A GUIDE TO THE TECHNICAL SPECIFICATIONS FOR AIRBORNE GAMMA-RAY SURVEYS

BY

R.L. GRASTY & B.R.S. MINTY

RECORD 1995/60

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AUSTRALIAN
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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

Minister for Resources: Hon. David Beddall, MP
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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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ISSN: 1039-0073
ISBN: 0 642 22366 1

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SUMMARY

The airborne gamma–ray spectrometric method has been increasingly used in recent years to assist mineral exploration, and both geological and environmental mapping. With this growth there has developed an increasing need to standardize the airborne measurements so that they will be independent of survey parameters. This report presents the technical specifications for a high sensitivity airborne gamma–ray survey. They describe the minimum requirements for system calibration, system monitoring, data acquisition and data processing that are required to ensure that the final processed data are of the highest possible quality. The technical specifications are accompanied by a guide to explain these specifications and provide additional insights into the airborne gamma–ray spectrometric method.

INTRODUCTION

In the last few years, the use of gamma–ray spectrometry for geological mapping and mineral exploration has shown considerable growth. With this growth, there has developed an increasing need to standardize the airborne measurements so that they will be independent of survey parameters. This will allow data from many different surveys to be combined into one coherent compilation, thereby enhancing their value for regional mapping. Standardization of the survey procedures will also allow instrument performance to be monitored, resulting in the early detection of possible equipment malfunctions.

Technical specifications for a high sensitivity airborne gamma–ray survey are given in Appendix A. The technical specifications describe the various calibrations, data acquisition, and data processing procedures that are required to standardize the airborne measurements to ground concentrations of potassium, uranium and thorium. They should be regarded as the minimum requirements for ensuring that the airborne survey and final processed data are of the highest possible quality.

The main body of the report is a guide to the technical specifications given in Appendix A. The layout and section numbering of the guide essentially follows that of Appendix A with each section of the guide providing an explanation of the corresponding technical specification, as well as providing insight into that aspect of the airborne gamma-ray spectrometric method. Both the specifications and the accompanying guide are intended to benefit the airborne geophysical contractors and their clients, as well as assist the technical inspector responsible for monitoring the survey.

1. INSTRUMENTATION

1.1 Gamma–ray Spectrometer

Modern spectrometers record at least 256 channels of spectral data in the range 0 –3 MeV, and use either temperature stabilized detector packages to minimise spectral drift or are self–stabilizing. The latter spectrometers monitor one of the prominent photopeaks to automatically adjust photomultiplier tube gains for each crystal to ensure spectral stability. The spectrometers normally record three additional windows to monitor ^{40}K gamma rays at 1460 keV, ^{214}Bi gamma rays at 1760 keV from the uranium decay series, and ^{208}Tl gamma rays at 2615 keV from the thorium decay series. A total count window is also recorded to monitor overall radioactivity levels. The detector count rates due to cosmic radiation increase exponentially with height above mean sea–level. A cosmic–ray window which records all incident particles above 3 MeV is commonly used to monitor this increase.

Table 1.1. Standard windows for natural radioelement mapping

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 – ∞

Window boundaries for 4–channel spectrometry should conform to those recommended by the International Atomic Energy Agency (IAEA, 1991) and are shown in Table 1.1. The positions of these windows are near optimum (Minty and Kennett, 1995), 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 in (or degradation of) the equipment.

Typical airborne spectrometers consist of packages of four 10.2 cm × 10.2 cm × 40.6 cm sodium iodide detectors. Increasing the detector volume increases the sensitivity of the spectrometer and therefore the accuracy in the measurements of potassium, uranium and thorium. However, there has to be a compromise between the efficiency of the airborne operation and detector volume. The larger the detector volume, the larger must be the aircraft to carry the increased detector load. In Australia, it has become an accepted practice that spectrometers for fixed–wing systems consist of two detector packages for a total volume of 32 litres. A helicopter system can achieve similar accuracies with a 16 litre system due to its slower flying speed and generally lower survey altitudes.

Resolution is a measure of the precision with which the energies of gamma rays can be measured by the spectrometer. Before the advent of self–stabilizing spectrometers, a ^{137}Cs source was used to adjust the gain of individual detectors so that the 662 keV photopeak would fall into the same channel. It was therefore convenient to measure the resolution of a system using a ^{137}Cs source. This resolution was specified as the full width of the 662 keV peak at half its maximum value – commonly called Full Width Half Maximum (FWHM) and measured as a percentage of the ^{137}Cs energy. However, modern self–stabilizing spectrometers are normally energy–stabilized using naturally occurring isotopes, either the ^{40}K photopeak at 1460 keV or the ^{208}Tl photopeak at 2615 keV. Since thorium sources are commonly specified for daily checks of system sensitivity, it is more appropriate to use the ^{208}Tl photopeak to monitor system resolution.

The sensitivity of a system, in terms of the counts per second per unit concentration of the radioelement, will depend on the overall system resolution. A system with a thorium resolution of 7 percent will detect essentially all 2615 keV gamma rays in the thorium window. Similarly, almost all 1460 keV gamma rays from ^{40}K will be detected in the potassium window. Consequently, for thorium and potassium, there is little advantage in improving the resolution much more than 7 percent.

The ^{214}Bi gamma–ray peak at 1760 keV from the uranium series is composed of three main gamma–ray emissions at 1730, 1765 and 1848 keV. Since the uranium window covers an energy range from 1660 to 1860 keV, there is an advantage in improving the resolution of the system as far as possible. Otherwise a significant fraction of the gamma–ray counts originating from the 1848 keV and 1730 keV photopeaks will be lost.

In the past, cesium resolutions were specified at better than 12 percent. With modern spectrometers, a cesium resolution of 10 percent is commonly achievable. For a typical airborne system, a cesium resolution of 10 percent corresponds to a thorium resolution of around 7 percent. We have therefore specified that the overall system resolution should be better than 7 percent based on the FWHM of the ^{208}Tl peak at 2615 keV.

1.2 Ancillary Equipment

A radar altimeter is an essential part of the equipment for gamma–ray surveying. Gamma rays are attenuated by air in an approximately exponential fashion for typical ranges of survey altitudes. Figure 1.1 shows how the potassium photopeak counts will vary with flying height over uniformly radioactive ground. Corrections for aircraft altitude are clearly an important part of the processing procedures to convert airborne count rates to ground concentrations of potassium, uranium and thorium.

Since the airborne count rates depend on the density of the air between the detector and the ground, they will also depend on air temperature and pressure. For surveys flown at approximately the same altitude above sea level, the effect of pressure changes on the measured count rates is relatively small. However, there are significant changes in pressure with barometric altitude and these changes have far more impact on the airborne count rates.

Correcting for temperature variations is also an important part of the processing procedures. Annual temperature variations can change the airborne count rate significantly over the same radioactive source. The importance of temperature and pressure corrections becomes greater in areas of rugged terrain where ground clearances can show marked variations.

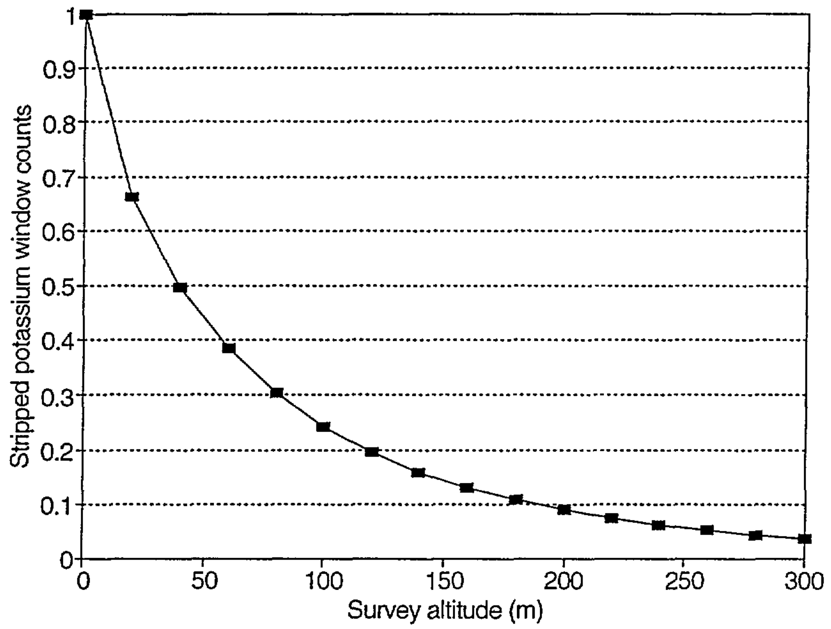

Figure 1.1. The variation of the stripped potassium window with survey altitude.

2. SPECTROMETER CALIBRATIONS

2.1 Calibration Frequency

There are several important steps in the conversion of the airborne counts to ground concentrations of potassium, uranium and thorium. These calibration processes are both time–consuming and costly. It is therefore important that these calibrations should not be performed needlessly.

Airborne gamma–ray spectrometers maintain their calibrations over long periods of time. The Geological Survey of Canada (GSC) has been carrying out surveys for many years. Table 2.1 shows the results of pad calibrations for the measurement of stripping ratios that have been carried out since 1987. The stripping ratios have stayed virtually unchanged for the past 7 years. Similarly, one would expect the sensitivity of a system to stay relatively constant over considerable periods of time – unless the aircraft was changed, or any significant changes were made to the gamma–ray spectrometer. We have therefore made the recommendation that all spectrometers should be calibrated every 12 months.

Table 2.1. Stripping ratios for the GSC 16.8 litre detector system

DATE	Alpha	Beta	Gamma	*a*
Nov 16 1988	0.2597	0.3550	0.8282	0.0779
May 14 1990	0.2583	0.3550	0.8019	0.0708
June 3 1991	0.2559	0.3487	0.8281	0.0743
Aug 5 1992	0.2560	0.3605	0.8278	0.0700
Apr 21 1993	0.2543	0.3538	0.7553	0.0608
June 2 1994	0.2474	0.3324	0.7495	0.0519

2.2 Cosmic Calibrations

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

(a) Radon decay products in the air.
(b) The radioactivity of the aircraft and its equipment.
(c) High energy cosmic–ray particles that interact with the air, the aircraft and the detector.

The count rate due to cosmic radiation increases exponentially with height above mean sea level in all spectral windows. Figure 2.1 shows the variation of the thorium window with barometric altitude for the AGSO 33.6 litre system. This exponential function can be determined and used to correct the data for cosmic–ray changes with altitude. However, at high altitudes, there can be temporal variations in the cosmic–ray background. Changes in the aircraft fuel level may also cause variations in the cosmic–ray background. The use of a cosmic window that records all incident particles above 3 MeV avoids these problems, since the cosmic background can then be estimated. 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.

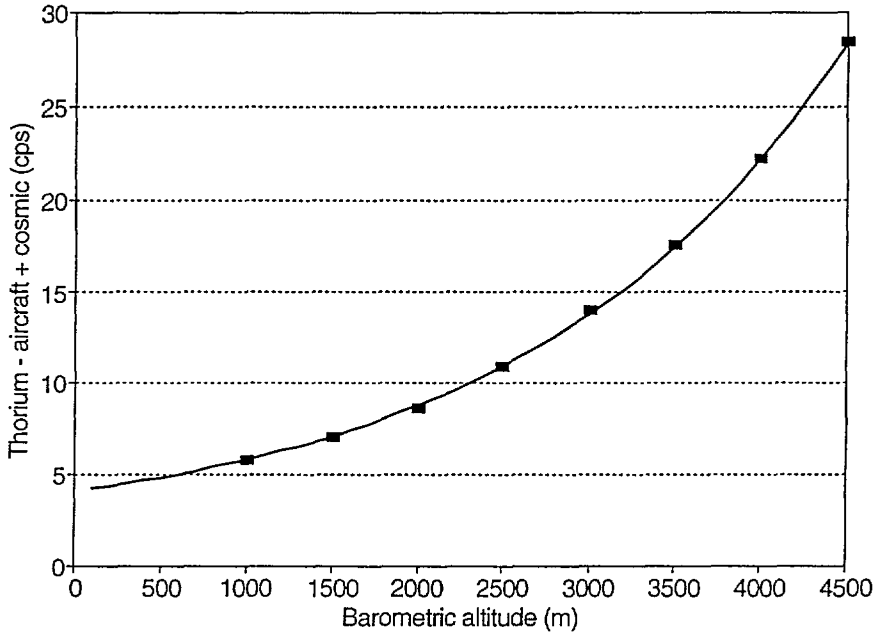

Figure 2.1. The variation of the thorium window with barometric altitude due to cosmic radiation.

In the absence of radon and terrestrial radiation, the count rate in the cosmic ray window is related to the counts due to cosmic radiation in any other spectral window or individual channel by the linear function:

$$N = a + bC \tag{2.1}$$

where

$N =$ the count rate in the given window ;
$a =$ the aircraft background count rate for that particular window ;
$b =$ the cosmic stripping ratio; the counts in the given window per unit count in the cosmic window; and
$C =$ the cosmic window count rate.

When the cosmic ray window count rate is zero, there can be no cosmic ray contribution in any of the other windows. The value of a is therefore the background in that particular window arising from the radioactivity of the aircraft and its equipment.

The values of a and b can be determined experimentally by means of a series of flights 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 4,500 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 minimised. Recommended flights were from 1,500 m to 3,000 – 3,500 m at 300 m intervals with a 10 minute measurement time.

Figures 2.2 and 2.3 show the relationship between the cosmic–ray window and the uranium and thorium windows for the AGSO 33.6 litre airborne spectrometer system . The measurements were obtained from flights over the Southern Ocean, west of Tasmania at barometric altitudes from 1,000 m to 4,500 m.

The requirements to fly at high altitude were designed to minimise any effects due to radon, in the belief that it was necessary to separate the aircraft and cosmic background contributions in each window. This can only be achieved provided there is no radon present at the altitudes flown. Figure 2.4 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. This has been a cause of concern not only for the contractors, but also for their clients.

The following theory will show 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 can be removed during the processing. We recommend that aircraft and cosmic calibration measurements be taken over the sea at only two barometric altitudes – 250 m and 2250 m. These cover the range of altitudes that can possibly be encountered in Australia. The lower limit is based on the fact that the sea has a small potassium concentration of approximately 0.03 percent 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 selected based on the height of Mt. Kosciusko.

We first show how the aircraft and cosmic background can be removed when no radon is present during the cosmic calibration measurements at the two altitudes.

Let the counts measured in channel i during the two calibration flights over the sea be n_i^1 and n_i^2. From equation (2.1)

$$n_i^1 = a_i + b_i C^1 \qquad (2.2)$$

and,

$$n_i^2 = a_i + b_i C^2 \qquad (2.3)$$

where

a_i is the aircraft background in channel i;
b_i is the stripping coefficient from the cosmic window into channel i and
C^1 and C^2 are the cosmic window counts at the two altitudes.

Solving equations (2.2) and (2.3) for a_i and b_i:

$$a_i = \frac{C^2 n_i^1 - C^1 n_i^2}{C^2 - C^1} \qquad (2.4)$$

and

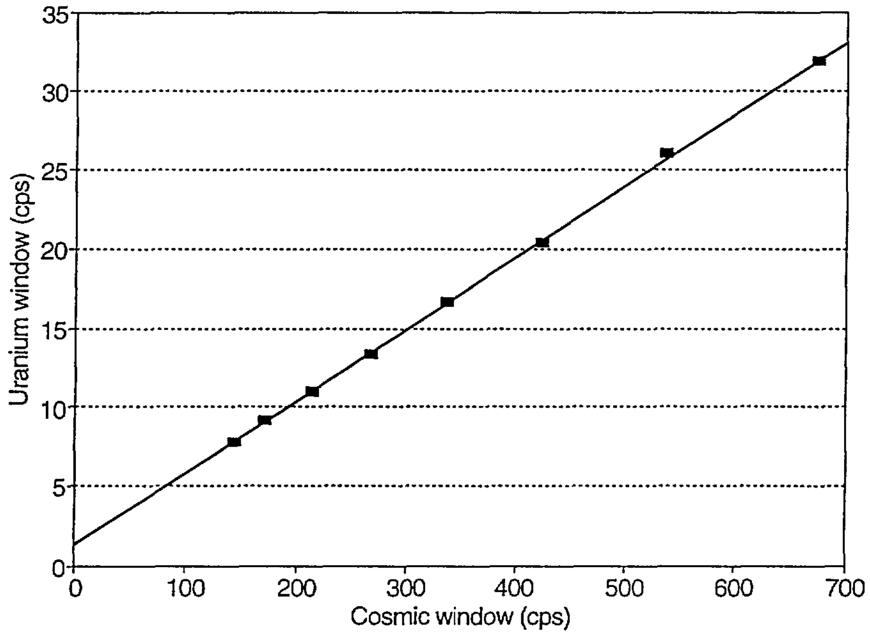

Figure 2.2. The variation of the uranium window with the cosmic window.

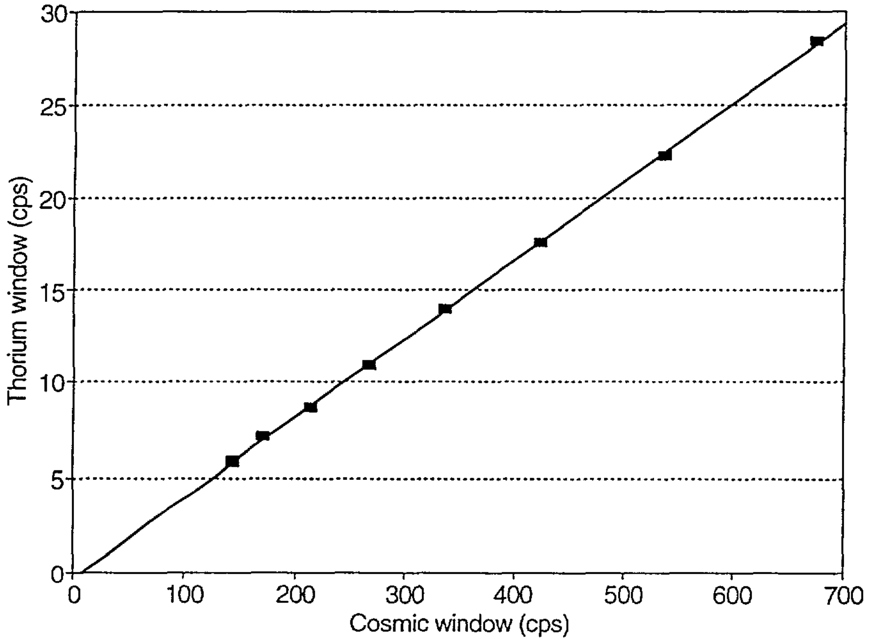

Figure 2.3. The variation of the thorium window with the cosmic window.

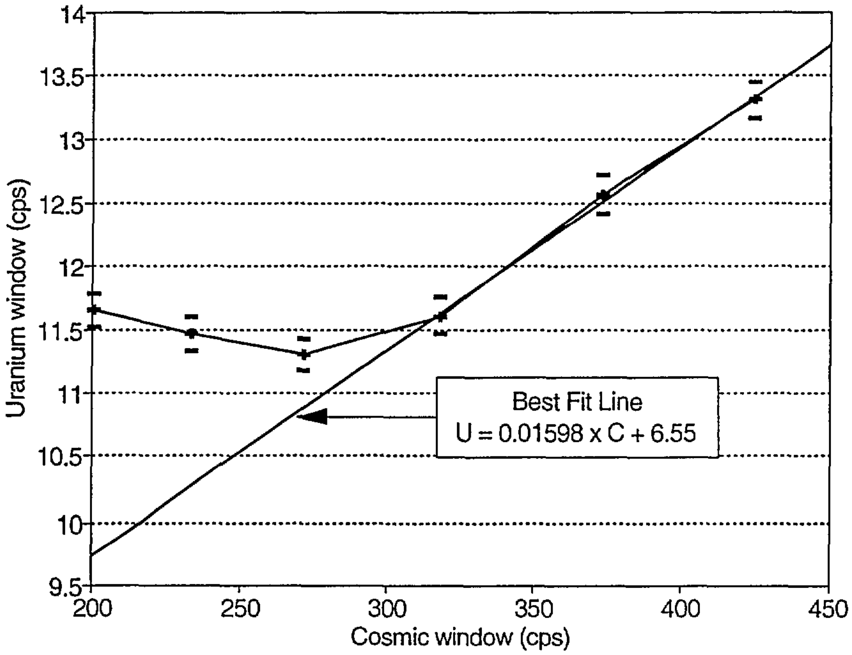

Figure 2.4. The variation of the uranium window with the cosmic window showing the effects of radon at the lower elevations.

$$b_i = \frac{n_i^2 - n_i^1}{C^2 - C^1}. \tag{2.5}$$

During a survey flight, the cosmic and aircraft background counts in channel *i* will therefore be given by:

$$a_i + b_i C_s = \frac{C^2 n_i^1 - C^1 n_i^2}{C^2 - C^1} + \frac{n_i^2 - n_i^1}{C^2 - C^1} C_s \tag{2.6}$$

where C_s is the recorded cosmic window counts during the survey.

In the case where the two cosmic ray measurements include different and unknown radon,

$$n_i^1 = a_i + b_i\, C^1 + R_i^1 \tag{2.7}$$

and,

$$n_i^2 = a_i + b_i\, C^2 + R_i^2 \tag{2.8}$$

where R_i^1 and R_i^2 are the counts due to radon in channel *i* at the two altitudes.

Solving equations (2.7) and (2.8) for a_i and b_i:

$$a_i = \frac{C^2 n_i^1 - C^1 n_i^2 - (C^2 R_i^1 - C^1 R_i^2)}{C^2 - C^1} \tag{2.9}$$

and,

$$b_i = \frac{n_i^2 - n_i^1 - (R_i^2 - R_i^1)}{C^2 - C^1}. \tag{2.10}$$

During a survey flight, the aircraft and cosmic background $(a_i + b_iC_s)$ will therefore be given by:

$$a_i + b_iC_s = \frac{n_i^2 - n_i^1}{C^2 - C^1}C_s + \frac{C^2n_i^1 - C^1n_i^2}{C^2 - C^1} - \frac{R_i^2 - R_i^1}{C^2 - C^1}C_s - \frac{C^2R_i^1 - C^1R_i^2}{C^2 - C^1}. \tag{2.11}$$

The term $[\frac{R_i^2 - R_i^1}{C^2 - C^1}C_s + \frac{C^2R_i^1 - C^1R_i^2}{C^2 - C^1}]$ is a linear combination of the two radon spectra which were present during the cosmic-ray calibration measurements at the two altitudes, and therefore has the same shape as a radon spectrum. Apart from this term, equations (2.6) and (2.11) for the aircraft and cosmic background are identical. In processing survey data, the aircraft and cosmic-ray components can therefore be removed using equation (2.6). The only effect of varying radon during the cosmic-ray calibration flights will be an unknown radon component which can be removed during processing of the survey data.

2.3 Radon Calibrations

The removal of the radon background component in the potassium, uranium and thorium windows is an essential part of the calibration process to convert the airborne count rates to ground level concentrations of potassium, uranium and thorium.

One procedure that is commonly used to remove radon level changes between flight lines has been described by Green (1987). This levelling procedure, whilst a useful data enhancement tool, does not remove radon and is not acceptable.

The IAEA (1991) have described the procedure to remove radon through the use of an upward looking detector that is shielded from ground radiation. Minty (1992) has described another procedure that utilizes the differences in spectral shape between a radon spectrum from the ground and one from the air surrounding the aircraft. These shape differences are monitored using the ratio of the high to low energy ^{214}Bi gamma–ray peaks at 1760 keV and 609 keV. Both these techniques require the measurement of a radon spectrum in the air and a uranium spectrum from the ground. The IAEA (1991) have recommended a series of overwater background measurements be used to determine the shape of a radon spectrum. However, in Australia suitable lakes may not be located near the survey area and alternative techniques are required.

A radon spectrum may be determined in a number of possible ways:

a) A series of high level backgrounds can be flown at the same barometric altitude on different days. They should be flown at least 800 m above the ground to avoid any ground radiation. Any differences in the spectra will be due to radon. The radon spectrum can be determined from a simple analysis of the spectra.

b) A radon spectrum can also be determined from one flight over the land. This flight should be at least 800 m above the ground to avoid any ground radiation. The measured spectrum will include the cosmic–ray and aircraft background plus a contribution from radon. The cosmic–ray and aircraft backgrounds can be removed from measurements over the sea at the same barometric altitude.

c) Repeat measurements over a survey test line will show differences which are due to radon variations. Any difference between the daily spectrum and the average of all measurements will be mainly due to radon. However, in this case it is important that the test line is flown at the same altitude and starts and stops in exactly the same place. Otherwise some of the differences will be due to variations in radiation from the ground. Figure 2.5 shows a series of spectra that were obtained from a helicopter system that hovered at the same location and height above the ground. The spectral differences are essentially due to radon.

The upward looking detector method and the spectral ratio techniques are similar procedures. Both require a knowledge of the ground contribution of both uranium and thorium into the radon window. In one case the radon monitoring window is the upward detector uranium window count rate, and in the other case it is the low energy 609 keV ^{214}Bi peak above the Compton continuum.

The relationship between the ground components of the uranium and thorium windows (U_g and T_g) in the main downward–looking detectors and the ground component in the radon window, u_g, is given by:

$$u_g = a_1 U_g + a_2 T_g, \tag{2.12}$$

The coefficients a_1 and a_2 can be determined from an analysis of data obtained by subtracting adjacent sections of lines. Through this subtraction procedure, radon, cosmic and aircraft components are then

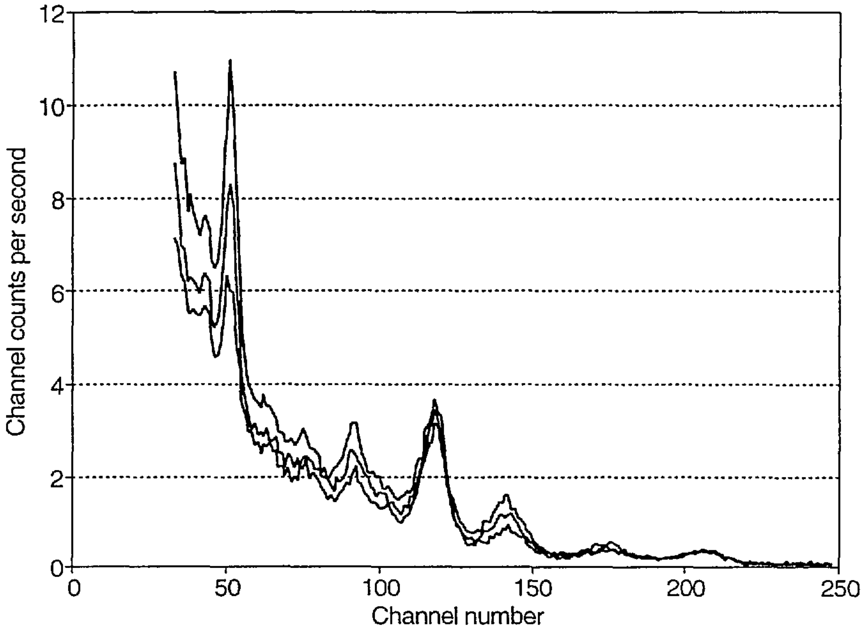

Figure 2.5. The gamma-ray spectra from a series of hover tests at the same location showing the effects of varying radon.

removed and any differences will be solely due to changes in the radioactivity of the ground. By looking at differences between adjacent sections for the entire survey area, the values of a_1 and a_2 can be determined by linear regression as described in IAEA (1991).

2.4 Pad Calibrations

The procedure for determining the calibration constants of a portable spectrometer and the stripping ratios of an airborne system is described in Appendix B (Pad Calibrations For Gamma-Ray Spectrometers).

2.5 Sensitivity and Height Attenuation Calibrations

The procedure for determining the sensitivity and height attenuation coefficients from flights over a calibration range is described in Appendix C (Calibration Ranges).

3. MONITORING PROCEDURES

3.2 Thorium Source Tests

Before a survey commences, it is important for the client to know that the equipment has remained the same since the last set of calibrations and that the various calibration constants are still valid. One way that this can be achieved is through the use of source tests.

For normal survey monitoring, we have recommended that thorium source tests be carried out before and after every days flying. The background corrected count rates in the thorium window serve to verify that the sensitivity of the system has remained the same throughout the survey. These source tests need to be quick to perform so that the flying operation is not disrupted. However, if the calibration is performed just once every twelve months, it is appropriate that source tests during calibration should be more stringent. Consequently we have specified tighter limits on the variations of the source test results for calibrations than for routine flying. The variation of the source tests have been specified as 3 percent during calibrations and 5 percent for daily survey monitoring. With both these limits, provided the detectors are adequately illuminated by the source, it will be easy to recognise if one detector out of a total of eight is not functioning.

In order to achieve this goal of 3 percent variation during calibrations, there are a number of factors to consider. These are the location of the source, the background count rates, the activity of the source and the counting time.

A source test is designed to verify that the system sensitivity has remained the same. It is therefore important that during the source tests each detector receives a similar gamma–ray flux. If the source is placed too close to the detector box, the closest detectors could be receiving significantly more radiation than the detectors that are farther away. However, if the source is far away from the detectors, the counts may be so low that unless very long counting times are used it may be difficult to detect changes in sensitivity.

The counts recorded by each detector will depend on the solid angle they subtend from the position of the source. The solid angle (S), subtended by a rectangle of length l and width w, to a point at height h above the center of the rectangle is given by:

$$S = 2\pi \cos^{-1} \sqrt{\frac{l^2 w^2}{\left(4h^2 + l^2\right)\left(4h^2 + w^2\right)}}. \tag{3.1}$$

From this formula, we were able to compare the solid angle subtended by the two inner detectors and the two outer detectors to the thorium source at different distances from the center of a detector package. Since the solid angle is proportional to the flux incident on the detector, the detected count rates will also be proportional to the solid angle. Consequently the ratio of the detected count rates from the inner and outer detectors will be proportional to the ratio of the incident fluxes. These results are presented in Figure 3.1.

The results show that provided the thorium source is farther than 40 cm from the detector package, the ratios of outer/inner flux will exceed a value of 0.8. At this distance, the inner and outer detectors will be

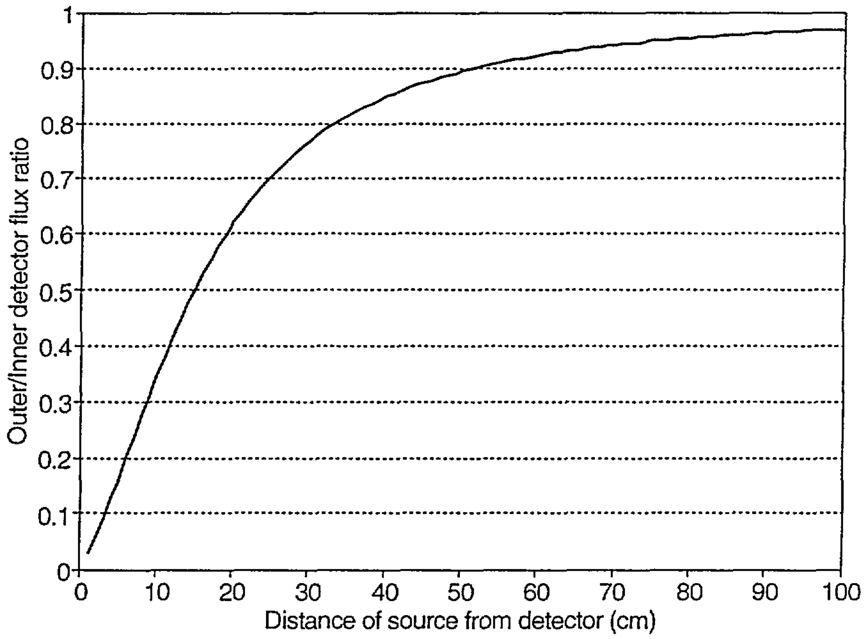

Figure 3.1. The ratio of the incident fluxes on the inner and outer detectors.

receiving very similar fluxes and therefore recording similar count rates. Consequently it will be easy to tell when one detector is not functioning.

In most contracts it is specified that the counts accumulated in the thorium window must exceed 10,000 counts. Since the standard deviation of a Poisson measurement is equal to the square root of the number of counts, the standard deviation in a recorded count of 10,000 is 100. This corresponds to a standard deviation of 1 percent. A variation of 5 percent would then most certainly be detected. However, this assumption does not take into account the subtraction of the background which can significantly increase the variation in the source counts.

The standard deviation in the difference of two sets of recorded counts A and B is given by:

$$\sigma(A-B)=\sqrt{\sigma^2 A+\sigma^2 B)} \tag{3.2}$$

As an example, if we record 10,000 counts with the source, and the background is 5,000 counts, then the counts originating from the source is 5,000. The standard deviation is then given by:

$$\sigma(10{,}000-5{,}000)=\sqrt{(5{,}000+10{,}000)}=122$$

This corresponds to a standard deviation of approximately 2.5 percent on the thorium source counts of 5,000. In such a situation, the source tests will frequently exceed the limit of 3 percent specified for calibrations.

In practice it is probably best to aim for a standard deviation due to Poisson counting statistics of around 0.5 percent. This could be achieved either by counting for a longer period of time or increasing the activity of the source. However, increasing the counting time by a factor of two will decrease the variation by the square root of two. Consequently, to reduce the variation from 2.5 percent to 0.5 percent (a ratio of 5), it would be necessary to increase the counting time of both the background and source measurements by a factor of 25. This may lead to an unrealistic measurement time. In this case it would be better to increase the activity of the source and possibly increase the counting time as well.

Variations in the thorium source counting time can be due not only to Poisson counting statistics, but also to the position of the source. Every effort should be made to eliminate these experimental variations which can be critical, particularly for the calibration source tests where the restrictions on the variations are more severe. Figure 3.2 shows the results of misplacing the source which is normally positioned 50 cm from the detector package. An error of only 1 cm between the pre and post calibration source tests will change the counts by 3.5 percent, resulting in the rejection of the calibration. Certainly for the calibration source tests and even for the daily source test, it would be appropriate to build a jig so that the source can be located in exactly the same place each time. Each source should be labelled and used in association with one particular aircraft and one particular detector package. This will help to avoid unnecessary variations which could lead to the rejection of a calibration by the client.

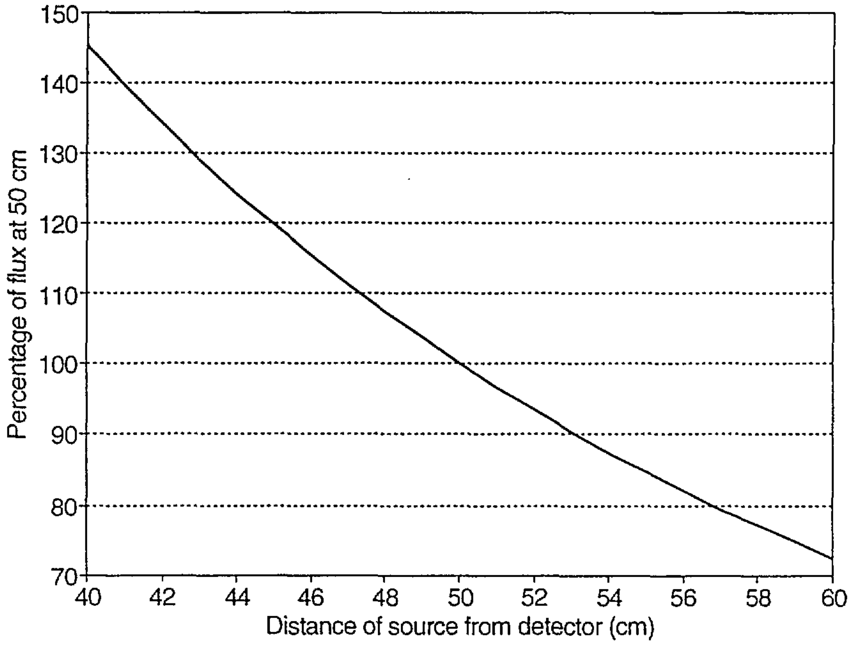

Figure 3.2. The variation in the gamma-ray flux due to errors in the position of the thorium source.

3.3 Daily System Resolution Checks

There are several different procedures that have been used to calculate the resolution of a particular gamma–ray peak. Figure 3.3 shows the background subtracted spectrum of a thorium source from an airborne system. The most simple procedure to measure the resolution of the 2615 keV thorium photopeak is to first determine its amplitude. The width of the peak (as the number of channels) at half the maximum amplitude can then be determined. This width is defined as the 'full width at half maximum', or

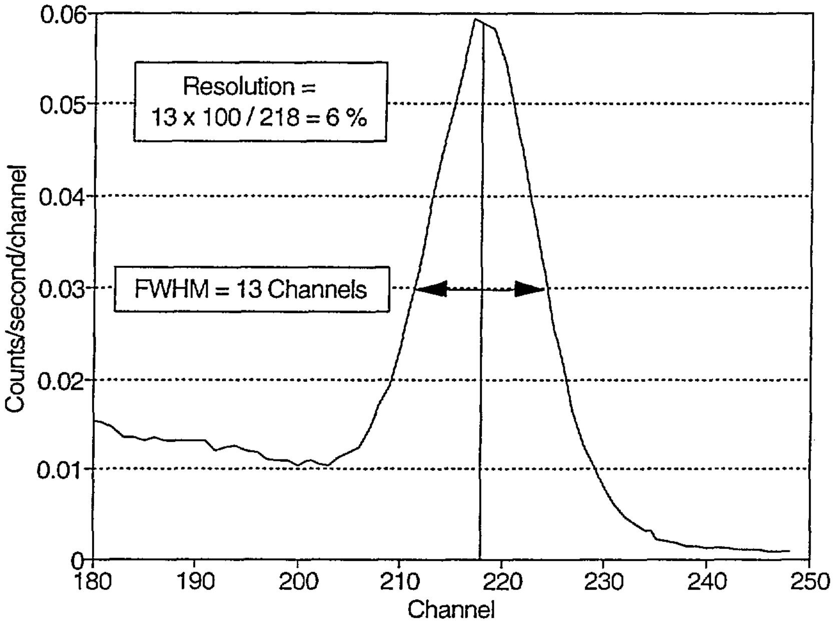

Figure 3.3. A thorium spectrum showing the procedure for determining resolution (FWHM = full width half maximum).

FWHM. The resolution is then calculated as:

$$R(\%) = \frac{100 \times FWHM(channels)}{Tpeak(channels)} \tag{3.3}$$

Alternatively, the FWHM can be calculated in keV. The keV per channel can be found from the channel position of two photopeaks, normally the potassium peak at 1460 keV and the thorium peak at 2615 keV. In equation (3.3), the channel position of the thorium peak would then be replaced by the energy of the thorium peak in keV (2615).

With this simple procedure, the resolution can be calculated in the field by the person responsible for monitoring the contract, from plots of the background subtracted thorium spectrum. It is preferred to the more complicated and rigid approach requiring the removal of a sloping background through the Compton continuum and fitting a Gaussian curve to the residual.

We have investigated the effect of changing system resolution on the sensitivity of an airborne system by comparing the photopeak counts rates at different resolutions. The flux distributions of potassium, uranium and thorium have been calculated by Kirkegaard and Lovborg (1974) and are shown in Figures 3.4, 3.5 and 3.6. The effect of the detector and photomultiplier on the incident flux is to broaden the discrete unscattered components. The continuous scattered flux component, however, will remain unchanged.

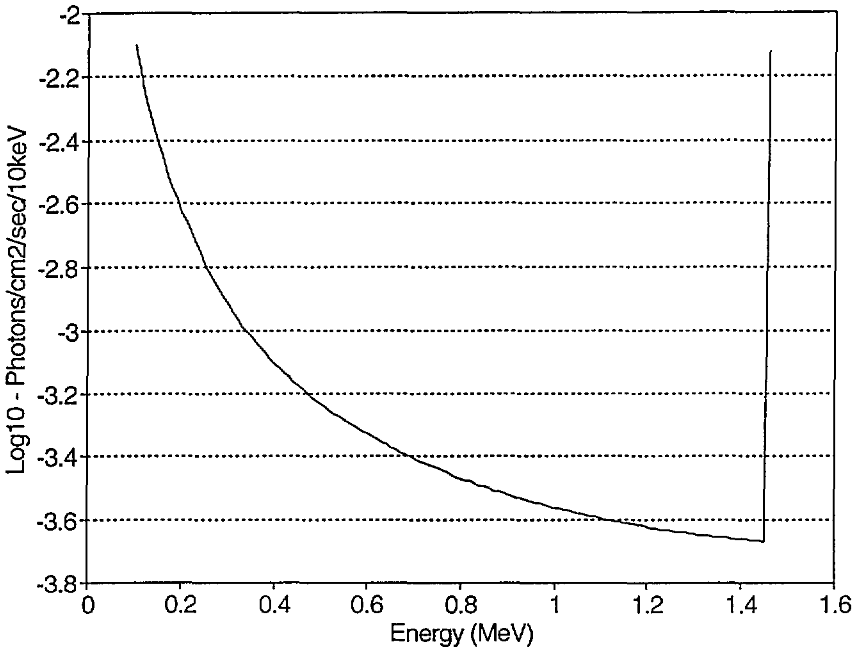

Figure 3.4. The potassium flux distribution in the air.

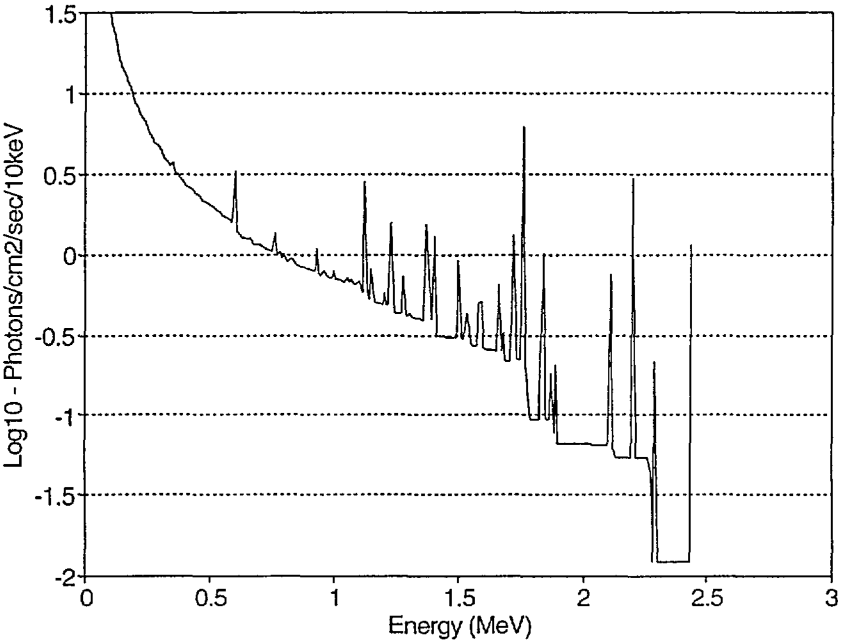

Figure 3.5. The flux distribution in the air from the uranium decay series.

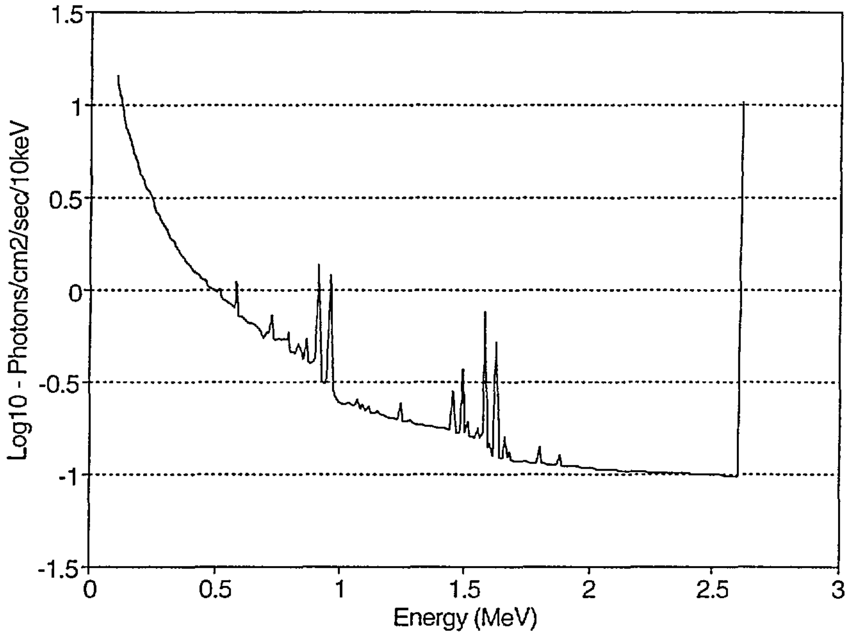

Figure 3.6. The flux distribution in the air from the thorium decay series.

The technique to broaden the three photopeaks was through the use of a gaussian filter of the form:

$$N_i = N \exp\left[\frac{(x - x_i)^2}{\sigma^2}\right], \tag{3.4}$$

where

σ = constant;
N = the count rate at channel x; and
N_i = the count rate at channel x_i.

The relation between *FWHM* and the constant σ is given by:

$$\sigma = \frac{FWHM}{2\sqrt{\ln(2)}} \tag{3.5}$$

Figure 3.7 shows the potassium photopeak with three different resolutions of 4.8, 8.5 and 12.1 percent which we have estimated would correspond to thorium resolutions of 4, 7 and 10 percent. Figure 3.8 shows the relationship between the thorium resolution at 2615 keV and the percentage of the photopeak counts detected in all three recommended windows (Table 1.1). The figure shows that for thorium resolutions between 4 and 7 percent, essentially all the 2615 gamma rays from ^{208}Tl are detected in the thorium window. Over the same range of resolutions, almost all the 1460 keV gamma rays from ^{40}K are also detected in the potassium window. Consequently, for both thorium and potassium, there is little advantage in improving the resolution beyond 7 percent.

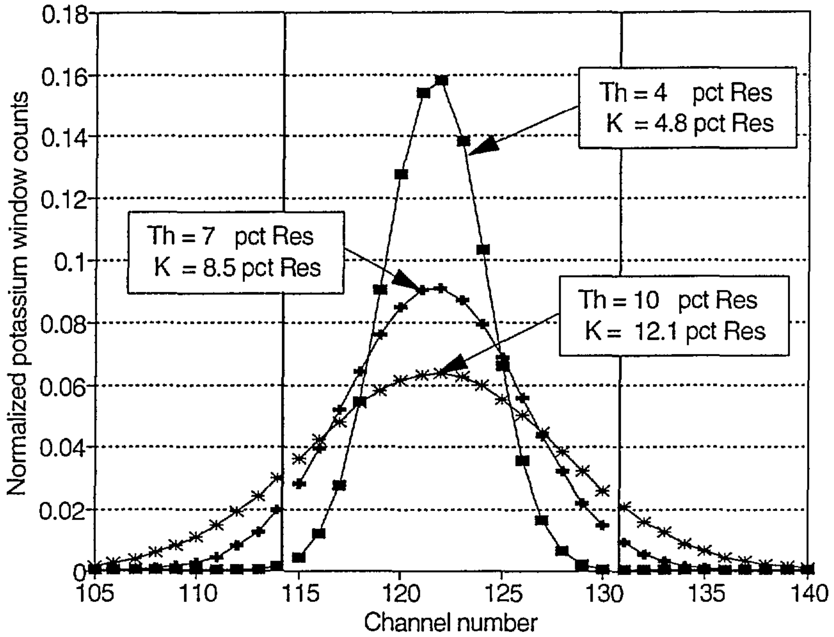

Figure 3.7. The potassium 1460 keV photopeak at different resolutions.

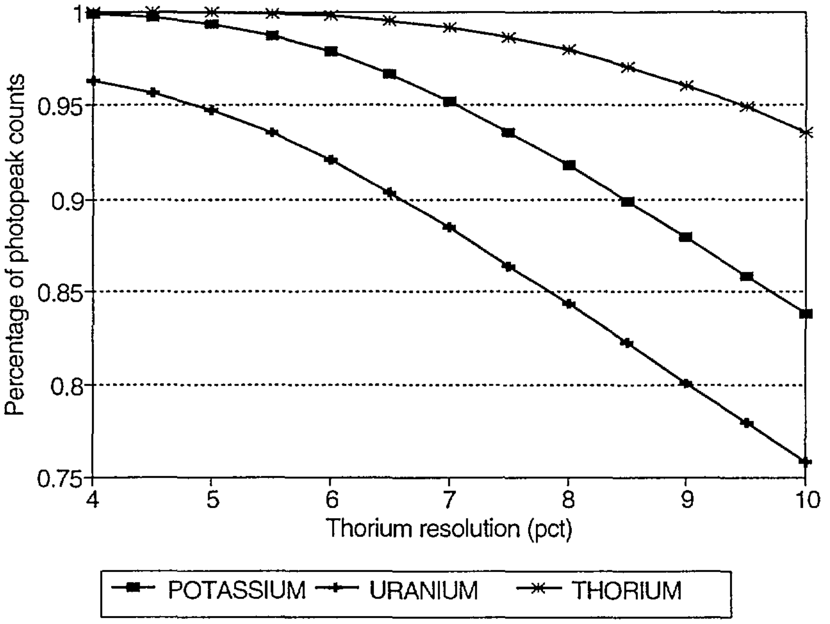

Figure 3.8. The variation of the photopeak count rates with thorium resolution.

In estimating the effect of resolution on the uranium window count rates, we took into consideration the three main ^{214}Bi gamma–ray emissions at 1730, 1765 and 1838 keV (Figure 3.5). Figure 3.8 shows that for uranium, there is some advantage in improving the thorium resolution from 7 to 4 percent, because the percentage of photopeak counts detected from the three principal gamma rays around 1760 keV will increase from around 88 percent to around 97 percent with a corresponding increase in sensitivity. There is therefore an advantage in keeping the resolution of the system as low as possible.

A cesium resolution of 10 percent seems to be a reasonably achievable goal. In practice, this corresponds to a thorium resolution of around 6 to 7 percent. We have therefore specified that the overall system resolution should be better than 7 percent, based on the full width half maximum of the ^{208}Tl peak at 2615 keV.

We have also investigated the effect of changing system resolution on the calculated potassium, uranium and thorium concentrations for a range of rock types. For this study, we utilized spectra recorded with a 16.8 litre system on the calibration pads at Grand Junction, Colorado in the United States (Grasty, 1982). From these measurements we were able to calculate pure potassium, uranium and thorium spectra at a survey altitude of 100 m. These spectra, shown in Figures 3.9, 3.10 and 3.11, were calculated for channels with an energy width of 12 keV. The recommended potassium, uranium and thorium window boundaries are indicated on each spectrum.

We assumed that the change in resolution was caused by the non–sympathetic drift of the detectors. A spectrum was first calculated from ground with typical crustal concentrations (2 percent potassium, 2 ppm uranium and 8 ppm thorium). Two new spectra were then calculated by gain–shifting the original spectrum. The first spectrum had a positive gain shift and the second a negative gain shift. These two spectra were then combined to form a new spectrum. The resultant effect was to decrease the resolution of the original spectrum. This new spectrum was then re–windowed and its resolution calculated. The new window data were used to calculate the new potassium, uranium and thorium concentrations assuming all the calibration constants had remained the same.

Figure 3.12 shows how the percentage errors in the calculated concentrations of potassium, uranium and thorium vary with the resolution of the system. A thorium resolution change of one percent (from 6 to 7 percent), causes approximately a one percent error in both the uranium and potassium concentrations.

The thorium concentration shows little effect, reflecting the relatively wide 400 keV thorium window. Similar results were found for ground with varying concentrations of the three radioactive elements.

In summary, thorium resolution changes of 1 percent (from 6 to 7 percent) have only a small effect on calculated ground concentrations. Such changes will be relatively easy to recognize using the simple procedure illustrated in Figure 3.3. The main use of monitoring resolution is to identify problems with detectors or photomultiplier tubes.

3.4 Spectrum Stability

For temperature stabilized systems, the thorium photopeak at 2615 keV typically drifts by about 2–4 channels per day. Self–stabilizing spectrometers perform considerably better and maintain the correct position of the thorium photopeak to within one channel.

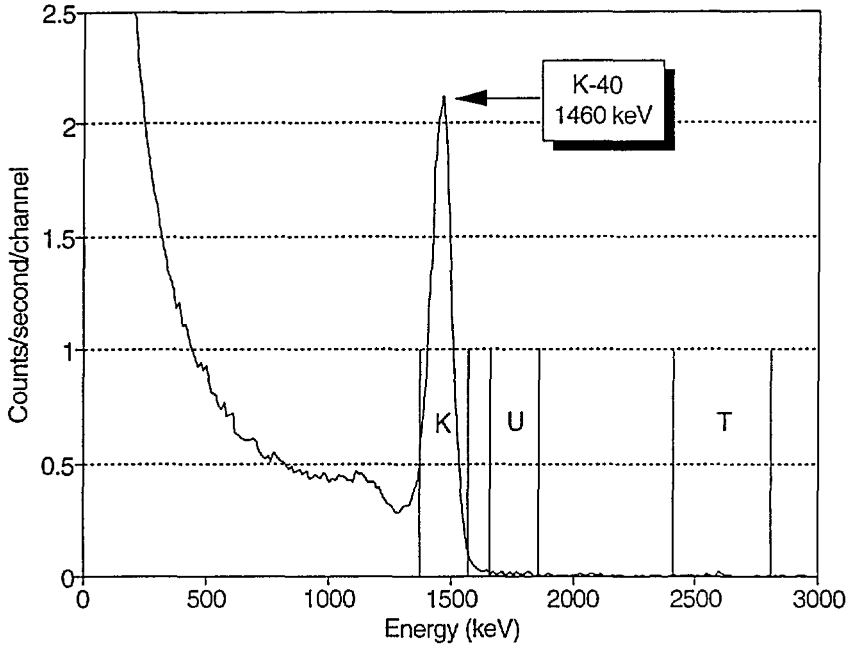

Figure 3.9. The potassium spectrum at a simulated altitude of 100 m obtained from measurements on the calibration pads at Grand Junction, Colorado, USA. The standard IAEA windows are indicated.

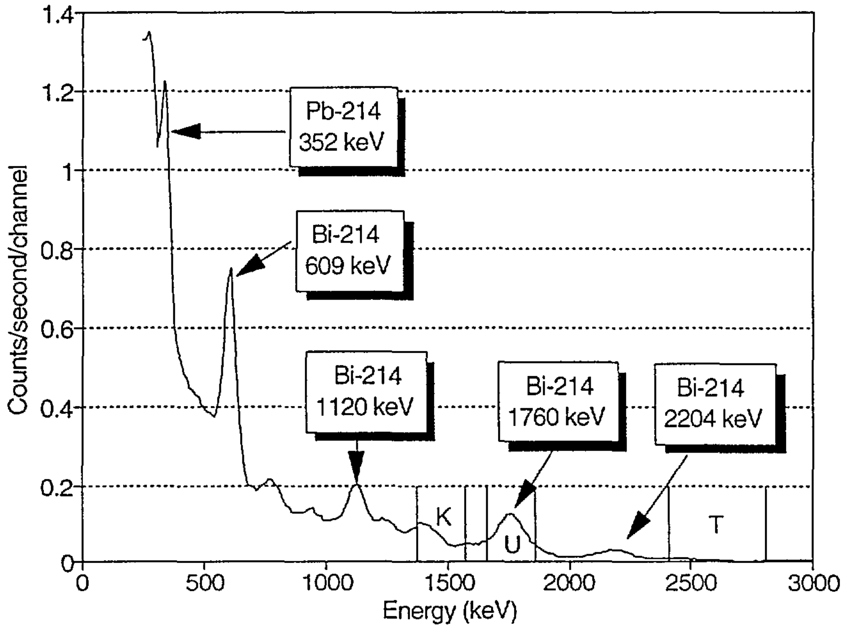

Figure 3.10. The uranium spectrum at a simulated altitude of 100 m obtained from measurements on the calibration pads at Grand Junction, Colorado, USA. The standard IAEA windows are indicated.

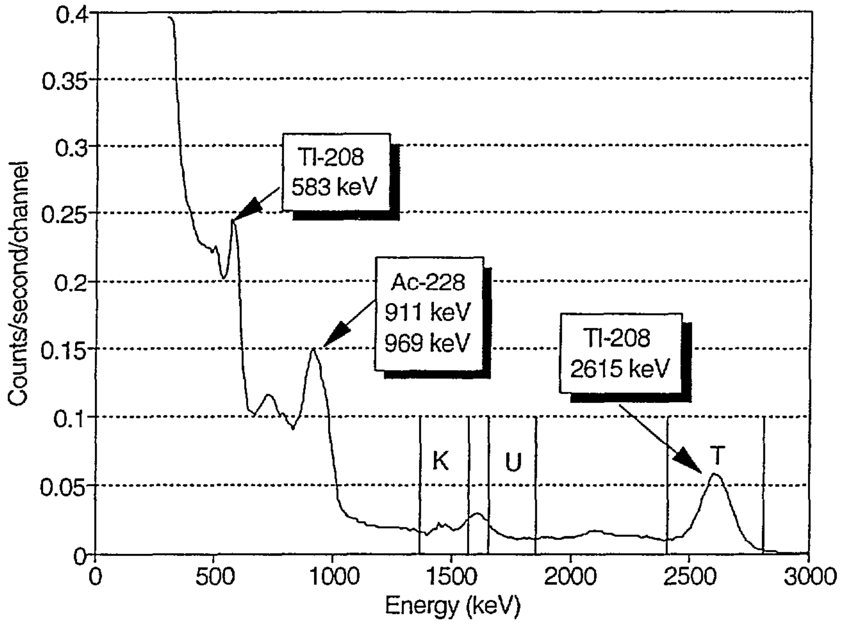

Figure 3.11. The thorium spectrum at a simulated altitude of 100 m obtained from measurements on the calibration pads at Grand Junction, Colorado, USA. The standard IAEA windows are indicated.

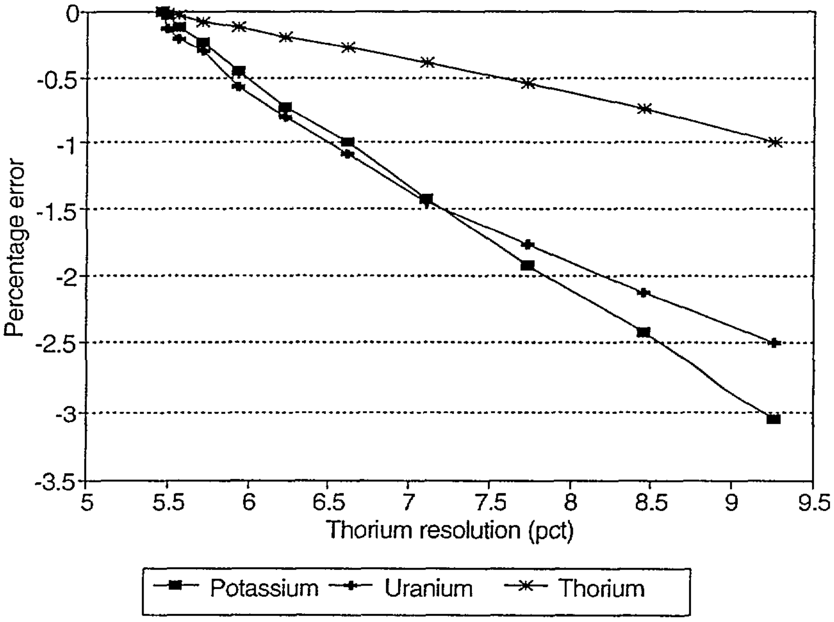

Figure 3.12. The percentage errors in the calculated concentrations of potassium, uranium and thorium for normal crustal material as a function of system resolution.

In order to estimate the effect of spectral drift on the measurements of potassium, uranium and thorium, we utilized gamma–ray spectra calculated from measurements on calibration pads (Figures 3.9, 3.10 and 3.11). From these spectra we were able to calculate the percentage errors in the calculated potassium, uranium and thorium concentrations of ground with varying concentrations of potassium, uranium and thorium. The energy drifts were measured as the channel shift in the position of the thorium photopeak which, for a spectrum with 12 keV per channel, would normally be located in channel 218.

Figure 3.13 shows the effect of energy drift for measurements over normal crustal material containing 2 percent potassium, 2 ppm uranium and 8 ppm thorium. Figure 3.14 shows the results for material with the same concentration of potassium and thorium but with a lower concentration (1 ppm) of uranium. Errors due to spectral drift on calculated uranium concentrations increase as the uranium/thorium ratio decreases.

These errors largely arise from incorrect stripping of the thorium counts from the uranium window. Errors in the stripping ratio alpha (α) will cause similar errors in the measurement of uranium (Figure 3.15). Figures 3.13 and 3.14 show that drifts of up to 2 channels at the 2615 keV thorium photopeak can cause significant errors, particularly for rocks with low uranium/thorium ratios. A channel drift of 2 channels at 2615 keV corresponds roughly to 1 channel at 1460 keV. We have therefore specified in the contract that spectra with a shift in the thorium 2615 keV photopeak of 1 channel (or 0.5 channels at 1460 keV) should be energy calibrated prior to sampling the conventional channels.

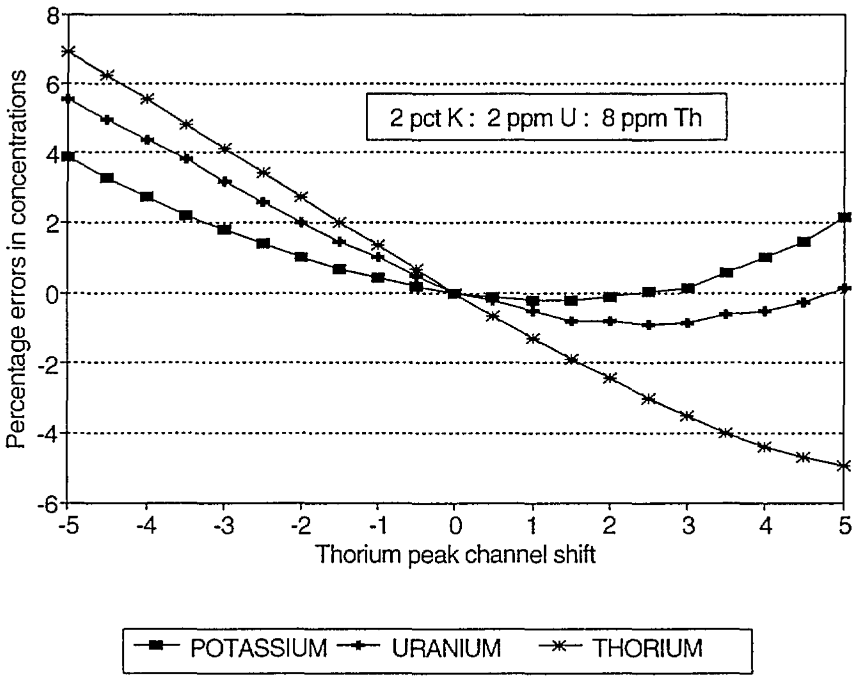

Figure 3.13. The effect of spectral drift on normal crustal material. The drift is measured as the change in the position of the thorium peak which should be located in channel 218.

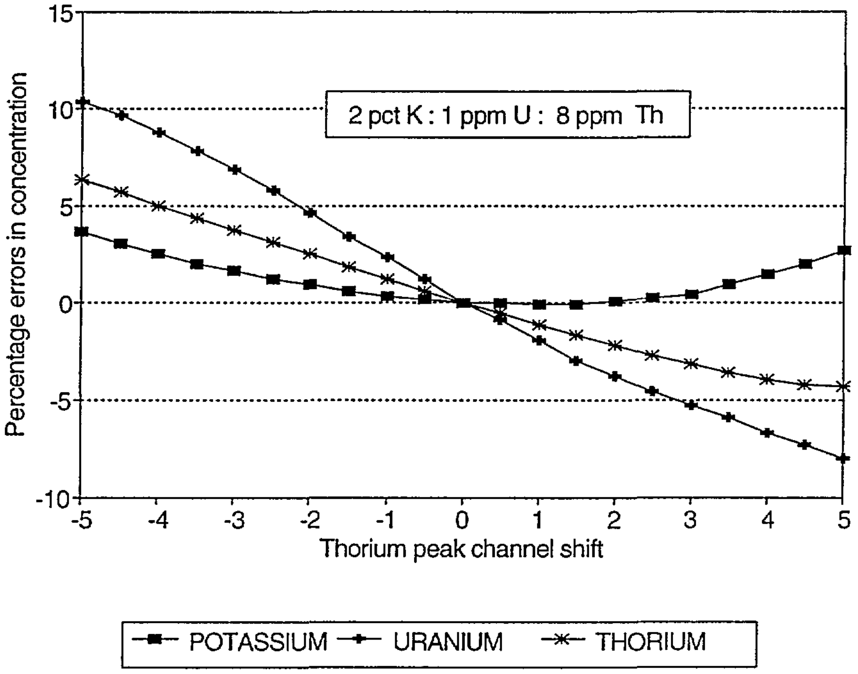

Figure 3.14. The effect of spectral drift on material with a low uranium/thorium ratio. The drift is measured as the change in the position of the thorium peak which should be located in channel 218.

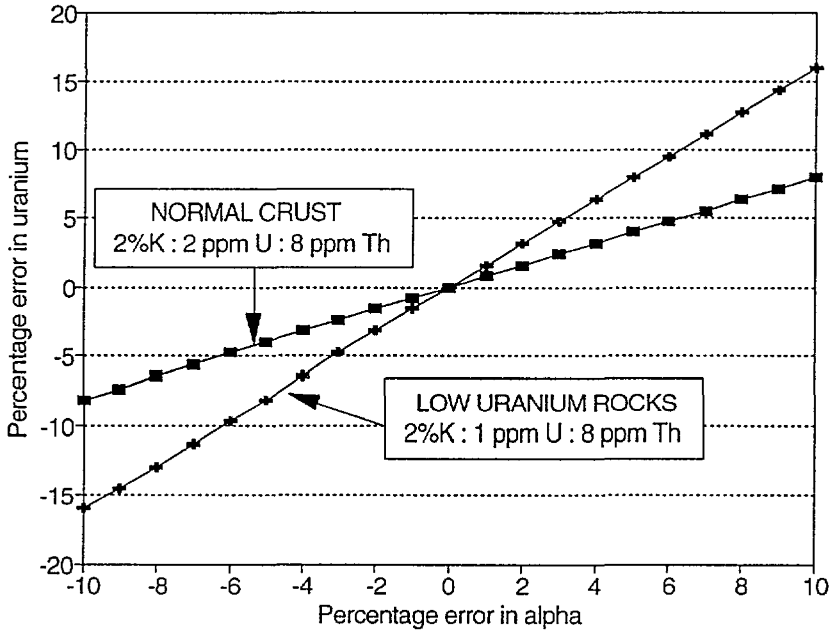

Figure 3.15. The effect of errors in the stripping ratio, alpha, on the measurement of uranium.

In order to monitor spectral drift, it is necessary that the potassium and thorium peak positions be calculated with some accuracy. Airborne spectra collected for 1000 seconds have little noise and with simple algorithms, the peak position can easily be found to ± 0.1 channels. By specifying that the potassium or thorium photopeaks be plotted to an accuracy of 0.1 channels, there will be no problem identifying when the spectrum has drifted out of specifications. If this occurs, the spectra will have to be energy calibrated to determine the counts in the standard windows.

3.5 Survey Test Line

The survey test line serves two main purposes. It can be used for monitoring the effect of moisture in the ground, and to monitor the behavior of the equipment in the air.

In selecting the survey test line, there are both practical and theoretical considerations. The survey test line should, if possible, be typical of the survey area. A road, or a ridge with bare outcrop would be unsuitable, since after rainfall, the ground would probably dry out before most of the survey area.

In some contracts it has been specified that the line should be flown north/south and in the same direction. At first sight the direction of the line would seem immaterial. However, for an east–west line, the pilot may have the sun in his eyes in the early morning. Consequently, the direction of the line has some practical significance. A line which is always flown in the same direction can assist the contract monitor since the survey test line plots can be overlaid directly without reversing them.

The purpose of the test line is to monitor the sensitivity of the system in the air. It is therefore best to make the day to day comparisons as easy as possible. The line should therefore be easy to navigate and have some readily identifiable features. A fence line would be suitable. The survey test line should have some reasonable level of radioactivity so that problems associated with counting statistics are minimized. The line should preferably be radioactively uniform so that deviations in the aircraft flight path will have minimal effect on the average counts rates. Some contract monitors prefer a survey test line with radiometric features. Provided these features are not too extreme and the line is easy to navigate, such a line should not be a problem.

In some contracts, the total count has been used to monitor changes in the ground response. The total count window was selected for its high count rate – thus minimising problems due to poor counting statistics. However, the total count is influenced by changes in the radon concentration of the air and is therefore unsuitable. Figure 3.16 shows a series of average total count and uranium window measurements over a survey test line in South Australia. The total count and uranium channel vary sympathetically since they are both influenced by radon changes. Potassium will also be somewhat affected by changes in radon. We have therefore selected thorium as the window of choice for monitoring the survey test line.

Changes in the thorium window count rate will be affected by changes in terrain clearance as well as those due to temperature and pressure. The thorium count rates should therefore be normalized to the nominal survey altitude at STP before being used for monitoring. The thorium window background should be removed prior to this normalization, otherwise the magnitude of the variations in the thorium window count rates will depend on the relative contributions from the ground and from the background.

Soil moisture is measured as the weight of water in one gram of dry material and is normally expressed as a percentage. An increase in soil moisture of 10 percent (from 10 to 20 percent) will decrease the airborne count rate in the thorium channel by approximately the same amount. Changes in soil moisture will commonly occur throughout the survey period, particularly for surveys of long duration. The specifications for the repeatability of the survey test line should not be so restrictive that they will cause frequent disruptions in the survey operations. A value of ±10 percent seems a good compromise in that significant moisture changes will be detected, but minor changes will not result in the suspension of flying.

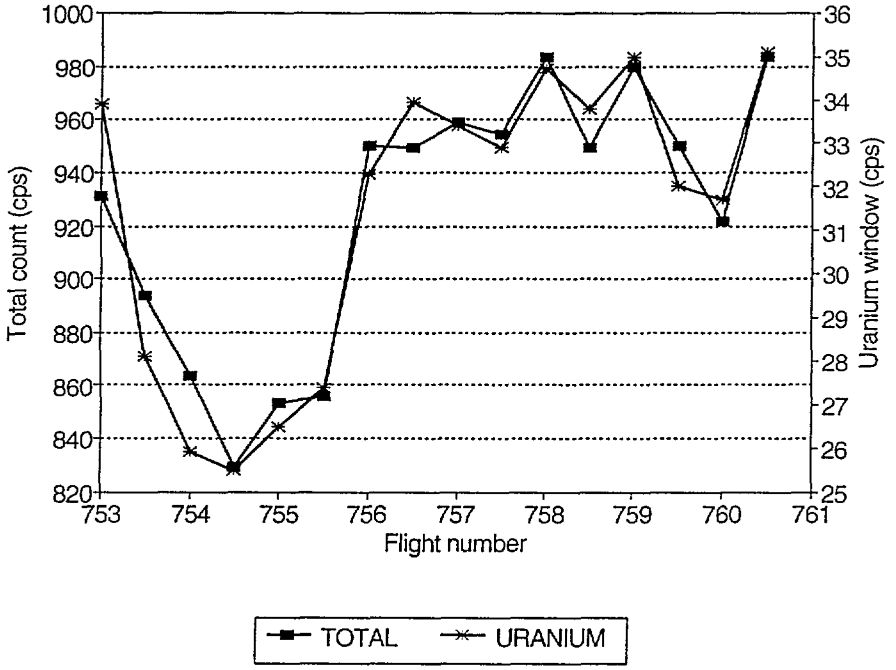

Figure 3.16. The average total and uranium window counts over a survey test line in South Australia showing the effects of varying radon concentrations.

One of the main problems in using a test line for monitoring soil moisture changes is that the test line may not be representative of the area being surveyed. It can rain on the test line, but the survey area may be completely dry, or vice–versa. This problem is difficult to overcome. We have attempted to address this problem, at least in part, by allowing a section of a previously flown line to serve as the test line.

Radon decay products are charged particles and attach themselves to dust in the air. These dust particles act as nuclei for the formation of rain drops. When it rains, these radioactive dust particles are deposited on the ground and increase the surface gamma–ray activity. The resultant increases in the airborne uranium channel can be significant. The decay product of radon, ^{214}Pb has a half–life of 27 minutes before decaying into ^{214}Bi with a half–life of 20 minutes. Consequently, these decay products will take two to three hours before they decay to negligible levels. It is therefore a recommendation that all flights be suspended for three hours after any rain in the survey area.

The survey test line also serves to identify any unusual sources of radioactivity that may be brought on board the aircraft. Figure 3.17 shows a sequence of average total and thorium window count rates over a survey test line. The anomalous peak on Julian day 220 is due to the presence of a camera on board the aircraft. This particular camera had a thorium rich anti–reflective coating which is easily identified on the thorium and total count plots. This increased background may not have been picked up during the thorium source test on the ground since, for this test, the background is removed.

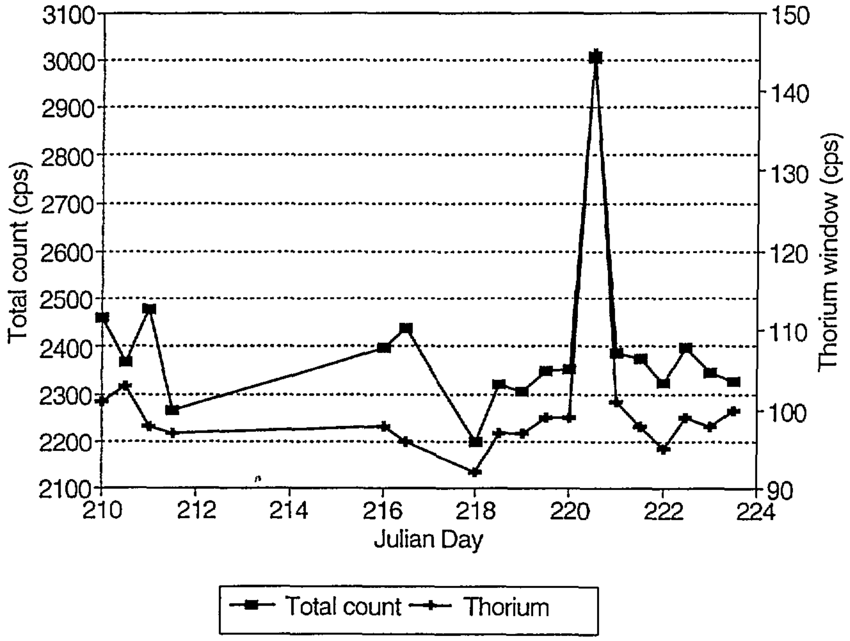

Figure 3.17. The average total count and thorium window over a survey test line showing the effects of a camera with a radioactive lens.

4. DATA PROCESSING

4.1 Dead–Time Corrections

Gamma–ray spectrometers require a finite time to process each pulse from the detectors. While one pulse is being processed, any other pulse that arrives will be rejected. Consequently, the 'live' time of a spectrometer is reduced by the time taken to process all pulses reaching the analyzer. For large volume airborne gamma–ray spectrometers with their associated high count rates, the dead–time can be significant and corrections must be made, particularly when measuring on calibration pads.

In Australia there are three types of airborne gamma–ray spectrometers that are currently being flown. The two modern self–stabilizing spectrometers have different characteristics. The Picodas ENMOS system, has analogue to digital converters (ADC) associated with each detector. For this system, the total dead–time, even at ground level is extremely small, and for all practical purposes can be neglected. The Exploranium GR-800 and GR-820 uses only one ADC. For the GR-820, dead–time corrections must be applied using the live–time information that is measured electronically. For the GR-800, each pulse processed by the ADC has a dead–time of 8 µs. The data output from the spectrometer includes the total counts (*N*) which are processed by the ADC. The total dead–time is therefore simply given by *N*×8 µs.

Dead–time corrections are made to each window using the expression:

$$N = \frac{n}{1-t} \tag{4.1}$$

where

N = corrected counts in each second;
n = raw counts recorded in each second;
t = recorded dead–time, the time taken to process all pulses reaching the detector in one second.

Alternatively, if the live–time is recorded, the corrected window counts in each second is given by:

$$N = \frac{n}{l}, \tag{4.2}$$

where

l = live time for each second;
n = raw counts recorded in one second.

Dead–time corrections should be applied to each window in the downward–looking detectors. However, for some spectrometers, dead–time corrections should not be applied to the cosmic–ray channel or the upward–looking data as these may be processed by different circuits. This information should be provided in the equipment manual.

4.2 Energy Calibration

For gamma–ray spectrometers that are not self–stabilizing, the count rates in the standard windows should be determined from the 256 channel data. If stabilized spectrometers are used, spectral drift should first be checked by monitoring the potassium and thorium channel positions from average spectra along flight lines. If the thorium peak is found to move more than 1 channel or the potassium peak by more than 0.5 of a channel, then energy calibration must be performed.

The channel positions of the potassium and thorium peaks are first used to determine the linear relationship between channel (C) and energy (E). This is given by:

$$C = S \times E + I \tag{4.3}$$

where S is the slope given by channels per keV and I is the intercept which corresponds to the zero energy channel position.

The procedure for determining the positions of the potassium and thorium peaks is not critical. However, it is important that the same procedure is followed in calculating the standard window boundaries for all spectral processing whether for calibrations or for the analysis of survey data.

If P_K and P_T are the peak channel positions for potassium and thorium respectively, then the slope S, is given by:

$$S = \frac{(P_T - P_K)}{(2615 - 1460)} \tag{4.4}$$

and

$$I = \frac{2615 \times P_K - 1460 \times P_T}{(2615 - 1460)} \tag{4.5}$$

Using equation 4.3, the window boundaries (in channels) corresponding to the lower and upper window boundaries (in keV) can be calculated. If whole numbers of channels are used to calculate the window counts, as the spectrum drifts, there can be discontinuous jumps in the number of channels used for each window. Fractions of channels should therefore be calculated at the window boundaries by linear interpolation of adjacent channels.

The lower and upper channel boundaries L_1 and L_2 as integer numbers, corresponding to window boundaries E_1 and E_2 (in keV), are related to S (in channels/keV) and I (in channels) by the equations:

$$L_1 = \text{INTEGER}(E_1 \times S + I + 0.5) \tag{4.6}$$

and

$$L_2 = \text{INTEGER}(E_2 \times S + I - 0.5) \tag{4.7}$$

When carrying out an energy calibration of gamma–ray spectra obtained from measurements on calibration pads, it is appropriate to determine the potassium peak position from the potassium pad and the thorium peak position from the thorium pad. It is also acceptable to use the channel positions of the 1120 keV and 1760 keV uranium photopeaks from the uranium pad and then solve equation (4.3) by linear regression. Based on our experience in analysing gamma–ray spectra, there is always an excellent linear relationship between channel and energy from the ^{208}Tl peak at 2615 keV down to the ^{137}Cs photopeak at 662 keV.

4.3 Cosmic and Aircraft Background Removal

The cosmic channel should be filtered before being used to calculate the cosmic and aircraft background components in each channel. A 10 to 20 point filter would be suitable.

The determination of the cosmic and aircraft background expressions for each spectral window has been described in section (2.2). This background, together with a possible component due to radon present during the cosmic calibrations, can be removed using an expression of the form:

$$N = a + bC \tag{4.8}$$

where

N = combined cosmic and aircraft background in each spectral window,
C = cosmic channel count ,
a is given by equation (2.4) and
b is given by equation (2.5)

Equation (4.8) is evaluated for each window at each data point using the filtered cosmic channel data and the results subtracted from the data.

4.4 Radon Background Removal

Two methods of estimating atmospheric background are acceptable. They are using upward looking detectors and the spectral ratio technique.

Because of the low count rate in the upward uranium window and the ^{214}Bi photopeak at 609 keV, these window must be filtered considerably to reduce statistical noise, before any calculations are performed. The uranium downward and thorium downward window data should also be filtered. For a 32 litre system with two upward–looking detectors of volume 8.4 litres, a 200 point running average would be suitable.

The procedure for calculating radon background from the upward looking detector data has been described by the IAEA (IAEA, 1991). However, the equations are considerably simplified with the technique described in section 2.2 for removing cosmic and aircraft backgrounds.

The radon component will now be given by:

$$U_r = \frac{u - a_1 U - a_2 T}{a_u - a_1 - a_2 a_T} \tag{4.9}$$

where

U_r = radon background measured in the downward U window;
u = measured count in the upward uranium window;
U = measured count in the downward uranium window; and
T = measured count in the downward thorium window.

a_1 and a_2 are proportionality factors that relate the uranium and thorium contributions from the ground into the upward detector. a_u is the ratio of the upward to downward uranium window for a pure radon spectrum, and a_T is the ratio of the thorium to downward uranium window for a pure radon spectrum. The measured count rates u, U and T used in equation (4.9) must first be corrected for cosmic and aircraft background. The radon counts in the total count, potassium and thorium windows can be calculated using the shape of the radon spectrum.

The spectral ratio technique is mathematically analogous to the upward detector technique. Apart from differences in the calibration coefficients, equation (4.9) can also be used to calculate the radon contribution to the uranium window by replacing the upward detector window with the low energy 609 keV photopeak.

4.5 Calculation of Effective Height

Since the airborne count rates depend on the density of the air between the detector and the ground, they will also depend on air temperature and pressure. For surveys flown at approximately the same barometric altitude, the effect of pressure changes on the measured count rates is relatively small. At sea–level, pressure can vary from a low of around 985 millibars to a high of around 1035 millibars. Figure 4.1 shows how these pressure ranges affect the airborne potassium counts at a survey height of 100 m. The results are compared to a value of 100 counts at a standard pressure of 1013 millibars.

There are significant changes in pressure with barometric altitude and these changes have far more impact on the airborne count rates. The relationship of pressure (P) to barometric altitude is given by:

$$P = 1013\exp(-h/8581) \qquad (4.10)$$

where h is the barometric altitude in meters.

Figure 4.2 shows how barometric pressure will vary from sea–level to an altitude of 1600 m. These pressure changes are far greater than the daily variations at one location. Figure 4.3 shows how the potassium photopeak count rate varies with barometric altitude over the same rock type at a survey altitude of 100 m. A count rate at sea–level of 100 increases to around 115 at an altitude of 1600 m – a significantly greater variation than is found from daily pressure variations.

Correcting for temperature variations is also an important part of the processing procedures since annual temperature variations can change the airborne count rate significantly over the same source of ground radiation. As shown in Figure 4.4, a temperature change of 40 degrees Celsius can change the airborne count rate at 100 m by more than 10 percent.

The importance of temperature and pressure corrections becomes greater in areas of rugged terrain where ground clearances can show marked variations. As shown in Figure 4.5, a temperature increase of 30 degrees Celsius will result in an 8 percent increase in the airborne potassium counts at a ground clearance of 100 m. However, this will increase to more than 20 percent for a ground clearance of 250 m.

In areas of rugged topography, the radar altimeter data should be lightly filtered for use in adjusting the stripping ratios for altitude and to carry out attenuation corrections. A 5 point filter would be suitable for smoothing sudden jumps that can arise when flying over steep terrain. They are then converted to effective height (h_e) at standard temperature and pressure (STP) by the expression:

$$h_e = h \times \frac{273}{T+273} \times \frac{P}{1013}, \tag{4.11}$$

where, h = observed radar altitude in metres;
T = measured air temperature in degrees C; and
P = barometric pressure in millibars.

If necessary, the pressure can be estimated from the barometric altitude using equation 4.10.

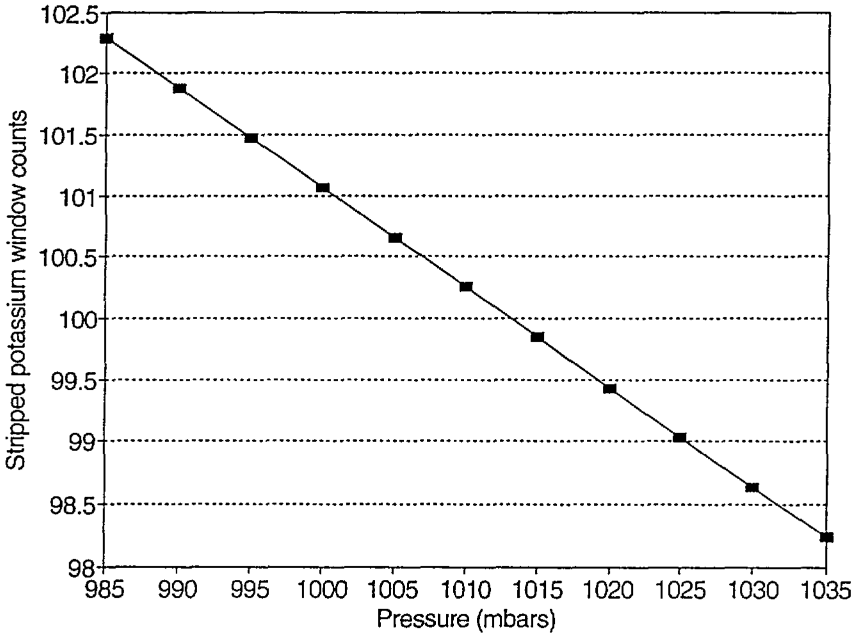

Figure 4.1. The variation of the potassium window counts as a function of pressure for a survey altitude of 100 m. The counts have been normalized to a value of 100 at 1013 mbars and a survey altitude of 100 m. The pressure ranges are typical of those that occur at sea-level.

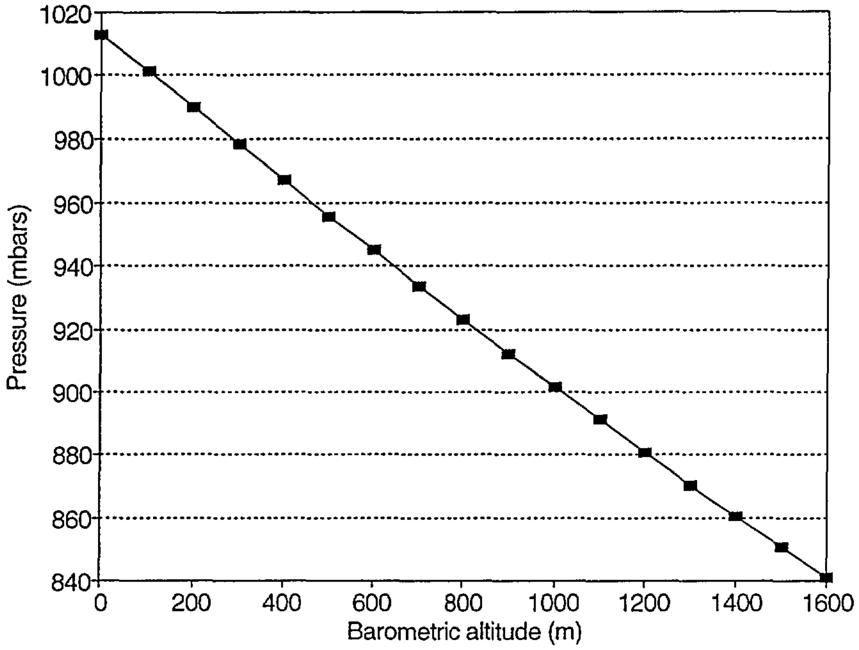

Figure 4.2. The variation of atmospheric pressure with barometric altitude.

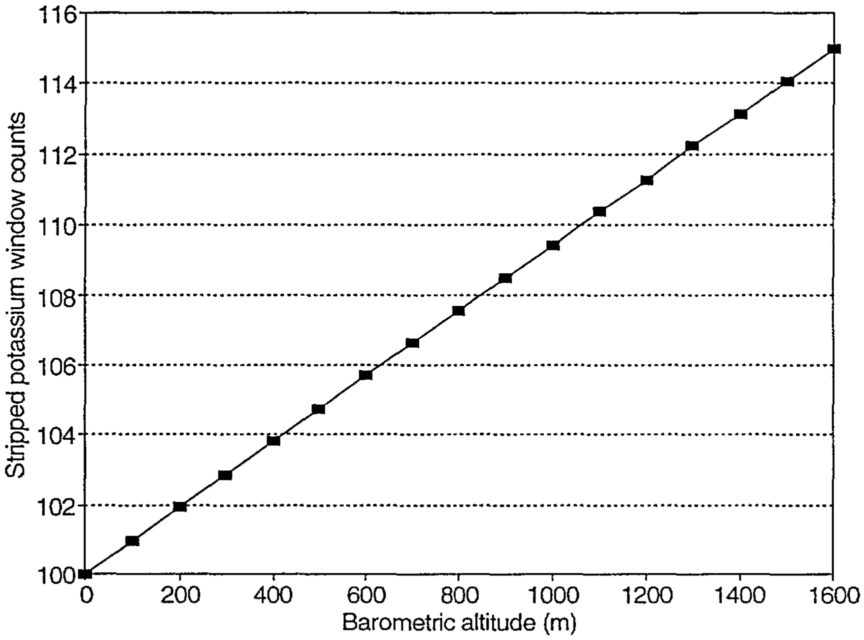

Figure 4.3. The variation of the potassium window counts as a function of barometric altitude. The counts have been normalized to a value of 100 at sea-level and a survey altitude of 100 m.

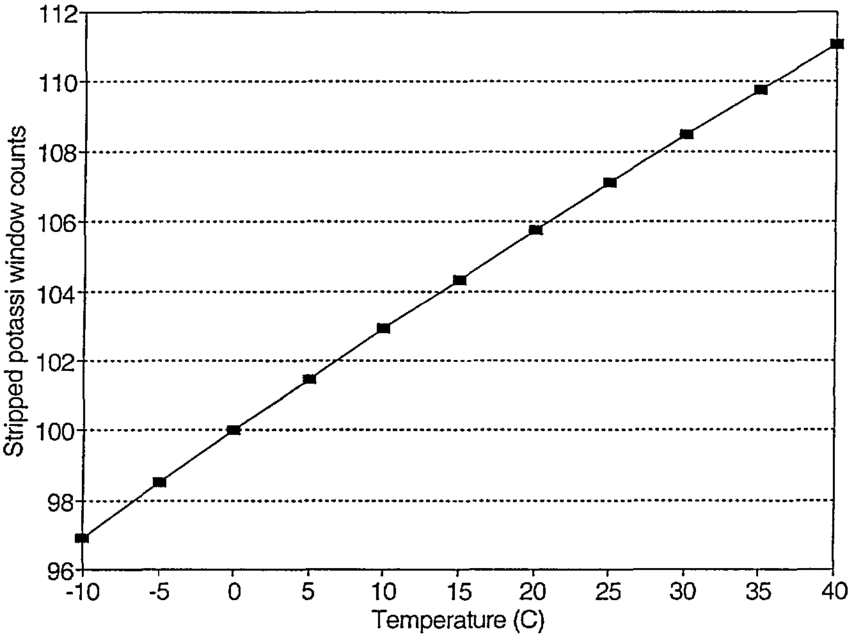

Figure 4.4. The variation of the potassium window counts as a function of temperature. The counts have been normalized to a value of 100 at 0°C and a survey altitude of 100 m.

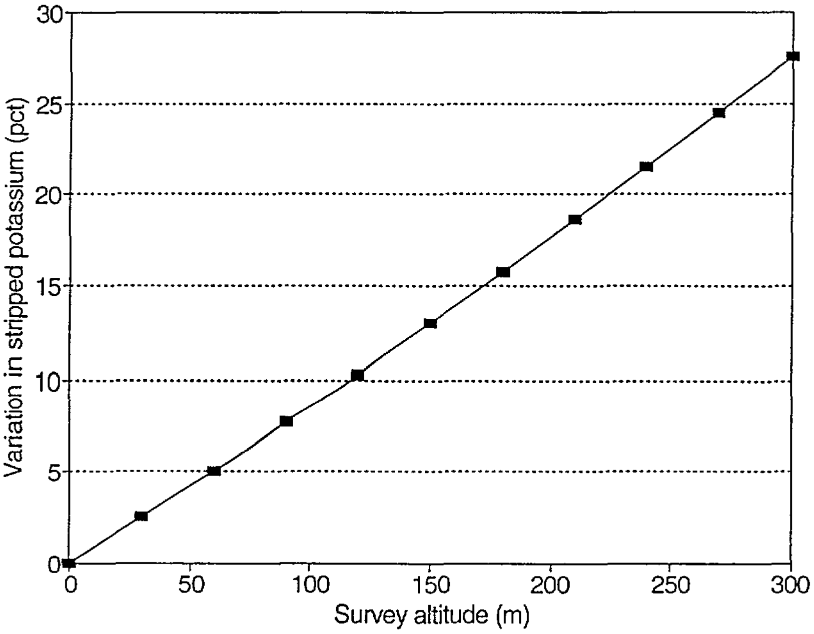

Figure 4.5. The percentage variation of the potassium window counts as a function of ground clearance for a temperature change of 30°C.

4.6 Spectral Stripping

The stripping ratios α, β, γ, a and g are determined over calibration pads and are therefore measured at ground level. Due to scattering of gamma rays in the air, the three principal stripping ratios α, β, γ increase with altitude above the ground. The increases in the three stripping ratios with altitude as shown in Table 4.1 are based on both theory and experiment. No corrections are applied to the reverse stripping ratios a and g because these are small and generally have little effect on the stripped count rates in each window.

Table 4.1 Stripping Ratio Increase with Aircraft Altitude at STP

Stripping Ratio	Increase per metre
α	0.00049
β	0.00065
γ	0.00069

Each of the three main stripping ratios should therefore be adjusted before stripping is carried out. Using the five stripping ratios, the background corrected count rates in the three windows can be stripped to give the counts in the potassium, uranium and thorium windows that originate solely from potassium, uranium and thorium. The stripped count rates in the potassium, uranium and thorium channels, N_K, N_U, N_{Th}, are given by:

$$N_K = \frac{\left[n_{Th}(\alpha\gamma - \beta) + n_U(a\beta - \gamma) + n_K(1 - a\alpha)\right]}{A}, \tag{4.12}$$

$$N_U = \frac{\left[n_{Th}(g\beta - \alpha) + n_U - n_K g\right]}{A}, \tag{4.13}$$

$$N_{Th} = \frac{\left[n_{Th}(1 - g\gamma) - n_U a + n_K a g\right]}{A}, \tag{4.14}$$

where

$$A = 1 - g\gamma - a(\alpha - g\beta). \tag{4.15}$$

4.7 Height Correction

The attenuation coefficients are normally determined from flights over a calibration range. If no temperature corrections are applied, attenuation coefficients will vary by 10 percent for a temperature change of 30 degrees Celsius (Figure 4.6). Consequently, it is just as important to carry out temperature and pressure corrections for calibration flights as it is for survey flights. For surveys in rugged terrain, errors in the attenuation coefficients can cause line to line level errors. This is because in climbing over an escarpment, the aircraft will generally follow a different barometric flight track than flying down the escarpment. Figure 4.7 shows how the height corrected potassium window counts will vary as a function of the error in the attenuation coefficient for ground clearances of 150 m, 200 m and 250 m. If the correct height attenuation coefficient had been applied, the true potassium window counts should have been 100 at the nominal survey height of 100 m. The higher the ground clearance, the more important it is to use the correct height attenuation coefficient.

The stripped count rates vary exponentially with aircraft altitude. Consequently, the measured count rate is related to the count rate at the nominal survey altitude by the equation:

$$N_{corr} = N_{obs}\, e^{-\mu(h_0-h)}, \qquad (4.16)$$

where

N_{corr} = the count rate normalized to the nominal survey altitude, h_0;
N_{obs} = the background corrected, stripped count rate at STP height h; and,
μ = the attenuation coefficient for that window.

In rugged terrain, problems may be encountered if the height exceeds 300 m because the statistical noise and any errors in background determination are greatly amplified. It is common practice in these conditions to limit the STP height in the exponential term to the equivalent of 300 m.

4.8 Conversion to Concentrations

The fully corrected count rate data can be used to estimate the concentrations in the ground of each of the three radioelements, potassium, uranium and thorium. This has the advantage that, for properly calibrated equipment, the results are independent of survey variables such as crystal volume and survey height.

The corrected window count rate data should be converted to ground concentrations of potassium, uranium and thorium using the following expression:

$$C = \frac{N}{S}, \qquad (4.17)$$

where

C = concentration of the radioelement (K%, U ppm or Th ppm);
S = broad source sensitivity for the window; and
N = count rate for each window, after dead–time, background, stripping and height correction.

The broad source sensitivities are obtained from flights over a calibration range as described in Appendix B.

4.9 Conversion of Total Count to Dose Rate

An estimate of the air–absorbed dose rate (in nGh^{-1} ie. nanograys per hour) at ground level from natural sources of radiation can be made from the total count rate using the expression:

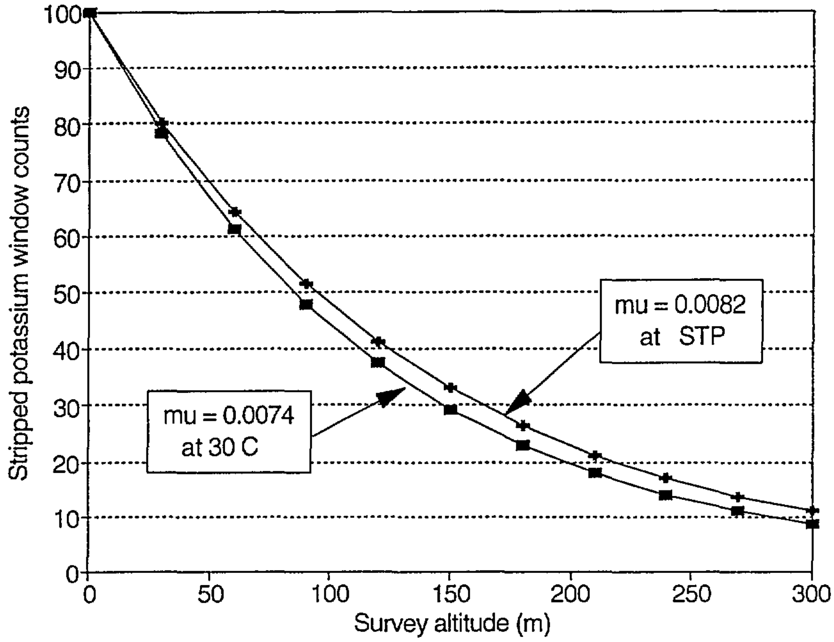

Figure 4.6. The effect of a temperature change of 30°C on the attenuation coefficient for potassium.

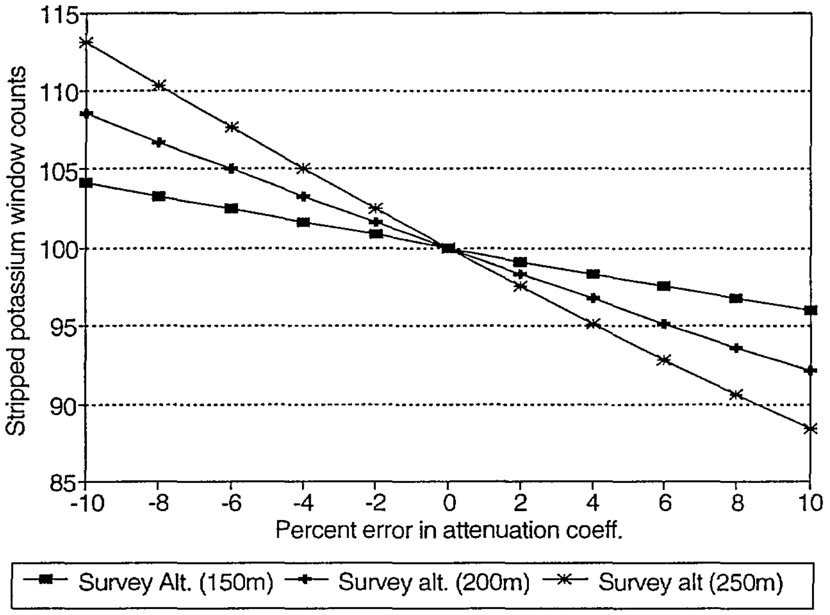

Figure 4.7. The effect of errors in the potassium attenuation coefficient on the height corrected potassium window counts. The counts have been normalized to a value of 100 at a survey altitude of 100 m.

$$D = \frac{N}{F}, \tag{4.18}$$

where

D = the air–absorbed dose rate in nanograys per hour;
F = the conversion factor determined experimentally from flights over a calibration range (Appendix B); and
N = the fully corrected total count rate.

The air absorbed dose rate in $\mathrm{nGh^{-1}}$ at ground level from uniform infinite sources of potassium, uranium and thorium is given by the following relationships:

1 percent potassium = 13.1 $\mathrm{nGh^{-1}}$
1 part per million of uranium = 5.43 $\mathrm{nGh^{-1}}$
1 part per million of thorium = 2.69 $\mathrm{nGh^{-1}}$.

The average air–absorbed dose rate in $\mathrm{nGh^{-1}}$ along the calibration range can then be calculated from the potassium (*K*), uranium (*U*) and thorium (*Th*) ground concentrations using the relationship:

$$A = 13.1 \times K + 5.43 \times U + 2.69 \times Th. \tag{4.19}$$

ACKNOWLEDGEMENTS

This work resulted from an AGSO co–ordinated collaborative project to standardize airborne gamma–ray spectrometric methodology in Australia, and was sponsored by the Australian Geological Survey Organisation, the Australian Society of Exploration Geophysicists, BHP Minerals, CRA Exploration, Des Fitzgerald and Associates, Exploration Computer Services, Geo Instruments, Geological Survey of NSW, Geological Survey of Queensland, Geological Survey of South Australia, Geological Survey of Victoria, Geological Survey of Western Australia, Geosat International, Geoterrex, Kevron Geophysics, MIM Exploration, Pitt Research, Tesla Airborne Geoscience, and World Geoscience Corporation. These organizations, as well as the Geological Survey of Canada, kindly provided much of the information reported here. Their valuable assistance is gratefully acknowledged.

The Ethiopian Institute of Geological Surveys kindly gave their permission to use their results shown in Table B5.1 and Figure 2.5. John Glynn of the Geological Survey of Canada derived equation 3.1, for the solid angle subtended by a rectangle and helped formulate the theory for cosmic calibrations (Section 2.2).

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APPENDIX A

TECHNICAL SPECIFICATIONS FOR AN AIRBORNE GAMMA–RAY SURVEY

1. INSTRUMENTATION

1.1 Gamma–Ray Spectrometer

A gamma–ray spectrometer system capable of recording at least 256 channels will be used. In order to minimize spectrum drift, the spectrometer must either be self stabilizing or be temperature stabilized and thermally insulated.

The main (4π) detectors will use at least 32 litres of sodium iodide crystals for a fixed wing system, whereas 16 litre will be acceptable for a helicopter survey. If upward detectors are used to monitor background radiation, the volume of the upward looking detectors must be at least one quarter of the main 4π detectors.

The system must permit cosmic–ray activity to be monitored using a window monitoring gamma radiation above 3000 keV.

Prior to the commencement of the survey or any calibration procedure, the overall system resolution must be better than 7 percent based on the full width half maximum of the ^{208}Tl peak at 2615 keV.

1.2 Ancillary Equipment

A radar altimeter will form part of the ancillary equipment and will have a range up to 760 m (2500 feet) and provide a digital output with a precision of 30 cm (1 foot).

Air temperature and pressure must be monitored. The temperature and pressure sensors must have a digital output with a minimal precision of 1 degree Centigrade for temperature and 0.1 percent for pressure. The digital output from a barometric altimeter may be used as an alternative to a specialized pressure sensor.

1.3 Data Recording

The following data must be recorded digitally for each 1 second (or less) counting interval:

- The entire 256 channel spectrum from the main 4π detectors;
- The following window counts from the main 4π detectors to the nearest whole number of channels :

⇒ Potassium	1370	–	1570 keV
⇒ Uranium	1660	–	1860 keV
⇒ Thorium	2410	–	2810 keV
⇒ Total Count	400	–	2810 keV
⇒ Cosmic	3000	–	∞ keV

- If upward-looking detectors are used to monitor background radioactivity, only the uranium window need be recorded;
- The system dead–time or system live time (if measured electronically) to an accuracy of ± 0.1 percent;
- The radar altimeter;

- Air temperature;
- Air pressure.

2. SPECTROMETER CALIBRATIONS

2.1 Calibration Frequency

All spectrometer calibrations should be carried out every 12 months. If any significant change has been made to the gamma–ray spectrometer, or the aircraft has been changed since any of these calibrations were performed, all the calibrations must be repeated. The tenderer must demonstrate, through the use of thorium source tests, that the equipment sensitivity has not changed since the last calibrations, otherwise all calibrations must be repeated.

2.2 Cosmic Calibration

Two flights must be made over the sea at barometric altitudes of 250 m and 2250 m to relate the cosmic–ray window to the combined cosmic and aircraft backgrounds of each window. The flying time at each altitude should be a minimum of 10 minutes. If upward detectors are used, the time should be increased to 15 minutes.

2.3 Radon Calibrations

The tenderer must demonstrate a capability to remove radon background using either upward–looking detectors or the spectral ratio technique.

2.4 Pad Calibrations

The airborne spectrometer system must be calibrated on an approved set of calibration pads for the measurement of stripping ratios.

2.5 Sensitivity and Height Attenuation Calibrations

A series of flights must be made over an approved calibration range to determine aircraft system sensitivities and height attenuation coefficients. The calibration range must be surveyed with a calibrated 256 channel portable spectrometer on the same day as the calibration flights.

2.6 Calibration Reporting

Prior to the commencement of the survey, all calibration information must be supplied to the client.

3. MONITORING PROCEDURES

3.1 Calibration Monitoring

Before and after every calibration, thorium sources tests must be performed to establish that the system sensitivity has not changed during the calibration. A source must be placed at least 40 cm from the center of each detector package so that all detectors are adequately illuminated. The average of the dead–time and background corrected thorium window count rate from the thorium source must be calculated. If the pre and post calibration source checks differ by more than 3 percent, the calibration must be repeated. The average of the pre and post calibration source tests must also not differ by more than 3 percent from the average of all other calibrations, otherwise that calibration must be repeated.

In order to verify that the system sensitivity has remained constant since the last series of calibrations, a thorium source test and a background measurement must be carried out prior to the commencement of the survey. If the dead–time and background corrected thorium window count rate varies by more than 3 percent from the average of all pre and post calibration source tests, all calibrations must be repeated.

3.2 Daily Thorium Source Tests

In order to verify that the system sensitivity has remained constant throughout the survey, thorium source tests and background measurements must be carried out before and after every days flying. If the dead–time and background corrected thorium window count rate differs by more than 5 percent from the average of all measurements carried out during the most recent calibrations, flights must be suspended until the problem has been rectified.

3.3 Daily System Resolution Checks

Each day the overall system resolution must be measured with a thorium source placed at least 40 cm from each detector package. If the resolution has changed by more than 1 percent (e.g. 6 to 7 percent) from the resolution at the beginning of the survey, flights should be suspended until the problem has been rectified.

3.4 Spectrum Stability

In order to monitor spectral drift during the course of a flight, the average spectrum for each flight line must be plotted. The plots must also indicate the potassium and thorium peak positions to one tenth of a channel. If the flight lines are less than 1000 seconds duration, spectra should be accumulated for at least 1000 seconds before plotting.

3.5 Survey Test Line

A survey test line at least 8 km in length (4 km for a helicopter survey) should be flown each day at the nominal survey altitude to monitor the effects of soil moisture and verify that the system is functioning correctly. If the background and height corrected thorium window count rate varies by more than ±10 percent from the mean of the previous measurements, flights should be suspended until the thorium count rate has returned to acceptable levels. If there is rain in part of the survey area or on the test line, 8 km (4 km for a helicopter survey) of a previously flown flight line can serve to monitor the effect of moisture.

All flights should be suspended for three hours after any rain in the survey area.

3.6 Survey Monitoring Reporting

The contractor shall maintain an equipment log noting all equipment serial numbers, equipment replacements and repairs throughout the survey and the results of daily resolution checks and source tests. All resolution checks, source tests and survey test line data should be recorded digitally and included as deliverables.

Cumulative plots should be made of the thorium source tests, average background and height corrected thorium count rates over the survey test line, and the average flight line spectra indicating the thorium resolution and the potassium and thorium peak positions.

4. DATA PROCESSING

4.1 Dead–Time Corrections

If the total dead–time is greater than 0.5 percent, all window data must first be corrected for dead–time using the expression:

$$N = \frac{n}{1-t} \qquad \text{(A4.1)}$$

where

N = corrected counts in each second;
n = all counts processed in each second by the ADC; and
t = the recorded dead–time, the time taken to process all pulses reaching the detector in one second.

Alternatively, if the live–time (L) is recorded, the dead–time t in equation (A4.1) should be replaced by ($1-L$).

If the dead–time or live–time is not measured electronically, it must be measured experimentally as described by the IAEA (IAEA,1991).

Dead–time corrections should be applied to each window in the downward–looking detectors. However, for some spectrometers, dead–time corrections should not be applied to the cosmic–ray channel or the upward–looking data. This information should be obtained from the equipment manual.

4.2 Energy Calibration

For all spectrometers, spectral drift should be checked by monitoring the potassium and thorium channel positions from average spectra along flight lines. The procedure for determining peak positions should be the same as was used during calibration. If the thorium peak is found to move more than 1 channel, or the potassium peak by more than 0.5 channels, energy calibration must be performed to determine the count rates in the standard windows.

4.3 Cosmic and Aircraft Background Removal

The cosmic and aircraft backgrounds for each channel are of the form:

$$N = a + bC, \tag{A4.2}$$

where:
N = the combined cosmic and aircraft background in each spectral window;
a = the aircraft background in the window (plus a possible small radon component);
C = the cosmic channel count; and
b = the cosmic stripping factor for the window.

The values of a and b for each window can be calculated from the two calibration flights over the sea. If an upward detector is used for monitoring radon, the values of a and b for the upward-looking uranium window should also be determined.

The cosmic channel should first be filtered to reduce statistical noise. A 10 to 20 point moving average filter would be suitable. The cosmic and aircraft background (plus a possible small radon component) must be evaluated for each window using the filtered cosmic channel (equation A4.2) and subtracted from the measured window count rates.

4.4 Radon Background Removal

There are two acceptable methods of removing atmospheric background due to radon decay products in the air. These methods are:

(a) The upward looking detector;
(b) The spectral ratio method.

The procedure to determine radon background using upward detectors has been described previously (IAEA, 1991). The spectral ratio method has been described by Minty (1992).

4.5 Calculation of Effective Height

In areas of significant topographic variation, the radar altimeter data should first be lightly filtered to smooth sudden jumps that can arise when flying over steep terrain which cause problems when height correcting the data. The data are then converted to effective height (h_e) at standard temperature and pressure using the expression:

$$h_e = \frac{h \times P \times 273}{1013 \times (T + 273)}, \tag{A4.3}$$

where

h = the observed radar altitude in metres;
T = the measured air temperature in degrees C;
P = the barometric pressure in millibars.

If a separate pressure sensor is not being used, the pressure can be estimated from the barometric altitude using the expression:

$$P = 1013\exp(-H/8581), \tag{A4.4}$$

where H is the barometric altitude in meters.

4.6 Spectral Stripping

The background corrected count rates in the three windows must be stripped to give the counts in the potassium, uranium and thorium windows that originate solely from potassium, uranium and thorium. The stripping ratios α, β, γ, a and g must be determined from measurements over calibration pads. The three principal stripping ratios (α, β and γ) increase with altitude above the ground as shown in Table 4.1.

Table 4.1. Stripping Ratio Increase with aircraft altitude at STP.

Stripping Ratio	Increase per metre
α	0.00049
β	0.00065
γ	0.00069

Each of the three main stripping ratios must be adjusted for altitude before stripping is carried out. If 5 stripping ratios are used, then the stripped count rates in the potassium, uranium and thorium channels (N_K, N_U, N_{Th}) are given by:

$$N_K = \frac{[n_{Th}(\alpha\gamma - \beta) + n_U(a\beta - \gamma) + n_K(1 - a\alpha)]}{A}, \tag{A4.5}$$

$$N_U = \frac{[n_{Th}(g\beta - \alpha) + n_U - n_K g]}{A}, \tag{A4.6}$$

$$N_{Th} = \frac{[n_{Th}(1 - g\gamma) - n_U a + n_K a g]}{A}, \tag{A4.7}$$

where

$$A = 1 - g\gamma - a(\alpha - g\beta). \tag{A4.8}$$

4.7 Height Correction

The background corrected and stripped count rates must be corrected for variations in the altitude of the detector using the equation:

$$N_{corr} = N_{obs}\, e^{-\mu(h_0-h)}, \qquad \text{(A4.9)}$$

where

N_{corr} = the count rate normalized to the nominal survey altitude, h_0;
N_{obs} = the background corrected, stripped count rate at STP height h; and,
μ = the attenuation coefficient for that window.

Where the STP height exceeds 300 m, a value of $h = 300$ must be used in equation A4.9 – ie. for height correction purposes, the aircraft altitude must be limited to 300 m.

4.8 Conversion to Concentrations

The corrected window count rate data must be converted to ground concentrations of potassium, uranium and thorium using the following expression:

$$C = \frac{N}{S}, \qquad \text{(A4.10)}$$

where

C = concentration of the radioelement (K%, U ppm or Th ppm);
S = broad source sensitivity for the window; and
N = count rate for each window, after dead–time, background, stripping and height correction.

The broad source sensitivities must be obtained from flights over a calibration range.

4.9 Conversion of Total Count to Dose Rate

The total count should be converted to air absorbed dose rate (in nanograys per hour) at ground level using the expression:

$$D = \frac{N}{F}, \qquad \text{(A4.11)}$$

where

D = the air absorbed dose rate in nGh^{-1};
F = the conversion factor determined experimentally from flights over a calibration range; and
N = the fully corrected total count rate.

5. DELIVERABLES

5.1 Digital Data

The following digital data should be delivered to the client:

All digitally recorded data from survey flight lines, calibrations, source tests and survey test lines as well as the processed window data.

5.2 Survey Records

The following survey records should also be delivered:

- The results of all source tests and calibration results.
- All cumulative spectral plots showing thorium resolutions with the potassium and thorium peak positions indicated.
- An operations report describing the acquisition and processing phases of the survey.

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APPENDIX B

PAD CALIBRATIONS FOR GAMMA–RAY SPECTROMETERS

1. THEORY

The spectra of potassium, the uranium series and the thorium series overlap. Because of this, each spectral window, which is used to detect one radioelement, will also contain some effect from the other two radioelements. Correcting for this spectral overlap is called 'stripping'.

The stripping procedure makes use of spectral ratios called stripping ratios. They are determined experimentally using concrete calibration pads containing known concentrations of potassium, uranium and thorium. A minimum of four are required to determine potassium, uranium and thorium spectra and to remove the background. Figures 3.9, 3.10 and 3.11 show the potassium, uranium and thorium spectra that were calculated from measurements using a 16.8 litre airborne package on calibration pads in Grand Junction, Colorado, USA.

There are several reasons for the spectral overlap shown in the figures. Due to Compton scattering in the ground, some counts from a pure thorium source will be detected in the lower energy potassium and uranium windows. Counts in the lower energy windows can also arise from the incomplete absorption of 2615 keV photons in the detector or from lower energy gamma–ray photons in the thorium decay series. Similarly, counts will be recorded in the lower energy potassium window from a pure uranium source. High energy gamma–ray photons of ^{214}Bi in the uranium decay series can also be detected in the thorium window.

The stripping ratios are the ratios of the counts detected in one window to those in another window for pure sources of potassium, uranium and thorium. A notation has been adopted in which α, β and γ are ratios of counts in a lower energy window to those in a higher energy window and a, b and g are ratios of counts detected in a high energy window to those detected in a low energy window.

α is the thorium into uranium stripping ratio, equal to the ratio of counts detected in the uranium window to those detected in the thorium window from a pure thorium source;

a is the reversed stripping ratio, uranium into thorium, equal to the ratio of counts detected in the thorium window to those detected in the uranium window from a pure source of uranium.

Similarly,

β is the thorium into potassium stripping ratio for a pure thorium source;

b is the reverse stripping ratio, potassium into thorium for a pure potassium source;

γ is the uranium into potassium stripping ratio for a pure uranium source; and,

g is the reverse stripping ratio, potassium into uranium for a pure potassium source.

From measurements on a calibration pad, the potassium, uranium and thorium window count rates n_K, n_U and n_{Th} are linearly related to the potassium, uranium and thorium concentrations of the pad, c_K, c_U and c_{Th}. The equations are:

$$n_K = s_{K,K}c_K + s_{K,U}c_U + s_{K,Th}c_{Th} + b_K, \qquad \text{(B1.1)}$$

$$n_U = s_{U,K}c_K + s_{U,U}c_U + s_{U,Th}c_{Th} + b_U, \tag{B1.2}$$

$$n_{Th} = s_{Th,K}c_K + s_{Th,U}c_U + s_{Th,Th}c_{Th} + b_{Th}, \tag{B1.3}$$

where b_K, b_U and b_{Th} are the background count rates originating from the radioactivity of the ground surrounding the pad, the radioactivity of the aircraft and its equipment, plus the contributions from cosmic radiation and the radioactivity of the air.

The nine '*s*' factors in these equations give the count rate in the three windows for each of the three radioelements. The six stripping ratios are given by:

$$\alpha = \frac{s_{U,Th}}{s_{Th,Th}}, \tag{B1.4}$$

$$\beta = \frac{s_{K,Th}}{s_{Th,Th}}, \tag{B1.5}$$

$$\gamma = \frac{s_{K,U}}{s_{U,U}}, \tag{B1.6}$$

$$a = \frac{s_{Th,U}}{s_{U,U}}, \tag{B1.7}$$

$$b = \frac{s_{Th,K}}{s_{K,K}}, \tag{B1.8}$$

$$g = \frac{s_{U,K}}{s_{K,K}}. \tag{B1.9}$$

Each of the equations (B1.1), (B1.2) and (B1.3) have four unknowns, the window sensitivities for potassium, uranium and thorium plus the background. Consequently from measurements on four calibration pads, these unknowns can be uniquely determined.

In practice, the four sets of equations in four unknowns can be reduced to a set of three equations with three unknowns by subtracting the count rates and concentrations of the blank pad from those of the potassium, uranium and thorium pad. The unknown backgrounds, b_K, b_U and b_{Th} are then removed from the computation. In matrix notation, the 3 x 3 count rate matrix **N** is then related to the concentration matrix **C** and the unknown 3 x 3 sensitivity matrix **S** by the matrix equation:

$$\begin{vmatrix} n_{K,K} & n_{K,U} & n_{K,Th} \\ n_{U,K} & n_{U,U} & n_{U,Th} \\ n_{Th,K} & n_{Th,U} & n_{Th,Th} \end{vmatrix} = \begin{vmatrix} s_{K,K} & s_{K,U} & s_{K,Th} \\ s_{U,K} & s_{U,U} & s_{U,Th} \\ s_{Th,K} & s_{Th,U} & s_{Th,Th} \end{vmatrix} \times \begin{vmatrix} c_{K,K} & c_{K,U} & c_{K,Th} \\ c_{U,K} & c_{U,U} & c_{U,Th} \\ c_{Th,K} & c_{Th,U} & c_{Th,Th} \end{vmatrix} \tag{B1.10}$$

where $n_{i,j}$ are the count rates and the $c_{i,j}$ are the concentrations after removal of the blank pad values. In matrix notation:

$$\mathbf{N} = \mathbf{SC} \tag{B1.11}$$

from which the sensitivity matrix containing the nine $s_{i,j}$ values in equations (B1.1), (B1.2) and (B1.3) may be evaluated using:

$$\mathbf{S} = \mathbf{NC}^{-1} \tag{B1.12}$$

2. CALIBRATION PADS IN AUSTRALIA

In Australia, there are six sets of calibration pads which were manufactured at three different times. One set of 1m × 1m × 30 cm transportable pads, owned by World Geoscience, was manufactured in Canada (Grasty et al, 1991). Four similar sets were constructed by Bruce Dickson at CSIRO and are owned by AGSO, Geoterrex, Kevron and the South Australia Department of Mines and Energy. The remaining set of five cylindrical pads, 2m in diameter and 0.5m deep is permanently installed at CSIRO facilities in North Ryde, NSW and can only be used for the calibration of portable gamma–ray spectrometers (Dickson and Lovborg, 1984).

Portable spectrometer calibrations performed on different sets of pads using the same equipment have given somewhat different calibration coefficients. The reason for this difference could have been spectral drift, operator finger problems or incorrect application of a geometric/density correction factor to compensate for the non–infinite size of the pads. However, there was always the suspicion that the grades of the pads were incorrectly assigned.

In order to check the reliability of the assigned concentrations of the pads, an intercalibration exercise was carried out in which the same spectrometer was calibrated on the three different groups of pads. Measurements were made first on the AGSO pads in Canberra. The spectrometer was then shipped to Bruce Dickson at CSIRO who made measurements on the permanent calibration facilities in North Ryde. Finally measurements were made by Bruce Dickson on the World Geoscience pads which at that time were located in Bundaberg in Queensland. The NSW Department of Mineral Resources kindly loaned their GR256 portable spectrometer for this intercalibration exercise.

Three five minute 256 channel spectra were recorded on each pad at all three locations. In case spectral drift had occurred between measurements, all spectra were energy calibrated by locating the channel positions of several prominent photopeaks. The peaks selected were the potassium peak at 1460 keV on the potassium pads, the 1120 keV and 1760 keV peaks on the uranium pads and the 2615 keV peak on the thorium pads. From the peak positions, the relation between channel position and energy was determined by linear regression, from which the count rates in the standard IAEA windows were calculated. If whole numbers of channels are used to calculate window count rates, as the spectrum drifts, there can be discontinuous jumps in the number of channels corresponding to each window. Fractions of channels were therefore calculated at the window boundaries by linear interpolation of adjacent channels.

All the pads in Australia give somewhat lower count rates than sources that are effectively infinite in size. Consequently, a geometric/density correction factor must be applied to the three window sensitivities derived using the pads. This geometric correction factor depends on the height of the detector above the pad surface. It also depends on the dimensions of the pads, their density, and on the linear attenuation coefficient of gamma radiation in the concrete. Using the computer program PADFLUX (Lovborg, 1984), the density/geometric correction factors were calculated for the three sets of calibration pads (Table B2.1). The stripping ratios and infinite source sensitivities for the portable spectrometer on the three sets of pads were then calculated using the program PADWIN (Lovborg, 1984) which had been modified to incorporate the geometric/density correction factors.

Table B2.1 Density/geometric correction factors for Australian pads

Pads	Size	Density ($g\ cm^{-3}$)	Potassium	Uranium	Thorium
CSIRO	2m diam. × 0.5 m	2.0	1.07	1.07	1.08
WGS	1m × 1m × 0.3m	2.25	1.16	1.17	1.19
AGSO	1m × 1m × 0.3m	2.0	1.17	1.18	1.21

Unfortunately, the World Geoscience pads were measured with the calibration pads still inside their plywood boxes. This will result in an apparent lower infinite source sensitivity for the portable spectrometer being calibrated. One centimeter of plywood can decrease the potassium count rate by 20 percent. This could easily explain the apparent lower potassium and uranium sensitivities that were initially found for the WGS pads, compared to those obtained from the CSIRO and AGSO pads. Consequently, the inter–calibration results are not reported here but will be reported at a later date after the measurements have been repeated with the pads removed from their boxes.

The results in Table B2.2 clearly show there are considerable differences between the sensitivities obtained from the AGSO pads and the CSIRO pads. The stripping ratios, however, give very similar results, because the potassium, uranium and thorium pads have relatively small concentrations of the minor radioelements.

Table B2.2 Calibration coefficients for infinite sources

Coefficient	AGSO	CSIRO
K (cps/pct)	4.26	3.73
U (cps/ppm)	0.376	0.331
Th (cps/ppm)	0.169	0.143
α	0.562	0.535
β	0.773	0.744
γ	1.095	1.049
a	0.063	0.050

Clearly, the differing sensitivities of the same spectrometer on the AGSO and CSIRO pads was an important issue that had to be resolved for the standardization of airborne gamma–ray measurements to ground concentrations. It was therefore decided to 'modify' the concentrations of the smaller AGSO pads so that they would give the same calibration constants as the CSIRO pads. The selection of the facilities at CSIRO as the Australian standard was an obvious choice since the facilities were permanently installed in the ground, had been used for many years in Australia, and had already been levelled to other facilities throughout the world (Dickson and Lovborg, 1984).

The adjustment of the AGSO transportable pads was achieved through the use of the calibration coefficients from the measurements at the CSIRO facilities. The concentrations were calculated from the energy calibrated IAEA window count rates after applying the appropriate geometry correction factor (Table B2.1). However, the calculated concentrations included an unknown background component, but this does not affect the calibrations, since the measurements on the background pad are subtracted from the measurements on all other pads during the calibration process. We chose to leave the concentrations of the background pads at their original values. Tables B2.3 and B2.4 give the newly assigned concentrations of the AGSO pads as well as those of the CSIRO larger pads. The errors quoted are those from the original analyses.

Table B2.3 Assigned concentrations of the AGSO pads

Pad	Potassium (%)	Uranium (ppm)	Thorium (ppm)
Blank	0.24 ± 0.02	0.48 ± 0.06	2.28 ± 0.12
Potassium	6.64 ± 0.06	1.20 ± 0.12	2.27 ± 0.20
Uranium	0.52 ± 0.02	43.67 ± 1.60	2.44 ± 0.19
Thorium	0.04 ± 0.02	7.05 ± 0.12	123.9 ± 2.0

Table B2.4 Concentrations of the CSIRO pads

Pad	Potassium (%)	Uranium (ppm)	Thorium (ppm)
Blank	0.19 ± 0.07	0.77 ± 0.063	2.26 ± 1.21
Potassium	3.87 ± 0.04	1.01 ± 0.10	1.24 ± 0.19
Uranium	0.39 ± 0.06	88.2 ± 1.8	1.40 ± 0.34
Mixed	0.17 ± 0.04	39.9 ± 0.9	91.1 ± 1.3
Thorium	0.07 ± 0.04	10.3 ± 0.5	160.1 ± 2.1

3. CALIBRATION OF PORTABLE SPECTROMETERS

A calibrated portable spectrometer is used to compare the ground concentrations of a calibration range with the airborne counts rates. The calibration of the spectrometer is therefore an essential part of the process to convert airborne count rates to ground concentrations of potassium, uranium and thorium.

The best calibration practice is to carry out the measurements with each calibration pad in exactly the same location. This procedure will ensure that the background is exactly the same for each set of measurements, which is a necessary requirement for calculating the calibration constants. While measurements are being performed, the other three pads should be kept at least 5 metres from the measurements location. This will eliminate any radiation from these pads being detected at the measuring site. It is also important that the pads should be removed from their boxes before any measurements are performed.

In practice, one may not have the use of a fork–lift operator or a pallet truck for the duration of the calibration. The pads will therefore have to be positioned and measured without moving them. In this case, the calibration site should be flat and relatively homogeneous in its radioactivity. To eliminate any cross–talk between pads, they should be placed at least 5 meters apart, center to center. It is important that the background radiation from the area surrounding the pads should be the same for each pad. However, because the pads are a good shield to gamma radiation from the ground, only a small fraction of any background radiation will be detected when calibrating. Unless the ground is both variable and high in radioactivity, or there are radioactive sources in the field of view of the spectrometer, problems of background variation from the surrounding ground are unlikely. If there is any doubt, the background at each pad location can be checked, prior to the measurements.

The time spent recording the window count rates on each pad controls the accuracy of the calibration constants. A longer counting time reduces uncertainties in the window count rate, which, in turn, will increase the accuracy of the calibration. For a typical 7.6 cm x 7.6 cm (3 inch x 3 inch) detector, a 10 minute counting time is realistic, providing calibration constants that are sufficiently accurate for all practical purposes. With this counting time, the total number of counts recorded in the potassium window on the potassium pad, the uranium window on the uranium pad, and the thorium window on the thorium pad will have reached approximately 10,000. This will result in uncertainties in the three window sensitivities of approximately one percent. It is recommended that two five minute counting periods should be made on each pad in sequence commencing with the background pad. The repeatability of the individual measurements will help to verify that the instrument is functioning correctly.

Atmospheric background arises from the decay products of radon. Radon is a gas and can diffuse out of the ground. The rate of diffusion will depend on such factors as air pressure, soil moisture, ground cover and temperature. The decay products of radon that produce the atmospheric gamma–ray activity, principally ^{214}Pb and ^{214}Bi, are attached to airborne dust particles. During the night, the air close to the ground is cooled and mixing of the air is reduced. The diffusing radon therefore stays closer to the ground and increases the atmospheric gamma–ray activity at ground level. In the early morning the ground and nearby air is heated by the sun, and the thermal activity increases the height of the mixing layer and reduces the radioactivity of the air at ground level. During the day, count rate changes in the uranium window of a portable spectrometer equivalent to ground concentrations of several ppm uranium have been reported in some parts of the world (Grasty, 1987).

In calibrating a spectrometer on the pads, it is essential that the atmospheric background component remains constant on all four pads during the time required to perform the calibration. This can best be done by monitoring the uranium window on the blank pad. In most places, this background variation will be insignificant and have little effect on the calibration constants. However, if significant background changes are found to occur, it may be necessary to monitor the background pad routinely, at the beginning and end of the calibration. If the background has changed significantly, the entire calibration must be repeated.

Before the calibration coefficients can be determined, the spectrum must be energy calibrated and the appropriate windows selected. This can be done following the procedure described in the previous section. The stripping ratios and infinite source sensitivities can then be determined using the program PADWIN. This program has the advantage over the straightforward matrix inversion technique in that the calibration constants and their associated errors are both calculated. These errors take into consideration Poisson counting errors as well as uncertainties in the concentrations of the pads.

The original PADWIN program has been modified to allow for the non–infinite size of both the transportable pads and the 2m diameter CSIRO pads. In calculating the calibration constants, the appropriate geometric/density corrections shown in Table B2.1 must be applied.

Table B3.1 gives typical calibration constants for a portable spectrometer with a 7.6 cm x 7.6 cm (3 inch x 3 inch) detector. For the standard window positions recommended by the International Atomic Energy Agency (IAEA, 1976), no counts should be recorded in the uranium and thorium windows from a pure source of potassium, consequently the reverse stripping ratios '*b*' and '*g*' should be zero. This is a useful check that the windows have been set in the correct position and the spectrometer was functioning correctly.

Table B3.1 Typical calibration constants for a 7.6 x 7.6 cm (3 x 3 inch) portable gamma–ray spectrometer.

Type	Coefficient	Calibration constant
Sensitivity	K (cpm/pct)	200
Sensitivity	U (cpm/ppm)	21
Sensitivity	Th (cpm/ppm)	7.8
Stripping ratio	α	0.584
Stripping ratio	β	0.547
Stripping ratio	γ	0.718
Stripping ratio	a	0.020
Stripping ratio	b	0
Stripping ratio	g	0

4. CALIBRATION OF AIRBORNE GAMMA–RAY SPECTROMETERS

This section describes the procedure for determining the various stripping ratios that are required as part of the calibration of an airborne system.

The pad calibration measurements should be made with the equipment in the aircraft being used for the survey. Before and after the pad calibration, thorium source tests must be carried out and recorded digitally. If the average dead–time and background corrected counts in the thorium window from the thorium source pre and post calibrations differ by more than 3 percent, the calibration must be repeated.

Depending on the detector configuration two different procedures are required.

a) The two detector packages are separated by more than one meter.

After the system has warmed up and has been properly tuned, two sets of measurements should be made, a background measurement with no source, followed by the thorium source measurement. The four calibration pads must then be placed centrally under each detector package, in turn, in a fixed reproducible position. The surface of the pads should be no more than 80 cm from the bottom surface of the detectors. While one pad is being measured, all other pads must be kept at least 10 m from the detector package being calibrated. Spectra should be recorded for a minimum of 5 minutes for each pad. The pads should then be placed under the remaining detector package and the process repeated. After the pad measurements have been made, the background and thorium source tests must be repeated. The average spectra should be plotted for each pad for a total of eight spectra and the average thorium and potassium peak positions indicated on the plots.

b) The two detector packages are less than one metre apart

Separate calibrations can be carried out for each detector package as described in the previous section. However, both sets of detectors can be calibrated at the same time as follows:

Background and thorium source tests are carried out as described previously. The pads are then placed, in turn, centrally under the two detector packages in a fixed reproducible position so that each package is receiving the same amount of radiation. The same procedure is then followed as described in section (a). For this configuration, the four average spectra from the pad measurements should be plotted and the potassium and thorium peak positions indicated.

For a self–stabilizing spectrometer, provided that the thorium peak is stable to ± 1 channel during the entire survey and during all calibrations, then the closest whole number of channels to the IAEA windows can be used. If the thorium peak position is found to drift by more than one channel at any time during the survey, the 256–channel spectrum must be used to recompute the IAEA windows. These window count rates are then used to compute the stripping ratios from the program PADWIN. For an airborne system, the geometric/density correction factor is not important since the stripping ratios are not affected by the size of the pads. If the two detector packages are calibrated separately, the average stripping ratios should be used for data processing.

The six stripping ratios for two different spectrometer systems are shown in Table B4.1. One system has good signal processing electronics (detector pulse shaping etc.) whereas the other system has poor signal processing. The system with poor signal processing has significantly higher stripping ratios. This arises because the pulse shaping of the detector signal results in overlapping pulses which cannot be separated by the multichannel analyzer. The stripping ratios are therefore a good measure of the quality of an airborne spectrometer system. For the standard windows, the value of b (the contribution of potassium into the thorium window) should be zero, and the contribution of potassium into the uranium window, g, should be very small.

The South Australian pads at Whyalla airport are installed in the ground with their top surface flush with the ground. This was done for practical reasons since a storage facility for the pads would then not be needed. However, the background radiation from the materials surrounding the pad varies along the length of the calibration site. This is particularly important during aircraft calibrations since a large fraction of the detected gamma–ray counts originate from the surrounding ground.

Measurements with the same aircraft and spectrometer system on these pads have shown that the background variation causes significant errors in the measurements of stripping ratios. Table B4.2 compares the stripping ratios measured on the calibration pads at Whyalla airport with those obtained from the World Geoscience Corporation (WGC) pads following the recommended procedure.

Table B4.1 Stripping ratios for two spectrometer systems

Stripping Ratio	Good System	Poor System
α	0.25	0.38
β	0.40	0.43
γ	0.81	0.92
a	0.06	0.09
b	0	0.01
g	0.003	0.06

Table B4.2 A comparison of the stripping ratios from the South Australian pads at Whyalla airport and those measured by bringing the WGS pads to the aircraft following the recommended procedure.

Stripping Ratio	Whyalla	WGC pads
α	0.283 ± 0.0009	0.277 ± 0.003
β	0.366 ± 0.015	0.438 ± 0.006
γ	0.565 ± 0.020	0.741 ± 0.10
a	-0.004 ± 0.013	0.041 ± 0.025
b	-0.025 ± 0.007	-0.002 ± 0.002
g	-0.005 ± 0.006	0.002 ± 0.002

The stripping ratios using the Whyalla pad facilities are quite different from those measured using pads brought directly to the aircraft. They are also quite different from those of a ‘good’ system reported by the IAEA (IAEA,1991) shown in Table B4.1.

Measurements were also made with a portable spectrometer on the pad surface and suspended on a tripod approximately 75 cm above the pad. This height is typical for the position of the detector package in some aircraft. These measurements also gave different stripping ratios, confirming that background variations were causing errors in the stripping ratios. The calibration of an airborne system over the Whyalla pads is therefore not recommended. However, the calibration constants for portable spectrometers calibrated on the pad surface would probably be acceptable, since with this configuration only a small background component is detected.

APPENDIX C

CALIBRATION RANGES

1. CALIBRATION RANGE SELECTION CRITERIA

Calibration ranges are used to calculate height attenuation coefficients for each window and to calculate sensitivity coefficients (counts per second per unit concentration) for any particular survey altitude. The sensitivity of the system depends on both altitude and source type. Since broad (semi–infinite) sources are the most common source type in the geological environment, we measure the sensitivity over a broad source with known concentrations of potassium, uranium and thorium. A series of flights at different altitudes over the calibration range are used to determine height attenuation coefficients and to predict the sensitivities of each window at any particular altitude.

Following the IAEA guidelines (IAEA,1991), an airborne calibration range should have the following features. It should:

(a) Be relatively flat;
(b) Have uniform concentrations of K, U and Th;
(c) Be close to a body of water for the measurement of background;
(d) Be free of flight restrictions;
(e) Be readily accessible for surface measurements;
(f) Be easy to navigate (a suitable calibration range should be a dirt road or a power line);
(g) Be about 8 km long, equivalent to about 150s flying time at 50 m/s;
(h) Have no hills within about 1 km of the flight line.

These guidelines were proposed for both practical and technical reasons. A topographically flat calibration range is desirable since the airborne system will have a different response at the top of a hill than it will in a valley, even though the aircraft is at the same survey altitude and the ground is uniform in radioactivity. In searching for a calibration range, a flat area is also a good starting point because varying terrain along a flight line usually means different rock types and corresponding variable radioactivity.

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. Uniform concentrations also ensure that at all altitudes the airborne and ground measurements are effectively sampling the same source.

A calibration range that is close to water removes any uncertainties associated with radon removal along the calibration range, since the background can be measured rather than calculated. Backgrounds can also be measured at different altitudes corresponding to the range of altitudes flown over the calibration range.

A calibration range along a power line, dirt road or a fence is easy to navigate and usually provides good access for ground measurements. However, in using such a feature, particularly a dirt road, it is imperative to verify that this feature has not affected the radioactivity of the ground. In Australia, many dirt roads are considerably more radioactive than the surrounding ground which makes it difficult for comparing ground and airborne 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. The IAEA guidelines do not specify any limitations on the concentrations of a calibration range. The only recommendation is that the calibration range be uniform in radioactivity.

Table C2.1. Percentage errors for 150 one second airborne and fifty 100 second ground measurements for a calibration range with 1 pct potassium, 3 ppm uranium and 6 ppm thorium.

	Radioelement		
	K	U	Th
Ground errors (percent)	1.2	2.1	1.8
Airborne errors (percent)	1.3	3.0	1.7

On the basis of 50 ground measurements and 150 airborne measurements, the errors in the ground concentrations and airborne count rates for a calibration range with concentrations of 1 percent potassium, 3 ppm uranium and 6 ppm thorium were calculated (Table C2.1). For these concentrations, the errors are acceptable, and the concentrations are therefore recommended as a lower limit for a calibration range (Table C2.2).

Table C2.2. Recommended minimum concentrations for a calibration range.

Potassium (%)	Uranium (ppm)	Thorium (ppm)
1.0	3.0	6.0

2. GROUND SAMPLING OF CALIBRATION RANGES

The ground concentrations of a calibration range should be measured with a calibrated portable spectrometer rather than through the geochemical analysis of soil samples which are normally dried to remove any free water. Variations in soil moisture affect the radiation output from the ground but not the geochemical analyses. A ten percent increase in soil moisture will change the gamma–ray emissions from ^{40}K and ^{208}Tl by a similar amount. However, the effect of moisture on ground measurements of ^{214}Bi is more complicated due to the loss of ^{222}Rn from the soil surface.

^{214}Bi is a decay product of the gas ^{222}Rn. In a soil, a certain fraction of ^{222}Rn which is produced through the decay of ^{226}Ra escapes from the soil particles into the soil pores. This emanating fraction is commonly called the emanating power of the material, and for a soil typically varies from 20 to 40 percent, but can exceed 50 percent (Markannen and Arvela, 1992). Since ^{222}Rn is a gas it can diffuse through the ground.

Furthermore, it has a relatively long half–life of 3.8 days, and can therefore diffuse considerable distances through the ground and subsequently into the atmosphere.
The variation of the ^{222}Rn concentration with depth has been calculated previously (Rogers et al., 1984). Figure C2.1 shows the soil gas radon concentration under three different soil moisture conditions designated as dry, wet and saturated. The diffusion coefficients were taken from typical values measured by Rogers et al. (1984). The soil gas ^{222}Rn concentrations for the three moisture conditions have been normalized to give a maximum ^{222}Rn concentration of 100 arbitrary units at large depths.

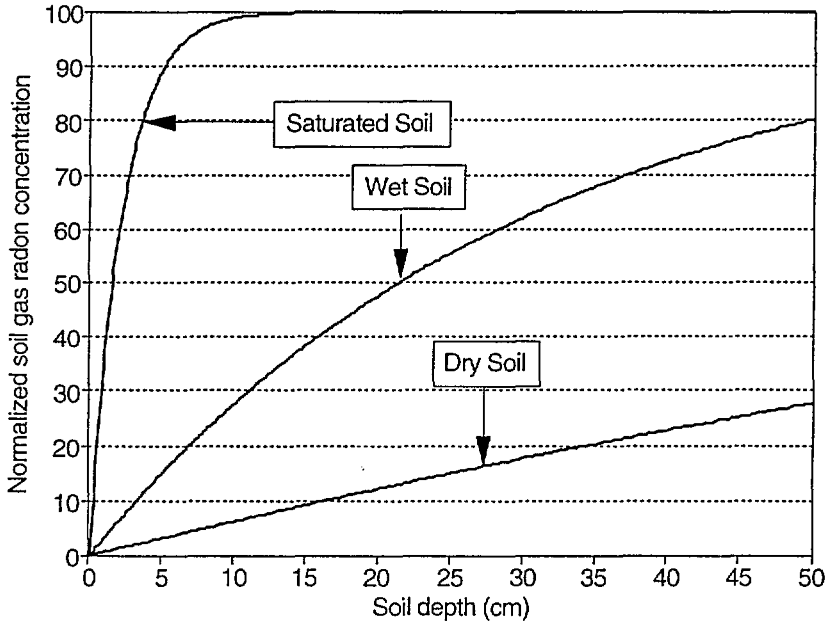

Figure C2.1. The variation of soil gas radon concentration with soil depth for soils with different moisture content.

The figure shows that there is a major difference in the soil gas ^{222}Rn distribution for the three different soil moisture conditions. Under saturated conditions, the ^{222}Rn concentration reaches its maximum value at a depth of about 10 cm. For the same soil under dry conditions, almost all the emanating fraction of ^{222}Rn is lost from the soil down to a depth of 10 cm.

Figure C2.2 shows that almost all the gamma radiation from ^{214}Bi at 1760 keV that is detected by an aircraft flying at 123 m originates from the top 20 cm of soil. However, for a dry soil, this is the region from which almost all the emanating radon is lost to the atmosphere. By combining the depth distribution of radon under different soil moisture conditions with the airborne gamma–ray response, we have calculated how the airborne ^{214}Bi count rate varies with soil moisture. These results are shown in Figure C2.3 for soils with different emanating power. Thus a soil with an emanating power of 0.5 can produce a higher ^{214}Bi gamma–ray flux under wet conditions than under dry conditions. This is contrary to the behavior of the gamma–ray fluxes from ^{40}K and ^{208}Tl which always increase as the soil dries out. Because there can be differences in the state of equilibrium between ^{226}Ra and ^{214}Bi in the soil, due to the loss of ^{222}Rn, laboratory analyses of ^{226}Ra is not recommended.

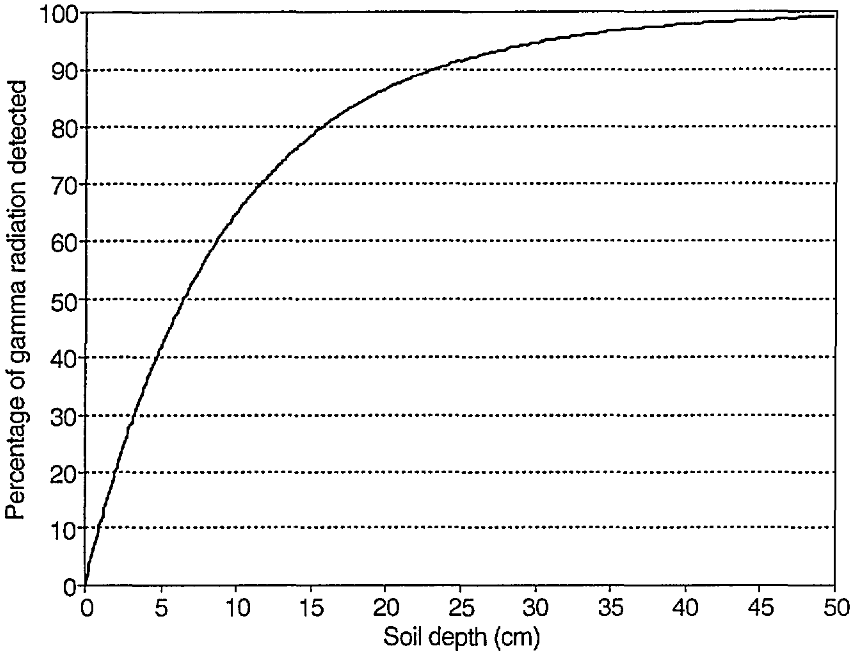

Figure C2.2. The response of an airborne gamma–ray spectrometer to soil depth.

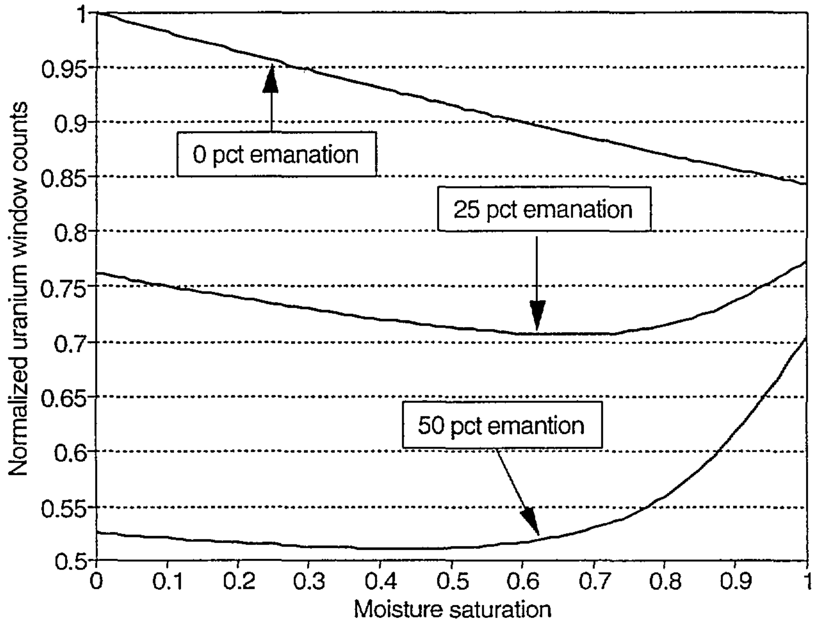

Figure C2.3. The variation of the airborne uranium window count rate over soil with different moisture content and emanation power.

Examples of the variation of the airborne potassium, uranium and thorium window counts rates with soil moisture are shown in Figures C2.4, C2.5 and C2.6 for an airborne calibration range at Breckenridge, near Ottawa, Ontario, Canada. The values shown in parenthesis in the figures are measured soil moisture values. The percent of moisture saturation, also shown in the figure, was calculated using a soil moisture model based on evapotranspiration.

The airborne potassium and thorium count rates are lowest in the winter and early spring as the ground is covered with snow or saturated with water. During the summer, as the soil was drying out, the gamma-ray counts from potassium and thorium increased significantly. However, as shown in Figure C2.6, the ^{214}Bi counts from the uranium window show the opposite effect, being lowest in the summer when the ground was driest. This situation arises because of the loss of ^{222}Rn from the soil surface.

The clay soils of this calibration range have a high emanating fraction and lose up to 60 percent of the ^{222}Rn they produce. Emanation fractions of soils would typically be around 20 to 25 percent. For such soils, the contrast between the behaviors of potassium, uranium and thorium would not be so extreme.

Another reason why geochemical samples are not recommended relates to the response of a gamma-ray spectrometer to sources at various depths as shown in Figure C2.2. Sources near the surface have a greater influence on the airborne measurement than sources at depth. Consequently, soil sampling would have to test for variations of radioactivity with depth.

One important aspect of the ground sampling is the use of the portable spectrometer to measure ground concentrations. In spite of the fact that these spectrometers are energy stabilized using an artificial source, the spectra can show significant energy drift. Although the stabilizing photopeak stays in the same channel position, the thorium and potassium photopeaks can move several channels due to a base level shift. Figure C2.7 shows the relation between energy and channel number for the same portable

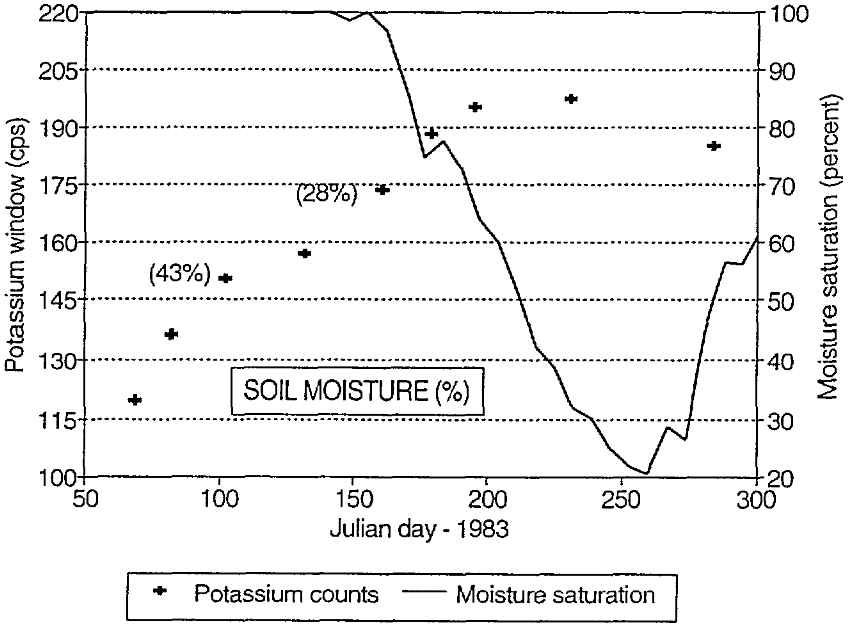

Figure C2.4. Seasonal variation in the potassium window count rate over the Breckenridge calibration range in Canada.

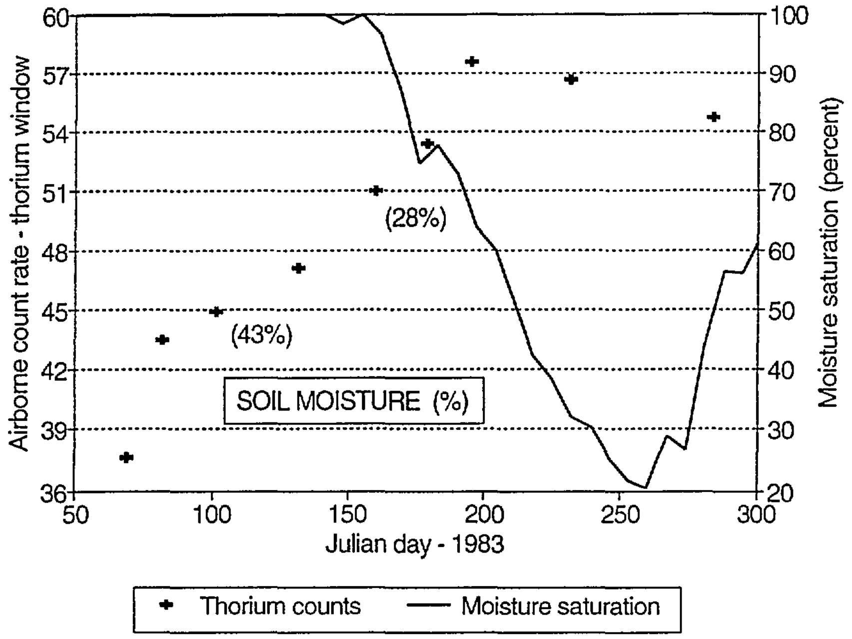

Figure C2.5. Seasonal variation in the thorium window count rate over the Breckenridge calibration range in Canada.

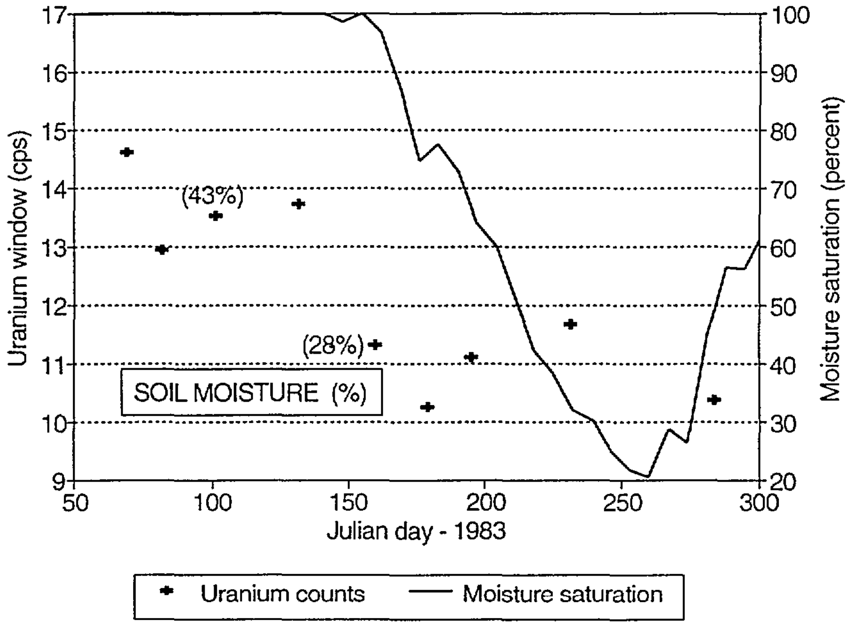

Figure C2.6. Seasonal variation in the uranium window count rate over the Breckenridge calibration range in Canada.

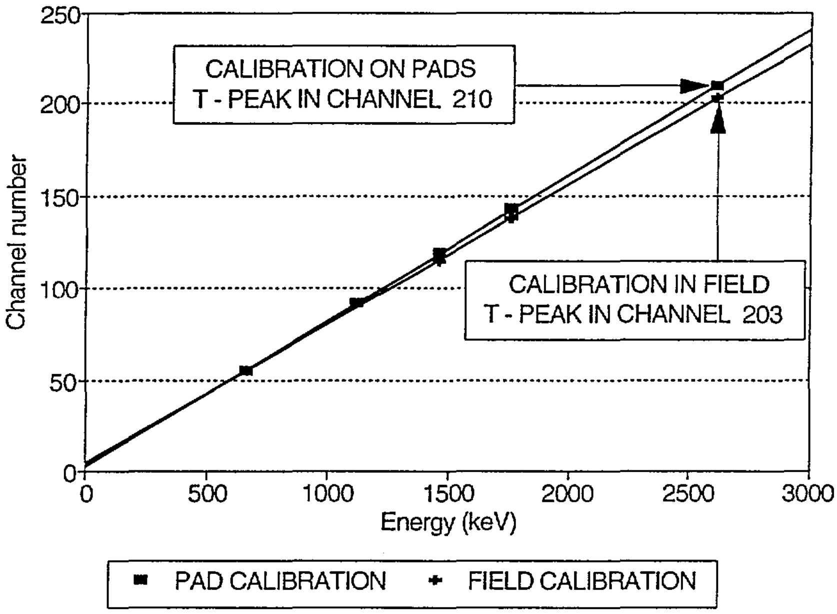

Figure C2.7. The relationship of energy to channel number for a portable gamma–ray spectrometer.

spectrometer using spectra measured on calibration pads and at a calibration site in the field. The thorium peak at 2615 keV drifted 7 channels between the two sets of measurements, even though the ^{137}Cs peak at 662 keV stayed in its correct channel position of 55.

As shown in Figure C2.8, such an energy drift can result in significant errors in the measurement of ground concentration. The potassium ground concentrations for the two sites would have been significantly under–estimated if energy calibration had not been performed. Such large spectral drift is rather unusual, but demonstrates that full 256 channel spectral data should be recorded and, if necessary, energy calibrated prior to sampling the conventional windows. Based on the intercalibration exercise, it is also important that when the spectrometer is calibrated, the calibration pads should be removed from their plywood container.

3. AUSTRALIAN CALIBRATION RANGES

3.1 Birkett Hill, South Australia and Cheltenham Creek, Queensland

Two airborne calibration ranges have been used in Australia for calibrating fixed–wing airborne gamma–ray spectrometer systems. These are at Birkett Hill, South Australia, and over the Cheltenham creek granite in Queensland. Both ranges lack many of the desirable features recommended by the IAEA, and this complicates the calibration exercise.

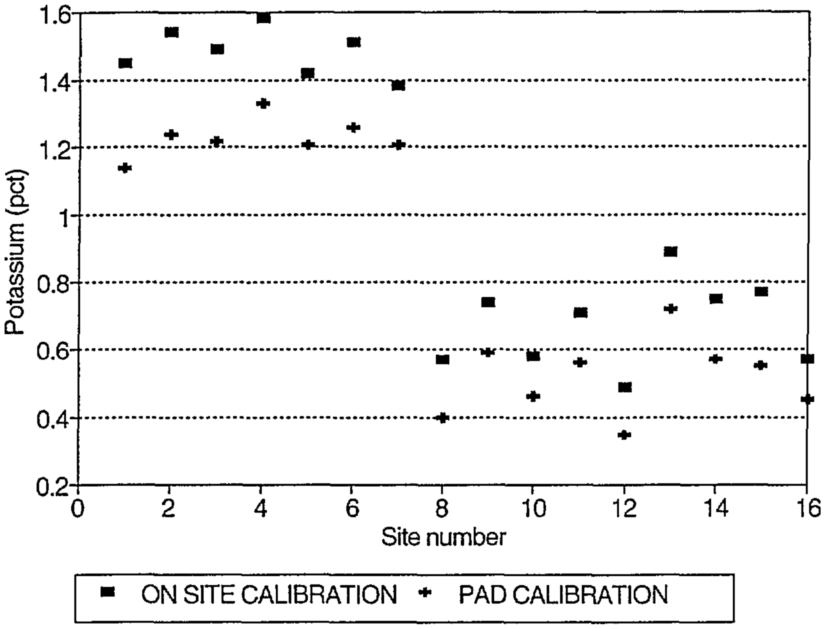

Figure C2.8. The effect of energy shift on the measured potassium concentration for two calibration sites.

Both the Queensland and South Australia calibration ranges are considerable distances from any large body of water. The Queensland range is approximately 150 km from the sea and the South Australia range about 50 km. For these distances it cannot be assumed that the background over the sea will be the same as over the calibration range. In these circumstances, the best alternative is to use the upward–looking detector or the full spectrum method for the removal of background. The lengths of the calibration ranges may be insufficient for a reliable background estimation and some additional flights at the survey altitude in the vicinity of the calibration ranges may therefore be required. However, the relatively high uranium concentrations of both calibration ranges has the advantage that the effect of errors in measuring the background are minimized.

Both the Queensland and South Australia calibration ranges are over granite, and were selected for their high levels of radioactivity. Their ground concentrations (Table C3.1) far exceeds those recommended as a minimum. Also, since the calibration ranges are over both outcrop and overburden, radiation levels are highly variable – particularly in uranium and thorium. This high variability can cause problems in estimating the airborne system sensitivities and height attenuation coefficients for a homogeneous infinite source.

In order to compare ground and airborne measurements over a calibration range with variable radioactivity, the ground measurement sites must be accurately located. Both calibration ranges have ground markers every 50 m which were surveyed in, using differential GPS. Not only must the ground measurement sites be accurately located, but it is equally important that the aircraft being calibrated should fly directly over the ground measurement sites and must therefore use real–time differential GPS for navigation. For a uniformly radioactive calibration range the exact location of the ground measurements and the aircraft flight path would not be critical.

Table C3.1. Approximate concentrations of the Queensland and South Australia calibration ranges

Range	Potassium (%)	Uranium (ppm)	Thorium (ppm)
South Australia	3.6	9.6	39.6
Queensland	3.6	5.5	18.8

3.2 Pinjarra, Perth, Western Australia.

One of the desirable characteristics of a calibration range is for it to be located close to the contractor's base of operations. The contractor clearly has the best capability to carry out the required yearly calibrations. They are experienced in the procedures required to analyze 256 channel airborne gamma–ray data which is readily adaptable to the analysis of multi–spectral portable gamma–ray measurements. The client may also not be available to carry out the ground measurements of the calibration range when the aircraft is ready to be calibrated. Most of the contractors are based in Sydney, New South Wales and in Perth, Western Australia. Neither the Queensland or South Australia calibration range is close to Sydney or Perth.

Several potential calibration range sites were investigated in New South Wales. The principal approach in selecting their location was their proximity to the sea or a large body of water. The next criteria was that the site had to be relatively flat and clear of trees. Using the 1:250,000 topographic maps, several potential areas for investigation were selected along the south coast of New South Wales and inland, close to a large lake. Since navigation is one of the major problems in the ground measurements, power lines were chosen to finalize the possible location. However, due to the limited time available, only a small number of the coastal areas were investigated and none of these sites met the concentration criteria laid out in Table C2.2.

In Western Australia, using the same selection criteria, several sites were also investigated which were less than about 20 km from the sea. Initial ground measurements were carried out under power lines close to Perth. The selection of power lines proved to be a distinct advantage since the electricity company gates were almost always unlocked and access was therefore not a problem. Utilizing the local geology maps (Wilde and Low, 1978) several sections of the ground under the power lines were initially chosen that exceeded 10 km in length and were located mainly on clay. Clay soils were preferred to sandy soils since they are normally more radioactive. Preliminary ground measurements identified significant levels of radioactivity along one 18 km length of line near Pinjarra, about 100 km south of Perth. This line was selected for detailed ground sampling.

With the help of BHP, most of the landowners along this potential calibration range were contacted by telephone and gave their permission to access their property. The ones that weren't contacted by telephone were visited personally. Due to the long length of the line, it was surveyed by driving along underneath the power line with the portable spectrometer slung close to the ground at the back of the vehicle. With this configuration, any absorption of the ground radiation by the wheels of the vehicle would be minimal.

The electricity pylons were located every 300 m. This proved to be convenient since it took approximately 100 seconds to drive slowly from pylon to pylon, by which time the spectrometer had finished sampling. Figures C3.1, C3.2 and C3.3 show the potassium, uranium and thorium ground profiles for the entire 18 km length of line. The profiles show considerable variability which is clearly undesirable. However, the line does have the advantage that more detailed ground measurements can easily be performed using a vehicle and the ground measurements sites are easy to locate for comparison with the airborne measurements. In addition, it is close to the sea for the measurement of background.

3.3 Helicopter Calibration Site, Bairnsdale, Victoria

In 1993, the United Nations Department of Economic and Social Development funded an airborne geophysical survey in Ethiopia. Calibration of the airborne radiometric equipment was achieved by hovering over a fixed location at heights from 60 m to 120 m. This was the first time that such a procedure had been carried out.

There are several advantages of calibrating a helicopter system 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 radioelements than it is for a calibration range for a fixed wing aircraft which may extend up to 8 km in length.

As part of their exploration initiative, the Victorian government supported a proposal by Geoterrex Ltd. to look for a helicopter calibration site. A suitable site was located near Bairnsdale, in Victoria which met most of the requirements recommended by the IAEA (1991). The only limitation was that the site was located about 50 km from the sea and therefore backgrounds measured over the sea may not be applicable at the calibration site and would therefore have to be calculated.

Figure C3.1. The potassium ground profile for the Pinjarra calibration range, Western Australia.

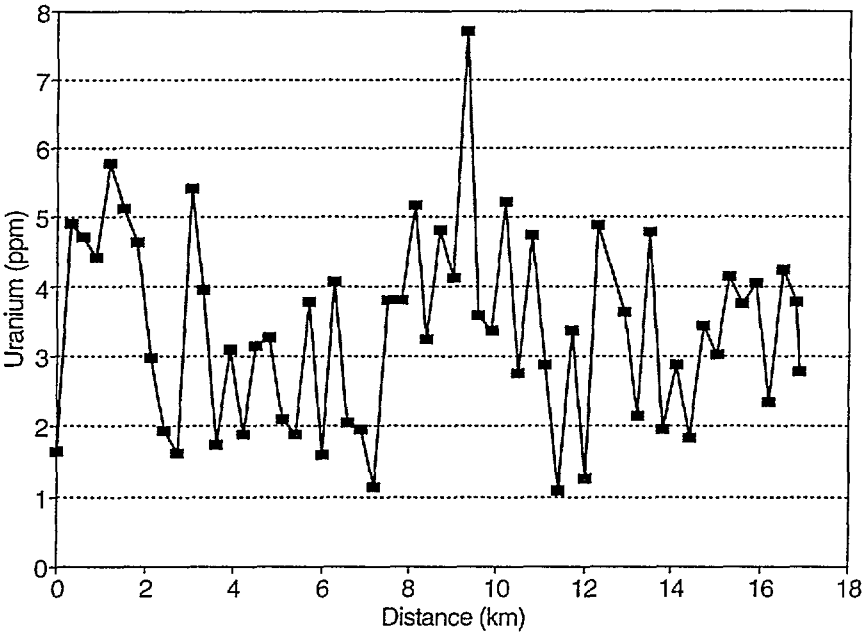

Figure C3.2. The uranium ground profile for the Pinjarra calibration range, Western Australia.

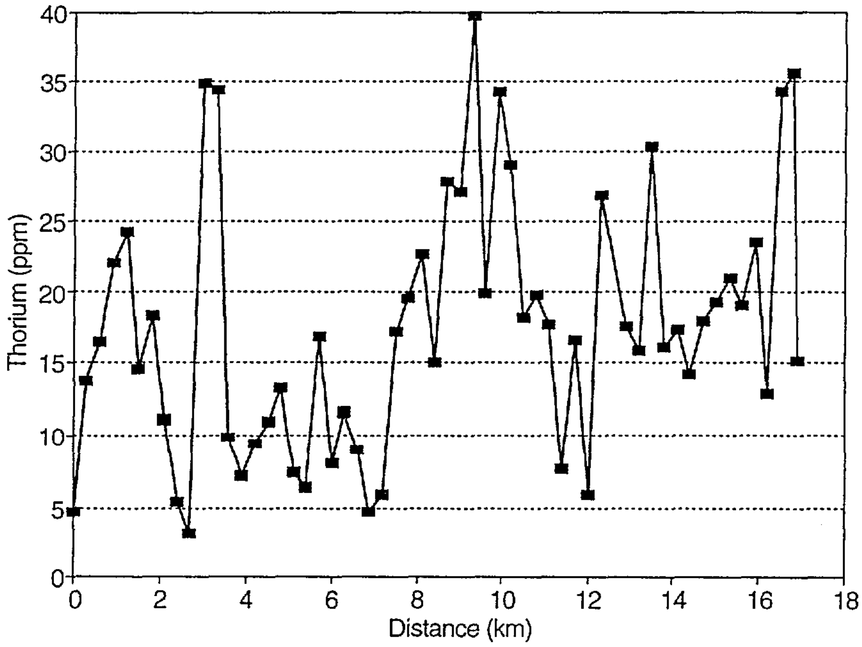

Figure C3.3. The thorium ground profile for the Pinjarra calibration range, Western Australia.

Table C3.2 gives the potassium, uranium and thorium concentrations of the Bairnsdale helicopter hover range as well as their associated standard deviations. The results show that the site is relatively uniform in radioactivity in all three radioactive elements and has sufficient levels of radioactivity to provide reliable estimates of sensitivity.

Table C3.2 Concentrations of the helicopter calibration range Bairnsdale, Victoria.

	Potassium (%)	Uranium (ppm)	Thorium (ppm)
Concentrations	1.39 ± 0.14	2.51 ± 0.39	10.6 ± 1.22

4. ANALYSIS OF BIRKETT HILL AND CHELTENHAM CREEK RANGES

Several different procedures have been used to analyze the data from the Queensland and South Australia calibration ranges. Initially the procedure involved a linear regression of the airborne count rates (the dependent) against the ground concentrations (the independent) for each measurement point on the ground. The variability in the radioactivity was initially considered to be an advantage since the slope of the regression line was assumed to be the sensitivity. However, due to smoothing of the ground data at the survey altitude, for a variable calibration range, a linear regression will always give a positive intercept indicating an apparent aircraft background and a corresponding low estimate of sensitivity.

Figure C4.1 illustrates the effect of smoothing the ground data by the aircraft using a simulated ground profile. The ground profile shows a sharp increase in radioactivity. The airborne profile will smooth out this sudden jump. Consequently, near the contact, the airborne data will be lower than the ground data where the ground is high in radioactivity. Correspondingly, the airborne data will be higher than the ground data where the ground is low in radioactivity. When carrying out a linear regression with such data, the slope of the line will give an apparently low sensitivity.

Figure C4.2 shows results of the ground and airborne uranium measurements for the Queensland calibration range. With such a scatter in the measurements, the slope of the regression line has little significance. The results of comparing the ground and airborne thorium measurements, where there is an apparently good correlation also gives an incorrect low sensitivity for the airborne system (Figure C4.3).

A regression line through zero generally gives a sensitivity which is close to the best estimate but can still be in error. This is because the points on the regression line at low concentration are given the same ‘weight’ as points at high concentrations.

For a uniform radioactive calibration range, the sensitivity of an airborne system can be determined by comparing the average corrected airborne count rates with the average ground concentrations. Since the airborne count rates are dependent on aircraft altitude, temperature and pressure, the aircraft altitude must

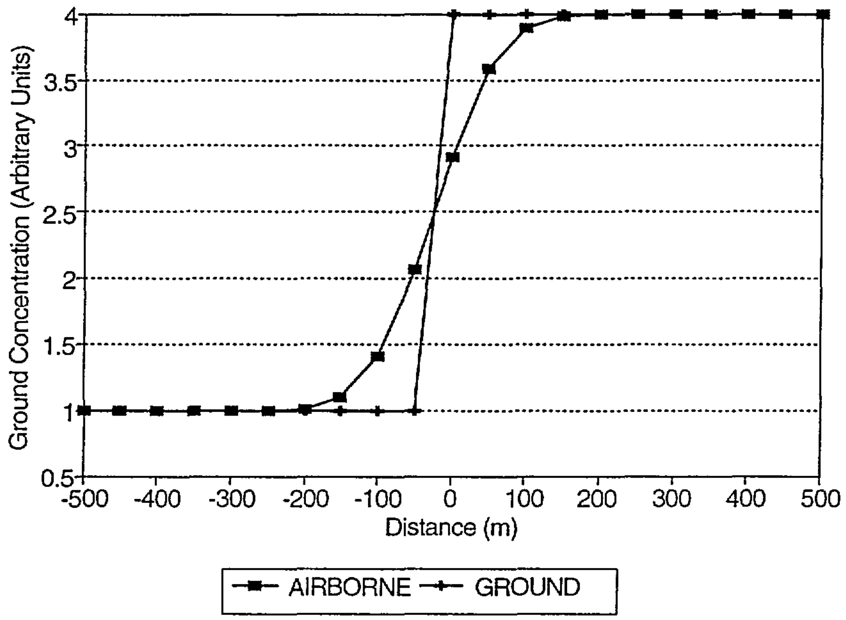

Figure C4.1. A simulated ground profile showing the relationship of the airborne counts to ground concentration.

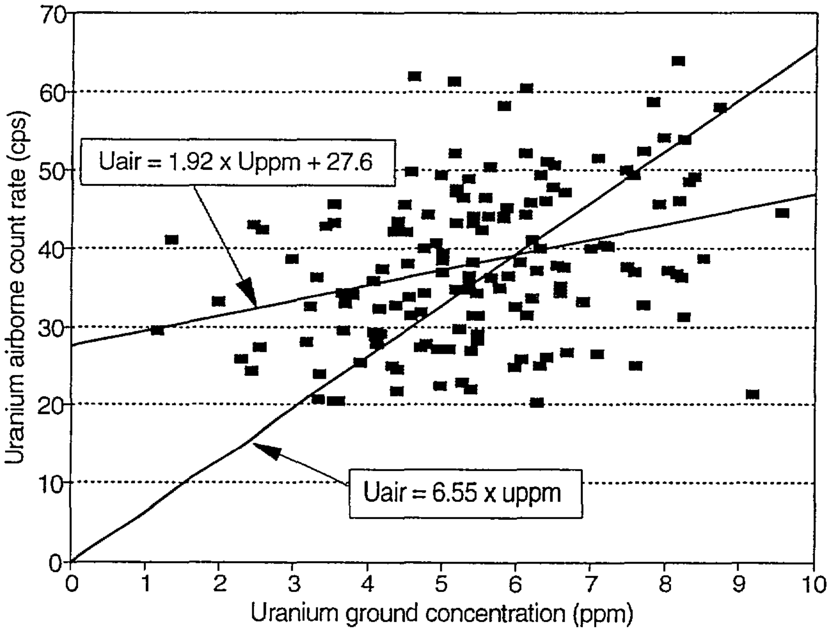

Figure C4.2. The relationship of the airborne uranium count rates with ground concentration for the Queensland calibration range.

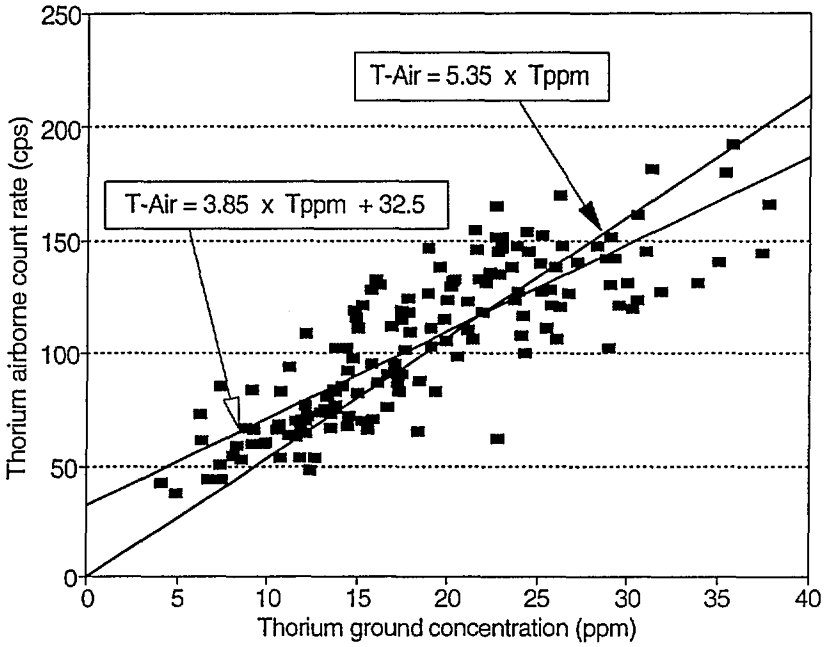

Figure C4.3. The relationship of the airborne thorium count rates with ground concentration for the Queensland calibration range.

first be converted to an equivalent altitude at standard temperature and pressure (STP). The average airborne count rate at the nominal survey STP altitude can then be computed from the series of flights atdifferent altitudes using an exponential relationship between the corrected airborne count rate and STP altitude. The sensitivity of the system is then determined by dividing the background corrected and stripped airborne count rates at the survey altitude with the average ground concentration.

We can demonstrate using a simple model that provided a calibration range is uniform in the across–flight direction, the sensitivity of an airborne system flying over a source which is inhomogeneous in the along-flight direction can be computed using the same procedure as for a homogeneous source.

Suppose g_1 to g_n are n ground concentration measurements taken every 50 m and a_1 to a_n are n corresponding airborne measurements.

Let f_k be a geometric factor that gives the fraction of the airborne count rate from an infinite homogeneous source that is contributed by a strip 50 m wide perpendicular to the flight path and at a horizontal distance of 50 × k meters from the measurement point. If

$$f_k = 0 \qquad \text{for all n > k,}$$

then for an inhomogeneous source, the airborne count rate, a_i, at position i, will be a linear combination of the contributions of each strip and is given by:

$$a_i = S[f_{-m}g_{i-m} + ... + f_{-1}g_{i-1} + f_0 g_i + f_1 g_{i+1} + ... + f_m g_{i+m}],$$

where S is the sensitivity (counts/sec/concentration) for an infinite homogeneous source.

Similar equations can also be formulated for all points from $i = 1$ to n. Also, since

$$\sum_{-m}^{m} f_i = 1,$$

then

$$\sum a_i = S \sum g_i .$$

The best estimate of system sensitivity is therefore obtained by dividing the average background corrected stripped count rates at the survey altitude by the average ground concentration of the calibration range.

5. RECOMMENDED CALIBRATION PROCEDURES

5.1 Birkett Hill, South Australia and Cheltenham Creek, Queensland

The calibration ranges serve two purposes: to calculate height attenuation coefficients and airborne sensitivities at the nominal survey altitude.

The values of the attenuation coefficients for each window can be determined by making a series of flights at different altitude over the calibration range. A typical series of flights would be from 60 m to 240 m at 30 m interval, but they should cover the range of altitudes encountered during the survey.

One of the questions that has to be addressed is the effect of differences in terrain clearance along the flight line. Figure C5.1 shows a profile of terrain clearance for one pass over the Queensland calibration range. This profile shows some variability in terrain clearance. In theory, the average airborne count rate along a line which is flown at a constant terrain clearance will not be the same for a line flown with varying terrain clearance but the same average altitude. This situation arises because of the exponential fall–off of radiation with altitude.

In principal, the airborne count rates, should be height corrected before relating them to the average altitude. In practice, provided the terrain is not too rugged and height corrections are not large, the average count rates along a line are almost identical to the average count rate after each measurement point has been height corrected to the average flying height. This was verified for the Queensland calibration range using the aircraft altitude shown in Figure C5.1 and the corresponding count rates.

We have shown that the best procedure for determining airborne sensitivities over non–uniform calibration ranges is to divide the average background corrected and stripped aircraft count rates by the average ground concentration. The resultant sensitivity will correspond to the average survey height at STP. This procedure is the same as it would be if the calibration ranges were uniform. The procedure is as follows:

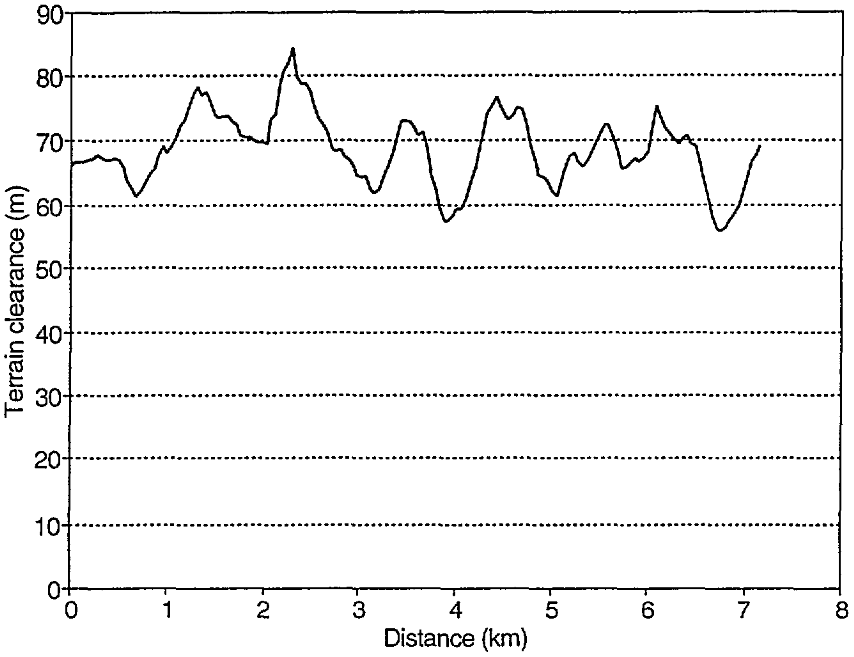

Figure C5.1. The variation of terrain clearance for the Queensland calibration range.

The mean count rates of the total count, potassium, uranium and thorium windows are first calculated for each pass over the line. Background radiation from the aircraft, cosmic radiation and radon must then be subtracted from the average window count rates. Because of the distance from the sea, this background will have to be calculated using the low energy 609 keV photopeak or an upward looking detector. The average air temperature, pressure and aircraft altitude must also be determined from which the equivalent aircraft altitude at STP can be calculated (equation 4.10).

Since the stripping ratios depend on STP altitude, they must first be determined using data presented in Table 4.1 from which the stripped counts at the STP altitude can be calculated using equations 4.11 to 4.14. The stripped counts can then be fitted to the exponential function (Equation 4.16) to give the height attenuation coefficient for each window.

The airborne sensitivity for each window (*S*) is determined by comparing the ground concentration of the respective window (*C*) with the stripped counts (*N*) at the survey altitude:

$$S = N/C$$

The stripped counts (*N*) at the survey altitude are calculated from the computed exponential relationship between stripped count rates and STP aircraft altitude.

The ground concentrations of the calibration range must be measured on the same day the aircraft is being calibrated. This will minimize any changes in soil moisture due to rainfall after the range has been flown. A 256 channel gamma–ray spectrometer must be used which has been calibrated on a set of concrete pads with known concentrations of the three radioactive elements. The concentrations used for the calibration must correspond to the assigned grades (Table B2.3 and B2.4) and the correct geometry/density correction must be applied (Table B2.1). The recorded spectrum at each measurement site must be energy calibrated using the average spectrum recorded along the line.

The procedures for the ground measurements in South Australia and Queensland are somewhat different, mainly due to differences in the length of the calibration ranges. For both calibration ranges there are ground location markers every 50 m. In South Australia it has become common practice to walk between the markers without carrying out any measurements. The ground concentrations in the vicinity of the markers were then determined by walking randomly around them. In Queensland, the procedure has been to walk between the markers while measuring and attempt to gauge the walking speed so that the measurement period ends at the next marker. This procedure has the advantage that it saves time which is an important consideration for the much longer Queensland range which requires approximately 150 measurements. It also has the additional advantage that any variations along the line will tend to be smoothed out.

Both procedures involve taking measurements while walking with the spectrometer. One important consideration is the absorption of the gamma radiation by the legs of the operator. Experiments carried out in Ethiopia by geophysicists from the Ethiopian Institute of Geological Surveys have shown that the legs can reduce the measured count rates considerably. 36 sites were measured both at ground level and with the detector held approximately 75 cm above the ground. The two sets of results were analyzed the same way, using the calibration constants obtained with the spectrometer calibrated on the pad surface.

The calculated ground concentrations are presented in Table C5.1 and clearly show a significant decrease in the apparent thorium and uranium concentrations at a height of 75 cm compared to the measurements at ground level. This decrease was attributed to the absorption of the uranium and thorium gamma rays by the legs of the operator. The apparent increase in the potassium concentration at 75 cm was attributed to high energy uranium and thorium gamma rays being Compton scattered into the potassium window.

Table C5.1. A comparison of portable gamma–ray measurements at ground level and 75 cm showing the absorption of gamma radiation by the legs of the operator.

Detector Height (cm)	K (%)	eU (ppm)	eTh (ppm)
0	0.194 ± 0.010	2.13 ± 0.08	11.13 ± 0.18
75	0.232 ± 0.012	1.90 ± 0.07	9.78 ± 0.14
Ratio (0cm/75cm)	0.84 ± 0.06	1.12 ± 0.06	1.14 ± 0.02

These results were obtained with the spectrometer being held with the detector close to the operator's legs. While walking, the detector would be swinging in an arc some small distance away from the legs. Therefore the solid angle subtended by the legs would be significantly reduced with the result that the count rates would not exhibit such large changes. However, the absorption of gamma radiation by the legs is clearly an important consideration when carrying out ground spectrometer measurements.

The effect of lateral inhomogeneities within the calibration range on the calculation of sensitivity and height attenuation coefficients is difficult to quantify. However, the following three criteria may assist a qualitative assessment of the data from these ranges. The data available to us for this study were the individual ground measurements, and background corrected, stripped, and height corrected airborne data at 80 m altitude interpolated to the ground measurement positions.

(a) The degree of correlation between the airborne and ground measurements.

Figure C5.2 shows a comparison of the calibrated potassium airborne measurements with the filtered potassium ground measurements for the Queensland calibration range. The filter coefficients (0.25, 0.5 and 0.25) for the ground measurements were calculated on the basis of the response of the airborne system to small areal sources on the ground at different distances from the detector. Plots such as these provide evidence that the airborne and ground surveys are sampling the same sources. Good correlations would not be observed if the aircraft was not flying directly over the calibration line, or lateral sources were influencing the measurements.

In practice, it would be better to compare the ground data with the airborne data flown at the lowest altitude rather than using the data flown at 80 m. The airborne and ground data should show the best correlation and therefore it would be easier to identify if the aircraft was not flying along the correct line. Before this comparison is carried out, the airborne data should first be height corrected to eliminate any count rate differences that were due to altitude variations.

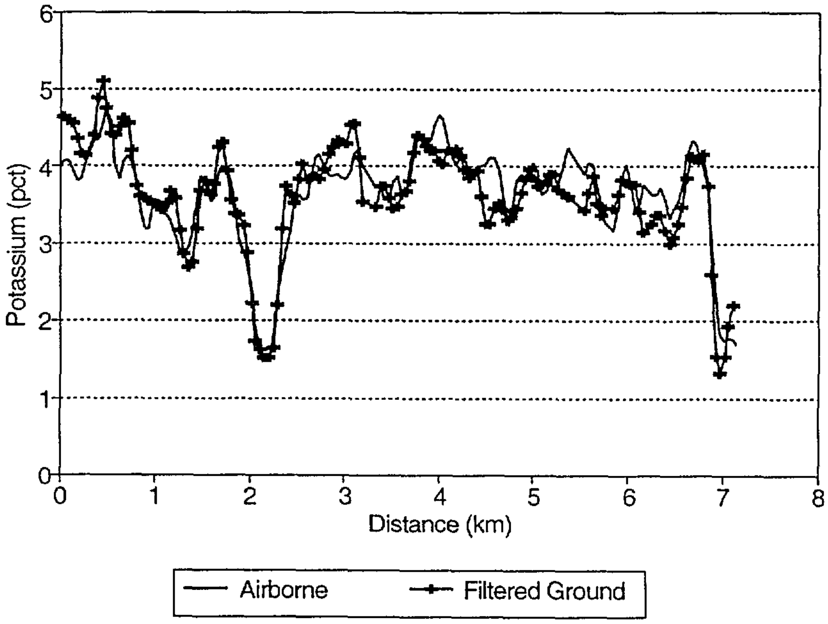

Figure C5.2. A comparison of the calibrated airborne potassium measurements with ground measurements for the Queensland calibration range.

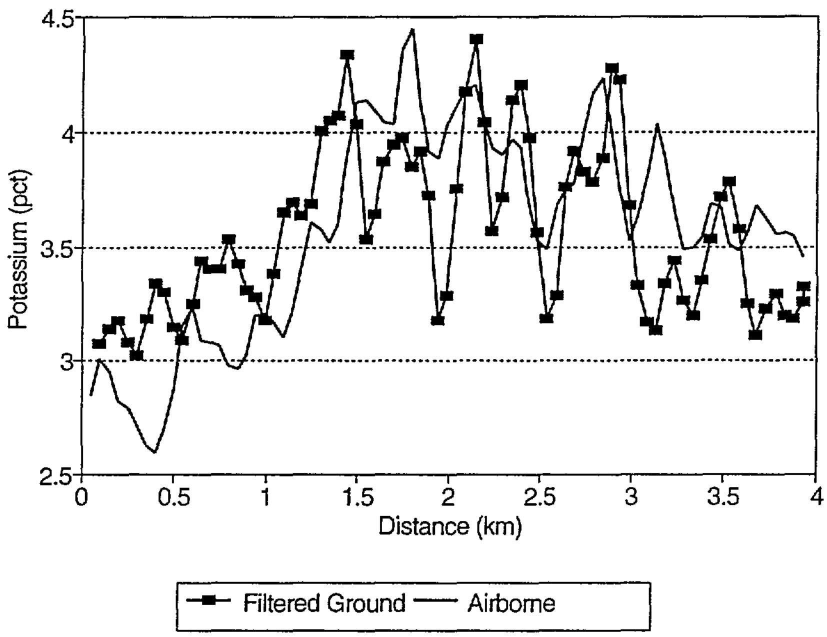

Figure C5.3. A comparison of the calibrated airborne potassium measurements with ground measurements for the South Australia calibration range.

As shown in Figure C5.3 for South Australia, there may be problems if the stripping corrections were incorrectly applied. In this figure, the potassium ground concentrations are generally lower than the airborne measurements at one end of the line and higher at the other. This could be attributed to the change in thorium and uranium concentrations along the line. Finally, the airborne and ground uranium profiles for the Queensland calibration range are rather unusual, as they exhibit extremely rapid variations (Figure C5.4). However, we speculate that in this case the variations are so rapid that the calibration range appears to behave as a randomly distributed source, and the exact location of the ground or airborne measurements may therefore not be important.

(b) A statistical analysis of the calibration range data.

Errors in the calculated sensitivities are due to both Poisson counting statistics and lateral inhomogeneities in the radioactivity of the ground. We have attempted to estimate the magnitude of these errors due to lateral inhomogeneity by comparing the theoretical variations in the sensitivity coefficients to the variations derived from an incremental analysis of the calibration range data as follows:

The sensitivities for successive 1 km sections of the calibration lines are calculated. Since the South Australia and Queensland calibration ranges have lengths of approximately 4 and 7 km respectively, we were able to calculate 7 independent sensitivities from the Queensland range and 4 from the South Australia range. The variations associated with the averages of these independent sensitivities will therefore include the effect of the Poisson counting statistics as well as lateral inhomogeneities in the source – provided that the variations due to lateral inhomogeneities are not systematic or correlate between 1 km sections of line. These variations are then compared to the theoretical statistical variations

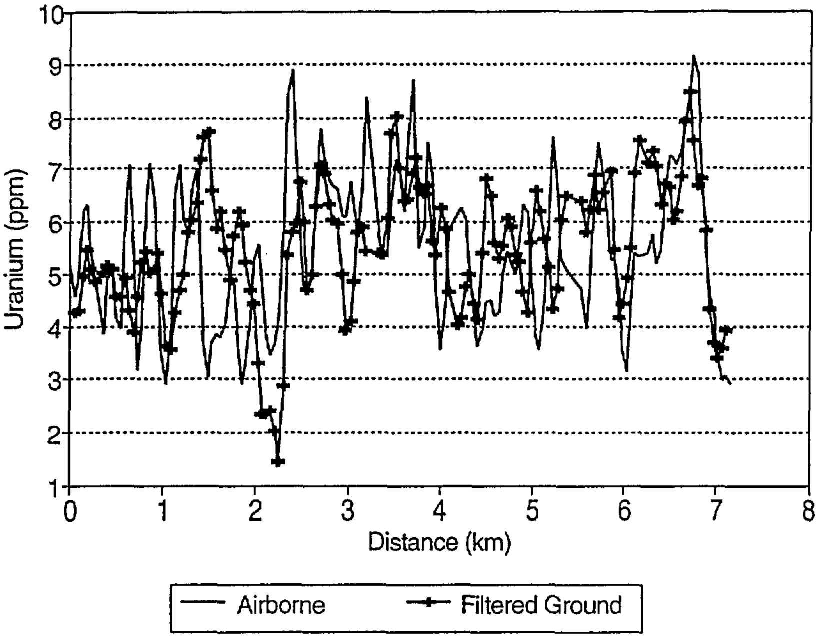

Figure C5.4. A comparison of the calibrated airborne uranium measurements with ground measurements for the Queensland calibration range.

only (Tables C5.2 and C5.3). The sensitivities calculated from 1 km sections give very similar results to the sensitivities calculated from the whole line. The theoretical statistical variations were calculated assuming that twenty ground measurements of 100 seconds were made along each 1 km section, and 20 one–second airborne measurements were recorded over each 1 km section. Typical calibration constants for the airborne and ground spectrometers were used in the calculations.

The results show that only a small fraction of the variations in the sensitivities from the seven 1 km sections of the Queensland calibration range can be attributed to Poisson counting statistics alone. The majority of the variations must therefore be due to errors arising from inadequate ground and airborne comparisons due to inhomogeneities in the across flight direction. For South Australia, the uranium and thorium theoretical and measured variations are comparable, suggesting that inhomogeneities were not significant contributors to the measured variations. In the case of potassium, we believe that the differences between the theoretical and measured variations are largely due to Compton stripping errors due to the variations of uranium and thorium along the line.

There are seven independent measurements from the 1 km sections of the Queensland calibration range. Consequently, the percentage errors in the mean sensitivities for potassium, uranium and thorium will be reduced by the square root of seven from the percentage error of the standard deviations. In the case of South Australia, the percentages will be reduced by a factor of two, because there are four independent measurements. The percentage errors in the mean sensitivities for the two calibration ranges are shown in Tables C5.2 and C5.3, indicating that both calibration ranges can be used to determine sensitivities to better than 5 percent for all channels at this altitude. However, this estimate assumes that the data have been adequately background corrected, stripped and height corrected, and that there are no systematic lateral inhomogeneities in the radioactivity of the calibration ranges. In addition, it should be noted that

Table C5.2. Airborne spectrometer sensitivities at 80 m altitude calculated from four 1 km sections of the South Australia calibration range.

Window	Sensitivity (cps/conc.)	Standard deviation (Percent)		% error on the mean	Sensitivity (best estimate) (cps/conc.)	N
		Actual	Theory			
Potassium	99.4 ± 6.5	6.5	2.0	3.3	99.6	4
Uranium	8.2 ± 0.4	5.3	4.6	2.7	8.3	4
Thorium	6.0 ± 0.4	6.1	4.9	3.1	6.1	4

Table C5.3 Airborne spectrometer sensitivities at 80 m altitude calculated from four 1 km sections of the Queensland calibration range.

Window	Sensitivity (cps/conc.)	Standard deviation (Percent)		% error on the mean	Sensitivity (best estimate) (cps/conc.)	N
		Actual	Theory			
Potassium	90.2 ± 4.4	4.9	1.8	1.8	90.2	7
Uranium	7.0 ± 0.8	11.9	6.3	4.5	7.0	7
Thorium	5.6 ± 0.6	10.4	2.8	3.9	5.6	7

the Queensland calibration range is significantly longer than the South Australia range and requires significantly more effort in ground sampling.

(c) The degree to which the data fit an exponential model of the fall–off of radiation with altitude.

A calibration range which is highly variable, particularly in the across flight direction, may be unsuitable for the determination of height attenuation coefficients. As the survey height increases, areas on the ground which are farther from the flight line are included in the detector's field of view. The airborne count rate variation with altitude may be quite different to the response over a homogeneous infinite source. Theoretically, if the ground is not uniform, the count rate could even increase instead of decrease with increasing altitude. Significant deviations from the exponential model for height attenuation could indicate that the calibration range is unsuitable for this type of calibration. The height attenuation data for the Australian calibration ranges were not available to us and we have therefore been unable to make this assessment.

5.2 The Pinjarra Calibration Range, Perth, Western Australia

The procedure for calculating the height attenuation coefficients and airborne sensitivities over the Pinjarra range is essentially the same as for South Australia and Queensland. However, the method for taking ground measurements with a portable spectrometer is somewhat different since the strip is flat and can probably be driven by a 4WD vehicle for most of the year.

Figures C3.1 to C3.3 show that the calibration range is quite variable. In order to compare ground and airborne measurements it would be better if a more detailed ground sampling strategy was used that involved additional measurements which were not directly under the flight path. In order to simplify the ground measurement procedure, we recommend that the portable spectrometer be mounted on a 4WD vehicle and securely fixed to some kind of support protruding from the rear of the vehicle. The detector should be suspended as low as possible but sufficiently high that there is no danger of it striking the ground over bumpy terrain. By keeping the detector height as low as possible, any shielding of the spectrometer by the wheels of the vehicle will be minimized.

A practical sampling strategy would be to drive down one side of the calibration range, approximately 25 m from the power line, returning back up the center, with the last measurement line being 25 m on the other side of the power line. Based on the results of our initial measurements, any of the most northerly 8 or 10 km of the line would be suitable. The advantage of using the northerly section is that a large section of the land is owned by one family who were very co–operative.

During the initial assessment of the site, it took approximately 100 seconds to drive at a comfortable speed between the electricity pylons which were located every 300 m. Therefore 100 seconds is a suitable sampling interval. By starting and stopping each measurement at a pylon, the location of the measurement can be accurately identified for later comparison with the airborne measurements.

With any calibration range, there is always the possibility that the ground and airborne measurements are not located in the same place. Possible sample location problems can be identified by comparing the average ground concentration for three successive measurements between each pylon with the calibrated airborne measurements. For this comparison, there would be no need to interpolate the airborne measurements to the exact ground location and it would also not be necessary to apply a filter to the ground measurements. Problems of sample location would be identified through mismatches of the two sets of data.

5.3 Helicopter Calibration Site, Bairnsdale, Victoria

The procedure for calibrating a helicopter system is basically the same as for a fixed–wing system. However, the measurement of the ground concentration of the calibration site is considerably easier to perform. The recommended sampling scheme is the same that was used in Ethiopia and has already been used for the calibration of a helicopter system under the Victoria Exploration Initiative.

Figure C5.5 shows the response of a detector at an altitude of 60 m to circular sources on the ground of different radii. For a homogeneous infinite source, 90 percent of the detected radiation is received from a circle of radius 190 m centered beneath the helicopter. This response curve can be used to design a sampling scheme for measuring the ground concentration of the calibration site.

Table C5.4 shows the response of circles of different radii which contribute increments of 10 percent to the measured count rate at 60 m. The sampling scheme was designed to sample each of the concentric circular rings equally with four measurements within each ring. The 36 measurements were located along two perpendicular lines in the north/south and east/west directions. The distance of each measurement location from the center of the circle is also indicated in Table C5.4. This sampling scheme has taken into consideration the response of the airborne system to sources on the ground. The average of all 36 ground measurements can therefore be used in conjunction with the average airborne count rates to determine the aircraft system sensitivity at any altitude.

Table C5.4. Response of a detector at 60 m to circular sources of different radii.

Percent of Infinite Source	Radius of Circle (m)	Measurement Location Distance from centre (m)
10	23	10
20	35	30
30	46	40
40	57	50
50	70	65
60	85	80
70	105	95
80	135	120
90	190	160

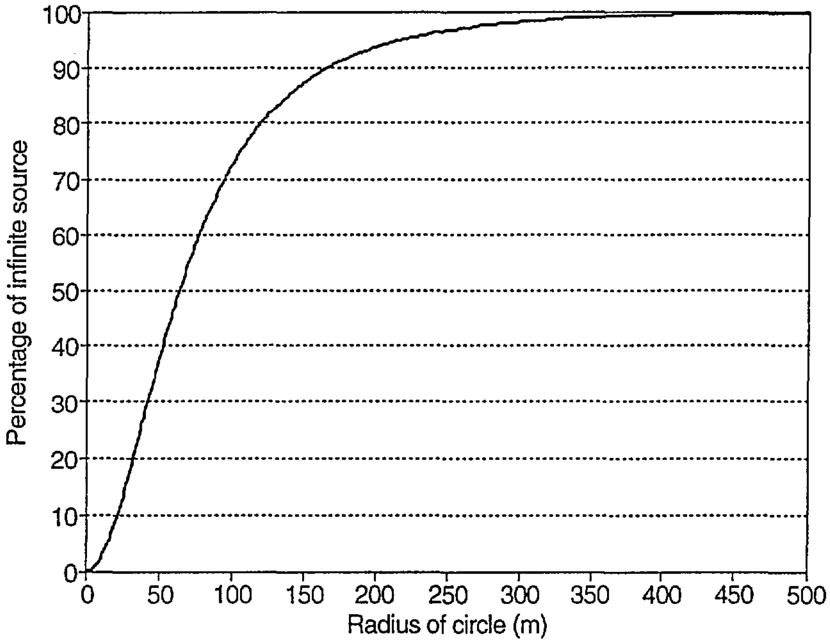

Figure C5.5. The response of an airborne spectrometer to circular sources on the ground for a survey height of 60 m.