65th EASTERN SNOW CONFERENCE
Fairlee (Lake Morey), Vermont, USA 2008

"Ground Truth" Snow Measurements – Review of Operational and New Measurement Methods for Sweden, Norway, and Finland

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ABSTRACT

Manual snow measurements are becoming increasingly expensive at the same time as climate change imposed snow alterations affect runoff and frost patterns; snow observations are included in runoff modelling, making reliable snow observations outmost important. Multiple new and modified ground-based techniques for monitoring snow depth, density, water equivalent (*SWE*), wetness, and layering have been tested over the last decade justifying a review of such methods. Techniques based on snow mass, electrical properties, attenuation of radioactivity and, other miscellaneous properties are reviewed. The following sensors seem suitable for registration of temporal variations: Ultrasonic (depth) and terrestrial laser scanning (depth), several snow pillows at the same location (*SWE*), CRREL/NRCS weighing sensor (*SWE*), Snowpower (depth, density, *SWE* and wetness), active and passive (cosmic) gamma-ray attenuation (*SWE*), and adjusted TDR-probes (density and wetness). Ground penetrating radar (GPR) is, depending on design and operation mode, suitable for different purposes; when arrays of antennas are pulled by a snowmobile the technique is suitable for monitoring of spatial variations in depth, density and *SWE* for dry snow. Techniques are under development which hopefully will improve the accuracy also for wet snow measurements. Frequency modulated continuous wave (FMCW) GPRs seem fit for measurement of snow layering. Some suggested techniques are not operational yet

Keywords: snow; automate; ground truth; review; GPR; ground penetrating radar "snow measurement technique"

INTRODUCTION

There is an increasing demand on snow information for various applications, but snowpack properties vary largely both in time and space and neither satellite retrieved nor ground-based measurements have managed to meet these demands yet. The three countries Sweden, Finland and, Norway, located between 55 to72°N and 5 to 32°E, use similar hydrological runoff models but have chosen slightly different approaches to gather snow information and implement it into runoff models.

The increased need for snow information can be exemplified by global warming primarily affecting winter conditions at high latitudes; characterization of the snow cover has therefore become an interest for many scientific fields. It is important for understanding of climate feedback (Harding, et al., 2002), for ecological processes (Jones, 2001), and for frost penetration (Lindström, et al., 2002). In northern regions such as Scandinavia, snow melt plays an important

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role in seasonal runoff differences. The largest volumes as well as the highest peaks in runoff normally occur during spring flood therefore snow conditions are vital to the management of water resources for hydropower (Laukkanen, 2004), domestic and industrial extraction. Snow information is also important for flood prediction and prevention (Birkeland, et al., 1998; Laukkanen, 2004; Luce, et al., 1998). Further more, measurements of snow accumulation and ablation are critical for studies of mass balance for glaciers and polar ices (Richardson, et al., 1997). Ice layers in snow play an important role for the timing of the snow melt release, for the possibilities of forage for reindeers, small mammals and bird of prey, and for avalanche risk assessment (Callaghan, et al., 2004; Gustafsson, et al., 2004; Marshall, et al., 2007; Pfeffer and Humphrey, 1996; Sing, et al., 1998). Detailed snow depth information is also required for validation of snowpack and snow drift models (Prokop, et al., 2008). Remote sensing techniques operating from satellites, aero planes, and unmanned flying vehicles have the advantage to ground-based techniques in that they cover much larger areas but they have lower accuracy and they are still dependent on ground-based techniques for validation.

Snow distribution is highly variable over different landscape types as exemplified by measurements in alpine (Marchand, et al., 2001), forested (Marchand, 2003), and arctic landscapes (Richardson-Näslund, 2004). The spatial variability of snow accumulation, melt, and formation of ice crusts is influenced by a variety of factors (altitude, latitude, slope, aspect, vegetation, wind exposure etc) and the sometimes large temporal variations during heavy snowfall and intense melt (Gray and Male, 1981).

Norway, located along the Atlantic coast has a maritime climate, very large altitude variations and a large fraction of bare mountains, Finland has a continental climate, lots of forests and is rather flat, and Sweden located in between Norway and Finland has vegetation, climate and topographic conditions somewhere in between. The National Weather Services (NWS) as well as most of the hydropower companies in the three countries use versions of the same runoff forecast model: the HBV-model (Beldring, et al., 2003; Bergström, 1992; Bruland and Killingtveit, 2002; Lindström, et al., 1997; Sælthun, 1996). These operational runoff forecast models rely largely on point observation of precipitation and temperature but attempts to include snow data (mainly remotely sensed snow covered area SCA, but also snow water equivalent SWE) have been made with varying degree of success.

Efforts to include remotely sensed data have been going on since the early 80's in Sweden. Airplane-borne gamma ray attenuation measurements were used in combination with the HBV-model (Bergström and Brandt, 1984; Brandt and Bergström, 1994), also inclusion of SWE retrieved from helicopter-born ground penetrating radar (GPR) were tested (Andréasson, et al., 2001; Brandt, 1991). Both types of measurements were judged useful for northern Sweden where climatological data coverage is poor (Brandt and Bergström, 1994). For middle Sweden the measurements were considered helpful for detection of homogeneity breaks in climate data (Brandt and Bergström, 1994). However the model structure was found to be poorly adapted for employment of this type of data, and the precision of the GPR positioning data was insufficient for establishment of relationships between terrain parameters and snow accumulation (Andersson and Lundberg, 2002; Andréasson, et al., 2001; Boresjö Bronge, et al., 2006). Use of SCA retrieved from satellite AVHRR-, Landsat-TM- and SAR-sensors have also been tested together with the HBV-model within the Hydalp project (Rott, et al., 1999). The first two mentioned sensors are optical sensors while the SAR (Synthetic Aperture Radar) is a microwave sensor. The SCA estimates were found to vary with each sensor making it difficult to combine several sensors for obtaining coverage on clouded days. The discrepancies between TM- and AVHRR-images appeared to be an effect of spatial resolution but the differences between TM and SAR were not simply related (Nagler and Rott, 1998; Turpin, et al., 2000). Determination of SCA using MODIS (an optical sensor), LANDSAT-TM and SAR data were also tested (Boresjö Bronge, et al., 2006) with similar results (problems with combination of several sensors). Implementation of NOAA-AVHRR SCA into a gridded version of the HBV-model was hampered by the lack of data on cloudy days (Johansson, et al., 2003; Johansson, et al., 2000). Detailed manual snow measurements were used to update the snow HBV-model with promising results (Lindström, et al., 2002; Lindström et.al. , 2002). The volume error of the snow melt flood estimated by the

HBV-model were reduced for basins with less than 30% forest cover and for basins with large volume errors when SCA (from Envisar Advanced Synthetic Aperture Radar and Terra MODIS) was used to update the HBV-model (Johansson and Lundholm, 2008). The satellite derived SCA was underestimated at north facing slopes due to poor illumination and a correction for this was applied.

In Norway many GPR measurements are reported, most of them operated from snowmobile (e.g. Andersen, et al., 1987; Marchand, et al., 2001; Marchand and Killintveit, 2001; 2004) but they do not seem to be used together with a runoff model. Snow observations from satellite have been tested since the early eighties (Andersen, et al., 1984; Johnsrud, 1985). Skaugen, (1999) combined data from satellite derived SCA-measurements and from snow pillows. He concluded that SCA-mapping had to be improved, particularly in forests and that melting had to be included in a more sophisticated way in the model. Satellite born (SAR) measurements within the project Snowtools have been used to discriminate between wet and dry snow (Guneriussen, 1997; Guneriussen and Johnsen, 2003) but the measurements did not seem to be implemented into the operational HBV-model. According to Engeset, et al., (2003) satellite-observed SCA was used qualitatively to detect when the models did not simulate the snow reservoir correctly but was not used directly in the HBV-model. The method required model calibration against SCA as well as against runoff (Alfnes and Udnaes, 2004; Engeset, et al., 2003; Udnæs, et al., 2007). The satellite sensors NOAA AVHRR and ERS-SAR were used for determination of SCA. Of these sensors, the AVHRR observations had good correlation with the model-simulated SCA. Operational use of SCA-data in the HBV-model was tested with the model calibrated versus both runoff and SCA (Udnæs, et al., 2007). Runoff was modelled almost as well as when calibrated versus runoff only, and the modelled SCA was largely improved. However, when deviations between the modelled and simulated SCA were used to trigger model updates only 28% of the updates improved the runoff simulations (Udnæs, et al., 2007). A method to update the snow depletion curve with remotely sensed SCA-data is described by Kolberg and Gottschalk, (2006).

In Finland satellite born microwave sensors have been employed to determine snow parameters but they do not seem to be used in combination with the runoff model. Regional SWE for dry snow has been estimated by the Special Sensor Microwave Imager (SSM/I) and an automatic inversion algorithm with an overall random square error of about 30 mm without any in-situ reference of SWE (Pulliainen and Hallikainen, 2001). The error varied with air temperature and precipitation conditions ranging between 23 and 58 mm for the investigated years. A combination of active and passive microwave sensors with a fixed incidence angle gave reasonable SWE-values for dry snow (Hallikainen, et al., 2003). SWE and snow depth estimated using SSM/I sensors, an artificial neural network and a ground-based snow data set as a reference performed very well when the neural network was trained with the experimental data (Tedesco, et al., 2004). Snow wetness has been estimated from ERS SAR (Koskinen, et al., 1997). GPR measurements in Finland seem rare with some exceptions i.e.Vajda, et al. (2006) report from a forestry application.

Even though many attempts to include different types of remotely sensed snow information in hydrological modelling have been made, the success has been moderate and this seems to be due to shortcomings in the models as well as uncertainties in the remotely sensed data.

When it comes to ground-based measurements, Sweden has a long tradition of manual snow measurements starting with forestry applications (Hamberg, 1896). The Swedish Hydrological and Meteorological Institute (SMHI) has, since the beginning of the twentieth century, operated a network of snow depth and density measurements made at open sites, mostly in agricultural areas and valleys (Forsler, et al., 1971; Nord and Taesler, 1973). Today they operate about 400 manual snow depth stations (most of them measured twice a month with a few measured daily). Tests with automatic snow depth gauges have been made, but these were not successful and no such gauge is now operational (personal communication, Marcus Flarup, SMHI). In addition, the hydropower companies operate their own manual and helicopter-operated GPR snow-surveys. Snow pillows were tested in the so-called representative basins (Persson, 1976), and have also been used in several research projects on land-surface atmosphere exchange processes as a complement to unreliable wintertime precipitation measurements, NOPEX (Lundin et al., 1999), LUSTRA (Berggren, et al., 2008). Snow pillows and other ground-based snow measurement techniques are currently compared within the Swedish project *Distributed measurement systems for improved snow- and runoff forecasts – integration into hydrological models*. In addition to snow pillows, a so-called *Snowpower* instrument, measuring snow density and wetness, (Stähli, et al., 2004) has been installed, an active gamma-ray source prototype will be tested, and measurements using an array of ground-penetrating radar antennas operated from a snowmobile will be used.

In Norway the first snow pillow was installed in 1967 (Andersen, 1981) and the Water Resources and Energy Directorate (NVE) now operates 23 pillows spread throughout the country (Sorteberg, et al., 2001). The pillows are circular, made of white PVC with a 1-m radius; having automatic transmission of real time-data. A detailed description of them can be found in Sorteberg, (1998). The hydropower companies also operate snow pillows (Statkraft; 13 pillows; "Glommens og Laagens Brukseierforening "(GLB) and Trønderenergi 6 pillows) collecting a large number of snow depth and density measurements which they report to NVE (Engeset, et al., 2004).

In the winter 2004/2005 two sensors measuring incoming and snowpack attenuated cosmic radiation were tested. The sensors did not seem adopted for the harsh Norwegian climate and did not produce any useful data (personal communication Bjørg Lirhus, NVE, Oslo).

In Finland intense snow course measurements were initiated in 1935 and in 2003 the Finnish Environment Institute (FEI) operated a network of 177 snow courses distributed over the country (Lundberg and Koivusalo, 2003). Each snow course is two to four km long; surveyed twice a month and is designed to include terrain types typical to the region (Lundberg and Koivusalo, 2003). Some 165 snow courses are today operated once or twice a month (Ymparisto, Finnish Environment, Institute, 2008). Snow pillows are not used today in Finland but a test made from 1970 to 1979 is reported by Kuusisto (1984).

In spite of numerous attempts to use snow measurements for runoff simulations (and for other purposes) this has not really become operational due to several reasons:

a) The runoff models are poorly adapted for use of distributed snow-information.

b) Difficulties in combining optical and microwave satellite measurements of SCA to monitor the quick temporal changes during cloudy periods.

c) Difficulties in establishing relationships between SCA and SWE.

d) Positioning of early GPR measurements was not accurate enough for establishment of snow/terrain relationships.

e) Poor verification of remotely sensed values versus "ground truth" measurements.

Many of these issues are now resolved. The use of distributed hydrological models and data assimilation techniques have provided better use of both remote sensing and ground-based data (e.g. Kolberg et al, 2006, Nagler et al, 2008). There is also work in progress to further adapt runoff models for distributed snow information (e.g. Boresjö Bronge, et al., 2006). A near real-time pre-operational system combining several satellite sensors allowing SCA-monitoring over the accumulation and melt season was presented by Malnes, et al. (2005). Large improvement in position technique for GPR measurements are now enabling establishment of snow-terrain relationships (Marchand and Killingtveit, 2001). However, the difficulties with poor verification of remotely sensed snow depth and density, *SWE*, and snow wetness data versus "ground-truth" measurements largely remains unsolved, thus aggravating the difficulties with establishment of relationships between SCA and SWE for models based on SCA. This may prove unnecessary when using the data in data assimilation applications of distributed models as shown by e.g. Nagler et al (2008), who developed a system for integration of remote sensing data, meteorological station data, and weather prediction data for short term runoff predictions. This made use of recent assimilation techniques for better adaptation of models to the distributed data (Kolberg, et al., 2006).

AIM AND SCOPE

The aim of this study is to review established and new ground-based methods (stationary and snowmobile pulled) to measure snow cover properties (depth, density, water equivalent, wetness, and layering) and to evaluate the functionality of these methods. The reviewed methods have been combined with suitability criteria in order to screen the best available and coming methods. The review focuses on methods for the three countries Sweden, Norway, and Finland. Snow characteristics such as radiation reflectance (albedo), radiation transmissivity, thermal properties, microstructure, impurities, chemistry, and snow accumulation are not treated here.

OTHER REVIEWS

Snow Hydrology (US Army Corps of Engineers, 1956), and the *Handbook of snow*, (Gray and Male, 1981), were long the prime references for snow measurements while snow monitoring by the National Weather Services (NWS) in many countries have been influenced by the continuously updated *WMO Guide to hydrological practices* (WMO, 1992). There are more recent reviews of snow measurement techniques (Harper and Bradford, 2003; Killingtveit and Marchand, 2005; Killingtveit and Sælthun, 1995; Kinar, 2007; Lundberg and Halldin, 2001; Pomeroy and Gray, 1995; Trabant and Clagett, 1990; Woodward and Burke, 2007). Ground penetration radar (GPR) techniques, also known as impulse radar or as radio echo sounding (RES) techniques when employed at lower frequencies (<10Mhz), have during the last decades become an invaluable tool for glaciologists (reviewed by Maurer, 2006; Plewes and Hubbard, 2001; Woodward and Burke, 2007). A working group was established in September 2007, within TC 318 Hydrometry under the European Standardisation Organization (CEN), to develop technical documents on the various methods for snow water equivalent measurements. The group consists of representatives from Austria, Czech Republic, England, Norway, Slovakia, Sweden, and Switzerland, the first method to be documented was the snow pillow technique (personal communication Björn Norell, Vattenregleringsföretagen, Östersund, Sweden).

REQUIREMENTS ON IDEAL TECHNIQUES

All permanent installations in the snow itself will disturb the snowpack by absorbing more solar radiation than the snow, thus producing local melt around the device but white, thin and small installations cause small or negligible disturbances. When part of the device is located above the snow and the rest is buried, the part perturbing above the snow has a large wind exposed area, vibrations in the device might form air pockets around the device, producing erroneous measurements.

Snow accumulation may also be disturbed by installations above the snow surface influencing the snow deposition pattern (enhanced deposition for decelerated wind speed and reduced deposition for accelerated). Large installations at the base of a snow cover such as snow pillows, weighing plates and lysimeters will change the heat and water exchange at the snow/ground surface. When water is prevented from leaving a shallow snowpack the snow might darken due to additional water content and thus absorbs more solar radiation.

The ideal snow measurement technique will not cause environmental harm and will not disturb the accumulation pattern by altering the wind field around the gauge. It should not influence the exchange of radiation, thermal heat and water between the snow and the atmosphere and/or the ground. The measurements must have a time resolution of the same order as the time constant for the processes, *i.e.*, typically an hour or less and they must resolve the dynamics of state variables, which means that water/snow quantities should be recorded with an accuracy of at least one mm. The technique should also capture the spatial variations of snow conditions relevant for application and work in all forms of terrain (steep and forested) and in all forms of snow (dry, wet, deep, shallow, and layered).

STUDIED TECHNIQUES

Automated techniques based on registration of snow mass, electrical properties of snow, snow attenuation of radioactivity are reviewed as well as miscellaneous techniques based on ultrasonic, laser and acoustic pulse velocity, barometric pressure, temperature, infra red radiation etc (See Table 1).

Techniques based on registration of snow mass

There are at least three techniques used for determination of snow water equivalent (*SWE)* based on registration of snow mass; snow pillows, *CRREL/NRCS* electronic snow water equivalent pressure sensors and weighing lysimeters.

Snow pillows

A snow pillow consists of a mattress type apparatus installed under the snow, level with the ground. The most common design is a circular pillow about 2-4 m wide made from reinforced rubber or stainless steel, filled with antifreeze liquid, but can come in other shapes and sizes. The pressure change caused by the weight of the snow is usually sensed remotely by pressure transducers. Snow pillows work well in areas with heavy snow and few freeze thaw events while they are not suited for use in snowpacks which bridge over the pillow (Johnson and Schaefer, 2002; Sorteberg, et al., 2001; Trabant and Clagett, 1990). The latter types of snowpacks, which contain ice lenses, are commonly formed in coastal mountain ranges and in wind-exposed locations where bridging from wind effects occur. The hard snow or ice layers may then cause over or underestimation of the *SWE* depending on whether the snow pillow supports part of the surrounding snow or the other way around. Another disadvantage with snow pillows is that they modify the temperature gradient of the snowpack by blocking the temperature-driven vapour flux at the soil/snow interface, this blocks the melt water transport into the soil. Dark pillows may absorb more energy than the surrounding soil; thus delaying the onset of snow accumulation in the autumn (Johnson and Schaefer, 2002; Trabant and Clagett, 1990).

Table 1. Automated measurement techniques for determination of snow depth (D), snow density (ρ), snow water equivalent (S*WE*), snow wetness (θ) and ice layers in the snow (IL). The X-mark indicates that the technique is suitable for this type of measurement; A is the approximate measurement area and the P in this column indicates a point measurement.

Techniques	D	ρ	*SWE*	θ	IL	A (m^2) or Distance/day	Works in			Undisturbed snow	Fixed (F) Mobile (M)	Environmental harm	References
							steep terrain	forests	wet snow				
Snow mass													
Snow pillow			X			5-10	No	No	Yes	No	F	(Yes)	(Sorteberg, et al., 2001; Trabant and Clagett, 1990)
Snow plate			X			5-10	No	?	Yes	(No)	F	No	(Johnson, 2004; Johnson and Schaefer, 2002)
Weighing lysimeter			X			25	No	Yes	Yes	No	F	No	(Storck, 2000; Storck, et al., 1999; Storck, et al., 2002)
Radioactive attenuation													
Gamma ray: active source													
Horizontally mounted		X			X	P	Yes	Yes	Yes	Yes	F	?	(Blincow and Dominey, 1974; Smith, et al., 1970; Wheeler and Huffman, 1984).
Vertically mounted			X									No	(Bland, et al., 1997)
Gamma ray: cosmic radiation			X			P	Yes	Yes	Yes	Yes	F	No	(Desilets, et al., 2007; Fritzsche, 1983; Gehrke, 1997; Osterhuber, et al., 1998)
Neutron probe						P	Yes	Yes	Yes	No	F	Yes	(Harding, 1986)
Electrical properties													
Snowpower	X	X	X	X		10 m	Yes	Yes	Yes	?	F	No	(Niang, et al., 2006; Stähli, et al., 2004);
Snow fork				X		P	Yes	Yes	Yes	No	F	No	(Sihvola and Tiuri, 1986)
Electromagnetic sensor				X		P	Yes	Yes	Yes	No	F	No	(Kendra, et al., 1994)
Capacitive sensor & Monopole antenna				X		P	Yes	Yes	Yes	No	F	No	(Denoth, 1994; 1997)
TDR-methods 1)		X		X		P	Yes	Yes	Yes		F	No	(Andersen, et al., 1987; Lundberg, 1997; Schneebeli, et al., 1998)
Ground penetrating radar GPR													(Andersen, et al., 1987; Bradford and Harper 2006; Granlund, et al., 2007; Gustafsson, 2006; Lundberg, et al., 2006; Lundberg and Thunehed, 2000; Lundberg, et al., 2000; Marchand, 2003; Marshall and Koh, 2007; Ulriksen, 1982; Yamamoto, et al., 2004)
Stationary			X		(X)	P	Yes	Yes	See art.	(Yes) 2)	F	No	
Snowmobile pulled						400 km/day	No	?	See art.		M	No	
Miscellaneous													
Barometric pressure gauge	X					400 km/day	Yes	Yes	Yes	(Yes) 2)	M	No	(Kennett, et al., 1996)
Thermistors and Light diodes	X			(X)		P	Yes	Yes	Yes		F	No	(Andersen, 1995; Maijala and Leionen; 2008)
Ultra-sonic depth gauges	X					P	Yes	Yes	Yes	Yes	F	No	(Goodison, et al., 1988)
Infrared radiation				(X)		P	Yes	Yes	Yes	Yes	F	No	(Semadeni-Davies, et al., 2001)
Terrestrial Laser Scanning	X					200	Yes	?	Yes	Yes	F	No	(Prokop, et al., 2008)
Penetrometer					X	P	Yes	Yes	Yes	Minor disturb.	F	No	(Schneebeli, et al. 1999; Birkeland et al. 2004)
Automatic snow depth sensor	X					P	Yes	Yes	Yes	Minor disturb	F/M	No	Sturm, 1999; Sturm, and Holmgren, 1999.
Acoustic sounding			X			P	Yes	?	No	Yes	F/M	No	*(Kinar, 2007; Kinar and Pomeroy, 2007)*

1) Special designed probes are needed; when used for wetness registration night-time refreezing of the snow or separate density measurements are required.

2) A sledge pulled by a snow mobile will cause a slight compaction of the snow so the snow density will be slightly over- and the depth underestimated unless the measurements are made at the side of the sledge.

"Pillows" made of stainless steel are animal and rodent proof, requiring less installation time (according to a producer Rickly hydrological company, 2007). Use of several pillows in parallel at the same location allows for identification and compensation for bridging. This is made possible by the comparison of the loads on different pillows. A method to detect and correct measurement errors using continuous measurements of snow depth, *SWE*, and snow base temperature is presented by Johnson and Marks, (2004). When the moving average of the snow base temperature during the preceding 24 hours exceeds zero, the snow cover is assumed to be melting, indicating that the *SWE* measurements for that period may not be trusted (Johnson and Marks, 2004).

Electronic snow water equivalent pressure sensor CRREL/ NRCS

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and the US Natural Resources Conservation Service (NRCS), since 1997, have conducted a collaborative effort to develop a snow water equivalent sensor to replace the fluid filled pillows. This device is called the CRREL/NRCS electronic snow water equivalent pressure sensor *(*Johnson and Schaefer, 2002). They have, based on theoretical analysis, tested different designs of load-cell equipped plates with promising results (Johnson, 2004; Johnson, et al., 2007; Johnson and Mark*s,* 2004). A design with one square centre panel surrounded by eight square inert panels to buffer perimeter stress and allow water to percolate through the panels was tested for two years (Johnson, et al., 2007). The test showed that both sensor design and installation significantly affect the measurement accuracy and that measurement errors can be reduced by matching the thermal properties of the plates (sensors) with the soil (Johnson, et al., 2007). Further development is however needed to elaborate a calibration technique that does not require nearby snow pillow measurements for calibration (Johnson, et al., 2007).

Weighing lysimeters

Lysimeters (25 m^2) consisting of large weighing framed bricks built around tree trunks were used to compare forests *SWE* and open field *SWE* for snow interception sublimation/evaporation studies (Storck, 2000; Storck, et al., 1999; Storck, et al., 2002). The bricks were made of, from top down: face planking, sloping plywood decking, wood joists, steel subframing, and load cell platforms. This is the only design adapted for use in forests, but the design disturbs the natural snow/ground heat and moisture exchange and absorbs more short-wave radiation than the snowpack itself.

Techniques based on attenuation of radioactive radiation

A water equivalent probe based on attenuation of radioactive radiation consists of a radioactive source that emits fast high energy neutrons and a detector that counts slow low-energy neutrons. The emitted fast neutrons are moderated into slow neutrons on collision with hydrogen forming a cloud that scatters back to the detector. The density of the slow-neutron cloud depends on hydrogen content, which is proportional to water content. The source can be an active gamma-ray point sources or the laterally extensive cosmic gamma radiation.

Neutron probes

A neutron probe, designed to determine soil density, consists of a vertical cylinder installed in the soil. The neutron probe could alternatively be used to measure changes in snowpack water equivalent. The sample volume varies with the hydrogen content; small volume for high hydrogen content in the measured material and vice versa. Five neutron access tubes were used for measuring changes in snow water equivalent; but increased melt around the access tubes for the probe was observed (Harding, 1986). Handling with a radioactive source is a disadvantage, and the technique does not seem to have been used further for this application.

Cosmic radiation probes

The high energy gamma portion of the incoming, background cosmic radiation constantly flowing through the earth's atmosphere partly penetrates the snowpack. The cosmic radiation is associated with the solar activity and varies with latitude and over time. The attenuation of the radiation is exponentially related to the mass of the medium through which it penetrates (Fritzsche, 1983; Gehrke, 1997; Osterhuber, et al., 1998). A device measuring the incoming and attenuated cosmic gamma radiation, using the energy levels between 5 and 15 MeV, proved to be an accurate, reliable, non-invasive, and non-mechanical instrument for measurement of the total snow water equivalent of a snowpack (Gehrke, 1997; Osterhuber, et al., 1998). A need for correction for detector temperatures was observed for temperatures below -12C° (Osterhuber, et al., 1998).

Two small sensors can be carried in back packs, one can then be mounted on the ground and the other about 10 metres above the ground (CSSL, 2008). When cosmic rays hit the sensors they generate tiny bursts of light, which are detected and measured by photodiodes monitored by a computer. The difference between the readings of the two sensors gives the SWE . The data can be sensed remotely. Local variations in cosmic radiation are small, so one sensor for the incoming radiation can be used for a larger area.

A spectacular application for the cosmic radiation technique was the estimate of scientist's crowd density expressed as *"water equivalents*" at the AGU meeting in 2007 (Desilets, et al., 2007). The technique can cover an area with a radius around 100 m and requires only moderately expensive equipment (US$ 10,000) (Desilets, et al., 2007). Two manuscripts covering the basis of the technique, operational characteristics like sample volumes, sensitivity, and precision, proof-of-principle experiments and calculations will soon be submitted (personal communication, Darin Desilets, Arizona University, US, 2008).

Since the cosmic radiation technique is similar to the neutron probe technique similar obstacles with identifying the measurement volume (area) might be expected. It might also face difficulties with separating soil water and *SWE*.

Active gamma-ray probes

Active gamma-ray sensors need a small sample of a radioactive salt or some other radioactive source placed on the ground for radiation to be registered above the snowpack. Early applications of this technique used a Geiger–Müller counting system (located above the snow level) measuring the amount of depletion of radiation caused by the presence of snow (Wheeler and Huffman, 1984). A more recent application of the technique is reported by Bland, et al. (1997) where a mixed Eu-152 source (about 70 MBq) was pushed through raceways placed on the soil surface prior to snowfall. A Ge-detector held above the snow and a multi-channel-analyzer were used to register the radiation. Field tests showed that the system detected *SWE* changes with greater sensitivity than attained with collecting of snow cores (Bland, et al., 1997).

Scintillators and associated electronics can today be made small and energy efficient enough to allow for measurements in battery or solar panel powered remote areas which are remotely sensed by a cell phone net. Ongoing tests of gamma-ray-prototypes in Finland and Sweden made within the project *Development of Gamma Water Instrument platform at the Baltic Shield* indicate the technique seems to work well with low radiation sources (Cs_{137} strength 370 Kbq) located at the soil surface in combination with a scintillation located one meter above the snow for *SWE* less than 300 mm (own tests and personal communication, professor Pulliainen, FMI, Finland). The sensitivity for larger water equivalents can be improved by using a stronger source.

The active gamma-ray probe is probably better than manual snow probing (gravimetric measurements), with respect to the ability to include ice layers formed close the soil surface in measurements of *SWE*. The technique works in all types of terrain and for all types of snow. An advantage with this technique is that a second scintillation could be located in the soil under the source thus also allowing the measurement of moisture fluctuations in top soil. Future work is needed before these prototypes will become operational.

Automatic recording of snow depth-density profiles based on attenuation of a gamma-ray source has been reported (Blincow and Dominey, 1974; Smith, et al., 1970). Gauges recorded gamma-ray transmission between two fixed tubes through which the transmitter and the detector were moved in parallel. Some such gauges have been operated remotely but the units are costly and the handling of a radioactive source is a disadvantage (Wheeler and Huffman, 1984). Local melt around the tubes can be expected when applied for long time measurements.

Techniques based on electrical properties of snow

Several probes for registration of snow depth, density, and wetness based on the electrical and dielectrical properties of snow have been designed and tested: Time domain reflectometry (TDR) probes, the *Snowpower* band, the snow fork, the capacitive sensor and the monopole antenna. Different ground penetrating radar (GPR) techniques based on the electrical and dielectrical properties of the snowpack have been designed and operated for many different purposes (snow depth, density, *SWE*, wetness, and layering) and are therefore presented under a separated heading. The GPR techniques utilize differences in dielectric constant (electrical permittivity) between air, ice, and snow at different frequencies and differences in electrical conductivity as a function of snow density and wetness.

TDR-methods

The time domain reflectometry (TDR) technique is widely used for determination of unfrozen water content in soils and was first tested for snow applications by Schneebeli and Davis, (1992). The technique was later tested in a laboratory for determination of snow wetness (Lundberg, 1997). Low weight sensors with high surface area to weight ratio for continuous registration of snow density and wetness were developed by Schneebeli, et al., (1998). For dry snow, changes in density of less than 5 kg, m^{-3} could be detected and small amounts of liquid water could be sensed. However, during long term observations problems occurred at the snow surface due to formation of air pockets around the sensors (Schneebeli, et al., 1998; Schneebeli and Davis, 1992). The free liquid water content estimated with the TDR probe was reasonable but additional measurements are required to evaluate the performance of the probe during continuous measurements (Schneebeli, et al., 1998). Separate density measurements (or night-time refreezing assuring zero wetness giving information regarding density) are required for wetness determinations with the technique.

Snowpower band

The recently developed *Snowpower* sensor is designed for simultaneous measurement of snow density, *SWE* and liquid water content (Niang, et al., 2006; Stähli, et al., 2004). It measures the dielectric constant of snow at multiple frequencies; both in the kHz range using a newly developed low frequency impedance analyser, and in the MHz range using an ordinary TDR analyser. The use of multiple frequencies enables the determination of both liquid and frozen water contents since the dielectric constant if ice has a strong variation with frequency in the kHz range. The sensor, consists of a 10 to 25-m long flat PVC-band cable, that can either be mounted horizontally to monitor one depth or mounted sloping from a mast to the ground to give information regarding vertical variations in snow density, *SWE*, and liquid water content. The TDR measurements on the sensor cable may be further utilized to investigate the spatial variation of liquid water in the snowpack by inverse modelling of the Telegraph equation (Schlaeger, 2005). However, the low frequency measurements are enough for determination of the average density, *SWE*, and wetness, therefore the TDR measurements are not included in the latest developments of the *Snowpower* system. The sensor has been tested at a high-alpine Swiss test site (Stähli, et al., 2004) and in an agricultural field in Canada (Niang, et al., 2006). According to the alpine test the sensing system was quite robust. However wind-induced vibrations formed air pockets around the cable when the sloping band was mounted high on the mast (Stähli, et al., 2004). Both tests indicates that the sensor produces results in agreement with manual snowpack measurements (Niang, et al., 2006; Stähli, et al., 2004). However, results from the Canadian study accentuate the importance for the estimation accuracy on the choice of low frequency and the algorithm for the snow temperature extrapolation (Niang, et al., 2006).

Snow fork, capacitive sensor and monopole antenna

The “Finnish snow fork” (Sihvola and Tiuri, 1986) is a hand-held tool that consists of a two-pronged wave guide that is inserted into the snowpack to determine its density and wetness. The real and imaginary permittivity and attenuation around 1 GHz is used. The probe can easily be carried in a back pack and the data is stored in a memory device that can be transmitted to a PC, but the probes are too large to be suited for the stationary registration of parameters since they will absorb solar radiation and create air pockets around the probes. Kendra et al. (1994) presented a similar design as the snow fork said to have higher spatial resolution and accuracy.

A flat capacitive device working with radio-frequencies (20 MHz) which can record snow density and liquid water content at several different levels is described by Denoth (1994). Later he presented a so called monopole antenna to record snow wetness (Denoth, 1997). The large sizes (19.5×12.5×1.7 cm for the capacitive device and the aluminum plate with radius 12 cm for the monopole antenna) are disadvantages with the two devices. They will absorb solar radiation and are therefore only suited for short-term measurements since they are sensitive to air-gap formation around the probes. A comparison of the Denoth capacitance sensor and the Finnish snow fork showed that wetness measured by the snow fork was consistently (1.5 times) greater than measured by the Denoth meter (Williams, et al., 1996).

Ground penetrating radar techniques

A large advantage with the ground penetrating radar (GPR) techniques is that they can be operated from snowmobiles or aircrafts thus allowing measurement over large areas and in most terrain types, even if they are not suited for use in dense forests and very steep terrains. On the other hand, disadvantages with the techniques are that interpretation of the measurements requires a skilled operator and data analysis is quite time consuming. Besides that, a minor compaction of the snow will take place when the radar is operated behind a snowmobile.

GPR systems transmit electromagnetic waves with frequencies between tens of megahertz and tens of gigahertz. The waves reflect from the snow-ground interface and from interfaces between snow layers with different density or structure (e.g., snow-ice interfaces). The data that can be measured include two-way travel time of the reflected waves, the time it takes them to travel from the snow surface to the ground and back to the snow surface, as well as their frequency, and amplitude. This data can be analyzed to obtain snowpack depth, snow density, and *SWE*. However, determining these snow properties is problematic when liquid water is present in the snowpack or when a substantial horizontal spatial variation in the snowpack density is present (Andersen, et al., 1987; Killingtveit and Sand, 1988). Besides, two-way travel time might also be hard to determine, for example, when the ground is very rocky or when the difference in dielectrical properties between the snow and the ground are small.

Different types of GPR systems are used in snow surveys: impulse radars, arrays of impulse radars, frequency modulated continuous wave (FMCW) and step-frequency continuous wave (SFCW) radars (these succeeded step-frequency radars). All of them can be used for line measurements, the most common application when a GPR system is transported on a vehicle, for example, a snowmobile, but they could also be used for point observations of temporal changes in snowpack variables when mounted stationary.

Impulse radar systems

Impulse radars transmit a short pulse containing a spectrum of frequencies concentrated around a certain peak frequency (usually referred to as the radar frequency). This frequency is typically less than 2 GHz, resulting in a vertical resolution > 6-8 cm. Such systems have to record samples at a rate at least 4 times the peak frequency of the transmitted wave to adequately represent the received signal (Marshall and Koh, 2007).

Two-way travel time of a radar wave is normally obtained directly in the time domain by comparing the received signal to a reference signal (typically a direct wave between the transmitter and the receiver). Radar wave amplitude can be measured either directly in the time domain or in the frequency domain using centroid frequency downshift method (CFDS) (Liu, et al.,1998).

If radar wave propagation velocity in the snowpack is known and the snowpack does not contain liquid water, snow density can be calculated using an empirical formula (Lundberg, et al., 2000). On the other hand, if the density is known[1], then propagation velocity can be determined using the same empirical formula. Snowpack depth is further obtained from the two-way travel time and propagation velocity; and *SWE* is calculated from the snowpack depth and snow density. Note, however, that in some cases it can be sufficient to estimate *SWE* directly from the two-way travel time using a general empirical formula (Ulriksen, 1982), or choosing an empirical formula for the observed snowpack density, with the density measured manually at one or several locations (Lundberg, et al., 2000).

Thus obtained estimates of snowpack depth and *SWE* tend to be inaccurate when liquid water is present in the snowpack or if snow density varies throughout the snowpack. However, if liquid water content is somehow determined, then radar wave propagation velocity and snow density can be modified to take it into account (Lundberg and Thunehed, 2000).

Arrays of impulse radars

In systems consisting of an array of impulse radar antennas, they are arranged in a line with known distances between them in such a way that the radar wave paths share a reflection point at the ground. Multiple measurements taken with these antennas can be used together to calculate radar wave propagation velocity and snowpack depth using the common mid-point method (CMP) (Gustafsson, 2006). However, as in the case of the simple impulse radar, the accuracy of estimation of snow density from radar wave propagation velocity will be lower when liquid water is present in the snowpack.

A solution to the problem with wet snow has been suggested by Bradford and Harper (2006). They used the common mid-point method to determine radar wave propagation velocity and snowpack depth, and used Fast Fourier Transform to determine the frequencies of the transmitted and received (reflected) signals. These frequencies were then used to calculate the slope Q^* of the linear function describing the relationship between radar wave attenuation and frequency in a given medium, which was done with the frequency shift method (Bradford, 2007). Q^* together with propagation velocity was then used to determine the complex component of electrical permittivity, which led to establishing the liquid water content in snow and an improved estimate of *SWE*.

Other methods of improving *SWE* estimates for wet snowpacks by determining the liquid water content are being developed (see, for example, the work on estimating liquid water content from radar wave attenuation using an experimentally established relationship between electrical conductivity and liquid water content in snow (Granlund, et al., 2007).

FMCW and SFCW radar systems

Frequency-modulated continuous wave (FMWC) radar systems transmit a continuous signal with frequency linearly increasing over time; the reflected waves are recorded, as well as the minimum and maximum frequencies and the total sweep time. Typically, these systems can generate frequencies of up to 40 *GHz,* resulting in a vertical resolution of 1-3 cm. Such high radar-frequency equipment can be achieved at a reasonable cost (as compared to impulse radars) since the received signal only needs to be sampled with kilohertz frequency, i.e. several orders of magnitude lower than the frequency of the transmitted signal. A recent overview of FMCW radar technology and its application for snow research can be found in Marshall and Koh, 2007).

In a FMCW system the received signal is mixed with a replica of the transmitted signal, which may be computer-generated rather than recorded by a radar antenna, and the frequency difference between them is obtained using Fast Fourier Transform. The frequency difference together with the frequency range (the difference between the maximum and minimum frequencies) and the total sweep time are used to calculate the radar wave two-way travel time (Yankielun, et al., 2004). Similar to the case of the impulse radar, snowpack depth is obtained from the two-way

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[1] Snow density can be measured manually at selected locations and assumed to be roughly constant throughout the area of interest (Sand and Bruland 1998) or taken to be linearly dependent on snowpack depth (Lundberg et al., 2006).

travel time if the radar wave propagation velocity is known or estimated from independently measured snow density. Finally, *SWE* is calculated from the snow density and snowpack depth. Application of this method is limited by the necessity to perform measurements on dry snow or to determine and take into account liquid water content. If the density varies considerably throughout the snowpack the accuracy of *SWE* estimates will be lower.

Another application of FMCW radar is in establishing snowpack stratigraphy, and multiband FMCW systems are particularly suitable to achieve good resolution (Koh, et al., 1996). If a survey of snowpack stratigraphy is combined with manual measurements of density in a snow pit, layers characterized by the same density can be followed through the length of the line of measurement. For a dry snowpack, with the propagation velocity calculated from the snow density for each layer, a very good estimate of snowpack depth and snow density, and, subsequently, *SWE*, can be obtained from the two-way travel time (Richardson, 2001).

Step-frequency continuous wave (SFCW) radar systems, which are in fact a discrete version of FMCW systems, transmit a continuous signal that steps through a number of frequencies, increasing the frequency by the same amount at each step. The length of each step is also constant, so the total sweep time is known (Iizuka, et al., 1984). SFCW radars have the same limitations as FMCW systems.

Miscellaneous techniques

Various other techniques have also been used to register snow properties. Acoustic sounding has been tested to determine *SWE*, ultrasonic sensors, thermistors, and light-diodes and an automatic probe penetrating the snow pack have been used to monitor temporal changes in snow depth, barometric pressure, and terrestrial laser scanning have been used to determine spatial variations in snow depth and infrared radiation has been used to determine if a snowpack is melting. The physical resistance of snow has been measured by the snow penetrometer, giving information on vertical snow structure.

Acoustic sounding techniques

SWE has been determined by sound propagation theory, a non-destructive and time saving method (Kinar, 2007; Kinar and Pomeroy, 2007). Two transducers located just above the snow surface send and receive continuous frequency-swept audible acoustic waves. Signal processing adapted from frequency-modulated continuous wave radar and seismology applications was performed on the reflection response from the snowpack, and an estimate of SWE was calculated. For dry snow in Saskatchewan, Canada, the correlation between SWE determined by this technique and by manual gravimetric sampling was high (0.86) while for the same site the correlation for wet snow was low (0.30). The correlation at a site situated in the Rocky Mountains of Canada was (0.78). The lower correlation in the Rocky Mountains might be due to the presence of well-drained snow with higher levels of liquid water content and the development of a larger number of snowpack layers (Kinar, 2007; Kinar and Pomeroy, 2007). The acoustically-determined values were in general underestimated. A smaller device that can be carried in a rucksack was also designed and tested. Future development of probes and tests with the technique are in progress and this might improve the operation of the method on wet snow (personal communication, Nicholas Kinar, Department of Geography, Centre for Hydrology, University of Saskatchewan, Saskatoon, Canada).

Thermistors and light-diodes

Thermistors and light-diodes placed on vertical rods have been tested in Norway to measure snow depth but results are not published (Andersen, et al., 1982). Temperature profiles, measured in small increments, can be used to determine snow depth by analysing the daily temperature amplitude (small within snow-pack, large above it) (Andersen, 1995). Maijala and Leinonen, (2008) lists the pros and cons with camera and LED pole measurement systems for snow depth measurements.

Barometric pressure

Changes in barometric pressure using a high precision barometer, attached to a PC to measure snow depth along fixed profiles was tested by (Kennett, et al., 1996). The elevation along profiles and distance between stakes were surveyed with snow-free and with snow-covered ground. The barometer was located on a sledge equipped with an odometer and pulled by a snowmobile at a constant speed (10 to 20 km, h^{-1}), using a trigger to mark the stakes in the data file. The snow depth at the stakes and the distance between the stakes were used to calibrate the barometer and odometer readings. The snow depth along the profile was calculated as the difference between the surface (from the barometer) and the bare ground (surveyed). Tests were performed on snow-free ground during both calm and windy conditions. The method worked well during calm conditions with an average depth value reported to 0±4 cm while the method did not perform well with strong wind. Compaction of the snowpack from the weight of the snowmobile and the sledge may be a problem when applied on low density snow.

Ultrasonic sensors

One of the first ultrasonic sensors was tested in the early 1980's (Gubler, 1981). The absolute precision of the sensor was found to be ± 3 cm and the sensor was found to have difficulties identifying the snow surface after low density snowfall and blowing/drifting snow affected the data for short periods. The problems with identifying the snow surface for low density snow were confirmed by a Canadian study (Goodison, et al., 1984). This latter study also found that the sensor continuously under-estimated snow depths by 2-3 cm. Ultrasonic sensors are today extensively used to monitor snow depths and a recent comparison of two ultrasonic sensors (Judd and Campbell) showed that sensor performance was affected by intense snowfall, extremely low temperatures, uneven snow surface, snow crystal type, wind speed, and by blowing/drifting snow. Both sensors measured snow depth within ± 1cm (Brazenec, 2005).

Self recording snow depth probe

The self-recording snow depth probe developed by Sturm and Holmgren (1999) measures snow depth by the use of a pole automatically inserted into the snowpack. The measurements are made by means of a sliding basket and magneto-strictive device. The depth is recorded with an accuracy of ± 0.5 cm by a portable datalogger placed in a rucksack. To start a measurement, the observer presses a button mounted on top of on the pole. The probe is designed for operation down to temperatures of -30°C, and approximately 200 depths can be measured within about ten minutes. The probe can also be delivered with a GPS (Sturm, 1999; Snow-Hydro, 2008).

Infrared radiation sensors

Infrared radiation sensors have been used to measure the difference in surface temperature over snow and bare ground in an urban area (Semadeni-Davies, et al., 2001) and to measure the increase in snow temperature in ski tracks due to friction in a laboratory (Buhl, et al., 2000). Since they give information regarding the snow surface temperature they could be used to detect if a snow surface is melting (0°C) or not.

Terrestrial laser scanning

Laser scanning of altitude is mainly applied from satellites or airplanes but terrestrial laser scanning TLS can also be used to record variations in snow depth with high accuracy, this later application has been used for avalanche protection (Prokop, et al., 2008). A standard deviation of 2 cm was observed over an area of about 500 by 500 m as compared to tachymetry when the device was mounted on a tripode.The accuracy can be improved if the scanner is permanently located on a concrete foundation (Prokop, et al., 2008). The accuracy is high but can not be generalized since it depends on many factors; the used device (beam divergence), methodology (scanning speed), quality check, measurement set-up (distance to observed surface) etc. A disadvantage with the technique is that a skilled operator is required to perform all data acquisition and post processing steps with high precision (to achieve reliable results). The purchase cost of the equipment is around 70000 - 120000 Euros (Prokop, et al., 2008).

Penetrometer

The penetrometer, also know as the *SnowMicroPen*, is an instrument developed by J. Johnson CRREL and M. Schneebeli, Swiss Federal Institute for Snow and Avalanche Research (SFISAR). The instrument can be carried in a rucksack and consists of a probe that is driven through the snow with a constant speed providing 250 hardness measurements per mm giving extremely detailed snow structure profile information (Schneebeli, et al. 1999; Birkeland et al 2004).

EVALUATION OF TECHNIQUES

No single method fulfils all criteria, for the ideal snow measurement technique therefore a combination of several techniques must be used to simultaneously record the snowpack temporal and spatial changes in depth, density, *SWE*, wetness, and its layering. The accuracy of the methods is seldom well documented so the accuracy characterisation in Table 1 is, therefore, only qualitative. Below are the pros and cons with the different techniques discussed for each parameter; however the techniques (Snowpower and impulse radar) designed for measurement of several snow parameters are discussed separately at the end.

Techniques designed to primarily measure one parameter

Depth: The ultrasonic snowdepth technique is a well documented technique suited for unattended, continuous, long-term point measurements for temporal variations in snow depth. The terrestrial laser scanning technique is recommended for spatial variations of snow depths in areas of up to about 500 by 500 m. The barometric method used from a snowmobile pulled sledge might be used for depth measurements along lines during stable air pressure conditions but the automatic depth probe by Sturm and Holmgren seems a better option.

SWE: None of the point-measurement techniques in Table 1 give values that represent more than a few square metres. The weighing-lysimeter technique is the only method adjusted for measurements in forests, this technique on the other hand suffers from severe problems regarding the air-water exchange at the snow/ground surface. The other mass methods suffer from problems associated with snow bridging, while the use of several snow pillows/plates at the same location allows for identification and correction of such errors (*Johnson and Marks*, 2004). The two radiation attenuation techniques (active and cosmic gamma radiation attenuation) as well as the acoustic sounding technique seem promising but are not operational yet.

Snow quality (wet/dry and wetness): None of the presented methods to register snow wetness, requiring installations in the snowpack itself, are well suited for long term measurements due to the risk of air pocket formation around the probes. The specially designed thin and bright TDR-probes (Schneebeli, et al., 1998) seem the best option today. However, snow density information is required for determination of the wetness. This means that separated density measurements are required unless night-time refreezing of the entire snowpack occurs. An infra red sensor mounted over the snowpack will give information about a melting snow surface (always 0°C). Temperature measurements in the snowpack can also be used to derive the snow quality (wet/dry) but gives no information on the liquid water content.

Detection of snow layers: The penetrometer designed for detailed snow structure profile information (Schneebeli, et al. 1999) is not suited for continuous measurements. There does not seem to be any technique specially designed for monitoring temporal evolution of snow layers except the horizontal gamma-ray gauges. Since such gauges are subject to local melt, costly, and the handling of a radioactive source is disadvantageous they can not be recommended. The possibilities for ground penetratin radar techniques to monitor snow layers are discussed below.

Techniques designed for simultaneous measurement of several parameters

For some applications it is desirable to measure several parameters at the same time. All ground penetrating radar (GPR) techniques share some common advantages in this respect. They can be used for non-invasive estimation of both snowpack depth and snow density leading to SWE estimates. Since they can cover large areas, they are well suited for calibration and validation of remote sensing techniques. Besides, GPR systems can be used to monitor changes in snow properties, such as freeze/thaw cycles and presence of liquid water (Marshall and Koh, 2007).

Impulse radar systems in their simplest form only have one channel (one transmitter and one receiver); they are suitable for spatial measurements of snow depth and SWE for dry snowpacks provided that the horizontal variations in snow density are moderate or can be related to snow depth (Lundberg, el al., 2007). Arrays of several impulse radar antennas, arranged in a line in such a way that the radar wave paths share a reflection point at the ground, can be used for recording of snow depth, density, and SWE over areas with large horizontal density variations (Gustafsson, 2006). The same type of systems can be used when liquid water is present in the snow, if the liquid water content is measured by analyzing the radar wave attenuation (Granlund, et al., 2007; Bradford and Harper 2006).

The FMCW and SFCW systems have a better vertical resolution, typically 1-3 *cm*, than impulse radar systems, which have a typical vertical resolution of 6-8 *cm*. This makes these systems much more suitable for establishing snowpack stratigraphy and if mounted stationary above the snowpack they seem suited for monitoring of temporal variations in snow stratigraphy. The better resolution is achieved because the FMCW and SFCW radar systems sweep through a wide frequency band increasing the frequency over time while transmitting a narrow frequency band at each given time, with frequencies up to several tens of gigahertz. This can be compared to impulse radar systems that use a single broad frequency band, only giving them frequencies of up to several gigahertz.

Another promising technique is the new *Snowpower* sensor. It can be used for simultaneous monitoring or measuring of local snow depth and density, *SWE*, and snow wetness. It has been shown to produce results in agreement with manual snowpack measurements (Niang, et al., 2006; Stähli, et al., 2004). However, the sensor cable is rather large even if it is flat, and may disturb the natural snowpack, especially during snow melt by absorbing solar radiation.

CONCLUSIONS

Manual measurements of snow are becoming increasingly expensive at the same time as climate change imposed snow cover alterations, changes biotic conditions, runoff, and frost patterns, thus making reliable snow observations outmost important. Remote sensing techniques cover large areas and have the potential to meet the needs of such snow information but they are still dependent on trustworthy ground-based measurement for validation. Since snow exhibits a large variation both in space and time a combination of techniques capturing both the spatial and temporal variations is required. Stationary placed ground-based-probes should be located in a way, which accounts for differences in snow accumulation and melt patterns. An ideal technique for studies of snow characteristics should:

- cause negligible disturbance on the natural snowpack.
- measure depth and *SWE* with hourly or better time resolution and with an accuracy of 1 mm.
- work in all terrain and snow types.
- distinguish between wet and dry snow and provide the liquid-water content.
- work continuously and have acceptable costs for installation and maintenance.
- give area estimates of the snowpack depth, density, water equivalent, and layering.

The following techniques seem suited for measurements of:

Depth**:** Ultrasonic snow-depth technique for point measurement, acoustic sounding technique for dry snow areas up to about 100 m by 100 m, Terrestrial laser scanning for areas up to 500 by 500 m for all types of snow. One channel ground penetrating radar (GPR) technique for dry snow over distances up to 400 km/day when spatial density variation is know or estimated. The density can be determined when an array of antennas is used in combination with the common mid-point technique. Promising techniques to also handle measurement on wet snow are under development*.

Water equivalent: Several snow pillows at the same location and the CRREL/NRCS electronic snow water equivalent pressure sensor* for areas up to about 10 m^2. Active gamma radiation attenuation techniques for point measurements and cosmic radiation* attenuation techniques for areas up to about 100 by 100 m. GPR-technique for distances up to about 400 km day^{-1} in dry snow when density is know or can be estimated. (See comment above regarding wet snow and spatial density variations.)

Density: From depth and water equivalent measurements or by GPR arrays combined with common mid-point technique*.

Quality (wet/dry) and wetness: Snowpack temperature measurements by thermistors for information regarding point snow quality (wet/dry) and snow surface temperature by infra red sensors for information regarding point snow surface wetness. Specially designed thin and bright TDR-probes* are good for snowpack point wetness. For line measurements GPR wave attenuation or GPR common mid-point method using Fast Fourier Transform and frequency shift methods* to determine the frequencies could be used.

Layering: Stationary mounted "standard" GPR-radars with high frequencies and Frequency Modulated Continuous Wave (FMCW) GPRs seem fit for temporal monitoring of snow layer formation and disintegration. When pulled by a sledge the GPR:s can be used for spatial measurements of the same parameters.

Several parameters: The new sensor named *Snowpower* combines several techniques for simultaneous measurement of local (up to 10 m distance) snow depth, density, water equivalent, and wetness. GPR is, depending on design and if the operation mode is suitable for different purposes; when arrays of antennas are pulled by a snowmobile the technique is suitable for monitoring of spatial variations in depth, SWE, and density for dry snow. Techniques are under development which will hopefully improve the accuracy for dry and wet snow measurements. FMCW GPRs seem fit for measurement of snow layering.

ACKNOWLEDGMENT

This study has been performed with support from the projects a) Development of Gamma Water Instrument platform at the Baltic Shield founded by Interreg IIIA Nord and by b) Distributed measurement systems for improved snow- and runoff forecasts – integration into hydrological models supported by the "Swedish Hydropower Centre - SVC" www.svc.nu. James Feiccabrino is acknowledged for reading and correcting the English.

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