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Continuous-time monitoring of liquid water content in snowpacks using capacitance probes: A preliminary feasibility study

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ABSTRACT

Liquid water in snowpacks rules wet snow avalanche formation, surface albedo and snowmelt runoff timing. By now, volumetric liquid water content (LWC) measurements are collected mainly with destructive methods, while continuous-time and non-invasive measurements would be preferable to track its time dynamics. Here, we assess the feasibility of continuous-time monitoring of LWC using EnviroSMART® capacitance sensors. These were conceived to track liquid water dynamics in soils, and their use in snow is evaluated here for the first time, as far as we know. A field case study was settled up in April 2013 within an Italian Alpine valley. An instrumental set up with eight capacitance sensors was installed. Two time-domain reflectometers were added to the aim of comparison. To assist in interpreting the signal of the capacitance sensors, two laboratory tests were run, and a FEM model was implemented. This preliminary study demonstrates that capacitance sensors are sensitive to increasing LWC, although their long-term installation in snow entails the development of an air gap around them, due to localized melting, air turbulence and solar radiation absorption, which hinders following LWC variations. As a result, capacitance sensors readings are challenging to be interpreted quantitatively. Perspectives on future investigation are discussed to bring the proposed procedure towards long-term applications in snowpacks.

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1. Introduction

The volumetric liquid water content of a snowpack (LWC, or θ) is defined as the ratio V_w/V of the volume occupied by liquid water (V_w) within a control domain V [10]. The distribution of liquid water within the snowpack influences (1) wet snow avalanche formation [3,20,21,36,57,58]; (2) the timing of snowmelt runoff [10,21]; (3) the surface albedo of a snowpack [13]. Continuous-time measurement of LWC dynamics is useful for many engineering purposes, such as civil and environmental protection, reservoir management, or interpretation of remote sensing imaging.

Liquid water in snow is originated by rain and melting [52], and its flow in the porous domain is rarely uniform. Rain-on-snow events contribute to LWC dynamics by direct infiltration of liquid water in the snowpack and, usually, by increasing snow density [33,53,59]. Frequently, infiltration occurs with the set up of isolated flow fingers [22,42], and it develops as an overlap of a matrix, homogeneous flow, and a preferential one [56], affected by the presence of snow fingers, ice layers and topographic irregularities. Point measurements of LWC provide local information about the wetness of snowpack [52]. Nonetheless, spatial and temporal resolution of the measurements are key issues in evaluating LWC dynamics for environmental applications.

A first group of methods to measure LWC is based on hand tests [15], centrifugal separation [5,27] or melting, freezing and alcohol calorimetry [16,18,21,23,60]. These methods are destructive and require direct manipulation of snow samples [52]. This makes them time-consuming to perform, and causes abundant uncertainties in the determination of LWC (as already pointed out by [9,28,51]). As a result, their usefulness in continuous-time monitoring applications is very limited.

An alternative to these approaches is given by electro-magnetic methods. They all infer LWC from the different values of the dielectric constants of the constituents of snow [51,52]. These methods include: (1) Time-domain-reflectometry-based instruments (TDR), which measure the return time of a multi-frequency voltage step transmitted through snow, and relate it to LWC thanks to the dependence of wave propagation velocity on the dielectric properties of the medium [26,31,41,43,48,50,51,54]. An industrial example of this type of instruments is the Finnish Snow Fork [54]; (2) capacitance instruments, which include the investigated

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medium as the dielectric part of the capacitor in an inductor-capacitor (*LC*) circuit, the resonant frequency of which depends on the dielectric properties of the medium [6,11,12,30,49]. An example of this type of instrument is the Denoth Meter; (3) Ground-Penetrating Radar (GPR), which generates an electromagnetic signal and measures the reflected wavefield, to determine a LWC map in the investigated region [4,19,32,35,40].

Electro-magnetic methods need less measuring efforts than calorimetry, centrifugal separation or hand tests. Nevertheless, because of the different thermal properties and the higher specific densities of the instruments with respect to snow [43], they are usually installed only for instantaneous, destructive and point measurements. All previous instruments of this type require the excavation of a snow-pit, to reach the chosen depth of investigation, and the positioning of the instrument on the sample surface (Denoth meter) or inside the medium (Snow Fork). As a result, no practical solution is available to run automatic, continuous-time and non-invasive measurements of the LWC, which could be of great usefulness, especially in monitoring LWC dynamics in seasonally inaccessible areas.

Here, we focus on testing the feasibility of continuous-time and automatic monitoring of LWC by means of a series of capacitance probes mounted on a support, which can be driven into the snowpack once for all. These probes have been widely used in soils [24,25,37,39,44], but, to our knowledge, they are used in snowpack for the first time. An experimental set-up was installed as a case study during April 2013, nearby the Cancano Dam, within Fraele Valley (Lombardy region, northern Italy), at an elevation of 1980 m a.s.l. To compare with the readings of these sensors, two TDR instruments were installed at the site at the beginning of the test. In addition, to try to better interpret the signal of the sensors, two laboratory tests were run, in which a snow sample was compacted around a sensor (and its access tube), and a Finite Element Method (FEM) model was formulated.

The work is organized as follows: in Section 2, methods are discussed, by introducing the instruments, and the tests. In Section 3, field results are shown and discussed by means of both FEM simulations and laboratory data. In Section 4, conclusions are given, and suggestions for further work are discussed.

2. Theoretical background and methods

2.1. Snow as a dielectric material

When dealing with a mixture, i.e. a medium composed by different constituents, such as snow [38], its dielectric properties (usually measured in the form of permittivity, or dielectric constant, ε_r, as a relative quantity with respect to the permittivity of air) are a function of the dielectric properties of its constituents [47]. The permittivity of a mixture is usually estimated through a mixture law, i.e. a formula which relates the permittivity of the mixture to the volumetric fractions of the constituents, and their dielectric constants. Permittivity is usually expressed as a complex number, with the real part $\varepsilon'_r(f)$, and the imaginary part $\varepsilon''_r(f)$, accounting for the effects of relaxation and conductivity on dielectric properties. We define the loss tangent as $\tan\delta(f) = \varepsilon''_r/\varepsilon'_r$.

The permittivity of air ($\varepsilon_{r,a}$) is $\sim$1, with $\tan\delta_a = 0\ \forall f$ [17,34,48]. The permittivity of water ($\varepsilon_{r,w}$), its real part $\varepsilon'_{r,w}$, its imaginary part $\varepsilon''_{r,w}$ and the loss tangent $\tan\delta_w$ are functions of the frequency of the field. The same can be said for ice [34], with the permittivity indicated with $\varepsilon_{r,i}$, the real part with $\varepsilon'_{r,i}$, the imaginary part with $\varepsilon''_{r,i}$ and the loss tangent with $\tan\delta_i$.

In the range between 1 MHz and 10 GHz, $\varepsilon'_{r,w} \sim 86$, with $\tan\delta_w \to 0$ [17,34,48]. In the same range, $\varepsilon'_{r,i} \sim 3.19$ [17], with $\tan\delta_i \to 0$. This range includes the operating frequencies of capacitance probes, hence representing the range of interest in our applications. This implies that $\varepsilon_{r,w} \sim \varepsilon'_{r,w}$, and $\varepsilon_{r,i} \sim \varepsilon'_{r,i}$ [51].

The permittivity of dry snow ($\varepsilon_{r,D}$) is a function of the volumetric fractions of ice and air. In the range between 1 MHz and 10 GHz, $\varepsilon_{r,D} \sim \varepsilon'_{r,D}$. Given the density of dry snow, ρ_D , and $\Phi = \rho_D/\rho_i$, where ρ_i is the density of pure ice (917 kg/m^3), $\varepsilon'_{r,D}$ can be expressed by [17,29]:

$$\varepsilon'_{r,D} = \left[\Phi(\varepsilon'^{1/3}_{r,i} - 1) + 1\right]^3 \sim \varepsilon_{r,D} \tag{1}$$

This relation (structure independent, and for spherical inclusions [17,29,46]) has proven to give a satisfactory estimation of the dielectric constant of dry snow, when compared to experimental data [17].

Liquid water increases the dielectric properties of snow. In general, the dielectric constant of wet snow ($\varepsilon_{r,s}$) can be expressed as the sum of $\varepsilon_{r,D}$ and a correction factor, $\delta\varepsilon$, which is a function of θ [17]. Here, according to [17] who proved its good performances, we adopt Looyenga's mixture law for wet snow:

$$\varepsilon'_{r,s} = \left[\varepsilon'^{1/3}_{r,D} + \theta\left(\varepsilon'^{1/3}_{r,w} - 1\right)\right]^3 \sim \varepsilon_{r,s} \tag{2}$$

Given that $\varepsilon_{r,s} \sim \varepsilon'_{r,s}$, we can use Eq. (2) to evaluate the dielectric constant of wet snow from the real part of the same dielectric constant [14,34].

2.2. Capacitance sensors

The EnviroSMART® capacitance sensors consist of two brass rings (external diameter equal to 50.5 mm, height equal to 25 mm), mounted on a PVC support guide. In Fig. 1, two pictures of an ENVIROsmart® capacitance sensor are reported. The PVC guide, with a number of sensors at the chosen distances, is inserted inside a PVC access tube (external diameter of 56.5 mm, thickness equal to 2.8 mm), which can be driven in the medium under investigation. Each PVC support can accommodate up to 16 different sensors, allowing to infer LWC at different spatial resolutions.

The brass rings are the plates of a *LC* circuit capacitor. The resonant frequency of the circuit, F_r, is linked to *L* and *C* according to the following formula:

$$F_r = \left[2\pi\sqrt{LC}\right]^{-1} \tag{3}$$

The rings operate as capacitor plates, a portion of the surrounding medium being the dielectric between them. The inductance *L* is placed inside the PVC body of each sensor. The capacitance part,

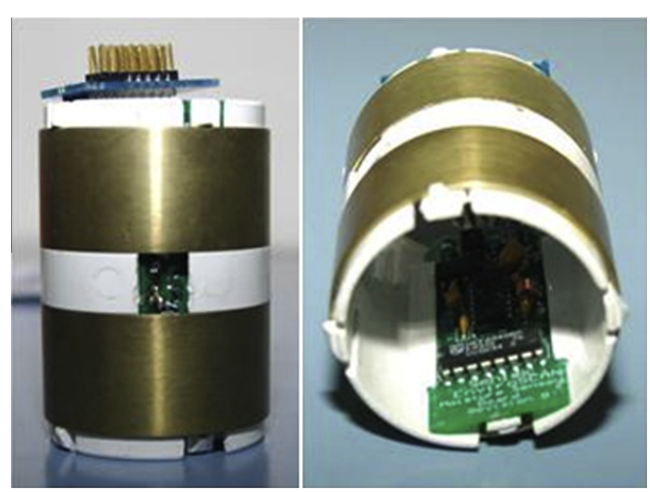

Fig. 1. Pictures of an ENVIROsmart® capacitance sensor (height equal to 74 mm, diameter equal to 50.5 mm).

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