INNOVATIVE IN-SITU SNOW PARAMETER SENSING SYSTEM ALLOWING ACCURATE REMOTELY SENSED DATA CALIBRATION FOR IMPROVED FORECASTING OF HYDRO POWER RESOURCES.

FINAL TECHNICAL REPORT.

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TITLE: *'Innovative In-situ Snow Parameter Sensing System Allowing Accurate Calibration of Remotely Sensed Data for Improved Forecasting of Hydro Power Resources'*

PROJECT CO-ORDINATOR:

- FZK - Forschungszentrum Karlsruhe GmbH, Germany (partner 1)

PARTNERS (order according to contract):

- KTH - Kungliga Tekniska Högskolan, Sweden (partner 2)
- SLF - Swiss Fed. Inst. for Forest, Snow, and Landscape Research as Part of Swiss Federal Research Institute WSL (partner 3)
- HQ - Hydro-Québec, Canada (partner 4)
- INRS - Institute National de la Recherche Scientifique, Canada (partner 5)
- SOM - Sommer GmbH & Co. KG, Austria (partner 6)

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Part 1: Publishable Final Report Non Confidential

1.1. Executive publishable summary

The objective of the SNOWPOWER project is to increase the precision of filling prognosis of hydro power stations to at least 20% by calibrating remotely sensed data with ground truth data determined by new snow measurement methods. Potential benefits are high, and e.g. only a 10% gain in forecast precision for Switzerland would correspond to a yield of 1.6 TWh or 32 M€.
By now a new electromagnetic cable sensor and a new developed bench-scale instrument (BSI) for snow moisture and density measurements allowing a monitoring of an area of up to 2000 m² and evaluation software has been developed in the laboratory. The software integrates an air gap correction algorithm and a reconstruction code of the electromagnetic signal that allows the determination of a moisture and density profile of the snow pack along the cable sensors.
Laboratory and field measurements during three winter periods (2001 – 2004), were carried out both at measurement sites in Switzerland (Davos) and Canada (Quebec) first with a laboratory prototype field system, consisting of a time domain reflectometry cable tester and an impedance analyser. Preliminary data of moisture and density were evaluated and compared to reference measurements in the concerned snow packs with excellent and promising results. Based on the experiences of the first winter campaign, a second campaign (winter 2002/2003) was launched where the measurement algorithms and the sensor installation methods were refined. During that time a bench-scale instrument, which replaced the laboratory field system, has been developed and was available for test measurements in the last winter period (2003/2004) at the Swiss test site.
Furthermore additional hydrological models and the corresponding forecast strategies for hydro power optimisation have been developed, so that the measured snow pack data on the ground can be used to calibrate remote sensing data (RADARSAT) and thus will significantly improve the water reservoir filling predictions.
Although another testing winter with the existing BSI is planned, the measurements already helped to improve snow hydrological models. Measurements on a catchment in Canada indicate that an improvement in precision of melt water run-off prediction of some what more than 20% has been achieved.

1.2. Publishable synthesis report

The main objective of the SNOWPOWER project was the efficiency enhancement of hydro power stations, which generate an ecologically very desirable type of energy
In this project we developed a method and created a device for snow density and snow liquid water content measurements which is innovative not only on the level of each single sensor but on method and system levels also. Beside the enhanced remote data calibration and better snow water equivalent (SWE) prediction, we achieved an overall improvement of the satellite data driven hydrologic computation.
Advances in snow hydrological modelling were achieved also. We got a better understanding of the start and development of snow melting processes and a better conversion of the measured physical data into snow properties distribution. We also obtained synergy results for the avalanche warning and flood prediction. This may also be developed for a better prediction of drinking water resources from snow covered areas. Finally the developed field installations and instrument fabrications including a remote control network help to make data collecting much easier.

The project consisted of 8 work packages (WP). First the development and laboratory production of the snow moisture and density sensor in form of a Polyethylene-coated flat-band cable with copper conductors which acts as an electrical transmission line was carried out. The sensor cable was fabricated by a cable manufacturer specialised on the production of high quality cables for low temperatures and harsh environment conditions. The cables were configured and tested in the laboratory. Important cable characteristics for snow moisture and density determination such as the different capacities of the sensors were determined. Both low and high frequency measurements with an impedance analyser and with a time domain reflectometer were used to determine the dielectric properties of snow. Based on these measurements an algorithm for the determination of snow density and snow liquid water content was established, improved and refined with real data of snow properties (dry and wet snow) during a first field campaign in the Swiss Alps. This field test confirmed the method and proved the suitability of the snow sensor system. Comparison with other reference measurement methods of density and water content measurements confirmed the accuracy of the method. This was the second milestone

The existing hydrological models from the project partners, such as HYDROTEL and ALPINE3D could considerably be improved and were extended to incorporate the ground truth data from the snow sensor and an interface to the snow sensor network software was developed. Major improvements have been achieved in EQeau, an algorithm for combining ground truth data with RADARSAT-1 data, by integrating a new approach for a distributed estimation of punctual snow density measurements. The new method uses both multiple regressions (altitude and latitude) and spatial interpolation (inverse distance). From the results it can be concluded that the rigorousness of the image processing chain of RADARSAT data have been improved. The temporal variation of the radar signal during the winter is low but comparable from one data set to another. It was shown that the new approach for the spatial interpolation of the punctual snow densities measurements is reasonably efficient ($R^2 = 0.83$). The improvement of SWE map accuracy of 6% was achieved using ScanSAR data from RADARSAT-1

An adequate installation method ensuring good stability of the sensor under windy conditions, thus minimizing the formation of an air gap around the sensor cable has been developed and an installation guide has been established. Following field experiments, a number of recommendations were identified for improving the quality of the coaxial cables used and for simplifying the design of the junction box between the sensor and the coaxial cables.

Based on the experiences with the laboratory prototype devices, a bench-scale instrument has been designed. This turned out to be most critical and time consuming work package since several problems were encountered during the project. At first the theoretical aspects of the technical realisation of measurements in the snow were assessed. To determine both density and water content of snow two electronic measurement techniques are necessary (Low-frequency Impedance Analysis and High frequency Time Domain Reflectometry Analysis). The system was designed to especially fulfil the requirements that are necessary when dealing with snow: wide range of temperature, low energy consumption and adequate for field use, i.e. light-weight and portable. The test of the bench-scale instrument (BSI) was carried out at the Swiss test site during the melting season in a third winter field campaign. As a conclusion of this test it can be stated, that the system worked failure-free for nearly 4 months in the harsh Alpine environment and has the potential to become an operational tool for the determination of large-scale snow pack density, liquid water content and snow water equivalent. Yet some fine-tuning of the system is still necessary to obtain reliable absolute measurement values. Therefore an adequate calibration with materials comparable to snow is indispensable.

A large-scale field test in Canada with the BSI could not be carried out as planned due to the delay of the BSI and climatic conditions. Therefore this work package had to be modified and measurements were carried out with the laboratory set-up. Nevertheless important investigations on the influence of temperature and dielectric mixing rule coefficient on the measurements that increase the accuracy of the method were obtained. It can be concluded that the integration of all available snow temperature measurements along the cable is the best method to provide a representative value of the cable temperature when strong variability in the temperature profiles are observed.

As a conclusion it can be stated that the new system has the potential to become an operational tool for the filling prognosis of hydro power stations and for calibrating remotely sensed data.

2.1. Objectives and strategic aspects

The main objective of the SNOWPOWER project is the efficiency enhancement of hydro power stations, which generate an ecologically very desirable type of energy. Thus it belongs as the central relevance to Key action 5.2.5 '*Other renewable energies*', because of its technical novelty, economic, environmental and social impact. It will contribute to the increase of the share of renewable energy in the European and global energy balance in producing electricity at a cost considerably under 0.15 €/kWh. Seven countries of the EU plus Switzerland and Norway operate hydro power stations where the catchments are under snow cover in winter. Several other countries of the world have the same situation, especially in Canada where some of the world largest hydro power stations are fed with snow melt.

Electricity from water is the cleanest energy transformation among the renewable sources. So, it addresses also the Key action 6.5.4 '*Improving the efficiency of new and renewable energy sources*'. Hydro power generation avoids emissions, any kinds, especially green house gases. Their efficiency enhancement is the best contribution to the global CO_2 reduction as required by the Kyoto agreements. The project will contribute to the consumer satisfaction and quality of life with more electricity without air pollution. The hydro power stations already have a high technical efficiency without severe consequences to the environment. This potential will be remarkably enhanced by the water management improvement as result of the project.

The proposed solution for efficiency enhancement will be suitable for new and existing plants without any restrictions. There is no need of any hardware installations in the power plant itself. By this way the sustainable management and quality of water can also be improved. In this sense it contributes to the EU policy of sustainable use of water resources at catchment-scale. A certain synergy effect will be expected to this policy. In case of project success Europe will have a good competition position for the industrial marketing of the technology and the Canadian partners will benefit directly from use of the technology and from exploitation in North America. In addition a new market will be created for the equipment and Europe will benefit by the increased demand for skilled employment. The Society will also benefit from better flood prediction and avalanche warning as well as better management of the water flux both for energy generation and for environmental needs. Drinking water resources that are fed by snow covered catchments will benefit from improved prediction methods. This situation is relevant in the alpine regions of, Austria, France, Germany, Italy and Switzerland as well as in the Nordic regions of Scandinavia.

The proposed method is innovative not only on the level of each single sensor but on method and system levels also. Beside the enhanced remote data calibration and better snow water equivalent (SWE) prediction, we expect an overall improvement of the satellite data driven hydrologic computation.

Advances in hydrological modelling can be expected also. We want to get a better understanding of the start and development of snow melting processes and a better conversion of the measured physical data into snow properties distribution. It is obvious that we will get synergy results for the avalanche warning and flood prediction as well as a better prediction of drinking water resources from snow covered areas. Finally the intended field installations and instrument fabrications including a remote control network will help to make data collecting much easier.

2.2. Scientific and technical description of the results

Within the project work was carried out on all of the 8 Work packages. 17 of the planned 20 Deliverables could be issued completely, whereas 1 Deliverable could only be issued partly and 2 could not be achieved due to a considerable delay in one Work package combined with seasonal reasons. 3 of the 4 planned Milestones could be achieved, whereas 1 Milestone could only be fulfilled partly.

2.2.1 WP 1 'Sensor development'

The new measurement method for snow properties was originally developed at FZK and will be highlighted by the following explanation. To make this model easier to understand, we use a simplified mixing rule of snow as a mixture of ice (I), air (A) and water (W). Their parts together give the uniform measuring volume:

$$I + A + W = 1 \qquad (1)$$

Mixing rules connect the volume parts and their dielectric coefficients $\varepsilon_I = 3.16$ (at measuring frequencies > 1 MHz e.g. by Time Domain Reflectometry), $\varepsilon_A = 1$ and $\varepsilon_W = 83$ (at 0°C) respectively to the mixture dielectric coefficient ε_M.

$$\varepsilon_M^{0.5} = I*\varepsilon_I^{0.5} + A*\varepsilon_A^{0.5} + W*\varepsilon_W^{0.5} \qquad (2)$$

To solve the task for the three unknown parts (I, A and W) we need a second measurement of the mixture dielectric coefficient ε_{M2}. This second measurement is made at low frequency with an impedance analyser(e.g. at 1 kHz), where the coefficient of ice is ε_{I2}=103.

$$\varepsilon_{M2}^{0.5} = I*\varepsilon_{I2}^{0.5} + A*\varepsilon_A^{0.5} + W*\varepsilon_W^{0.5} \qquad (3)$$

From (1), (2) and (3) one can determine I, A and W and calculate the snow density D.

$$D = I*\gamma_i + W*\gamma_w \qquad (4)$$

with γ_i and γ_w as the densities of ice and water respectively. The density has a distribution which will be volume integrated in order to achieve the Snow Water Equivalent (SWE), which is the product of snow density and snow depth and indicates the amount of water a snow pack would give if it was melted. SWE is the key parameter for forecasting of water resources in snow covered regions.

In WP 1 the development and laboratory production of the snow moisture and density sensor in form of a PE-coated flat-band cable with copper conductors (Fig. 1) which acts as an electrical transmission line was carried out. This included the development of an air gap correction algorithm and of a reconstruction code. First the electromagnetic field around the sensor structure was calculated for different moisture and air gap conditions with a numerical calculation code existing at FZK. An optimal cross section was chosen after several sensor cable cross sections were investigated.

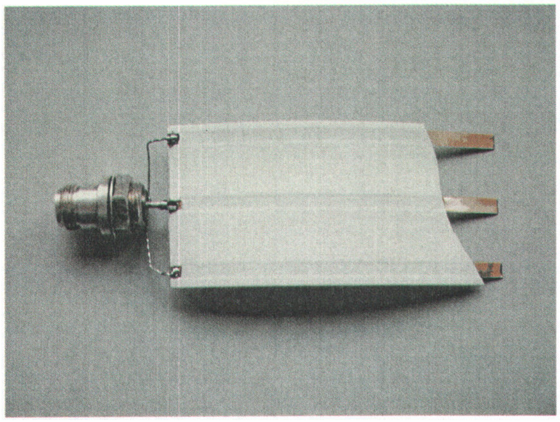


Figure 1 – Cable sensor with copper conductors visible

The sensor cable was fabricated by a cable manufacturer specialised on the production of high quality cables for low temperatures and harsh environment conditions. Figure 1 shows the developed cable sensor. The cables were configured at FZK and the cable sensors were built and tested in the laboratory. Important cable characteristics for snow moisture and density determination such as the different capacities of the sensors were determined.

Concerning the air gap correction algorithm, KTH first made literature studies about quasi-TEM mode propagation on multi-conductor transmission lines. Several questions regarding the possibility of using the proposed three-conductor cables were investigated, such as how the dominant part of the signal (which can be decomposed into one even and one odd mode) will look like when the cable is submerged in a homogeneous medium, how asymmetric air gaps affect the mode propagation along the cable when the modes will not be the simple even and odd modes or how the air gap with known typical shape can easily be described by a very small number of parameters.
A preliminary study of an elliptically shaped air gap, described with only one parameter, indicated that it is theoretically possible to recover both the snow permittivity and the air gap parameter, using data from one even mode experiment and one odd mode experiment. However, the stability of such a procedure, against measurement errors, has not yet been investigated.
As a tool for treating the problems related to these questions, FZK and KTH used a semi-analytical approach relying on the assumption that the flat conductors are embedded in an elliptically stratified environment. Thus, the boundaries insulation-air and air-snow are confocal elliptical surfaces around the conductors. The elliptical shape is a reasonably good approximation for the thin insulation, and it seems quite representative for the air gap. The size of the air gap has been defined as the distance insulation-snow at the middle of the broadside of the cable. Using quasi-TEM analysis, the reactive transmission line parameters for different values of the air gap and the dielectric constant of the snow have been calculated. The influence of the air gap increased with increasing dielectric constant. Examples: A dielectric constant of 3 and an air gap of 1 mm correspond to a dielectric constant of 2.25 with no air gap. A dielectric constant of 1.5 and an air gap of 1 mm yields a dielectric constant of 1.4 with no air gap.

The reconstruction code for determining snow profiles was developed at FZK. Both frequency and time domain methods were investigated and the so-called inverse problem was solved. An exact algorithm with Greens functions and an optimisation approach was considered. The possibilities and limitations of a Fourier transform of the measurement data from time to frequency domain and back were investigated. The reconstruction algorithm was coded and tested with artificial measurement data. Finally a new software for the convenient evaluation of the measurement data was written (*GetMoisture*). The algorithm for the reconstruction of the moisture profile of the cable sensors was integrated.

2.2.2 WP 2 'Laboratory trials'

To test and improve the snow moisture and density sensor a laboratory set-up was built. This included the mechanical design, writing software for instrument control and data acquisition and the selection of materials with dielectric properties comparable to snow. The sensor cable was buried in a tank with different materials simulating dielectric properties comparable to snow (Fig. 2 and Table 1).

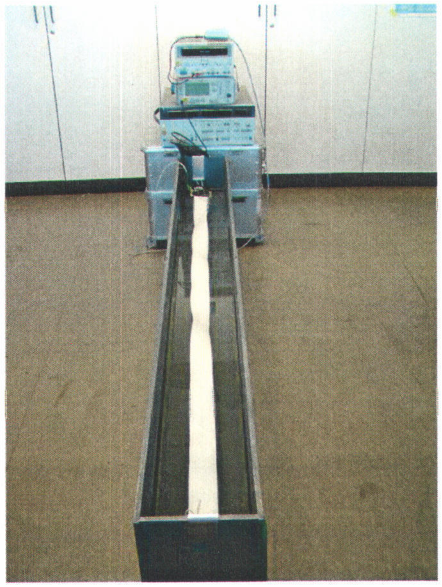


Figure 2 - Laboratory set-up and tank used for calibration

Table 1 - Materials used for calibration with corresponding permittivities (ε_M), measured low frequency capacity(C_M) and transit time characteristics(T_M/T_A) of an electromagnetic TDR pulse.

Material	ε_M	C_M [pF/m]	T_M/T_A
Air	1.00	8.67	1
Sugar	2.01	16.49	1.317
Glass	3.18	24.6	1.559
Salt	3.20	24.54	1.572
Water	80		3.508

A computer program was written to control a time-domain reflectometer (*Tektronix 1502B*) and an impedance analyser (*Hewlett Packard 4192 A*), acquire the electromagnetic impulse response of the sensor and process the data with the reconstruction code prepared. All program parts were integrated in the *GetMoisture* software code.

To assess the maximum errors in dielectric coefficient and air gap size, first of all the cable parameters had to be determined. The industrially manufactured cables show tolerances in dimensions and in the dielectric constant of the coating. Therefore it is necessary to verify the cable parameters after the manufacturing process and correct the calculated transmission line parameters if necessary. In the case of the three-wire flat-band-cable sensor, the necessary correction procedure will be shown.
The flat-band cable can be represented by the equivalent circuit in Figure 3 with 3 capacities.

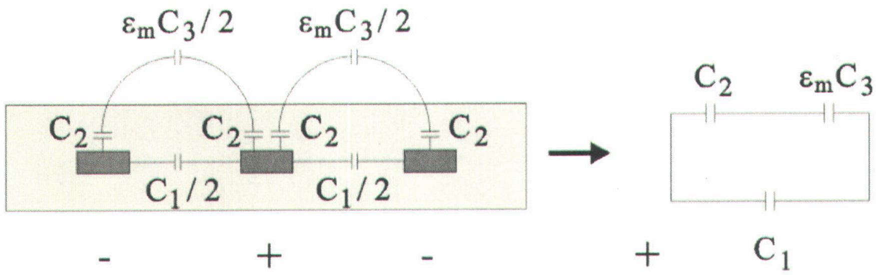


Figure 3 – Cross cut of 3-wire-flatband-cable and corresponding equivalent circuit.

Capacity C_1 describes the electrical field lines from one wire through the dielectric medium to the other wire, whereas the capacities C_2 and C_3 are derived from the series configuration of coating-medium-coating.

The total capacity C_{mi} between the conductors is:

$$C_{mi} = C_1 + \frac{C_2 \varepsilon_{mi} C_3}{C_2 + \varepsilon_{mi} C_3} \qquad (1)$$

For the determination of the unknown capacities C_1, C_2 and C_3 one needs 3 measurements of the total capacity in 3 different media. In this case we use measurements in air with $\varepsilon_{m1} = 1$, oil with $\varepsilon_{m2} = 2.15$ and water with $\varepsilon_{m3} = 80$. From transit time measurements the corresponding pulse velocity v_i is calculated. Assuming any but constant inductance L, the following equation yields the corresponding total capacities:

$$v_i = \frac{1}{\sqrt{LC_{mi}}} \qquad i = 1, 2, 3 \qquad (2)$$

The resulting non-linear equation system can be solved numerically for C_1, C_2 and C_3. From transit time both the pulse velocity and the total capacity C_m can be derived. The dielectric constant of the unknown medium yields from equation (1) as follows:

$$\varepsilon_m = \frac{(C_m - C_1)C_2}{C_3(C_2 - C_m + C_1)} \qquad (3)$$

For moisture measurement techniques that are based exclusively on the determination of transit times, the absolute value of the inductance is not significant. Yet for further investigations, e.g. the determination of the spatial distribution of the capacity along a transmission line, it is necessary. From the measurement point of view the reflection of a pulse can be evaluated according to the following equation:

$$r = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad (4)$$

with r as reflection coefficient (relationship of amplitude of transmitted and reflected pulse), Z_L as characteristic impedance of the transmission line and Z_0 as basic impedance (mostly 50 Ω).

Z_L can also be determined in the frequency domain with a network analyser. To do this a cable of any length is provided with a short cut and with an open circuit and the corresponding input impedances Z_{short} and Z_{open} are measured. The impedance is determined according to:

$$Z_L = \sqrt{Z_{short} Z_{open}} \qquad (5)$$

This procedure is sufficient for measurements at low loss cables and with low precision demands. If all transmission line parameters L, C, R, and G are to be determined, it is necessary to determine S_{11} and S_{21} of a piece of cable of known length and to do an inversion according to SOMLO (1993). The crux of this procedure is the calibration of the networkanalyzer at the interface between coax-cable and flat-band cable. Furthermore the inversion algorithm is numerically instable at transmission line lengths that correspond to multiples of half the wavelength (BAKER-JARVIS et al. 1990). Therefore it is advantageous to determine L and C of a low loss cable with the time-domain reflectometry (TDR). A high frequency compatible resistance is connected to the end of a longer piece of cable. If the load impedance matches the coax impedance Z_L , then a generated TDR pulse that propagates along the cable is perfectly absorbed and no reflection occurs (GRIVET 1970). From the measurement of Z_L and the corresponding v , the inductance can be determined with equation (2) and the following (6):

$$Z_L = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad (6)$$

with ω as radian frequency.

As for the example of the three wire cable shown in Fig. 3, the results achieved with this method can be shown. The outer conductor is on mass potential and only an excitation of the inner conductor takes place. So the three wire cable is run with one of three possible modes and can be regarded as two wire system. Therefore a description with the usual capacity – and inductance matrices of multi-wire systems is not necessary. Table 2 shows the results for a 1.93 m long cable immersed in different materials.

Table 2 – Measurement results of a three wire cable sensor with symmetrical excitation.

Medium	ε	Single transit time [ns]	Propagation velocity [m/s]	ε_{eff}	Capacity [pF/m]
Air	1	7,107	$2,715 * 10^8$	1,218	17,48
Oil	2,15	9,676	$1,994 * 10^8$	2,258	32,27
Water	80	26,773	$7,209 * 10^7$	17,29	228,78

The inductance was determined from measurements of resistance and transit time in air. The effective dielectric constant ε_{eff} corresponds to the dielectric constant of a homogeneous medium that is able to replace the stratified structure of coating and surrounding material without changing the propagation characteristics.

The measurement results lead to the values shown in Table 3. There is a good correlation between experiment and numerical field simulations achieved with the program MAFIA. The slightly higher deviation of the capacity C_2 is due to the variation of the coating thickness caused by the manufacturing process. Note that the values depend on both the cable thickness and the spacing.

Table 3 – Equivalent circuit elements for thin (1.3 mm) and thick (3mm) three wire cable sensor.

Equivalent circuit element	Experiment Thin cable	MAFIA Thin Cable	Experiment Thick cable Small spacing	Experiment Thick cable Large spacing
C_1	3,4 pF/m	3,4 pF/m	8,597 pF/m	2,947 pF/m
C_2	323 pF/m	276 pF/m	111,189 pF/m	130,175 pF/m
C_3	14,8 pF/m	15,3 pF/m	12,715 pF/m	17,852 pF/m
L	756 nH/m	741 nH/m	756 nH/m	756 nH/m

From these values the characteristic line of the cable sensor can be calculated. As expected, the transit time increases and the impedance of the transmission line decreases with increasing dielectric constant of the surrounding medium. Due to the relatively fast approximation of the impedance to the final value, it is unreliable to derive the moisture from the measurement of the amplitude of the reflected signal.

The performance of the reconstruction code under various disturbing conditions was evaluated. The laboratory experiments confirmed a sufficient accuracy of the measurement system (e.g. not more than 2% uncertainty in the volumetric water content for air gap sizes less than 2 mm).

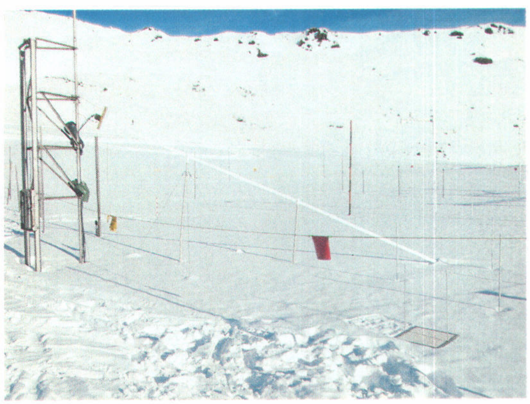
2.2.3 WP 3 'Field test

a.) Swiss test site Davos

In WP 3 the snow sensor and the laboratory set-up was tested in the field and the results were compared with reference measurements.
At the beginning of project month 4 FZK and SLF/WSL set up four flat band cable sensors at the Davos Weissfluhjoch (WFJ)-test site in Switzerland at an elevation of 2550 m. A 10 m inclined flat-band cable was mounted for monitoring vertical variations in the snow properties in the run of the winter (Figure 3). To keep the band stable also during situations of heavy wind and massive snow load three poles were positioned under the cable and a new suspension with two springs was tested to prevent the cable from ripping.

Both measures showed to be an important improvement compared to an earlier set-up, however, they were not able to solve the problems completely. In addition to the sloping cable sensor, three cables were placed horizontally on the snow cover in the course of the winter to measure the spatial variability of the liquid water content and snow density, and especially for detecting water conducting zones during the main snowmelt. The first cable was laid out at a snow depth of 72 cm on 11th of December 2001, the second at a snow depth of 117 cm on 28 January 2002, and the third at a snow depth of 164 cm at the end of month 6. These cables followed the natural settlement of the snow pack. No apparent problems arose regarding the placement of the horizontal cables, however, it is not clear if these cables possibly interrupt or deviate the natural water flow in the snow pack. This issue was investigated in the second field test (2002/03) within WP 6 by conducting dye tracer experiments.

The electronic measurement devices of the system (TDR cable tester, impedance analyzer HP 4092, PC) were placed in a shelter ~10 m away from the flat-band cable (Fig. 3).



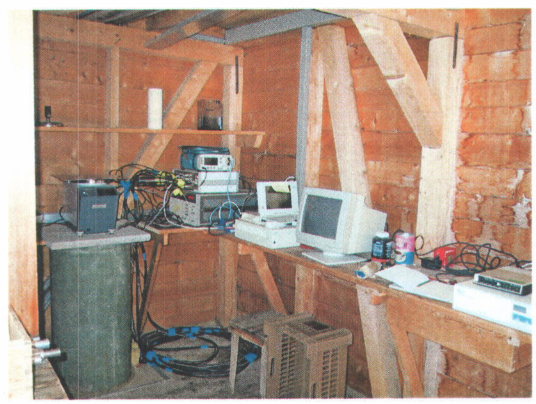


Figure 3 - The cable sensor system at Weissfluhjoch Davos (2550 m): the sloping flat-band cable (left), and the electronic devices in the shelter (right).

The high frequency measurements started on December 11, 2001, whereas the low frequency measurements could not be ran before January 15, 2002, due to a technical problem. After that date, the measurements were running successfully. Only one major incident occurred when a heavy windstorm damaged one of the mountings. However, this damage was repaired immediately. Additional monitoring of snow pack properties at Weissfluhjoch/Davos was carried out during the whole winter. At the end of month 7, the impedance analyser for the low-frequency measurements broke down and could not be repaired. It was replaced at the beginning of month 9, just in time before the melting period started. So the lack of data is not a severe problem for the data evaluation. The Davos measurements were stopped at the end of the melting period in month on June 22, when all the snow on the measurement site was gone.

The signal traces resulting from the cable sensor were evaluated using the '*GetMoisture*' software. The following snow parameters were determined and compared to different reference methods: Bulk dielectric constant, bulk snow density and liquid water content (all mean values along the cable).

Figure 4 shows the measured densities and Figure 5 the measured liquid water contents with two horizontal cables of the snow pack in comparison to manual reference measurements.

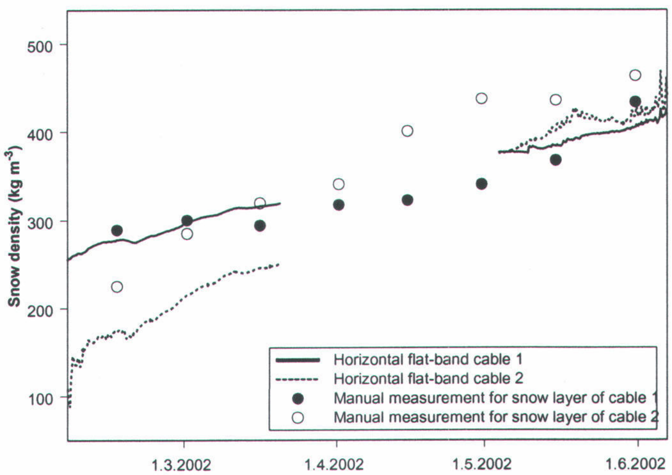


Figure 4 – Measured density along the two horizontal cables during winter 2001/2002. Dots show manually determined density of the corresponding snow pack layers. Due to a break down of the impedance analyser no data were available from late March to early May.

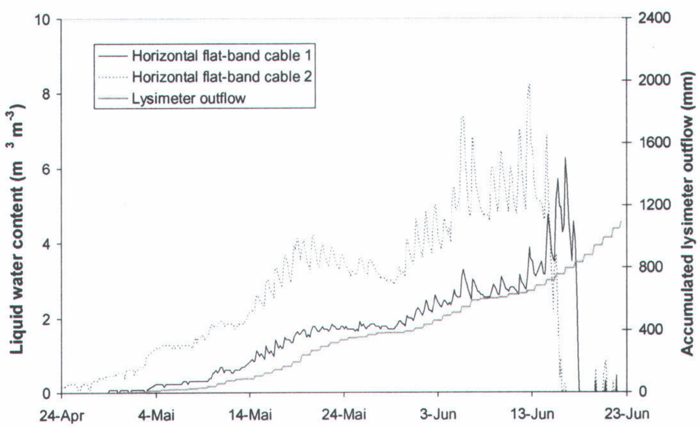


Figure 5 – Liquid water content (average value along two horizontal cables) during the melting period of spring 2002. Comparison with accumulated melt-water outflow from the lysimeter adjacent to the sensor.

For distinct situations, the reconstruction code was tested and some moisture profiles of the snow pack could be established. One example is shown in Figure 6.

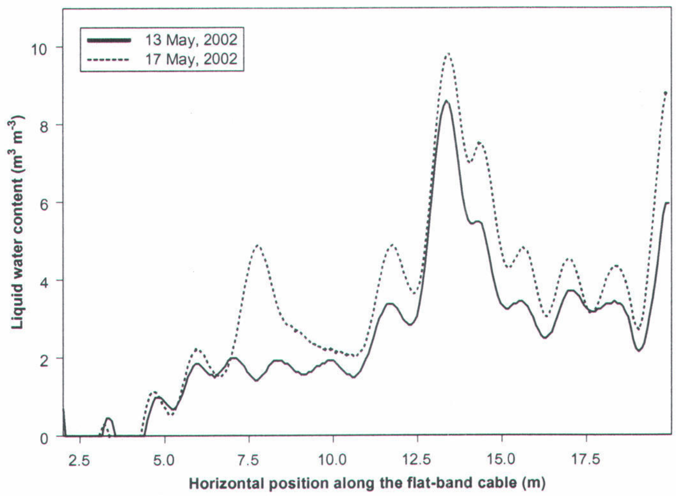


Figure 6 – Spatial variability of liquid water content along horizontal flat-band cable 2 on 13 and 17 May 2002.

The measurements yielded very good and plausible results. The correspondence with reference measurements on the site was excellent. In general, the field test 2001/02 of Work package 3 at WFJ/Davos showed that the measurement system has potential to become an automatic, unattended tool enduring harsh winter conditions (thick snow pack, low temperatures). With the exception of some weeks in December, where an erroneous setting prevented the impedance analyzer from running, and in April, where a break down of an internal electronic component forced us to replace the impedance analyzer, the system ran more or less failure-free throughout the entire winter season.
However, with regard to the suspension and the set-up of the sloping flat-band cable a number of imperfections showed up, which were investigated and improved in WP 6.

b.) Canadian test site Quebec

Although not planned in WP 3 INRS and HQ, started preliminary field tests in December 2001 as an opportunity for the Canadian partners to get more familiar with the SNOWPOWER sensor and the measurement methodology. The Chapais experimental Farm of Agriculture and Agri-Food Canada (AAFC), south of Quebec City (Canada), was selected as the test site. Two 20 m long cable sensors were installed diagonally sloping on wooden posts, with one end on the ground surface and the other end at a height of 1.5 m. A temporary polyethylene shelter was installed to protect the coaxial connectors all winter long and to protect the instruments at the time of measurements (Figure 7).

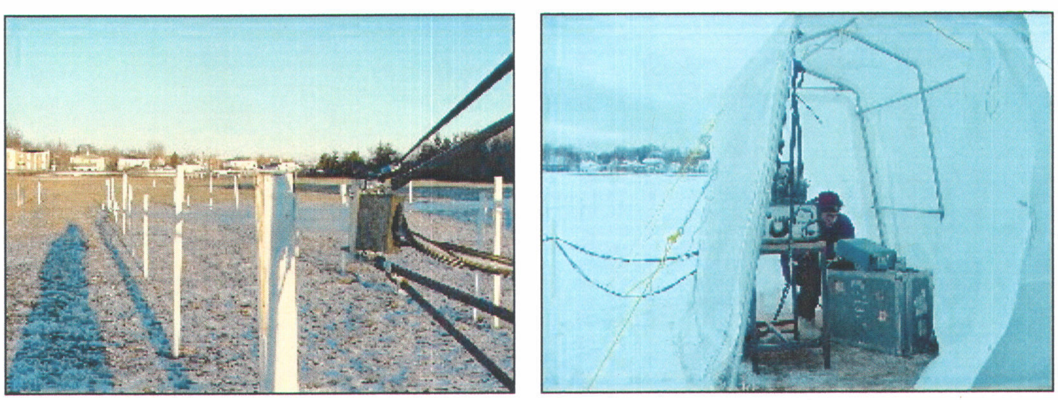


Figure 7 - SNOWPOWER installation at Chapais experimental site for winter 2001-2002

The low- and high-frequency measurements were conducted on 9 different days during the winter. Snow properties were characterized regularly in the vicinity of the cables. Meteorological data were acquired continuously by an automatic weather station.
The first data sets revealed the need for some technical adjustments. After that, the measurement system was satisfactory operational under our environmental conditions from February 15.
The low frequency measurements were quite different from those made by FZK and SLF at WFJ/Davos, which was mainly caused by electromagnetic interferences with other sources (possibly radio waves).The high-frequency measurements from the TDR showed the expected variations from dry to wet snow. The air to snow transition zone was generally visible.
It was also observed that the cable sensors were never completely covered by snow. The maximum snow depth measured near the low end of the cable was 53 cm. Measured snow densities ranged from 250 kg/m³ to 400 kg/m³. The measured snow liquid water content in April reached 6%. Snow accumulated differently on both sides of the cable, due to the wind and melted earlier around the wooden posts, creating holes in the snow cover. Finally, the weight of snow and ice was sufficient to bent the cable vertically and horizontally particularly at the end of the winter. These observations showed the need to consider better ways to obtain an optimal cable installation for next winter.

Furthermore the measurement algorithms was improved and refined with real data of snow properties (dry and wet snow). This first field campaign proved the suitability of the snow sensor system. Comparison with other measurement methods confirmed the measurement accuracy. This was the second milestone

2.2.4 WP 4 'Hydrological modelling' –

WP 4 already started in the first year and lasted until the end of the project. The existing hydrological models from the project partners, such as HYDROTEL and ALPINE3D could considerably be improved and were extended to incorporate the ground truth data from the snow sensor and an interface to the snow sensor network software was developed.

a.) Contribution of the Canadian Partners

The Canadian partners INRS and HQ proposed the HYDROTEL hydrological model to be used with the SNOWPOWER instrument and EQeau (RADARSAT-1) to determine the spatial distribution of Snow Water Equivalent (SWE). The HYDROTEL model is a distributed model which is able to update its spatial distribution of SWE from a network of snow survey stations. So, SWE and thickness of snow pack derived from SNOWPOWER data can immediately be used instead of the actual snow survey data, or in conjunction with them.

For the 2003-2004 winter season, a set of SNOWPOWER probes was installed at a watershed site south of Quebec City and bi-hourly measurements of snow depth and snow density were taken from mid-February through the beginning of April. Weekly snow profiles including temperature, density, snow grain types and diameters were also obtained to test the probes. Previous studies showed that the French CROCUS model for snow pack simulation (*Meteo-France*) was able to simulate accurately the temporal evolution of the snow pack thickness as measured by a laser probe at three sites for three winter periods in Northern Québec (Savary, 2002). For this watershed, the second simulated stream flow peak and volume, without snow cover updating, were too low. If the snow cover is updated using the snow survey data of the Québec Department of Environment, the simulated stream flows are quite similar to the measured ones, so that the flood volume is approximately the same. In this specific case, simulations in which the snow survey data are replaced by SNOWPOWER data, snow sampler data taken at the SNOWPOWER site or daily simulated CROCUS data, even if added to snow survey data, did not lead to more accurate stream flow simulations. It can be noticed, however, that the first increase of stream flow as simulated from CROCUS data is more similar to the measured stream flows than with the other ways of snow cover updating. These results show the importance of snow cover updating. In order to obtain very good results, great care should be taken for the choice of strategic measurement sites with the largest spatial representativeness. Also, the SNOWPOWER site chosen for practical reason was not ideal for snow cover updating, as it was located in an agricultural field.

An updating comparison was also tried for the main stream flow station in another watershed. Daily SNOWPOWER data were then simulated using the French CROCUS (Météo-France) snow model. The CROCUS model was applied on the watershed using the available data at three meteorological stations in the mid-watershed sector to drive it. The CROCUS obtained values at those stations were then assumed to be SNOWPOWER probes values and used to update the state variables of the HYDROTEL model. The initial simulation, without snow cover updating, led to a clear underestimation of peak flows. Here, updating the snow cover from snow survey data does not lead to results as good as for the first watershed. There is an increase of the simulated flows but they are still too low when compared to the observed values. Another updating approach has been obtained by simulating daily values of SNOWPOWER probes at the actual SNOWPOWER site and at three more sites where meteorological stations exist for the center section of the watershed. In that case, the peak flow and volume of the first flood are much better simulated and the second ones are even better, the simulated peak flow being only slightly higher than the observed peak. Another simulation was tested in which the CROCUS values were assumed to be available only on the dates of the snow surveys. The result is similar to the one using daily CROCUS values and snow survey values. One can conclude that a more frequent availability of snow cover values of less than 15 days is not necessary, but as a matter of fact, the availability of daily data by the SNOWPOWER system is very important in case of heavy snowfalls or if intensive melting occurs after a snow survey made at intervals of two weeks and before a major flood event.

Concerning the application of EQeau, a spatial and temporal analysis of the signal variability over the La Grande watershed has been done. The backscattering coefficients were extracted from three (3) RADARSAT-1 SCN data set acquired in 2003-2004 but also in 2000-2001 and 2002-2003. It was observed that no particular variation of the backscattering coefficients were associated with a specific land use class. Temporal variation of the mean signal during the winter is generally equal or less than 1dB but this could be observed for each data set. Generally, the backscattering coefficients are lower in November and increase during the winter. The normal variation of the backscattering coefficients with the angles of incidence is not completely eliminated using the temporal ratio for the angles below 23° and above 38°. Finally, the meteorological conditions at the moment of acquisition (rain, wet snow) introduce significant variation of the backscattering signal.

Major improvements have been achieved in EQeau, an algorithm for combining ground truth data with RADARSAT-1 data, by integrating a new approach for a distributed estimation of punctual snow density measurements. The new method uses both multiple regressions (altitude and latitude) and spatial interpolation (inverse distance). The random mean square error could be minimized to 23 kg/m^3 (former RMSE 37 kg/m^3) and a regression coefficient R^2 of 0.83 could be achieved. The EQeau software was then modified to run the new approach: read the Hydro-Quebec historic density measurements, calculated the regression, read the MNA, applied the regression for each pixel, estimated the density for each pixel.

Using the new spatial interpolation approach for snow density as well as new filtering method (Lee) and a re-sampling pixel size of 375 x 375 m (instead of 50 m), it is now possible to explain 78% of the variation of the SWE of the snow pack with an error of 29 mm. This value is better then the error of 39 mm of the former model. Figure 8 shows a comparison of the estimated and measured SWE with the new model.

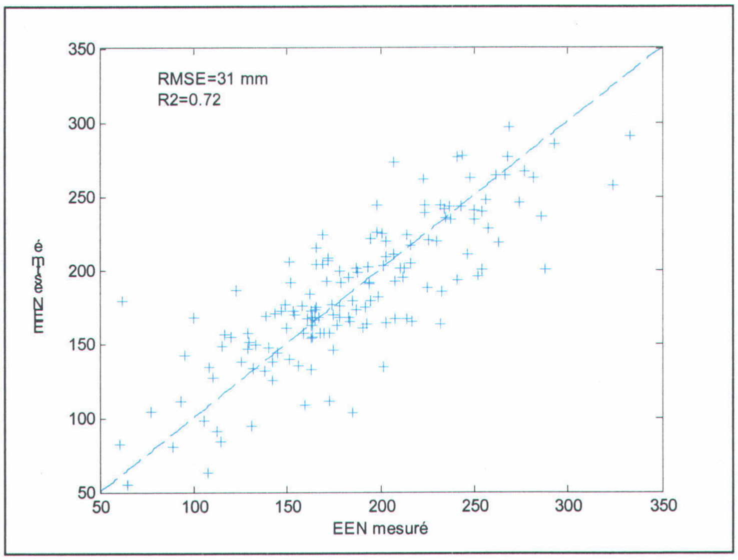


Figure 8 - Comparison of estimated and measured Snow Water Equivalent.

It can be stated that the direct interpolation of the SWE measured in the field (method applied to densities) allows to explain 72% of the variation of the SWE with an error of 31 mm. So the add on of the radar image allows a 6% gain of information and 2 mm in precision. The maps of the SWE established with the modified EQeau model show a continuous spatial distribution in contrast to the former version. They also show a spatial gradient from East to West with much higher SWE data in the Eastern sector.

From the results it can be concluded that the rigorousness of the image processing chain of RADARSAT data have been improved. The temporal variation of the radar signal during the winter is low but comparable from one data set to another. It was shown that the new approach for the spatial interpolation of the punctual snow densities measurements is reasonably efficient (R^2 = 0.83). The improvement of SWE map accuracy of 6% was achieved using ScanSAR data from RADARSAT-1

b) Contribution of SLF/WSL

The Swiss partner developed a distributed hydro-meteorological model (ALPINE3D) designed for alpine and sub-alpine environment. Its purpose is to be used as a snowmelt runoff prediction tool in alpine catchments. ALPINE3D is built up by a number of sub-modules that have been developed and tested extensively in earlier work (SNOWPACK (Lehning et al., 2002), a snow model developed at SLF originally for avalanche risk assessment; a vegetation model, adapted from Koivusalo and Kokkonen (2002); a radiation distribution model (Fierz et al., 2003); and the groundwater-runoff module of PREVAH (Gurtz et al., 1999)).

ALPINE3D has been tested against snow and run-off data from 2 watersheds where the SNOWPOWER sensor was installed. Figure 9 shows an example of simulated incoming shortwave radiation on a sunny day in January 2003 (12 p.m.) reflecting the great spatial variation due to topography realistically reproduced by the model.

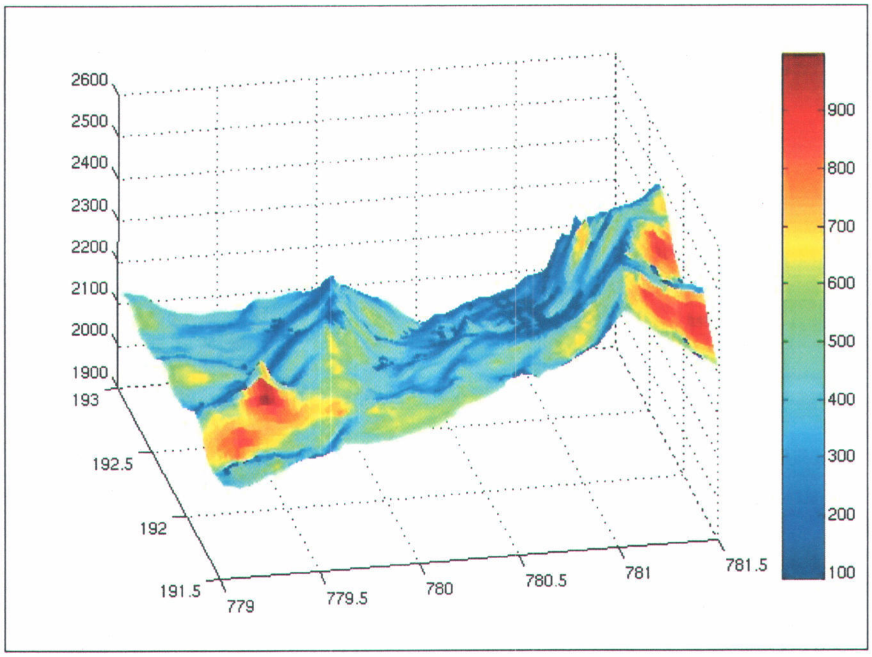


Figure 9 - Incoming shortwave radiation on the January 15, 2003 at 12 p.m.

A first approach for updating the simulated snow depth, or the SWE respectively, with actual snow measurements, such as data from the SNOWPOWER sensor, has been introduced into the model. This updating approach was tested for one winter season in a subalpine watershed in central Switzerland (Alptal). The test showed that the improvement of the SWE simulation strongly depended on the frequency of available measurements, as well on their location. With the (manual) snow measurements in the Alptal that were taken weekly at some places and monthly at others this updating of the SWE lead to a varying degree of improvement of the SWE simulation at various sites (Figure 10). Obviously, the method was quite rigid and produced an alteration of the snow cover that was somewhat overestimated. Overall, the coefficient of determination R^2 for SWE and snow depth at all 15 locations and all measurements was only increased from 0.80 to 0.81 in this case. However, with the SNOWPOWER sensor providing SWE at an hourly or daily basis, it can be expected that such an updating algorithm becomes more efficient.

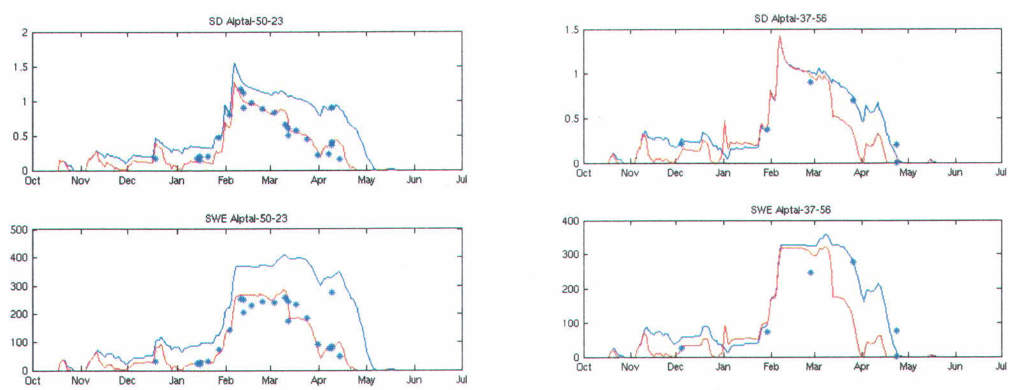


Figure 10 - Simulated (lines) and manually measured (dots) snow depth (top) and SWE (bottom) for two selected sites in the Alptal catchment: a site with weekly measurements (left) and a site with monthly measurements (right). The blue line shows the simulation without snow updating, and the red line represents a simulation with the updating routine.

2.2.5 WP 5 'Development of bench-scale instrument

This turned out to be the most critical and time consuming work package since several problems were encountered during the project.

At first the theoretical aspects of the technical realisation of measurements in the snow were assessed. To determine both density and water content of snow two electronic measurement techniques are necessary (Low-frequency Impedance Analysis and High frequency Time Domain Reflectometry Analysis). The system was designed to especially fulfil the requirements that are necessary when dealing with snow: wide range of temperature, low energy consumption and adequate for field use, i.e. easy and portable. The system consisted of the following modules shown in Figure 11.

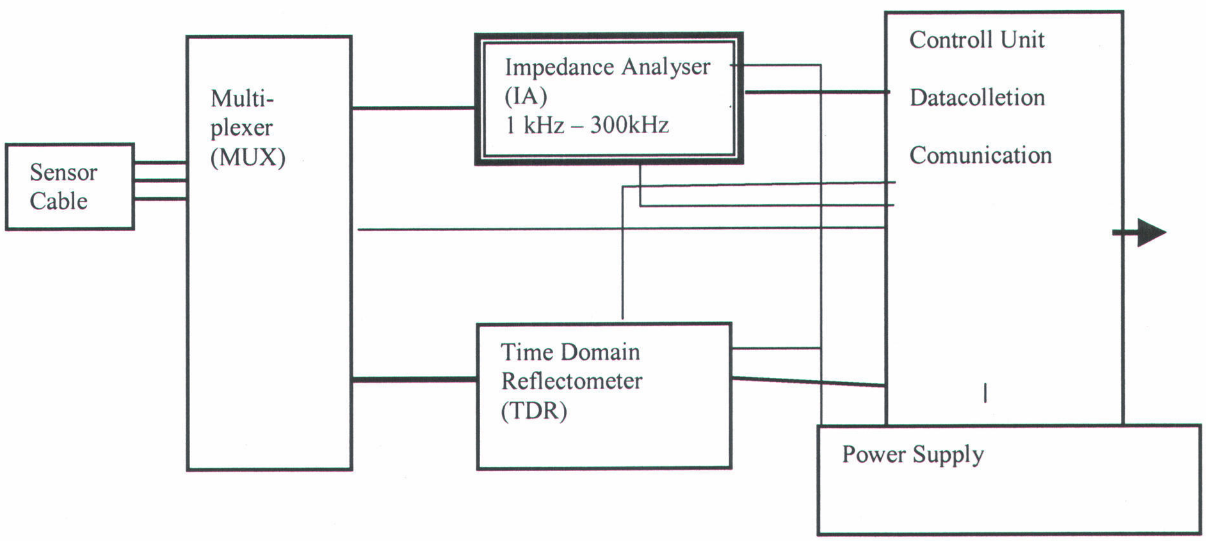


Figure 11 – Modules for the bench-scale instrument

Concerning the low-frequency Impedance-Analysis, the first step for the development of the entire measurement system was the start of the design and configuration of the low-frequency impedance analyser. The measurement frequency is adjustable by software command and is generated by the DDS-method (direct digital synthesis). This measurement frequency is transformed to a measurement bridge, which is connected to the sensor cable. In the control unit, the magnitude and phase of the resulting voltage in the bridge is evaluated, digitalised and calculated and displayed via an interface.
The technical specifications are as follows:

Power supply: 12 V dc
Operating temperature: - 40 °C +40°C
Measurement frequency: 1khz........300khz
Measurement range: 10 pF......4000 pF
Data display: Magnitude and phase of complex capacitance
Parameterization: Remote control of measurement program via serial interface.

A detailed sketch of the set-up for the Impedance analyser module is shown in Figure 12.

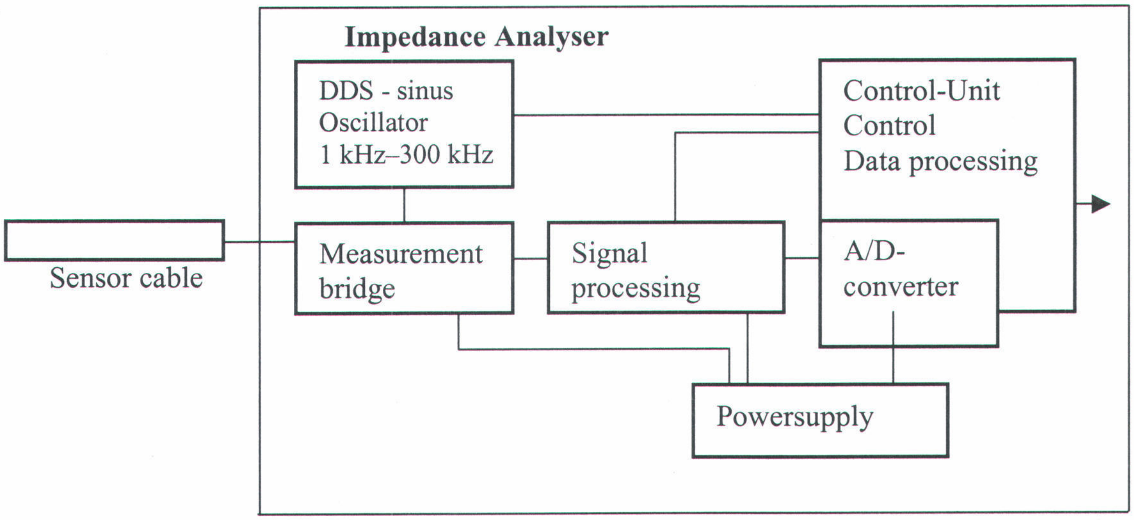


Figure 12 – Detailed sketch of impedance analyser module.

a.) Impedance analyser module

A test set up for experiments for the signal processing was conducted. Also experiments with the measurement bridge in relation to measurement object-frequency-measurement were carried out. The first laboratory test showed very good results concerning especially the capacitance measurements at the low frequency range between 1 and 50 kHz. Fig. 8 shows a comparison of the new IA and the HP 4192 for the capacitance measured depending on the frequency.

It was impossible to have the bench-scale instrument ready at the start of the second project winter (2002/2003), and also the plan to test the device at the Swiss test site during the melting season in May 2003 could not be realized. But it was possible to test the bench-scale instrument in a test field at SOM. Despite the promising laboratory results, the field tests revealed some serious influences of electromagnetic radiation. The following problems were encountered:

The long cable with its shape had the effect of a very powerful antenna, so that influences from terrestrial signals occurred. These signals were mainly electromagnetic radiation as for example radio waves. Unfortunately no shielding could be applied to the cables, as the influences of the environment are the objects of investigation. Further more despite the performance of a four-point measurement the influences of the high capacitance connection cables could not fully be eliminated.

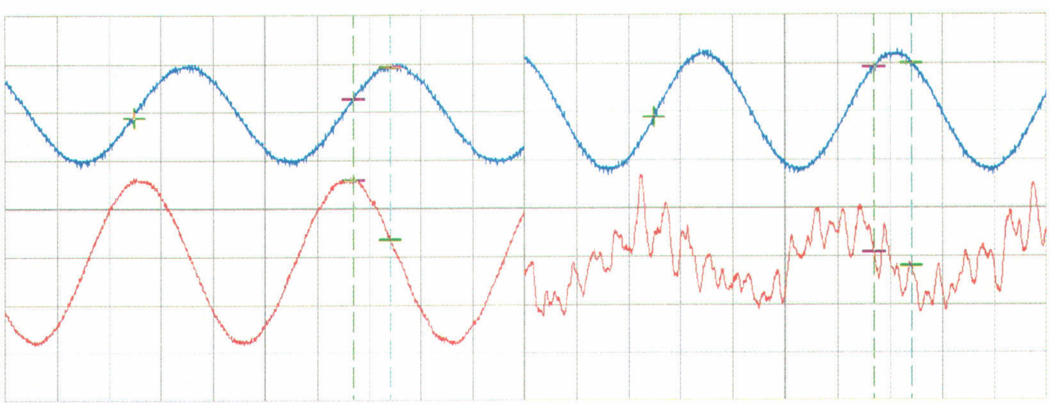


Figure 13 - Capacitor(left) versus flat-band cable (right). Blue: excitation, red: signal.

Figure 13 shows a comparison of the excitation and the detected signal for a perfect capacitor in the laboratory and for the flat-band cable sensor. The disturbances of the signal are clearly visible. In fact the peaks due to the disturbing influences could exceed the signal of interest. So an accurate measurement of the capacitance along a long cable in the field is not possible with this initial concept.

Therefore an improved concept for the IA had to be developed which included a number of changes in technology. At first a new input amplifier was implemented, which was less sensitive to long cables and their capacitances as they are high for the connection cables. The second and major change was the application of a powerful filter. The best filter specifications concerning the problem had a Quadratur Synchron Demodulator Filter that was eventually chosen. This filter is very narrow banded and allows a direct output of the complex values. Thirdly all the relays were replaced by analogue switches. And finally a more precise determination of voltage was installed.

The new concept had the advantages that it was less sensitive to the influences of the cable length. The input signal was extremely filtered and fully digital processed. Further more the instrument showed a better long term stability.
Yet there are to face a few drawbacks related with the setup such as a more complex structure, higher costs of the electronic components and an increase in the current consumption compared to the initial concept. Figure 14 shows the circuit board of the new IA.

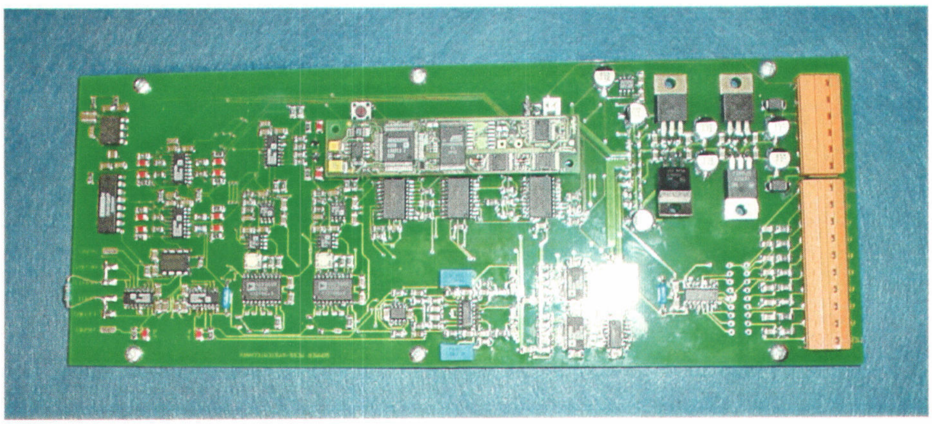


Figure 14 - Circuit board of improved IA

b.) Time Domain Reflectometry module

After detailed investigations of available TDR cable testers, a suitable TDR module was chosen and tested for application in the bench scale instrument. It was decided to use the *Campbell Scientific TDR 100* since it fulfilled the described requirements (power consumption, ruggedness, field compatibility, etc.). After suitable configuration of the module, it was also tested in the field.

c.) Multiplexing module

The BSI was finally equipped with a multiplexing module which allows the selection of 4 connected flat band cable sensors. Figure 15 shows the final design of the BSI with the different interfaces for the cable sensors, TDR module, modem and communication.

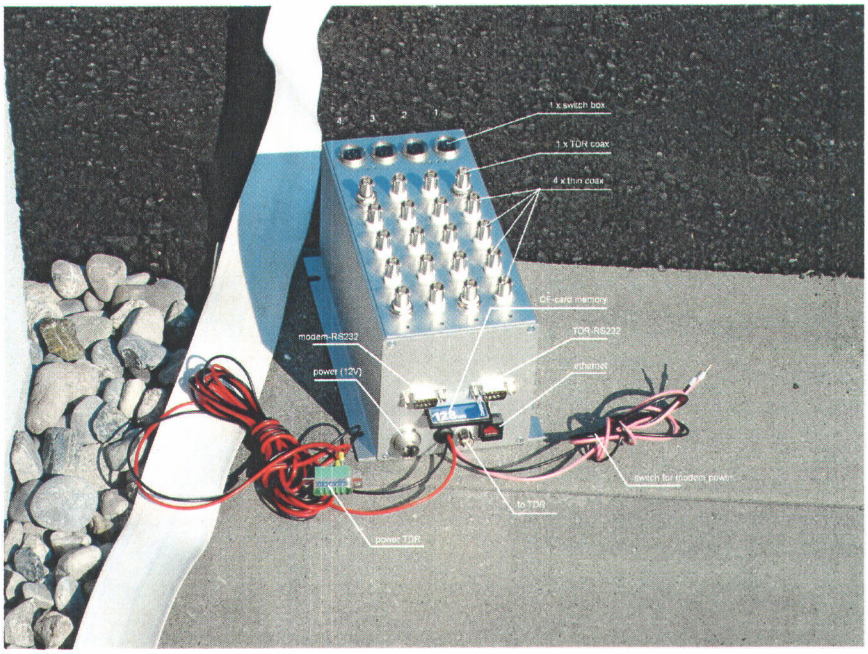


Figure 15 - BSI with IA-module, Multiplexer and option for TDR module connection

d.) Control Unit

The main component is an Embedded Web Module - 16-Bit CPU 80186 with 20 MHz. This control and communication unit supports TCP/IP, PPP, HTTP and FTP protocols. The measurement specific paramters are edited by browser access to *ini*-files. The data of every measurement is stored on a Compact Flash Card and if possible automatically send via FTP to a FTP-Server. The Compact Flash Card allows to archive the data of a few month and can easily be replaced for data collection, if no remote access is possible. Figure 16 shows the floating chart of the control and communication unit. With the BSI also 8 additional analogue inputs are available, e.g. for temperature measurements for air temperature and snow temperature profiles or for ultrasonic snow depth measurements.

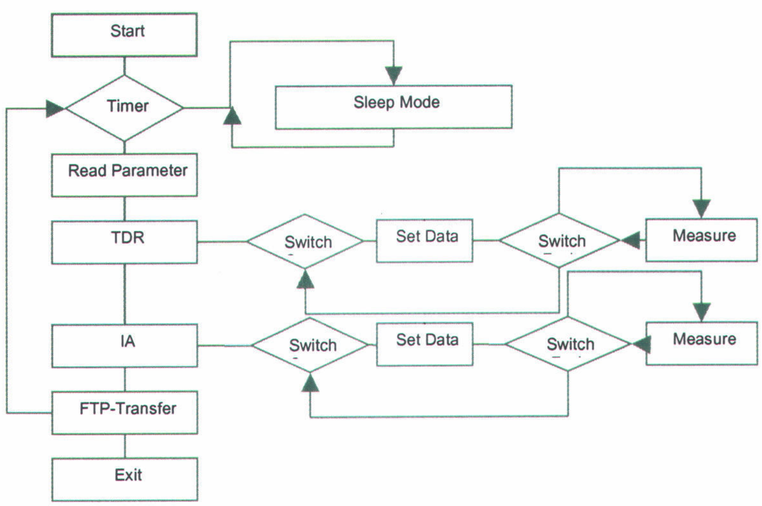


Figure 16 - Control unit - Measurement and Data storage

Finally the possible set-ups of the modules of the BSI (TDR, IA and multiplexing component (MUX)) in the field (illustrated in Figure 17) were discussed. It was decided to realize set-up 'C', which houses all the modules in one small box that can be installed close to the flat-band cable sensors. Thus only short lengths of coaxial cables (< 6m) are required which improves the signal quality, reduces signal losses and simplifies the calibration procedure of the system.

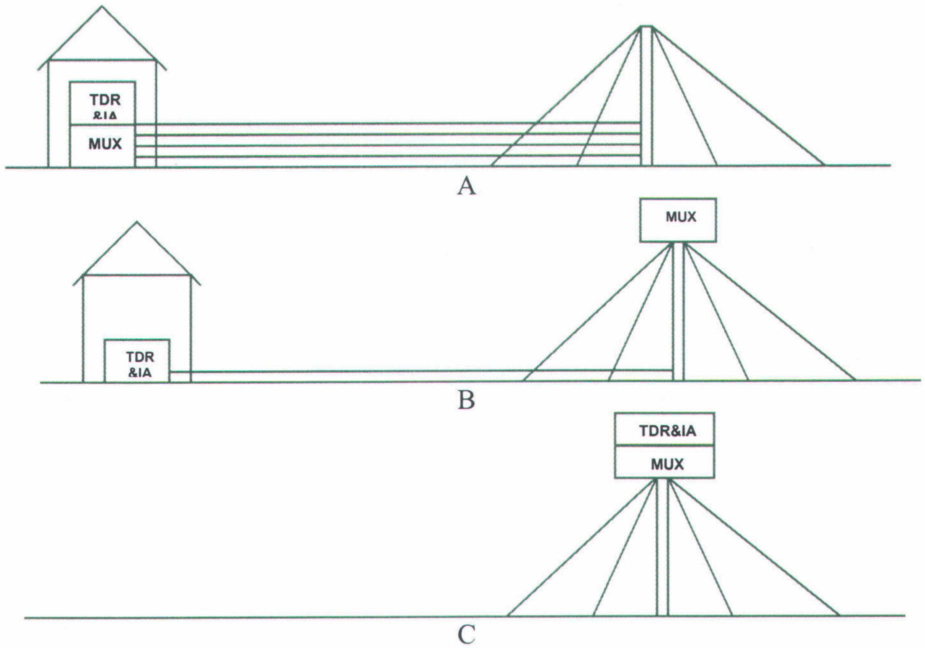


Figure 17 - Possible arrangements (A, B, C) of TDR, IA and MUX of BSI in the field.

2.2.6 WP 6 'Field test of bench scale instrument

In WP 6, the second field campaign, originally the test of the bench-scale instrument (BSI) was planned. Due to the delay of WP 5, the BSI was not ready for installation at the beginning of the second winter. Therefore WP 6 had to be run with the laboratory-scale instrument set up. Learning from the experiences and problems of the first field campaign, we extended WP 6 with very important field tests concerning the sensor installation in the field and the interactions of the sensor with the snow pack properties. A lot of valuable data were collected and the installation of cable sensors as well as the correct interpretation of the data could be significantly improved.
This WP was again carried out simultaneously at the Swiss and Canadian test sites.

a.) Swiss test sites (Davos and Alptal)

At the beginning of month 15 FZK and SLF/WSL set up an 8 m sloping flat band cable sensor at Weissfluhjoch/Davos (WFJ)-test site (CH) at an elevation of 2550 m for monitoring vertical variations in the snow properties in the run of the winter and to test a new installation method. To keep the band stable also during situations of heavy wind and massive snow load this time no poles were used but the cable was mounted with a steeper sloping angle and with a specially designed brake suspension. Three additional flat-band cables were laid out horizontally during winter and were covered by snowfall. An installation of a second sloping cable was carried out in April 2003 at Davos before the melting season with the aim of testing a different installation fixation and testing a new measurement algorithm which needs two sloping cables with different angles. Due to serious problems due to installation and disturbances of the measurements, the algorithm did not work and finally this approach was given up.
The system uptime was high also in the second winter (80%). The automatic start of the measurements occasionally failed at the interface between the controlling PC unit and the Tektronix. This happened mainly at very low temperatures, so this might be a temperature problem of the electronic components of the Tektronix device, which was not built to operate under such low temperatures.

During the test at WFJ we closely inspected the behaviour of the snow band cable and the electronic system under harsh alpine winter conditions. In particular, the following critical components of the system were examined:

- **Suspension and set-up of the sloping cable**

The original suspension, consisting of a wooden fastener attached with ropes to two iron springs, failed twice during the first winter: after a heavy wind storm in the second half of January, and towards the end of the winter season, when the snow load (maximum snow water equivalent: 740 mm) became too heavy and a spring broke. Consequently, an improved suspension was designed for the second winter consisting of a cylinder with a mechanical brake (Fig. 18), which kept a constant pressure on the cable. The suspension adjusted continuously when the snow load increased, by releasing the cable.

The sloping angle of the cable sensor is one of the key-factors for the formation of an air gap around the flat-band cable, as well as for the bending of the cable inside the snow pack.
In the first winter we set up the cable at an angle of 30° to the ground surface and tried to keep it in its original position by fixing it on 3 vertical poles. Such poles, however, proved to have negative impacts during the snowmelt by preferentially melting the snow and generating air gaps around the pole. Also a sharp bend of the cable formed at the head of the mid-pole after snow pack settling during the melting period (Fig. 19). In addition, the poles were not stable enough to withstand the heavy snow load and bent considerably towards the end of the season. Consequently, for the second winter we decided to set up the cable at a steeper angle (45°) and to omit the supporting poles. The steeper installation reduced the snow load on the cable, and the cable was kept in its original position during the whole winter. However, we noted increased flickering of the cable in moderate to high wind speeds in the absence of supporting poles. These movements of the cable most likely generated the large air gaps observed at the surface, and may have caused a cable failure during a snow storm in January 2003. A further complication was a 90° twist of the cable around its own axes, which may have increased the water flow along the cable (Fig 20). In the last winter season (2003/3004) the sensors where again mounted with springs and the cable was attached to guiding ropes all along to the ground.

Figure 18 - Suspension of the snow cable sensor for winter 2001/02 (left), winter 2002/03 (middle) and winter 2003/2004 (right).

This suspension has proven to be the most effective in ensuring good stability of the sensor under windy conditions, thus minimizing the formation of an air gap around the sensor. Following field experiments, a number of recommendations were identified for improving the quality of the coaxial cables used and for simplifying the design of the junction box between the sensor and the coaxial cables.

- **Air gap problem**

Air gaps along the flat-band cable are highly undesirable since they both falsify the electronic signal and may also transfer melting water preferentially along the cable. The influence of an air gap on the measurement results can be partially corrected with our correction method, but with respect to a potential preferential water transport along the cable it was crucial to thoroughly inspect the size of the air gap and evaluate its importance as water flow path.

At both sites the air gap showed up in different sizes and shapes, depending on wind speed, wind direction and melting intensity (Fig. 20). The assumption of a symmetric air gap, which is made in the correction algorithm, was not appropriate for many situations. There were dates (27 Feb, 2003; Alptal) where an up to 5 cm opening formed on one side of the band-cable, whereas the other side was in close contact with the snow. At the WFJ site the air gap was mostly generated by wind. Hence, the compass orientation of the flat band cable was decisive for the shape of the air gap. We also observed that air gaps were able to fill up again when the wind conditions had changed. Our overall conclusion was that the shape of the air gap at the snow surface was very dynamic and unpredictable. Inside the snow pack, we did not find evidence for significant voids around the cable when we excavated the flat-band cable at the sub-alpine site, Alptal, on March 1, 2003. This was at a stage when the snow pack had settled to a density of 290 kg m^{-3} and liquid melt water had penetrated to the bottom of the snow pack (Fig. 21).

Close inspection of the flat-band cable was also carried out to examine whether the snow-band had conducted melt-water preferentially during the snowmelt. A dye tracer had been applied 15 days earlier (prior to the snowmelt) on the snow surface (area indicated in Fig. 16). A vertical profile was excavated along the cable and perpendicularly at the lower end of the cable. No stained water was detected at the lower end of the cable whereas to the left and right of the cable end considerable stained areas were detected originating from lateral water transport along snow layers. There is evidence that some dye did follow the cable for some distance before finding alternative flow paths to the side of and below the cable, but we did not find indications of extensive lateral water flow expressed in terms of intensely stained areas following the direction of the cable. We think that we can conclude in general that water flow along the cable is not greater than the natural lateral water flow in the snow pack.

Concerning thermal effects of the sensor on the surrounding snow, we found some thermal radiation effects of a horizontal cable only once, shortly after it was laid out on the snow surface and the coverage by fallen snow was only very shallow. But as soon as the cable was covered with more than 10 cm of snow, this effect was not found anymore.

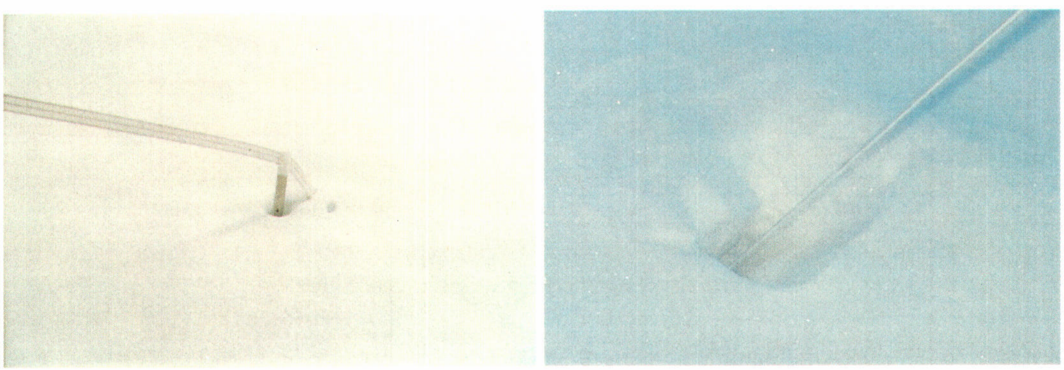


Figure 19 - (left) Preferential melting around the supporting poles and formation of a sharp bend at the head of the pole in winter 2001/02. (right) Large air gap at the air-snow-interface of the twisted sloping cable in winter 2002/03.

Alptal, 12-Feb, 2003 | Alptal, 27-Feb, 2003 | Weissfluhjoch 12-Jan, 2003 sensor 1 | Weissfluhjoch 12-Jan, 2003 sensor 2 | Weissfluhjoch 20-Feb, 2003

Figure 20 - Observations of air gaps at the snow surface in the vicinity of the snow cable sensor.

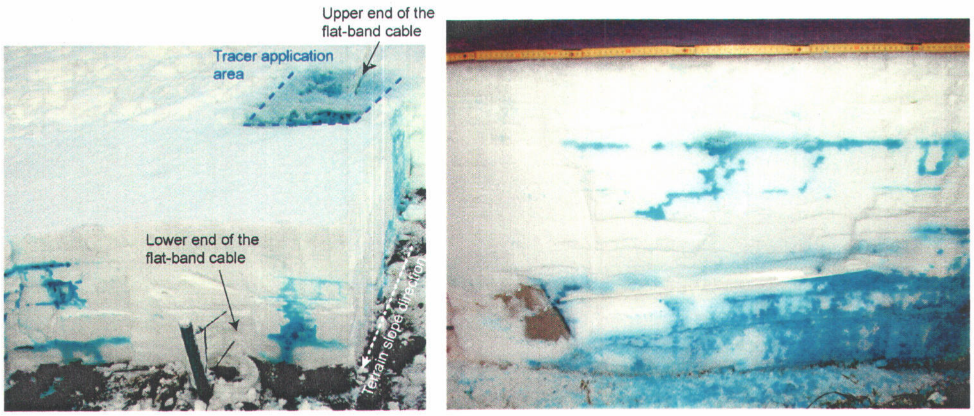


Figure 21 - Dye tracer indicating the water flow paths during a melt event at the Alptal-site. (left) Front view at the cable end showing no dye tracer in close vicinity of the cable. (right) Vertical cross-section along the flat-band cable. Terrain slope-direction is indicated.

- **Comparison of snow sensor measurements with manual measurements**

Dielectric constant, bulk snow density, and liquid water content of snow pack (mean value along the cable) were again calculated from the raw signals and the moisture distribution along one of the horizontal cables was reconstructed for different stages of the winter. The natural settling of the snow cover was reflected nicely in the horizontal cable measurements. The snow density increased from initially 100-200 kg m^{-3} to approximately 500 kg m^{-3} at the end of the winter season, which was in accordance with manual snow density measurements of the corresponding snow layers. The two cables located at two different depths of the snow pack also reproduced correctly a higher density in the lower part of the profile in February (cable 1) and a faster compaction in the upper part during the snowmelt (cable 2). However cable 2 seemed to have systematically underestimated density, which we think may be explained by spatial differences in the measurement spots of cable and manual density measurements.

No liquid water was detected with the horizontal cables until the end of April, after that the snow pack had reached its maximum depth. This is supported by the automated snow temperature measurements, which indicate dry snow conditions and temperatures well below zero before this period. Once the snowmelt set in, we measured the steadily increasing liquid water content with the horizontal cables indicating the downwards penetration of the wetting-front. The upper cable (no. 2) not only reflected an earlier and faster increase in liquid water content than the lower cable, it also reacted more clearly to the diurnal variation caused by melting during the day and refreezing during the night.

With regard to the spatial variation of liquid water, the horizontal flat-band cable nicely demonstrated the formation of preferential water flow paths adjacent to the cable, which is the natural process of water transport in a melting snow pack. The horizontal cable at about 1 m below the snow surface indicated in mid May an emerging water conducting zone at 14 m from the cable end, as well as a newly developing flow finger at 8 m from the cable end.

The measurement results yielded good correspondence of the snow pack density with manual reference measurements taken twice a month at the measurement site. Also, the determination of liquid water content from measurements of the dielectric constants according to Tiuri et al. (1984) gave plausible results, both compared to lysimeter data taken on the test field and with regard to the spatial variation of flow fingers that we normally experience in a natural snow pack.
We learned that the suspension of the cable sensors is a crucial point in the measurement. For successful measurements it is indispensable to reduce the following sources of error:

- Air gaps between cable sensor and surrounding snow must be minimized, although it is possible to correct for minor effects.
- The suspension of the cable sensors must allow the cable to settle with the snow pack, but at the same time must be robust enough to withstand heavy winds and snow loads.

b.) Canadian test site Quebec

Although not planned in WP 6, INRS and HQ made additional field tests in winter 2002/2003 to improve the installation method, to get experiences of the system in an additional but different snow pack and to study algorithms for relating non-polarimetric (RADARSAT-1) and polarimetric radar data (RADARSAT-2) with point measurements (i.e. snow density, SWE). Also the *EQeau* model was adapted to make use of the data from the cable sensor.

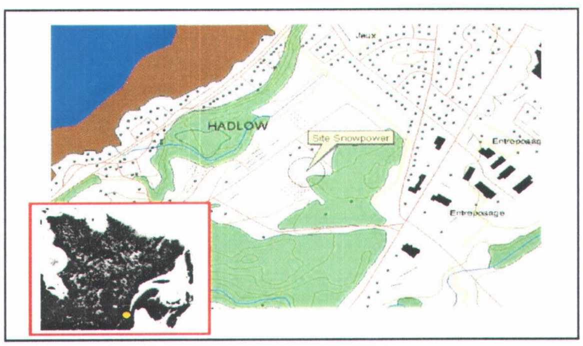


Figure 22 - Study site location

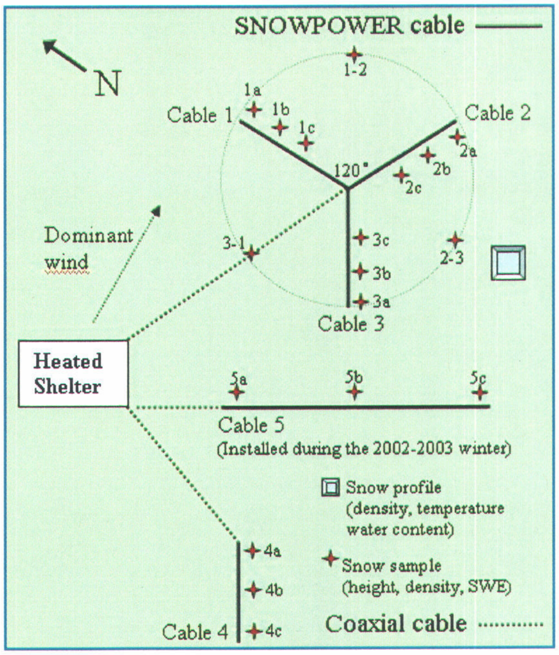
Again the Chapais Experimental Farm of Agriculture and Agri-food Canada was chosen as research site (Fig. 22). The field has a mostly flat surface with a slope of 0-0.5%. An automated weather station installed on the site records different meteorological parameters such as air, snow and soil temperatures, etc.

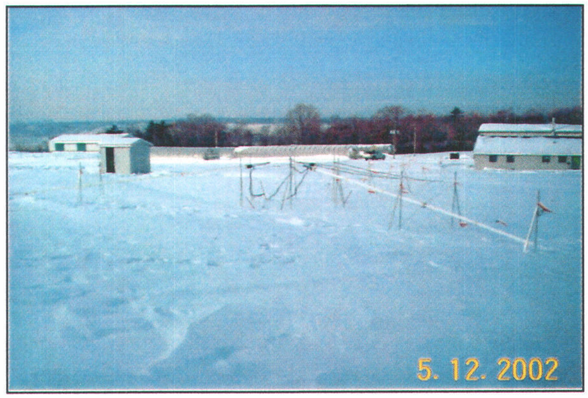
- **Installation design**

The physical installation of the sensor in Canada was developed around three objectives: (1) to test different support types and to find the most suitable one for this environment; (2) to acquire data on a larger surface for inputs into hydrological models and comparison with remote sensing images and (3) to get a diversified dataset in order to better validate the measurements.

Four 10 m flat band cables were installed at the experimental site in the fall of 2002. Four cables were tested. To obtain data on the larger area possible, a "star shaped" installation was designed, using three sloping cables starting from a central point, 1.5 m above the ground, oriented in opposite directions at

a 120° angle and ending to the ground level (Figure 23). The covered area was approximately 300 m². The other cable was installed horizontally (horizontal cable) at 25 cm above the ground.
Through 32 m coaxial cables, each sensor was hooked up to a multiplexer into a heated shelter (15°C). Each cable was sequentially selected for Time Domain Reflectometry (TDR) and impedance analyzer measurements, a computer controlled process.





	Type	Length	Installation	Height	Coax. length
Cable #1	Thick	10 m	Sloping	1.5 m to 0 m	30 m
Cable #2	Thick	10 m	Sloping	1.5 m to 0 m	30 m
Cable #3	Thin	10 m	Sloping	1.5 m to 0 m	30 m
Cable #4	Thin	10 m	Horizontal	15 cm	30 m
Cable #5	Thick	20 m	Horizontal	1 cm	10 m

Figure 23 - Sensor installation at the Canadian experimental site and sampling plan.

From December 18, 2002 to March 20, 2003, weekly measurements (high and low frequencies) were made. Throughout the season, concurrent field data have been acquired. Every week, 12 snow cores were collected to measure snow depth (cm), snow water equivalent (SWE, mm) and the mean snow pack density (kg m^{-3}) around the cables. A weekly snow profile was also done at the test site, 100m from the SNOWPOWER installations. The CROCUS model was therefore used to extrapolate temperature profiles at the cables, prior to the melting season. During the melting season, at the time of the measurements, another snow profile was done near the cables, giving the snow temperature, density and liquid water content at every 10 cm.

- **Results and discussion**

During winter season 2002-2003, no significant rain or melting event had happened, leaving the snow cover relatively dry from the beginning of January through mid-March (Figure 24). During that period, the diurnal air temperature stayed generally below the freezing point. On March 20, the melting period began with an increase of air temperatures steadily above zero, combined with significant rainfall events and no refreezing period until March 31. A rainfall event happened from late March 20 to the next morning. Despite all this incoming water, the wet front advance was limited to the top layers because of the low temperatures in the snow pack. So the underlying layers stayed relatively cold and dry on March 21. On March 26 and 27, the snow cover was completely in an isothermal state. Another rain event occurred. All snow layers show significant liquid water content (>3%). From March 31st through April 9th, the air temperature dropped back below 0°C and the snow pack refroze completely. After that, a cycle of diurnal melting followed.

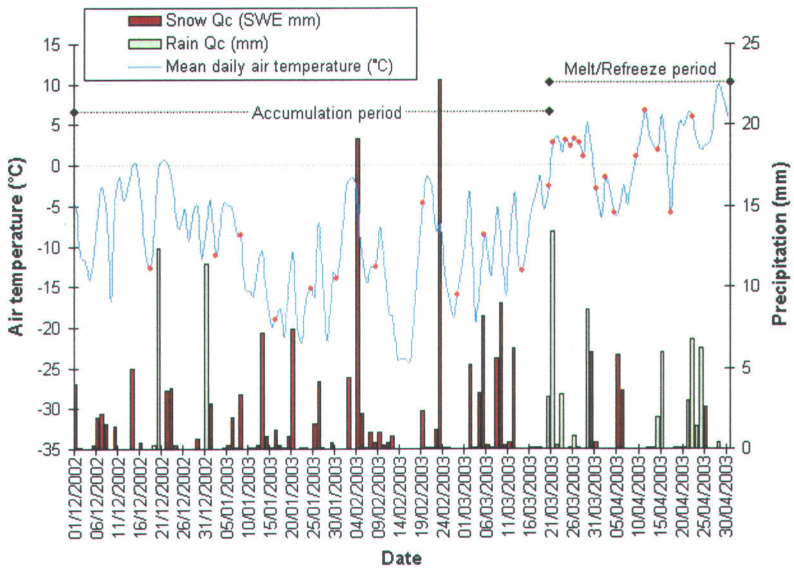


Figure 24 - Daily variations of air temperature and precipitation

- **Estimation of snow density**

Since the temperature has a major influence on the low-frequency dielectric constant of ice (temperature range –30ºC to 0ºC) (Schlaeger, 2003), the estimation of snow densities from SNOWPOWER must take snow temperature into account. For the period prior to March 20 (dry snow), we used simulated snow temperature profiles. Starting March 20, we used temperature profiles measured near the cable. For each date of acquisition, 2 to 4 repetitive SNOWPOWER measurements were made.

The first calculated snow parameter is the snow density. Figure 25 shows the comparison between field measurements and the densities simulated from the SNOWPOWER measurements. The number of repetitive SNOWPOWER measurements is indicated for each date. The densities were simulated using large and small spacing. The relative mean error is also shown. It does not take into account the very high simulated values of January 2 (icy rain event).

For the accumulation period, the relative mean error is between 10% and 20%. From January 25 to March 20, simulated values are generally underestimated. However, a significant ice layer present in the snow profile may have caused some overestimations of the field measurements. Another source of error could be the simulated snow profile that we use and how it is handled in *GetMoisture*. For the melting period, the mean relative error increases for large spacing. Simulated densities are even more generally underestimated, even if field measurements in the snow pit are more reliable. On occasions, the cables were still wet from previous rain events but it does not show on the results.

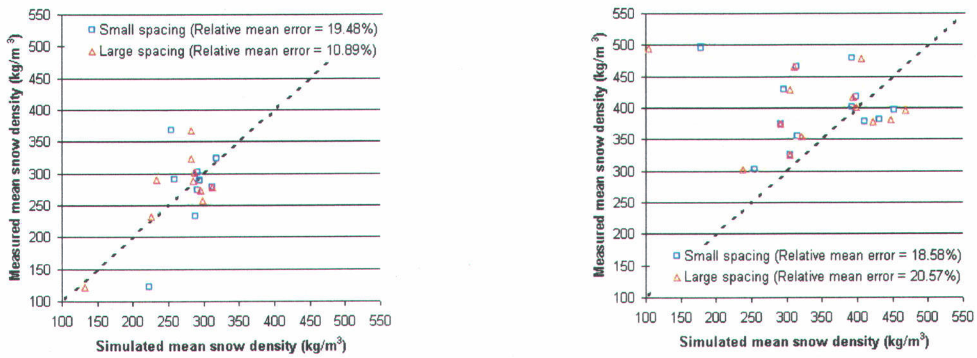


Figure 25 - Comparison between simulated density from SNOWPOWER measurements and the field measurements.

- **Snow liquid water content**

The snow water content was also calculated from the SNOWPOWER measurements at the cable, using the *GetMoisture* program. The water content, measured every 10 cm in the profile, was interpolated to obtain a mean value. Figure 26 shows the comparison between simulated snow water content from SNOWPOWER measurements and these field measurements.

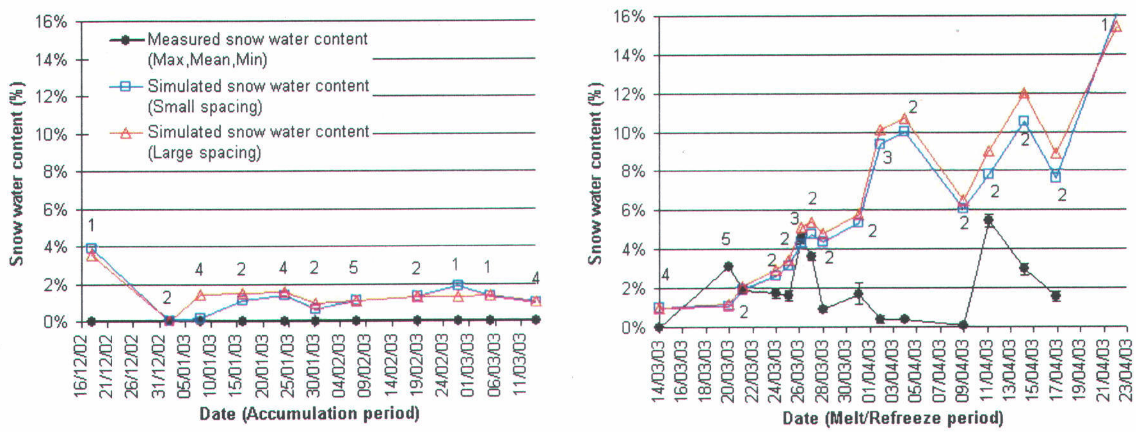


Figure 26 - Comparison between simulated snow water content from SNOWPOWER measurements and the field measurements

For the accumulation period, the low air temperature insures that there was no liquid water content in the snow. However, the SNOWPOWER calculated values are steadily around 1% or 2%. During the melting/refreezing period, the SNOWPOWER calculated values increase from 1% to over 10%, even when the snow cover refroze completely in the first week of April. Again, the rain events do not seem to affect the results.

- **Snow depth**

The SNOWPOWER probe can also be used to provide the snow depth. Combined with snow density, depth makes it possible to determine the Sow Water Equivalent (SWE) which is one of the most important parameter in snow hydrology. The snow depth can be given directly by the high frequency measurements from TDR. With the sloping cable installation, it is the product of the length of the cable covered by snow and the sine of the angle formed by the slopping cable and the normal. The length of the cable covered by snow is given by the transition zone, detected on the TDR trace. The *GetMoisture* program uses the tangents to the trace for this purpose. With the Chapais installation (Figure 27) we can easily determine the sine of the angle.

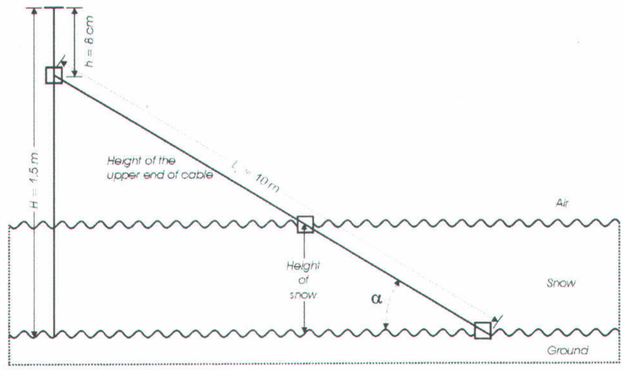


Figure 27 - Determination of the sine of the angle for sloping cables at the Chapais test site

Using the installation configuration we are able to calculate the snow depth with the following equations:

$$\sin\alpha = \frac{(H-h)}{L} \qquad d(x) = \sin\alpha . L_e(x)$$

with d(x) as the snow depth and $L_e(x)$ as the electromagnetic length of the buried portion of the cable.

The snow depth was calculated for the accumulation only, to avoid rain events. Figure 16 shows the comparison between simulated snow depths and measured snow depths at the entry point of cable.

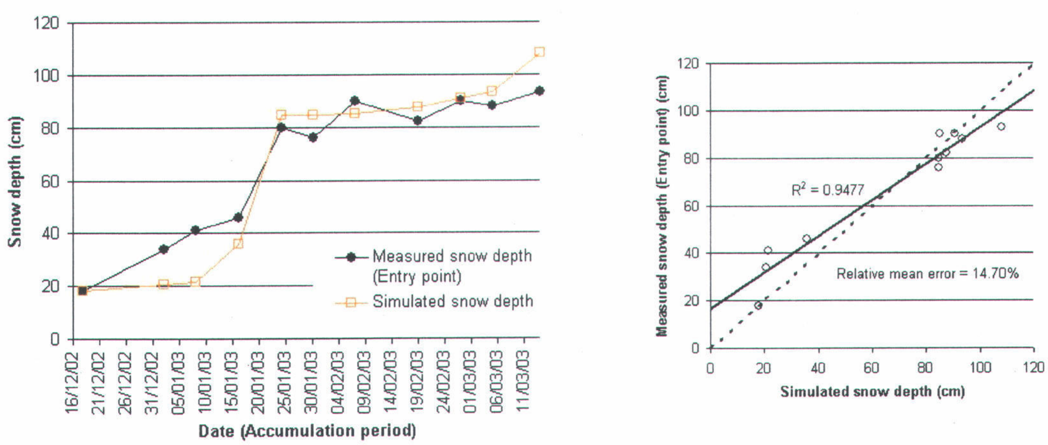


Figure 28 - Comparison between simulated snow depth and measured snow depth at cable #3 entry point

The simulated snow depth was in good agreements with field measurements especially for the end of the accumulation period. Difference at the beginning of January could be an aftermath of the icy rain. The overall mean relative error is at 15%. However, we get a good correlation coefficient of $R^2 = 0.95$.

- **Snow Water Equivalent (SWE)**

Using the simulated snow depth and snow density, we could calculate SWE using the following equation:

$$SWE = D * d(x) \qquad (3)$$

with D as the simulated snow density and d(x) is the simulated snow depth. Figure 29 shows comparison between calculated snow water equivalent and measured snow water equivalent.

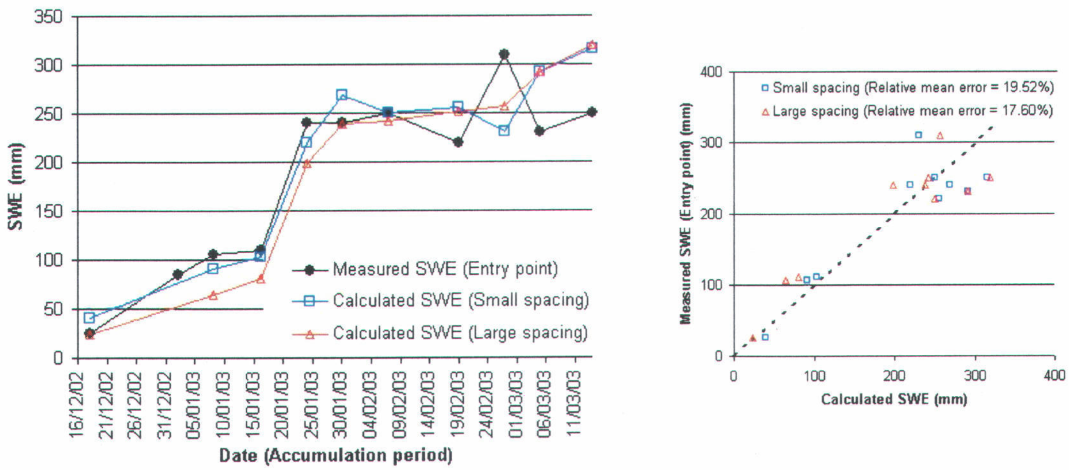


Figure 29 - Comparison between calculated snow water equivalent from SNOWPOWER measurements and the snow water equivalent at he sensor

Both small and large spacing showed good correlation with measured SWE equivalent at the cable. Good agreement at the beginning of the accumulation period results from underestimation of snow depth and overestimation of the snow density. Mean relative error stays between 15% and 20%.

2.2.7. WP 7 'Large-scale field test'

Originally planned as a large-scale field test, this work package had to be modified mainly due to the significant delay that was faced in WP 5. We extended this WP 7 with the field test of the BSI which could not be carried out in WP 6 due to delay and seasonal reasons and with important investigations on the influence of temperature and dielectric mixing rule coefficient. Therefore we again installed an additional sensor cable at the Swiss test site in Davos and a laboratory set-up at a Canadian test site near Quebec at the beginning of winter 2003/2004.

a.) Contribution of the European partners

At the end of project month 30, the first prototype of the BSI was available for installation at the Swiss test site. It was installed on March 31, 2004. Concerning the suspension of the sloping cable that was adopted from Hydro Quebec specifications, it can be concluded that it was a clear improvement compared with the earlier methods. However, although the cable seemed in proper shape and no superficial damage was visible (Fig. 30), we found out that one of the internal copper conductors was broken mainly due to the heavy snow load of the 2004 winter. Fortunately we could repair it and measurements with the BSI could be run immediately.

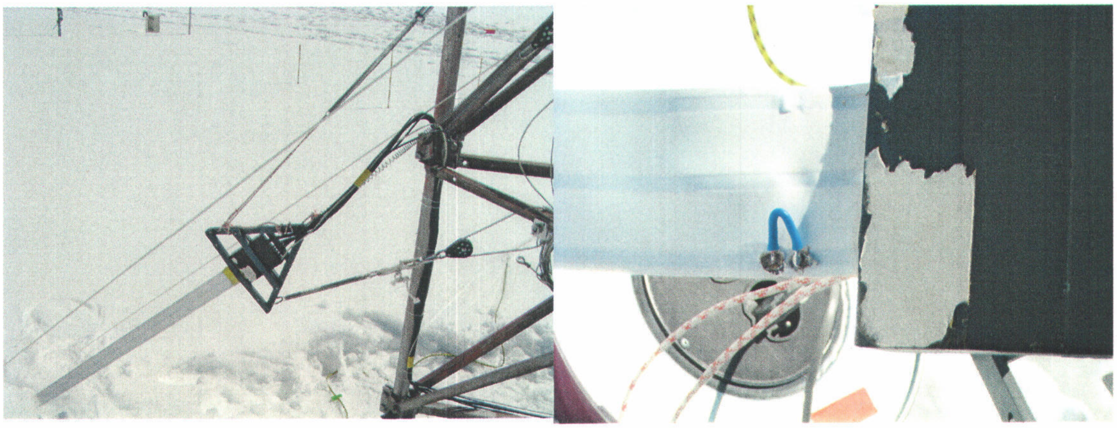


Figure 30 - Installed cable at Swiss test site and repair of broken conductor

Contrary to expectations, winter conditions at the Swiss test site prevailed until July 20. This allowed a complete test program of the BSI equipment and provided us with a data set over nearly 4 months. The first prototype of the BSI has been running from March 31, 2004 to its replacement on July 1, 2004. The second BSI prototype was equipped with an internal multiplexer allowing the networking of 4 sensor cables and with a TDR module for the high frequency measurements. Also, this complete system ran failure-free until the end of the measurements on July 20, 2004. It also could be demonstrated that the communication with the BSI and the data transfer via modem worked excellently.

The first results of capacitance measurements showed that the measured capacities made sense and were in accordance with the experiences of the laboratory devices from the previous years. At the end of the winter season, the system was dismounted and the data were evaluated. It turned out, that the measured capacities with the BSI were somewhat higher than with the laboratory devices from the previous seasons, but they were more stable and showed a better signal quality with lesser deviations. Since no adequate calibration of the BSI prototype was possible so far, the measured capacities were corrected by an offset for calculating the dielectric constants as well as the densities and the liquid water content of the snow pack, so that they could be compared to the data acquired with the laboratory test set-up. The determined dielectric constants for certain low frequencies were comparable to previous measurements with the laboratory test set-up, yet at the end of the winter, the values tend to be too high. Two reasons could explain this effect, one being the provisional rough calibration, the second being another preferential water flow along the cable at the end of the melting season. It also turned out that when only low frequency measurements are used it is quite difficult to detect the exact cable length in snow (due to installations with spring bearings). This could also contribute to the high values at the end of the season.

Figure 31 shows a comparison of the measured densities with manual reference measurements taken every fortnight. Also the snow depth is shown. It can be seen that the measured BSI densities correlate well with the reference measurements and also the decrease in the average density of the snow pack due to new snow fall is monitored perfectly. Only at the end, the values again tend to be too high, because of the same reasons as described in the previous paragraph.

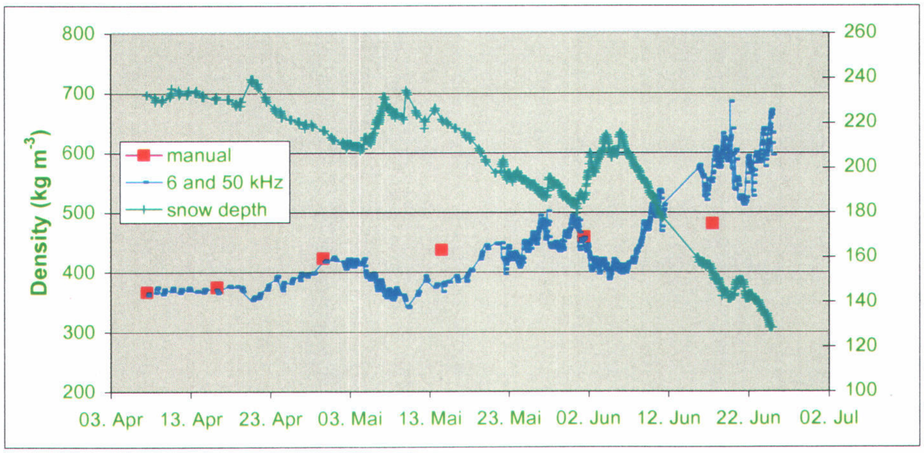


Figure 31 - Comparison of BSI density measurements (based on 6 and 50 kHz) with manual reference measurements together with snow depth measurements (in cm) at the Swiss test site.

The estimated liquid water contents during the test period are shown in Figure 32. Also, the registered accumulated outflow of liquid water at the lysimeter is shown. Although, there is a good correlation between the accumulated outflow and the shape of the curve of the liquid water contents, the absolute values for the water content are far too high, again as a result of the reasons described.

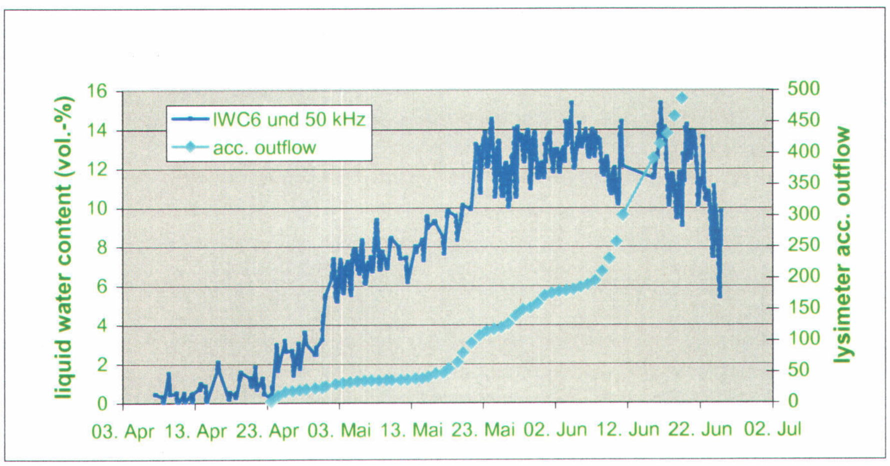


Figure 32 - Comparison of liquid water content measurements from the BSI prototype (based on 6 and 50 kHz) with accumulated outflow of the lysimeter at the Swiss test site.

As a conclusion of the first field test of the BSI it can be stated, that the system worked failure-free for nearly 4 months in the harsh Alpine environment and has the potential to become an operational tool for the determination of large-scale snow pack density, liquid water content and snow water equivalent. Yet some fine-tuning of the system is still necessary to obtain reliable absolute measurement values. Therefore an adequate calibration with materials comparable to snow is indispensable. Yet one must not underestimate the efforts for an adequate calibration, such as availability and homogeneity of the adequate materials and reliable reference values of dielectric properties (especially at low frequencies).

Further detailed analysis of the SNOWPOWER-sensor measurements at Weissfluhjoch/Davos were made. The frequency dependence of the impedance measurements (low frequencies), as well as the temperature influence on these results was investigated. Also, a method to calculate the spatial variation of liquid water content along horizontally installed SNOWPOWER cables at a certain depth in the snow pack from the high frequency data was developed at SLF using a simplified differential algorithm, as an alternative to the more computationally demanding inversion technique. Figure 33 shows the preferential flow patterns of the melt water that was detected with this new algorithm.

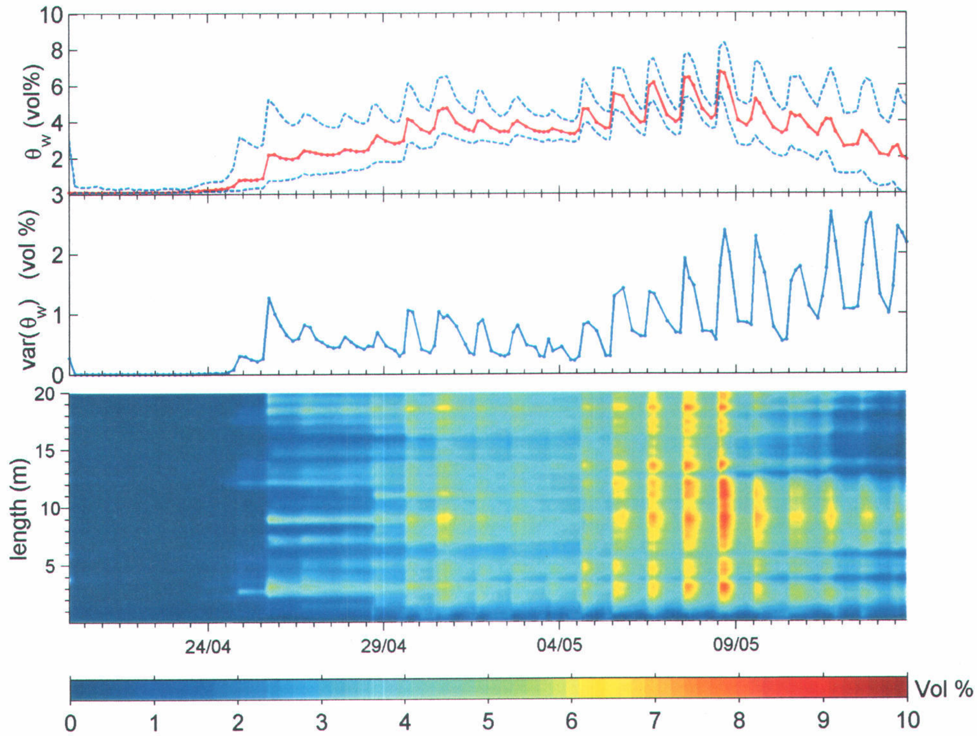
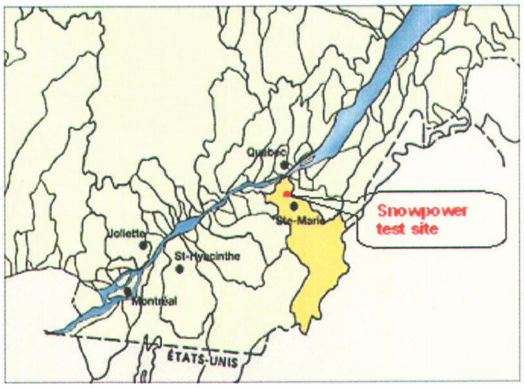


Figure 33 - Preferential flow patterns detected with the high frequency (TDR) measurements of the SNOWPOWER sensor.

Additional calculations concerning the electronic behaviour of the cable sensors were made at KTH. The series resistance, R, was calculated from analysis of the fields around the conductors. Typical values for the even mode are 0.5 ohm/m at 100 MHz and 1.2 ohm/m at 500 MHz. Hence, for longer cables (>10 m) the attenuation due to R should be compensated for in the reconstruction algorithm. Regarding unsolved pitfalls in the usage of the sensor cable, the problem with mode-scattering when the cable has an asymmetric surrounding medium has been investigated theoretically and experimentally. The results show that mode-scattering degrades the resolution of the reconstruction. Mode-scattering also makes the cable more sensitive to extraneous radiation, since the unwanted odd-mode is more receptive for radiation.

b.) Contribution of the Canadian partners

The second part of the modified WP 7 was the large-scale field test. Due to the delay and the unavailability of the BSI at the beginning of the Canadian winter season, the measurements were started with the laboratory test set-up in Southern Canada at a sub-watershed of the *Chaudière*-River, at 45 km south of Quebec city. The field site was equipped with numerous meteorological instruments. A picture of a map and the set-up cable is shown in Fig. 34.



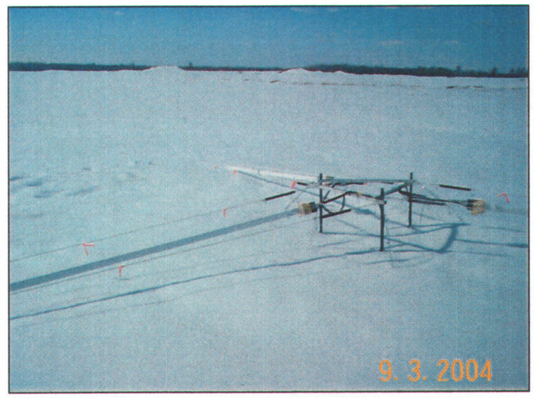


Figure 34 - Test-site localisation and SNOWPOWER cable installation at the agricultural field

A "star shaped" installation was chosen, using three sloping cables at an angle of 28° from the ground, starting from a central point (1.2 m above the ground). The electronic measurement devices of the system were placed in the shelter approximately 15 m away from the cable sensors.

The measurements started on February 17, 2004 and ran automatically until the end of the winter season (March 26, 2004). With the exception of some days, where a short circuit prevented the electronic measurement devices from running, the electronic system ran more or less failure-free throughout March 26. Snow cores were collected to measure snow depth (cm), SWE (mm) and the mean snow density (kg m^{-3}) around the flat-band cables. In the same time a snow profile, giving the snow temperature, density and snow liquid water content at every 10 cm, was also done. The Denoth Meter (Denoth 1989), Snow Density Sample and Dial Stem Thermometer were used for snow water content, snow density and snow temperature measurements.

During February 2004, no rain or melt had happened leaving the snow cover relatively dry. The air temperature stayed below the freezing point. The most snow accumulation had happened in this period. At the beginning March (1 and 2) the first rains occurred with an increase of the air temperatures steadily above zero. This period is followed immediately by a fall of the air temperature below 0°C and the snow then refroze completely. An intensive melting cycle began at March 26 with significant rainfall events and a significant increase of the air temperature. Due to the important wind speed (because the test site is located in an open area) and the frequent rainfall events, the snow pack stayed relatively compacted (density > 300kg/m^3) during the study period.

Unfortunately, the BSI was not available during the Canadian winter season and then the large-scale field test could not be carried out as planned. But nevertheless, important field tests and evaluations of the method concerning mainly the temperature influence and the dielectric properties of the cold seasonal snow pack in Canada could be carried out.

First, the influence of the variability of the temperature within the snow cover on the accuracy of the density determination was tested. As explained in previous reports the snow temperature has a considerable effect on the permittivity of ice ε_{ice} and then on the snow density and on snow water content determination. The mean value of snow temperature profile can provide a representative value in alpine conditions where the vertical variations are not significant. But, in cold seasonal and shallow snow pack as Canadian conditions these variations can be important (Table 4).

Table 4 - Snow depth, surface and air temperature, mean and standard deviation of snow temperature profiles for study dates around the flat-band cable.

Date	Depth (cm)	T(°C) Surface	T(°C) Air	Mean	St. Dev.
17-02-04	67,00	-10,00	-13,68	-10,22	6,61
24-02-04	82,00	-9,75	-12,00	-3,40	2,08
01-03-04	73,00	0,00	3,00	-3,07	1,29
03-03-04	70,00	0,00	1,00	0,00	0,00
05-03-04	71,50	-1,50	-1,50	-1,75	0,84
10-03-04	68,00	-1,50	-6,00	-2,88	1,89
16-03-04	68,50	-1,50	-7,00	-2,43	2,02
24-03-04	68,00	-3,00	-5,00	-2,94	0,98
26-03-04	62,00	0,00	5,00	-1,43	0,42

The temperature gradient in a snow pack depends on many factors including the temperature difference between the air and the soil, the snow density, and the thermal properties of the soil. These factors are varying spatially and temporally in northern conditions. One has to take into account that the temperature gradients generate a change in the snow structure (melting process, ice up process) which has a large influence to the snow density and to the snow liquid water content. That leads to develop new methods for temperature calculation in order to find a representative value. The following three assumptions were evaluated:

- Cable temperature calculated at the mid-point of the cable:
- Cable temperature calculated as a weighted average of all temperatures (linear interpolation)
- Cable temperature calculated at the at the weighted average of all temperatures (spline interpolation)

It was noticed that the average snow temperature calculated with the linear interpolation and that calculated with the cubic spline interpolation gives almost similar results (less than 0.5°C). That can be explained by the finesse of the resolution of temperature data (10 cm). Nevertheless, we found a slight difference at February 17 and at March 16 when the snow temperature profiles were very variable.
On March 3, the three methods give the same results because the snow pack was completely in an isothermal state. As expected, on February 24 when the snow accumulation is at maximal accumulation (Table 4), the average temperature calculated at the midpoint of cable over-estimates the temperature compared to the two others methods. Obviously the different results between these three methods are mainly dependent to the vertical variability of the temperature in the snow pack.

To see their impact on snow density and snow liquid water content, the results were compared with manual observations. In the same time we evaluated the influence of the exponent mixing-rule-factor (α) which can also have an effect on the results. Three values of α were tested: 0.3 (Looyenga 1968) and 0.3333 and 0.5 (Birchak 1974). All simulations were based on measurements taken at the 30 kHz frequencies and with the TDR. The air gap phenomena around the cable were not noticed during the study period, so that only results of the small connection are shown here. Figure 35 shows the simulated snow densities using the three methods of temperature calculation in comparison with manual observation for α=0.3. It can be seen that the two interpolation (cubic spline and linear) methods give the same results because their average cable temperatures are almost similar. Maximum differences between the two interpolation methods and the temperature at the midpoint of cable occur at February 24 (about 11 kg/m^3) and March 10 (about 10 kg/m^3). These differences are not significant compared to the temperature differences.

It was also noticed that the simulations results were not in agreement with the manual observations on February 24, March 10, and March 26. At February 24, the snow depth was at the maximal height (82 cm), and the air temperature was steadily under 0°C. The snow was dry and the snow–soil interface was covered by crust ice caused by water percolation. On March 10, due to the important preceding rainfall events, combined with a decrease of air temperature (Fig.4), the snow was dry and also very hard. Despite all this incoming water from preceding dates, the wet front advance was limited to the top layers because of the low temperatures in the snow pack. When the water percolates from the surface to the underlying and below zero snow layers, the water front advance tends to create both ice fingers and horizontal ice layer. So the underlying layers stayed relatively cold and dry on March 5 at night (0:00) and March 6 in spite of the rain. On March 26, the melting period was intensive and rain event occurred. All snow layers shown significant liquid water (>3%).

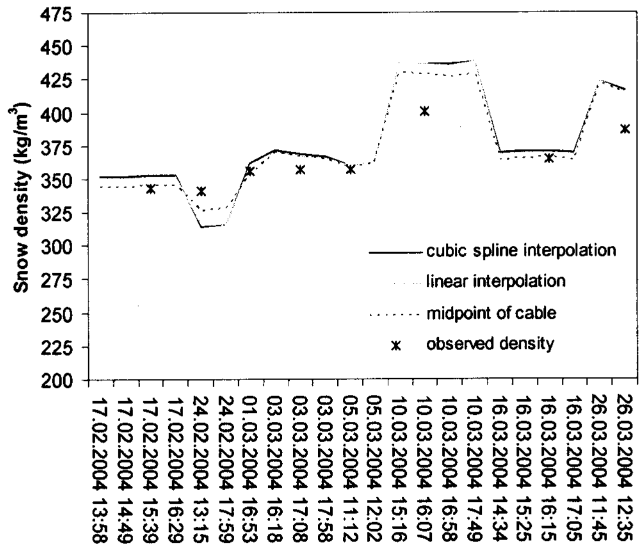


Figure 35 - Simulated snow densities using the three methods of temperature calculation and in comparison with manual observation. α=0.3.

Figure 36 presents the results of simulated snow water content in comparison with manual observation. Snow water content obtained by the *Denoth*-Meter (Denoth 1989) is well in agreement with the simulations results and the three methods of temperature calculation give the same results (about 0.02% of difference). One can see clearly the two periods when the snow was wet: 1) at March 3 where the snow pack was an isothermal state and it had rained one day before at March 2, and 2) at March 26 during the intensive melting period.

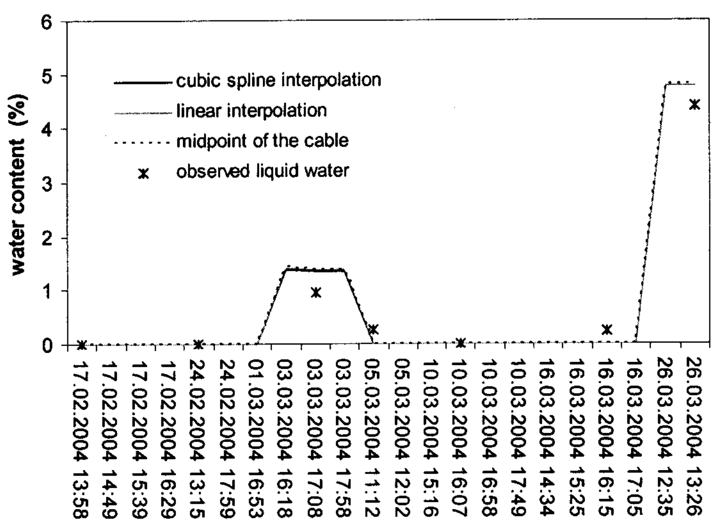


Figure 36 - Simulated snow water content using the three methods of temperature calculation and compared with manual observations. α=0.3.

Concerning the simulation results when the Looyenga's exponent mixing-rule-factor α was at the fourth order, they were well in agreement with the observed snow densities and snow liquid water content. The two methods of temperature interpolation (cubic spline and linear interpolation) gave the same results and seem to be the best methods. For the snow density, the mean relative error is 3.12% and the mean absolute error is 11.50 kg/m^3. If we select only the reliable field density measurements, the relative error became 0.70% and the absolute error 2.50 kg/m^3 only. For the snow liquid water content the mean relative error is 0.62% and the mean absolute error is 0.15%. When the Birchak's exponent mixing-rule-factor was used (0.5), snow densities were underestimated and snow liquid water contents overestimated.

It can be concluded that the integration of all available snow temperature measurements along the cable is the best method to provide a representative value of the cable temperature when strong variability in the temperature profiles are observed. Results show that the 30 kHz is the best low frequency to be used jointly with the 200 kHz or the TDR capacitance measurements for the determination of the snow density when the snow pack is dry. The best accuracy for snow density based on 30 kHz and TDR (alpha = 0.3333) shows a relative error of 2,75% or 10 kg/m^3 compared to snow profile data collected at the entry of the cable in the snow. When the snow is wet, the combination of 30 kHz and TDR measurements gives more accurate results than the combination of two low frequencies measurements. The mean relative error on the liquid water content then was 0.54%.

2.2.8 Dissemination

In addition to the dissemination activities made since the beginning of the project and discussed under the management aspects in the previous progress reports, the WP 8 was begun in the current period. This involves attempts to estimate the potential market for the Snowpower-System. In addition to existing contacts with the Norwegian companies *Statkraft* and *Sintef*, additional contacts were established with the Norwegian company *Sensortekknik.*

As described in the TIP systematic information and marketing actions are planned, in order to reach potential users in the EU, principally in the countries with the highest proportion of hydroelectric power, namely Austria, Sweden, Italy, France, and Germany. During the summer period, contacts were established with *Carlo Gavazzi Space (CGS),* an Italian remote sensing company in view of future integration of data from the SNOWPOWER System with other data collection systems, such as satellite, aircraft etc. Also contacts were established with the University of Innsbruck –Avalanche section and with the *Centre d'Etude des Neige of Meteo-France.*

Similar dissemination actions are planned for associated states in Norway and Switzerland. These activities are described in more detail in the TIP.

Additional contacts have been established with Chile and Hydro-Quebec is planning information and marketing activities in Canada. These activities will be described in greater detail in the TIP.

2.3. Assessment of Results and Conclusions

The results of the project are described according to the work packages carried out.

In WP 1 the development and laboratory production of the snow moisture and density sensor was carried out, which represents the first milestone. The work included the development of an air gap correction algorithm and a snow profile reconstruction code. It was confirmed that concerning the accuracy of the measurement system in laboratory that there is not more than 2% uncertainty in the volumetric water content for air gap sized less than 2mm.

Thus the functioning of the sensor met the criteria of accuracy and the algorithm for the air gap correction and the reconstruction code could be integrated thus reducing the uncertainty in the water content calculation

In WP 2 the measurement accuracy especially in case of air gaps and inhomogeneous snow profiles was assessed. The performance of the reconstruction code under various disturbing conditions was evaluated. The laboratory experiments again confirmed a sufficient accuracy of the measurement system.

In WP 3 the technical prototype system was tested in the field and the results were compared to point sensor reference measurements. The measurement algorithms were improved and refined with these real data of snow properties (dry and wet snow). The field campaign proved the suitability of the snow sensor system. Comparison with other measurement methods confirmed the measurement accuracy in the field again with not more than 2% uncertainty in the volumetric water content for air gap sized less than 2 mm, which was the second milestone.
Some experiences in this field campaign revealed new questions concerning the installation of the sensors and their interactions with snow during settling and melting processes. To clarify these questions, some additional experiments had to be carried out which was carried out in the second field campaign of WP 6.

In WP 4 the existing hydrological models of the partners and the corresponding forecast strategies for hydro power optimisation were developed and enhanced. Mainly the measurement results of the field campaigns were the input for the models and comparisons. It has been demonstrated that the extended hydrological models of the project together with the ground and RADARSAT data significantly improved the water reservoir filling prediction. The RADARSAT data were combined with the ground data (snow core measurements). The backscattering signals of the radar sensor were correlated with the snow properties at the sensor test sites resulting in an improved backscattering model. It was found, that the temporal variation of the average backscatter coefficient during the winter is about 1 dB, which is in the order of the radiometric accuracy. However, the pattern is constant from one winter to another. The backscattering coefficients are the lowest in November and increases in winter. Major improvements were achieved concerning the determination of the snow density. The new algorithm developed in the project uses both multiple regressions (altitude and latitude) and spatial interpolation (inverse distance). The random mean square error (RMSE) could be minimized to 23 kg/m^3 (former RMSE 37 kg/m^3) and a regression coefficient R^2 of 0.83 could be achieved.
Based on these results at representative locations maps of snow properties were produced for all the La Grande watershed (800 km x 300 km) in Canada. With this new algorithm integrated in the EQeau software, it is possible to explain 78% of the variation of the Snow Water Equivalent (SWE) of the snow pack with an error of 29 mm compared to 39 mm of the former model. It can also be stated that the direct spatialisation of SWE alone (same method applied to densities) allows to explain 72% of the variation of the SWE with an error of 31 mm. So the add on of the radar images only allows a 6% gain of information and 2 mm in precision.

In WP 5 the bench-scale instrument (BSI) including a sensor network was developed. An impedance analyser for the low-frequency measurements was designed, manufactured and tested. A commercially TDR-module for the high frequency measurements was also tested and was integrated in the bench-scale instrument (BSI). Options for an integration of the system into a data acquisition network by remote data transmission were developed also. This WP 5 turned out to be much more work intensive than planned. Due to problems with electromagnetic interference the original design of the impedance analyser had to be revised and updated, which led to a considerable delay. But finally the milestone was met and a weather-proof bench-scale instrumentation with accuracy comparable to the laboratory equipment was manufactured.

WP 6 was started earlier than planned due to seasonal reasons. Although at the beginning of this WP 6 the bench-scale instrument was not available, the measurements were started with the existing technical prototype field system. Due to some new questions that originated from experiences of the first field campaign, mainly concerning the proper installation of the cable sensors and the interaction

of the cables with the snow, WP 6 was extended to investigate these points. Some important experiments on the interaction of the sensor and the snow pack were carried out at a second Swiss test-site near Zurich. These experiments were completed by tracer experiments and the melt water flow around the cable was assessed. Similar experiments were carried out at the Davos test-site. Also a second field test was carried out in Canada with a set-up identical to the tests in Switzerland. The results revealed that the preferential water flow around the cable and the development of air gaps are low and neglectable, if the sensors are installed according to the installation guide which was established based on the experiences of the precedent field experiments. It also turned out that the differences in snow pack characteristics (moisture, density, etc.) between Alpine (Swiss) and cold seasonal (Canadian) snow packs must be taken into account.
The test of the BSI, which was planned for this WP 6 was completely shifted to WP 7.

WP 7 was originally planned as a large-scale field test in Canada. Due to the delay of the BSI and the BSI field test which could not be carried out in WP 6, this WP 7 had to be modified. The field test of the BSI was carried out in Switzerland during spring 2004. The BSI was extensively tested during a four months campaign in Switzerland and fulfilled all of the qualities expected including reliability, resistance to extreme weather conditions and dependable transmission of data. The system turned out to be good for operational use. Facility and usability of data compared with manual measurements. Substantial cost savings and payback on investment within one season appear to be possible. The system met all performance requirements, but requires some refinement of calibration procedures. Another result concerns quality of data measured with the new system: more representative compared to point measurements, simultaneous measurements of density and liquid water content of a snow pack. Automatic data acquisition as well as transmission to a central control point is also possible. Furthermore the system allows non-destructive measurements. Another advantage is online monitoring as well as continuous measurements.
Since the BSI was not available for the third winter field campaign in Canada, The tests were carried out again with the laboratory set-up. Further experiments showed that it is very important to consider the temperature of the snow pack and correct the measurements for this effect. A suitable correction and temperature measurement mode was established. Also the effect of the dielectric mixing rules on the measurement accuracy was investigated and permitted to enhance the accuracy.
As a conclusion of the testing at a small catchment in Canada it has been shown that the expected improvements in reservoir filling predictions are obtained with the SNOWPOWER method.

In WP 8 the exploitation and dissemination activities were assessed and started. As a general assessment and potential financial benefits associated with SNOWPOWER, at Hydro-Québec in Canada currently some 350 to 400 series of snow profiles are conducted on average each winter. The number of snow profiles varies from year to year. Early in winter, snow profiles are conducted monthly. The frequency is increased toward spring time as a function of the evolution of the melting season and our confidence in the information available.
Costs of snow profiles vary from site to site: helicopter costs for northern isolated site and personnel costs. On the average, one could estimate the cost of a snow profiles to 2K CAN$, for a total each year of some 750K CAN$. One has to consider that the current information on SWE arising from snow measurements is lacking accuracy. At the best it is suspected, out of field tests conducted in March of 2002, that the margin of error is running close to 10%. A snow profile transect of for example 10 points would at best provide an estimate of the SWE over a region with a margin of error of 10%. To estimate this error we compared results of snow profiles to a population of 233 measurements over a 15 km corridor. INRS-ETE compared snow pit data to actual snow profiles data. The existence of a systematic bias was identified, data from snow profiles are under-estimated when compared to snow pit data. The importance of this under-estimation is also variable. An increase in accuracy would result in more accurate forecast of the spring runoff and the amount of water available to the production facilities. The value of a gain in accuracy is difficult to assess with precision since it varies according to market conditions, climatological contexts, uses made of the information, magnitude of the gain in accuracy over conventional snow profiles and models used to simulate the benefits. Nevertheless, according to various evaluations, HQ estimates that they could confidently expect economic gains in excess of one million CAN$ annually.

2.4. Acknowledgements

We take this opportunity to thank the personnel of the consortium members for their contributions and their dedicated efforts which contributed to the success of the project. In particular we thank the personnel of SLF, INRS and HQ who were not directly involved in the project for their contribution in servicing of the field test sites, collecting of reference data and other activities which also substantially contributed to the projects success.

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Part 3: Management Final Report
Confidential

3.1. List of deliverables

Deliverable No	Deliverable title	Delivery planned	Delivery issued	Nature*
1	Sensor for use with laboratory instruments	6	3	Eq
2	Air gap correction algorithm and code	5	5	O
3	Snow profile reconstruction algorithm and code	5	9	O
4	Laboratory test set-up	5	4	Eq
5	Measurement accuracy assessment report for air gaps, inhomogeneous profiles	9	9	Re
6	Improved air gap and snow profile reconstruction codes	9	9	O
7	Sensor system for field use with laboratory instruments	9	5	Eq
8	Data set of field campaign (sensor measurements, point measurements, weather conditions, snow conditions)	12	11	Da
9	Evaluation report of the measurement results	12	12	Re
10	Installation guide for the sensor system	12	26	Re
11	Refined measurement algorithms and codes	12	17	O
12	Extended hydrological model which uses the data available from the snow sensor	27	36	Me
13	Algorithm for combining ground truth with RADARSAT data	30	36	Me
14	Model for predicting water reservoir filling based on the data available from the snow sensor	30	36	Me
15	Data set of predicted and actual water reservoir filling levels for the field campaign in Canada	36	36	Da
16	Bench-scale instrument with detailed description	18	30	Eq
17	Data set of field campaigns in Switzerland	27	35	Da
18	Evaluation report of bench-scale instrument	27	35	Re
19	Comprehensive data set for a catchment in Canada (ground and RADARSAT data)	36	n.a.	Da
20	Report on suitability of the sensor network for operational use	36	n.a.	Re

n.a. not achieved in the dimensions planned. Further tests in a field campaign in winter 2004/2005 are necessary to complete these two deliverables.

3.2. Comparison of initially planned activities and work actually accomplished.

WP 1, 3 and 4 were conducted according to plan.
There were some minor delays in WP 2 mainly due to personnel shortage, but these could be resolved shortly thereafter.

WP 5 was considerably delayed due to unforeseen electrical interference problems in combination with climatic conditions. However the objectives of the WP were achieved. But the delay had effects on WP 6 and 7, which therefore had to be modified. The field test of the BSI was shifted from WP6 to WP 7 due to the delay and climatic conditions. But the information was obtained by field tests with laboratory devices in Switzerland and Canada and led to design improvements in BSI and the installation of the sensor as well as important information on the interaction of the sensor with the snow pack, which contributed to an increase in the accuracy of the measurements.

The large-scale of WP 7 could also not be carried out as planned in Canada because of early melting. Nevertheless a smaller scale catchment test was carried out with the laboratory set-up and yielded sufficient data for the purpose of the WP. The extensive trials of the BSI which where carried out in Switzerland confirmed the reliability and the resistance to extreme cliamte conditions, as well as the proper functioning of data collection and transmission.

The dissemination work of WP8 was carried out throughout the duration by publication of articles in technical and scientific journals by presentation at international conferences and by information displayed on the internet site.

Concerning exploitation discussions took place with potential users in Austria, Switzerland, Norway and Chile. After the conclusion of the project, these contacts will be further pursued by the partners, who may negotiate sub-licenses.

HQ, the largest potential user in North America intends to pursue further tests and envisages the installations of a number of systems in the future.

3.3. Management and co-ordination aspects

The performance of the consortium was in the main excellent. The partners were working with great enthusiasm and motivation. At one point the project was slightly delayed by personnel shortages at KTH, but this was resolved by additional effort and minor subcontracting at FZK.

In general the work plan was respected and fulfilled according to schedule as explained above.

Other minor delays were occasioned by climatic condtions, but the dedication and flexibility of the consortium members assured the achievement of project objectives in spite of such difficulties.

Concerning deliverables all but two were completed. Deliverable 15 and 20 could not be carried out as the BSI was only available after the melting had begun in Canada, but equivalent trials in Switzerland confirmed the suitability for operational use.

The interest of the partners is such that this work will be carried out during the coming winter by INRS, SLF and SOM.

The established contacts will last throughout the end of the project. Another winter field period is envisaged after the conclusion of the project with more detailed tests on the bench-scale instrument both in Switzerland and Canada.

Every partner organized at least one project meeting. These meetings were held at least 6 months, with work package meetings among the involved partners as needed. The organisation of each meeting was perfect. This is valid also for the field tests, which required detailed logistics and big efforts especially in the harsh environment of Alpine and Canadian winter seasons.

The communication between partners was generally assured by email, as well as on the project internet site, which is also available to the public. However confidential information is not available on the site.

In addition individual problems which arose were discussed by telefon, which in most cases resulted in rapid decisions to resolve the situation.

The contacts formed in the course of the project will result in future contacts and cooperation among the partners and a number of interesting ideas have been evoked which in some cases may lead to continuing research or future projects.

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4. Glossary

AAFC: Agriculture and Agri-food Canada
AGU: American Geophysical Union
BSI: Bench-Scale Instrument
C: capacitance
EGU: European Union of Geoscience
FD: Frequency Domain technique,
G: conductivity
GetMoisture: evaluation software for measurement data
GHz: Gigahertz,
HP 4192: Impedance analyser by Hewlett-Packard
HYDROTEL, EQeau, CROCUS, COUP, SNOWPACK, Alpine3D: different existing hydrological models
IA: Impedance analyser
MHz: Megahertz,
MUX: Multiplexing device
PE: Polyethylene
Permittivity: dielectric constant (ε)
RADARSAT-1: Canadian radar satellite launched in 1995
SAR: synthetic aperture radar,
SWE : Snow water equivalent (depth of water that would cover ground if snow pack was liquid)
TEM: Transversal electromagnetic
TDR: Time Domain Reflectometry, model Tektronix 1502B
TWh: Tera Watt hour
WFJ: Weissfluhjoch (measurement site at Davos)