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BACKGROUND MEASUREMENTS IN GAMMA-RAY SURVEYS

R.L. Grasty
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BACKGROUND MEASUREMENTS IN GAMMA-RAY SURVEYS

Abstract

Airborne gamma-ray data from Malawi, Africa were used to develop an automated system for computing on-line atmospheric background radioactivity. The atmospheric backgrounds were calculated using lead-shielded upward-looking detectors calibrated from airborne measurements over a large lake and areas with varying proportions of uranium and thorium. The method was tested by producing atmospheric uranium background maps and background corrected uranium count rate maps from two different areas.

The procedure was used to test two other methods of monitoring atmospheric background. One was high altitude flights at 600-700 m and the other repeated flights at survey altitude over a test line. It is shown that high altitude flights require corrections for cosmic-ray increases with altitude as well as scattered thorium gamma-radiation from the ground. With these corrections, high altitude data could still give erroneous backgrounds at the survey altitude because of non-uniform distributions of airborne radioactivity. Data from repeated test lines at the survey altitude compared favourably with the background measured with the upward-looking detectors provided the data were normalized to a constant thorium value. This normalization reduced errors due to deviations in the aircraft flight path over areas of variable radioactivity.

Theoretical studies of the system configuration showed that most of the radiation measured in the upward detector was direct radiation from the ground. The use of lead to shield the upward detectors was found to be unnecessary, since adequate shielding was provided by the downward detectors.

Studies of experimental data showed that the cosmic-ray background increase with aircraft altitude could be monitored more easily using a cosmic-ray window which recorded all counts above 3 MeV, than with a barometric altimeter.

Résumé

Des données sur le rayonnement gamma, recueillies par avion au Malawi en Afrique, ont été utilisées pour mettre au point un système automatisé de calcul en direct de la radioactivité atmosphérique naturelle. Les rayonnements atmosphériques de fond ont été calculés en recourant à des détecteurs à visée vers le haut blindés au plomb et étalonnés d'après des mesures aériennes réalisées au-dessus d'un lac de grande superficie et de zones à teneurs variables en uranium et en thorium. Cette méthode a été mise à l'essai dans la production de cartes du rayonnement d'uranium atmosphérique de fond et de cartes des taux de comptage d'uranium corrigés pour le rayonnement de fond de deux régions différentes.

Cette méthode a été utilisée pour mettre à l'essai deux autres procédés de surveillance du rayonnement atmosphérique de fond. Dans le premier cas, on a effectué des vols à haute altitude (600-700 m) et dans le second cas, des vols répétés à une altitude de levé suivant une trajectoire d'essai. Dans les vols à haute altitude, il faut apporter des corrections pour le rayonnement cosmique qui augmente en altitude ainsi que pour le rayonnement gama du thorium diffusé à partir du sol. Malgré ces corrections, les données de haute altitude peuvent encore indiquer des rayonnements de fonds erronés à l'altitude choisie pour les levés en raison des distributions non uniformes de la radioactivité atmosphérique. Les donnée recueillies au cours des vols répétés au-dessus de trajectoires d'essai se comparent avantageusement au rayonnement de fond mesuré par les détecteurs à visée vers le haut à condition que les données soient ramenées à une valeur constante du thorium. Cette normalisation a eu pour effet de réduire les erreurs causées par les écarts de vol de l'avion au-dessus de zones de radioactivité variable.

Des études théoriques de la configuration du système ont montré que la gande partie du rayonnement mesuré par les détecteurs à visée vers le haut provenait directement du sol. Le blindage de plomb autour des détecteurs orientés vers le haut s'est avérée inutile étant donné que les détecteurs orientés vers le bas ont procuré un blindage suffisant.

Des études de données expérimentales ont montré qu'il pouvait être plus facile de surveiller l'augmentation du rayonnement cosmique de fond avec l'altitude en recourant à une fenêtre du rayonnement cosmique de fond avec l'altitude en recourant à une fenêtre du rayonnement cosmique qui enregistre tous les comptes au-dessus de 3 MeV qu'en utilisant un altimètre barométrique.

INTRODUCTION

The Geological Survey of Canada has been involved in airborne gamma-ray surveys since 1967 when it developed one of the first high sensitivity spectrometer systems (Darnley and Grasty, 1970). In compiling the airborne gamma-ray data to produce maps of the ground concentration of potassium, uranium and thorium, one of the most difficult problems to overcome is the variation in the radioactivity of the air. In Canada, these atmospheric background variations can be monitored by flying over the abundant lakes and bodies of water. The GSC, however, is frequently involved in airborne surveys overseas through, the Canadian International Development Agency (CIDA). In many of these countries there are very few lakes and alternative methods of measuring atmospheric background must be found. One possible procedure is to use upward-looking detectors which are shielded from the ground radiation, thereby monitoring radiation in the air above the aircraft (Foote, 1969). The GSC, however, has had no practical experience with this method and very little information is available in the scientific literature.

In 1985 the United Nations funded an airborne geophysical survey in Malawi which included gamma-ray spectrometry. This survey was flown by Hunting Geology and Geophysics Ltd. of the United Kingdom at 1 km line spacing using two helicopters and one fixed-wing aircraft. The helicopters covered the more mountainous parts of the country and the fixed-wing aircraft the remaining area. Upward-looking detector data were collected by the fixed-wing aircraft.

Following discussions with the Government of Malawi and the United Nations, a research project was initiated between Hunting Geology and Geophysics Ltd. and the Geological Survey of Canada, for a detailed study of the upward-looking detector data to assess its capability for computing atmospheric backgrounds. Results of this study were also to be used to develop standards and procedures which could be incorporated into the technical specifications of contracts for similar surveys in Canada and overseas.

Acknowledgments

We thank the government of Malawi and particularly James Chatupa, the Chief Geologist of the Geological Survey Department, who gave full support to this project. The airborne survey of Malawi was funded by the United Nations through their Natural Resources Division who also fully encouraged this study.

We also express our appreciation to Mark Parker and Steven Thomas of Hunting Geology and Geophysics Ltd. who were responsible for the fieldwork in Malawi and provided valuable advice throughout the period of research in England. Susan Jones and Gary Jackson of Hunting Geology and Geophysics gave invaluable assistance in accessing and processing the computer data base from Malawi.

Bart St. John-Smith critically read the preliminary report submitted to the Government of Malawi and made many useful comments which have been incorporated in the final paper.

INSTRUMENTATION

The gamma-ray spectrometer flown in a fixed-wing Cessna 404 Titan aircraft was a Geometrics GR-800D system. The detector configuration shown in Figure 1 consisted of three thermally insulated boxes each of which contained four

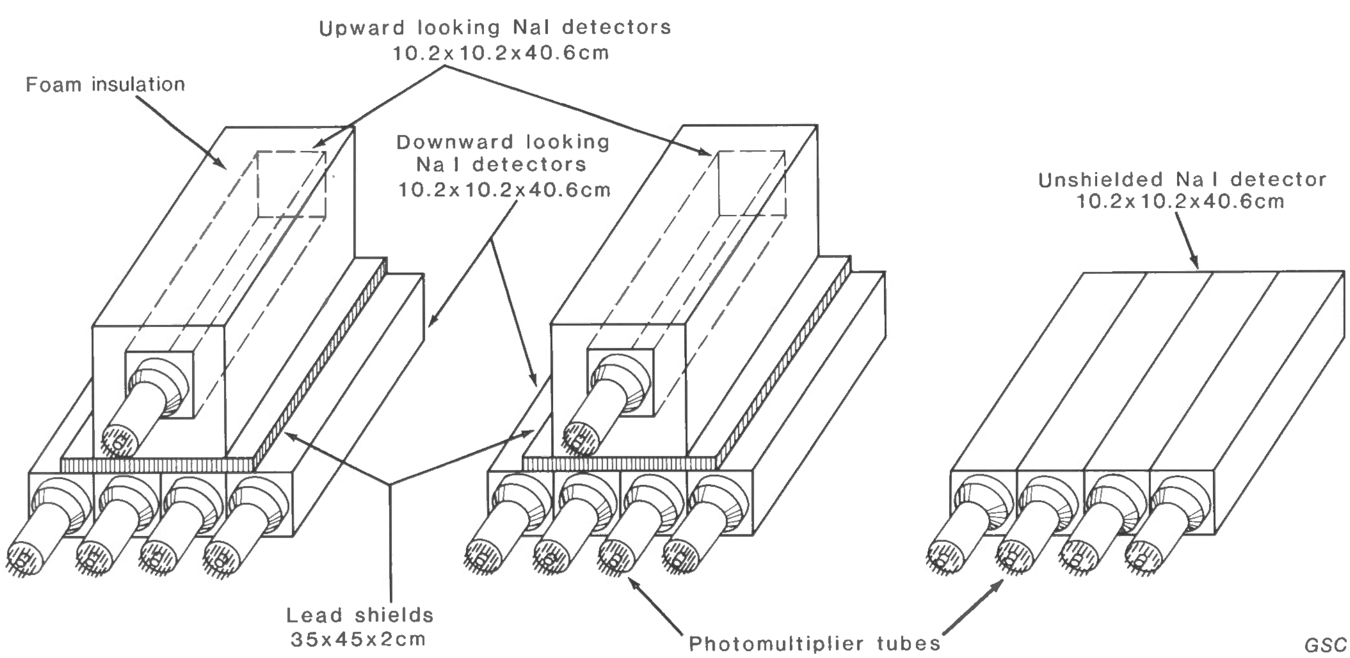

Figure 1. A schematic diagram showing the configuration of the downard detectors and the upward-looking lead-shielded detectors.

Table 1. Spectral windows used to measure gamma-rays

Element analyzed	Isotope used	Gamma-ray energy (MeV)	Energy window (MeV)
Potassium	40K	1.46	1.37 – 1.57
Uranium	214Bi	1.76	1.66 – 1.86
Thorium	208Tl	2.62	2.41 – 2.81
TOTAL COUNT			0.41 – 2.81

Table 2. The system sensitivities derived from the calibration pads at Lanseria, South Africa (Corner and Smit, 1983)

	K window	U window	T window	Up window
Counts/sec/pct K	268.4	4.99	0.787	0.0
Counts/sec/ppm eU	21.55	23.24	2.489	1.10
Counts/sec/ppm eTh	6.12	4.415	13.59	0.253

10.2 × 10.2 × 40.6 cm sodium iodide detectors giving a total system volume of 50L. A single 10.2 × 10.2 × 40.6 cm detector, in its own thermally insulated box, was mounted on a lead sheet on top of two of the detector packages. The lead shield, approximately 35 × 45 × 2 cm, weighed 34 kg. Because of their thermal insulation, the upward-looking detectors were not in direct contact with the lower detectors but were separated from them by approximately 10 cm.

Table 1 shows the energy windows used for monitoring the gamma radiation from potassium, uranium and thorium detected in the three downward-looking detector packages. Only gamma-rays in a single energy window from 1.66 to 1.86 MeV were recorded from the two upward-looking detectors. This energy window was selected to monitor gamma radiation from bismuth-214 produced by the decay of radon in the air.

An anticoincident circuit was incorporated in the detector system so that if a gamma-ray was detected in both the upward and downward detectors within a period of 0.75 microseconds, the gamma-ray in the upward detector would be rejected. The gamma-ray in the downward detector, however, was recorded. This particular feature increases the shielding of the upper detectors by eliminating 2.62 MeV gamma-rays from thorium in the ground which lose some of their energy in the downward detectors, pass through the lead shield and are then detected in the uranium window of the upward detector.

Before the survey commenced, the equipment was calibrated on the pads at Lanseria Airport, South Africa (Corner and Smit, 1983). The results of the calibration are shown in Table 2 as a sensitivity matrix for both the upward and downward detectors. However, the calibration data are not used in the procedure for monitoring atmospheric background because the energy distribution of radiation on the pads at ground level is quite different from the distribution at survey height.

BACKGROUND RADIATION

In any airborne radioactivity survey three sources of background radiation exist.

1. The radioactivity of the aircraft and its equipment,
2. Cosmic radiation, and
3. Airborne radioactivity arising from daughter products of radon gas in the uranium decay series.

The radioactivity of the aircraft and its equipment is constant and is due to the presence of small quantities of natural radioactive nuclides in the detector system and in the airframe.

The cosmic-ray background is caused by cosmic-ray particles interacting with nuclei present in the air, aircraft or in the detection system itself. The cosmic-ray contribution increases with aircraft altitude but shows only minor variations on a day-to-day basis due to changes in atmospheric pressure (Grasty and Carson, 1982). Small variations are observed with latitude and with the eleven-year solar cycle and with the size of the aircraft (Burson et al., 1972), The cosmic-ray contribution in each radioelement window can be removed by monitoring a high-energy window from 3-6 MeV which is unaffected by variations in the radioactivity of the ground (Burson et al., 1972). Alternatively, the cosmic-ray contribution may be removed using an experimental relationship between cosmic-ray count rate and barometric altitude, as is shown later in this paper.

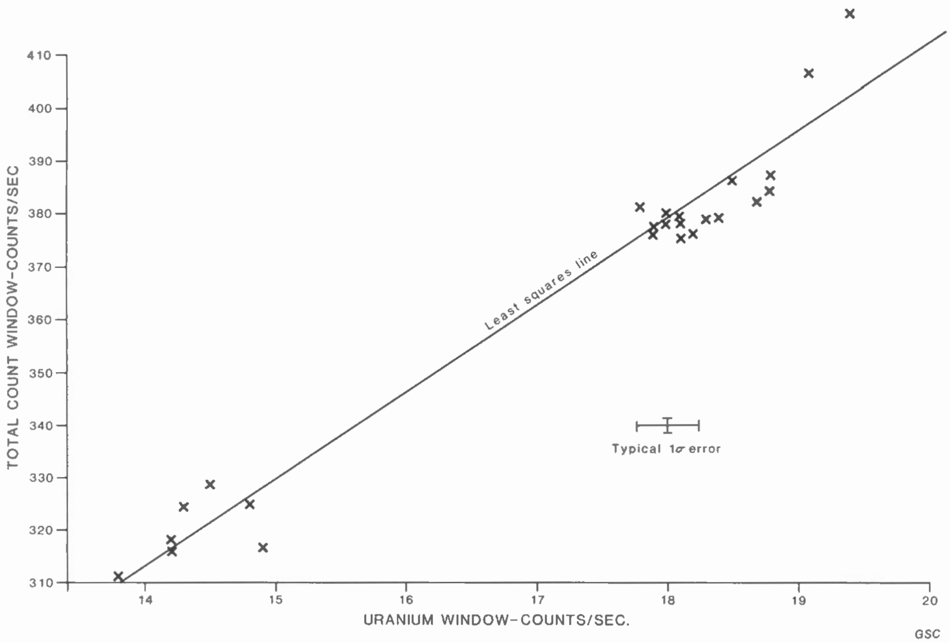

Figure 2. The relationship between the uranium and total count window for background measurements over Lake Malombe.

By far the most difficult background radiation component which has to be removed arises from the decay products of radon. Radon, being a gas, can diffuse out of the ground. Furthermore it has a half life of 3.8 days. The rate of diffusion will depend on such factors as air pressure, soil moisture, ground cover, wind speed and temperature. The decay products, lead-214 and bismuth-214 which produce the airborne gamma-ray activity, are attached to airborne aerosols and consequently their distribution is dependent to a large extent on wind patterns. Under early morning still-air conditions the airborne aerosols and the attached decay products are concentrated at ground level. As the day progresses, increasing air turbulence tends to mix the air to a greater extent and reduce the atmospheric background close to the ground.

The difficulty of monitoring airborne radioactivity arises because the gamma-ray spectrum of radon daughter products in the air is virtually identical to the gamma-ray spectrum originating from the uranium decay series in the ground. Since accurate measurements of the ground concentration of uranium are of prime importance for uranium exploration and geological mapping, it is essential to measure the atmospheric background as accurately as possible. The technique adopted by the Geological Survey of Canada has been to fly over a lake before the commencement of a survey flight. Since the concentrations of radioactive nuclides in the water are several orders of magnitude lower than that of normal crustal material, the activity measured will be the total background contribution from all three sources. Fortunately in most of Canada lakes are abundant, and the background values can be updated frequently during the course of the survey. This method has proved satisfactory where large lakes are present and homogeneous mixing of the radioactive decay products has occurred.

Over water, backgrounds in the total count and potassium windows are found to be linearly related to the uranium window (Grasty, 1979). This is because changes in all three windows are controlled almost entirely by fluctuations in the concentration of bismuth-214 in the air. This linear relationship between the three windows is shown in Figures 2 and 3 for data recorded over Lake Malombe in Malawi. The thorium over water count rate remains almost constant, irrespective of changes in the uranium window, because only a small percentage of bismuth-214 gamma-rays are sufficiently high in energy that they can be detected in the thorium window.

In this paper we show how the upward-looking detector data may be used to calculate the over water background count rate in the uranium window. The total count and potassium over water background count rate may then be calculated directly from their linear relationship with the uranium background as shown in Figures 2 and 3.

THEORY

In this section we present the theory for calculating the over water uranium background from the upward-looking detector data. To simplify the theory we make the assumption that all the measurements are taken at the same barometric altitude and consequently the cosmic-ray contribution to all the windows is constant. We also make the assumption that the aircraft flies at a constant ground clearance and therefore the relationships between the up and down detectors for sources of radiation in air or in the ground remain constant. In a later section, we show how the theory may be modified to take into account changes in the cosmic-ray component.

Let u be the measured upward detector count rate,

u_g the upward detector count rate originating from radiation in the ground and

u_B the background upward detector count rate originating from cosmic radiation, the aircraft and its equipment and daughter products of radon in the air. This background count rate is the count rate that would be measured over water.

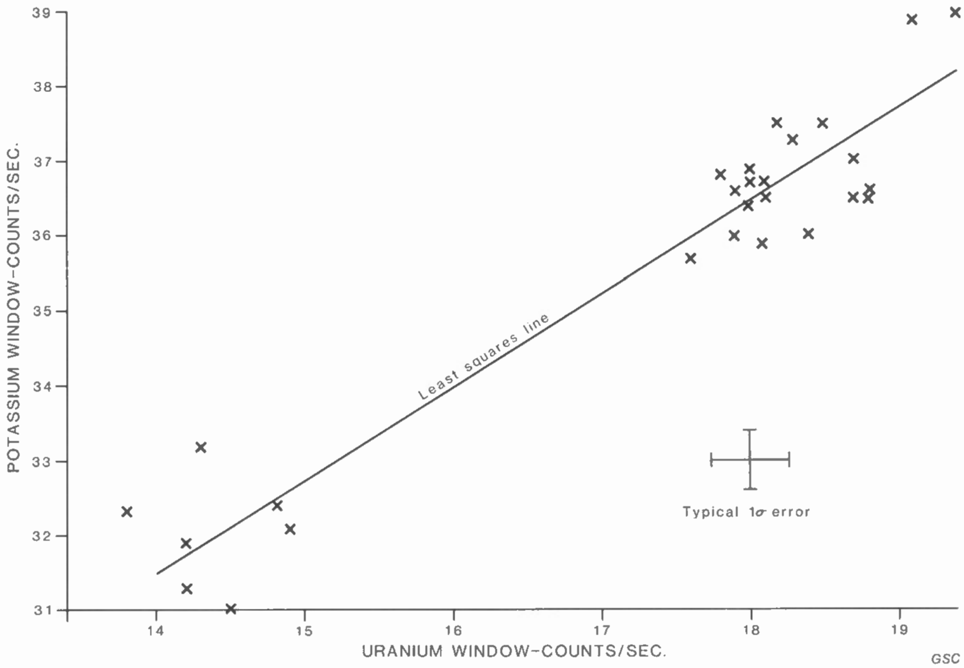

Figure 3. The relationship between the uranium and potassium window for background measurements over Lake Malombe.

Similarly, let

U be the measured downward uranium window count rate,

U_g the downward uranium window count rate originating from uranium in the ground and,

U_B the background downward uranium window count rate that would be measured over water.

Similarly, let

T be the measured downward thorium window count rate,

T_g the downward thorium window count rate originating from the ground and

T_B the background downward thorium window count rate that would be measured over water. This value is constant.

The relationship between the measured window count rates and their respective ground and background components are given by the following set of equations:

$$u = u_g + u_B \quad (1)$$

$$U = U_g + U_B \quad (2)$$

$$T = T_g + T_B \quad (3)$$

The upward detector count rate originating from the ground, u_g, will depend on the concentration of uranium and thorium in the ground. The components of the uranium and thorium downward window count rate, U_g and T_g that originate from the ground will also depend on the concentration of uranium and thorium in the ground. Consequently the upward detector ground component u_g is related to the downward detector ground components U_g and T_g by the linear equation:

$$u_g = a_1U_g + a_2T_g \quad (4)$$

where a_1 and a_2 are constants to be determined.

In addition the over water upward detector count rate, u_B, will be linearly related to the over water downward detector count rate, U_B, i.e.

$$u_B = a_3U_B + a_4 \quad (5)$$

where a_3 and a_4 are constants to be determined.

Substituting for u_B and u_g from equations (4) and (5) in equation (1) we get,

$$u = a_1U_g + a_2T_g + a_3U_B + a_4 \quad (6)$$

which from equations (2) and (3) gives,

$$u = a_1U - a_1U_B + a_2T - a_2T_B + a_3U_B + a_4 \quad (7)$$

From equations (6) and (7) we find that U_B, the overwater uranium background may be calculated from the measured count rates in the up and down detectors u, T, U and T_B using the relationship:

$$U_B = \frac{u - a_1U - a_2(T - T_B) - a_4}{(a_3 - a_1)} \quad (8)$$

The error in the calculated value of U_B will depend on the number of one second samples, N, over which the up and down detector count rates are evaluated. Assuming that the errors associated with the constants a_1, a_2, a_3, a_4 and the thorium background T_B, are small compared to the errors in the calculation of the mean detector count rates, then the variance in the calculated value of U_B, (σ^2U_B), is given by:

$$\sigma^2U_B = \frac{1}{N(a_3 - a_1)^2}\left| u + a_1^2U + a_2^2T \right| \quad (9)$$

System calibration

In order to make use of equation (8) and calculate the uranium over water background, U_B, it is first necessary to determine the four constants (a_1, a_2, a_3 and a_4) as well as the thorium over water background, T_B. The constants a_3 and a_4 can be calculated from a series of over water measurements where the uranium background, U_B, shows significant variation. The greater the variations in U_B, the more accurately the coefficients a_3 and a_4 can be determined.

Figure 4 shows how the upward window count rate u_B varies linearly with the downward uranium window count rate U_B for a series of measurements taken over Lake

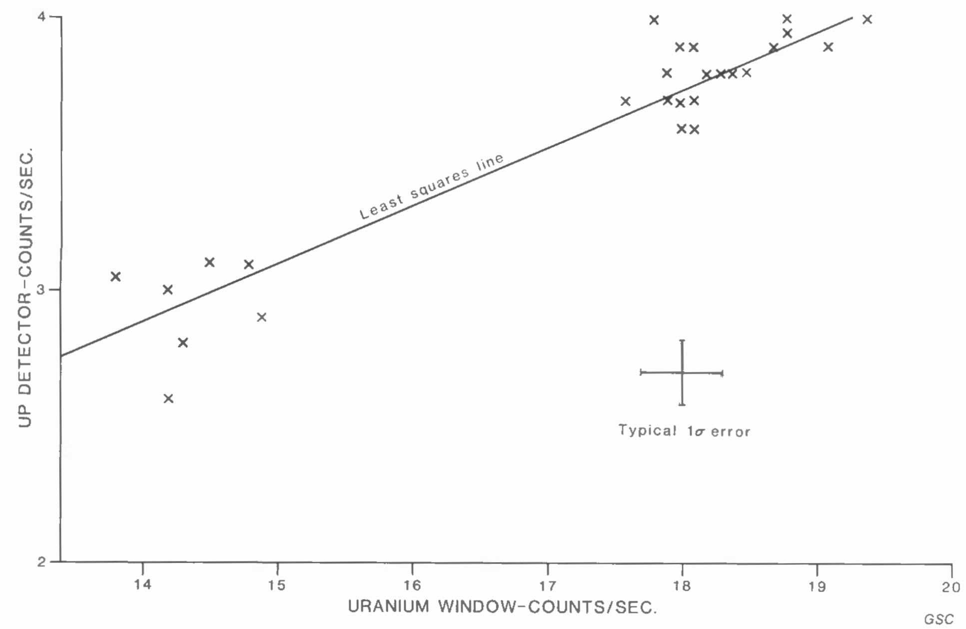

Figure 4. The relationship between the downward-looking uranium window and the upward-looking detector count rates for background measurements over Lake Chilwa.

Chilwa on six different days during production flying. This particular set of data was selected for the determination of the coefficients a_3 and a_4 because the data covers a range of atmospheric background variations and also Lake Chilwa is sufficiently large that the mean count rates in the various windows can be measured accurately.

In selecting the sections of lines over Lake Chilwa which were used in the analyses, it was found useful to compare the mean and variance of the high energy thorium window counts. On flight lines where the lake was shallow and thorium gamma radiation from beneath the lake was being detected, the variance of the one second counts was found to be much higher than the mean count rate. The mean thorium over water count rate T_B for all measurements was found to be 13.1 ± 0.2 counts per second.

By least squares fitting, the relationship between the upward and downward uranium window count rates was found to be: $u_B = 0.2136\ U_B - 0.110$ (10)

This equation is shown in Figure 4 together with the calculated errors associated with the upward window count rate u_B, which are given by $(u_B/N)^{1/2}$, where N is the number of one second samples over which the count rates were averaged. The value of N was approximately 200.

In order to calculate the constants a_1 and a_2, we make use of the relationship in equation (4) which relates the ground component of the upward-looking detector count rates, u_g, to the ground component of the downward looking thorium and uranium window count rates T_g and U_g.

Some equipment manufacturers have recommended using calibration pads, to derive the relationship between the up and down detectors for sources of ground radiation. However, the distribution of gamma radiation at ground level is quite different from the distribution at a survey altitude of 123 m (Beck, 1972). In addition, calibration pads of finite dimensions cannot be considered as an infinite source of gamma radiation. Consequently, the constants a_1 and a_2 derived from calibration pads at ground level may well be significantly different from their actual values at the survey altitude. For this reason, it was decided to evaluate the constants from the airborne data.

In order to use equation (4) to evaluate the constants a_1 and a_2 it is necessary to remove the overwater background component from both the upward and downward detectors so that the only component of gamma radiation that remains comes from the ground. One way this can be achieved is by using data from sections of flight lines which are adjacent to a lake over which the background can be measured. The average over water background from both the up and down detectors can then be subtracted from the average values over the adjacent land as illustrated in Figure 5. The only assumption in this method is that the background over the land is the same as it is over the water. By utilizing sections of flight lines which are close to the water, problems of local atmospheric background variations can be minimized.

In areas where lakes are not present, an alternative procedure can be used. This procedure removes the over water background component by subtracting the average count rates from adjacent sections of a flight line. The average count rates remaining after the subtraction correspond to differences in the ground concentration of the two adjacent sections of lines. The advantage of this procedure is that particular sections of line can be selected.

To obtain reliable estimates of a_1 and a_2 it is necessary to separate the uranium contribution to the up detector (a_1) from the thorium concentration (a_2). This can best be achieved by selecting sections of lines with a large range of uranium-to-thorium ratios. These sections should also have a high average count rate and be adjacent to a low count rate area for the background. Errors in the mean count rates, u_g, U_g and T_g, required to solve equation (4) will then be minimized.

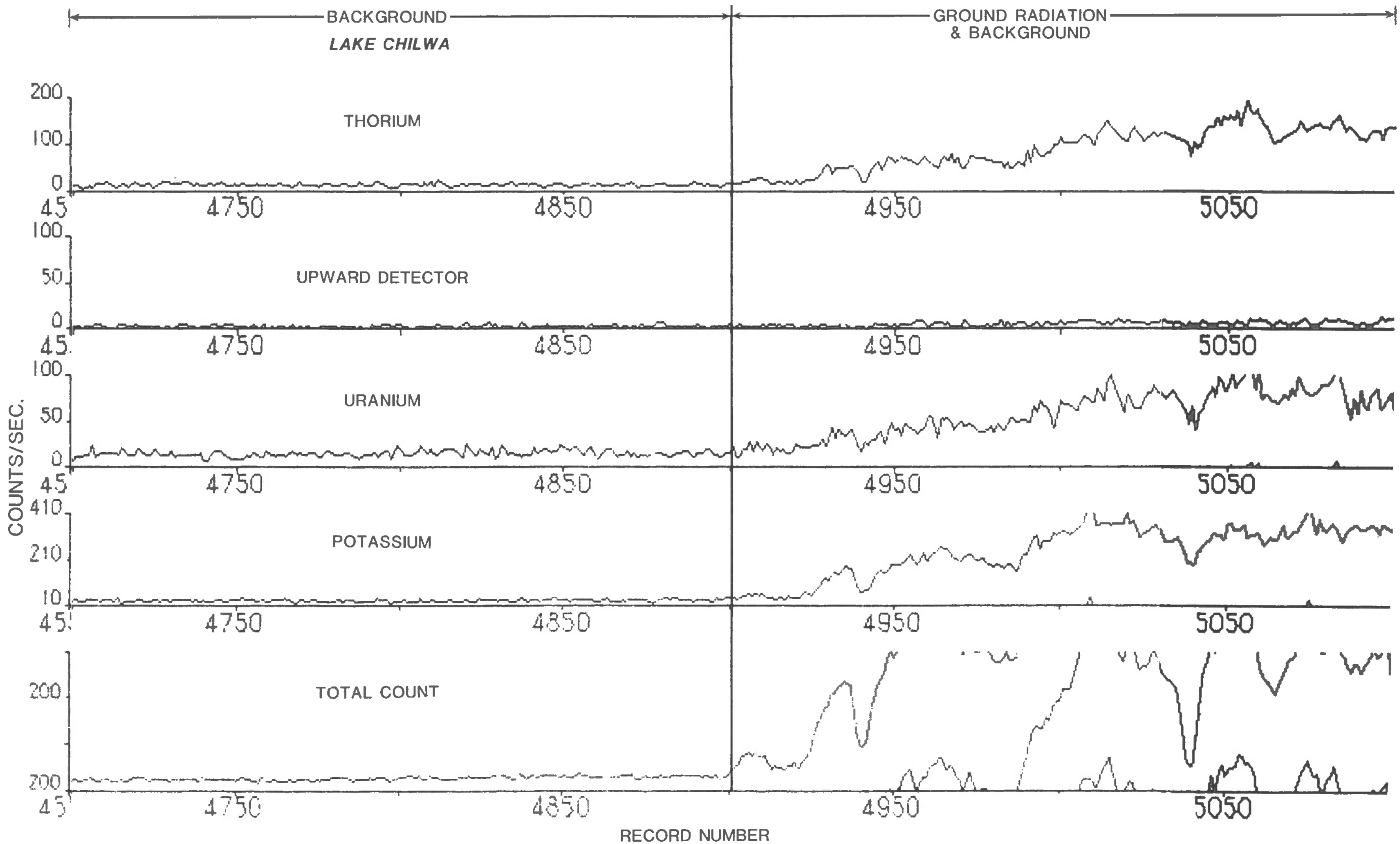

Figure 5. A profile showing the section of line and adjacent background used to derive the relationship between the up and down detectors for sources of ground radiation.

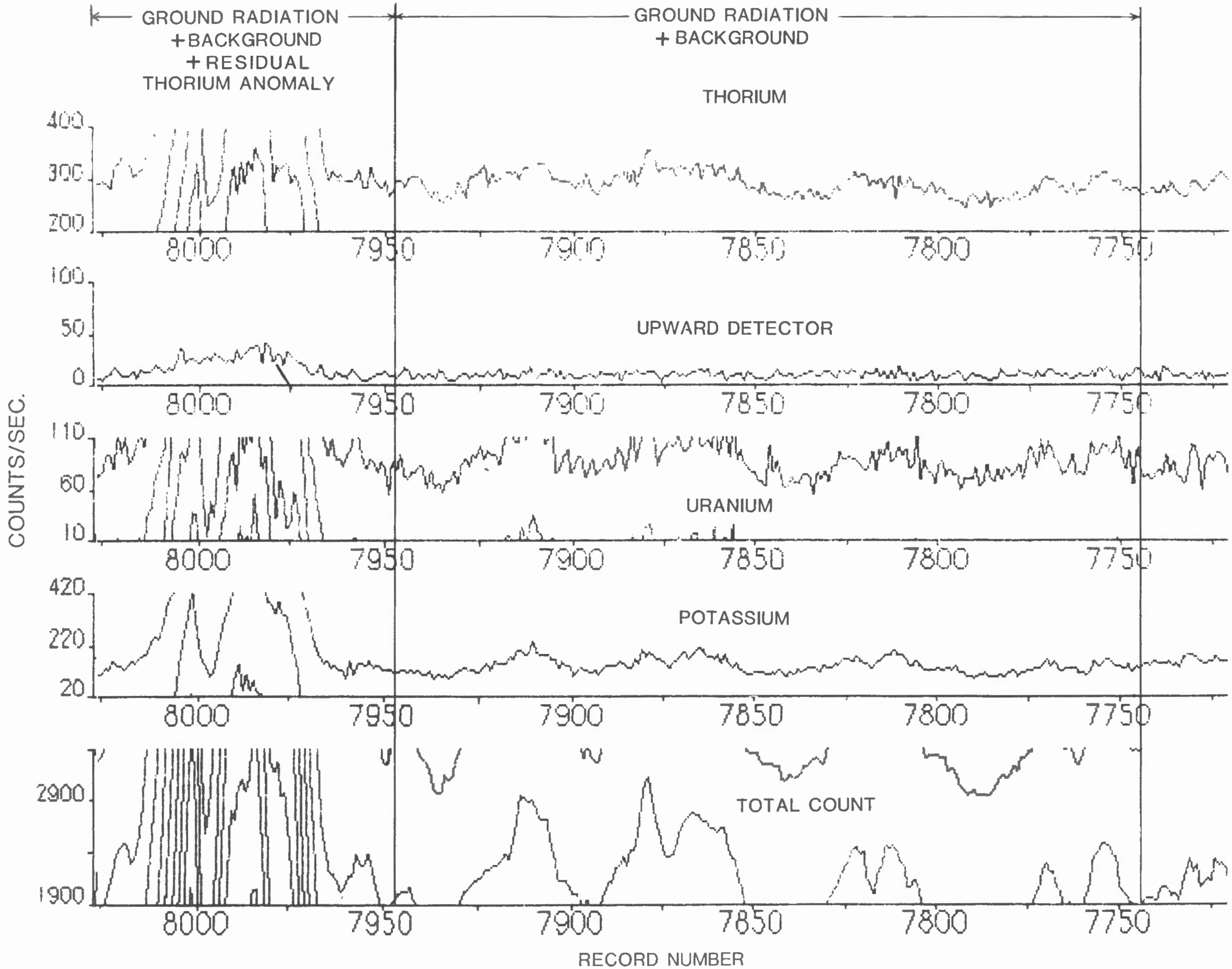

Figure 6. A profile over a thorium anomaly showing the adjacent section used to remove background radiation.

The coefficients a_1 and a_2 in equation (4) were calculated by a least squares technique using the background component of lines adjacent to Lake Chilwa as illustrated in Figure 5, as well as areas where there were uranium and thorium anomalies. An area with anomalous thorium is shown in Figure 6 together with the adjacent low count rate area used to remove the over water background, so that only the ground component remains. The count rates indicated are uncorrected. The profiles of Figure 6 show the increase in the upward detector count rate when the aircraft passes over the anomaly.

The least squares solution for a_1 and a_2 can be found by solving the two simultaneous equations:

$$a_1 \sum U_g^2 + a_2 \sum U_g T_g = \sum u_g U_g \quad (11)$$

$$a_1 \sum U_g T_g + a_2 \sum T_g^2 = \sum u_g T_g \quad (12)$$

The relationship between the ground component of the count rate in the up detector u_g to the ground component in the down detector, U_g and T_g was calculated to be:

$$u_g = 0.0265 U_g + 0.0178 T_g \quad (13)$$

In order to assess how well this equation fitted the observed data, the measured increases in the ground component of the upward detectors when passing over the thorium and uranium anomalies were plotted against the calculated increase using equation (13). These results are presented in Figure 7 together with the calculated and measured increase in the upward detectors when the aircraft passed from water to land. They clearly show that the ground component of the down detector windows can be used to predict the ground component in the upward detector over a wide range of ground concentrations.

From equation (8), using the calculated values of the coefficients a_1, a_2, a_3 and a_4 and the thorium background (13.1 counts per second), the over water uranium window count rate is found to be given by:

$$U_B = 5.35u - 0.142U - 0.0951T + 1.83 \quad (14)$$

RESULTS

Using equation (14) we have a method for determining the background count rate in the downward looking uranium window that originates from cosmic radiation, the aircraft and its equipment plus decay products of radon in the air. How well does the method work in practice? The ultimate test is to apply the procedures to an entire survey data set to see if it can successfully remove day-to-day variations in airborne radioactivity.

Before the method was applied to an entire survey, calculated backgrounds were first compared to the measured values over a lake. The results are shown in Figure 8 for all data recorded over Lake Chilwa. The average count rates in all three windows (u, U and T) were derived by averaging anywhere from 140 to 365 samples. The errors in the averge count rates are also indicated. Because the same data set was used to calculate the coefficients a_3 and a_4 of equation (5), the comparison cannot be considered as an independent test. However, the uranium background was calculated using the more complex equation (14) which corrects for radiation from the ground. In addition, Figure 8 shows how well the predicted and measured background count rates compare in areas of low radioactivity where problems frequently occur. An analysis of the results showed that the uranium background could be predicted to an accuracy of 0.8 counts per second, a similar value to that predicted theoretically using equation (9).

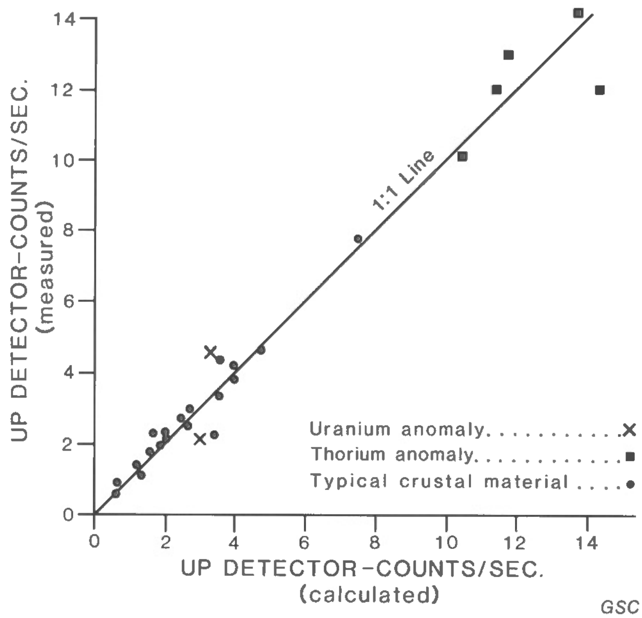

Figure 7. A comparison of the measured ground component of the upward detector and the calculated value using the derived equation (13).

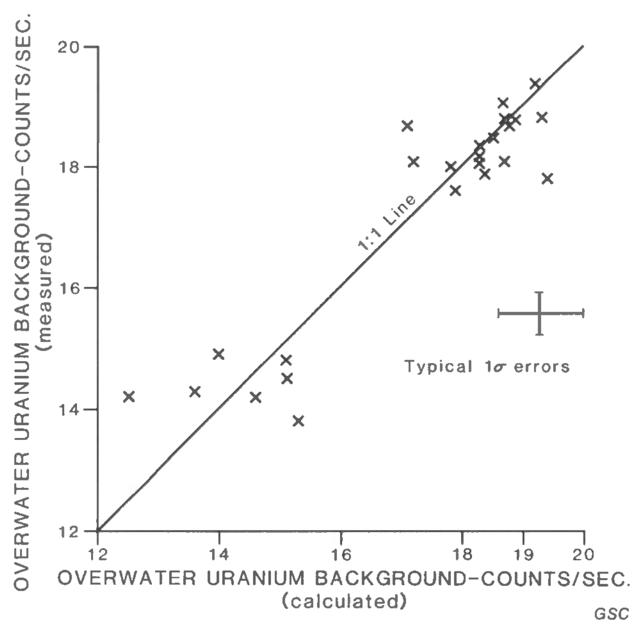

Figure 8. A comparison of the measured over water uranium window count rate and the calculated value using the upward detectors.

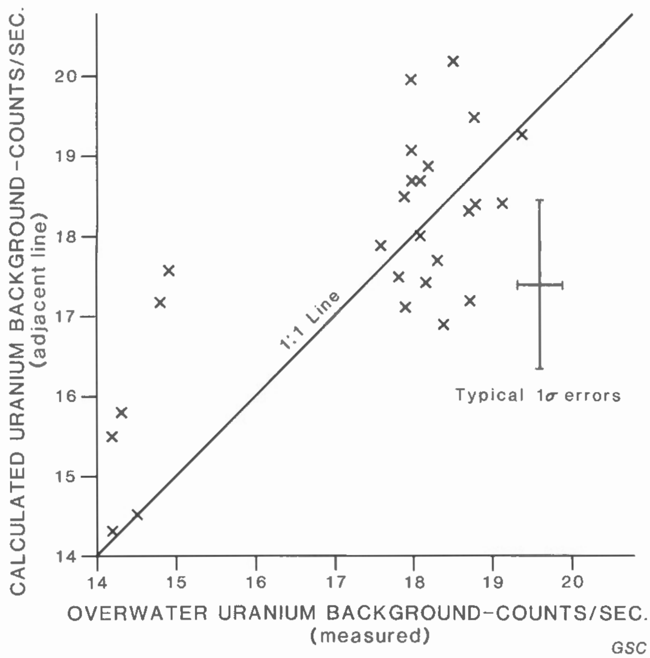

Figure 9. A comparison of the measured over water uranium window count rate and the calculated value over an adjacent section of ground using the upward detectors.

A similar test of the method can be performed using data recorded over land where a component of ground radiation is recorded in the up detectors. In this case, data from an adjacent body of water must be used to estimate the background. Figure 9 shows the comparison between the calculated over land background and the adjacent background over Lake Chilwa. The flight line sections analyzed were selected to be within about 10 km of Lake Chilwa corresponding to about 200 one second samples. The comparison between the two backgrounds cannot be considered as an independent test of the method, because much of the same data was used to calculate the relationship between the up and down detectors. However, it is an important test to verify that the coefficients have been derived correctly. The root means square difference between the calculated background and the adjacent over water background was calculated to be 1.2 counts per second. This is very similar to the value calculated purely theoretically using equation (9).

Following these initial tests, an automatic procedure was developed for processing an entire survey. The first area selected included Lake Chilwa.

The first stage in this development was the production of a background map of the entire survey area.. This requires the backgrounds to be determined for every data point. Because of statistical noise, it is first necessary to filter both the upward detector data as well as the downward uranium and thorium data. In selecting the particular length of filter, there has to be a compromise. If the filter is too long, atmospheric background may vary over its length. With too short a filter, the background may be inaccurate because of statistical noise associated with the measurements.

A simple 201 point moving average filter was used on each flight line data set. This length of filter was selected so that the uranium background could be calculated to an accuracy of one count per second. This accuracy was based on map production experience in Canada where backgrounds are sometimes manually adjusted by one count per second generally over low count rate areas, simply for the cosmetic appearance of the map. With this 201 point filter, which corresponds to a short distance of approximately 10 km, only minor atmospheric background variations were expected.

In applying this filter, one practical problem that had to be resolved related to the data at the beginning and end of each flight line. The first 100 points of each flight line were given the same value, the average value of the first 201 points. A similar procedure was applied to the last 100 points. No attempt was made to incorporate data from a flight flown immediately before or after the one being filtered, because these lines could have been fill-in lines flown in a different area. The 201 point filter was applied to the upward detector data and the downward uranium and thorium windows. For each data point, the uranium background was then calculated using equation (14). The background data was then gridded and contoured using a standard software package to produce the background uranium map shown in Figure 10. On this map, the shoreline of Lake Chilwa is indicated as well as the dates on which various sections of the map were flown.

The most obvious feature on this background map is the large anomaly in the middle of the lake. This anomaly was found to be caused by an extremely radioactive island, a carbonatite. Figure 11 is a radioactive profile over this island showing the total count rate exceeds 25000 counts per second in the downward detectors. At this high count rate, pulse pile-up will occur and the spectrum will be distorted. This problem wil not occur with the upward detectors because of their small volume and separate electronics. Because of spectral distortion in the downward detector system the relationship between the up and down detectors will be quite different from that previously calculated. Consequently, where the count rates are so high that the system capabilities are exceeded, the calculated background cannot be considered reliable. Fortunately this is an extremely unusual occurrence and it is a simple matter to reject any data from the background calculation where the count rates are high.

Apart from the problem due to the high count rate over the carbonatite, Figure 10 gives every indication that the background has been calculated successfully. The map shows that areas with different backgrounds were flown on different days and that different areas of the map flown on the same day give similar background levels. In addition, there are no obvious changes in background level across the shoreline of the lake indicating that radiation from the ground has been successfully removed.

Following the background map, a uranium contour map was produced. This was done by first calculating the 201 point filtered background for each flight line and then subtracting this background from the original one second data. The uranium background corrected count rates were

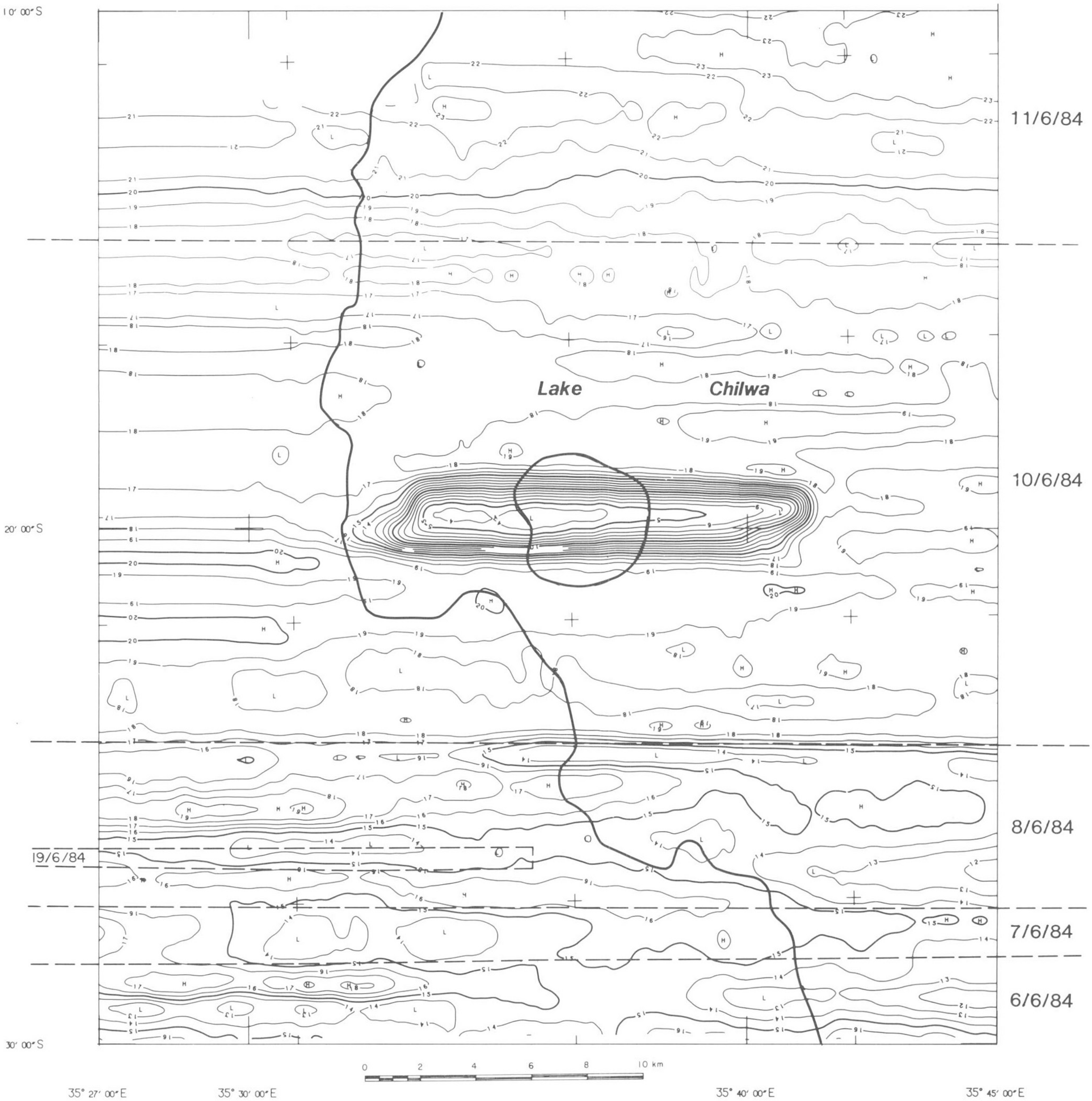

Figure 10. The background uranium count rate map for the Lake Chilwa area.

first stripped for the effects of high energy thorium and then height corrected, following standard procedures, before final gridding and contouring. Figure 12 shows the uranium map which was produced automatically, with no manual adjustment of the background.

Apart from the anomalous over water background associated with the island and its high count rate, the background appears to have been calculated correctly. There are no obvious level changes between flight lines which would occur if the backgrounds were incorrectly calculated. The uranium background count rate over the lake fluctuates around zero which is to be expected because of statistical errors. We therefore concluded that the upward-looking detector data can be used for an automatic method of calculating uranium backgrounds.

In practice it is probably best to utilize data from the actual survey area for deriving the various sytem calibration constants, (a_1, a_2, a_3 and a_4 in equation (8)). However, in some cases this may not be possible, for instance if lakes are not in the area surveyed. It was therefore decided to test the method on data from a different area in Malawi, but using the calibration constants determined from the Lake Chilwa area.

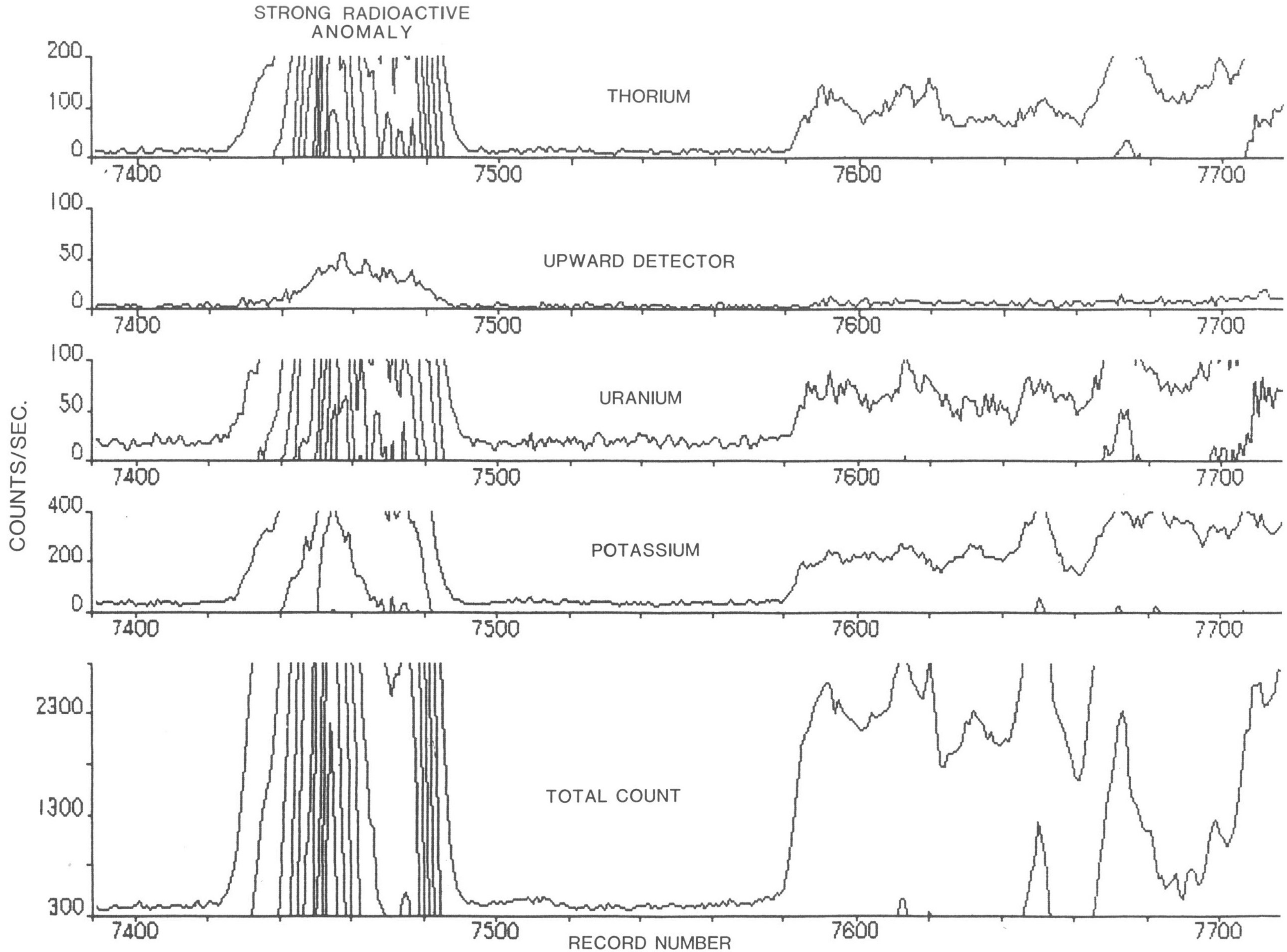

Figure 11. A profile over the carbonatite island in Lake Chilwa showing the high count rates.

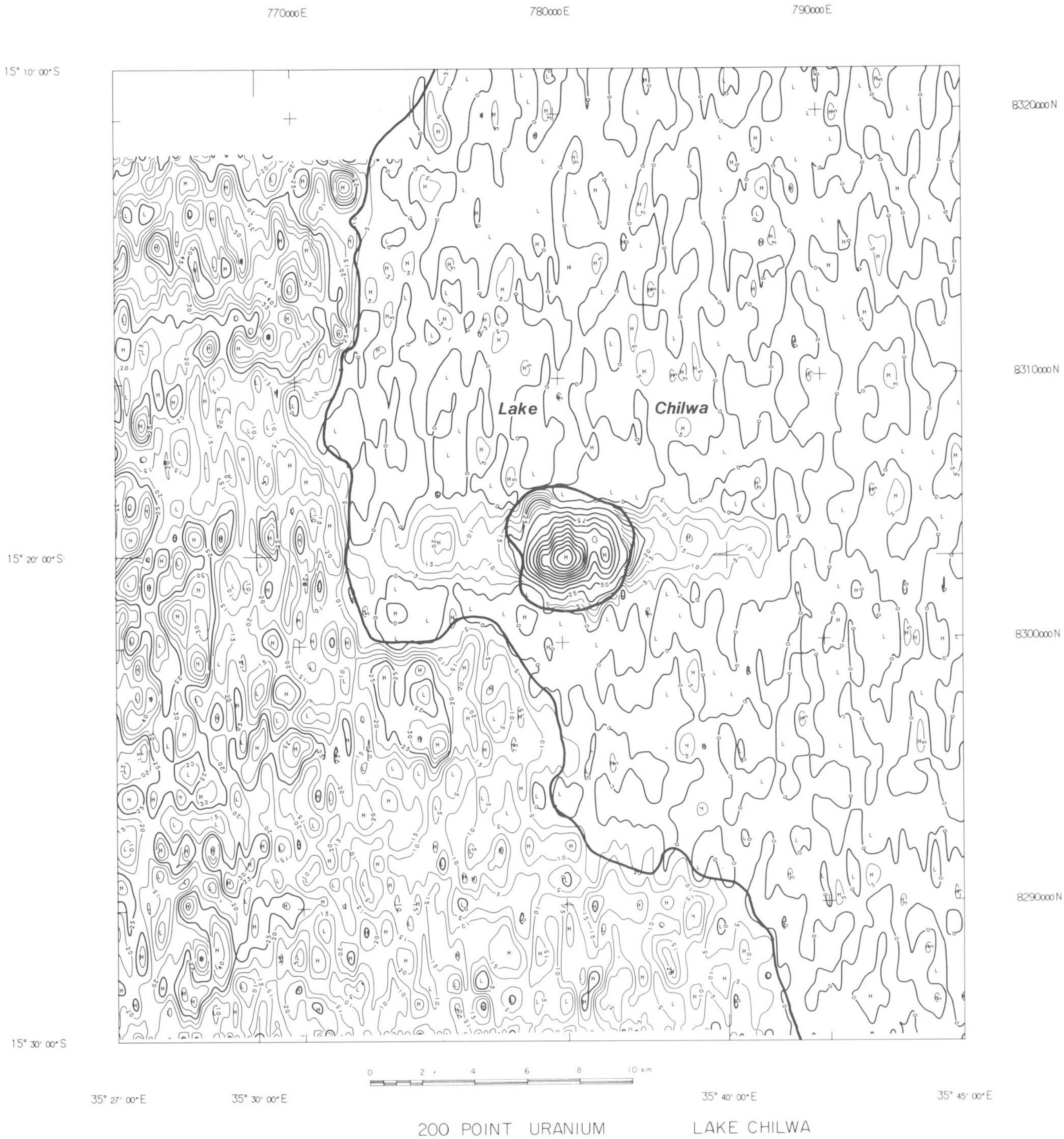

Figure 12. The final corrected uranium count rate map for the Lake Chilwa area.

The area selected was approximately 35 × 55 km and included Lake Malombe, over which significant background fluctuations had been observed. The advantage of choosing a test area that includes a lake is that after background subtraction the uranium count rate should be zero over the lake. In addition background changes would not be expected to occur when flying across the shoreline of a lake.

The procedure followed in producing the maps from the Lake Malombe area were identical to those carried out for the Lake Chilwa area. In addition, a uranium map and a background map were also produced using a shorter length 51 point moving average filter which will give increased statistical noise in the calculated uranium background. These four maps are shown in Figures 13 to 16.

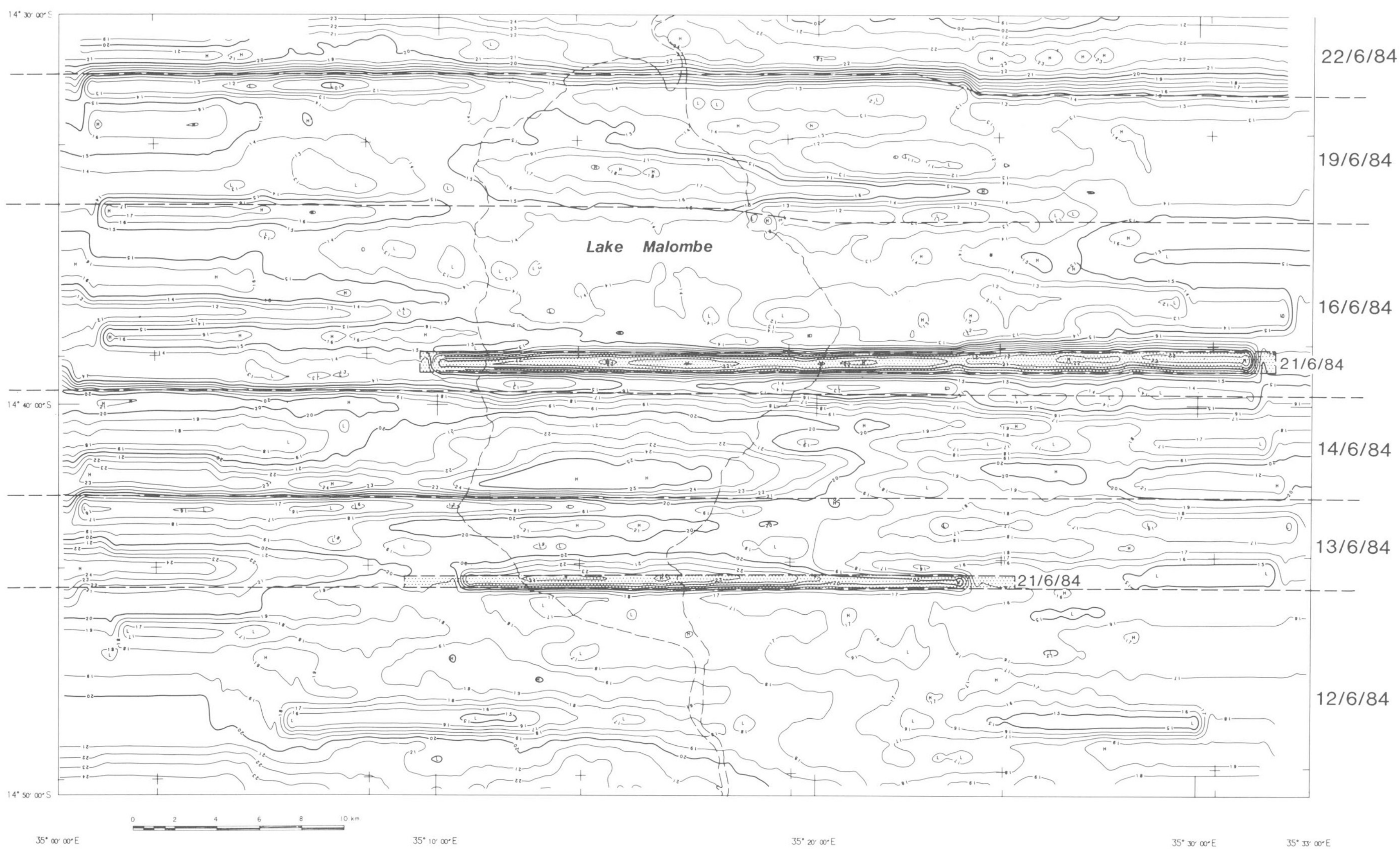

Figure 13. The background uranium map for the Lake Malombe area using a 201 point filter.

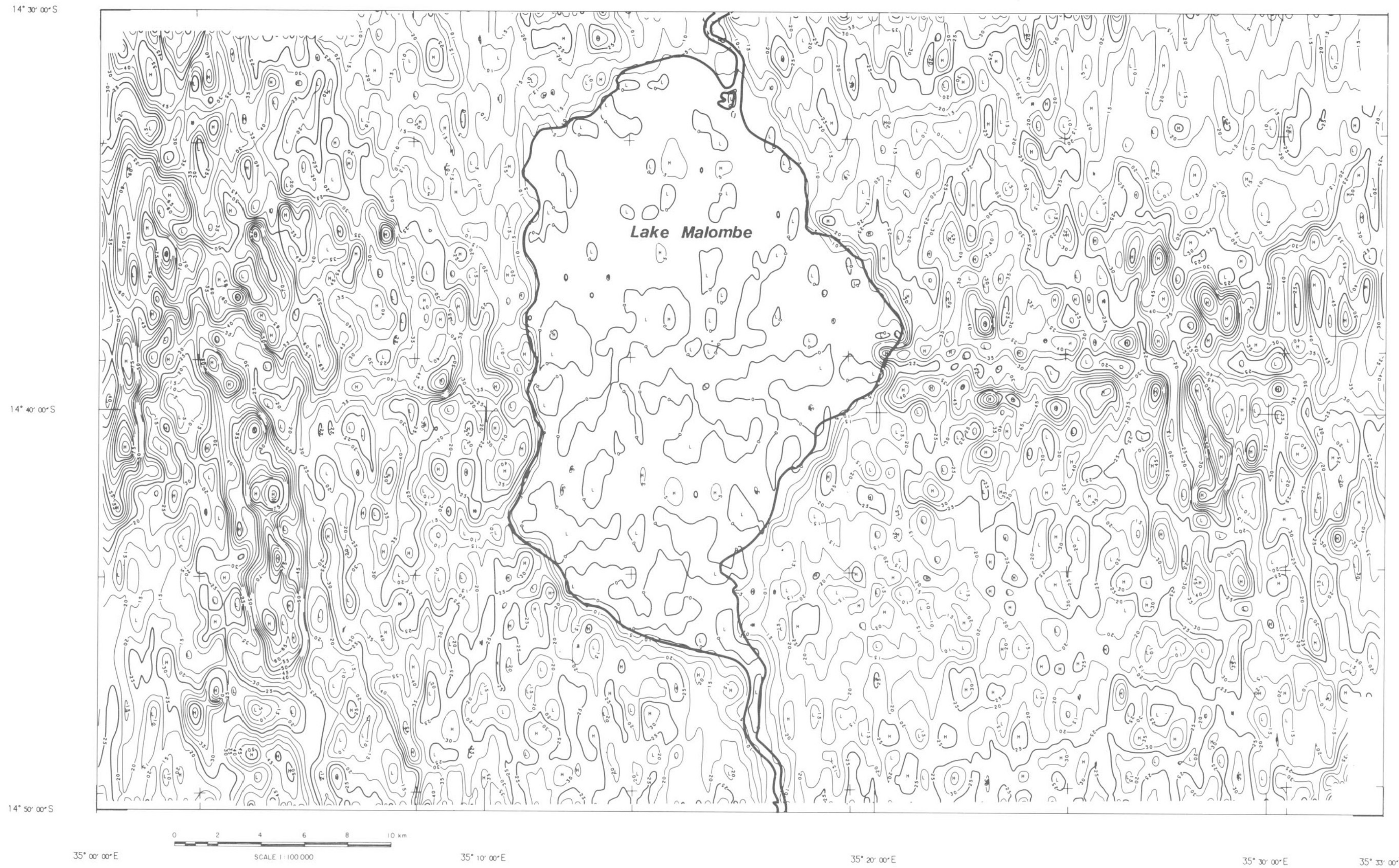

Figure 14. The final corrected uranium count rate map for the Lake Malombe area using a 201 point filter.

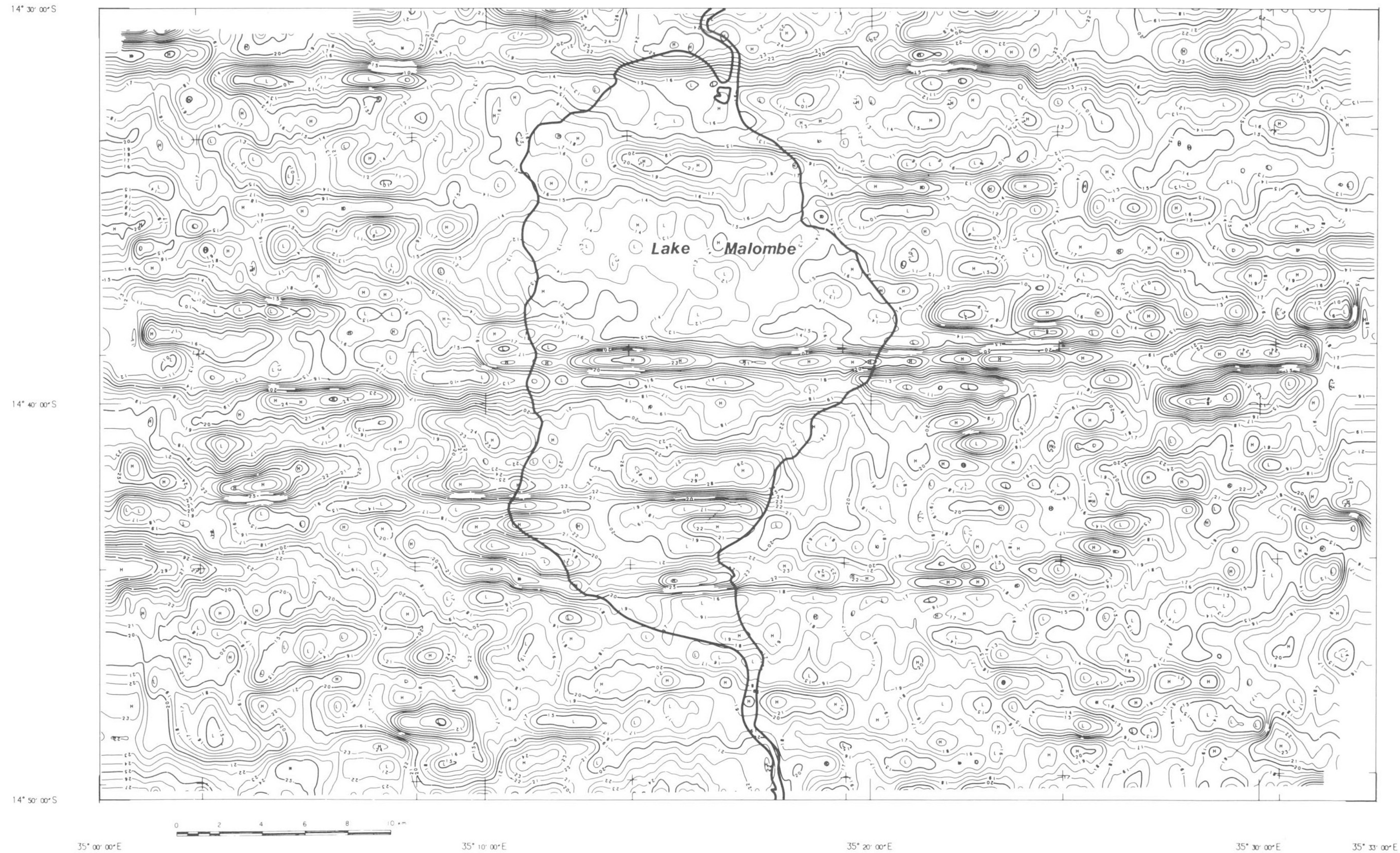

Figure 15. The background uranium map for the Lake Malombe area using a 51 point filter.

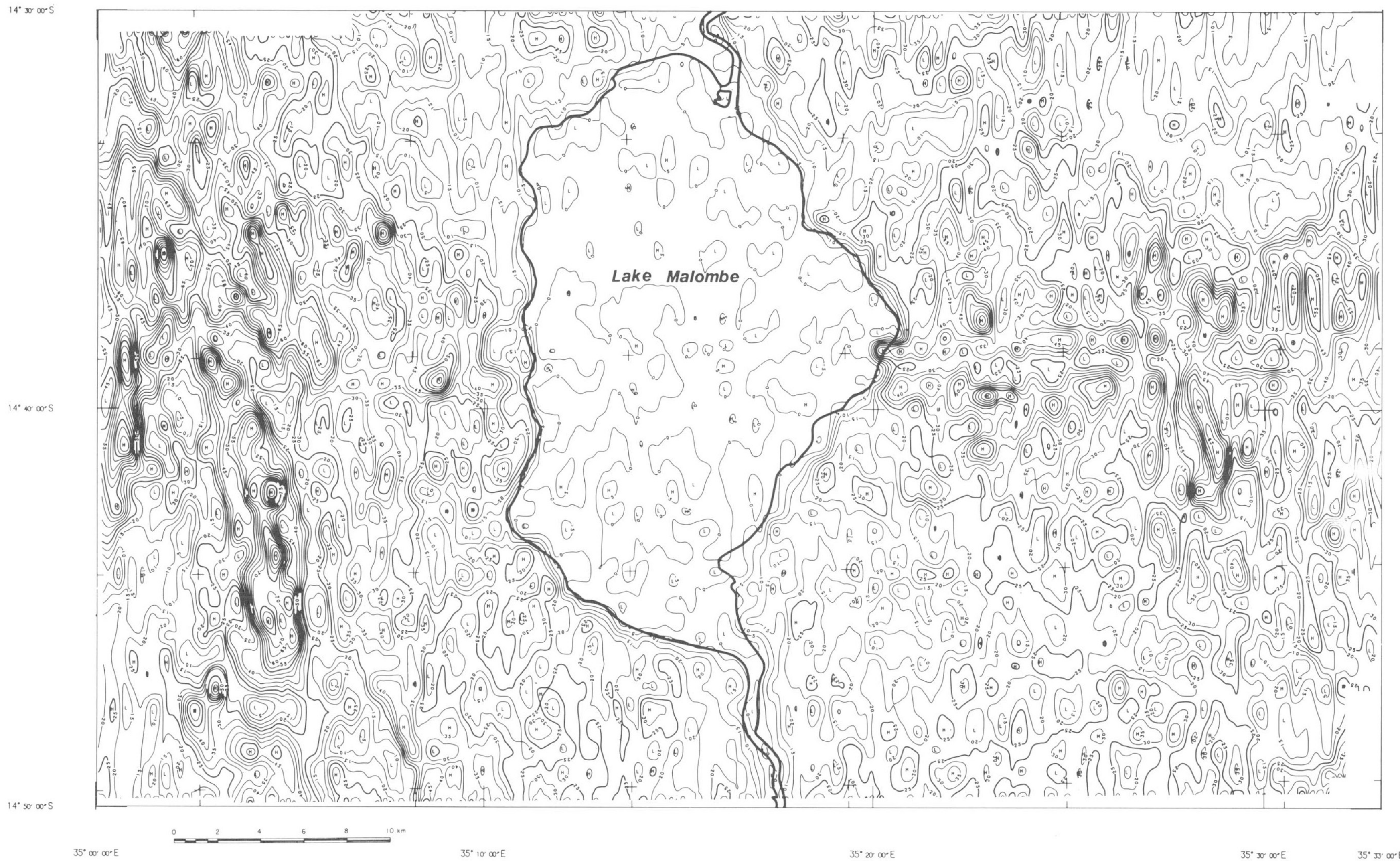

Figure 16. The final corrected uranium count rate map for the Lake Malombe area using a 51 point filter.

Figure 17. The uranium-to-thorium count rate ratio map for the Lake Malombe area.

The background map (Fig. 13) obtained using a 201 point running average filter, clearly identifies the days with different backgrounds. As expected, this is not quite so evident in the 51 point background map (Fig. 15) because of its increased noise level, which results in contours crossing areas flown on different days. For both maps the background remains constant across the shoreline of the lake, strongly suggesting the calibration constants derived from the Lake Chilwa area are also applicable for the Lake Malombe area. This would be expected if no system changes had occurred.

Apart from a level change between adjacent flight lines on the eastern shore of Lake Malombe, there is little difference between the two final uranium maps (Fig. 14 and 16) and the background appears to have been calculated correctly. The level change is fairly conspicuous on the maps obtained using the 201 point filter (Fig. 14). The particular flight which caused this problem was one with a high background which varied considerably over a short distance. This was partly the reason that a map was also produced using a shorter filter. However, the shorter filter did not completely solve the problem. One possible explanation is that there was an inversion layer close to the survey altitude where the daughter products of radon were concentrated. As the aircraft increased its altitude passing from the lake to the land, it could have passed through the inversion layer resulting in changes in the relationship between the up and down detectors for the atmospheric background component. If this was the case there is little that can be done except a manual level adjustment of the uranium background.

In comparing the maps using the two different length filters, there appears to be some advantage with regard to visual appearance in using the shorter filter. Although the background cannot be determined as accurately with the shorter filter, the increased statistical noise results in more contours crossing adjacent flight lines. The level changes that occur between adjacent flight lines, particularly in low count rate areas therefore tend to be obscured by the statistical noise in the calculated uranium background.

A uranium-to-thorium ratio map was also produced. Such maps are generally more sensitive to background errors. This ratio map shown in Figure 17 has no obvious visual defects and provides further evidence that the background can be determined reliably.

COSMIC-RAY BACKGROUND CORRECTIONS

In the analysis of the Malawi data from the Lake Chilwa and Lake Malombe areas, no corrections were applied for cosmic-ray background increases with altitude because there were only minor altitude variations within the two areas. Any minor cosmic-ray background variations would probably not be distinguishable on the final map because topographic level changes are generally related to geology and not to a particular flight line. In mountainous areas however, cosmic-ray background corrections can be important, especially if quantified gamma-ray data are required. In this section we show how these corrections can be applied.

Cosmic-ray window method

One method of carrying out cosmic-ray background corrections is to use a high energy cosmic-ray window from 3 to 6 MeV (Geometrics, 1979; Burson et al., 1972). This window is high enough in energy that it is not influenced by changes in the radioactivity of the ground or the air. It can be used as a monitor of the cosmic-ray contribution to any of the standard gamma-ray windows shown in Table 1 since the cosmic-ray spectrum remains the same shape at any altitude (Purvance and Novak, 1983). In practice there is no need to restrict the cosmic-ray window from 3-6 MeV. The cosmic-ray background can be monitored by recording all counts above 3 MeV. This has the advantage of increasing the cosmic-ray count rate approximately four times.

In utilizing the cosmic-ray window, it is necessary to carry out a series of tests at high altitude, to establish the relationship between the cosmic-ray window and the standard potassium, uranium, thorium and total count windows. This is normally done by flying at very high altitude, above the influence of decay products of radon in the air. Alternatively, the measurements can be carried out over the sea, well away from the land, preferably when there is an on-shore breeze.

Figures 18 and 19 show the results of a series of measurements flown between 1500 m and 4500 m (5000 to 15000 ft.) over the ground in Morocco. The system used had a volume of approximately 17 litres. The clear linear relationship between the cosmic-ray window from 3 to 6 MeV and the four standard windows shows that any effects of radon in the air are minimal. Based on such linear relationships, it is a simple procedure to incorporate cosmic-ray background variations into the calculation of the uranium background.

For the Malawi data, the calibration constants used to derive the atmospheric background equation (14) were obtained from flights over Lake Chilwa, which is at an altitude of approximately 500 m above sea level. Consequently, any atmospheric background corrections are strictly only valid for surveys flown at this altitude. However, by using a cosmic-ray window, the count rates measured at altitudes higher than 500 m can be reduced to their value at 500 m by using linear equations such as those shown in Figures 18 and 19. The actual equations will depend on the volume of the detectors and the particular aircraft.

Suppose the cosmic-ray window count rate, C, is related to the upward uranium window count rate u, and the downward uranium and thorium window count rates U and T by the equations:

$$u = m_u C + b_u \quad (15)$$

$$U = m_U C + b_U \quad (16)$$

$$T = m_T C + b_T \quad (17)$$

where m_u, m_U and m_T are constants and b_u, b_U and b_T are the aircraft backgrounds in the respective windows.

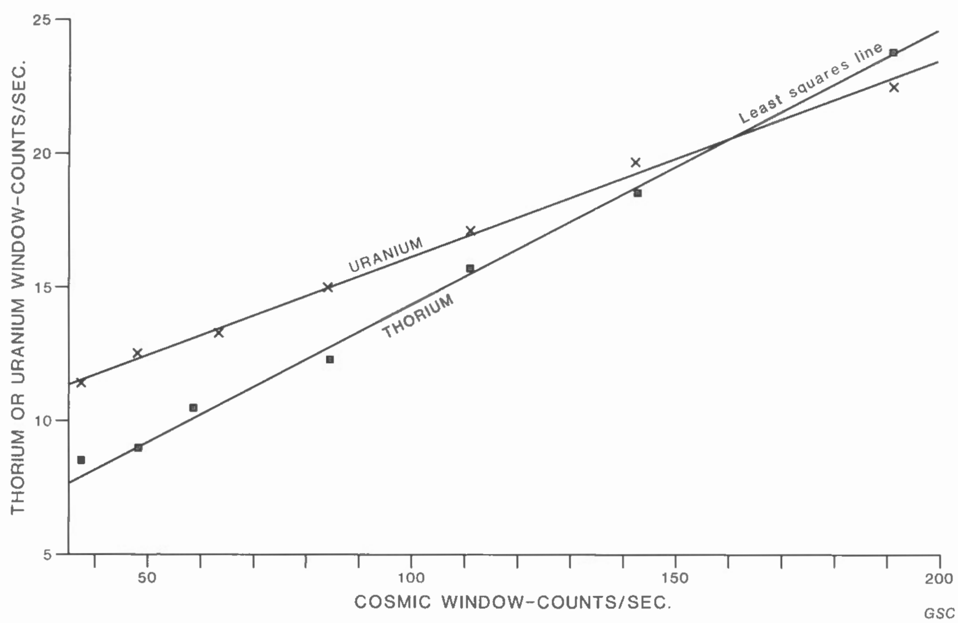

Figure 18. The variation of the uranium and thorium window with the cosmic-ray window count rates.

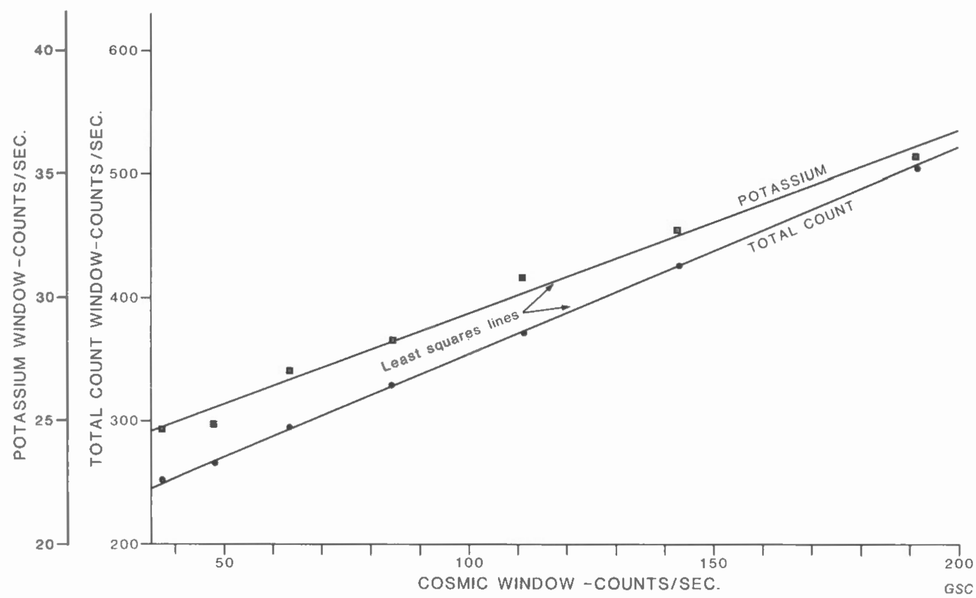

Figure 19. The variation of the potassium and total count window with the cosmic-ray window count rates.

The calculated uranium background at 500 m (U_{B500}) can be calculated directly from equation (14) by replacing the three window count rates u, U and T by:

$$u = u_h - (C_H - C_{500}) m_u \quad (18)$$

$$U = U_H - (C_H - C_{500}) m_U \quad (19)$$

$$T = T_H - (C_H - C_{500}) m_T \quad (20)$$

where C_H is the observed cosmic-ray window count rate at altitude H above sea level and C_{500} is the measured cosmic-ray window count rate at 500 m. u_H, U_H and T_H are the observed upward and downward uranium and thorium window count rates at altitude H.

The uranium background, U_{BH} at altitude H, may then be calculated using equation (14) and equations (18) to (20). It can easily be shown to be given by:

$$U_{BH} = 5.35u_H - 0.142U_H - Q.0951T_H + AC_H + B \quad (21)$$

where A and B are constants which will depend on the characteristics of the system. This equation is identical to equation (14) apart from the addition of a linear cosmic-ray term whose magnitude depends on the increase in the cosmic-ray window count rate at the survey altitude from the value at 500 m.

An alternative technique of correcting for cosmic-ray background increases with altitude is to first remove the entire cosmic-ray component and aircraft background from the upward and downward windows using equations (15) to (17). The atmospheric background component due to radon daughter products in the air can then be calculated separately using modified forms of equations (8) and (14) (Geometrics, 1979).

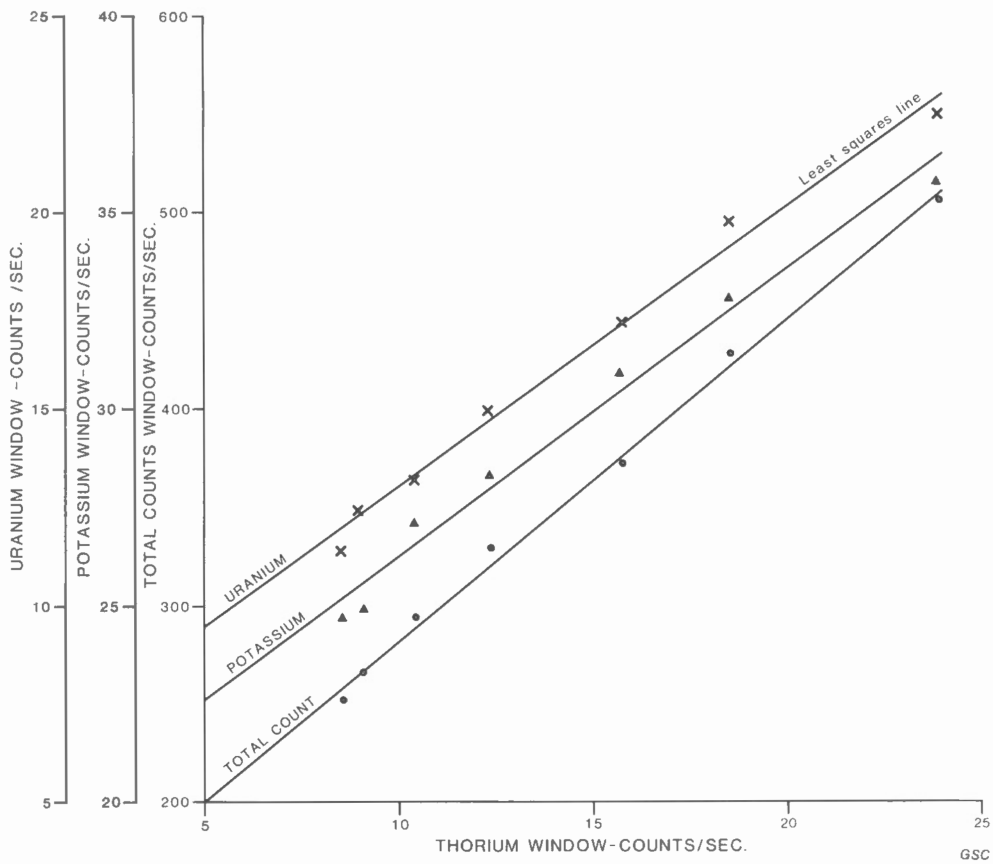

Figure 20. The variation of the uranium, potassium and total count window with the thorium count rate.

Barometric altitude method

An alternative method of carrying out cosmic-ray background corrections makes use of the barometric altimeter to determine the variation of the over water thorium window count rate with altitude. From the experimentally measured cosmic-ray spectral shape, the variations of the potassium, uranium and total count window with altitude can then be determined.

In Figure 20 the relationships between the thorium window count rate and the other three window count rates are shown for the same 17 litre system flown in Morocco (Fig. 18 and 19). The relationship between the thorium window and the other three windows was found to be:

$$U = 0.715T + 5.87 \quad (22)$$

$$K = 0.727T + 19.0 \quad (23)$$

$$Int = 16.33T + 120.3 \quad (24)$$

The excellent correlation (R>0.99) for all three equations is a good indication that there were no variations of radon daughter concentrations at the altitudes flown. From these equations, it is a simple matter to correct any of the window count rates measured at any one altitude to another altitude, provided the relationship between the thorium count rate and barometric altitude is known.

Experimentally, it is found that the over water thorium window count rate T, is related to the barometric altitude H, by the equation:

$$T = A \exp(\mu H) + B \quad (25)$$

when A, μ and B are constants. Figure 21 shows this relationship for the 17 litre system.

A simple practical way to determine the constants A, μ and B is to estimate the count rates at three different altitudes, X, X + h and X + 2h. If the thorium count rates at these altitudes are T_1, T_2 and T_3 respectively,

$$B = \frac{T_1T_3 - T_2^2}{T_3 + T_1 - 2T_2} \quad (26)$$

$$\mu = \frac{loge\ ((T_3 - T_2)/(T_2 - T_1))}{h} \quad (27)$$

$$A = (T_1 - B) \exp(\mu X) \quad (28)$$

Using the data presented in Figure 21 for altitudes of 1524 m, 3048 m and 4572 m (5000, 10000 and 15000 ft.), the variation of the thorium window count rate with barometric altitude is given by:

$$T = 0.6075 \exp(0.000732\ H) + 6.65 \quad (29)$$

where H is in metres.

This equation was derived from a series of measurements over the ground. To avoid detecting any thorium ground radiation, only data above 1500 m was used. In practice, it would be better to derive the equation from overwater measurements which cover the range of topographic relief of the survey area.

By substituting equation (29) into equation (22) an exponential expression is found for the cosmic-ray variation of the uranium window count rate with barometric altitude. It is given by:

$$U = 0.715 \times 0.6075 \exp(0.000732\ H) + \text{constant} \quad (30)$$

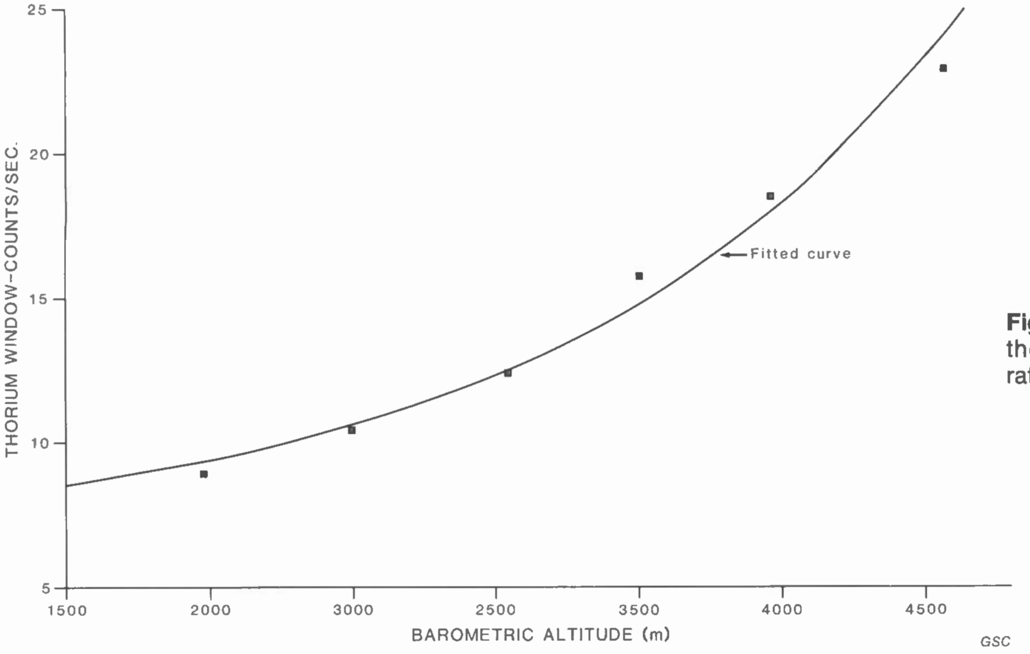

Figure 21. The variation of the thorium window count rates with barometric altitude.

Because of the presence of daughter products of radon which tend to be concentrated at lower altitudes, this expression normally cannot be derived by flying over water in the ranges of altitude to be encountered during the survey.

From equation (30) the uranium window count rate, U_H at an altitude H can be readily calculated at 500 m. Similarly the upward-looking detector count rate and the thorium window count rate can be normalized to 500 m, the altitude for which the upward-looking detectors were calibrated. The atmospheric uranium background can then be calculated using equation (14) and then corrected back to the original measurement altitude by making use of equation (30). The equation for the uranium background U_{BH}, at altitude H, is found to be of the form:

$$U_{BH} = 5.35\ U_H - 0.142\ U - 0.0951 + A \exp(0.000732\ H) + B \quad (31)$$

where A and B are constants. This is similar to the original equation (14) apart from the addition of the exponential term.

Comparison of cosmic correction methods

Based on our experience of correcting gamma-ray data for cosmic-ray background increases with altitude, the cosmic-ray window method has several practical advantages over the barometric altimeter method.

1) The relationship between the barometric altimeter and the thorium count rate is an exponential and therefore more difficult to derive than the linear relationship between the cosmic-ray window and the standard four windows.
2) The calibration of the barometric altimeter method is a two-stage procedure. The exponential variation of the thorium count rate with altitude must first be derived, followed by the linear relationship between the thorium window and the other windows. The calibration for the cosmic-ray window method is a simple single step procedure.
3) After the calibration has been completed, the cosmic corrections are easier to apply with the cosmic-ray window method because of the simple linear relationships.
4) One possible disadvantage of the cosmic window method is the counting statistic error associated with the cosmic-ray count rate. However, in the 3-6 MeV window the count rates are sufficiently high that even correcting for cosmic-ray background changes on a second-by-second basis results in errors of less than one count per second in the uranium channel for a 50 litre high sensitivity system. In practice there is no need to restrict the cosmic-ray window from 3-6 MeV. By recording all counts above 3 MeV, the cosmic-ray count rate is increased approximately four times which would reduce the errors even further.
5) The cosmic-ray window method also allows for small changes in the solar cosmic-ray flux due to latitude and solar cycle variations (Burson et al., 1972). This could be important for surveys carried out at high altitudes.

ALTERNATIVE BACKGROUND MEASUREMENT PROCEDURES

We have shown that the upward-looking detector data can be used to monitor atmospheric background variations. There are, however, two other possible alternative methods which could be used and in some cases have been incorporated into airborne survey contract specifications.

The first method consists of flying at high altitude above the ground, generally around 700 m. At this altitude, it is considered that the ground radiation is reduced

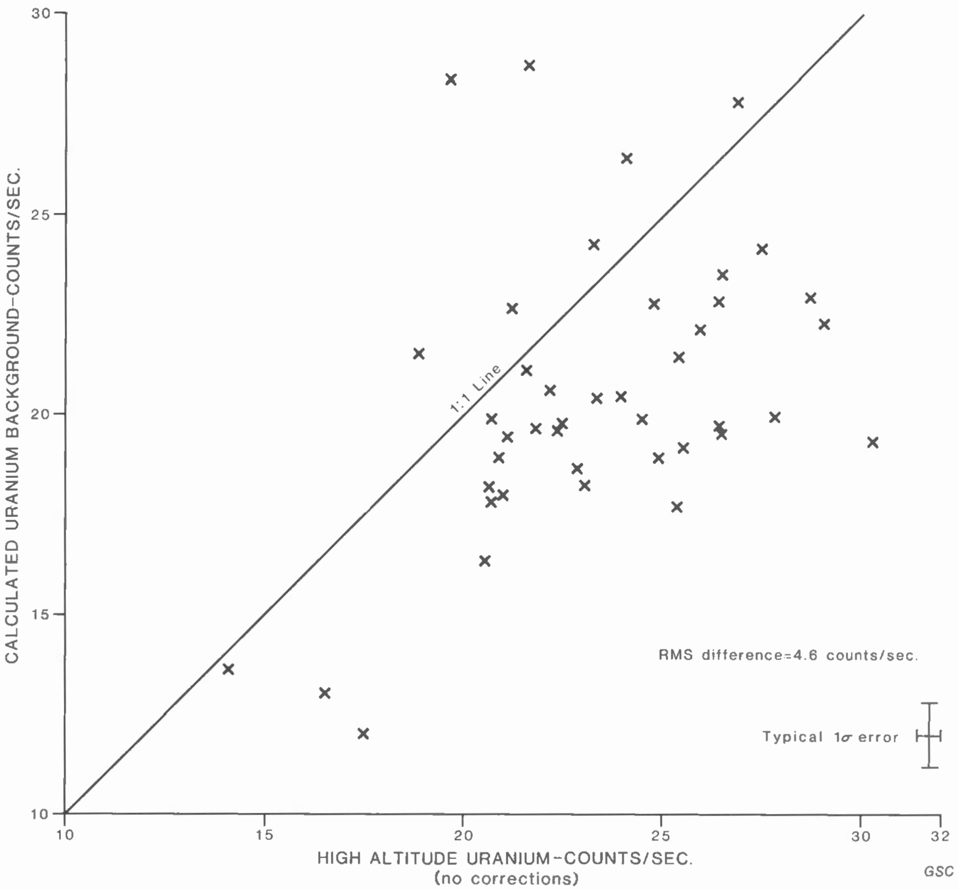

Figure 22. The variation of the uranium count rate at an altitude of approximately 650 m (2000 ft) with the background calculated from the upward looking detectors.

to negligible proportions and the radiation detected is the total background (atmospheric, cosmic plus aircraft) which can be applied at the survey altitude.

The second method consists of repeating flights over the same test line. It is assumed that any variations in the measured radioactivity over this test line can be attributed to atmospheric background variations. By periodically flying over a lake on the same day as the test line is flown, the daily test line variations can then be used to determine the over water background on any particular day.

During the survey operations in Malawi, it was standard practice to collect data for both of these methods for possible use in the compilation procedures. High altitude data was recorded normally once during each sortie. Generally two sorties were flown each day, and were flown at altitudes from 690 to 740 m above the ground. For each base of operations, a test line was selected and was generally flown at the beginning and end of each sortie.

In this section we compare the results of these two methods with those obtained from the upward-looking detector data which has been shown to be reliable.

High altitude method

In Figure 22 we compare the high altitude average uranium window count rate for the downward-looking detectors with the uranium background from the upward-looking detector data. This background was obtained from survey data flown at the closest time to the high altitude flights. In attempting to explain the large scatter in the results, it was realized that there were some significant corrections which needed to be applied to the high altitude data before the data could be properly compared.

In Figure 23, the high altitude thorium window count rate is plotted against the barometric altitude. The results show that variations in the thorium window count rate are due to differences in the barometric altitude which varies from around 1200 to 2250 m. This is to be expected from equation (29) which shows the thorium background varies exponentially with altitude. This would also be true for the uranium background as indicated in equation (30).

The results in Figure 23 also show that even at the same barometric altitude, the thorium window shows some variation. This was felt to be due to radiation from the ground being detected at the altitude flown. Changes in the altitude of the aircraft above the ground and the radioactivity of the ground itself would cause this component of ground radiation to vary for the same barometric altitude. This thorium component would contribute to the uranium window due to incomplete absorption of the high energy gamma radiation. There also remains the possibility that some component of ground radiation from uranium can be detected in the uranium window.

On Figure 23 the exponential curve indicates the estimated variation of the thorium background with barometric altitude. This curve was calculated to pass through the

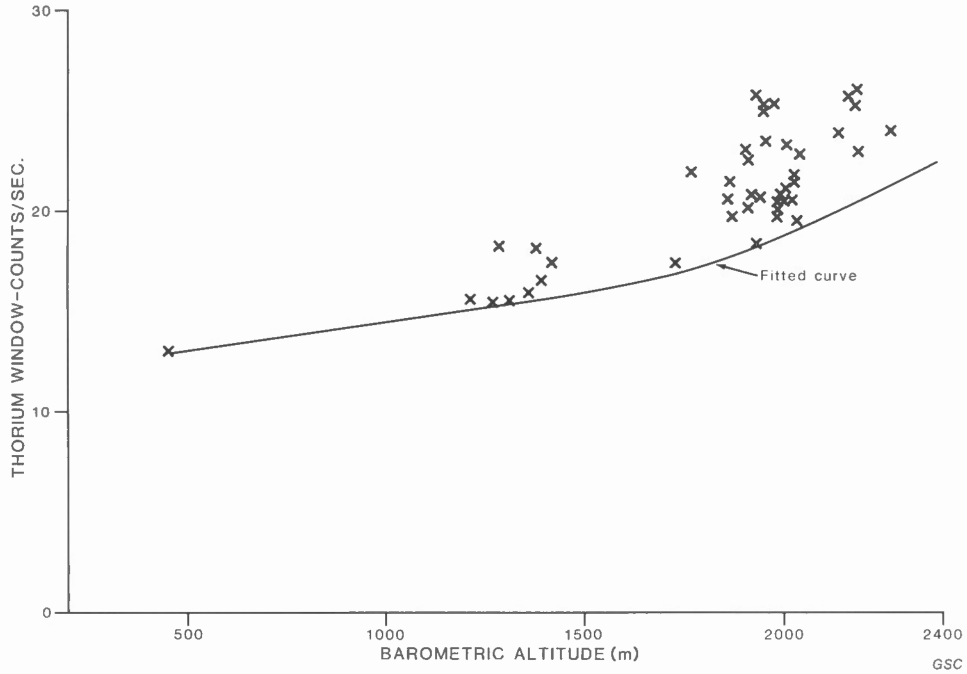

Figure 23. The variation of the high altitude thorium count rate with barometric altitude.

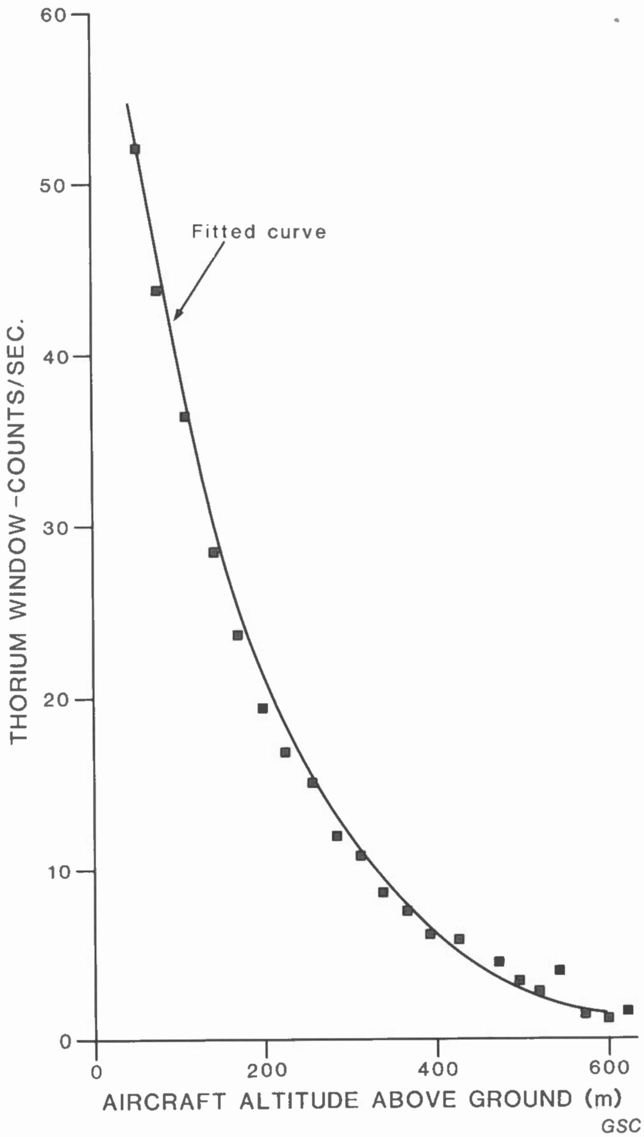

Figure 24. The thorium count rate variation with altitude above the ground.

known value of the over water thorium background at 500 m as well as the lowest points of the high altitude tests. Consequently at any altitude, the difference between the exponential curve and the measured value would be solely due to thorium gamma radiation from the ground. Figure 23 indicates that this ground component varies between zero and 7 counts per second.

In order to assess the significance of thorium ground radiation to the high altitude results, data were analyzed from a series of flights at altitudes from 80 to 620 m over the ground, with the GSC gamma-ray spectrometer system. The flights were carried out over a large island in Lake Ontario and continued over the water so that the overwater background could be measured at the same altitude. The thorium window count rates, T, are shown in Figure 24 after subtracting the background over Lake Ontario. An exponential curve has been fitted to the data and is given by:

$$T = 71.7\exp(-0.00624 \times H) \qquad (32)$$

where H is the height in metres above ground.

From these results, the thorium count rate at an altitude of 123 m above the ground is reduced to approximately 3 per cent at an altitude of 700 m. In Malawi, the thorium window count rate at the survey altitude can typically vary between 50 and 200 counts per second. This would correspond to variations in the high altitude thorium count rate from 1.5 to 6 counts per second which is the typical range indicated in Figure 23. Based on the estimated shape of the thorium spectrum, at 700 m (Grasty, 1985), approximately 0.6 counts are detected in the uranium window for every count in the thorium window. Consequently we would expect anywhere from 1 to 4 counts per second in the uranium window due to thorium gamma radiation from the

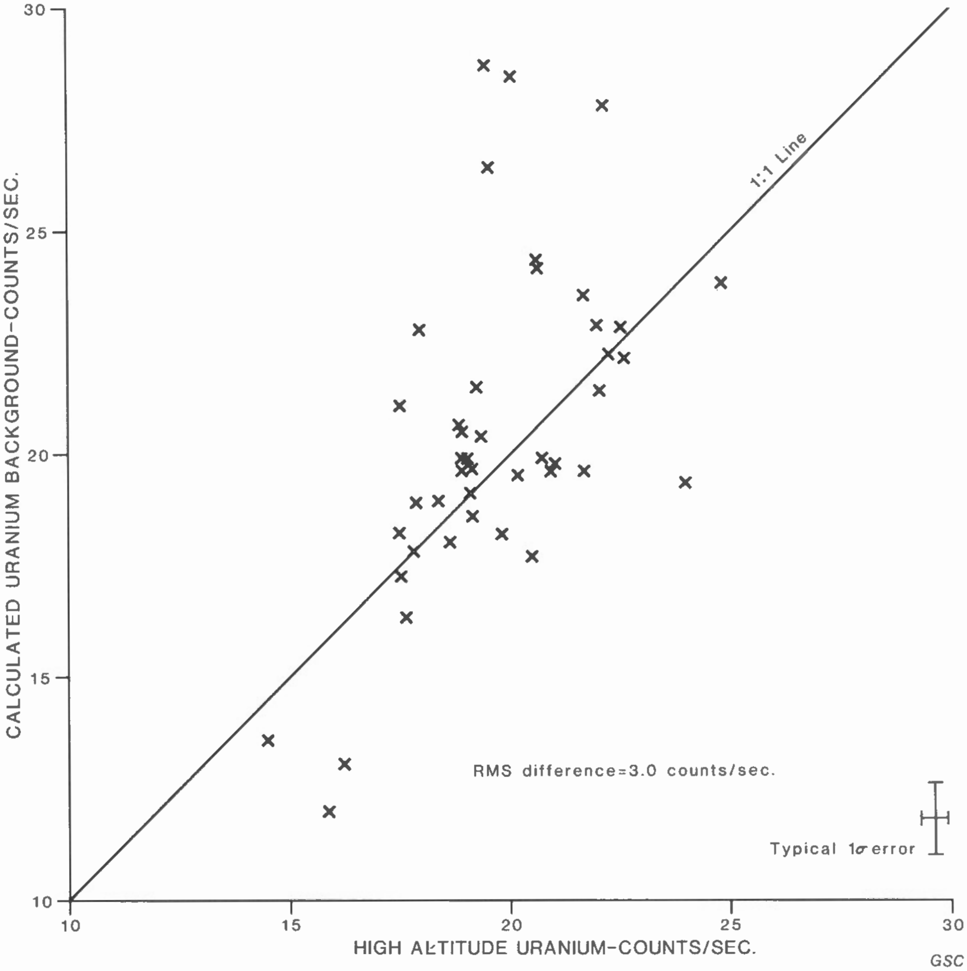

Figure 25. The calculated uranium background at 1500 m compared with the background measured with the upward-looking detectors.

ground. An analysis of the potassium and uranium results from the test flights over the island in Lake Ontario showed that the effects of direct ground radiation from uranium can be neglected, because the lower energy gamma radiation from uranium is almost completely absorbed in the air.

In deciding whether the high altitude results can be used to estimate the background at the survey altitude, we have shown that two basic corrections must be applied to the data. The uranium count rates must be corrected for changes in barometric altitude and also be corrected for thorium ground radiation that has been scattered into the uranium window. The original data shown in Figure 22, were first normalized to a barometric altitude of 1500 m using the exponential shown in Figure 23 assuming 0.7 cosmic-ray counts were detected in the uranium window for every count in the thorium window. This was the value indicated in equation (22) for a similar system used in Morocco. From Figure 23 we also estimated the thorium contribution and the corresponding scattered uranium contribution using an estimated stripping ratio of 0.6 for these high altitude flights. It was found that differences in the barometric altitude between the various flights could cause errors as high as 4.5 counts per second in the uranium window which is similar to the errors arising from scattered thorium in the ground.

In Figure 25, the corrected high altitude uranium window data are compared with the uranium background at the survey altitude of 123 m as calculated from the upward-looking detector data. The root mean square (RMS) difference between the high altitude results and those at survey altitude is now reduced from 4.6 counts per second to 3.0 counts per second. After correction, the high altitude results are much closer to the 1:1 line, because the cosmic and thorium contributions have been removed.

In spite of these corrections, in some instances there are considerable differences between the two measurements. Analysis of the four major outliers showed that the upward-looking detector data were obtained from early morning flights when the uranium backgrounds at the survey altitude were amongst the highest recorded in Malawi. Presumably, the radon daughter products were concentrated near the ground, in the still air conditions. Consequently the upward-looking detector measurements at the survey altitude are considerably higher than the measured value of 700 m. When the four outliers are removed the RMS difference between the two sets of results reduces from 3.0 to 2.0 counts per second.

Based on these results we have concluded that provided the air is well mixed, measurements at an altitude of around 700 m can provide reasonable estimates of the

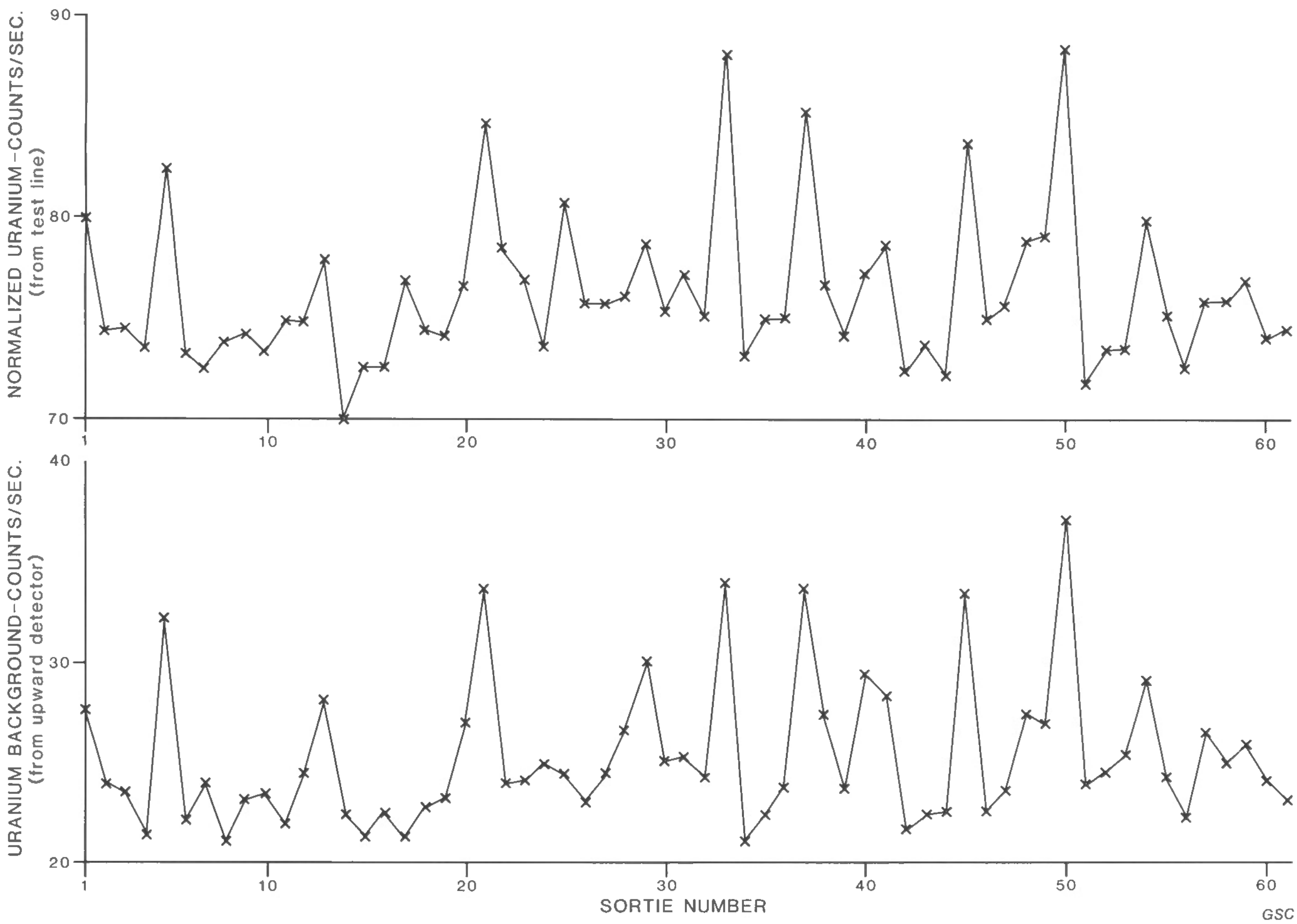

Figure 26. The variation of the normalized uranium count rate over a high activity test line for different sorties compared with the background calculated Sfrom the upward detectors.

background at the survey altitude. However, in using the high altitude data, corrections must be applied for cosmic-ray variations with altitude and also for scattered thorium gamma radiation from the ground. It should also be mentioned that if there are any variations in atmospheric radioactivity with time or location, one high altitude measurement will not suffice.

Low altitude test lines

We have analyzed approximately 170 data sets from four test lines flown from different bases in Malawi. These test lines were almost always flown at the beginning and end of each sortie, with two sorties generally being flown each day.

In developing a method of using these data to monitor atmospheric background variations a major problem to overcome is the difficulty of flying over the lines in exactly the same place. This was found to be particularly important in areas of variable radioactivity. An analysis of the daily thorium count rate showed that a large part of the variations in the measured count rates along three of the four test lines was due to difficulties in reproducing the aircraft flight path. The thorium count should have stayed relatively constant apart from minor fluctuations due to soil moisture changes.

The problem of the variability in the measured ground radioactivity was largely overcome by a simple normalization procedure. It was assumed that any daily variations in the thorium window count rate would result in a proportional change in the uranium window count rate. These thorium variations were converted to an equivalent uranium count rate correction based on the uranium-to-thorium count rate ratio of the ground. This ratio requires a measurement of the uranium background which was obtained from one flight using the upward detectors.

In figure 26 the normalized uranium count rate is compared with the uranium background calculated from the upward-looking detector data for all sorties over one test line. This particular test line had the highest radioactivity of all four test lines analyzed and also had a large variation in the thorium count rate. The data clearly show a good correlation between the two data sets. It is interesting to observe that early morning flights which generally occur every fourth sortie normally show a much higher count rate than the flights later in the day.

From the normalized observed uranium count rate, the uranium background can be calculated provided the background is known on one particular day. Consequently in theory it is only necessary to make one overwater background to tie in the normalized low altitude test line data to

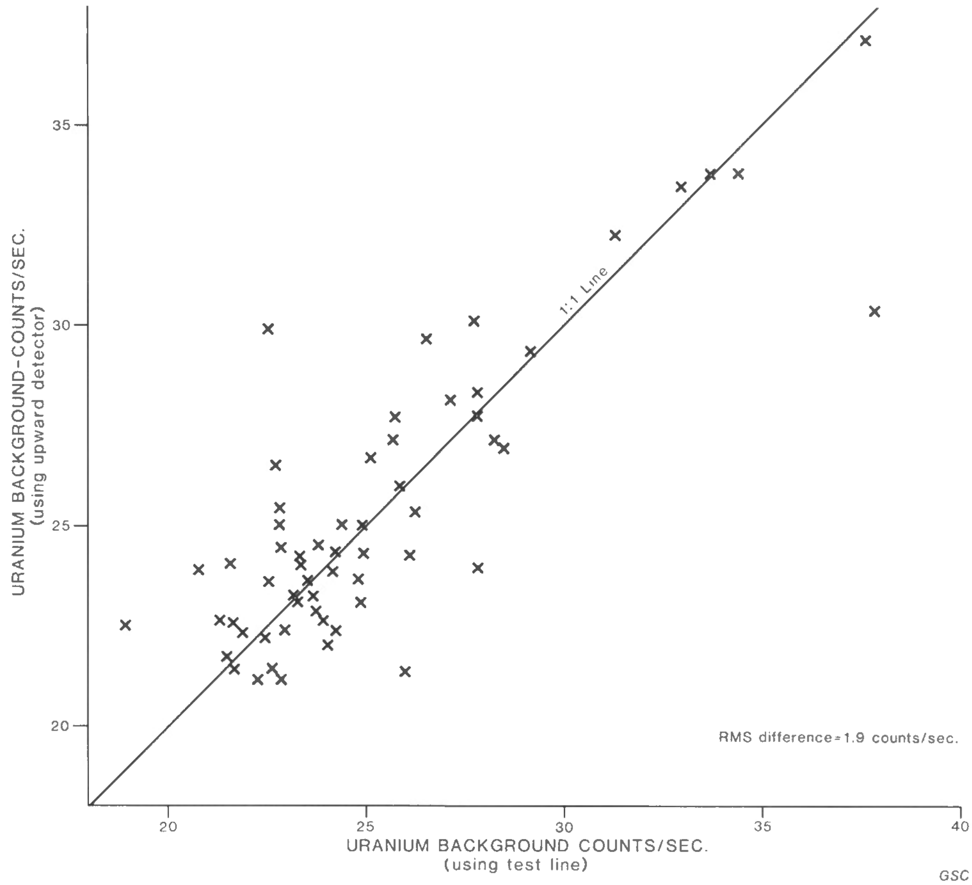

Figure 27. A comparison of the background calSculated from a high activity test line with the background from the upward detectors.

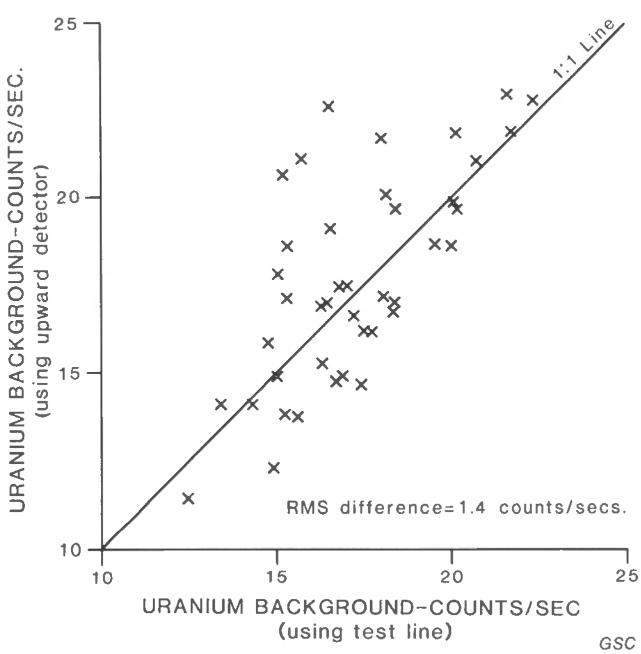

Figure 28. A comparison of the background calculated from a low activity test line with the background from the upward detectors.

a background. In practice, it would be desirable to carry out several such over water flights. In Figures 27 and 28, the uranium background from the upward-looking detector data is compared to the background obtained from the normalized low altitude test lines. In these examples, the background for one flight over the test line was calculated from the upward detector data to obtain the uranium-to-thorium count ratio for the ground. Figure 27 is taken from the same data shown in Figure 26, whereas Figure 28 is from a low altitude test line of much lower and uniform radioactivity. The average concentrations of uranium on the two lines are estimated to be 6 ppm and 0.6 ppm.

In the case of the low radioactivity test line the root mean square difference between the two backgrounds has a value of 1.4 counts per second which is virtually the same value with no normalization of the observed uranium count rate. This is because the line is uniform along its length (and presumably either side of the line) and therefore the aircraft flight path is not critical. For the more radioactive and inhomogeneous test line, the root mean square difference is reduced significantly from 3.3 to 1.9 counts per second after normalization.

Based on our studies of the low altitude test flights in Malawi, we have come to the following conclusions:

1) Low altitude test flights can be used to monitor atmospheric background provided the background stays relatively constant on a particular day and does not vary from place to place.

2) The best line to choose is one which is low in radioactivity and is in a homogeneous area so that the flight path is not critical.
3) Several measurements of over water background should be used to tie in the observed uranium count rate over the test line to the uranium background and to determine the uranium-to-thorium count rate ratio of the line.
4) If the line is inhomogeneous, as evidenced by the variable thorium count rate, improved results can be obtained by normalizing all observed counts to a constant thorium value using the uranium-to-thorium count rate ratio of the line.

DETECTOR CONFIGURATION OPTIMIZATION

We have shown that with the detector configuration illustrated in Figure 1, the upward-looking detector data can be used to monitor atmospheric background. However, one drawback of such a system is the extra weight of the additional detectors and lead shielding which is of major concern in airborne survey operations. One important question that needs to be answered is how significant are the lead shields and are they really necessary? Based on a comparison of our experimental results and some simple calculations we are able to show that the lead shields, which weigh a total of 68 kg, serve very little purpose. By removing the lead shields, it can be shown that the number of counts recorded in the up detectors will not change significantly since most of the radiation is thorium and uranium gamma radiation from the ground, which has not passed through the down detectors and the lead shield.

The observed count rate at a height h above the surface of a uniformly radioactive ground is given by:

$$N = N_o\ E_2\ (\mu_A{}^H) \qquad (33)$$

N_o is the count rate at ground level, μ_A is the linear attenuation coefficient in air of the gamma radiation concerned and E_2 (x) is given by:

$$E_2(x) = \int_{t=1}^{\infty} \frac{e^{-xt}dt}{t^2}$$

If the gamma radiation also passes through additional absorbers of sodium iodide and lead the observed count rate will be given by:

$$N = N_o\ E_2\ (\mu_A H + \mu_N H_N + \mu_L H_L) \qquad (34)$$

where H_N and H_L are the thickness and μ_N and μ_L the linear attenuation coefficients of sodium iodide and lead respectively.

The densities and attentuation coefficients of air, sodium iodide and lead are shown in Table 3 for energies of 1.76 and 2.62 MeV corresponding to the uranium and thorium windows. These values can be used to determine the effect on the detected window count rates of the different layers of absorbing material. The results of these calculations are shown in Table 4, which were evaluated from equation (34) by numerical integration and are for unscattered primary radiation. From this table we are able to compare the observed count rate in the upward detectors calculated using equation (13) with the theoretical values calculated from the downward detector count rates. To simplify the calculations, the comparisons are performed separately for uniform sources of uranium and thorium.

Table 3. Physical properties of absorbing materials

Material	Density	Mass attenuation coefficient (cm^2g^{-1})		Linear attenuation coefficient (μ)	
	$g cm^{-3}$	1.76 MeV	2.62 MeV	1.76 MeV	2.62 MeV
Air (NTP)	0.00129	0.0479	0.0391	0.00618 m^{-1}	0.00504 m^{-1}
NaI	3.67	0.0438	0.0394	0.161 m^{-1}	0.144 cm^{-1}
Lead	11.35	0.0489	0.0440	0.555 cm^{-1}	0.499 cm^{-}

Table 4. Attenuation effect of absorbing materials

Energy		Thickness of absorbers (H)		$\Sigma\mu H$	(1) E_2 (μH)
(MeV)	AIR	NaI	Pb		
1.76	123 m	—	—	0.76	0.215
1.76	123 m	10.2 cm	—	2.40	0.022
1.76	123 m	10.2 cm	1.91 cm	3.46	0.006
2.62	123 m	—	—	0.62	0.269
2.62	123 m	10.2 cm	—	2.09	0.034
2.62	123 m	10.2 cm	1.91 cm	3.04	0.010

(1) Fraction of ground level count rate.

Table 5. A comparsion of theoretical and observed upward detector count rates

Ground concentration	(1) Observed	(2) Theoretical (complete Pb & NaI) shielding	Unattenuated component (1) – (2)
1 ppm eU	0.233 c/s	0.041 c/s	0.192 c/s
1 ppm eTh	0.162 c/s	0.015 c/s	0.147 c/s

Table 6. Predicted upward detector count rates with no lead shield

Ground concentration	(1) Theoretical perfect NaI shielding	(2) Unattenuated component (Table 5)	Predicted value (1) + (2)
1 ppm eU	0.150 c/s	0.192 c/s	0.342 c/s
1 ppm eTh	0.051 c/s	0.147 c/s	0.198 c/s

For a 50L system flying at an altitude of 123 m, over a source of 1 ppm uranium in radioactive equilibrium, 8.8 gamma rays per second will be detected in the uranium window (Grasty, 1985). For a source of pure uranium, the thorium window count rate can be neglected. When completely shielded by 1.9 cm of lead and 10.2 cm of sodium iodide, the uranium count rates will be reduced by a factor of 0.006/0.215 (Table 4). Consequently, the observed count rate for a shielded 50L system will be 0.246 counts per second. Since the count rates in the windows are approximately proportional to detector volume (Lovborg, 1984), the theoretical up detector count rate will be reduced by a factor of 6 compared to a 50L system when it is completely shielded from direct radiation from the ground and is therefore 0.041 counts per second. Experimentally, equation (13) shows that the actual observed count rate for 8.8 counts per second in the downward detectors is 0.233 counts per second. This is almost six times as many gamma rays as predicted theoretically if the lead and sodium iodide were behaving as a perfect shield.

The observed and theoretical count rates for a perfectly shielded upward detector system can be calculated in a similar fashion for a pure source of thorium.

A 50L system flying at an altitude of 123 m over a source of 1 ppm thorium will detect 6.1 counts per second in the thorium window and 2.0 counts per second in the uranium window (Grasty, 1985). When completely shielded by 1.9 cm of lead and 10.2 cm of sodium iodide, the thorium count rate of a 50L system will be reduced by a factor of 0.010/0.269 (Table 4), corresponding to 0.227 counts per second. Since the count rates are proportional to volume, the thorium window count rate for a system with a volume of the upward detector system will be reduced by a factor of six with a resulting count rate of 0.038 in a thorium window. Although the upward detector system has only a uranium window, some counts will be detected because of incomplete absorption. Approximately 0.4 counts per second, can be expected in the uranium window for every count in the thorium window (Løvborg, et al., 1977). Consequently, if the upward detectors were perfectly shielded we would expect 0.015 counts per second when flying over a ground containing 1 ppm thorium. In practice, a significantly higher count rate is observed. Equation (13) shows that for 6.1 counts per second in the thorium window and 2.0 counts per second in the uranium window, a total of 0.162 counts per second will be observed in the uranium window of the upward detectors.

The observed and theoretical upward detector count rates for pure sources of uranium and thorium are presented in Table 5 which shows that the majority of the radiation detected in the upward-looking uranium window has not passed through the lead shield and the downward looking sodium iodide detectors.

Based on the data presented in Table 4, we can determine the effect on the observed count rate of removing the lead shield. The results are summarized in Table 6, in which we have assumed that the unattenuated component of the observed count rate remains the same. By comparing the observed count rates (Table 5), and the predicted count rates when the lead shield is removed (Table 6), we find that the count rates will increase by approximately 50 per cent for pure sources of uranium and 22 per cent for thorium.

In order to determine the effect of removing the lead shield on the measurement of the uranium background, it is necessary to make use of equation (9) which relates the variance in the measurement of the uranium background $\sigma^2 U_B$ to the upward and downward detector count rates u, U and T. Due to the magnitude of the various constants and the respective window count rates, equation (9) can be approximated by:

$$\sigma^2 U_B = \frac{u}{N(a_3 - a_1)^2} \qquad (35)$$

where a_1 is the up-to-down uranium window ratio for ground sources of bismuth-214 and a_3 is the ratio for airborne sources. From equation (13), a_1 has the value 0.0265 and from equation (1) a_3 has the value 0.2136. By substituting these values in equation (35), we obtain:

$$\sigma^2 U_B = \frac{28.6}{N} u \qquad (36)$$

By removing the lead shield, a_1 is the only term in equation (35) which will change significantly. From Tables 5 and 6, a_1 will increase in the ratio of 0.342 to 0.233 i.e. by a factor of 1.468, giving it a value of 0.0389. The error in the calculated value of the uranium background will then be given by:

$$\sigma^2 U_B = \frac{32.8}{N} u \qquad (37)$$

Both equations (36) and (37) depend on the count rate in the upward-looking detector u. However, by removing the lead shield, u will not change significantly. this is because the counts in the upward detector arise mainly from bismuth-214 in the air, cosmic radiation and the radioactivity of the aircraft. In addition, the component due to uranium and thorium in the ground is primarily radiation which has not passed through the lead shield and downward detectors (Table 5) and will therefore be unaffected by removing the shield.

A comparison of equation (36) with a lead shield and (37) without the shield, shows that by counting for only 15 per cent longer, to increase the number of one second samples, N, the same accuracy is attained in measuring the uranium background when the lead shield is removed. This minor increase in the averaging period, is unlikely to have any significant effect on monitoring the background. It can therefore be concluded that for the detector configuration used for the Malawi survey, as illustrated in Figure 1, there is no significant advantage in using lead shields.

The large component of ground radiation reaching the upward detector, is undoubtedly because of the separation of the up and down detectors (Fig. 1), which allows the up detectors to 'see' the ground. By reducing this separation, the ground component could be reduced and would be expected to compensate for the small effect of removing the lead shields.

CONCLUSIONS AND RECOMMENDATIONS

Analyses of airborne gamma-ray data from Malawi have shown that atmospheric background variations can be successfully monitored using upward-looking detectors which are partially shielded from ground radiation by a 2 cm thick lead shield and 10 cm of sodium iodide. Theoretical studies showed that the lead shielding was unnecessary for the particular detector configuration studied because most of the radiation received by the upward detectors was direct radiation from the ground which had not passed through the lead shield.

Based on our studies we would recommend the following detector configuration for airborne gamma-ray surveys where atmospheric background is to be monitored.

1) 50L of downward-looking sodium iodide detectors for monitoring ground radiation. These would normally consist of three boxes of four 10.2 × 10.2 × 40.2 cm detectors.
2) Two single sodium iodide detectors, 10.2 × 10.2 × 40.6 cm for monitoring atmospheric background. These should be placed on top of two downward-looking detector boxes with the minimum clearance possible to reduce direct radiation from the ground
3) A lead shield between the upward and downward detectors is unnecessary.
4) A single energy window from 1.66 to 1.86 MeV for the upward detectors is all that is required to monitor gamma radiation in the air.
5) An anticoincident circuit should be incorporated in the detector system to increase the shielding of the upward detectors by eliminating high energy gamma radiation that is recorded in both the up and down detectors. (The effect of this procedure was not studied but is simple to incorporate into the electronics of the system.)

The following calibration procedure is recommended for monitoring atmospheric background with this particular detector configuration.

1) Repeated flights should be carried out over a lake at the survey altitude to relate the upward and downward detector count rates for sources of atmospheric background radioactivity due to radon daughter products in the air.
2) The relationship between the up and down detectors for sources of ground radiation should be derived at the survey altitude and not at ground level using calibration pads. This is because the angular distribution of gamma radiation varies with altitude and calibration pads cannot be considered an infinite source of gamma radiation.
3) The up and down detector response should be derived separately for sources of thorium and uranium in the ground. This should be done by utilizing flight line sections with different proportions of uranium and thorium which are adjacent to a lake over which the background can be measured. Alternatively the over water background component can be removed by subtracting data from adjacent sections of a flight line.
4) Further theoretical and experimental studies are recommended to evaluate the effect of ground clearance on the calculated uranium background. If this effect is significant, it may be necessary to apply height dependent calibration constants.

The upward looking detector data were used to test two other methods of monitoring atmospheric background. Based on our studies we have found that in Malawi.

1) High altitude flights at 600-700 m above the ground require corrections for cosmic-ray increases with altitude and scattered thorium gamma radiation from the ground.
2) High altitude flights can still give erroneous backgrounds at the survey altitude even after the appropriate corrections have been applied. This was assumed to be because of non-uniform distributions of airborne radioactivity.

3) Repeated flights at survey altitude over a test line can provide reliable estimates of atmospheric background provided the data are normalized to a constant thorium value. This normalization procedure utilizes the uranium-to-thorium count rate ratio of the ground.to reduce the errors associated with deviations in the aircraft flight path.
4) The best test lines to use are those which are homogeneous and low in radioactivity.
5) Several measurements of over water background should be used to tie in the observed uranium count rate over the test line to the uranium background.
6) Test lines cannot be used if there are local or time variations of atmospheric background.

Cosmic-ray background increases with aircraft altitudes were also studied. It was found that cosmic-ray background could be successfully monitored by using a barometric altimeter or by means of a cosmic-ray window above 3 MeV. Based on our studies we recommend using the cosmic-ray window because this allows for variations in the cosmic-ray background due to solar activity and is more simple to calibrate and apply. A cosmic-ray window which records all counts above 3 MeV is preferred to one restricted to 3-6MeV because of the significantly increased count rates.

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