SNOWPACK SNOW WATER EQUIVALENT MEASUREMENT USING THE ATTENUATION OF COSMIC GAMMA RADIATION

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ABSTRACT

Incoming, background cosmic radiation constantly fluxes through the earth's atmosphere. The high energy gamma portion of this radiation penetrates many terrestrial objects, including the winter snowpack. The attenuation of this radiation is exponentially related to the mass of the medium through which it penetrates. For the past three winters, a device measuring cosmic gamma radiation -- and its attenuation through snow -- has been installed at the Central Sierra Snow Laboratory, near Donner Pass, California. This gamma detector, measuring energy levels between 5 and 15 MeV, has proved to be an accurate, reliable, non-invasive, non-mechanical instrument with which to measure the total snow water equivalent of a snowpack. This paper analyzes three winters' worth of data and discusses the physics and practical application of the detector for the collection of snow water equivalent data from a remote location.

INTRODUCTION

For most of the past 80 winters in the American West, snow surveys have been conducted to measure the amount of water equivalent stored in the seasonal snow cover. Within the snow zone, precipitation, water stored as snow, and spring runoff are all intimately linked. Throughout the decades the variation in volume of available snow-water has spanned everything from severe drought to inundating flood. As we race toward the turn of the century, the pressure to efficiently manage the west's most precious resource -- water -- reaches an all-time high. Competition for water between domestic use, industry, agriculture, fisheries, riparian health, and recreation will only increase. Since much of the west receives its water from melting snow, the accurate assessment of the snowpack snow water equivalent is a vital first step in any available-water forecast.

DATA COLLECTION PROBLEMS

One of the foremost techniques for predicting available snowpack snow water equivalent (SWE) is hand-measuring the snowpack. This is most commonly done with a sampler consisting of sectional aluminum tubes that are fitted together and used to core an entire cross section of the snowpack. This core is then weighed to determine its water content. This coring sampler is relatively simple and therefore quite reliable. In most snowpacks, several cores can be sampled in a short period of time. But manually obtaining a snow core is an invasive procedure, negating the possibility of sampling the exact same parcel of snow twice, a critical disadvantage when assessing the changing condition of a snowfield. Also, the effects of icing and compaction as the corer is thrust through snow layers of varying densities and temperatures may be difficult or impossible to combat, resulting in faulty data. And because travelling to and from measurement sites precludes 'round-the-clock data collection, manual measurements simply cannot provide enough information to satisfy snow-water forecast models that demand real-time data from the ever changing snowpack.

Snow sensors, or snow pillows -- fluid filled bladders (approximately 7.5 m^2) made of steel or rubber -- have been widely used for snow-water measurement at remote sites. Snow pillows are installed at ground level and weigh the overlaying snowpack as it accumulates. The weight of the water (stored as snow) pressurizes the pillow's fluid, and that pressure is monitored by a pressure transducer or a stilling well with shaft encoder. Data can then be transmitted back to regional field offices.

For a variety of reasons, snow pillows remain a less-than-ideal instrument with which to remotely measure total snowpack snow water equivalent.

To minimize snowpack forces of creep and glide, snow pillows demand a rather large, flat area. Almost by definition, these are rare in a montane environment. Consequently, many snow pillows are sited on meadows, locations that flood frequently and may not be representative snow sites within the watershed.

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Difficulties with the maintenance of the pillows revolve around protecting the site and instrumentation from human and animal vandalism; detecting pin hole leaks in the plumbing that become more pronounced with additional weight of deep snowpacks; and maintaining the integrity of any fluid/electronics interface. Since a snow pillow weighs the overlaying snowpack, it is highly susceptible to the pack's combined forces of differential settling, creep, and glide. These forces are not only tremendous (an above timberline, late season 5-meter-deep snowpack at an average density of 450 kg/m^3 applies a pressure of 2 x 10^4 N/m^2 to the snow pillow surface), but tend to show up in the snow pillow data stream and are troublesome to interpret.

The formation of very strong basal layers in deep snowpacks is a common occurrence. Basal layer bridging of the snow pillow surface by the snowpack may occur, and once established, subsequent snowfall may not be detected by the pillows until late-season warming and collapse of the strong basal layers. Bridging can result in lower-than-actual snow water equivalent values being recorded.

The antifreeze fluids that pillows contain -- typically water-diluted propylene glycol, ethanol, or a mix of the two -- pose no significant environmental hazard, but are compounds foreign to the mountain environment nonetheless. The threat of leaks or spills during or after installation are enough to justify the apprehension of wildland managers and ecologists to approving additional snow pillow sites.

Logistics associated with the transport of heavy, bulky snow pillow parts and fluids into rough and remote country are formidable, especially into designated wilderness areas where the landing of support aircraft are prohibited.

Even with advancements in snow pillow design and materials, many of these same problems that plagued pillows forty years ago are still present today.

THE GAMMA DETECTOR

Cosmic gamma radiation constantly fluxes through the earth's atmosphere. High energy gamma photons -- originating from the realm of black holes, supernovae, particle annihilation, and other non-thermal astrophysical phenomena -- penetrate many terrestrial objects, including the seasonal snow cover. The attenuation of monochromatic gamma rays by matter is given by the generalized equation

$$\ln(I_s/I_o) = -kx \qquad (1)$$

where

I_o is the measured intensity of the gamma energy at the detector in the absence of an absorber;
I_s is the measured intensity of gamma energy with the absorber present;
k is the linear attenuation coefficient for the absorber; and
x is the thickness of the absorber.

Equation (1) describes a narrow beam of radiation and must be modified when dealing with a plane wave. The attenuation of plane wave cosmic radiation through water more closely follows

$$y = a(1+b(x/c))e^{(-x/c)} + (1-a)(1+b(x/d))e^{(-x/d)} \qquad (2)$$

where

a is .60, the fraction of background energy that is gamma;
b is .25, a term for estimating the dose buildup factor;
c is 50.8, the gamma attenuation coefficient (cm);
d is 711.2, the primary attenuation coefficient (cm);
x is the thickness of water (cm); and
y is the attenuation factor.

Starting in 1994, instrumentation groups within Sandia National Laboratories were directed to develop civilian, dual-use applications for their radiation detection and telemetry systems. As a direct response to this mandate, early in February of 1996 two gamma ray detectors were installed at the Central Sierra Snow Laboratory (CSSL) at elevation 2100 m near Soda Springs, California. One detector was buried with its top plate flush with the soil surface and the other was mounted on a mast above snow surface. The above- and below-snow detectors were approximately 10 meters horizontal distance from each other. The gamma detectors, manufactured by eV Products* of Saxonburg, Pennsylvania, are scintillation detectors, each housed in a waterproof, stainless steel cylindrical case measuring 15 cm long and 10 cm in diameter. They detect incident gamma photons from a paraboloidal volume overhead, a cross section of which is approximated by the $\cos^2 x$ function. The detectors effectively measure gamma radiation up to 15 MeV. Both detectors were connected to a desktop computer running an acquisition program that logs the number of counts from 512 separate channels, each channel identifying a discreet energy band. Figure 1 is a typical energy spectrum from a detector clearly showing two energy peaks associated with soil isotopes of potassium and thorium. For this

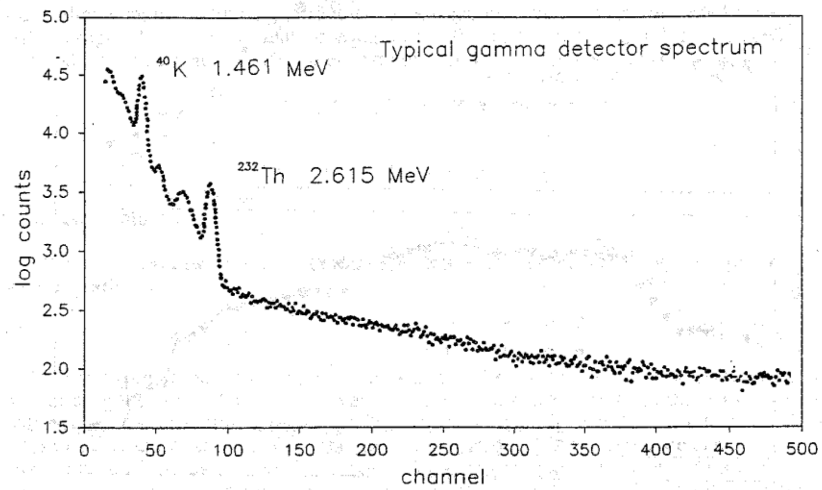

Figure 1. Energy spectrum from the reference gamma detector, CSSL, winter 1996.

study, only energies greater than 5 MeV were considered, thereby eliminating any effect of soil radiation with energies less than 3 MeV. (These two energy peaks, however, are used in calibrating the energy distribution from the rest of the spectrum.) Once an acquisition sequence commenced, particle counts from each detector were logged; we ran each acquisition sequence for three hours, eight per day.

A comparison of the detector acquisition sequences from both above and below the snowpack yield the attenuation factor y due to the liquid and solid water stored in the snow. Using Newton's Method (an approximation series to find the roots for the above non-linear equation), we solve equation (2) for x.

For winter 1996, total SWE values were obtained daily through the gamma detectors. Manual SWE values, measured less frequently, were considered ground-truth and used to analyze the gamma detector data. During winter 1996, snow cores were taken at a location approximately 30 meters NW of the gamma sensors. Some differential melting between these two locations was observed. Because we were late installing the field detector (February 9), the snowpack (depth 153 cm, SWE 52 cm) immediately above and around the site had to be disturbed.

For winter 1997, both the reference (tower) and field (buried) detectors were relocated at the CSSL. The reference detector was mounted atop a tower 10 meters above the ground and the buried field detector was located 4 meters from a snow pillow monitored by the Natural Resources Conservation Service (NRCS), part of that agency's SNOTEL network. At their new locations the gamma detectors were now approximately 6 meters horizontal distance apart. The early season snowfall delayed the installation of the field detector; attenuation data collection commenced on January 10, 1997. During the two weeks previous, the snowpack (depth 168 cm, SWE 66 cm) surrounding the CSSL had absorbed and outflowed more than 450 mm of rainfall, resulting in an average snowpack density of 393 kg/m^3, 130% of average. These rains contributed to very strong basal layer formation within the snowpack not only around the CSSL, but along a great length of the Sierra Nevada. Snowpack bridging of many of the Sierra's snow pillows resulted. Not until late season melt weakened these layers did the bridging collapse and the snow pillows begin to read accurate SWEs. During winter 1997, snow cores were drawn from the snowpack within a 10 meter radius of the buried field detector. Figure 2 is a plot of winter 1996 and 1997 data showing the gamma detector SWE values against manual SWE measurements. Also displayed is data from the accumulation period of winter 1998.

DETECTOR CALIBRATION

During summer 1997, the field detector was removed from the CSSL and brought south to San Vicente Reservoir (San Diego County), California, for underwater calibration. While logging data to the same acquisition program as at the CSSL, the detector was submerged and 12-hour data runs completed at various depths. To alleviate any doubt about the maximum SWE the detector might be able to discern, the deepest run was conducted at a depth of 7.6 meters -- sufficient enough for even an El Niño-influenced Sierran snowpack.

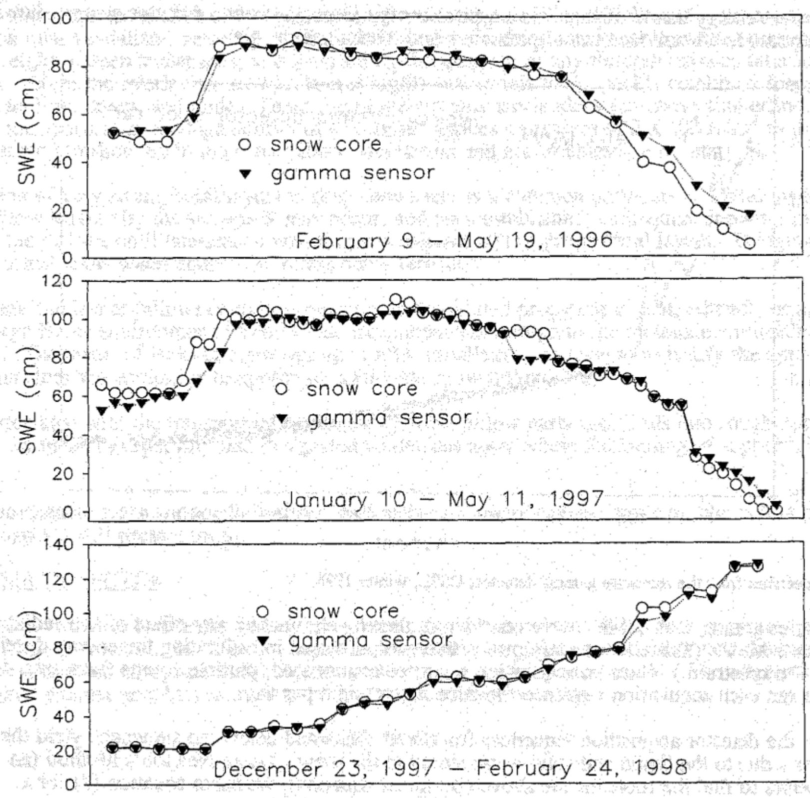

Figure 2. Coincident SWE measurements from the gamma detectors and hand measured snow cores, CSSL, 1996, 1997, and 1998. Data from 1996 and 1997 were collected using personal computer acquisition software; 1998 data was logged directly to a data collection platform.

(The underwater test also confirmed the integrity of the detector waterproof housing: it remained water tight.) Figure 3 shows that the data from the calibration run subscribes very closely ($r^2 = 0.997$) to the theoretical

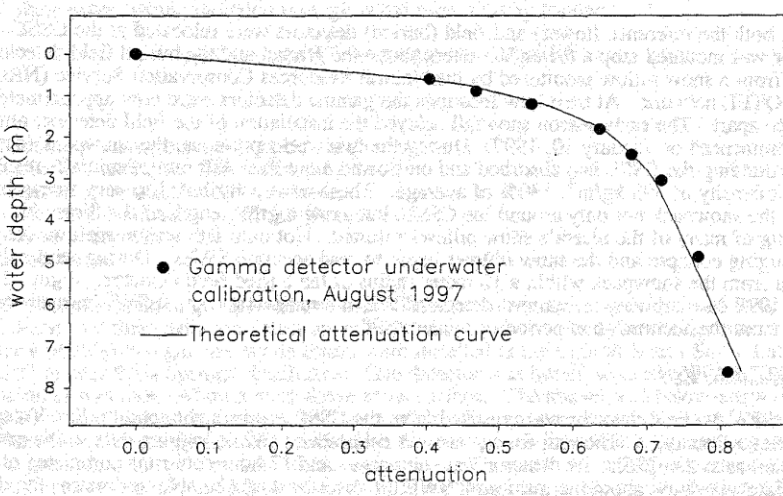

Figure 3. Gamma detector underwater calibration data, San Vicente Reservoir.

attenuation curve.

Also during summer 1997, calibration of the gamma detector for temperature variations was carried out in a temperature-controlled chamber. Shifts in the detected energy distribution were recorded through a +40 to -40°C temperature range. It was found that no adjustments for instrument temperature are needed until instrument temperature drops below -12°C, then temperature affects the attenuation factor by the linear relation

$$T_{cf} = 1+(t+12°C)/126.1°C \qquad (3)$$

where

T_{cf} is the temperature correction factor; and
t is the measured temperature (°C).

The attenuation factor y is adjusted by T_{cf}. This simple temperature-compensating algorithm can be written for any data collection platform.

WINTER 1998

One of the goals of the gamma detector winter trials is to test the instrument's worthiness as a device for measuring SWE at a remote site. As a step in weaning the gamma detectors from the personal computer running the data acquisition program, a prototype "bread board" was designed as an interface between the gamma detectors and a Handar Model 555* data collection platform. The gamma detector is linked directly to the transmitting package of the data collection platform enabling the gamma detector data to be transmitted via GOES satellite and downloaded onto the internet. The power consumption of the detectors including the data logger interface circuitry is 12 volts at 30 milliamps. Figure 4 is a schematic of a probable configuration of a remote installation incorporating two gamma detectors, a data collection platform, solar panel, battery, antenna, etc. A waterproof field enclosure large enough to hold the instrumentation would be buried just below soil surface offering both protection and security from vandalism.

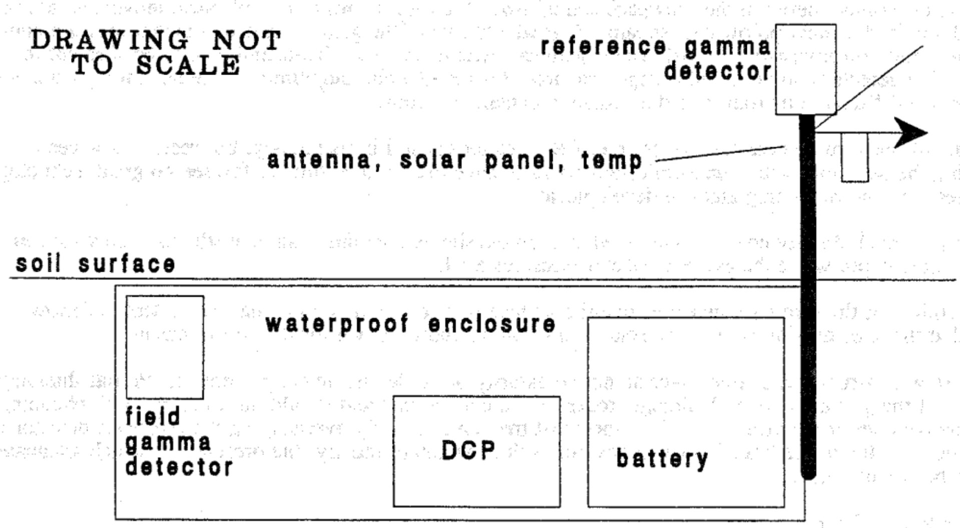

Figure 4. Generalized schematic of a remote site configuration including gamma reference and field detectors.

The field detector and new data logger interface were installed at the CSSL late autumn 1997. The field detector was positioned immediately adjacent to the NRCS snow pillow. Data collection commenced December 23. Figure 5 is a regression analysis of the SWE data from the gamma detectors and snow cores taken at the CSSL for winters 1996, 1997, and through February 24, 1998. The correlation (r^2 = .97) between the detectors and ground-truth measurements for 105 data points is good.

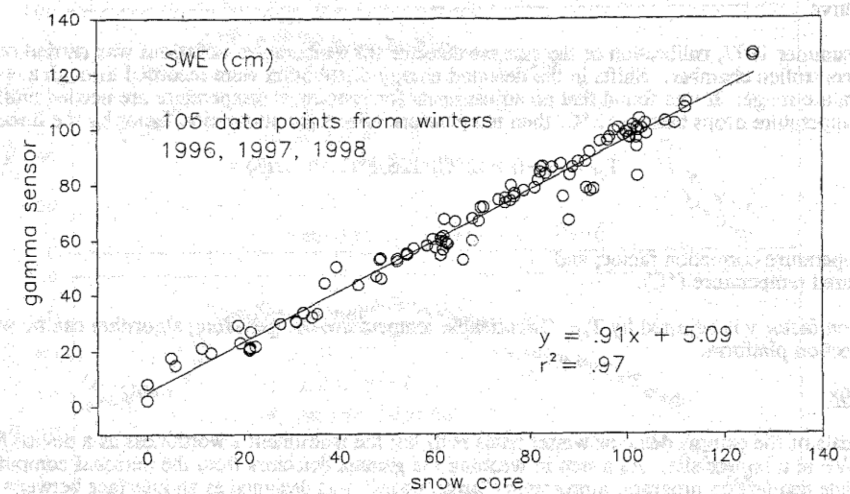

Figure 5. Snow core and gamma detector SWE for winter 1996, 1997, and through February 24, 1998, at the CSSL.

CONCLUSION

Using established principles of attenuation of high energy photons through water, the gamma detectors have proved to be accurate devices with which to measure the water mass contained in the seasonal snow cover. The total snowpack SWE measured by the gamma sensor agrees well with coincident hand measured values; data from the underwater runs agree well with the theoretical attenuation curve.

The gamma detectors have many advantages over existing instrumentation. The problems associated with snow pillows, namely: basal layer bridging and the snowpack effects of differential settling, creep and glide, all stem from physical contact between the snowpack and pillow. The forces born of that physical movement are often recorded within the snow pillow data stream. A great attribute of the gamma detectors is that they are non-mechanical and non-invasive. We believe the gamma detectors to be a reliable and viable replacement for snow pillows. The detectors do not require large, flat areas for installation, and eliminate the need for great amounts of material and fluids to be transported to distant mountain environs.

Packaging of the gamma detectors for remote, field locations is still in its infancy, but recent advances in interfacing the detectors with a data collection platform have been successful; we foresee no great technological challenges with the remaining areas of development.

Average snowpack density could be measured at a remote site by combining an acoustic distance sensor to measure snow depth while the gamma detector measures SWE.

When positioning the reference detector, one should take into consideration the maximum depth of snow expected at the site, making sure the detector will be above snow surface for the entire season.

The presence of structures or tree cover do not necessarily preclude instrument placement. Partial shielding or scattering of the gamma rays by buildings, rocks, etc. are a constant and should not interfere with obtaining a representative energy spectrum. We do suspect that tree cover directly overhanging the reference detector may cause problems due to the branches being covered with snow intermittently, the presence of which attenuates some of the cosmic rays.

FUTURE RESEARCH

Throughout these field trials, we made no measurements to determine the variation, if any, of intensity of the incident cosmic rays over time or space. It is therefore not known at this time whether a reference gamma detector would necessarily be required at each remote measuring site. If no variations are observed temporally, a reference detector could be run for a finite period of time -- say over a week during summer -- then relocated to the next site, effectively establishing "base line" energy distributions. If no variations are observed spatially, one reference detector could be adequate to service a wide area of deployed field gamma detectors.

Another area of future research is to run trials to determine the effect of detector angle on the measured energy distribution. This will be valuable information when site restrictions necessitate mounting the detectors less than plumb.

Acknowledgments

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*Mention of specific equipment brands is for information purposes only, no endorsement is necessarily implied.

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