AIRBORNE SNOW SURVEY DEVELOPMENT USING THE GAMMA METHOD

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INTRODUCTION

An accurate measurement of areal distribution of water equivalent of snow cover is essential for operational forecasting of snowmelt floods. The northern plains of the United States has major snowmelt flooding over portions of the area about every 3 years. The National Weather Service (NWS) has the responsibility for providing flood warning services in the United States and therefore has a need for measurement of the water equivalent of the snow cover in various river basins.

The difficulty in obtaining accurate and representative measurements of snow cover by ground surveying or of actual snowfall by precipitation gages is well known.[1,2] Where strong winds occur during and following snowfall, as in the plains area, errors in determining average basin values are greatly enhanced.

Interest in using aerial gamma radiation surveys to measure the average water equivalent of the snow cover started in the NWS in 1969. A very heavy snow cover existed over most of the north central plains during the spring of that year. Efforts were made to obtain the services of a plane suitably equipped with a gamma radiation measuring system but were not successful. A research team was sent into an area of greatest snow cover to evaluate the effectiveness of the ground reporting network and to determine if new techniques might be employed to improve the accuracy of the average water equivalent basin estimates. It was concluded that there were severe limitations as to the degree of accuracy that could be obtained with changes in the ground measurement program. A research project was initiated in the fall of 1969 to evaluate the aerial gamma radiation approach and to initiate the development of a system that could meet the operational requirements of the NWS river forecasting service.

THEORETICAL GAMMA ATTENUATION BY SNOW AND AIR

The basic principle of the gamma radiation approach is that gamma photons from the ^{238}U, ^{232}Th, and ^{40}K isotopes in the soil are measured by the airborne detector system. With the presence of snow, the mass of the water equivalent attenuates the gamma radiation and the measured flux at the aircraft level is proportionally less. Monoenergetic gamma photons of energy, E, originate in the soil and suffer Compton (elastic), photoelectric (absorption), and pair production (absorption and re-emission) interactions in the soil, air, and detector. Those that reach the detector before any collision, called uncollided gammas, can be treated analytically. The following equation was developed to calculate the count rate per unit time, N, due to these uncollided gammas.

$$N = (A/(2\mu g))E_2(\mu_A h + \mu wWE) \qquad (1)$$

where:

A = Terrestrial source activity (gammas/g-sec) times the detector sensitivity (counts $*cm^2$/gamma)

E_2 = Exponential integral of the second kind

μg = Mass absorption coefficient of soil (cm^2/g)

μ_A = Mass absorption coefficient of air (cm^2/g)

h = Air mass (g/cm^2)

μw = Mass absorption coefficient of water (cm^2/g)

WE = Water equivalent (g/cm^2)

Empirically, the uncollided gamma count rate, ϕ, has been found to be:

$$\alpha = (K/(2\ \mu g))\exp(-\alpha WE) \tag{2}$$

where:

K = Terrestrial source strength

α = Attenuation coefficient (cm^2/g)

Since the monoenergetic gammas do suffer Compton collisions, there is a large component of the total gamma flux at the detector that has a continum of energies which tends to mask and distort the observation of the monoenergetic gamma component. The total flux, monoenergetic plus continum, is called the gross flux and is measured by the detector as the gross count rate. Measurements show this component to have the same analytic form as equation 2.

The mass absorption coefficient of soil is related to the soil moisture content and a good approximation can be expressed as:

$$\mu = \mu g_o(1 + M) \tag{3}$$

where:

M = The measured soil moisture, i.e., soil moisture weight divided by soil dry weight

μg_o = The dry soil attenuation coefficient

If areial surveys are made on different dates of the same area, the ratio of the count rates, whether peak area or gross count, is:

$$N_1/N_2 = [(1 + M_2)/(1 + M_1)]\ \exp[-\alpha(WE_1 - WE_2)] \tag{4}$$

Equation 4 is used to obtain a change in water equivalent between two surveys of the same site, with subscripts 1 and 2 indicating values for the two surveys.

RESEARCH PROGRAM IN THE UNITED STATES

The research work conducted by the NWS on the aerial gamma radiation technique has been in cooperation with the EG&G, Inc., and the research is based on the work and techniques developed in the early 1960's in the Soviet Union.[3,4] Many different techniques and operating procedures have been evaluated since the research began. These have included the two basic approaches of using the gross count and the uncollided gamma count rates for ^{40}K and ^{208}Tl. Both of these approaches are based on the relation given by equation 4. Surveys were made for several years at various heights above ground (61 m, 91 m, 152 m, 229 m, and 305 m) to determine this effect on the accuracy of the techniques. Other techniques, such as a dual detector and using data from more than one height, were also tested. The results of additional research were reported.[5] To obtain the accuracy required for operational use (standard deviation of about 1 cm for survey lines of 16 km), it has been found necessary to correct for variations in the height of the aircraft, air density and cosmic radiation influence, soil moisture and daughter products emission of radon gas.[6]

Aerial surveys have been conducted over special survey lines since the fall of 1969. The principal site for the research study has been a 13.6-km line near Luverne, Minnesota, having an elevation of 442 m and located in a slightly hilly area which often has a snow cover greater than the surrounding area. A second study site has been a 6.7-km line in a high valley at an elevation of 2130 m in the Rocky Mountains near Steamboat Springs, Colorado. This site has a much deeper, more continuous, and a longer lasting snow cover.

SYSTEM DESCRIPTION

The Aerial Radiological Measuring System (ARMS) was the first system utilized for the studies and was owned by the U.S. Energy Research and Development Administration (ERDA) and operated by EG&G, Inc. The aircraft, a Beechcraft Twin Bonanza, carried 14 10-cm by 10-cm cylindrical NaI(Tl) gamma detectors and a data acquisition system consisting of a 200-channel pulse height analyzer and one single channel analyzer.

A new gamma system, Remote Airborne Measurement of Snow (RAMS), was constructed in 1975-76 from readily available components. It was designed so that it has the following characteristics, which are necessary for use in the NWS river forecast service:

1. Adaptable for use in light planes and portable for use in leased planes.
2. Operable by two persons, a pilot and system operator, who also serves as a navigator.
3. Modular with readily available components.
4. Detector system with a total sensitivity to provide sufficient counts for an accuracy of less than 1 cm for water equivalent over a 16-km line.
5. Capable to store sufficient information for later calibration checks and computation of mile by mile average water equivalents.
6. Capable to store background radiation and soil moisture data for use on-board calculations.
7. Capable of computing line averages of water equivalents while data processing is continuing.

The RAMS system measures only the counts in specific energy "windows" rather than the entire spectrum. Figure 1 shows the relative positions of each window on the spectrum. The C window in figure 1 is used to measure the cosmic ray contribution to the gamma spectrum. The L and U windows measure the ^{214}Bi (a daughter product of radon gas), which is found in both the soil and the atmosphere. The K and T windows are for the ^{40}K and ^{208}Tl and include the counts representing the uncollided gammas from these isotopes in the soil. Gross count for the new system includes the total count rate from 60 keV to 3 MeV. The principal components of the RAMS system are shown in figure 2.

The system utilizes eight 15.25 x 15.25 cm NaI(Tl) crystals whose outputs are summed and fed to six single-channel analyzers (SCA's). The SCA's serve as the gamma energy windows. The output of the SCA's, as well as digitized temperature, pressure, altitude, clock and tagward data, are transferred to a desk type calculator for analysis and storage on cassette tape.

A programmable calculator is part of the data acquisition analysis and storage component of the RAMS system and provides the flexibility needed for snow surveys. Programs can be created and stored on cassette tape to:

1. Collect survey data.
2. Compute snow water equivalent.
3. Collect system test data.
4. Calibrate the system.
5. Receive and send data to external devices, such as the cassette tape.

The calculator may be used for quality control while the flight is in progress. For example, low count rates could be signaled to the operator via the printer or visual readout so that he can consider resurveying a particular line.

Data from bare ground flights over the prescribed survey line are required for determining the water equivalent for surveying the snow cover. These include data for each window, the altitude, temperature, and pressure for the survey flown, the elapsed time, and the average soil moisture for each line. The raw data from the bare ground flight are reduced to the counts representing the uncollided gamma in each window for the specific air mass for each line. The gross count data are retained in the raw form. The data for each line for which a snow survey will be made are placed on the cassette tape.

During the actual snow survey, the current data are processed under program control in the on-board calculator to produce the data in the same form as that for the stored bare ground survey. Soil moisture conditions under the snow must be estimated or established by ground measurement prior to the flight.

SYSTEM CALIBRATION PROCEDURES

The primary objective of the calibration is to define the parameters of the gamma energy spectrum windows as shown in figure 1. The following parameters must be obtained for each window.

1. The cosmic contribution to the gamma count rate versus air pressure.
2. The aircraft gamma background contribution.
3. The relative radon daughter gamma contribution.
4. The terrestrial ^{238}U series gamma contribution.
5. The ^{40}K terrestrial gamma contribution.
6. The ^{232}Th series gamma contribution.

CALIBRATION FOR COSMIC CONTRIBUTION

The calibration is best accomplished by flying at two high altitudes (1500 m and 3500 m) on days with low radon gas concentration. Low radon gas is generally observed following the movement of a high pressure system into an area. The terrestrial contribution is also very low at higher altitudes. The difference in the counts for each window at the altitudes gives the relative cosmic count rate for each window, or what is called the cosmic shape. These may be designated by using the subscript S with the window letter identifiers.

To normalize the different spectrum contributions to an absolute magnitude at a specific pressure, the observed counts at 3500 m are divided by those observed at 1500 m to obtain the ratio C35/C15. The cosmic shape for each window (T_S, U_S, and K_S) is then multiplied by the ratio C35/C15. This then gives the absolute cosmic magnitude in each window for that pressure. The same approach should be done to obtain the absolute cosmic magnitude for each window at the pressure associated with the 1500 m spectrum.

By flying at several altitudes and therefore different pressures, a plot of the absolute cosmic contribution versus pressure can be developed for each window. These relations have the form:

$$C_i = k_i e^{\left(\frac{1055 - P}{184}\right)} \qquad (5)$$

where:

i = The C, U, T, and K windows

C_i = Absolute cosmic contribution in window, i, at pressure P (counts per minute)

k_i = Count rate due to cosmic radiation in window, i, at pressure of 1055 g/cm^2 (counts per minute)

P = Atmospheric pressure at flight level (g/cm^2)

The approach assumes the cosmic spectrum shape is constant with pressure over the range of pressure for the altitudes flown.

CALIBRATION FOR AIRCRAFT CONTRIBUTION

To find the aircraft background contribution, i.e., the aircraft spectrum, the absolute cosmic spectrum at 3500 m is subtracted from the total observed spectrum at the same level. This assumes that the aircraft spectrum is constant for changes in pressure and time. The assumption for time is realistic since all the radioactive emitters in the aircraft have long half lives.

CALIBRATION FOR RADON DAUGHTER CONTRIBUTION

The relative contribution from radon daughters for each window may be determined by flights over a large body of water on days with different levels of radon concentration. The flights should be flown at the same flight levels that give the same atmospheric pressures. The window data from the two flights are subtracted to yield a radon spectrum shape. If an air filter system for collecting and measuring the magnitude of the radon gas daughters is used, the filter count rate may be correlated with the radon window count rates to arrive at a radon spectrum shape.

CALIBRATION FOR TERRESTRIAL CONTRIBUTIONS

Flights over three land ranges containing different ratios of ^{40}K, ^{232}Th, and ^{238}U concentrations in the soil may be used to obtain the gamma pulse height window response to each of these radioactive species. These are the predominant gamma emitters found in the soil. If the concentrations of each emitter are known, three equations involving three unknown variables may be written to describe the gamma count rate in each window, providing the cosmic, aircraft background, and radon contributions have been removed. The equation for the counts, KC, in the K window is:

$$KC = A_{KK} K + A_{KU} U + A_{KT} T \qquad (6)$$

where:

A_{KK} = The number of counts due to ^{40}K

A_{KU} = The number of counts due to Compton tails of gamma components from Uranium daughters in the U window

A_{KT} = The number of counts due to Compton tails of gamma components from Thorium daughters in the T window

The equation for the counts in the U window has only two terms: one for those counts due to Uranium daughters; the other for those due to the Compton tails of gamma components from Thorium daughters in the T window. The only term in the equation for the T window is for those counts due to the Thorium daughters (^{208}Tl).

If the necessary documented courses are not available, an empirical technique may be used to obtain pure ^{40}K, ^{232}Th, and ^{238}U spectra. The method utilizes pulse height spectra from three different ranges of different ^{40}K, ^{232}Th, and ^{238}U concentration ratios and multiple subtractions provide the pure spectra. From these data, the spectral stripping ratios can be found that are required to establish the photopeak extraction equations.

A third method for obtaining the ^{40}K, ^{232}Th, and ^{238}U contribution to the gamma counts in the pulse height windows is the use of simulator pads. Several concrete pads containing different ratios of ^{40}K, ^{232}Th, and ^{238}U are available in the United States and Canada to simulate the calibration ranges described above. The aircraft is simply parked over each pad and the response of each window measured. One must have at least four simulators to write four equations in four variables; the fourth variable arises from background contribution due to finite simulator size.

OPERATIONAL TESTS

Several experimental surveys have been conducted over sections of the northern plains states during periods of heavy snow cover. These have produced data for operational use, as well as provide information for test and evaluation of the various procedures. In addition, two large-scale semi-operational programs have been conducted. Aerial snow surveys of the entire U.S. drainage basin of Lake Ontario were conducted for the International Field Year of the Great Lakes (IFYGL) in the spring of 1973 using the ARMS system. Water equivalents were determined for each of the network flight lines shown on figure 3 by the gross count and ^{40}K and ^{208}Tl techniques. Table 1 is a comparison of the IFYGL results using the three techniques with that obtained by extensive ground surveying.

Table 1. Water equivalent (cm) of snow cover on IFYGL calibration lines

	Aerial measurements[1]				Snow tube[2]
Line	Gross count	^{40}K	^{208}Tl	Average	Line average
ROCH-180	2.9 ± 1.3	3.4 ± 1.0	3.6 ± 1.4	3.3 ± 1.0	3.3 ± 0.3
SYRC-050	9.8 ± 2.6	9.1 ± 1.0	9.3 ± 1.9	9.4 ± 1.0	9.3 ± 1.1

[1] Errors shown are one standard deviation.
[2] True average lies within these limits for 90 percent confidence.

A second major operational test was conducted in cooperation with Environment Canada over the Souris River Basin in North Dakota and Canada. Aerial snow surveys were flown over a pre-selected network of lines similar to those for the IFYGL surveys, as shown in figure 4. The average snow cover of the Souris River Basin is near the minimum for which the accuracy of the system would provide significant information. In addition, the area is subject to high wind movement, which causes considerable variation in the deposition of the snow. Two calibration lines in Canada and two in North Dakota were heavily sampled on the ground. A comparison of the airborne measurement with the ground water equivalent averages is shown in table 2.

Table 2. Airborne and snow tube water equivalent (cm) measurements in the Souris River Basin

Line no.	February 1975 Airborne	February 1975 Snow tube	March 1975 Airborne	March 1975 Snow tube	March 1976* Airborne	March 1976* Snow tube
ND-51	2.1	2.5	1.9	1.3	2.0	1.3
ND-52	0.9	1.8	1.8	0.5	0.0	0.0
CA-6	4.1	3.6	4.4	3.6	8.6	9.4
CA-7	3.3	4.3	4.1	4.3	9.4	13.7

*The new RAMS system was used in March 1976.

The average disagreement between the airborne and snow tube measurements is about 1 cm. This is expected from the standard deviation of the airborne data about the ground based data at the Luverne, Minnesota, and Steamboat Springs, Colorado, research lines.

Results of the research studies and the success of the two field testing programs indicate the usefulness of aerial gamma techniques for operational purposes. The procedures require background surveys under no snow conditions and measurement or forecast of soil moisture to establish the bare ground conditions. Likewise, a reasonable estimate or measurement of the soil moisture is required for operational use of the techniques. This is due to problems associated with the inter-relation of the snow cover and the upward movement of the soil moisture which have also been investigated.[7]

SUMMARY

The data acquisition system and the techniques for processing the data are under continual development by the NWS and ERDA. The accuracy of the current techniques for using the radiation data to compute the water equivalent of the snow cover is considered adequate for operational use by the NWS.

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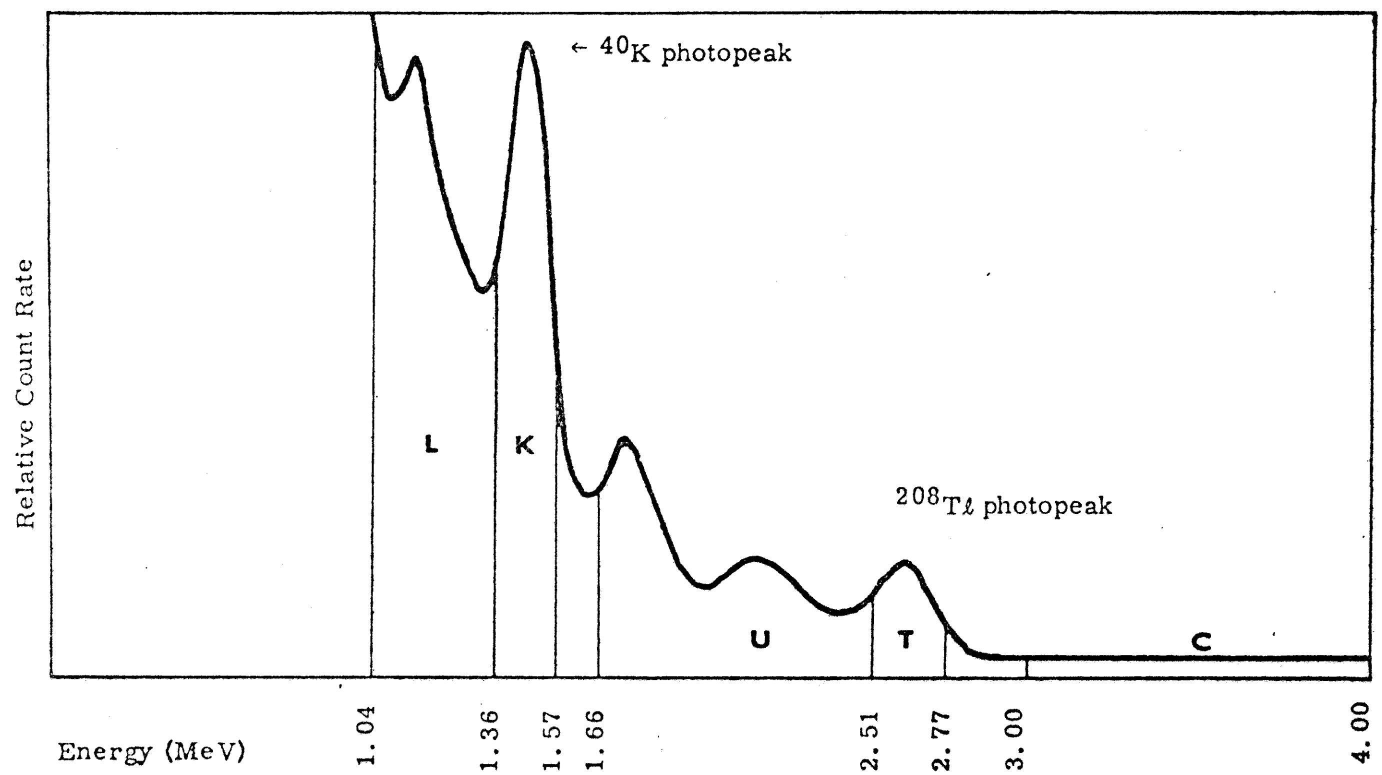

Figure 1.--Relative positions of energy windows measured by the KAMS system.

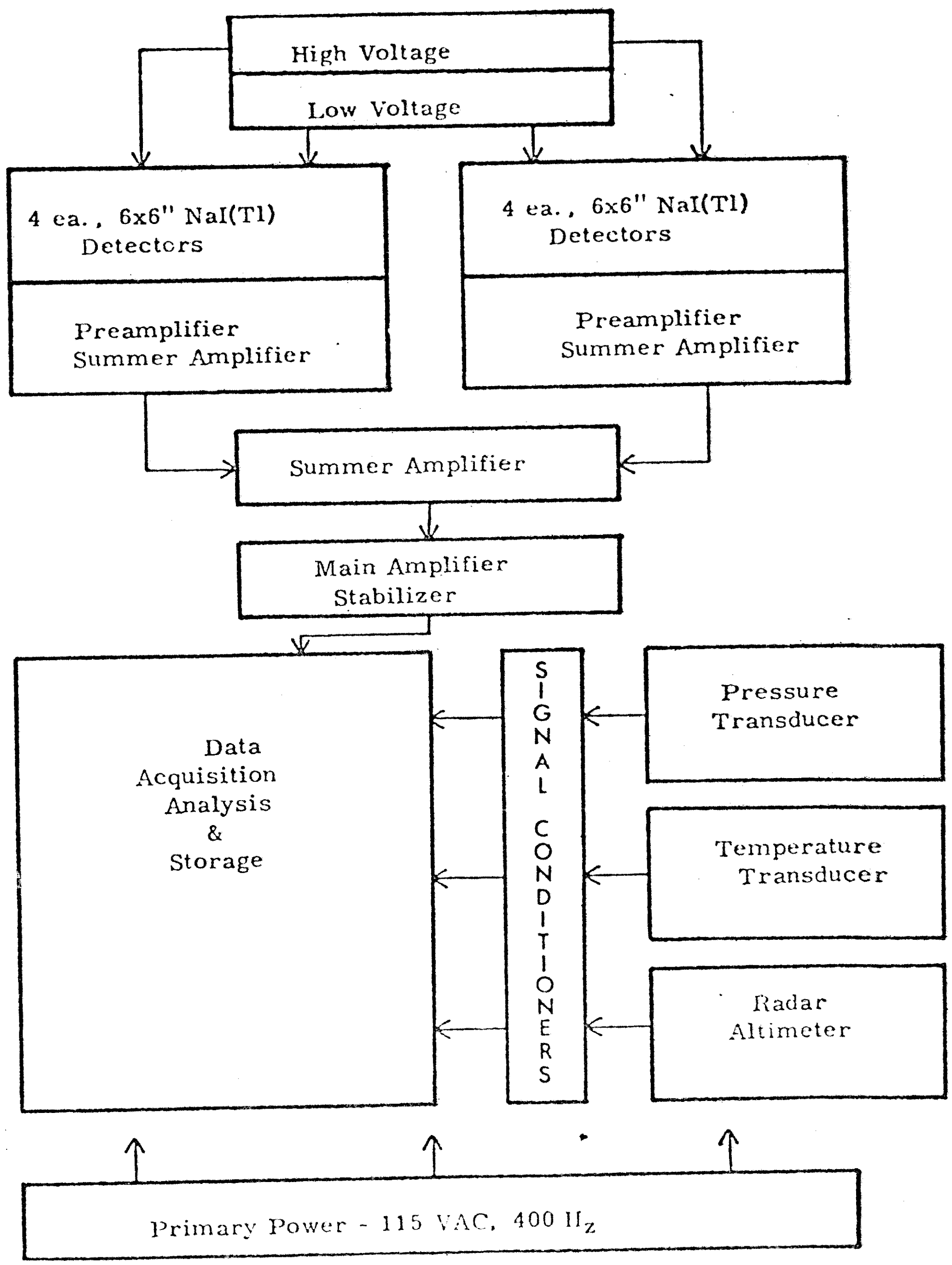

Figure 2.--Principal components of the RAMS system.

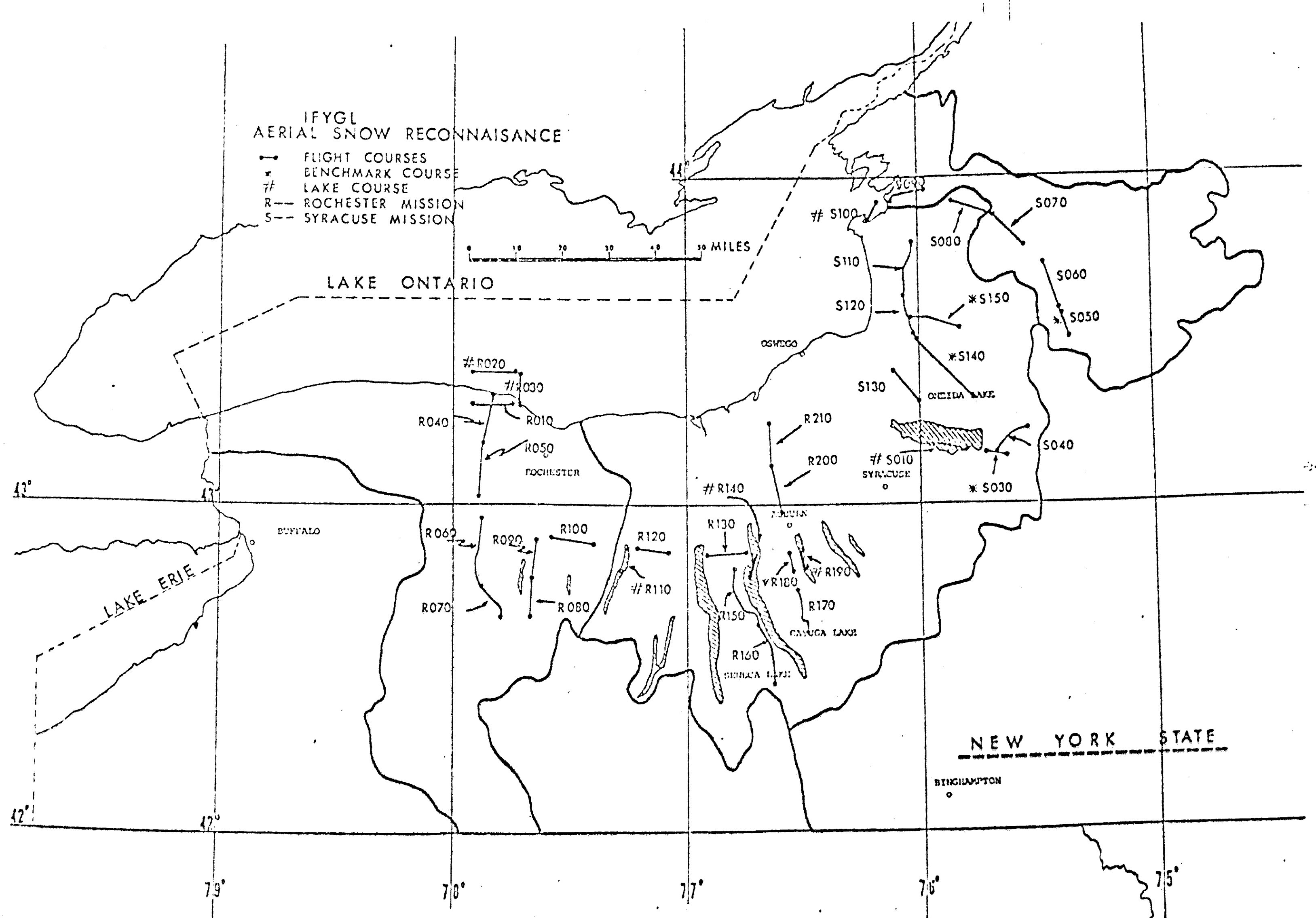

Figure 3.--Gamma flight lines for Lake Ontario Basin in the United States.

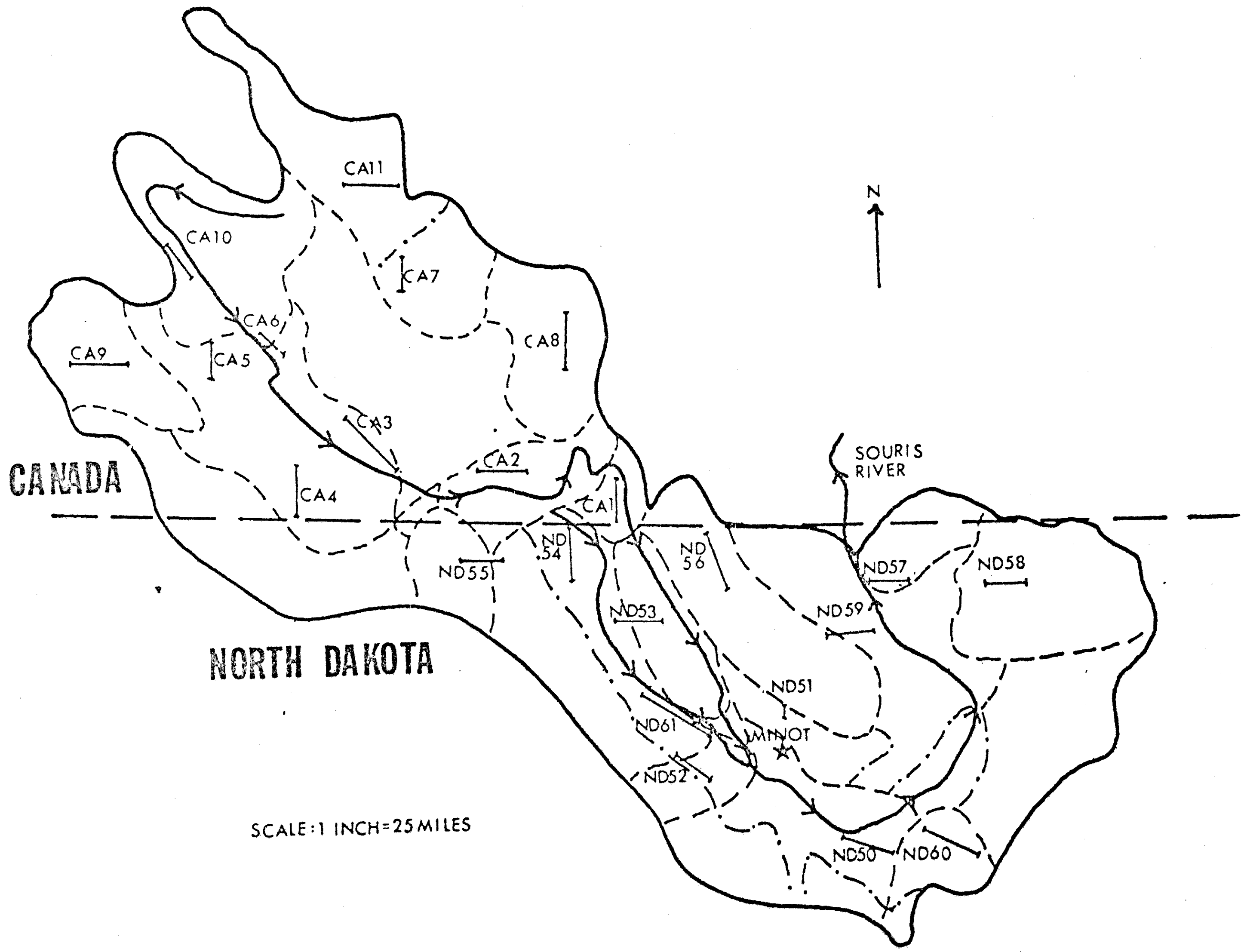

Figure 4.--Souris River Basin gamma flight lines.