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THE APPLICATION OF ISOTOPIC PROFILING SNOW GAUGE DATA TO AVALANCHE RESEARCH

By

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Introduction

The Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, is involved in research regarding the nature and causes of snow avalanches in the San Jaun Mountains of southwestern Colorado. A profiling isotopic snow gauge has been a part of the instrumentation network utilized by this project during five consecutive winters. The gauge was provided to aid in the development of an avalanche occurrence forecast model which was the objective of a study funded by a contract with the Bureau of Reclamation, Division of Atmospheric Water Resources Management. An Aerojet Nuclear gauge was operated during the first three winter periods, 1971-1974, while a modified gauge, constructed by Idaho Industrial Instruments, was operated during the latter two winter periods, 1974-1976.

The earlier gauge was installed by Aerojet Nuclear personnel in December of 1971 at the Red Mountain Pass site (3400 m). The prototype of this isotopic gauge was developed by Dr. James L. Smith, U.S. Department of Agriculture, Forest Service, Berkeley, California. The first radioactive gamma transmission snow gauge was used successfully during the winter of 1964-1965 (Smith, 1965, 1967). As this first gauge required an operator, the next step in the development was the fabrication of a remotely operated, telemetered gauge. This work was undertaken by the Aerojet Nuclear Company with funding from the Division of Isotopes Development of the Atomic Energy Commission.

The field unit of the Aerojet Nuclear gauge consists of a radioactive source, 10 mc$^{13/}$Cs, and a scintillation detector, each horizontally suspended in one of the two parallel access tubes which extend vertically from below ground to a height greater than the maximum anticipated snow accumulation. The scintillation detector is a sodium iodide crystal. This crystal is attached to a photomultiplier tube and both are sealed in a cylindrical aluminum case. The photomultiplier signal is transmitted by a coiled cable to a preamplifier housed in the lift unit. The lift unit consists of two reels connected to a drive shaft. One reel is positioned at the top of each of the parallel access tubes.

A remote gauge of this type requires the following additional components: 1) a telemetry system via commercial data-telephone, which communicates data and commands between the field unit and the base station; 2) a field unit which has the function of decoding and executing commands (i.e. taking snow density data, running the lift motor, etc.) and formating the acquired data for transmission; and 3) a base station which receives the data, formats the commands for transmission to the field unit, and reduces and prints out the data in digital and analog form. The base station for this gauge was located in Idaho Falls, Idaho, at the Aerojet Nuclear facility, National Reactor Testing Station. The personnel at Aerojet would transmit the resultant data to INSTAAR Project Headquarters, Silverton, Colorado, by mail. The original intent was that the Aerojet gauge could be interrogated daily, or more frequently, at prescribed intervals. However, the low quality of telephone transmission between Red Mountain Pass and Idaho Falls precluded the operation of the computer link in an automatic mode. Therefore, data runs were essentially limited to one per day during the conventional work week when personnel were available at the base station.

The INSTAAR study was concerned with monitoring physical changes within the snowcover on a daily or even hourly basis. The full value of the gauge could only be realized if data acquisition could continue uninterrupted from one day to the next. It was therefore necessary to develop some type of locally operated on-site readout capability. Such a facility would not only provide continuous data access, but the location of the gauge would no longer be dependent on the availability of telephone service. The loss of both telephone service and 110 VAC power at a high alpine site is not unusual during storm periods, the very time when data regarding avalanche studies must be available.

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The existing gauge was modified to meet various new specifications by Idaho Industrial Instruments, Inc. While the modified version is similar in structure to the Aerojet gauge, basic differences exist in the measurement technique and data acquisition systems. A collimated Co^{60} source and a ganged GM tube detector system replaces the Cs^{137} source and photomultiplier detector. $Cobalt^{60}$ has approximately four times the water penetration ability of Cs^{137} enabling greater spacing between source and detector, thus increasing the horizontal zone of measurement. Access tube spacing was increased to 1.0 m. Geiger-Müller tubes provide excellent temperature stability over a range of +50°C to -50°C. They are durable, long lasting and inexpensive. The GM tube is a straight digital event transducer and is not count rate sensitive. No precision pulse shaping or high precision power supply is required. The lower efficiency compared to the photomultiplier systems is overcome by paralleling several GM tubes within the detection unit. By collimating the source the scatter is greatly reduced. Coupled with sufficient counting time, the GM tube acts as a discriminator and approaches the overall efficiency of a photomultiplier system.

The onsite controller and readout located in the instrument cabin 30 m from the gauge allow both manual and automatic operation. The detector unit may be operated in a manual mode within any segment of the snowcover where specific measurements are required or the system may be placed in automatic mode and a profile of the entire snowcover made with the detector system automatically returning to the bottom after reaching a preset upper limit. A console LED display indicates the vertical position of the detector system and nuclear counts for each position. A printer also provides a hard copy of the count data. The system is powered by direct-current with the batteries receiving occasional trickle-charging from 110 VAC. The Red Mountain gauge can be operated for approximately two weeks without the need for charging the batteries.

Any isotope source is gradually decaying and requires a constant correction for this decay. The calibration of the present gauge is achieved by having the measurement event dependent rather than time dependent. This is accomplished by a reference detector which is driven by a small microcurie source of the isotope used. The reference scaler is programmed to accept a specific number of counts from the source and then terminate the counting period. This establishes the same statistical accuracy for the system throughout the lifetime of the source; however a longer time period is required to obtain a specific measurement. As an example, if the time to receive 10,000 counts at the detector is 10 seconds initially, in 5.2 years the time constant would gradually have increased to 20 seconds.

Installation of the Profiling Snow Gauge

When a profiling snow gauge is to be utilized in avalanche research, careful consideration must be given to the location of the gauge. For the INSTAAR study, the location was initially determined by the availability of 110 VAC power and telephone service. Fortunately, both were available at the Red Mountain Pass snow study site. Numerous parameters relating to meteorology and snow structure are measured at this location and it was considered highly desirable to be able to have access to such data adjacent to the snow gauge.

A standard snow study site is by definition a level area, below tree line, protected from the wind and easily accessible by the observer. An actual avalanche starting zone is certain to be in sharp contrast with the above definition. A common dilemma in avalanche research results. While it is highly desirable, theoretically, to locate instrumentation within an avalanche starting zone, the practical limitations are obvious. In addition to the need to avoid the destructive force of the avalanche itself, sloping surfaces offer additional difficulties. Local snow structure is influenced by solar radiation and wind patterns, according to slope angle and orientation. Mechanical processes involved in creep and glide of the snowpack relate to the type and shape of the ground surface beneath the snow as well as to the slope angle and orientation. The difficulties involved in determining a representative slope become apparent and one returns to the concept of a standard snow study site for instrument location.

It then becomes necessary to extrapolate data obtained at a level, sheltered site to what may actually be happening on adjacent slopes, both above and below timberline. Such empirical relationships can be established between study plot and release zone, although many years of observation may well be an essential requirement. Therefore, if a profiling snow gauge is to be installed for avalanche research in an area where such a relationship has been or is in the process of being established, it should certainly be located at the site where these studies are underway.

Support structures required for the access tubes should be located in the lee of the instrument opposite the direction of the prevailing wind to prevent drifting of snow near the tubes. The access tubes should be maintained with a highly reflective surface in regard to both short and long wave radiation to prevent melting of the snow in contact with the tubes.

Field Calibration

On-site calibration and accuracy tests have been carried out adjacent to the Red Mountain Pass gauge by relating the density values of the profiler to those conventional measurements obtained by acquiring samples of known volume from the wall of a snowpit (see Table 1). This method is considered to possess a potential accuracy of 0.001 Mg/m^3 (Bader, 1939).

Table 1. Isotopic Profiler-Snow Pit Correlation at Red Mountain Pass, Winter 1971-1972

	Mean Density (Mg/m^3)		Water Equivalent (mm)		Standard Deviation of Density Values at 5.0 intervals
Date	Profiler	Pit	Profiler	Pit	
Dec. 22	.266	.273	144.0	156.4	0.012
Jan. 11	.244	.283	242.8	259.0	0.014
Jan. 19	.280	.268	272.0	274.0	0.009
Jan. 26	.279	.295	266.9	284.9	0.011
Feb. 1	.287	.294	277.8	284.2	0.013
Feb. 9	.282	.299	287.5	319.5	0.017
Mar. 3	.282	.278	357.1	353.5	0.015
	Mean Deviation		Mean Deviation		
	0.017		12.8		

The same type of field calibration was undertaken following the installation of the modified gauge. At that time data reduction (conversion of nuclear counts to snow density) was based on a log-linear relationship derived from calibration in water. These calibration values did not agree with subsequent field calibration in natural snow. It was determined that increased scatter occurred when the radiation passed through snow, thus increasing the ratio of counts to density compared to the relationship based on water samples of various thicknesses. Figure 1 shows a comparison between snow pit data and profiler data based on the initial calibration values. The snow pit was located approximately 10 m from the profiler. Note that the stratigraphic agreement is excellent and only the calibration relationship required adjustment resulting in the data provided in Figure 2.

A second aspect of field calibration requires that the source and detector be located in a precise horizontal plane such that maximum counts are achieved. This may be undertaken in a calibration tank or in air. Periodic checks should then be made to identify any misalignment of source and detector which may develop. If maximum count level is established in air above a snow surface, the source-detector system should be located at least 40 cm above the snow to avoid scatter from the surface.

Application of Data to Avalanche Research

There are numerous criteria in use today for categorizing types of snow avalanches. One basic genetic discriminator divides all avalanches into two groups: direct action and delayed action. A direct action avalanche occurs during or immediately after a storm and is the result of the increased stress applied to the snowpack in the form of new snow. This type of avalanche is the immediate consequence of a prevailing meteorological situation. A delayed action avalanche is the result of gradual changes taking place within the snowcover over a longer period of time. Such avalanches may occur as the culmination of a slow load build-up, with a weak layer within the snowpack being the eventual zone of failure, or may occur without the increased stress of additional loading when gradual adverse metamorphism continues until existing stress exceeds the deteriorating strength at some point within the

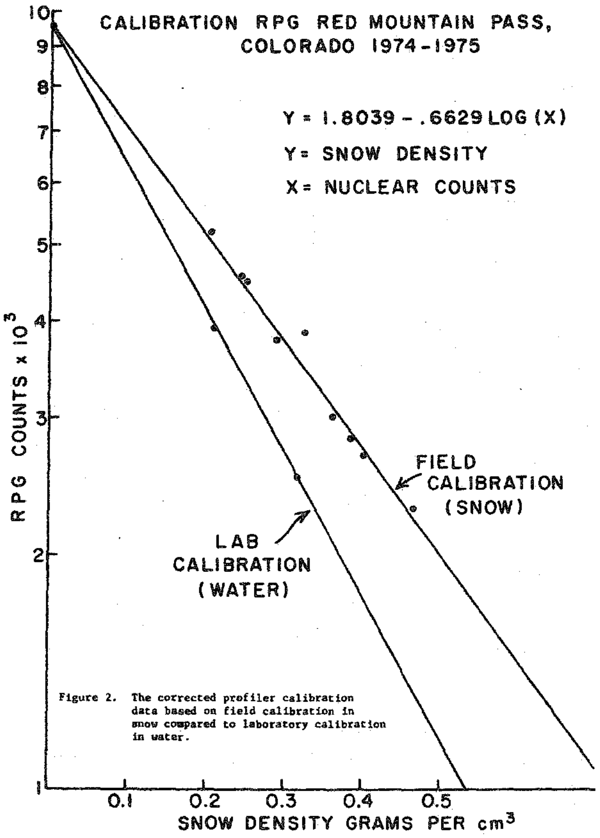

Figure 2. The corrected profiler calibration data based on field calibration in snow compared to laboratory calibration in water.

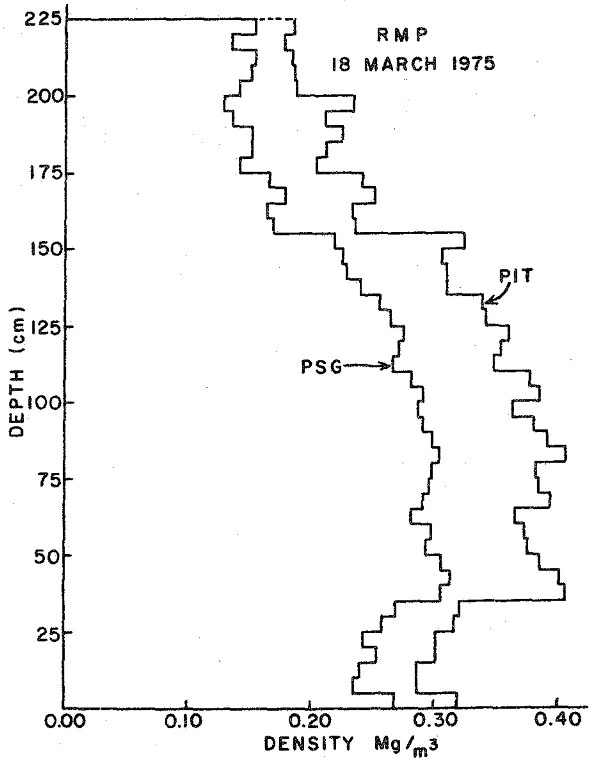

Figure 1. A comparison of snowpit and profiler density data for field calibration purposes.

snowpack. This may occur both during mid-winter when temperature-gradient metamorphism results in depth hoar formation, and in the spring when the snowpack becomes isothermal and the bonds between the individual grains break down. Therefore, instrumentation and field methods have been developed to measure new-snow accumulation as well as changes in old-snow structure.

The standard methods for monitoring physical and structural changes on and within the snowpack involve the following. To measure accumulation, some type of recording precipitation gauge is used. Special problems are encountered, however, as most gauges available are primarily designed to measure precipitation in the liquid phase. When the intent is to monitor the precipitation rate of snow, provision must be made to prevent capping or clogging of the gauge orifice due to high snowfall rates. Periods of high precipitation intensity are of great interest to avalanche research and therefore an unfortunate moment not to be receiving data. An additional drawback associated with this method of snowfall recording is that the accuracy of the gauge may be greatly influenced by the wind field in the vicinity of the orifice. At wind speeds often associated with winter storms such a gauge tends to underestimate the actual amount of mass being delivered to the snowpack. An alternate method is to measure new snow increments falling on a snow board placed on the surface of the snow prior to the storm and to melt samples taken from the boards in order to determine water equivalent. Inaccurate measurements by this method result when the initial portion of the sample is removed by wind, as well as when melt occurs through solar heating of the board. The ideal surface on which to measure new snow increments is not an artificial device which obstructs the natural terrain, but rather the snow surface itself. Such a method is employed by the profiling gauge.

Among the derived properties of snow, density is perhaps the most used as an index of snow type. The standard method in avalanche studies for measuring density involves digging a pit through the pack to the ground and then extracting samples of a known volume from the wall of the pit and weighing each sample to determine density. The stratigraphic frequency at which these values can be obtained is determined by the thickness of the sample container, generally from 3.0 to 5.0 cm. Since zones of weakness are often only 0.5 cm or less in thickness, critical information concerning the strength properties of the snowpack may well be overlooked with this method. In addition, this type of measurement is destructive and therefore useless in terms of accurate in situ studies of changes in density with time. The anisotropic nature of snow precludes the possibility of taking density samples in adjacent locations during successive days or perhaps even hours in time and still being able to assume an accurate time-stratigraphic profile. Changes in snow structure as a function of spatial variation may equal or exceed those changes which one wished to monitor.

The rate and amount of settlement which takes place within the snowpack is another index which can be related to snow strength. A layer of newly fallen snow in the absence of wind exists as a delicate cellular matrix. Although the individual crystals may interlock mechanically, they adhere weakly at points of mutual contact. Gradually as the snow settles, the stellar or similarly complex crystalline shapes are reduced to a more spherical grain. Such a shape permits greater amounts of common surface area to exist among the grains. In the absence of significant temperature gradients (approximately 0.1°C/cm), intergranular bonding is enhanced and strength increases. The density profiles produced by the isotopic gauge may serve as in indicator of snow settlement. One simply locates a particular layer within the snowpack which is easily identifiable due to a particularly high or low density value in relation to surrounding layers. The vertical movement of this layer reflects the degree of settlement within this immediate area. The settlement rate of snow involved in an individual storm can be observed by noting the compression of that layer which represents the appropriate storm increment.

Data Analysis

In terms of general snow structure, two types of avalanche release exist. The first is referred to as a loose-snow avalanche and occurs when snow crystals which adhere poorly to each other collect on a slope steeper than their angle of repose. Failure begins near the surface when a small amount of cohesionless snow slips out of place and starts moving down the slope. The second type is known as a slab avalanche and occurs when snow lies on a slope in a cohesive layer which is poorly bonded to the snow or ground below. The slab event presents a greater hazard because it incorporates larger amounts of snow, and also because the wide variety of snow conditions which lead to its formation cause problems in predicting such events.

The layered structure of a natural snowcover is directly related to slab releases. Stratigraphic data regarding the alternating weak and strong layers within the snowcover are extremely valuable to avalanche prediction. Weak layers comprising potential shear failure zones exist within new snow, at old snow-new snow interfaces, and within the old snow structure. Stratigraphy within new snow is primarily a function of meteorological conditions at the time of deposition while structure within older snow layers may be a consequence of metamorphic changes occurring over a period of weeks or even months. An example of a weak layer within new snow as detected by the profiling gauge and a light-wieght (0.1 kg) ram penetrometer appears in Figure 3. This condition alone did not produce avalanche releases but three days later on January 28, 1975, 53.0 cm of new snow containing 46.6 mm of water was recorded at Red Mountain Pass. This new snow combined with the weak layer below produced a widespread cycle of slab avalanches.

The development of a layer of temperature-gradient snow or "depth hoar" at the base of a snowcover is a common phenomenon in the Rocky Mountains. The thickness and degree of metamorphism of this layer often exerts a significant influence on avalanche activity during the entire winter season. The ability to continuously monitor density values within the basal layer is made possible with the profiling gauge. Figure 4 provides an example of the progressive development of this snow layer from early winter to December 23, 1974. At that time the accumulation of additional snow provided a load sufficient to initiate slab avalanches which released within this weak basal layer. Avalanche activity associated with the depth hoar layer continued throughout January and well into February until virtually all of this type of snow structure had been removed from the various avalanche paths.

Figure 5 shows the basal temperature-gradient layer as it existed on April 15, 1973. Such data describe the snow structure at the study site only and it must be noted that when considering the avalanche paths themselves, significant portions of this stratigraphy may have been removed by avalanche activity. This was in fact the case by the latter portion of the 1974-1975 winter. However, Figure 5 is representative of the snow structure as it existed in the majority of avalanche starting zones on April 15, 1973. Only a limited amount of mid-winter avalanche activity had occurred during the 1972-1973 season. During the third week in April, the snow temperatures in most avalanche release zones had reached 0.0°C and as free water began to percolate down through the snowcover, it came in contact with a complex stratigraphy which had been developing over the past four to six months. On April 27, a widespread cycle of large wet slab avalanches began. Subsequent investigations of the avalanche fracture lines indicated that these slabs failed within the old layer of temperature-gradient snow near the ground. It is significant to note that once mature depth hoar has developed, even though the temperature gradient which caused it to form diminishes as the winter progresses, no significant inter-granular bonding occurs and a condition of relatively low mechanical strength continues into the spring. This condition is even more apparent from the rammsonde data in Figure 5 than from the density data. This is because the direct relationship between strength and density for dry snow is not easily applied to wet snow. As free water begins to melt the bonds between grains and reduce mechanical strength, associated density values may remain unchanged. However, it is apparent from the density profile that temperature-gradient processes dominated the lower 75 cm of the profile through much of the winter; fine-grained, equitemperature snow generally exhibits a consistent increase in density with depth (Figure 5, 75 to 220 cm) while temperature-gradient snow does not, tending rather to inhibit settlement and thus densification rate (Figure 5, ground to 75 cm). Therefore, given the density profile alone, an experienced observer would recognize a snowcover with a significantly weak basal layer.

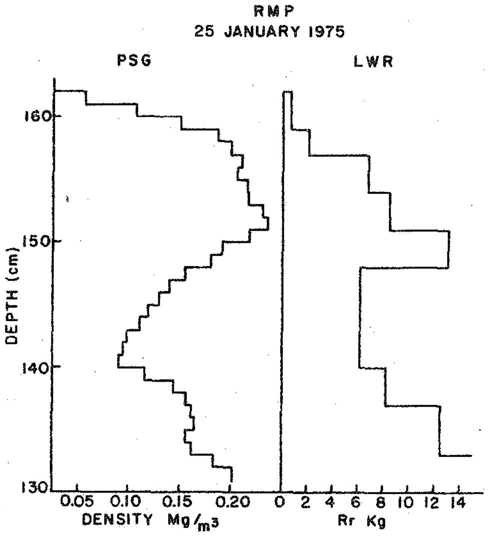

Figure 3. Comparison of stratigraphy provided by profiler density values and light-weight rammsonde (0.1 kg.) strength data. The weak, low density layer is a new snow accumulation in the absence of wind. Above this layer is a stronger, higher density slab deposited during a period of relatively high winds.

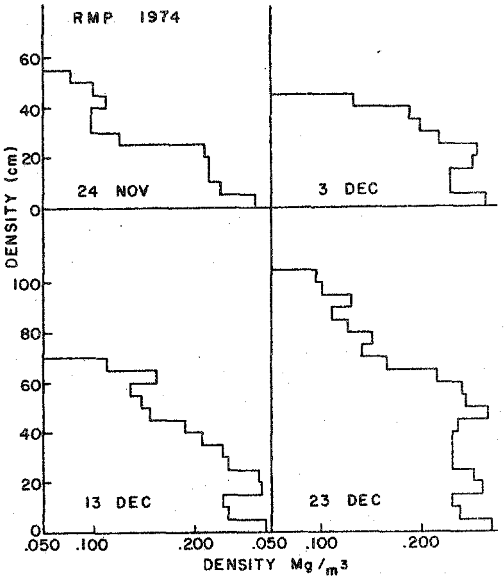

Figure 4. Sequential development of a structurally weak temperature-gradient layer at the base of the snowcover as monitored by profiling snow gauge density values.

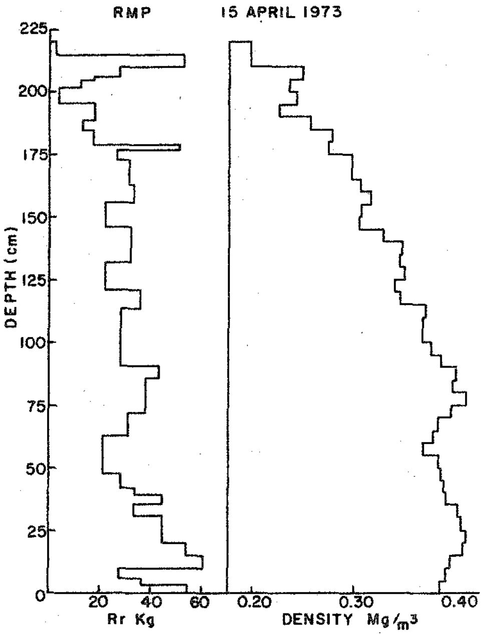

Figure 5. Comparison of rammsonde strength data and profiler snow density values within a mature snowcover.

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