CS725, an accurate sensor for the snow water equivalent and soil moisture measurements

Yves Choquette[1,]*, Pierre Ducharme[2] and James Rogoza[3]
[1] Institut de recherche d'Hydro-Quebec (IREQ), Varennes, Qc, CANADA
[2] Consultant, St-Eustache, Qc, CANADA
[3] Campbell Scientific Canada Corp., Edmonton, AB, CANADA.

RESUME : Le CS725 est fabriqué par Campbell Scientific (Canada) Corp – CSC et est breveté par Hydro-Québec. Le CS725 est conçu pour déterminer quatre fois par jour l'équivalent en eau de la neige (ÉEN) jusqu'à une valeur de 600 mm et l'humidité du sol en mesurant le rayonnement gamma naturel du sol sur une superficie de plus de 100 m^2. Les performances du capteur CS725 sont mises en évidence selon les résultats obtenus par Hydro-Québec depuis plus de 5 ans. Les données ÉEN de référence sont principalement obtenues selon la méthode de la fosse à neige. La technique du carottier est également utilisée, mais elle présente plus d'inconvénients à produire des données fiables dans des conditions de neige glacée. Le CS725 produit des données précises de l'ÉEN peu importe le type de sol (inorganique ou organique) grâce à une méthode de calibration que nous avons développée. Nous avons appris que l'examen d'une période de données suffisamment longue durant la saison estivale doit être réalisé afin de régler adéquatement les paramètres du CS725. Nous avons également constaté que l'humidité du sol durant l'hiver ne varie pas de façon significative et que ce paramètre est considéré constant simplifiant par conséquent les équations mathématiques. De l'ensemble de nos expérimentations, nous avons démontré que le CS725 est capable de quantifier l'équivalent en eau de la neige du couvert nival à un degré de précision de ±5%.

MOTS-CLEF : rayonnement gamma, atténuation, ÉEN, fonte de neige, humidité du sol, CS725.

ABSTRACT: The CS725 is manufactured by Campbell Scientific (Canada) Corp – CSC and patented by Hydro-Quebec. The CS725 is designed to determine four times a day the snow water equivalent (SWE) up to 600 mm and soil moisture by measuring the natural ground gamma radiation over an area of more than 100 m^2. The performances of the CS725 sensor are highlighted according to the results collected over more than 5 years by Hydro-Quebec. The manual SWE reference data are mainly collected from the snow pit method. The snow core technique is also used, but has more drawbacks to produce reliable data under icy snow conditions. The CS725 delivers accurate SWE data regardless of soil type (inorganic or organic) through a calibration method that we have developed. We have learned that a long enough off-snow period must be investigated in order to set properly the CS725's parameters. We have also found that the soil moisture does not vary significantly during the winter season and it is considered constant thereby simplifying the mathematical equations. From all our investigations, we have proved that CS725 is able to quantify the SWE of a snowpack at an accuracy level of 5±%.

KEYWORDS: gamma radiation, attenuation, SWE, snow melting, soil moisture, CS725.

1 INTRODUCTION

Information on the snow water equivalent (SWE) is essential to agencies involved in water management. Agriculture activities and drinkable water forecasts are impacted by the maximum amount of SWE. The flood warning and the hydraulic power are also affected annually by this maximum SWE. But more importantly, one has to know the daily snow melting rate to really optimize the hydraulic powerhouse's production and alleviate floods. Sporadic manual surveys are not ideal tools in achieving this objective. However, for more than a century, snow samplers have been used to measure the SWE through the initiative of James E. Church (http://en.wikipedia.org/wiki/James_E._Church).

2 RERERENCE DATA

In order to demonstrate the accuracy of the CS725 data in our icy snow conditions, it was necessary to develop new techniques. Indeed, in spite of many trials to prove the ±5% accuracy on the CS725 data, the well known snow core technique was not reliable enough. Therefore, we have adapted the snow pit technique by enlarging the dimensions of the sampler to get a volume of 1000 cm^3 of snow for each snow layer sampled at 5 cm thickness. By weighing snow

---

Corresponding author address: Yves Choquette, Institut de recherche d'Hydro-Quebec, Qc, CANADA;
tel: +1 450 652 8448; fax: +1 450 652 8424;
email: choquette.yves@ireq.ca

samples with an electronic balance (accuracy = 1g; weights are between 150 and 500 g) from top to the bottom of the snowpack, we have obtained very good results, the errors on SWE being in the range of 1 to 3 % respectively for dry and icy snow. This technique is better adapted and more reliable to validate the CS725's accuracy.

3 THEORY AND DESCRIPTION OF THE CS725

The gamma radiation is naturally produced by some elements in the soil. More specifically, Potassium-40 (^{40}K) and Thallium-208 (^{208}Tl) are of most interest in this study. They respectively emit in the 1,460 and 2,613 MeV range. The gamma signal attenuation varies with the presence of water between the elements radiation source in the soil and the CS725. So, soil moisture (SM) and the snowpack reduce the number of radiation counts (*N*) recorded per period of time (set to 24h) by the CS725. Except for short term statistical fluctuations, the level of radioactivity of the ground is constant over the energy windows of interest (half-life of the order of 10^9 years). We therefore consider that the signal emitted by a totally dry soil and in absence of snow or water above ground is constant (N_o).

The CS725 detects the gamma radiation using a thallium-doped sodium iodide (NaI(Tl)) crystal optically coupled to a photomultiplier tube which produces an electric signal (counts). The *N* values are reliable because the gain of the detector is temperature compensated and the firmware removes numerically the background and cosmic radiation. For more details about the CS725, see (Martin and al., 2008; Choquette and al., 2010), and the CS725's manual on the CSC web site http://www.campbellsci.ca/cs725.

Assuming saturated soil moisture (SSM) during the winter, SWE can be calculated using the simplified equation 1:

$$SWE = \left(\frac{-1}{\beta}\right) * \ln\left[(N) * \left(\frac{(1+1.11*SSM)}{(N_o)}\right)\right] \qquad (1)$$

where *β* is an effective linear attenuation coefficient (cm^{-1}). The *β* coefficients (they vary with the snowpack) were determined using a numerical model. An upcoming paper will describe this model. The hypothesis of a constant value of soil moisture (the *SSM* value) under a 20-30 cm thick snowpack was confirmed after doing experimental soil core measurements (see Figure 1). Section 4 will give more details.

In summer or in off-snow season, *SWE* = 0, *β* is set to a constant value and the *SM* can be calculated based on the relatively simple equation 2:

$$SM = \left(\frac{N_o}{1.11*N}\right) - \left(\frac{1}{1.11}\right) \qquad (2)$$

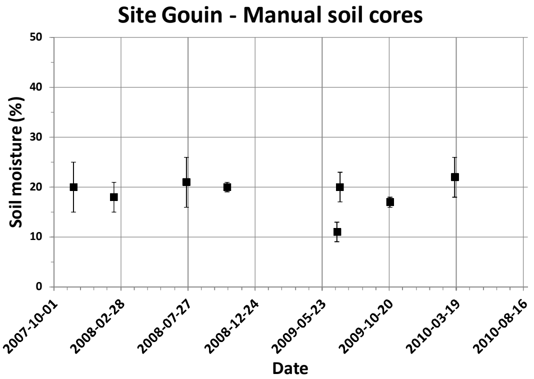

Figure 1. Soil moisture measured with core samples at Gouin site during years 2007 to 2010. Averages and standard deviations are derived from at least 3 samples.

From both equations, a decrease in the *N* values results in an increment of *SWE* or *SM*. The CS725 calculates *SWE* up to 600 mm and *SM* data four times a day. Tests done in the laboratory have shown the potential of this technology to measure higher *SWE* values.

4 SITE CALIBRATION

A detailed description of the method relating to the determination of the CS725's parameters to calibrate a site will be presented elsewhere. The present paper highlights the most critical aspects of this calibration process in order to achieve the specified accuracy of the CS725.

The most significant parameter impacting the *SWE*'s accuracy is the *SSM* constant in equation 1. Each site will have its own *SSM* value that is associated with saturated *SM* as previously mentioned. We have experimented different methods to determine this value: 1- soil core sampling during early spring or late fall; 2- soil core sampling during winter period under a snowpack thickness higher than 30 cm or 3- by analysing data series of *SM* calculated according to the equation 2. The access of all sites at the right time (where the *SSM* condition occurs) is the principal difficulty of method 1. Method 2 is then more appropriate for soil core sampling because the sampling period is longer. However, frozen soil conditions are sometimes observed leading to the impossibility of sampling. In order to evaluate the soil moisture, the core samples are dried for 24 hours at 120℃. The %moisture is expressed as the water weight divided by the weight of dry soil. Method 3 is the preferred approach due to the availability of continuous information and also because the *SM* values are based on the radiation signal detected by the CS725.

Methods 1 and 2 have been tried at the Gouin site and the results are shown in Figure 1. It is obvious that *SM* measured during winter time (February 2008, March 2010) is similar to measurements done during end of fall when a saturated soil condition was met (November 2007, October 2008 and 2009). A *SSM* value of ~20% is retained as the saturated state for this site.

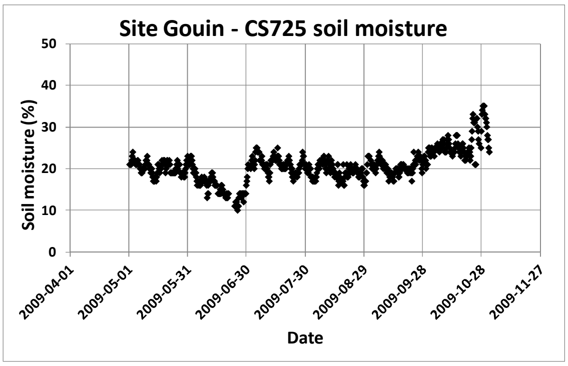

Figure 2. Soil moisture determined according to method 3 using N_K data – year 2009.

The Figure 2 illustrates the result according to the method 3 based on the ^{40}K signal for the year 2009. As previously observed from manual cores, the driest soil condition was recorded at ~10% on June 25th. The *SM* variations are well correlated with the meteorological conditions, an increase being observed following liquid precipitation. The continuous monitoring of the *SM* by the CS725 gives the opportunity to measure the oversaturated soil moisture (OSM) condition encountered during the end of October (or end of autumn) just before the arrival of the first snowfall. This condition sometimes lasts for a few days and is representative of a frozen soil. The OSM condition is never met during the off-snow season even after a heavy rain because the water streams down.

Under a thick snowpack, the temperature of the top soil layer gets back near the freezing point condition. The soil then drains naturally from the OSM condition towards its saturated state. From all of our observations and measurements, a rule of thumb is considering to estimate the *SSM* value from the knowledge of a water oversaturated soil condition. When 70% of the OSM value is considered, the *SSM* parameter is generally well established and *SWE* data are accurate.

From Figure 2, OSM = 33-34% in 2009 and *SSM* is calculated as 23-24%. A bias of few percent on *SSM* has little impact on the *SWE* accuracy (few mm). Moreover, *SM* is not necessarily constant all over the target area and it could vary by 10 to 15% within a few meters of distance depending on the soil nature. Historical yearly data at the Gouin site has shown a range of OSM from 30 to 35% which leads to a *SSM* range of 21 to 25%.

In order to calculate *SWE* according to equation 1, the next step is the determination of N_o since *SSM*, *N* and β are now known. It is possible to calculate N_o using only one or few *N* data for a site where *SM* varies very little (±5%) like a sandy soil. However, a better practice is to consider more data especially for heterogeneous site where a mixture of organic and inorganic matter are present. Generally, the gamma radiation signal comes from the inorganic part and the water is more concentrated in the organic part. Resolving equation 1 for each *N* data point considering that β and *SSM* values are constants, a series of data are generated. Assuming that the summation of all *SWE* values must equal to 0 during the off-snow season, a series of instantaneous N_o values along time is then calculated from spring up to the autumn period. After the record of two complete cycles of dry-wet *SM* condition, a "plateau" N_o value is generally obtained with a high reliability. An example is shown in Figure 3. Each site is then characterized by two N_o data respectively for ^{40}K and ^{208}Tl energy windows.

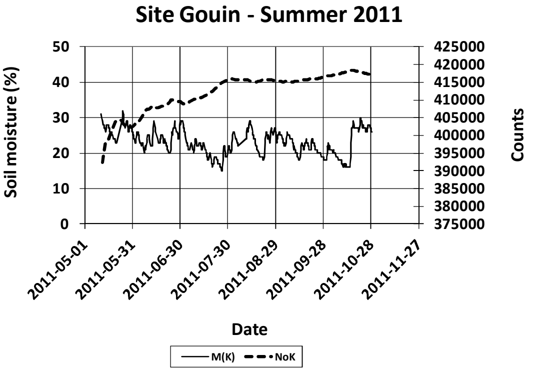

Figure 3. Soil moisture (solid line) and N_o variations (dashed line) using N_K data – year 2011.

We have described how the CS725 calculates *SWE* and *SM* based on ^{40}K signal. Same rules and equations are applied to calculate *SWE* and *SM* based on ^{208}Tl signal.

Both SWE_K and SWE_{Tl} should be equals all winter long. The two corresponding formulations of equation 1 can then be used to derive equation 3 which, as one can notice, provides a way to estimate *SWE* without any knowledge of the soil moisture content (or the *SSM*). We label this calculated value of *SWE* as SWE_{ratio} :

$$\mathrm{SWE}_{\mathrm{ratio}} = \left(\frac{1}{\beta_K - \beta_{Tl}}\right) * \ln\left(\frac{N_{Tl} * N_{oK}}{N_{oTl} * N_K}\right) \qquad (3)$$

Despite that the equation 3 is less accurate than equation 1 to estimate *SWE*, it is very useful to detect the onset of the snow cover at a site. After a site is calibrated (so N_o values are known), a SWE_{ratio} value over a threshold is indicative of the presence of snow on ground. Again, as *SSM* and N_o, this threshold is site specific and must be tuned properly. If so, *SWE* data will rarely be reported during the off-snow season. However, pools of liquid precipitations could form on the ground. These could be temporally misinterpreted as a snow cover. Setting a threshold value helps to discard these events from a real snow cover. This threshold is also useful to filter some of the variations in the SWE_{ratio} values associated with the fact that the mathematical margin of errors on these is higher.

5 RESULTS

The objective of this paper and conference is not to present a detail description of all the results we have obtained during the last 5 years. It will be done in future communications. Our goal is however to illustrate the importance of conducting a strict calibration process at each site in order to get reliable and precise data of S*M* and *SWE* from the CS725.

5.1 Soil moisture

In section 4, we already described some results for the Gouin site for years 2007 to 2011. As shown in Figures 1 to 3, the *SM* varies from high (~35%) to low (~10%) levels. Those levels are representative of historical annual highest and lowest *SM* measured by the CS725 at this site. The first data collected by a CS725 (in fact, at that time, the name was GMON) was obtained on November 15, 2007. The retained or initial *SSM* value (20%; standard deviation = ± 5%) was determined according to method 1 using 4 soil core samples over the target area. The standard deviation of ±5% is relatively small compare to historical data observed at other sites (closer to ±10%), this means the *SM* of this site at that time was relatively homogeneous. However, one sample (12%) was mainly driving this *SM* deviation, the other 3 results being closer together (22, 21 and 26%). The CS725 assuredly measures a much larger surface (more than 100 m^2) than the total surface of the soil cores (few tens of cm^2). An initial *SSM* value of 20% was confirmed a bit too low after analysing the results of the years 2008 and subsequent. This low bias in *SM* induces some high bias in the reported *SWE* numbers. Methods 2 and 3 were useful to confirm this bias and a definitive *SSM* value was set to 23% inducing a 4 mm correction of the *SWE* values which, of course, is not a major issue.

More important biased (15% or more) on *SSM* could impact systematic error in *SWE* as high as 20-25 mm or even worse. This error range is in the same magnitude as of the snow core technique and is not desirable. It is also higher than the accuracy specification of the CS725 (±15 mm) for a total *SWE* of 300 mm.

After few months of operation at a new site called “wood Gouin”, we have noticed bias in our data. Method 1 was applied the first month (in November) as previously described. An initial *SSM* value was calculated (73%) with a standard deviation of 9%. We then set the corresponding parameter in the CS725 and noticed an important negative bias (15 to 25 mm) to the *SWE* estimates when compared to snow pit measurements. We then start doubting the accuracy of our initial *SSM* value and setting.

We have tried afterwards to sample soil cores according to method 2 during the same winter but without success because of the presence of a thick layer of ice on the ground at the base of the snowpack. The following spring, three weeks after the complete melting of the snow pack, we took some soil core samples and obtained an average value of 51% for *SSM*. A subsequent analysis of the sequence of *N* data using the method 3 confirmed this value. We therefore concluded that the initial setting of *SSM* was wrong and that one needs to be cautious if only method 1 is used to establish *SSM*.

After collecting at least three years of data, we conclude that we had bad luck during the initial soil core sampling in November 2008 due to the fact the soil was probably in an OSM condition. Without having in hand a sequence of *SM* measurements, it could be difficult to accurately estimate the *SSM*.

We know that an OSM condition occurs with a frozen soil when the night air temperature is lower than 0℃ in absence of a snow cover. However, when sunshine heats the ground during the day, the ice in the soil can melt sufficiently and disappear. This could generate an OSM condition which is not easily recognized during the sampling (it does if ice is still present because the head of the hammer sampler did not usually reach the 25-30 cm depth needed to characterize the moisture of a typical soil). So, the right *SSM* (51%) was set definitively for the winter 2011 season. Figure 4 shows the impact of the two *SSM* values on the *SWE* data for the winter 2011 at the site “wood Gouin”. A bias of 20-22 mm is observed.

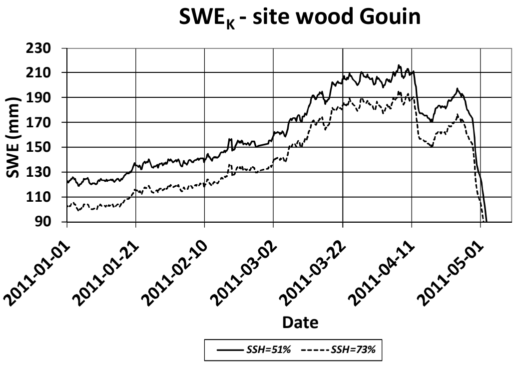

Figure 4. *SWE* values at “wood Gouin” for *SSM* = 51 and 73% – year 2011.

5.2 Snow water equivalent

We have showed the importance of correctly setting the *SSM* parameter which has the most impact on the accuracy of the *SWE* results. The second in importance is the N_o parameter. We found a wide range of values for our sites, typically from 200k to 500k counts per 24 hours. As illustrated in Figure 3, the calibration process of N_o is progressive and extends over some time. Accordingly, N_o setting can vary by some 25k counts before stabilizing to its final value. We have already observed more significant variations at other sites and the highest recorded increase was close to 100k.

This means a range of fluctuations of the order of 20 to 25% which is far away from the 2% limit we have set. Indeed, a small variation of 2% in the N_o value does not modify the *SWE* result by much (order of 1 mm) and it is considered negligible. We have observed this behaviour at LaLoutre station which is characterized by a manmade site (Figure 5).

It is obvious from equation 2 that if an inorganic soil does not show large *SM* variation as it is supposed to be, the N_o/N ratio will be kept relatively constant. It is exactly what we observe at LaLoutre, *N* is fairly invariant so does the N_o relationship in function of time. This kind of site is very easy to calibrate because the *SM* does not vary by much, in the order of 10%. Selecting a *SSM* value (typically between 13 to 15%) does not induce significant bias on *SWE*. A short sequence of *N* measurements and ultimately the first *N* value allows calculating a reliable N_o value.

However, the LaLoutre site is not a typical kind of soil we have to deal with at our CS725 stations. LaLoutre is a weather station where the top soil layer was removed and replaced with sand in order to minimize the vegetation growing. Since our snow lines are disposed in wood areas (like “wood Gouin”), the *SM* variation is usually higher than 10%, and some sites have shown more than 50% from May to October. It is then necessary to properly determine the N_o parameter for both ^{40}K and ^{208}Tl.

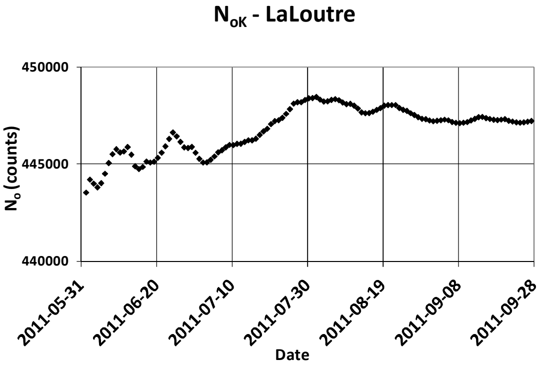

Figure 5. N_o evolution for LaLoutre site – year 2011.

Once the calibration process is completed, the CS725 data can be reprocessed if the new parameters have a significant impact on *SWE* (and *SM*). All *N* series of data for the “wood Gouin” site were processed again and the results for winter 2011 are illustrated in Figure 6.

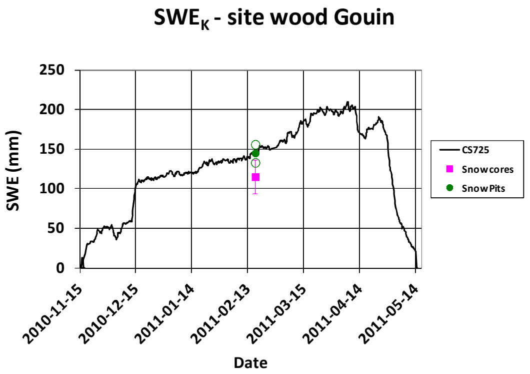

Figure 6. *SWE* values (CS725, snow cores and snow pits) at “wood Gouin” – year 2011.

In order to verify the accuracy of the CS725 data, snow cores and snow pits are done. Regarding the snow cores, an average *SWE* value of 115 mm ± 21 mm was measured. This value is bias low compare to the reported value by the CS725 (148 mm) on February 17. We have regularly observed low biased data from snow cores compare to CS725 results mainly when icy layers are presents in the snowpack. It is why we use the described snow pit technique to get more accurate reference estimates of *SWE*.

As illustrated in Figure 6, three snow pits are generally done at a site in order to evaluate the *SWE*. From the snow core measurements, maximum, minimum and average snow heights are identified inside the area observed by the CS725. The spots are generally located in a radius of 5 to 7 m from the post holding the CS725. Then, we expected the three *SWE* snow pits measurements to be somewhat different. In Figure 6, we illustrate the process using the manual measurements made at the “wood Gouin” site in February 2011.

The filled circle (145 mm) represents the *SWE* associated to the average snow height. The values 133 (minimum snow height) and 156 mm (maximum snow height) are respectively the lowest and highest *SWE* content (open circles). We note a 3 mm difference between the average snow pit *SWE* and the estimate from the CS725, a 2% difference. Typically, this level of accuracy on *SWE* is expected after 2 or 3 years of CS725 data analysis following accurate settings of the calibration parameters.

We present in Figure 7, the evolution over time of the accuracy and the standard deviation of ten CS725 in comparison with reference measurements. The improvement noted over the first few years of operation is in part due to improvement to the calibration process and to the refinement of our snow pit technique. The message behind Figure 7 is that if *SWE* reference data and site calibration process are well done, the CS725 is able to report *SWE* inside an accuracy of ±5%.

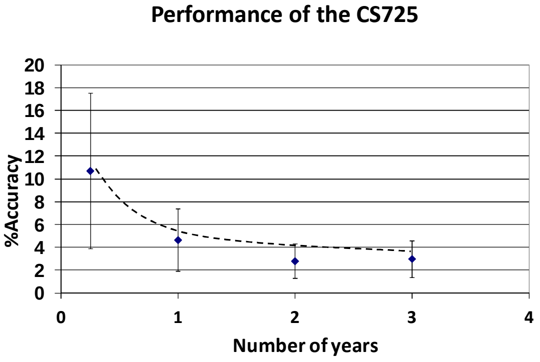

Figure 7. Performance of the CS725 over the years of data collection.

This level of performance is however usually reached after one year of analyzed data. We have also learned that spring time, right after the snow melting, is the best time to set up a new CS725 site. This allows for soil sampling while ground is still saturated and for estimating the *SSM* value. Having in hand this value during spring time enables the possibility of finalizing the calibration process (N_o determination) a few months later (~ 0.25 year) before the first snow arrives. By doing so, the accuracy (*SWE* difference between the CS725 and snow pits data) during the first winter is better than if the CS725 is started during the autumn. In this later case, for organic soil, N_o is not definitively set up because soil conditions stay wet and two complete cycles of dry-wet *SM* condition are not encountered. It is then required to wait until the next spring-summer season to complete the site calibration. Since a high proportion of our sites were up to now started late summer or during the autumn, it is not surprising to see an average accuracy of 11% and a standard deviation of 7% at the mark time 0.25 year.

6 CONCLUSION

The present paper describes the importance of the calibration process of a site in order to achieve the performance specifications of the CS725. Making reliable and accurate *SWE* reference data is also pointed out as another very important task in the demonstration of the performances. The snow core technique is not reliable enough especially for icy snowpack and it was demonstrated that the snow pit approach suits better our Quebec icy and wet snow conditions. We have demonstrated after five years of field operation that the CS725 provides, if properly calibrate, accurate *SWE* measurements.

7 ACKNOWLEDGMENTS

We thank Hydro-Quebec Production for the financial support. We also thank our collaborators from IREQ.

8 REFERENCES

Carroll, T.R., Schaake, J.C., 1983. Airborne snow water equivalent and moisture measurement using natural terrestrial gamma radiation. Optical engineering for cold environments, Proceedings of the Meeting, Arlington, VA, pp. 208-213.

Choquette, Y., Lavigne, P., Ducharme, P., Houdayer, A. and Martin, J.P. 2010. Apparatus and method for monitoring snow water equivalent and SM content using natural gamma radiation, US Patent 7,800,051 B2, Sept 21.

Grasty, R.L., 1982. Direct Snow-Related Equivalent Measurement by Air-Borne Gamma-Ray Spectrometry. Journal of Hydrology, 55, pp. 213-235.

Martin, J.P., Houdayer, A., Lebel, C., Choquette, Y., Lavigne, P. and Ducharme, P., 2008. An unattended gamma monitor for the determination of snow water equivalent (SWE) using the natural ground gamma radiation. IEEE Nuclear Science Symposium conference Record, pp. 983-988.