Reducing Statistical Noise in Airborne Gamma-Ray Data Through Spectral Component Analysis

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ABSTRACT

A procedure has been developed for analyzing and processing multi-channel airborne gamma-ray data. 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. Since the procedure makes use of all the counts in the spectrum as well as the correlation between potassium, uranium and thorium, the reduction in statistical noise is found to be significantly greater than for multi-channel spectral fitting. An analysis of both simulated and measured survey data has shown 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. Maps produced using these new windows were found to show significantly more geological information than those produced by the standard 3 window method.

Compared to the multi-channel spectral fitting procedure, the technique has the advantage that following this pre-processing procedure, the standard 3 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. This technique can be applied not only to airborne gamma-ray survey data but to any series of gamma-ray measurements.

INTRODUCTION

Measurements of the ground concentrations of potassium, uranium and thorium by airborne gamma-ray spectrometry is a well-established technique. In the early stages of the development of airborne gamma-ray spectrometry, only 4 energy windows were recorded. These windows were centered on the ^{40}K gamma-ray peak at 1460 keV, the 1760 gamma-ray peak from ^{214}Bi in the uranium decay series and the 2615 peak from ^{208}Tl in the thorium series. A fourth total count window covering a broad energy band was used to monitor overall levels of radioactivity.

Since the early 1980s it has become common practice to record 256 channels of spectral data covering an energy range from 0 to 3000 keV. However, little of this information has been utilized, the full spectrum simply being used to monitor the spectral drift of the system and check that the equipment is functioning correctly.

There has been much debate about the merits of using the 256-channel information to derive better estimates of the ground concentrations of potassium, uranium and thorium. Grasty *et al.* (1985) and Minty (1996) have shown that with a weighted least squares fitting procedure, it is possible to reduce the errors in the uranium and thorium ground concentrations by approximately 25% compared to those resulting from the standard three window method. This corresponds to an effective detector volume increase of 50%. Recently Minty (1996) has shown the results of multi-channel processing on two large data sets in Australia. His results demonstrate that there is some benefit in multi-channel processing in terms of increasing the definition of radiation patterns on the ground.

The main disadvantage in carrying out a spectral fitting procedure is that potassium, uranium and thorium spectra must be determined experimentally for each system and cover a range of flying heights. However, by using the procedure described in this paper, it is possible to determine all statistically significant spectra for an entire gamma-ray data set. With this knowledge, it is then possible to reconstruct new potassium, uranium and thorium windows which have now incorporated information from all other parts of the spectrum. These new windows are found to have significantly less noise than the original raw windows. Compared to the spectral fitting procedure, this technique has the additional advantage that following this pre-processing procedure, the standard three-window analysis can be carried out.

In this paper we briefly describe the spectral component analysis procedure and then show the results of our analysis of several gamma-ray data sets. These are from

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1. a survey flown in Nevada by Newmont Exploration;
2. a series of flights over the Geological Survey of Canada calibration range;
3. a detailed airborne survey flown in Bulgaria;
4. measurements from a carborne system; and
5. measurements from a portable gamma-ray spectrometer.

Finally, we discuss the benefits of this type of analysis through the use of simulated data.

GAMMA-RAY SPECTRAL COMPONENT ANALYSIS

A series of n measured 256-channel spectra can be expressed as a linear combination of m unknown spectral shapes together with their amplitudes or concentrations. In matrix notation this can be written as

$$\mathbf{X} = \mathbf{C}\Gamma\mathbf{S}^T + \Delta \qquad [1]$$

where $\mathbf{X}$ is an $(n \times 256)$ matrix of observations, $\mathbf{C}$ is an $(n \times m)$ orthonormal matrix of concentrations, $\mathbf{S}$ is a $(256 \times m)$ orthonormal matrix of spectral shapes, Δ is an $(n \times 256)$ matrix of disturbances caused by the stochastic nature of radiation detection and Γ is a diagonal matrix used to normalize $\mathbf{C}$ and $\mathbf{S}$.

For an airborne gamma-ray survey flown at the same survey altitude, the measured spectra (after removal of the background) are composed of linear combinations of just three spectra originating from potassium, uranium and thorium. When the airborne survey is carried out at different survey altitudes there are changes in the gamma-ray spectral shapes from all three radioactive elements. However, Dickson *et al.* (1981) have shown that over the range of altitudes normally encountered in airborne gamma-ray surveying, the spectral shapes from each of the three radioelement can be made up of linear combinations of just two spectral shapes. Therefore, a total of six spectral shapes should be sufficient to explain all real variations that occur in airborne gamma ray spectra. The problem is to find the six spectral components as well as their corresponding amplitudes or concentrations (matrix $\mathbf{S}$ and matrix and $\mathbf{C}$ in equation 1).

A common way to determine the spectral components is the principal component (PC) technique which is described in many textbooks such as *Multivariate Analysis* by Mardia *et al.* (1979). The PC technique is a general linear transformation of all the variables to produce uncorrelated variables (in this case, uncorrelated spectral shapes) that explain a decreasing amount of variance. For instance, the first PC is the single spectral shape which explains most of the sample variance while the second PC explains most of the sample variance not explained by the first PC, etc.

The method has been applied to a variety of problems in the geological sciences (Joreskog et el., 1976, and Davis (1973)) and has also been described by Gower *et al.* (1984) for analyzing optical reflectance spectra of sea water. Dickson (1980) and Dickson *et al.*, (1981) have also described a modified version of the PC technique to analyze gamma-ray measurements on calibration pads and is similar to the method applied in this paper.

However, there are problems in using the standard PC technique as well as Dickson's (1980) method to analyse gamma-ray spectra. The main problem is that in a series of airborne gamma-ray measurements there are real variations due to changes in ground concentration as well as variations due to Poisson counting statistics. The standard PC technique does not distinguish between these two types of variations. The problem is further complicated because the lower energy channels have higher counts and therefore relatively lower statistical variations than the higher energy channels. If this is not taken into consideration, the spectral components may not reflect the real spectral shapes since they will also depend on the varying Poisson noise acoss the spectrum. These problems were solved by Hovgaard (1997) who developed a spectral component analysis method for use in nuclear emergency situations where the nuclide compositions were unknown.

One of the problems in utilizing these spectral components is that they represent a mixture of gamma-ray fields. Hovgaard used linear combinations of the spectral components to reconstruct spectra which were more informative and represented spectra from man-made sources of radiation such as cesium. The method described in this paper is a modification of Hovgaard's original method. In this paper, the spectral components as well as their concentrations are derived in the same way but are then used to reconstruct new spectra which have significantly less statistical noise than the original observed spectra. New potassium, uranium and thorium windows can then be determined from the reconstructed spectra.

AIRBORNE DATA FROM NEVADA

Analysis of components

The gamma-ray spectral component analysis procedure was carried out on an airborne data set from Nevada provided by Newmont Exploration. The survey was flown at a nominal altitude of 120 m and a line spacing of 400 m. using a detector volume of 16.8 l. The data set was originally selected to test procedures for removing the extreme radon variations that occurred during the course of the survey (Grasty and Hovgaard, 1996).

Figures 1a to 1h show the first eight spectral components. These spectral components are a mixture of spectra originating from potassium uranium and thorium which we have attempted to interpret. For this particular survey, the origin of some spectral components are relatively easy to identify, being due to the large radon variations within the data set. In these figures the spectra have been scaled and the magnitude of their vertical axes do not reflect the importance of the individual components.

Figure 1a shows the first spectral component with the major gamma-ray peaks being identified and is typical of any airborne spectrum. This particular component accounts for most of the signal and is the average spectrum. Figure 1b is the second spectral component and is the spectral shape which accounts for most of the signal after removal of the first component. In this spectrum, the main gamma-ray peaks from ^{40}K at 1460 keV and ^{208}Tl from the thorium series are also readily identified together with strong negative peaks from the uranium series. This spectrum can be interpreted to be the result of the large radon variations which occur in this data set. By combining this component with the average spectrum (the first component) it is possible to create spectra with varying proportions of radon.

The third component (Figure 1c) shows a negative thorium peak at 2615 keV and a positive ^{40}K peak. By combing this spectral component

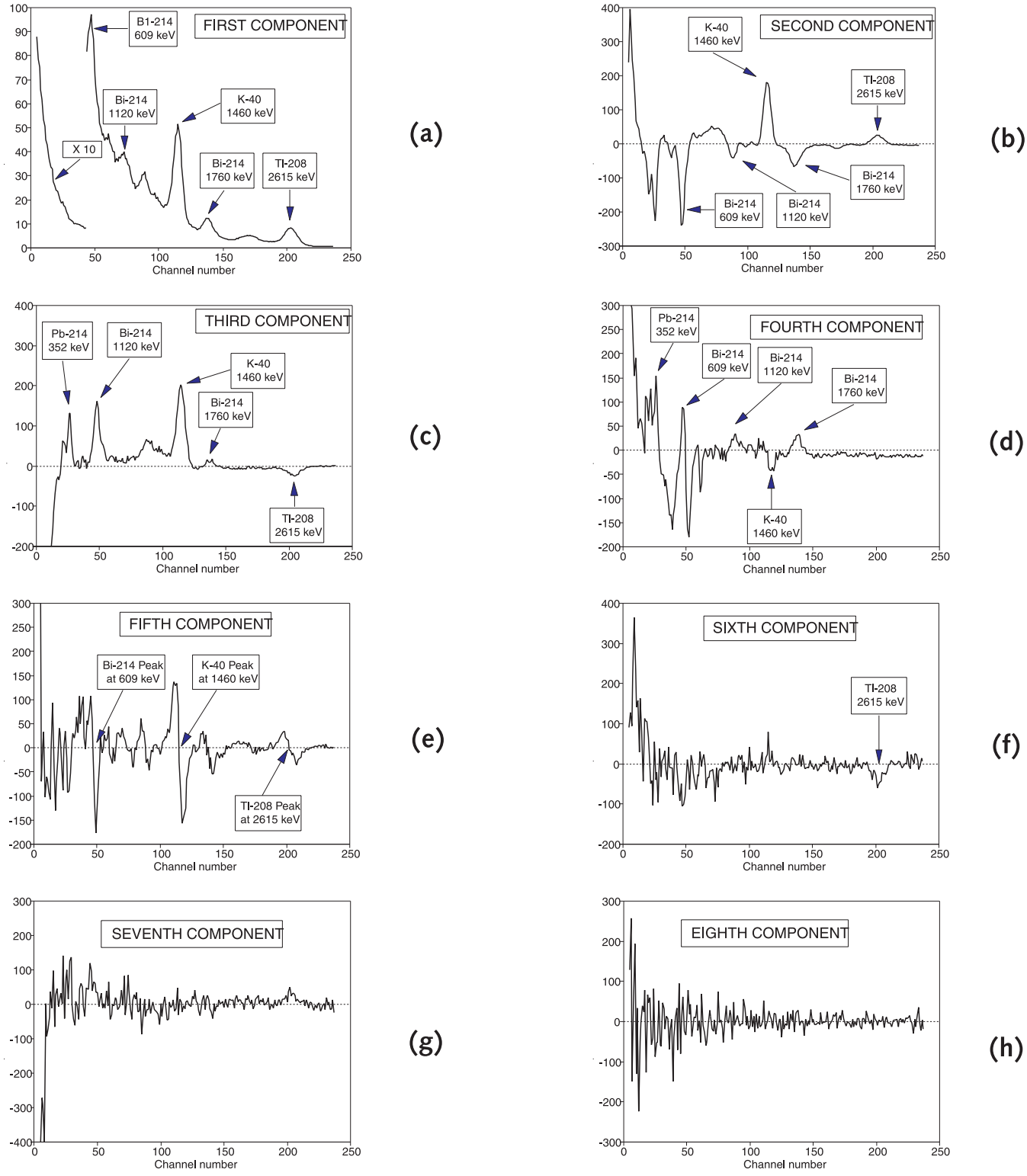

Figure 1: *The first eight spectral components from the Nevada survey.*

with the first and second components it is possible to create spectra with different proportions of potassium, uranium and thorium.

An airborne uranium spectrum originates from radon decay products in the air as well as from uranium decay products in the ground. The two spectra from these sources of radioactivity have different shapes due to the differences in the paths that the gamma-rays travel to reach the detector. The fourth component (Figure 1d) can be interpreted to be the result of these differences. It shows gamma-ray peaks principally from the uranium series and has similar features to the second component (Figure 1b). By combining the second and fourth components in different proportions, it is possible to create spectra with varying proportions of radon. It is interesting to note that the second and fourth component spectra are similar to the secondary uranium spectrum component calculated by Dickson *et al.* (1981) from attenuation measurements on calibration pads.

The fifth spectral component (Figure 1e) is due to the spectral drift of the spectrometer and can be recognized through the asymmetry around all the major peaks in the average spectrum (Figure 1a). Since this spectral component is negative on the high energy side of the potassium peak, adding this spectrum to the average spectrum will cause the potassium peak to move to a lower channel. Similarly, subtracting this component from the average spectrum will move the potassium peak to a higher channel. The magnitude of the energy shift will depend on the proportions of the components that are combined.

Only a few features can be seen in the sixth spectral component (Figure 1f). Most of this spectrum is simply due to noise which can be identified by the high frequency components. Spectral components six, seven (Figure 1g) and eight (Figure 1h) show the boundary between the signal components and the noise components due to Poisson counting statistics. Depending on how many channels are used in the analysis, about 240 additional components are calculated. These remaining spectral components show no significant features and are interpreted as being due to noise.

Map production and analysis

The spectral component analysis gives the spectral components as well as the amplitude of the components at each individual measurement point. This amplitude is the amount of each component that is present in the measured spectrum. In airborne data where there are only natural radioactive elements, we have found that eight spectral components are sufficient to explain the real spectral shapes present in the data. From the amplitudes and first eight spectral components, it is then possible to reconstruct the measured spectra at each measurement point. In reconstructing the spectrum in this manner the noise components have largely been removed and the reconstructed spectrum is much less noisy. This is illustrated in Figures 2a and 2b which show two measured and reconstructed airborne spectra from the first eight spectral components of the Nevada data set. The potassium, uranium and thorium windows can then be recalculated from the reconstructed spectrum. The standard processing can then be carried out to produce maps of the concentration of potassium, uranium and thorium as recommended by the International Atomic Energy Agency (1991).

Figures 3a and 3b show maps of the original thorium window and the reconstructed thorium window using the first eight spectral components. Both maps were produced using the same gridding procedure with no corrections applied for background or altitude changes. In

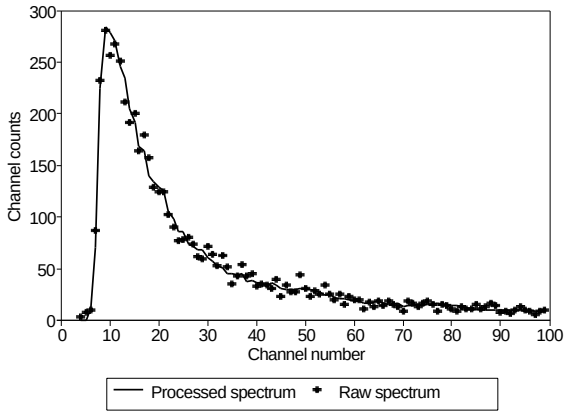

Figure 2a: *A raw and processed airborne spectrum showing the low energy channels.*

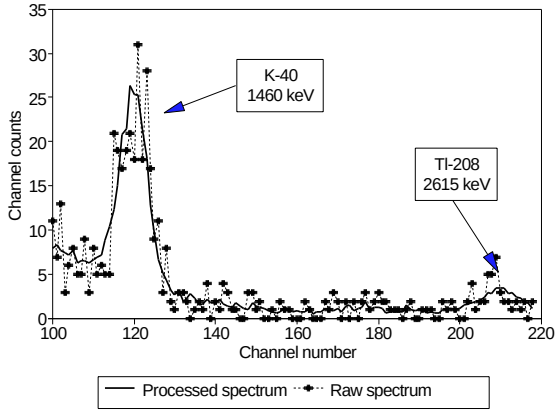

Figure 2b: *A raw and processed airborne spectrum showing the high energy channels.*

producing the maps, a certain amount of smoothing of the data is required to interpolate the data to a regular grid. This smoothing was minimized by using the smallest possible search area so that the benefits of the processing method would best be demonstrated.

The reconstructed thorium window map shows a reduced amount of speckle compared to the raw window map. This demonstrates that the new processing method has reduced the noise in the original data. Subtle features show more clearly on the processed thorium map. For instance, the semi-circular feature in the upper centre of the processed thorium map cannot be identified in the raw thorium map. The contours between different colour levels are also much smoother in the processed map. It is also easier to recognize differences between adjacent flight lines caused by altitude variations.

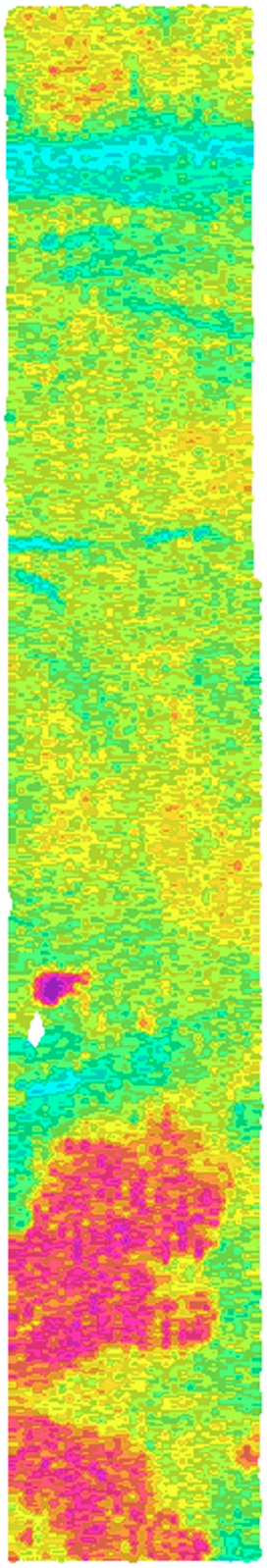

Figure 3a: *A raw thorium window map from the Nevada survey.*

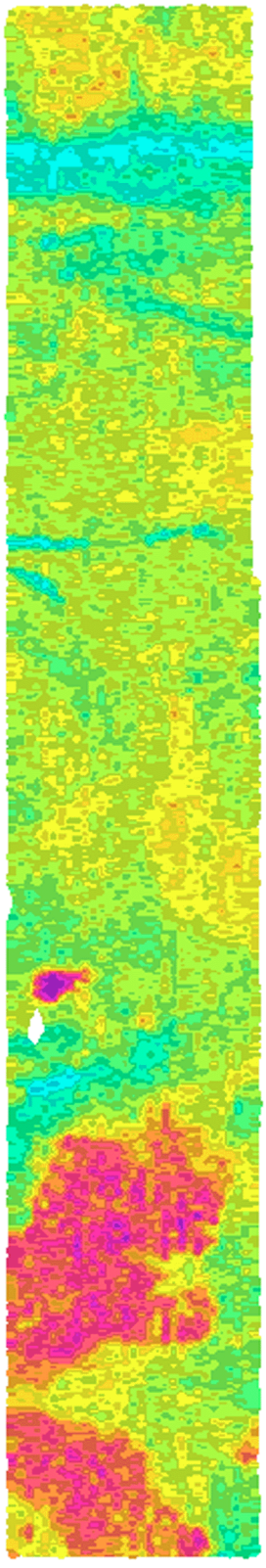

Figure 3b: *A reconstructed thorium window map from the Nevada s*

Table 1: ***A comparison of the background corrected and stripped potassium window counts before and after window reconstruction.***

Survey altitude (m)	Reconstructed counts	Original counts	Volume increase
57	184.7 ± 16.3	185.4 ± 20.4	1.6
117	106.7 ± 10.7	107.5 ± 14.4	1.8
184	60.4 ± 9.1	59.0 ± 12.1	1.9
245	37.8 ± 6.3	37.0 ± 9.6	2.4
306	22.1 ± 5.7	20.0 ± 7.9	2.3

Table 2: ***A comparison of the background corrected and stripped uranium window counts before and after window reconstruction.***

Survey Altitude (m)	Reconstructed Counts	Original Counts	Volume Increase
57	14.4 ± 2.0	14. ± .6	7.5
117	9.4 ± 1.5	9.3 ± 5.3	12.3
184	5.4 ±1.2	4.7 ± 4.8	21.7
245	3.3 ± 1.0	3.7 ± 4.2	15.1
306	1.9 ± 0.9	2.4 ± 4.0	12.9

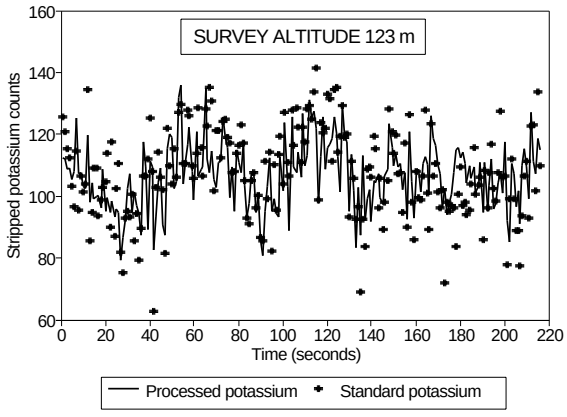

Figure 4a: *A standard and processed potassium profile flown at 123 m over the Breckenridge calibration range.*

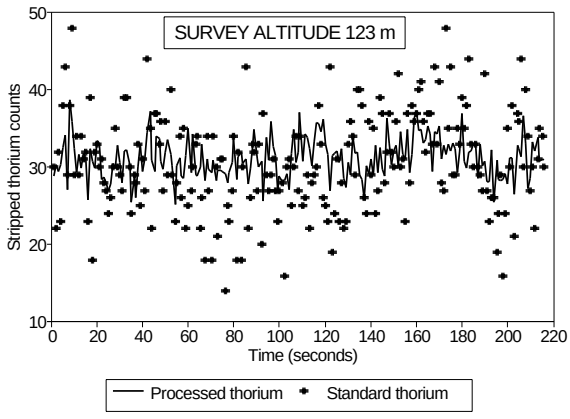

Figure 4c: *A standard and processed thorium profile flown at 123 m over the Breckenridge calibration range.*

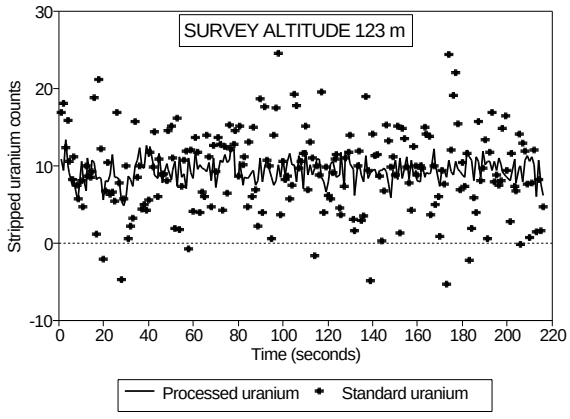

Figure 4b: *A standard and processed uranium profile flown at 123 m over the Breckenridge calibration range.*

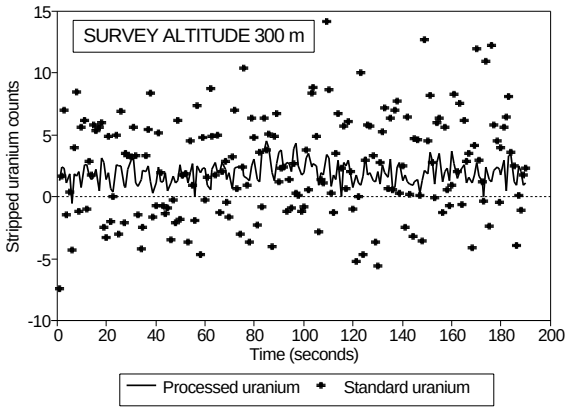

Figure 4d: *A standard and processed uranium profile flown at 300 m over the Breckenridge calibration range.*

Table 3: ***A comparison of the background corrected and stripped uranium window counts before and after window reconstruction.***

Survey Altitude (m)	Reconstructed Counts	Original Counts	Volume Increase
57	46.0 ± 4.00	45.9 ± 8.2	4.3
117	31.1 ± 2.6	30.6 ± 6.4	6.3
184	19.7 ± 2.2	20.0 ± 5.5	5.9
245	13.3 ± 1.5	13.3 ± 4.5	9.3
306	8.5 ± 1.4	9.2 ± 4.0	7.1

OTHER EXAMPLES OF SPECTRAL COMPONENT ANALYSIS

The new processing procedure can be applied not only to airborne data but to any series of gamma-ray spectral measurements. In this section we show some of the results from a variety of other airborne gamma-ray data sets as well from carborne systems and portable gamma-ray spectrometers. In all examples, eight spectral components were used in the analyses.

One of the difficulties in estimating the reduction in statistical noise that can be achieved with the new processing procedure is to separate real variations due to changes in ground radioactivity from those due to statistical noise. We have therefore analyzed a data set flown over the Breckenridge calibration range near Ottawa (Grasty and Charbonneau, 1974) where the potassium, uranium and thorium concentrations are relatively uniform. The test range was flown using a 33 l system at nominal survey heights from 60 m to 300 m at 60 m intervals. Background measurements were also made over the Ottawa river at the same altitudes.

Figures 4a, 4b and 4c show the background corrected and stripped potassium, uranium and thorium windows at a typical survey altitude of 123 m, where the stripping procedures follow those recommended by the International Atomic Energy Agency (1991). The profiles show a significant reduction in statistical noise particular for the uranium and thorium measurements. Tables 1 to 3 show the average and standard deviation at all five altitudes for potassium, uranium and thorium respectively. Since the variance is equal to the measured counts it is therefore proportional to the detector volume. Consequently, from the reduction in statistical variance, we have been able to calculate the effective relative volume increase due to the new processing method. This effective volume increase is shown in Tables 1 to 3 and reaches a value of almost 20 for the stripped uranium measurements at an altitude of 300 m. This is illustrated in Figure 4d which shows the original and reprocessed uranium profiles at 300 m.

Ratio maps can be extremely useful in mineral exploration as shown in a variety of papers presented at this conference. However, one of the main problems in the use of such maps is that they are relatively more noisy than the individual radio-element maps. Figures 5a and 5b show two uranium/thorium maps from the Kozloduy area in Bulgaria. This survey was flown at a mean altitude of 90 m with a line spacing of 100 m using a 50 l system (Hetu *et al.*, 1990). The two maps are the ratios of the uranium and thorium window data, one using the original raw windows and the other using the reconstructed windows. Both maps were made using identical gridding routines and were made to demonstrate the differences between the traditional and the new method. No effort was therefore made to suppress features caused by navigation problems. The processed ratio map clearly has significantly less noise than the raw ratio map with more observable geological features and is therefore much more useful for interpretation purposes.

The new processing method was also tested on gamma-ray data from a car-borne system with one $4 \times 4 \times 16$ inch detector. Figure 6 shows a section of the thorium window profile before and after reconstruction using the complete data set in the analysis. Because of the real variations in thorium concentration, a flat section of the profile was selected to demonstrate the benefits of the new processing technique. Analysis of the variations of the raw and reconstructed profiles shows that the reduction in statistical noise using the new procedure is equivalent to an effective volume increase of approximately ten.

The method has also been tested on a series of portable gamma-ray spectrometer measurements. Figure 7 shows two profiles of the raw and reconstructed uranium window data from 56 measurements taken along the Breckenridge calibration range. The reconstructed uranium window shows significantly less noise the original window, the reduction in statistical noise being equivalent to an effective volume increase of 3.5.

DISCUSSION

We have found that the new method significantly reduces the statistical noise compared to the standard window method and is significantly better than the spectral fitting method described by Grasty *et al.* (1981) and Minty (1996). There are two basic reasons for this.

Firstly, in the spectral fitting procedure the airborne spectra must first be determined experimentally using calibration pads to simulate the spectra from potassium, uranium and thorium. However, with this type of measurement it is difficult to simulate airborne spectra at energies below about 400–500 keV. This is because a significant fraction of the low energy gamma-rays measured at aircraft altitude is downward scattered skyshine radiation from sources several hundred meters away. Consequently the standard spectral fitting procedure cannot be used below an energy of about 500 keV. An even higher energy limit may be necessary in the northern hemisphere due to the presence of ^{137}Cs at 662 keV unless the variable ^{137}Cs spectrum shape is taken into consideration (Hovgaard, 1997).

The new method does not have these limitation and the analysis can be carried out over all energy ranges. Although there is little spectral information in the low energy part of the spectrum, there is information on overall levels of radioactivity. At a typical survey altitude of 123 m approximately 60% of the measured counts are below 600 keV.

The second reason why the new method achieves better results than the spectral fitting method is because of the strong correlation between potassium, uranium and thorium both in their detector response as well as their occurrence in nature. If potassium, uranium and thorium are perfectly correlated then apart from three scaling constants which can be determined from the average spectrum, the total count is the best estimate of the window counts or concentrations. In this situation, a spectral component analysis will show that just one component is sufficient to explain the entire data set. However, the standard spectral fitting method will use three or even six components in the analysis. Consequently, the propagation of statistical errors in the observed spectra will result in greater statistical errors in estimates of ground radioelement concentration.

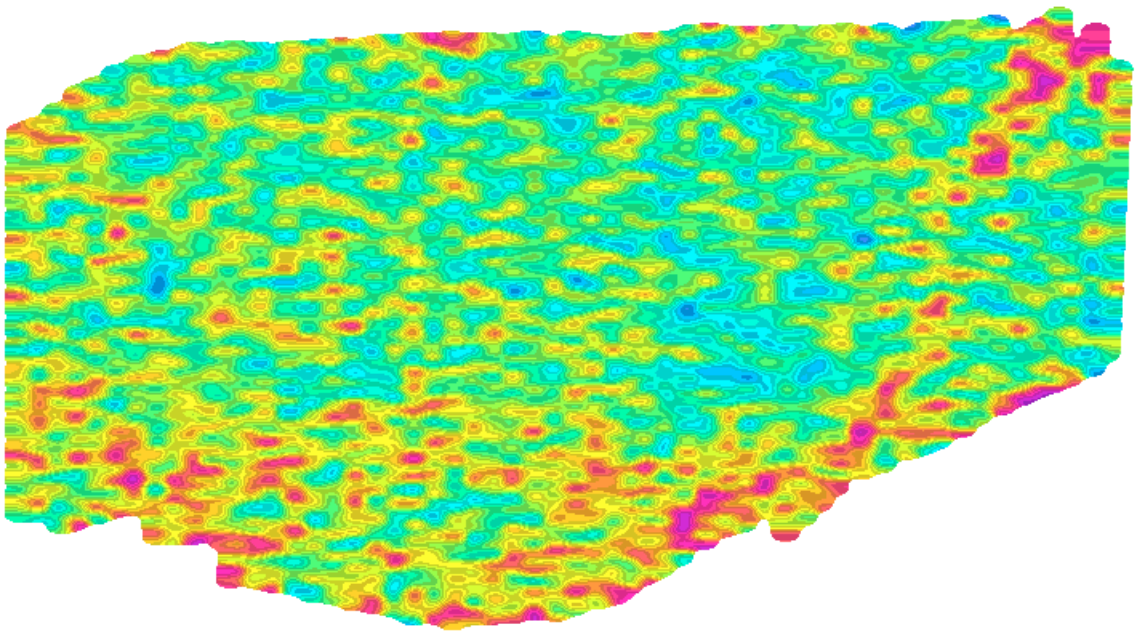

Figure 5a: *A raw uranium/thorium ratio map from the Kozloduy area, Bulgaria.*

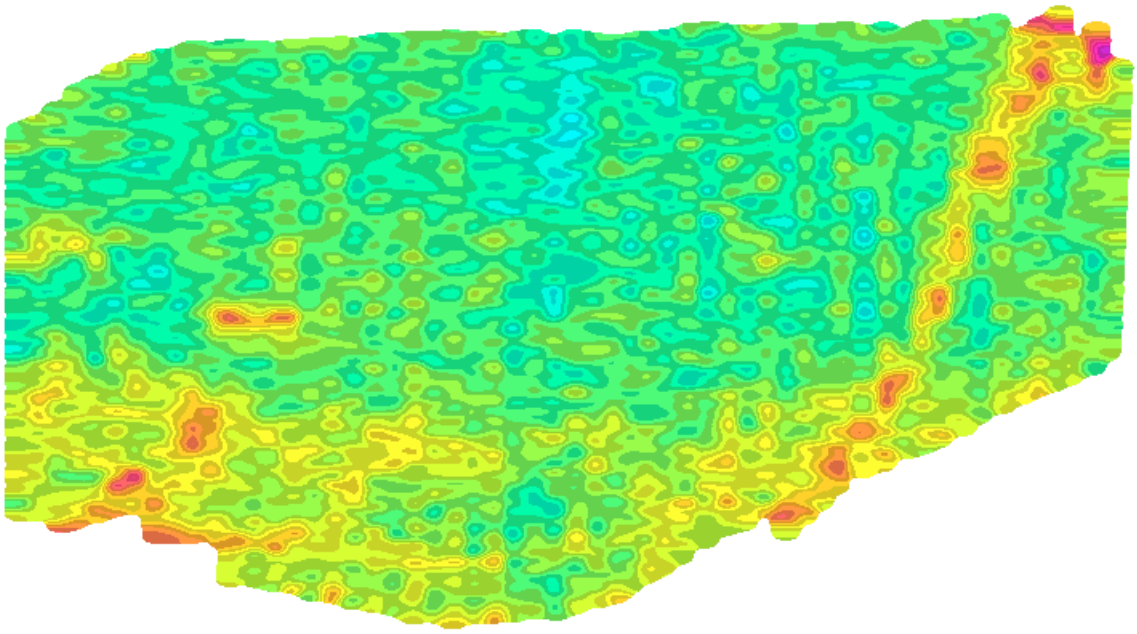

Figure 5b: *A processed uranium/ thorium ratio map from the Kozloduy area, Bulgaria.*

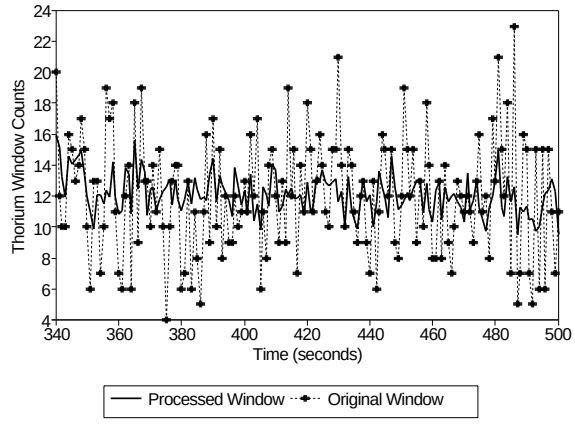

Figure 6: *A raw and processed thorium profile from a car-borne system.*

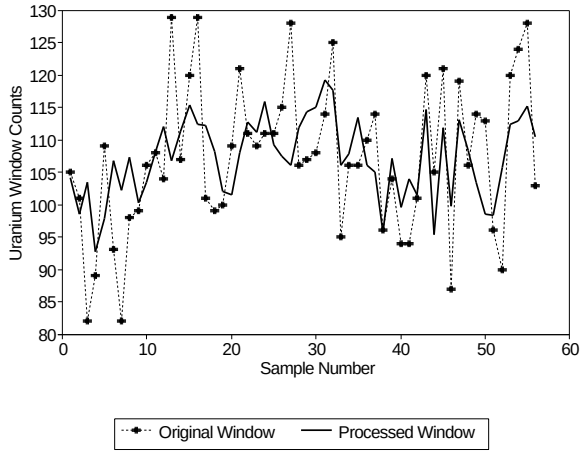

Figure 7: *A raw and processed uranium profile from a portable spectrometer.*

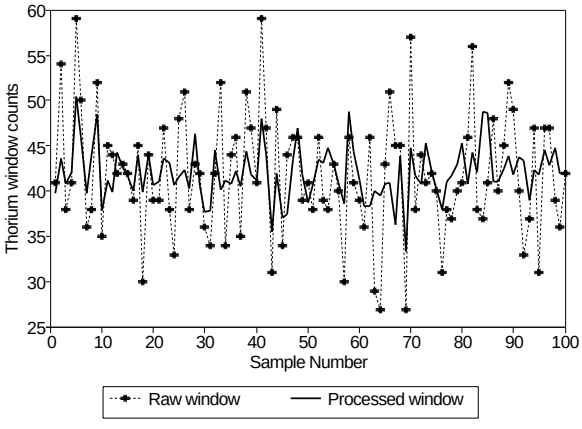

Figure 8: *A simulated raw and processed thorium profile using the average airborne spectrum from the Nevada survey.*

It is difficult to use real data to calculate the reduction in statistical noise that can be achieved by the new processing method. The reason for this is that the observed variations are the result of both statistical variations as well as variations due to changes in ground radioactivity. In order to address this problem we have carried out Monte Carlo simulations using an average spectrum from the Nevada data set. From this average spectrum a series of simulated spectra were created using a Poisson number generator and added to the Nevada data set. The raw and reprocessed potassium, uranium and thorium windows were then calculated from this new data set of simulated and measured spectra. Figure 8 shows the raw and reconstructed thorium window calculated from the simulated data set. It was found that the relative reduction in the variance of the reconstructed windows corresponded to an effective volume increase of 1.6, 4.3 and 5.2 for potassium, uranium and thorium respectively.

One particular advantage of the new method is that it does not depend on the ordering of the spectra. Consequently at the boundaries of different rock types, the reconstructed windows will show no evidence of spatial filtering and retain all features relating to changes in radioactivity. Figure 9 shows the results of Monte Carlo simulations of an airborne gamma-ray spectrometer flying over the boundary of two rocks units with 1 and 2 ppm thorium. At the boundary, the potassium and uranium concentration also changed from 9% to 3% and from 4.5 ppm to 1.5 ppm respectively. The spectra used in the simulations came from measurements on large calibration pads as described by Dickson *et al.* (1981) with a volume of 32 l and a flying height of 70 m being assumed. In the spectral component analysis, 27 different ground concentrations with different proportions of potassium, uranium and thorium were also included. The figure shows that the reconstructed thorium window has retained the boundary position as well as the thorium concentrations.

One possible concern in the analysis is that small anomalies of possible economic interest may be lost. These anomalous features may appear in only a few airborne measurements out of many tens of thousands of measurements. However, if the component spectra do not fit the observed spectra at these particular anomaly locations, an additional component will be included. In addition, all anomalies from natural sources of radiation are caused by changes in the ground concentration of potassium, uranium and thorium. Consequently, six spectral components should be sufficient to explain any real changes in the observed spectra from potassium, uranium and thorium (Dickson *et al.*, 1981).

In the northern hemisphere there may be two spectral components due to different depth distributions of ^{137}Cs from the Chernobyl nuclear accident (Hovgaard, 1997). An additional component may also be required to account for changes in the proportion of the cosmic-ray background to the radiation from the ground. This would be particularly important if there are large topographic variations within the survey area. There may also be additional components due to equipment malfunctions including spectral drift (Figure 1). Figure 10 shows one anomalous airborne spectrum from 4,000 measurements in which one particular channel had an anomalous reading due to electronic noise. This problem was identified from the sixth spectral component shown in Figure 11. The record number of the problem spectrum was located by plotting the amplitude of this component (Figure 12).

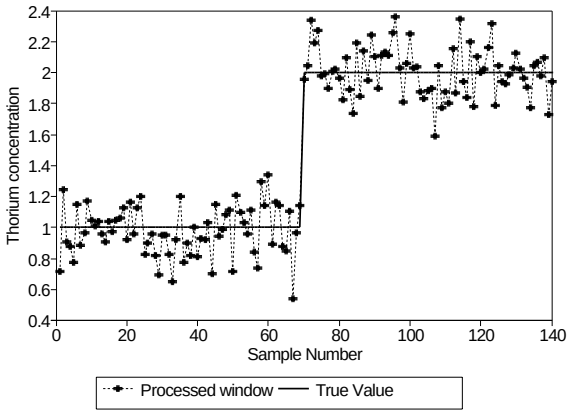

Figure 9: *A simulated reconstructed thorium profile over a step function.*

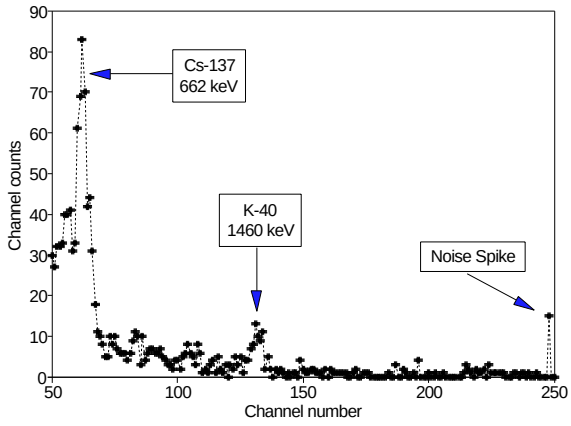

Figure 10: *A spectrum showing a noise spike.*

FUTURE DEVELOPMENTS AND RECOMMENDATIONS

Since the reconstructed spectra have significantly less statistical noise than the original measured spectra, the new technique has benefits in any full spectral analysis. For example, Minty (1992) has developed a spectral ratio technique to monitor atmospheric radon background changes. After spectrum reconstruction, the calculated radon background will be more reliable allowing it to be updated more frequently. By combining the various spectral components in different proportions, it may also be possible to create a pure radon spectrum. This would then allow continuous measurements of the radon background without the necessity of extracting particular photopeak from the spectrum. A similar procedure has been demonstrated by Hovgaard (1997) for monitoring low levels of ^{137}Cs due to atmospheric weapons testing.

Due to the Chernobyl nuclear accident and atomic weapons testing, a large part of the northern hemisphere is contaminated with ^{137}Cs. In these areas upward-looking detectors are normally used to monitor atmospheric background variations. There is no reason why the upward window counts cannot be incorporated into the spectral component analysis. This would allow better estimates of the upward detector count rates thereby improving the background measurements

Another application of the spectral component analysis relates to identifying a possible problem due to spectral drift which is identified as the fifth spectral component in the Nevada data (Figure 1). Through spectral reconstruction, it will be possible to locate the channel positions of the major gamma-ray peaks more reliably than from the original spectra, allowing better any energy calibration procedures.

In the limited number of airborne survey data sets we have analysed, eight spectral components are sufficient to explain the real spectral shapes present in the data. For these surveys only eight components are necessary in the spectrum reconstruction to retain all the spectral information. However, it is recommended that the spectral components should always be examined to verify that no real spectral information is being lost from the reconstructed spectra. In view of the computational requirements in analyzing many thousands of multi-channel spectra, it is also recommended that the analysis be carried out on a flight basis. We have found that with a 100 MHz Pentium processor it takes roughly 10 minutes to process one hour of 1-second measurements.

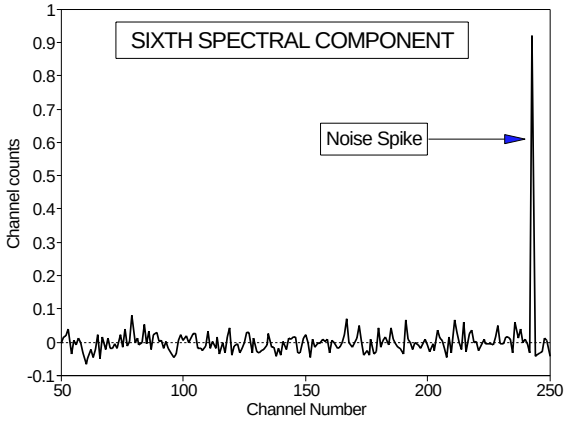

Figure 11: *The sixth spectral component showing the noise spike.*

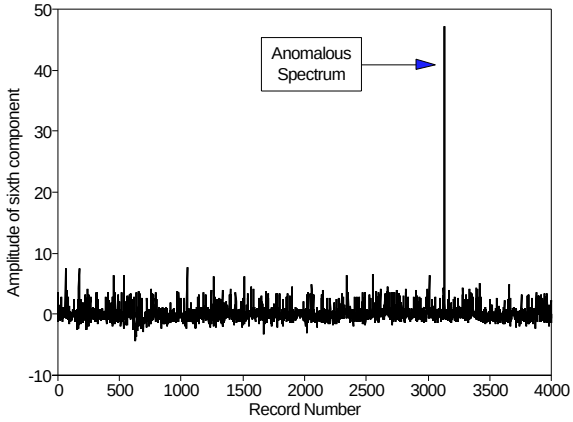

Figure 12: *A profile of the sixth component identifying the problem spectrum.*

CONCLUSIONS

This paper has shown that there is considerable improvement in applying the proposed spectral analysis method to airborne gamma-ray data. An analysis of both simulated and measured survey data has shown that for uranium and thorium, it is possible to achieve a reduction in statistical noise equivalent to an effective increase in detector volume by a factor typically between 3 and 4. The technique has the advantage over the standard spectral fitting procedure that no experimental measurements are required. An additional advantage is that following this pre-processing procedure, the standards already developed by the International Atomic Energy Agency (1991) for the three-window analysis can still be carried out.

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REFERENCES

Davis, J.C., 1973, Statistics and data analysis in geology, John Wiley and Sons, New York, NY.

Dickson, B.H., 1980, Analytic methods for multi-channel airborne radiometrics. M.Sc. thesis, University of Toronto, Toronto, Ont.

Dickson, B.H., Bailey, R.C., and Grasty R.L., 1981, Utilizing multi-channel airborne gamma-ray spectra, Can. J. Earth Sci, **18**, 1793-1801.

Gower, J.F.R., Lin, S., and Borstad, G.A., 1984, The information content of different optical spectral ranges for remote chlorophyll estimation in coastal waters, Int. J. Remote Sensing, **5,** 349-364.

Grasty, R.L., and Charbornneau, B.W., 1974, Gamma-ray spectrometer calibration facilities, Geol. Surv. of Can., Rep. of Activities, Part B, Paper 74-1B, 69-71.

Grasty, R.L., Glynn, J.E., and Grant, J.A., 1985, The analysis of multichannel airborne gamma-ray spectra: Geophysics, **50**, 2611-2620.

Grasty, R.L., and Hovgaard, J., 1996, The calibration of upward looking detectors in gamma ray surveys: Proceedings 66th annual meeting of Society of Exploration Geophysicists, Denver, 1423-1425.

Hetu, R., Rangelov, R., Grant, J.A., Grasty, R.L., and Graham, D., 1990, Monitoring natural and man-made radiation by airborne gamma-ray spectrometry, Kozlodui area, Bulgaria: Geol. Surv. of Can., Open File 2573.

Hovgaard, J., 1997, A new processing technique for airborne gamma-ray spectrometer data (Noise adjusted singular value decomposition), Am. Nucl. Soc. Sympos. on Emergency Preparedness and Response, San Francisco.

International Atomic Energy Agency, 1991, Airborne Gamma Ray Spectrometer Surveying. Tech. Rep. 323, Internat. Atom. Energy Agency, Vienna.

Joreskog, K.G., Klovan, K,E., and Reyment, R.A., 1976, Geological factor analysis, Elsevier, New York, NY.

Mardia, K.V., Kent, J.T., and J.M. Bibby, 1979, Multivariate analysis, Academic Press, New York, 581 pp.

Minty, B.R.S., 1996, The analysis of multichannel airborne gamma-ray spectra. Ph.D thesis, Australian National University, Canberra, Australia.

Minty, B.R.S., 1992, Airborne gamma-ray spectrometric background estimation using full spectrum analysis: Geophysics, **57**, 279-287.