GMON, A NEW SENSOR FOR SNOW WATER EQUIVALENT VIA GAMMA MONITORING

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ABSTRACT: GMON is a Gamma MONitor that measures the absorption of the natural gamma radiation through the snow cover and reports the snow water equivalent (SWE) for a large ground area typically of 100 m^2 by tracking the number of hits recorded on a daily basis from potassium (^{40}K) and thallium (^{208}Tl) energy windows respectively located at 1.46 MeV and 2.61 MeV. The sensor element is a conventional thallium doped sodium iodide scintillator NaI(Tl) coupled to custom electronics both embedded in an aluminium housing containing high performance insulating material preventing thermal shock damage when the sensor is exposed to -40°C.

Developed and patented by Hydro-Québec to improve the hydraulic power management, Hydro-Québec grants to Campbell Scientifc (Canada) Corp. a license to manufacture and commercialize the GMON.

From results obtained by the Institut de recherche d'Hydro-Québec during 2006-08 winter seasons, it was demonstrated that GMON measures the SWE content of a snowpack achieving the desired accuracy level for an accumulation up to 400 mm of water.

Work is presently under going to improve the GMON performances for higher SWE content, typically in the range of 400-700 mm of water.

KEYWORDS: Snow water equivalent, sensor, natural ground gamma radiation.

1. INTRODUCTION

Snow pack depth is not a good indicator of the snow water equivalent (SWE) since snow density is so variable in space and time. Snow densities can range from 0.1 to 0.4 g/cm^3 under the influence of sunshine, wind, temperature and liquid or freezing precipitations, heat and moisture exchanges with the underlying surfaces.

A number of models have been developed over the years to simulate the behavior of the snow pack and derive information on its characteristics including SWE (Essery, 2001).

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All of these models are based on some knowledge of the surrounding environment, be it air temperatures, hours of sunshine, precipitations, etc. which can be obtained from a network of weather stations and numerical weather models.

The accuracy of the information derived from these models is limited unless one uses a complex snow pack model in conjunction with comprehensive and reliable data sets covering the large list of factors impacting on the evolution of the snow pack.

GMON is a Gamma MONitor and was patented by Hydro Quebec. It measures the natural gamma radiation from the ground and its attenuation by the snow pack. From this data one derives estimates of SWE at six hours intervals. The ground area monitored by the GMON is dependent on the mounting height. An area of 85 m^2 is typical for a GMON mounted at 3 meters.

The energy ranges of interest for SWE evaluation are defined by the potassium (^{40}K) and thallium (^{208}Tl) windows where their centroïd peaks are respectively located at 1.46 MeV and 2.61 MeV.

2. THEORY

In the case of a detector installed over an infinite ground surface considered to act as a monochromatic source of gamma radiation, and considering uniform distribution of the radioactive source within the soil, one can derived the following equation 1 to estimate the number of counts detected by the detector (Fritzsche, 1982) :

$$Nu = S\int_0^{\infty} dz \int_0^{\pi/2} d\theta \int_0^{2\pi} \frac{A_o R(\theta) e^{-(\mu_a h + \mu_w SWE_o)\sec(\theta)} e^{-\mu_g z \sec(\theta)} \tan(\theta)}{4\pi} d\phi \quad (1)$$

where:

- Nu = gamma count rate (sec^{-1})
- $R(\theta)$ = angular detector response
- A_o = effective detector area (cm^2)
- h = Mass of air between ground and the detector (g/cm^2); physical altitude * density of air
- S = soil activity $(g\ sec)^{-1}$
- μ_g = soil mass attenuation coefficient (cm^2/g)
- μ_a = air mass attenuation coefficient (cm^2/g)
- μ_w = snow mass attenuation coefficient (cm^2/g)
- SWE_o = snow water equivalent (g/cm^2)

and where z is the soil depth, θ is the angle between zenith and the line between a source element and the detector, ϕ varies from 0 to 360° and spans the horizontal surface.

Equation 2 is obtained following integration of equation 1 according to dϕ and dz.

$$N = \frac{S}{2\mu_g}\int_0^{\pi/2} A_o R(\theta) e^{-(\mu_a h + \mu_w SWE_o)\sec(\theta)} \sin(\theta) d\theta \quad (2)$$

Using density values of air and water at the standard pressure and temperature of 1013 mb and 273K, one can rewrite the

($\mu_a h + \mu_w SWE_o$) term

as (β*(SWE + 0.001165*H)

where

- β = effective linear attenuation coefficient for water (cm^{-1})
- H = height of GMON above ground (cm).

Using a constant value for the density of air does not induce a significant error in the equation for the range of heights of GMON (a few meters). The margin of error induced in the cases of extreme atmospheric conditions is inferior to 1 mm of SWE.

Based on existing works on the subject, the gamma emissivity of the ground surface and the attenuation coefficient of soil vary with soil water content and accordingly equation 2 is rewritten to equation 3 (Fritzsche, 1982; Vershinina , 1971) :

$$N = \frac{S_o}{2\mu_{g_o}} * (1/(1+1.11M)) \int_0^{\pi/2} A_o R(\theta) e^{-(\mu_a h + \mu_w SWE_o)\sec(\theta)} \sin(\theta) d\theta \quad (3)$$

where
- S_o = soil activity in case of a dry soil
- μg_o = mass attenuation coefficient of dry soil

Normally, detectors have an angular response lying between isotropic ($R(\theta)=1$) and $\cos(\theta)$). In practice, the resulting integral functions can be nicely approximated by the equation 4 below over the range of 0 to 30 cm of SWE.

$$N = \left(\frac{N_o}{1+1.11M}\right) e^{(-\beta(SWE+0.001165H))} \quad (4)$$

where

- N_o = number of gamma count per unit of time for one given window of energy as if the GMON is lying on the ground with no snow cover and no available humidity within the soil.
- M = soil humidity, expressed as the ratio of the mass of water over the mass of the dry soil (% weight)
- β = linear attenuation coefficient for water (cm^{-1})
- H = Height of the GMON above ground level (cm)
- SWE = Snow water equivalent (cm)

Equation 4 could be easily rearranged to allow for the calculation of SWE using informations on site specific field parameters (*N_o, M);* the constant β value, and the set of 24 hours counts reported by GMON. Integration over 24 hours periods has been selected to reduce to less than 1% the normal statistical fluctuations on the gamma count rate.

3. ENERGY SPECTRUM AND WINDOWS OF INTEREST

Figure 1 shows a typical gamma spectrum called "histogram" of a sample composed of a mixture of a geological standard SY-3 from Oka, Québec (Gladney, 1990) and of potassium carbonate (K_2CO_3). This mixture is used in laboratory to simulate mainly the potassium and thallium soil natural gamma emissions. Peaks and windows associated to potassium ^{40}K (energy centroïd = 1.46 MeV) and thallium ^{208}Tl (energy centroïd = 2.61 MeV) are easily identifiable both with the SY-3 mixture and at field tests conducted so far by both by Hydro Quebec and Campbell Scientific (Canada) Corp.

Despite the fact that some Bismuth peaks look suitable in Figure 1 as indicators of SWE, we discarded that possibility since these are associated with the radon decay cycle (Grasty 1997). It takes the form of a gas highly soluble in water. Its concentration is therefore function of the atmospheric ventilation and of precipitations.

So, SWE can be derived from potassium and thallium energy window counts (N_k and N_{Tl}) using equation 4 if one knows the values of the specific parameter sets (N_{oK}, β_K *and* N_{oTl}, β_{Tl}). H, the height of GMON above ground, is readily available and one uses a constant value for M (soil moisture) throughout the winter season.

The photons produced from the absorption of the gamma by the NaI(Tl) crystal are amplified by a photmultiplicator and a charge amplifier. The performance of this amplification is temperature dependent. A first correction is therefore applied to the data using an algorithm to remove this temperature gain shift (Martin, 2008). It takes the form of a correction factor taken from a look-up table which has been developed empirically in laboratory. Since this unique table was implemented for all the sensors, a second algorithm called "rebin" for fine tuning the gain shift correction for each sensor was built in the firmware of the GMON to assure both potassium and thallium energy peaks are located inside the respective predefined windows. Those algorithms were robust and reliable enough to correct inside a 50 keV range at any time and any temperature conditions the centroid positions of ^{40}K and ^{208}Tl.

Before hand, the counts N_K and N_{Tl} need to be stripped of noises since the counts associated by the GMON to a specific window also include gamma resulting from a partial absorption of gamma associated with higher energy peaks in the histogram (Figure 1). Data could also be cleaned of gamma resulting of build up of two low energy gamma hitting simultaneously the detector. But this latter contribution is neglected, not being statistically significant.

The stripping of the data is done first by removing the background noise from the histogram. This noise can come from various sources in the environment and from atmospheric and cosmic sources in the energy level over 2.8 MeV. We are currently developing a more robust stripping procedure for GMON performance improvement and this second step is related to the Bismuth counts cleaning in the vicinity of the thallium and the potassium windows.

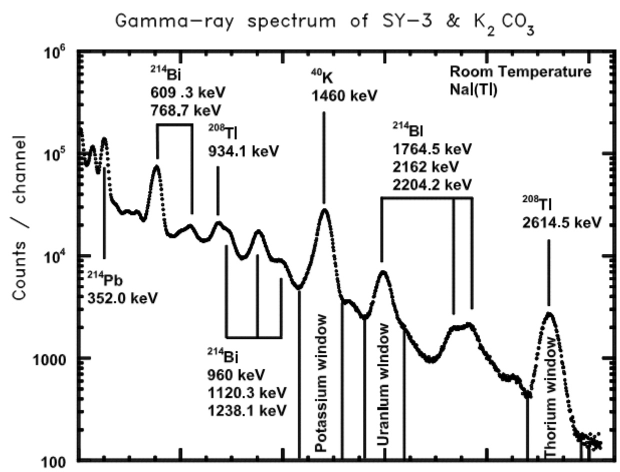

Figure 1: Gamma spectrum of a mixture of SY-3 and potassium carbonate (K_2CO_3).

4. PARAMETER SETS DETERMINATION

To report SWE data, the GMON parameter sets (N_{oK}, β_K *and* N_{oTl}, β_{Tl}) must be determined considering that *H* and *M* are known. The *M* value is determined and measured just prior to the apparition of the snow cover at the site. As previously mentioned, *M* is set to a constant value and assumed to be invariable during the winter season. This assumption introduces an error in the estimation of SWE since fluctuations in soil moisture under the snow cover impact on the rate of emission of gamma by the underlying ground surface. This margin of error on SWE is quite small (few mm) in the cases of sandy soils with low moisture contents (10-15% wt). Organic soils will typically present higher proportion of moisture (30 to 40% wt). Field tests conducted at a number of sites and in presence of different types of soil indicate a resulting margin of error of less than 4% in the case of a 400 mm SWE. Work is presently under progress to reduce this error by improving the stripping procedure and allowing for direct estimate of the soil moisture content under a snow cover.

The linear attenuation coefficients (β) for both potassium and thallium energy windows were initially determined by experimentation using a 1.5 square meter pool containing a precise depth of water in order to confirm the exponential nature of the relation between the number of counts per unit of time (here selected to 24h). The relationship is showed in Figure 2.

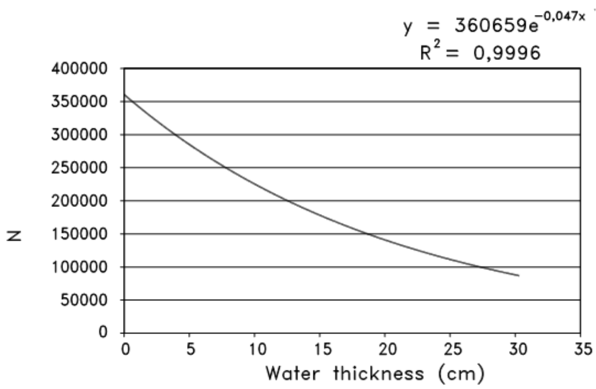

Figure 2: Exponential relationship of the number of gamma count per unit of time in the potassium window against the water thickness.

However, it was understood from our field tests that the linear coefficients were slightly different when a delimited water plan (the pool) intercept the gamma emission compare to an infinite water plan (the snow cover). Using field tests data sets and a numerical model to simulate the response of GMON over different snow pack, we were able to set the linear attenuation coefficients to be used by GMON. This simulation model is described in details elsewhere (private publication). It does confirm the response of GMON and delivers results in agreement with the field tests.

The parameters N_{oTl} and N_{oK} are set experimentally during the first few months of operation of a GMON at a site and in absence of a snow cover. These parameters are site specifics and are fixed in time. Effectively N_o is function of the mechanical characteristics of the GMON and of the rate of gamma emissions by the soil. If the soil at the site is not altered, the rate of emissions of gamma can be considered constant year after year given the very long half-life of the natural radio-isotopes associated with the potassium (1.28 x 10^9 years) and the thorium series (~10^8 years).

On the first day of operation of a GMON at a site, soil samples are collected to measure the soil moisture content. These soil samples are dried up in an oven (120°C during 24h). Knowing *N* reported by the GMON for both energy windows during the same day, specific N_o values are calculated using rearranged equation 4 since SWE is equal to 0 and M is known following the drying process of soil samples. During the season where snow cover is absent, *N* reported by the GMON are used to derive more accurate N_o values considering the statistical fluctuations in the natural gamma emissions. It is obvious that integration of all the SWE values derived from the data set collected over that period without a snow cover must sum up to 0.

5. GMON CONSTRUCTION

The GMON is briefly described here but a more detailed information is available from the patent document (Choquette, Y, 2008). The GMON is composed of 1- gamma detecting element, 2- custom printed circuit board (PCB), 3- a communication board, 4- an aluminium housing and 5- a collimator.

The gamma detecting element of the GMON is a commercial 7.62 cm (length) x 7.62 cm (diameter) NaI(Tl) photomultiplier tube – voltage divider assembly modified by the manufacturer for operations at very low temperatures (-40°C) and supporting important temperature gradient (8°C/hour). This detector is physically linked to the custom PCB. The ports on the communication board provide for RS-232 protocol communications and firmware/software updates.

A metal brass or aluminium cylinder enclosure is used to mechanically protect the detector and the main electronic board. It also diffuses the heat generated by the electronic towards the detector. An external air-tight aluminium cylinder protects the entire assembly from moisture. The free space between the inner and outer cylinders is filled with a commercial high performance insulating material that provides highly efficient thermal protection. The internal temperature is successfully controlled even during extreme cold spells down to -40°C as demonstrated in laboratory and during field tests.

An annular lead collimator is located at the bottom of the outer aluminum cylinder wrapping the NaI(Tl) crystal. The collimator partially shields against cosmic and ambient radiations and sets the target ground surface.

6. FIRMWARE/SOFTWARE

The custom PCB of the GMON run a firmware and a software which respectively builds/stores the histograms on a daily basis and calculates the SWE and soil humidity values every 6-hours based on the detected gamma counts cumulated during the previous 24 hours. The signals coming out of the gamma detector are sampled continuously by the firmware at 30 mega samples/sec. The SWE and soil humidity calculations are done after the "rebin" and the temperature gain shift algorithms which are applied on the raw data and controlled by the firmware. Other data are stored in the non-volatile memory such as detector temperatures and self-diagnostic data. The recorder capacity of the GMON gives an autonomy of 5 years of operation. More details are reported by Martin, 2008.

7. FIELD TESTS SET-UP

The GMON is powered with 12V lead-acid batteries which are recharged with a solar panel. Typically, 100 Ah batteries and an 80W solar panel could be used to power the GMON. The GMON is attached to a tripod or to a post bolted to a concrete base and hanged up generally at a height of 300 cm over the ground. The total observation area of the GMON is $85m^2$ when mounted at this height. Antennas permitting satellite or modem communications of the data to the remote center are also fixed to the supporting structure. Figure 3 shows a typical field test installation.

8. FIELD TEST RESULTS

A total of seven field tests were conducted at Hydro Quebec during winter 2008 and two additional tests were conducted in Alberta by Campbell Scientific (Canada) Corp. One site in Quebec was in operation since 2005 and 3 consecutive years of data were obtained and showed in Figure 4. Despite the fact the data were collected with different GMON prototypes that have been modified over this development period, the average accuracy level was kept quite constant and inside the 5 to 10% range compared to reference data as showed in Figure 4.

Two reference data sets are illustrated. The snow core technique is identified as the operational technique. The snow pit was used to decrease the error of the manual measurement. It is generally understood that the snow core technique may underestimate SWE especially in cases of wet snow or in presence of embedded ice layer. To prevent this underestimation and succeed in getting more accurate reference data, the snow pit technique was used. It consists of digging up the snowpack by successive 5 cm layers down to the ground. A fixed volume of each layer is weighted in order to calculate its density and then the SWE content. Afterwards, the SWE of the snowpack is determined just by adding all the individual SWE layers data.

9. CONCLUSION AND FUTURE WORK

GMON was patented by Hydro Quebec and Campbell Scientific (Canada) Corp will commercialize the sensor. Up to now from field test results obtained in Quebec and Alberta, the accuracy performance of the GMON for SWE estimation is inside the 5-10% range for SWE level less than 400 mm which is much better than the operational snow core technique largely used in Canada and west of USA. Also, GMON reports SWE data four times a day and determines the snow melting rate, a very important information for hydraulic power management. Work is presently undergoing to improve the GMON accuracy performances for higher SWE content, firstly in the range of 400-700 mm of water and in a second time, for SWE higher than 700 mm.

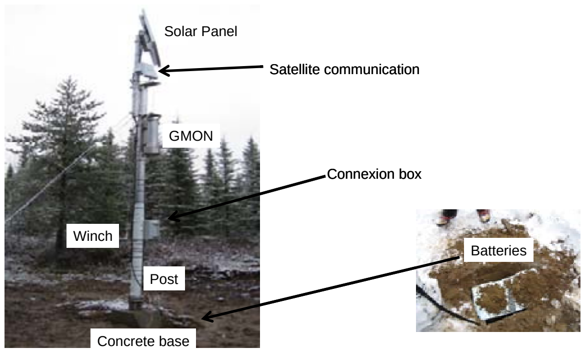

Figure 3: Typical GMON field test installation.

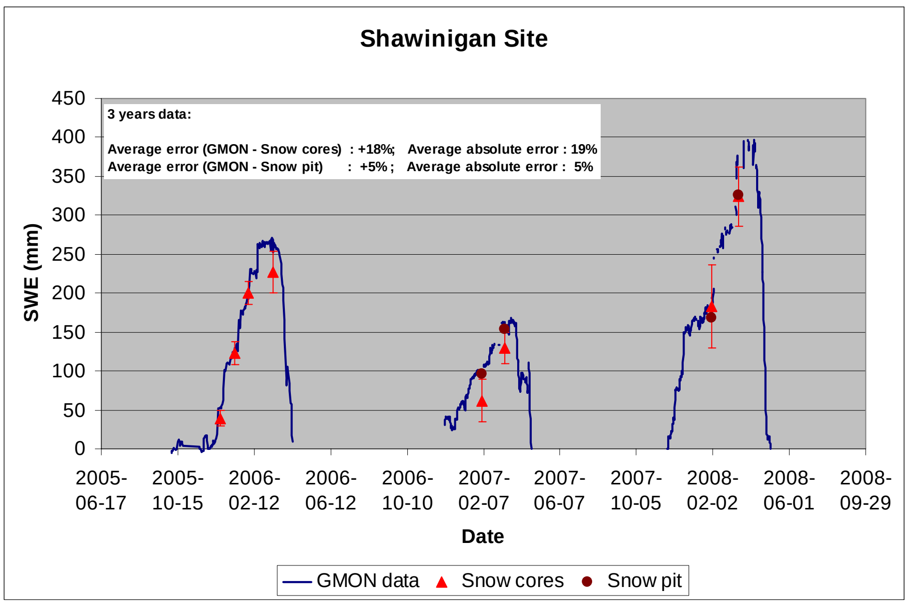

Figure 3: Results from the GMON Shawinigan site.

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