GAMMA RADIATION SYSTEM FOR AERIAL SNOW SURVEYING

by

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ABSTRACT

A gamma radiation measurement system for the aerial determination of the water equivalent of the snow cover has been developed for the National Weather Service in the United States. The research and the results of field testing leading to the development of the system Remote Airborne Measurement of Snow is reviewed. The components and techniques for calibration and operational use of the system are described. The gamma radiation flux is measured by the airborne detectors for four energy windows representing cosmic, ^{40}K, ^{232}Th, and ^{238}U, from which water equivalents are derived. Background radiation surveys over selected flight lines with no snow cover are required prior to actual surveying. The accuracy of the system is considered adequate for use in an operational river forecasting program.

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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 servic

Technical considerations. 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.

$$N = (1/(2\,\mu g))E_2(\mu_A h + \mu w WE) \qquad (1)$$

where:

E_2 = exponential integral of the second kind

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

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Aerial Test and Evaluation

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 2,130 m in the Rocky Mountains near Steamboat Springs, Colorado. This site has a much deeper, more continuous, and a longer lasting snow cover.

Many different techniques and operating procedures have been evaluated since the research began. This has 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/.

The two primary measuring techniques that have been tested are the gross count and the peak area (using both the areas for ^{40}K and ^{208}Tl). Equation 4 is the basic relation used for both approaches.

An output pulse height spectrum from an aerial NaI(Tl) detector system is shown in figure 1. The total count (integral under the spectrum from 50 keV to 3 MeV) is the gross count rate used for the gross count technique. The number of uncollided gamma count rates is indicated by the area under the peaks near 1.46 MeV for ^{40}K and near 2.62 MeV for ^{208}Tl. Several methods were tried to determine the number of uncollided gamma counts for ^{40}K and ^{208}Tl. These included calculating the area under the peak above a line created by the extrapolation of the spectrum on either side of the peak.

The results of the early studies clearly indicated that corrections for soil moisture were required for both the gross count and peak area approaches. Techniques for introducing soil moisture corrections and adjusting the measured counts were reported /6/

As a result of Compton scattering and other factors, the count rate for any energy segment of the spectrum in figure 1 is composed to a large extent of counts induced by gammas that originated at a higher energy level. Equations were developed to calculate the number of uncollided counts that are observed in the energy level near the 1.46 MeV for ^{40}K and 2.62 MeV for ^{208}Tl by removing the counts from radiation originating at a higher energy level. This theoretically gives the number of uncollided counts from ^{40}K and ^{208}Tl sources in the soil. In the ARMS system, the count rates of uncollided gammas for ^{40}K and ^{208}Tl in the northern plains area average about 2500 per minute and 500 per minute respectively for flights at 152 m. The fractional uncertainty in water equivalent determination due to counting statistics is therefore considerably greater for ^{208}Tl than for ^{40}K.

The daughter products of radon gas in the atmosphere (^{214}Bi) introduce considerable counts that affect the gross count and the counts under the peak for ^{40}K and the total effect varies considerably within a day and from day to day. Approaches to minimizing this problem have been developed /5/.

To obtain the accuracy required for operational use (standard deviation of about 0.5 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 /5,6,7/.

The average disagreement between the airborne and snow tube measurements is 0.7 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 following section describes a prototype system designed to provide data required for the three techniques of computing the water equivalent of the snow cover and have water equivalent values for pre-selected lines computed while the data collection process is in progress. The procedures require background surveys under no snow conditions and measurement or forecast of soil moisture to establish the base 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 /9/.

Criteria for New System

The ARMS system that has been used in the research program provides more data than required for determining the water equivalent of snow. In addition, considerable processing and computer time are required for either the research or operational mode. The criteria for an operational system for use in the NWS river forecasting service are:

1. Should be adaptable for use in light plane, preferrably portable for use in leased planes.

2. Should be operable by only two persons, a pilot and a system operator, who also serves as a navigator.

3. System should be modular with readily available components.

4. The detector system total sensitivity should provide sufficient counts for an accuracy of less than 1 cm for water equivalent over a 16-km line.

5. Should have capability to store sufficient information for later calibration checks and computation of mile by mile average water equivalents.

6. Should have capability to store background radiation and soil moisture data for use in on-board calculations.

7. Should have capability of computing line averages of water equivalents while data processing is continuing.

Data Collected by New System

The new system, RAMS (Remote Airborne Measurement of Snow), measures only the counts in specific energy "windows" rather than the entire spectrum, as in the older ARMS system. Figure 5 shows the relative positions of each window on the spectrum. The C window in figure 5 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 includes 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.

System operation. Gamma photons are continuously incident on the NaI crystal detectors and are converted to a single pulse train by the preamplifier-summing arrangement. Atmospheric pressure, temperature, and aircraft altitude are converted to analog voltage signals by their respective transducers and signal conditioners. Both the SCA's and digitizers convert gamma and air parameters (pressure, temperature, altitude) signals to pulses suitable for input to the scalers.

When the operator presses the manual start switch, the scalers collect gamma and air parameter data for a time interval set by the scaler timer. The design interval for the scaler timer is 20 seconds, but is variable from 0.1 second to 9×10^9 seconds. At the end of the 20-second time interval, the scaler, chronometer, tagwords, and increment time are all transmitted through the daisey chain to the buffer in 1.3 msec. The scalers are reset to zero and another 20-second collection interval started. The buffer transfers the data to the calculator under calculator program control in approximately 0.2 seconds. This allows sufficient time between data collection intervals for processing and printing of data by the calculator for each line segment. The calculator program also controls mathematical operations and the storage of data on the cassette tape. When the operator presses the manual stop switch, the scalers, chronomete tagwords, and increment time are immediately transferred to the buffer, and data acquisition stops until the manual start switch is again pressed. Data transfer, mathematical operations, and data storage on tape again occur under the control of the calculator program.

During calibration, the data collection can proceed from push button control on the scaler timer. Thus, one is not forced to include the calculator during system calibration if it is not desired.

Data transfer time. The system generates 13 registers of data each 20 seconds. These must be transferred and stored in less than 10 seconds in order to meet survey requirements. Table 4 lists some important transfer times.

Table 4.--Time to transfer data from 13 registers to the printer

Source to destination	Transfer time
Scalers to buffer	1.3 m sec
Buffer to calculator memory	0.2 sec
Calculator memory to cassette tape	1.5 sec
Scalers to cassette tape	2.3 sec
Calculator memory to printer	4.3 sec

The printer is the slowest data transfer device, but data packing (forcing two or three data values into one line or register) will reduce the time to transfer all 13 registers to the printer.

The minimum time for data transfer from the scalers to the cassette tape is 2.3 seconds, which may be considered to be the maximum operating speed of the system (one data accumulation cycle per 2.3 seconds).

Single channel analyzer (SCA) energy calibration. The SCA energy bands must be positioned accurately in order to measure the ^{40}K, ^{214}Bi, and ^{208}Tl photopeak count rates and cosmic continuum precisely. A method utilizing a pulse height analyzer (PHA) was checked. This method simply synchronizes the SCA with the PHA. Only that portion of the pulse height spectrum (or energy spectrum) that passes through the SCA appears on the PHA display. The method performs well for the photopeaks of interest. About 5 keV position accuracy is possible.

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.

The temperature, pressure, and altitude digitizer conversion constants must also be verified.

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:

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

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

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.

Water equivalent values for each line are computed and printed within seconds after line is flown by use of the following equation:

$$WE = 1/\alpha \left[\ln(N_1/N_2) + \ln\left(\frac{1 + M_1}{1 + M_2}\right) \right] \tag{7}$$

where:

WE = water equivalent (cm)

N_1 = bare ground count rate (counts per minute)

N_2 = snow cover count rate (counts per minute)

M_1 = soil moisture for bare ground flight (percent)

M_2 = soil moisture for snow cover flight (percent)

Equation 7 is used to calculate the water equivalent using the ^{40}K, ^{208}Tl and gross count techniques. However, due to the uncertainty induced by variations in radon gas concentration, the gross count calculations are not generally programmed for the on-board computer. The gross count data are stored and the computed water equivalent values are later compared with those from the ^{40}K and ^{208}Tl computations. Since the count statistics of the gross count are better than those for the spectral peak area methods, they are used to prorate the spectral line values to mile-by-mile water equivalents when these data are required.

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 usi the radiation data to compute the water equivalent of the snow cover is considered adequate for operational use by the NWS.

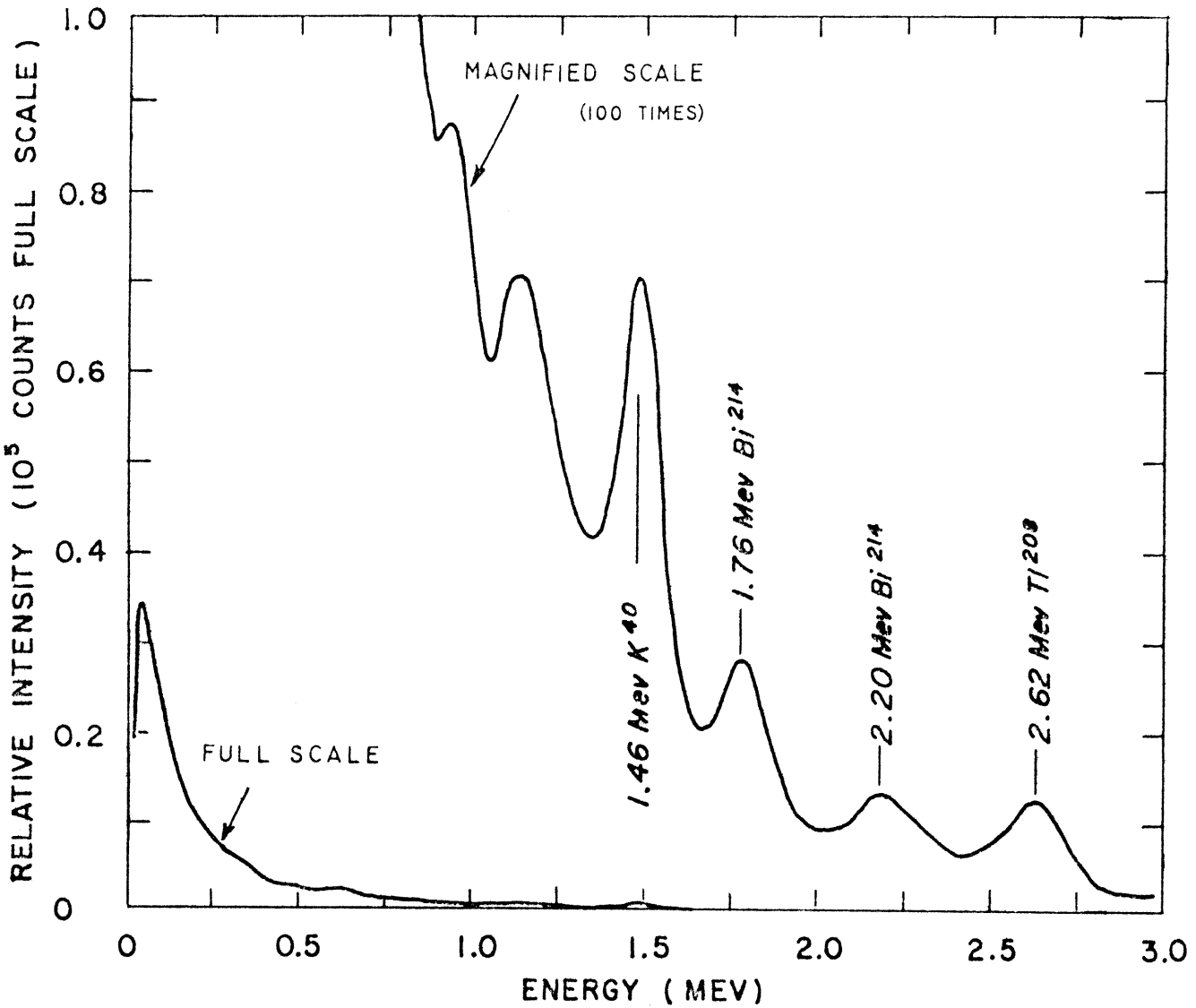


Figure 1.--Spectrum from an aerial gamma radiation survey

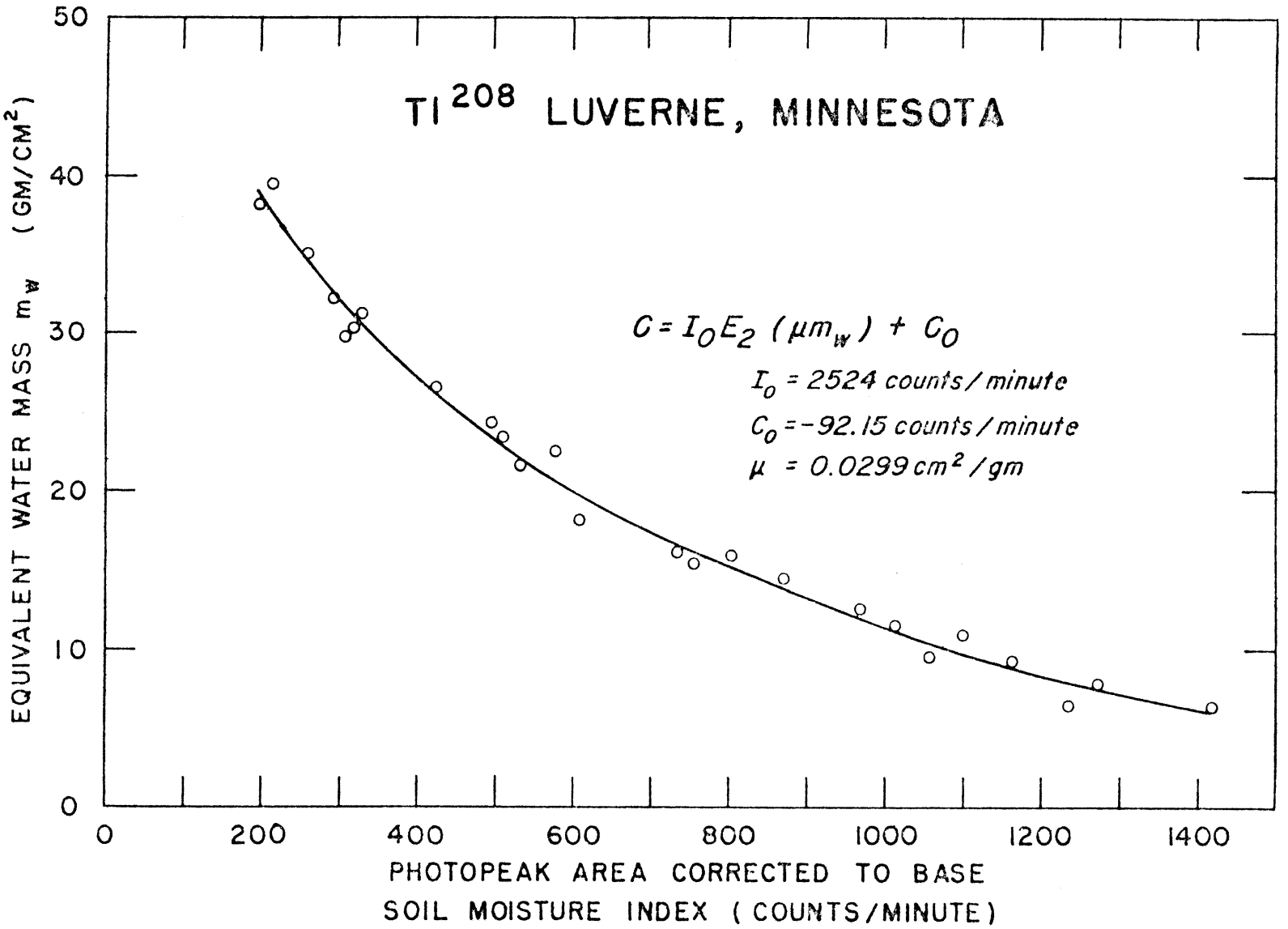


Figure 2.--Relation between Tl^{208} photo peak area and equivalent water mass

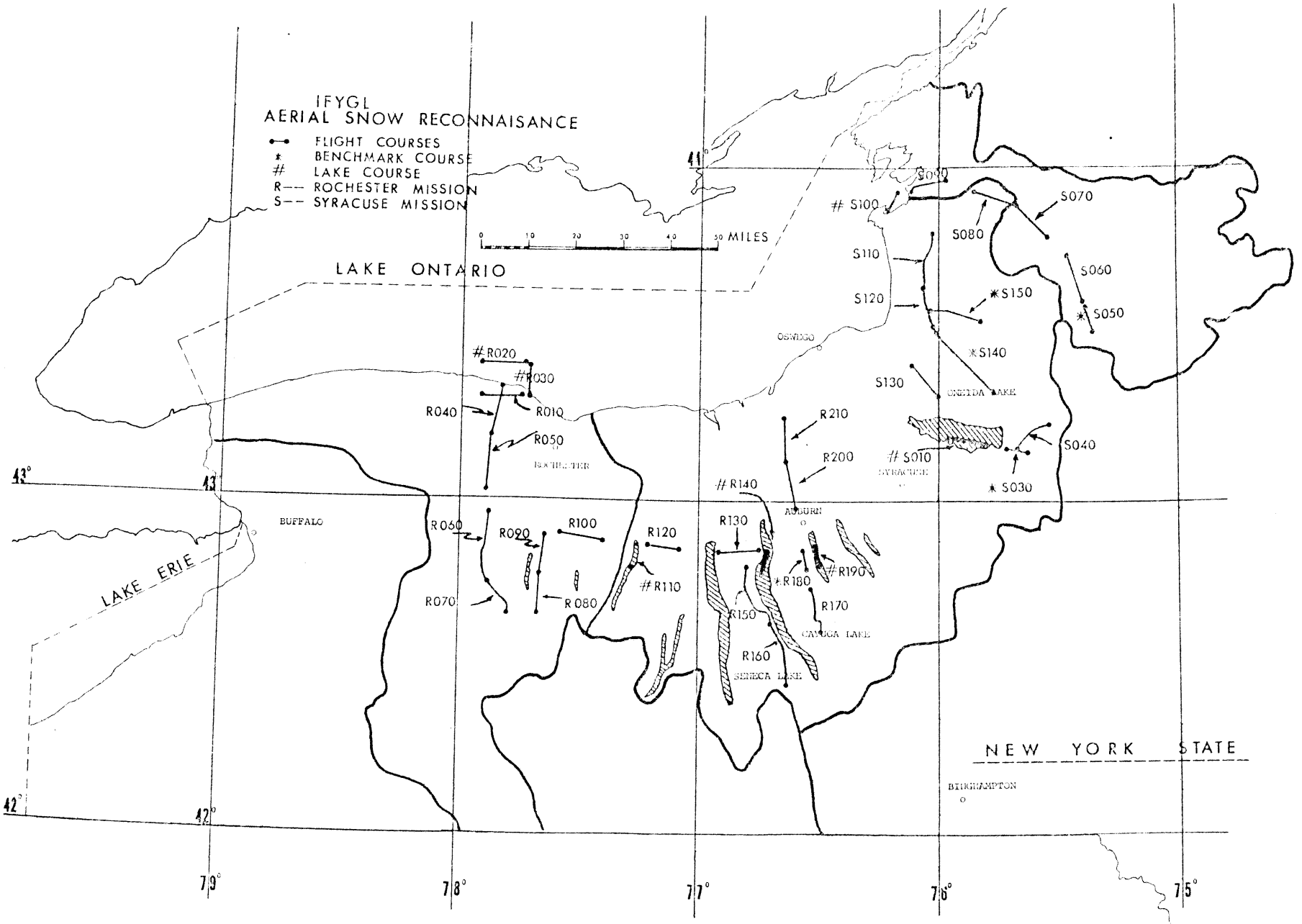


Figure 3.--Gamma flight lines for Lake Ontario basin in the United States.

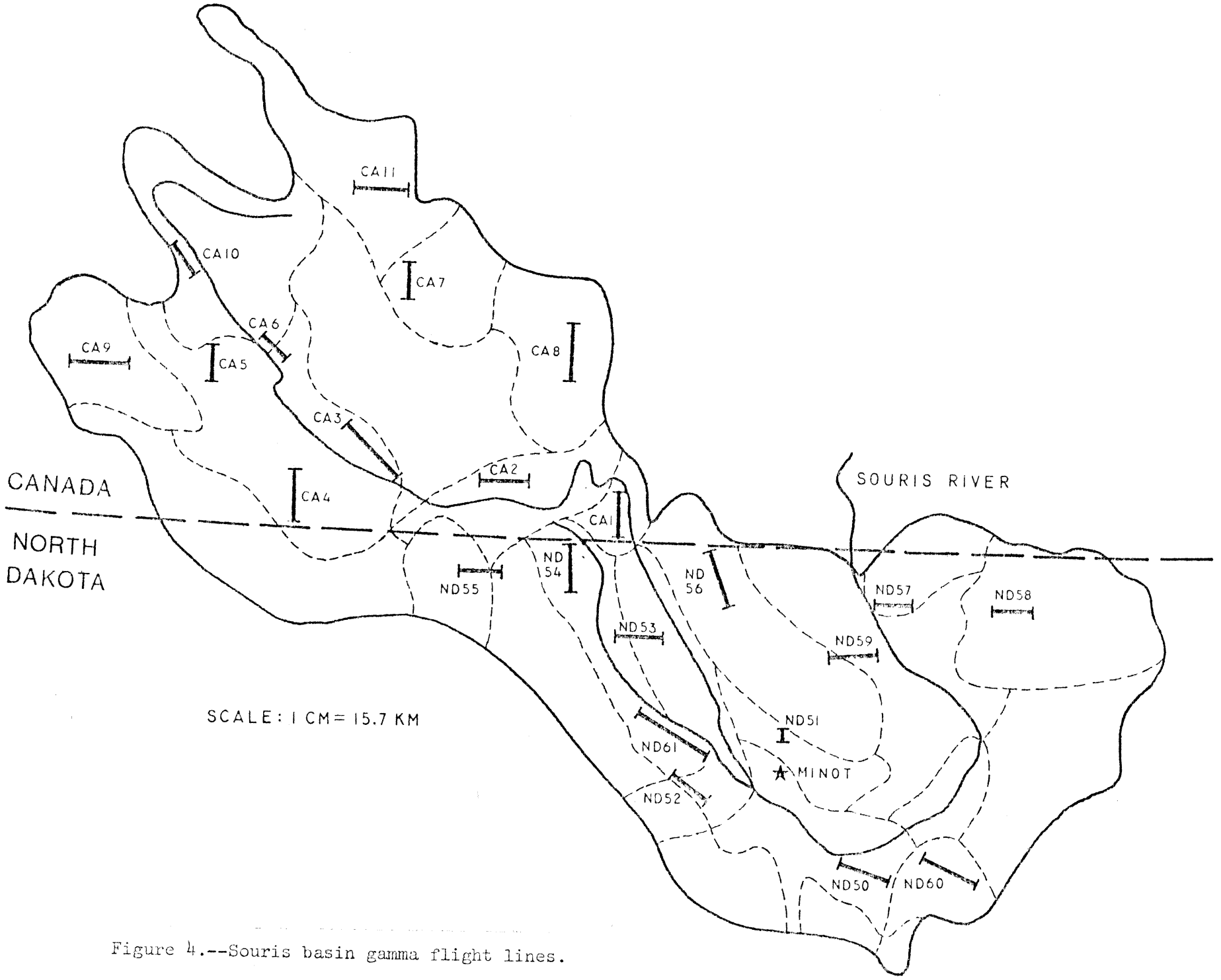


Figure 4.--Souris basin gamma flight lines.

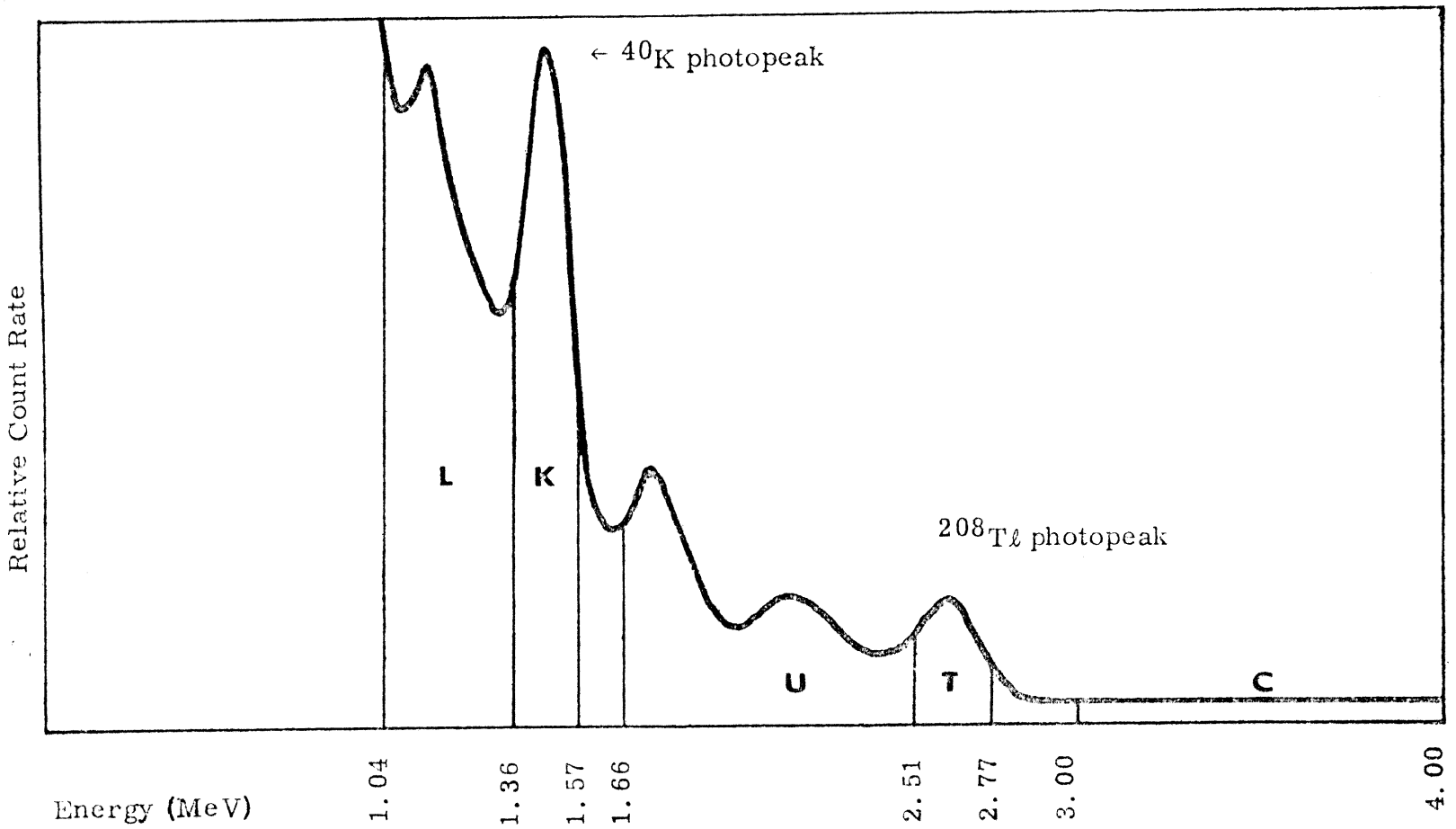


Figure 5.--Relative positions of energy windows measured by the RAMS system.

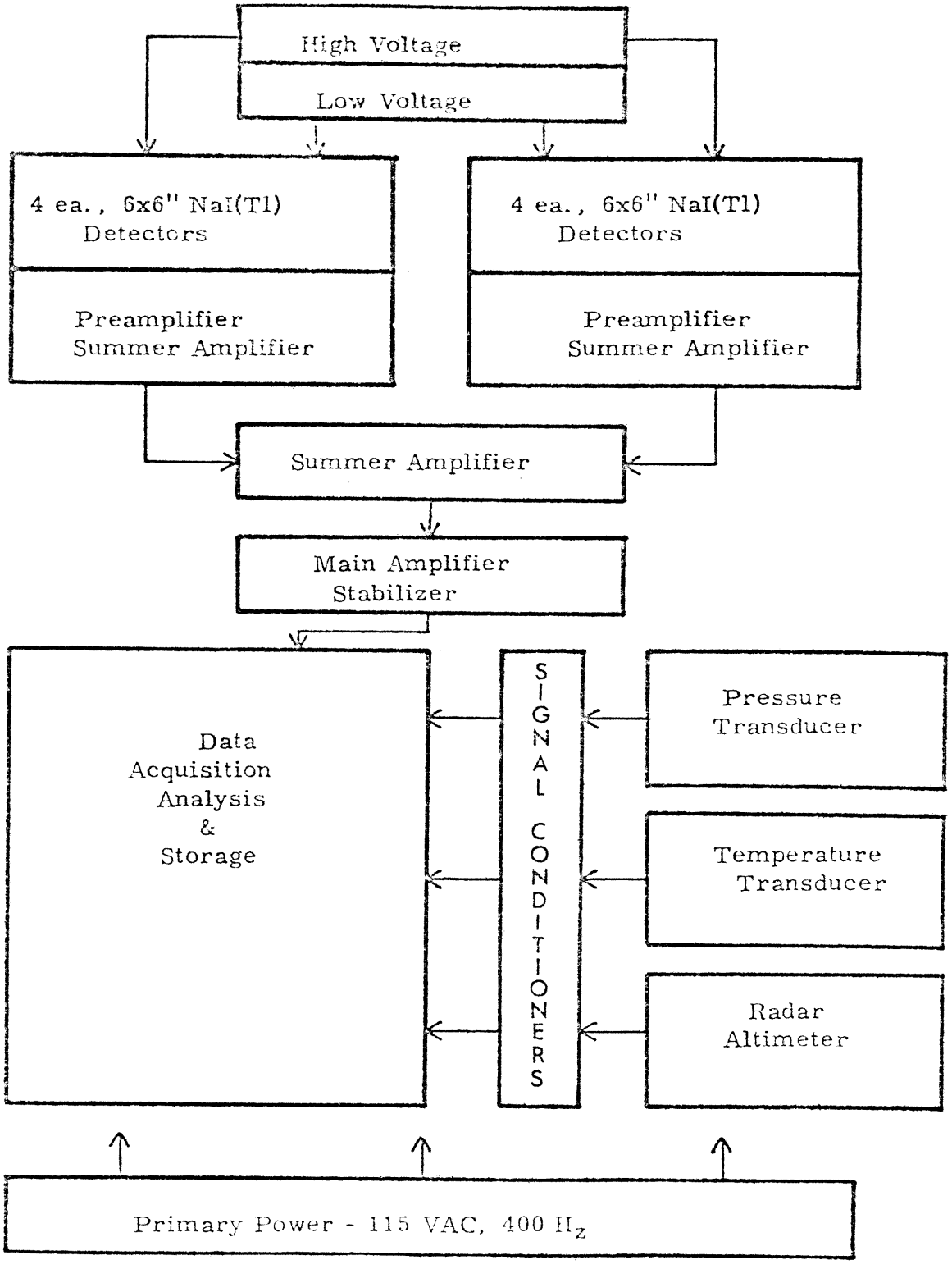
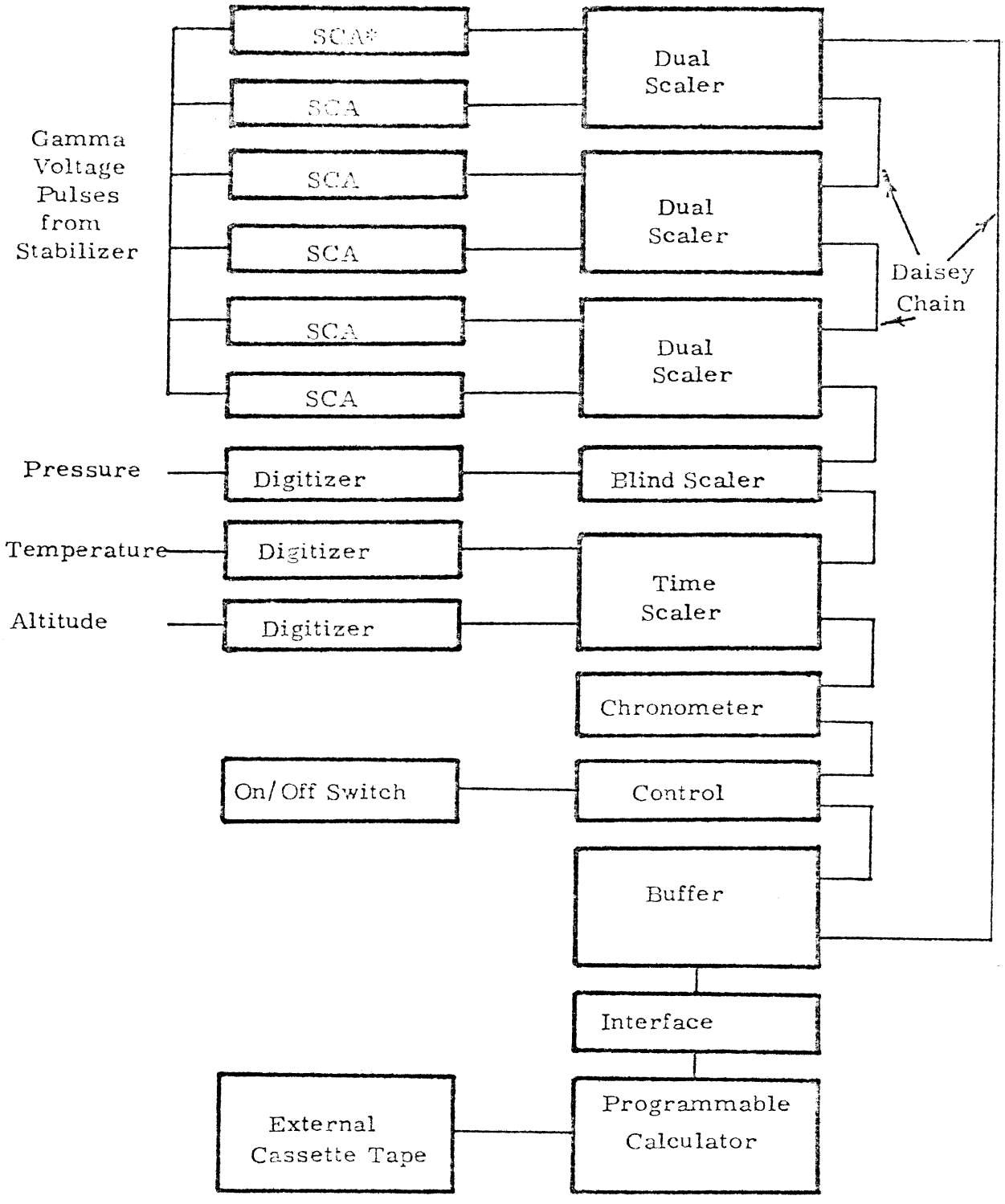


Figure 6.--Principal components of the RAMS system.



*SCA means single channel analyzer.

Figure 7. Components of the RAMS data acquisition system.