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OPERATIONAL AIRBORNE MEASUREMENT OF SNOW WATER EQUIVALENT USING NATURAL TERRESTRIAL GAMMA RADIATION

By

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Introduction

Research has been conducted by the National Weather Service (Peck, et al., 1971; Peck and Bissell, 1973; Bissell and Peck, 1973; Bissell, 1974; Larson, 1975) and by EG&G, Inc. (Anderson, et al., 1969; Jones, et al., 1973; Fritzsche and Feimster, 1975; Fritzsche, 1977, 1979) to develop a technique using natural terrestrial gamma radiation to measure snow water equivalent from a low flying aircraft. A program has recently been introduced by the National Weather Service to develop and maintain an operational airborne gamma radiation snow survey program in North Dakota, South Dakota, western Minnesota, and a portion of Saskatchewan (Peck, Carroll, and Van Demark, 1979). The airborne snow survey program is intended primarily to provide real-time snow water equivalent data to the National Weather Service Forecast Offices and the Minneapolis and Kansas City River Forecast Centers for use in the spring flood outlooks and flood forecasts made for the upper Midwest. After an appropriate data base of airborne snow water equivalent data is developed, it will be possible to incorporate the airborne snow cover data directly into the conceptual snow accumulation and ablation model of the National Weather Service River Forecast System used to simulate river discharge from mean areal temperature and precipitation data (Carroll and Peck, 1979).

A third generation airborne detection package has been developed by EG&G, Inc. which uses five 10x10x40 cm downward-looking NaI(Tl) scintillation crystals and two 10x10x20 cm upward-looking crystals used to measure the atmospheric radon daughter contribution (Fritzsche, 1979). The Pulse Height Analyzer accumulates and processes the gamma radiation spectra for each flight line before they are analysed and recorded on magnetic tape by a Hewlett-Packard 9825 computer (Carroll and Vadnais, 1979). The airborne system is flown by commissioned NOAA Corps Officers in a twin-engine Rockwell Aero Commander leased with the National Ocean Survey, NOAA. The Soil Conservation Service collects real-time soil samples along specific flight lines which are analyzed by the National Soil Survey Laboratory, SCS, in Lincoln, Nebraska. The soil moisture and radiation data are used to calculate snow water equivalents in the air which are available after each snow survey flight. Three snow survey missions are normally scheduled for the upper Midwest during February and March when airborne and ground data are collected on a selected number of the 234 flight lines in the upper Midwest. At the conclusion of each ten day mission, soil moisture and snow water equivalent data are reported to National Weather Service offices for use in generating spring flood outlooks.

Technique

The gamma flux near the ground originates primarily from the natural ^{40}K, ^{238}U, and ^{208}Tl radioisotopes in the soil. In a typical soil, 96 percent of the gamma radiation is emitted from the top 20 cm (Zotimov, 1968). After measures of the background (no snow cover) radiation and soil moisture are made, the attentuation of the radiation signal due to the snowpack overburden is used to calculate the amount of water in the snow cover. Each flight line is approximately 20 km long and 300 m wide; consequently each snow water equivalent measurement is a mean areal value for approximately 6 km^2 of snow cover.

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Presented at 48th Annual Western Snow Conference, Laramie, Wyoming, 1980 April 15-17.

Three operational and independent snow water equivalents are calculated by measuring the attenuation of the gamma radiation flux in specific windows of the radiation spectrum (Figure 1). The three mean areal snow water equivalents are calculated using data from the K window (1.36-1.56 MeV), the Tl window (2.41-2.81 MeV), and the gross count (GC) energy spectrum (.41-3.0 MeV) (Carroll and Vadnais, 1979). The potassium photopeak is consistently the strongest in the energy spectrum and has been used successfully to measure snow water equivalent in Canada (Grasty, 1979) and in the US (Peck, Carroll, and Van Demark, 1979). The gross count window accumulates an order of magnitude more counts than the K and Tl photopeak windows. Consequently, gross counts are useful when measuring the variability of snow cover along a line or a mean areal snow cover with 15 to 25 cm of snow water equivalent.

The concentration of radioisotopes in the soil is assumed to remain constant. Errors occur in the window counts primarily due to errors associated with airmass computation and the limited time available in which to collect radiation data over a flight line (i.e., counting statistics). To measure the error associated with airmass computation and counting statistics, radiation spectra were repeatedly collected over a flight line at an altitude of 150 m; results are given in Table 1.

Table 1
Airmass and Counting Statistics Errors

Window	*Counts (Mean)	Standard Deviation	Coefficient of Variation	N
K	2990.4	65.1	.022	10
Tl	1065.0	34.9	.033	10
GC	30538.9	1018.6	.033	10

*Note: Counts are normalized to one minute and 17 g airmass.

The strongest signal (Figure 1) and smallest error (Table 1) are represented by the K window while the larger error in the Tl window is associated with the reduced signal. The error in the gross count measure is due, in large part, to the presence of atmospheric radioactivity from radon gas in the large window.

The principal sources of error in calculating snow water equivalents using any of the three windows are incorporated in: (1) the stripping equation derived during the calibration procedure, (2) the measurement of airmass (i.e., temperature, pressure, and radar altitude), (3) the measurement of mean areal soil moisture for a flight line, (4) the measurement of the radon gas contribution to the gamma flux spectrum, and (5) counting statistics. Nonetheless, the technique is capable of measuring snow water equivalent with an accuracy of 1 cm.

Data Analysis

The detection system is designed to record both the up and down 512 channel spectra on magnetic tape at the end of each flight line. Mean areal snow water equivalents for the total line are calculated using the window data in the spectra and soil moisture data. Additionally, the detection system can record window data on tape at intervals as frequent as 2 seconds (100 m) which can be used to investigate the variability of the snow cover along a flight line.

To investigate the variability of the snow water equivalent along a calibration flight line near Bottineau, North Dakota, background window data were collected at 20 second intervals on 1979 November 3 on line ND117C and over-snow window data were collected at 5 second intervals on 1980 March 10. Figure 2 shows the attenuation of the gross count window due to snowpack overburden, the variability of the radioisotope concentration along the 21 km flight line, and the repeatability of the background and over-snow gross count window measurement. Figure 3 shows the background and over-snow K window counts for 20 second intervals. Again, the variability of the radioisotope concentration and the repeatability of the measurement is represented.

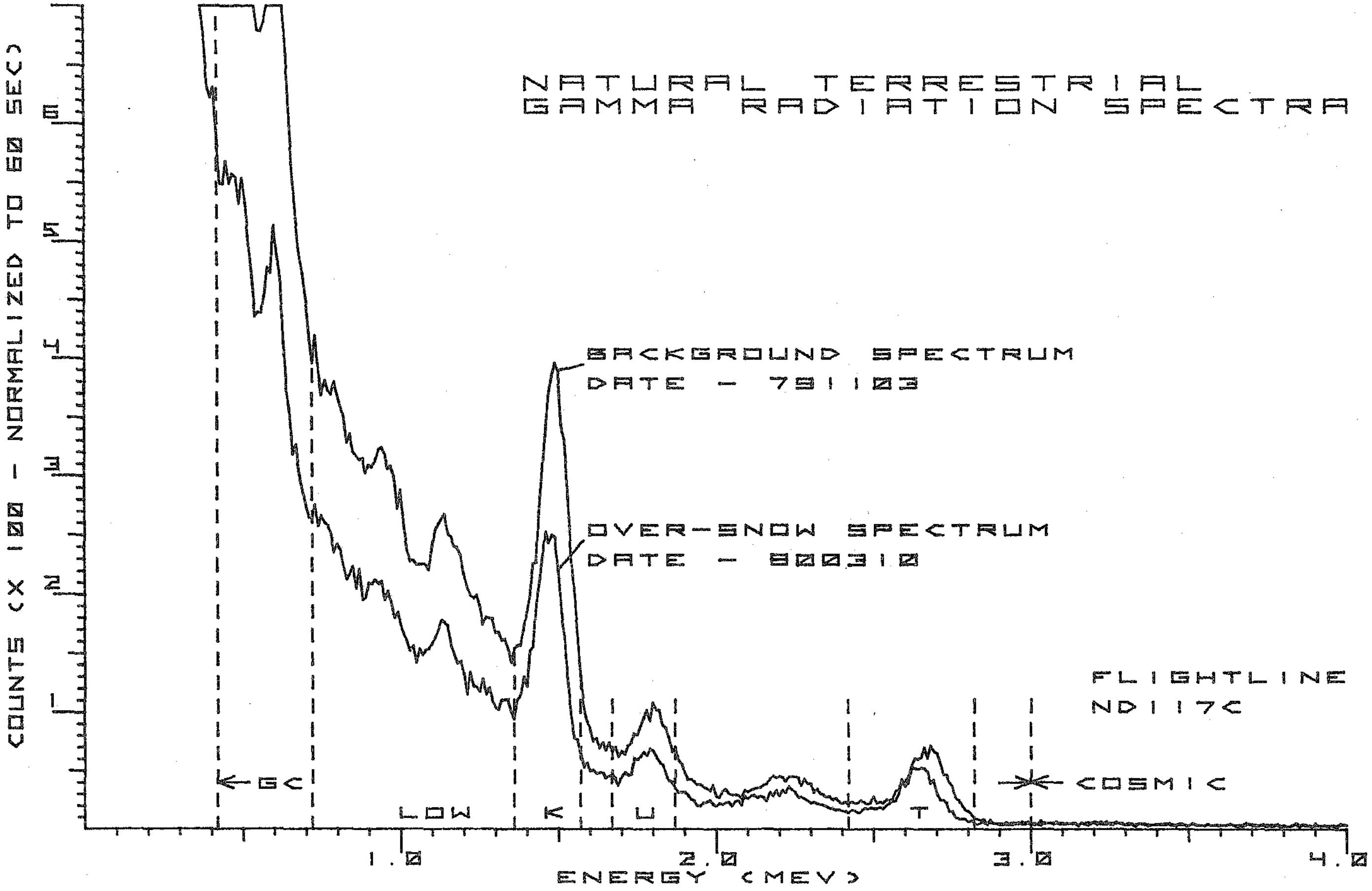

Figure 1. Natural terrestrial gamma radiation spectra for background (no snow cover) and snow cover condition. The attenuation of the signal due to the snowpack overburden is used to calculate snow water equivalent for the K, Tl, and GC windows.

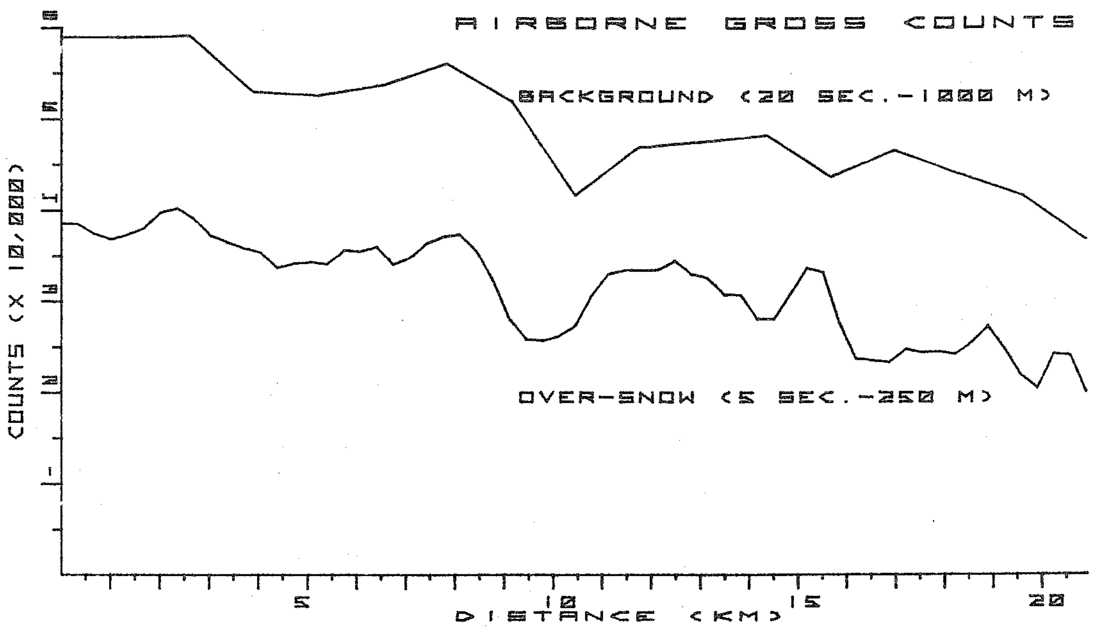

Figure 2. Airborne gross count background data collected at 20 second (1000 m) intervals and over-snow data collected at 5 second (250 m) intervals.

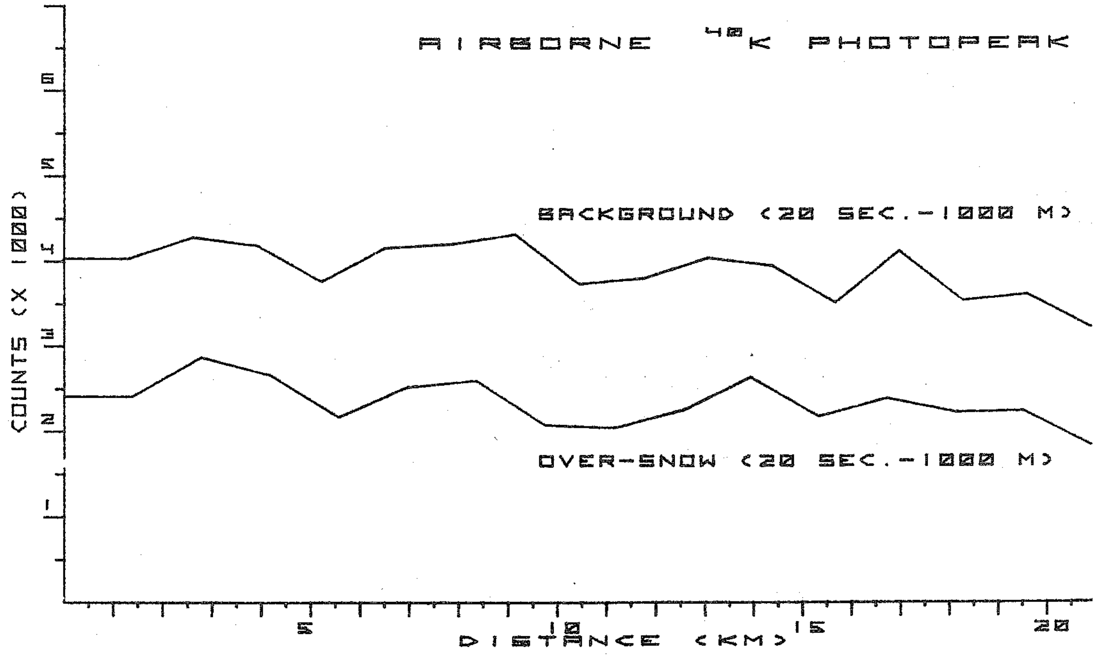

Figure 3. Airborne ^{40}K photopeak background and over-snow data collected at 20 second (1000 m) intervals.

Ground soil moisture samples are routinely collected at 26 sites along the 21 km flight line when airborne radiation data are collected. Background and over-snow soil moisture samples were collected on November 6 and March 5 respectively and are represented in Figure 4. Low antecedent soil moisture conditions were measured in the fall and remained essentially unchanged through the early spring. The soil moisture values measured in March are lower than would typically be expected for continuous snow cover conditions (Peck, 1974) and may be related to the long snow-free periods during which desiccation could occur near the soil surface.

Typically, the coefficient of variation for 20 to 30 soil samples along a flight line ranges from 0.2 to 0.3; consequently, the mean soil moisture for a line is used when calculating both the mean areal snow water equivalent for a line and for the partial snow water equivalents using radiation data collected at intervals along a line.

Snow Water Equivalents

Snow water equivalents were calculated for line ND117C by using: (1) the K, Tl and GC window values from the accumulated radiation spectrum for the total length of the line (each gives a mean areal value for the 6.3 km^2 area), (2) the 20 second interval background and over-snow K photopeak data, and (3) the 20 second interval background and 5 second interval over-snow gross count window data. In addition, ground snow cover data were collected. Table 2 gives the results of the airborne and ground mean areal snow water equivalent calculations for the flight line.

Table 2
Mean Areal Snow Water Equivalents (cm)
Survey Date: 1980 March 2-10

Calibration Line	Flight	Airborne				Ground		
		Date	SWE_K	SWE_{Tl}	SWE_{GC}	Date	SWE	Standard Deviation
ND117C	A	10	5.3	5.6	3.0	7	5.1	1.5
ND117C	B	10	5.1	5.8	3.3			

Airborne snow water equivalents using the gross count data tend to be lower than the K window, Tl window and ground snow cover estimates. The underestimate is related to the inability to properly account for the large radon gas contribution in the gross count window. Consequently, airborne snow water equivalents reported for the 79 flight lines flown in early March were calculated using the following relationship:

$$SWE= SW(^{40}K)*0.75 + WE(^{208}Tl)*0.25 + WE(GC)*0.0$$

Nevertheless, it is possible to use the gross count interval data to examine the snow water equivalent distribution along the flight line.

Figure 5 gives the snow water equivalent values along the flight line for: (1) the gross count window using the background and over-snow radiation data represented in Figure 2, (2) the K photopeak window using the background and over-snow radiation data represented in Figure 3, and (3) the ground snow course data collected using an Adirondack sampling tube for approximately 400 depth and density samples along the flight line.

Error Analysis

Principal errors associated with the K and Tl window airborne snow water equivalent measurements are related to mean areal soil moisture estimates and counting statistics. Approximately 26 soil samples are collected at representative sites along a 20 km calibration flight line and the mean value is used to represent the mean areal soil moisture over the flight line. An error of 5 percent in the soil moisture estimate gives an error of 2 percent in the snow water equivalent measurement. Figure 6 gives the percent error in the

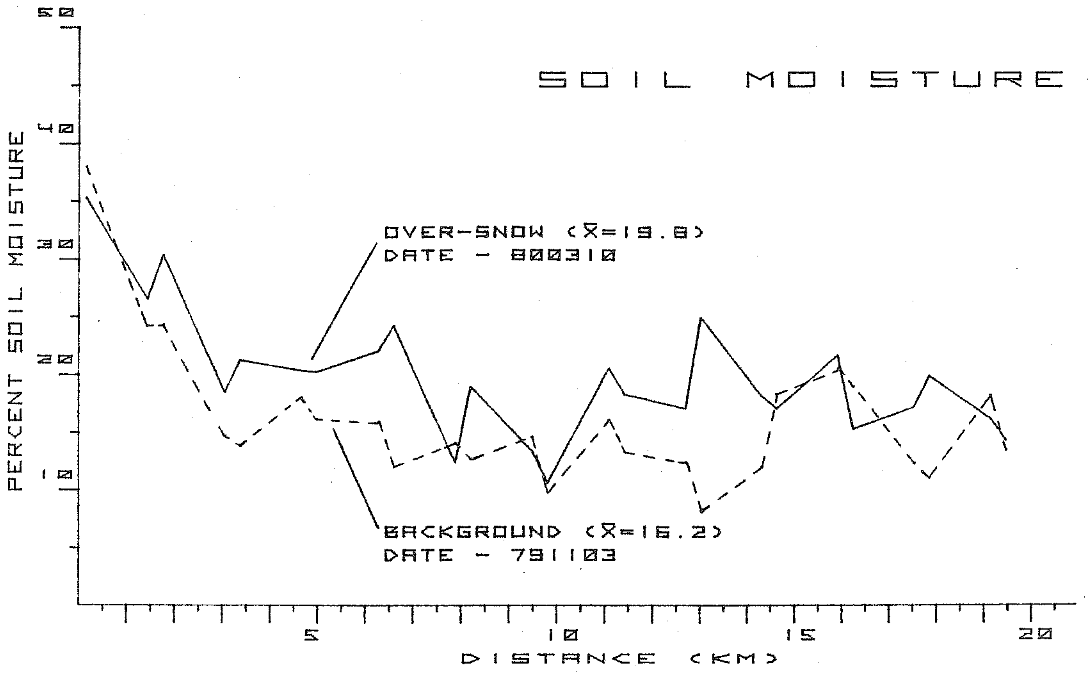

Figure 4. Ground soil moisture data collected at the time of the background and over-snow airborne missions. Percent soil moisture = (wet-dry/dry) * 100.

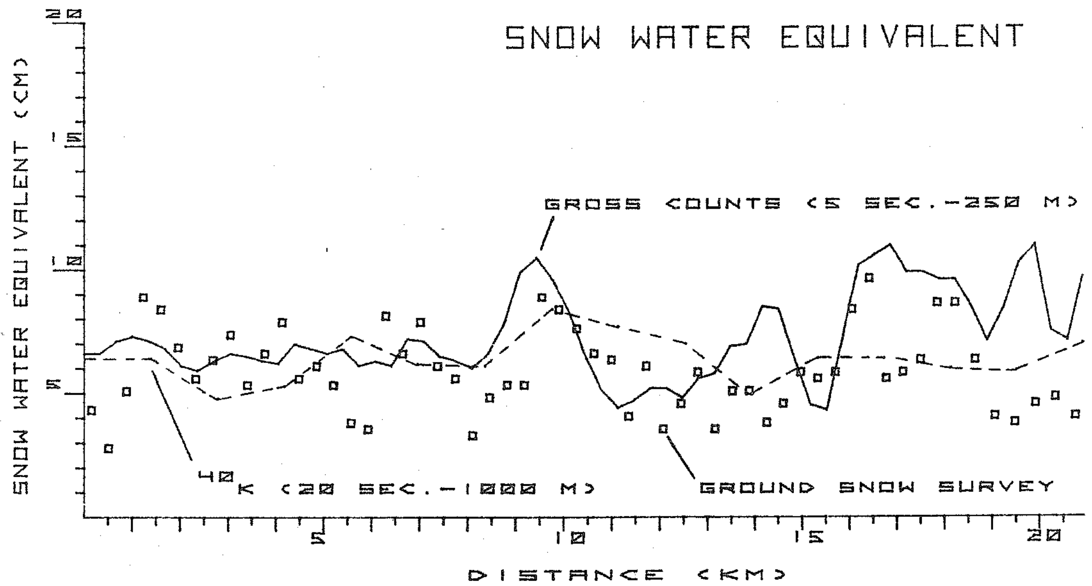

Figure 5. Snow water equivalent calculated from gross count window (5 seconds), K window (20 seconds) and ground snow cover data collection.

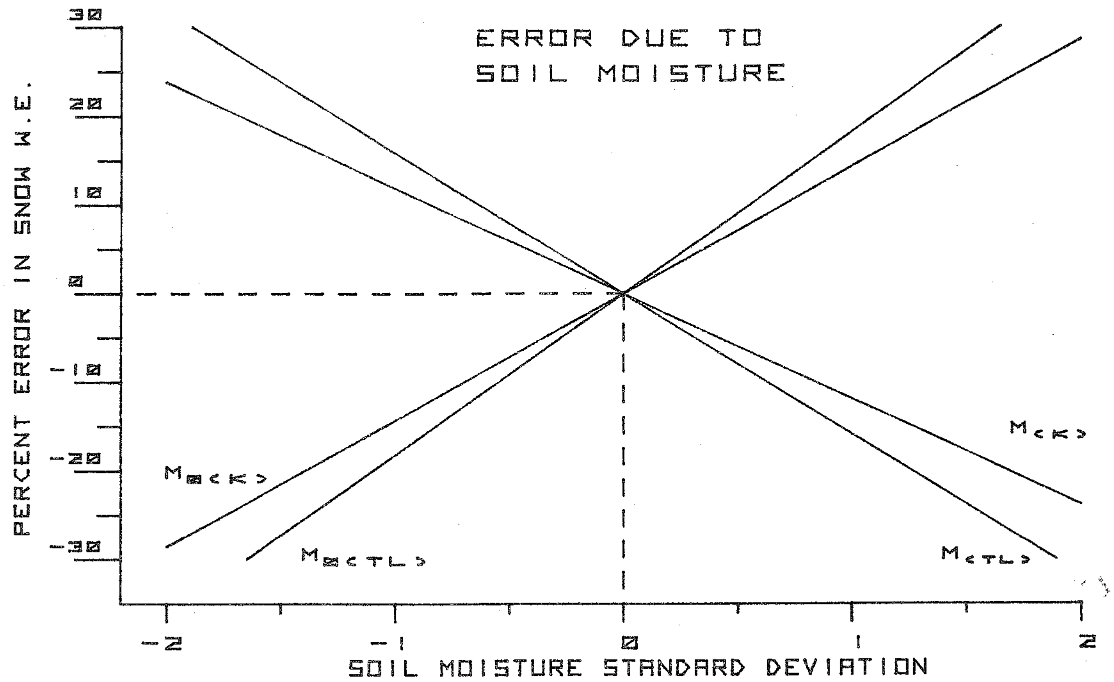

Figure 6. Percent error in snow water equivalent due to error in mean areal soil moisture estimate. An overestimate of background soil moisture gives an overestimate of snow water equivalent (M_0 = background soil moisture; M = over-snow soil moisture).

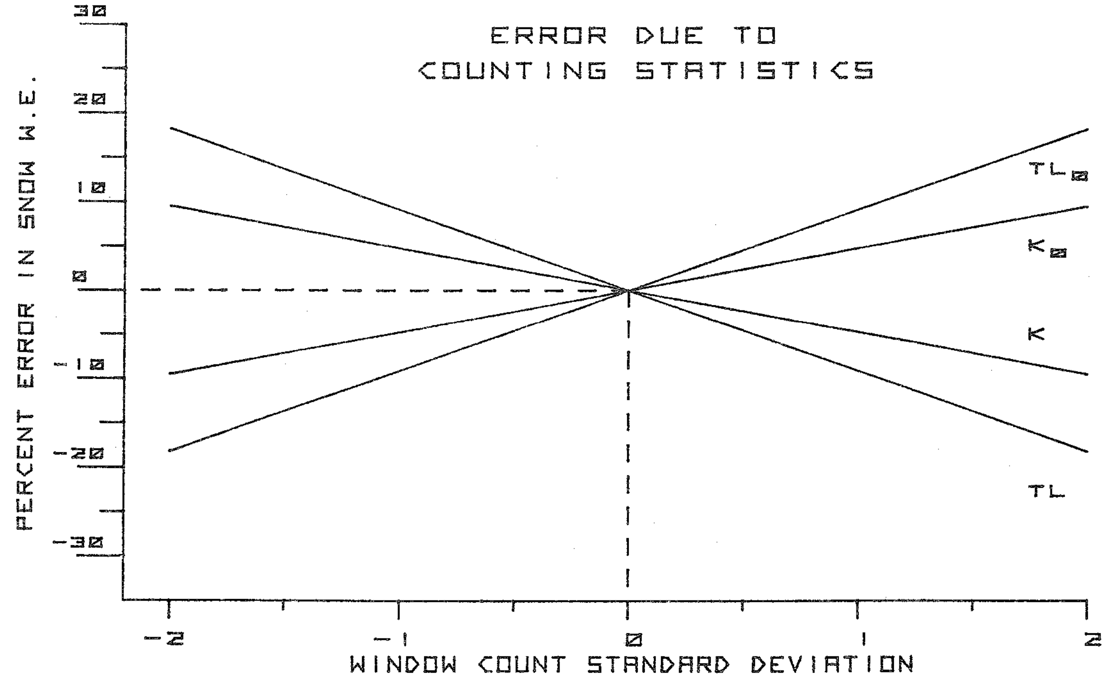

Figure 7. Percent error in snow water equivalent due to errors in counting statistics. An overestimate of over-snow window counts will give an underestimate of snow water equivalent (K_0 = background counts; K = over-snow counts for the potassium window).

K and Tl window snow water equivalents associated with measurement error of the background and over-snow mean areal soil moisture estimates. For example, an overestimate in background soil moisture of one standard deviation would give an overestimate in the K and Tl window snow water equivalents of approximately 14 and 17 percent respectively.

A second source of error is associated with the counting statistics of the two photopeaks. Figure 7 gives the percent error in the K and Tl window snow water equivalents associated with the error related to length of time available to accumulate counts in the energy spectrum. Shorter flight lines tend to have greater errors due to poor statistics; consequently, most flight lines are at least 15 km in length. An overestimate of one standard deviation in background K and Tl photopeak counts gives an overestimate of approximately 5 and 9 percent respectively in the snow water equivalent measurement (Figure 7). The K photopeak tends to be less sensitive to counting statistics and soil moisture errors because it is a comparatively strong signal (Figure 1).

Problems and Additional Research

Two fundamental problems remain with the airborne gamma radiation snow survey technique. Radon gas can contribute significantly to the counts accumulated in the gross count and K windows. The problem is particularly acute when temperature inversions occur and little atmospheric mixing takes place. The detection system is designed to measure the radon gas contribution by using a set of upward-looking crystals (Fritzsche, 1979). Additional calibration data must be collected and analysed to satisfactorily account for the radon gas contribution and force the gross count data to behave properly. Secondly, the current procedure requires a measure of soil moisture to use the airborne radiation data most effectively. However, recent techniques in spectral analysis developed by Grasty (1979) preclude the necessity of taking ground soil moisture samples. It may be possible, with additional research, to refine sufficiently the technique to calculate reliable operational snow water equivalents without the need for ground data.

Future developments and research will be focused in four principal areas. First, additional spectral analysis will be required to overcome problems associated with atmospheric radon contribution and the necessity of ground soil moisture data collection. Second, research is being planned with the U.S. Geological Survey and the University of Saskatchewan to maximize the use of airborne snow survey data to examine snow water equivalent distribution and redistribution along a flight line and over a watershed. Third, airborne radiation data can be used to calculate both mean areal and partial soil moisture values along a flight line under no snow cover conditions (Carroll, 1979). This capability has not been fully exploited by the National Weather Service, but the technique can measure mean areal soil moisture over large areas at critical times during the hydrologic and agricultural cycles. Fourth, procedures will be developed to incorporate the airborne snow survey data directly into the snow accumulation and ablation model of the National Weather Service River Forecast System used to forecast river discharge (Carroll, 1978). After a data base of airborne snow survey data is available and both the soil moisture accounting model and the snow accumulation and ablation model can be properly calibrated, it will be possible to incorporate both the airborne soil moisture and snow cover data directly into the NWSRFS for maximum utilization of the airborne gamma radiation data.

Conclusion

The aforementioned difficulties notwithstanding, the airborne gamma radiation technique has three distinct capabilities: (1) reliable mean areal snow water equivalents can be calculated on an operational basis for large areas of the upper Midwest where no snow course data were previously available, (2) distribution of snow water equivalent along a flight line can be examined in 1000 m intervals for both research and operational purposes, and (3) mean areal soil moisture values can be calculated for large areas with no snow cover.

Acknowledgements

The National Weather Service is grateful to the many conscientious individuals who have contributed to the success of the operational Airborne Snow Survey Program. Special thanks go to the Soil Conservation Service in North Dakota, South Dakota, and Minnesota and the National Soil Survey Laboratory, SCS, for collecting and analyzing an endless procession of soil samples.

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