# An Airborne Gamma-Ray Snow Survey in the James Bay Region

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## ABSTRACT

A demonstration airborne gamma ray snow survey was carried out in the James Bay region of Quebec in 2002. Planned flight lines were flown in March 2002 under snow-covered conditions and re-flown, after-snowmelt, in early June 2002. The purpose of this survey was to demonstrate that the snow water-equivalent (SWE) could be measured in the test area using the airborne gamma ray survey technique. The SWE is calculated by monitoring changes in total gamma ray activity and gamma ray emissions from potassium and thorium. Eight survey lines, approximately 45 km in length and 500 m apart were flown at a survey height of 80 m and a speed of 190 km/h. A real time differentially corrected Global Position System (GPS) was used for navigation. While the snow survey was being flown, ground measurements of snow-water equivalent were carried out to verify the airborne results. One survey line was flown twice in March and twice in June to determine the repeatability of the measurements; as a result, an experimental error equivalent to 5 mm in SWE was estimated. In this area, the ground and airborne measurements of SWE were included in a range from 100 mm to 150 mm.

Keywords: gamma-ray spectrometry, SWE.

## INTRODUCTION

An accurate estimate of the distribution of snow water equivalent (SWE) is needed to forecast the run off from snowmelt, to regulate water storage in reservoirs and also for general hydrologic understanding of large catchment areas. Obtaining an accurate estimate involves considerable expense in labor and time because the distribution of snow is highly variable and many point measurements must be made. This is particularly true for areas like the James Bay region of northern Quebec where there is little or no easy access for taking the ground measurements.

In the 1960's, a SWE measurement technique based on the airborne measurement of the attenuation of natural gamma radiation by a snow cover was developed in Russia (Kogan et al., 1965). Following the successful application of the method in Russia, similar research was carried out in the United States (Peck et al., 1971), where the method is now routinely used by the National Weather Service (Carroll et al., 1999)), and in Canada, where a large experimental

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airborne gamma ray snow survey demonstrated the viability of the technique (Loijens and Grasty, 1973).

To investigate the potential of carrying out airborne gamma ray snow surveys in the James Bay region of Quebec, a small demonstration survey was conducted in 2002 to test the method and its application to a larger area in the specific context of northern Quebec. A survey area close to 200 $km^2$ was covered in order to produce a map of snow water equivalent in this area.

## METHOD

Radioactive isotopes of Potassium (K), Uranium (U) and Thorium (Th) occur naturally in the ground. As they disintegrate, gamma-rays of discrete energies are produced and travel in the surrounding space. In gamma-ray spectrometry surveys, prominent high intensity gamma-rays are monitored and counted in 3 specific energy windows which relate respectively to the decay series of Uranium, Thorium and Potassium. The intensity of each of these photopeaks can then be related to the concentration in the ground of these elements. In addition, a wide 'Total Count' window that includes all gamma rays produced by the decay of K, U and Th is also monitored.

The attenuation of the gamma radiation by a snow cover constitute the foundation of gamma-ray snow surveying. By comparing the gamma ray count rate for a survey with snow with the count rate obtained when there is no snow, the SWE can be calculated. A gamma-ray snow survey therefore consists of two flights. A first flight is conducted when there is no snow on the ground, either on the previous fall or on the following spring. It provides the baseline gamma radiation from which attenuation due to snow will be calculated. The second flight, the snowline, is performed under snow cover conditions. A gamma ray snow survey is described schematically in Figure 1.

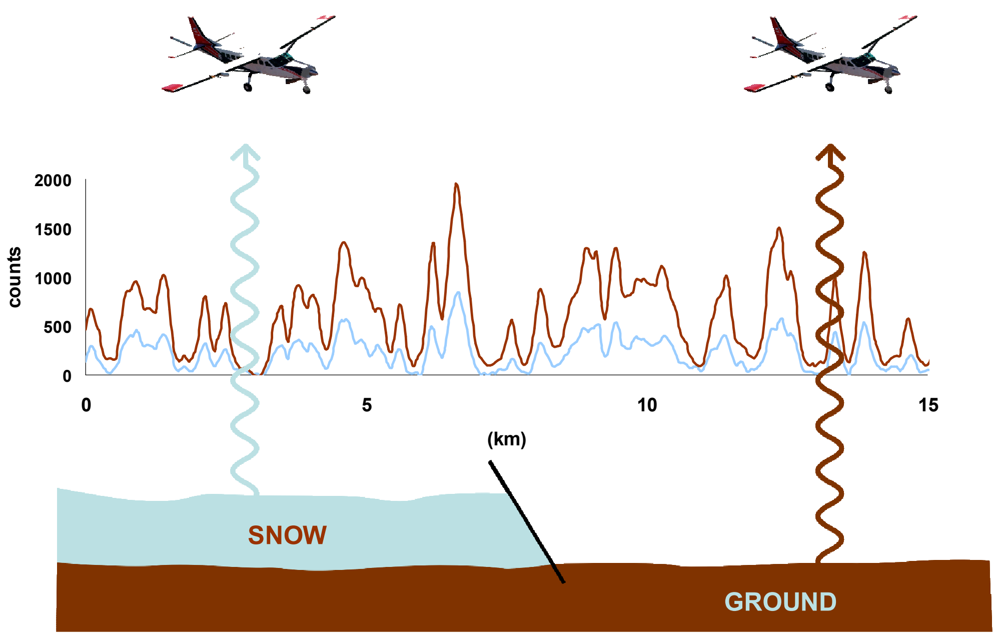


Figure 1: Principles of operation of gamma ray snow survey.

Above an infinite homogeneously radioactive half-space emitting mono-energetic gamma radiation, the relationship between the detector count rate *N* and the flying height *H* can be closely approximated by an exponential of the form:

$$N = N_o \exp(-\mu_a H) \qquad (1)$$

where:

$N$ is the count rate at the aircraft height for the particular gamma ray energy being considered,
$N_0$ is the count rate at ground level,
$\mu_a$ is the linear attenuation coefficient in air at Standard Temperature and Height (STP), and
$H$ is the equivalent height of the aircraft above the ground at Standard Temperature and Height (STP).

The equivalent height at STP is obtained from the following expression:

$$H = H_a \times \{273.15/(T + 273.15)\} \times (P/1013.25) \qquad (2)$$

where,
$H_a$ is the actual aircraft altitude.
T is the air temperature in degrees Celsius, and
P is the barometric pressure in millibars.

Based on equation (1), the ground level count rate at each measurement point for the baseline survey is given by:

$$N_{oB} = N_B \exp(\mu_a H) \qquad (3a)$$

and for the snowline survey by:

$$N_{oS} = N_S \exp(\mu_a H) \qquad (3b)$$

where,
$N_B$ and $N_S$ are the recorded count rate for the baseline and snowline survey respectively, and
H is the equivalent aircraft altitude at each measurement point.

The relationship between the ground level count rates with and without snow also follows a simple exponential and is given by:

$$N_{oS} = N_{oB} \exp(-\mu_w D) \qquad (4)$$

where:
$\mu_w$ is the linear attenuation coefficient for water and
$D$ is the water-equivalent of the snow

From equation (4), the water-equivalent of the snow is then given by:

$$D = (1/\mu_w)\ln(N_{oB} / N_{oS}) \qquad (5)$$

In this equation, the ground level count rates are calculated using equations 3a and 3b. This requires knowledge of the linear attenuation coefficient of gamma radiation in air $\mu_a$. and in water $\mu_w$ to be known. The snow-water equivalent can theoretically be calculated using any of the 4 typical energy windows (Total Count, Potassium, Uranium and Thorium) of the gamma ray spectrum, but in practice the Uranium channel usually yield low counts and Uranium window data are not used for calculation of SWE.

## THE SURVEY

### Data Acquisition Program

The survey area was located about 25 kilometers south of the village of Radisson in the James Bay region of Quebec. It was surveyed by flying a grid-based flight plan consisting of eight 45-km long parallel lines spaced 500 m apart, as presented Figure 2. It enclosed a total area of roughly 200 km$^2$.

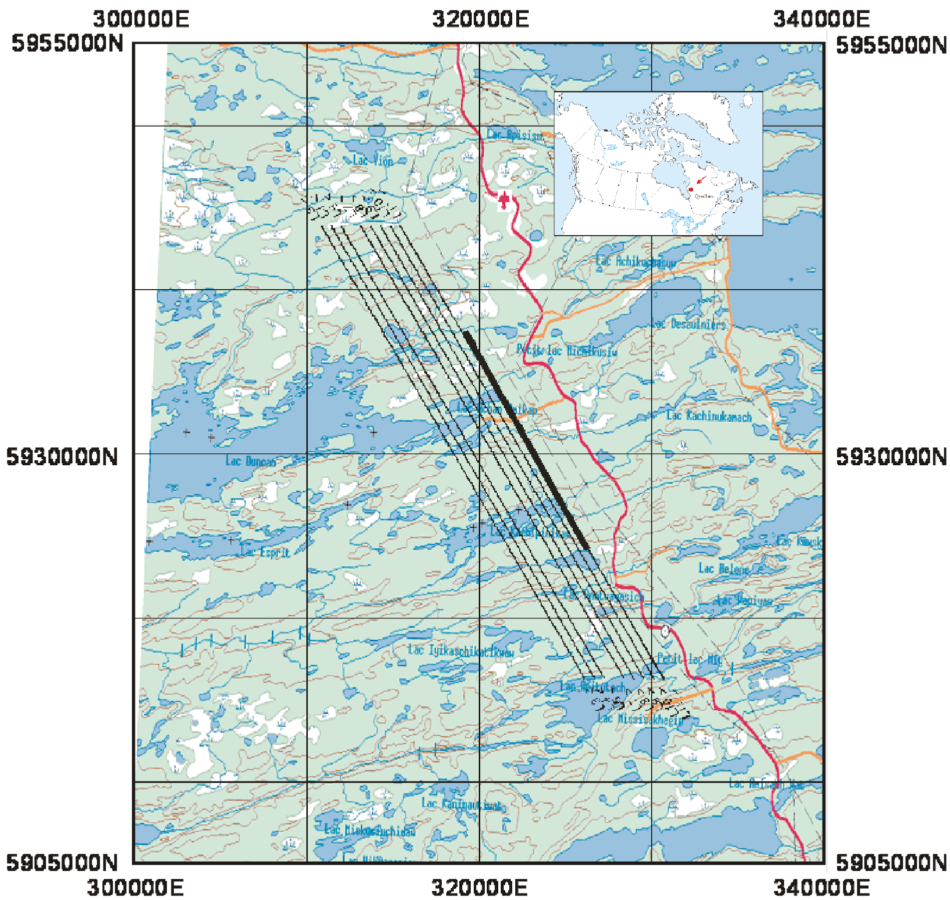


Figure 2: The survey flight plan in the James Bay region. Coordinates are in UTM, zone 18N.

The detection system was installed in a Cessna 404 Titan. It comprised an Exploranium GR820 gamma-ray spectrometer and 12 thallium activated sodium iodide (NaI(Tl)) prismatic scintillation crystals of 10.2 cm × 10.2 cm × 40.6 cm for a total detection volume of 50 litres. A Real-Time Differential GPS unit (RTDGPS) was used for navigation and provided a positional accuracy of less than 3m.

All lines were flown at a flying height of 80 m and at a nominal speed of 140 knots (260 km/h). The snowline data acquisition was performed on March 21, 2002, while the gamma-ray baseline data acquisition was conducted the following spring on June 5, 2002 .

The specific survey location was chosen to cover some of Hydro Quebec snow course lines in this area. It was also representative of the James Bay region environment, comprising rolling hills, forested areas, swamp, and many small lakes. Snow course measurements were obtained on March 22, 2002 along the easternmost flight line.

**Calibration**

In order to evaluate the linear attenuation coefficients for all the windows of interest, a calibration flight was performed on June 6, 2002, at the Geological Survey of Canada calibration range at Breckenridge, north of Ottawa. This is a well established range known for its homogeneous radioactivity.

The calibration flight was carried out from altitudes of approximately 60 m to 220 m at 30 m intervals. Immediately following these measurements, a series of background measurements were made at the same altitudes over the Ottawa River to determine the background due to cosmic radiation, atmospheric radon and aircraft radioactivity.

The attenuation coefficient can be evaluated by resolving equation (1) for the linear attenuation m using the airborne count rates obtained at each altitude in relation to the corresponding STP heights. This is a standard procedure for airborne spectrometer calibration and is described in (IAEA, 1991). Results are presented in Table 1. The values of the linear attenuation of water were then calculated from the values for air by multiplying by 1.11 (Davisson, 1965).

**Table 1. Attenuation coeficients calculated from the calibration flight data.**

| Spectral window | Linear Attenuation Coefficient for air (per meter) | Linear Attenuation Coefficient for air (per $g/cm^{-2}$) | Linear Attenuation Coefficient for water (per cm) |
|---|---|---|---|
| Potassium | -0.008840 | -0.0650 | -0.0721 |
| Uranium | -0.007841 | -0.0606 | -0.0673 |
| Thorium | -0.006987 | -0.0540 | -0.0600 |
| Total Count | -0.007157 | -0.0554 | -0.0615 |

## DATA PROCESSING

Thorium data exhibited low and inconsistent count rates in this area which resulted in a significant statistical error on the measurements. Thorium data was therefore also rejected for calculation of SWE.

Potassium and Total Count channels line data were then processed according to standard procedures (as described in IAEA, 1991), which consists of noise reduction through singular value decomposition (Hovgaard and Grasty, 1999), removal of superposed photopeaks in the window of interest (known as the stripping correction), and removal of atmospheric, cosmic and aircraft background radiation. The line data were then normalized to ground level through application of equation 3 using the calculated values of the linear attenuation for air of Table 1.

## RESULTS

The maps of SWE in the survey area obtained from the Total count and Potassium airborne data are presented in Figure 3. Due to the statistical nature of the gamma ray counting process, a map of SWE calculation for each data point will yield a very noisy image and compromise the identification of features of interest. Therefore, the line data was filtered with an averaging filter along 15-km sections of the flight lines. Data was then gridded using a weighted average gridding algorithm which calculates a grid value using all data points that fall within an ellipse of 1200 m (across line) by 500 m (along line). Data points were weighted using a cosine squared weighting function. Seven and a half kilometers were trimmed off the ends of each line before gridding to compensate for the length of the averaging filter.

## DICUSSION

To investigate the reliability of the SWE calculations, one flight line was flown twice, during both the baseline and snowline data acquisition. This flight line was the easternmost line, overflying the ground snow course. The 45 km long line data was subdivided into 3 sections of 15 km, and SWE calculations were performed and averaged over each of those sections. The results presented in Table 2 quantify the repeatability of the measurement. Notably, measurement could be reproduced with an average closure of about 4 mm. This corresponds to only about 2 % to 3 % of the measured values.

The practical accuracy obtainable with the equipment used for this survey was evaluated by calculating an apparent SWE for the repeat line data obtained during the baseline data acquisition. By using one flight line as the baseline and its reflight as a dummy snowline, apparent SWE calculations were performed and are presented in table 3. It provides a quantitative estimate of the measurement error produced by this system which is then evaluated to be in the range of 5 mm of SWE, or 3-5 %.

**Table 2. Repeatability of the airborne SWE measurements.**

| Line | Section 1 | Section 2 | Section 3 |
|---|---|---|---|
| Total Count Window | | | |
| 1st pass | 129 | 148 | 131 |
| 2nd pass | 128 | 144 | 124 |
| Potassium Window | | | |
| 1st pass | 117 | 152 | 143 |
| 2nd pass | 120 | 150 | 151 |

Various factors will influence the repeatability and the accuracy of the measurement system. Measurements of radioactivity are statistical in nature and poor statistics will contribute to the measurement error. This effect is minimized by optimizing the count rates registered by the system, which is achieved by maximizing the detector volume and the integration time of the spectrometer and minimizing the flying height. Another important consideration is the quality of the navigational system and the ability of the pilot to fly exactly the same course on the snow and baseline flight. This is particularly important in areas of variable ground radioactivity such as in the test area of northern Quebec where there are many lakes, bogs and swamps. The RTDGPS unit and the survey navigation system used for the flight operations ensured that survey lines could be repeated, in practice, to within 10 to 20 meters.

**Table 3. Practical accuracy of the SWE measurements.**

| Window | Section 1 | Section 2 | Section 3 |
|---|---|---|---|
| Total Count | -1.3 | -3.2 | 0.0 |
| Potassium | -0.1 | -5.3 | -2.3 |

The SWE estimates obtained from the airborne measurements, either from the Total Count or Potassium channels, are included between 100mm and 150mm. This constitutes an acceptable range of SWE for this location at this time of the year. Moreover, it can be observed in the maps of Figure 2 that SWE estimates from neighboring line data present smooth and coherent transitions from one flight line to the other. It appears indicative of a line to line data correlation. The gridding algorithm creates some smoothness in the maps, but the correlation observed is actually seen in the line data itself. At the flying height and flight line spacing used during this survey, measurements from neighboring flight lines are sufficiently independent from each other, so that the data correlation observed has its origin in ground surface and snow cover features.

The validity of the SWE estimates is furthermore substantiated by comparing the snow course measurements with the airborne data (Figure 4). Both sets of data are in a similar range of SWE with an average difference in SWE of approximately 20 mm, and as well, present both a northward decreasing trend. There are significant differences in the ground-based profile versus either of the airborne-based profiles, but the very different sampling area from which measurements are obtained has to be taken into consideration. The field of view of the airborne gamma-ray system is at least of the order of the flying height, 80 m, while the snow course data were obtained using a snow sampling tube with a diameter of 10 to 15 cm. Therefore some short wavelength variations are present in the snow course measurements, while they are averaged out in the airborne measurements.

It should be mentioned that the flight plan used in this demonstration survey was unconventional in regard to basin-scale gamma-ray snow surveys. Usually, flight lines are arranged in an irregular pattern that covers the area of interest. The location of each flight lines is chosen on a compromise between various factors. Significantly, the expected representativeness of the survey line in relation to a local, or a wider, area is a primary factor in flight planning, while its general suitability for low-level flight operations will also influence decisions. In the survey described here however, a regular pattern was flown and no preconception on the survey area was needed. At the line spacing interval, this result in a uniform density of data points over the survey area while, during grid calculations, the maximum interpolation length will then be the flight line spacing.

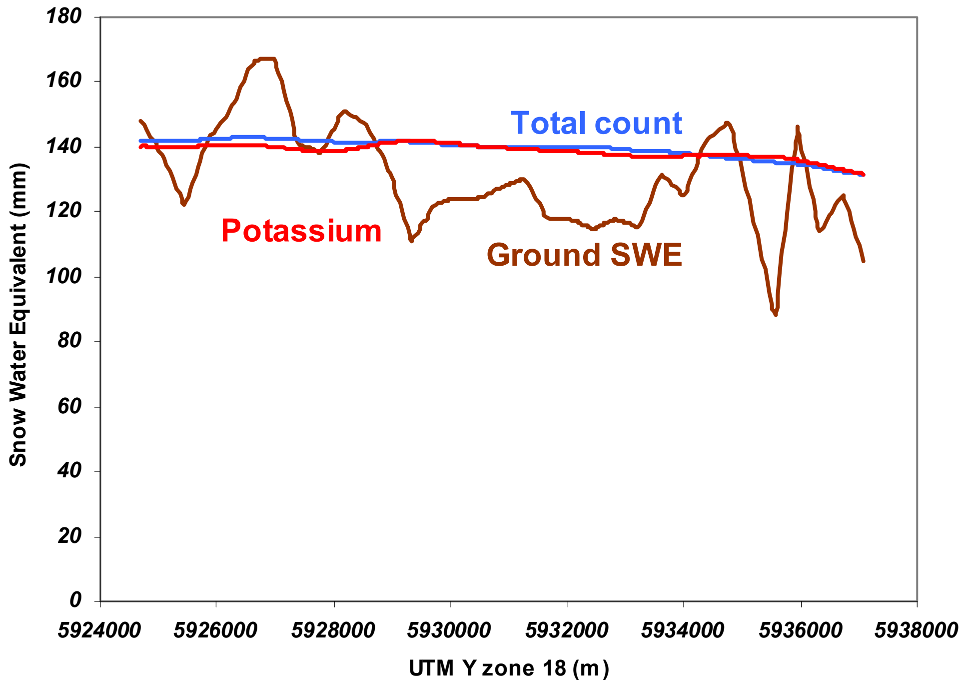


Figure 4: Comparison of SWE from gamma-ray survey with SWE from ground-based measurements. The red line is the SWE calculated from the Potassium window, and the blue line, from the Total Count window.

**CONCLUSION**

It should be emphasized that the airborne gamma-ray technique measures, in effect, the SWE, as ice and liquid water cause the same attenuation on the gamma radiation. Therefore, measurements include all components of SWE, being ice grains, interstitial liquid water, ice lenses, ice layers or standing water above ground, and they all contribute equally to the attenuation of the gamma radiation.

The specific circumstances prevailing in Northern Quebec, namely the flight operations context, the typical ground radioactivity and the typical snow cover height and extent were demonstrated in this study to be within the range of a successful application of the airborne gamma ray technique. Overall, the results of this survey demonstrate here again the validity of this technique for SWE mapping of a large area.

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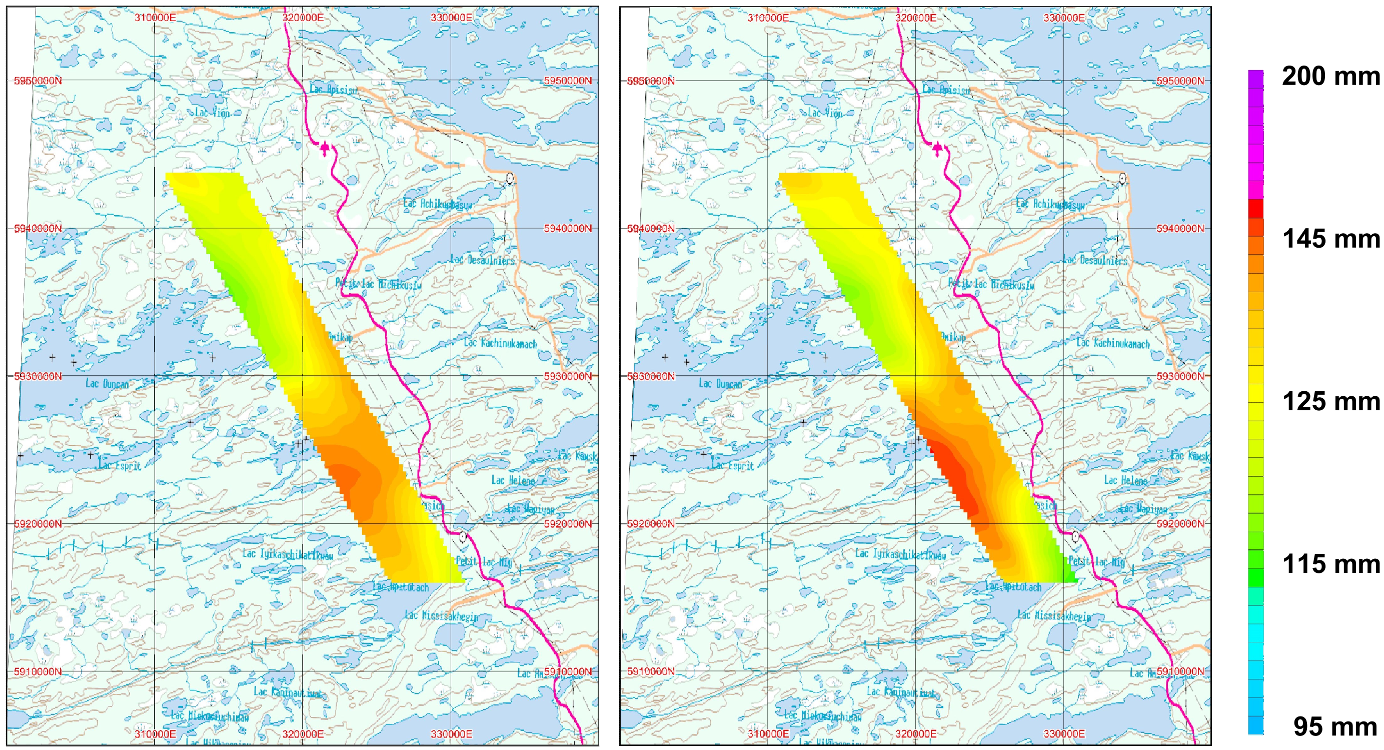


Figure 3: Maps of SWE in the survey area obtained from the airborne Total Count window data (left) and Potassium data (right). Coordinates are UTM, zone 17N.