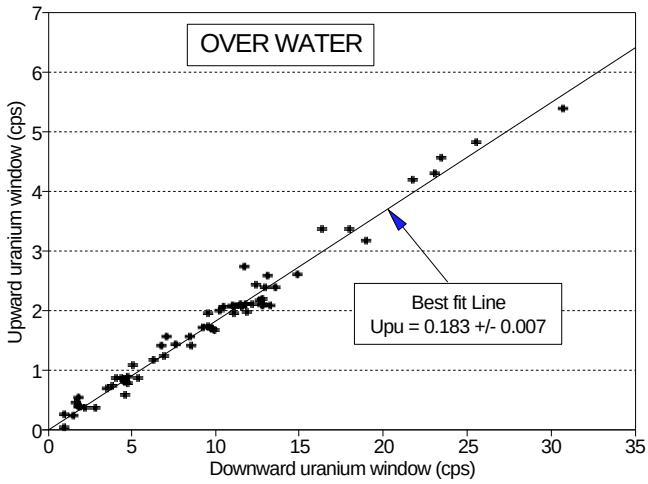

Figure 2: *Calibration of the upward detector from flights over water.*

One of the procedures to monitor changes in atmospheric radioactivity is through the use of upward-looking detector which are largely shielded from ground radiation by the main downward-looking detector. The IAEA(1991) has described how these detectors can be calibrated. Part of this calibration procedure involves a series of flights over a lake on days with different concentrations of ^{222}Rn. Figure 2 shows the results of a series of flights over a lake in Canada after removal of cosmic and aircraft background. The ratio of the upward/downward to sources of ^{222}Rn in the air is one of the required calibration constants.

In many countries, lakes are few and far between and an alternative procedure is required to determine this particular calibration constant. Figure 3 shows a plot of the average upward and downward window count rates over a test line flown with the same system during the course of the same survey. The slope of this line is very close to the value obtained over land. The small difference may be the result of uranium count rate variations in the downward detectors due to changes in soil moisture, aircraft flight track or flying height.

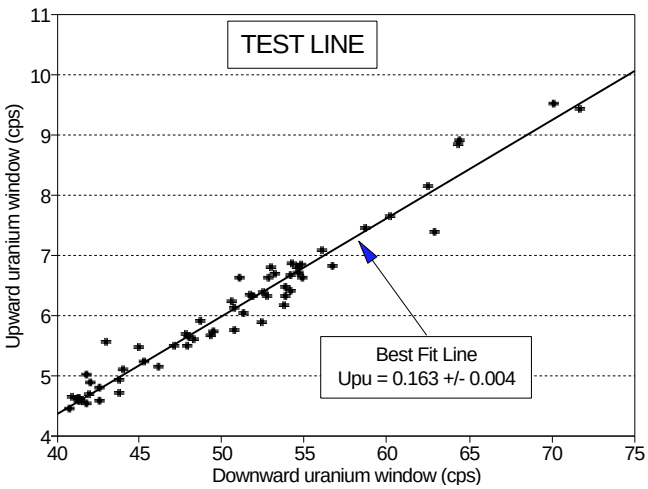

Figure 3: *Calibration of the upward detector from flights over a test line.*

Unfortunately the upward detector is not perfectly shielded from the ground by the main detectors. A correction must therefore be made for the influence of ground radiation into the upward detectors. The IAEA (1991) attempt to separate the ground contribution of uranium and thorium into the upward detector which has proved difficult because of the strong correlation between the uranium and thorium windows. However, Grasty and Hovgaard (1996) have shown that because of this correlation, the contribution of ground radiation into the upward detector can be predicted from either the uranium or thorium window. This simplifies the upward detector calibration considerably.

One of the common criticisms of upward detectors is that they cannot work if the radon is concentrated below the aircraft. However, the excellent linear relationship between the upward and downward detectors in figures (2) and (3) strongly suggests that for these series of flights, radon is distributed uniformly in the atmosphere. The main disadvantage of the upward-looking detector method is the increased weight of the detector package and the associated increased flying costs.

In Australia, a spectral-ratio method has been developed for the estimation of atmospheric radon background Minty (1991) which was originally proposed by Kogan *et al.* (1971). The method uses the relative heights of ^{214}Bi series photopeaks to determine the contribution of airborne radon to the observed spectrum. The method is based on the observation that the low-energy ^{214}Bi photopeak at 0.609 MeV from atmospheric radon suffers far less attenuation relative to the ^{214}Bi peak at 1.76 MeV than is the case for radiation from the ground. The ratio of the counts in the two photopeaks is therefore diagnostic of the relative contributions of atmospheric and terrestrial ^{214}Bi to the observed spectrum.

The spectral ratio method also has its limitations. It cannot be used at low altitude since it relies on the layer of air between the aircraft and the ground to modify the shape of the ground spectrum. Forested areas or non-radioactive overburden will also modify the shape of the ground spectrum resulting in erroneous background estimates. In addition, the method cannot be used in most of the northern hemisphere due to the presence of ^{137}Cs from atomic weapons testing or the Chernobyl nuclear accident. This is because ^{137}Cs emits gamma rays at 662 keV which interferes with the measurement of ^{214}Bi at 609 keV.

BACK CALIBRATION

A large part of the world's land area has been covered by airborne gamma-ray surveys, many of which have not been standardized (Grasty *et al.*, 1995). This vast source of gamma-ray data is potentially valuable not only to the geologist but also to the health physicist for assessing background radiation levels. This realization prompted the IAEA to investigate the possibility of standardizing old gamma-ray data commonly called "back calibration".

The basis of back calibration is to compare the airborne count rates with the concentration of the ground as measured with a calibrated portable gamma-ray spectrometer. There are three procedures that have proved successful, some of which require considerable more time and effort than others. These procedures are to compare airborne and ground measurements (a) along one flight line, (b) over several large uniformly radioactive areas, and (c) at the intersections of roads and flight lines.

The first procedure was used in Malaysia where one particular flight line was selected as a calibration line (Grasty *et al.*, 1992). Four ground measurements were taken along this line at the intersection of roads or tracks with the aircraft flight track. Airborne sensitivities and their associated errors were first determined at each measurement site. These sensitivities were then used to calculate the overall window sensitivities. Figure 4 shows a comparison of the ground measurements and the airborne measurements after the airborne data was calibrated.

The second procedure was originally proposed by the IAEA who recommended that a minimum of five different areas should be used for the calibration (IAEA, 1990). The potassium, uranium and thorium airborne sensitivities were determined by relating the average airborne count rates with the average ground concentrations for each area. This procedure has been the basis for back-calibrating airborne surveys in Australia (Dickson and Scott, 1991). A background radioactivity map of the Czech republic has also been produced following a similar procedure (Mánova and Matolín, 1995). In this case, the airborne total count was back-calibrated to dose rate using the average ground level dose rates for each area surveyed.

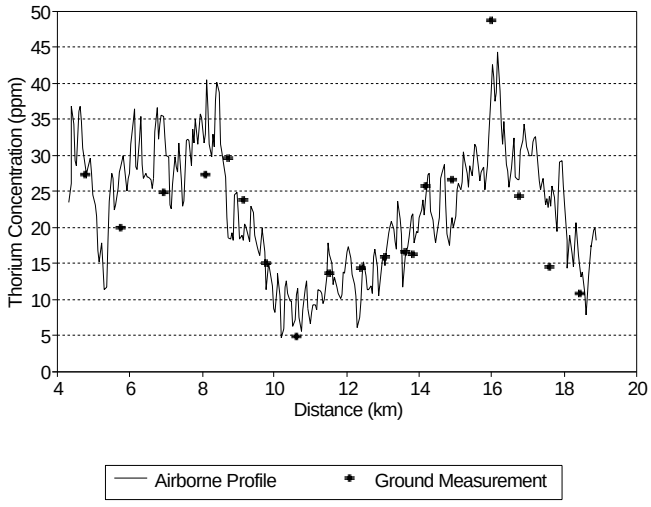

Figure 4: *The relationship between the thorium ground concentration and the calibrated airborne measurements in Malaysia.*

Following the success of the back-calibration of the Malaysian data, the IAEA sponsored back-calibration programs in Argentina and Portugal. In the case of Portugal, the data included airborne spectrometer measurements as well as ground and carborne total count scintillometer measurements made in the 1950s (Torres and Grasty, 1995).

The third procedure was used in Namibia, where ten different surveys were each individually back-calibrated (Duffy *et al.*, 1994). These surveys, representing almost 100 000 line kilometers of airborne data, were flown with a variety of spectrometers, spectral windows and survey parameters over a period of 12 years. Approximately 50% of the data were original analogue chart traces which were digitized. Ground measurements were made at twenty calibration sites within each of the airborne survey areas. The selected calibration sites were in areas of uniformly elevated radiometric signature and subdued topography at the intersections of flight lines and roads. Such locations would also have been used by the survey aircrews for navigation (fiducial markers on flight records), thereby assuring that the ground and airborne measurements were at the

same location. The quality and consistency of the final map products demonstrated that analogue radiometric data can be successfully recovered and combined with digital data to assist in exploration and environmental studies.

MULTICHANNEL ANALYSIS

Ever since the large government sponsored uranium survey programs in the United States and Canada in the late 1970s, it has been common practice to record 256 channels of spectral information. Until recently, little of this information has been utilized. Usually the data was converted to the four standard windows with the full spectrum simply serving to show that the equipment was functioning properly.

Much of the theory for the processing of multichannel spectra was developed in the 1980s. Dickson *et al.* (1981) used a principal component analysis to study the change in shape of the gamma-ray spectrum as a function of the survey altitude using plywood sheets to simulate the attenuation of gamma-rays in the air. They found that the spectra of each of the three radio-elements were composed of essentially two components, whose proportions varied according to the survey altitude. The spectra at any survey altitude could then be calculated by combining the two components in the appropriate proportions.

A theoretical analysis of the spectrum from typical crustal material showed that by multi-spectral fitting, the thorium and uranium concentration errors could be reduced by approximately 25% compared to the standard three window method (Grasty *et al.*, 1985, Minty 1996). However, there are practical problems in carrying out full spectral analysis of one second data due to the small number of counts in each channel, particularly at the high energy end of the spectrum. Minty (1996) overcame this problem by combining non-adjacent channels into 11 separate regions of interest thereby increasing the number of counts. He has developed a practical methodology and processed two large surveys in Australia using this technique. The final processed maps show improved resolution of geological features compared to the three-window method.

In these proceedings, Hovgaard and Grasty (1997) describe a new spectral analysis method which appears to be significantly better than the spectral fitting method. The technique uses up to 256 channels of data from the entire survey data set to identify all statistically significant spectral shapes which are then used to reconstruct new potassium, uranium and thorium windows. After this reconstruction, the new windows are found to have significantly less noise than the original raw windows. Hovgaard and Grasty (1997) found that for uranium and thorium, the reduction in statistical noise is equivalent to increasing the detector volume by a factor typically between 3 and 4. The technique has the advantage that following this pre-processing procedure, the standard three-window analysis can be carried out. An additional advantage over multi-spectral fitting is that no model experiments are required to derive the potassium, uranium and thorium spectra at different heights.

The new spectral analysis technique can benefit any spectral analysis technique. For instance, the measurement of atmospheric background using the spectral ratio technique will be more reliable allowing the background to be updated more frequently. The upward detector spectrum could also be included in the spectral analysis to improve background estimation.

One problem in airborne gamma-ray spectrometry is due to the attenuation of the airborne signal by forest cover which results in low estimates of the ground concentration. Minty (1996) has demonstrated a procedure based on spectral shape for estimating the effective height of the detector from the source of radiation in the ground. This effective height includes the attenuating effect of the intervening layer of air as well as any non-radioactive overburden or forest cover. However, due to statistical errors, the calculated distances can only be made by accumulating spectra over considerable distances. By applying the spectral processing technique to reduce statistical noise, it may be possible to correct for forest cover (or non-radioactive overburden), thereby helping in the interpretation of the data.

CONCLUSIONS

The first airborne gamma-ray spectrometer surveys were flown almost 40 years ago. It is only in the last five to ten years that airborne gamma ray spectrometry has become accepted as being a useful tool not only for uranium exploration but also for geological mapping and mineral exploration. To a large extent, this is due to the development of standards for the acquisition, calibration and processing of the airborne data. The increasing use of gamma ray spectrometry over the past decade indicates that it will play an even more important role in geological mapping and mineral exploration in the future.

ACKNOWLEDGEMENTS

The International Atomic Energy Agency has played a major role in developing standards for gamma ray surveying through various consultants reports on the construction of calibration facilities, preparation of laboratory standards etc., some of which are referenced in this paper. However, there have been many other programs in gamma-ray spectrometry that the IAEA have supported, including regional/international workshops and training programs as well as an estimated 30 technical assistance missions to different countries. All of these have helped to promote the role of airborne and ground surveying not only for uranium exploration and environmental monitoring but also for geological mapping and mineral exploration. The primary initiator of these programs has been Mohamad Tauchid who had the enthusiasm, energy and endless perseverance to negotiate through the bureaucracy of a large organization such as the IAEA. Much of the work presented in this paper is a direct result of Mohamad's foresight and efforts while he was at the IAEA.

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