ARTICLE IN PRESS
RSE-09717; No of Pages 15

Remote Sensing of Environment xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Snow density and ground permittivity retrieved from L-band radiometry: Application to experimental data

Juha Lemmetyinen [a,*], Mike Schwank [b,c], Kimmo Rautiainen [a], Anna Kontu [a], Tiina Parkkinen [a], Christian Mätzler [c], Andreas Wiesmann [c], Urs Wegmüller [c], Chris Derksen [d], Peter Toose [d], Alexandre Roy [e], Jouni Pulliainen [a]

[a] Finnish Meteorological Institute, FI-00101 Helsinki, Finland
[b] Swiss Federal Research Institute WSL, CH-8903 Birmensdorf, Switzerland
[c] Gamma Remote Sensing AG, CH-3073 Gümligen, Switzerland
[d] Environment Canada, M3H 5T4 Toronto, Ontario, Canada
[e] Université de Sherbrooke, J1K 2R1 Sherbrooke, Québec, Canada

ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form 13 January 2016
Accepted 2 February 2016
Available online xxxx

Keywords:
Microwave radiometry
Retrieval
Snow density
Ground permittivity
SMOS
SMAP

ABSTRACT

The potential of retrieving the bottom layer snow density and soil permittivity under dry snow cover conditions from L-band passive microwave observations was analyzed using multi-angular brightness temperatures measured at horizontal and vertical polarization over two test sites in northern Finland. The near-continuous time series of L-band brightness temperatures covers a total of six winter seasons, over both dry mineral soil in a forest clearing, and organic soil over a wetland site. Detailed measurements of snow and soil conditions are available from both sites. Complementing a previous theoretical study, we show that dry snow cover influences the observed L-band brightness temperatures as a result of both impedance matching and changes in the refraction angle at the snow–soil interface. Exploiting these effects, we demonstrate the retrieval of the bottom layer snow density and the influence of dry snow cover on simultaneously retrieved soil permittivity — a consideration which is currently not accounted for in Soil Moisture and Ocean Salinity (SMOS) retrievals of soil permittivity in the presence of dry snow. Depending on season, the mean bias error between retrieved and in situ snow density measured in the lower snow layers was between -6 kg m^{-3} and 15 kg m^{-3} for the forest clearing site, and between 37 kg m^{-3} and 90 kg m^{-3} for the wetland site, demonstrating the feasibility of the retrieval approach at the plot scale. In winter conditions, the ground permittivity retrieved without considering the impact of dry snow on L-band emission was, on average, 35% lower for both test sites, which indicates possible errors in current SMOS ground permittivity retrievals under dry snow conditions. The application of SMOS data to simultaneously retrieve dry snow density and ground permittivity is a complex task due to heterogeneous land cover and snow/soil conditions within SMOS pixels ($\approx$45 km resolution). An approach that considers land cover variations and the spatial variability of snow cover is required to fully determine the feasibility of the methodology to aid e.g. improving estimates snow water equivalent from other sensors, and to take into account effects of dry snow in SMOS-based retrievals of ground permittivities. The results should also be applicable to other L-band sensors in space, such as the recently launched NASA Soil Moisture Active Passive (SMAP) mission.

1. Introduction

Components of the terrestrial cryosphere, including seasonal snow cover and soil freeze/thaw (F/T) state play a key role for hydrological, climatological, and ecological processes in northern latitudes. For example, changes in the seasonal cycle of soil-snow states have a major impact on the annual carbon balance (Melaas et al., 2013; Xu et al., 2013; Schuur et al., 2015) and vegetation growth (Kim, Kimball, Zhang, & McDonald, 2012), while snow cover, influences the large scale energy budget through albedo feedbacks (Fletcher, Zhao, Kushner, & Fernandes, 2012), controls insulation of the soil (Gouttevin et al., 2012) and contributes to river runoff in large areas of the Northern hemisphere (Barnett, Adam, & Lettenmaier, 2005). Observing elements of the terrestrial cryosphere using remote sensing is an appealing option, in particular due to the typically sparse in situ observation networks available in Arctic and sub-Arctic regions, including the northern boreal forest zone.

A method for estimating snow water equivalent (SWE) using an assimilation scheme combining passive microwave observations with in situ measurements of snow depth was introduced by Pulliainen (2006). The method applies satellite measurements of brightness

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.rse.2016.02.002
0034-4257/© 2016 Elsevier Inc. All rights reserved.

Please cite this article as: Lemmetyinen, J., et al., Snow density and ground permittivity retrieved from L-band radiometry: Application to experimental data, *Remote Sensing of Environment* (2016), http://dx.doi.org/10.1016/j.rse.2016.02.002

temperatures at Ku and Ka bands ($\approx$19 and $\approx$37 GHz) in an iterative inversion of the Helsinki University of Technology (HUT) snow emission model (Pulliainen et al., 1999). The implementation of the algorithm in an operational context within the ESA GlobSnow project is described by Takala et al. (2011). The GlobSnow SWE retrieval algorithm assumes spatially and temporally constant values for air-, snow- and vegetation temperatures, snow density, soil surface roughness and soil permittivity (Takala et al., 2011; Lemmetyinen et al., 2015). The consideration of the spatio-temporal dynamics of snow density and ground permittivity through independent satellite retrievals could improve the retrieval of SWE.

The SMOS (Soil Moisture and Ocean Salinity) mission, the second in a series of Earth Explorer Opportunity missions by the European Space Agency (ESA), was launched in November 2009 (Kerr et al., 2010). Originally designed to provide global information on near-surface soil moisture and ocean salinity, the SMOS application range was expanded recently to the observation of a number of state variables relevant for the cryosphere, including the detection of thin sea-ice (Kaleschke, Tian-Kunze, Maaß, Mäkynen, & Drusch, 2012) and the monitoring of soil F/T processes (Rautiainen et al., 2012, 2014). Retrievals of landscape F/T state is also a goal of the National Aeronautics and Space Administration (NASA) SMAP (Soil Moisture Active Passive) mission (Entekhabi et al., 2010), launched in January 2015.

Recent theoretical and model-based analyses (Schwank et al., 2014; Schwank et al., 2015) indicated the distinct sensitivity of L-band microwave emission with respect to dry snow. While causing virtually no scattering and very low absorption at L-band, dry snow cover affects brightness temperatures observed from above the snow surface through impedance matching and refraction near the snow–soil interface. Impedance matching by dry snow reduces dielectric gradients and consequently increases thermal emission of the scene. This is because in a typical case, the permittivity of snow ($1 < \varepsilon_S < 2$ for snow density $0 < \rho_S < 500$ kg m^{-3}) is lower than the permittivity of fully frozen ground ($\varepsilon_G \approx 5$), while still being larger than the permittivity of air ($\varepsilon_{air} = 1$). On the other hand, refraction caused by the snow-layer in contact with the ground surface leads to a steeper incidence angle at the ground surface in comparison with the observation angle (Snell's law). Because emission from the ground beneath the dry snow is the dominant source of L-band emission, refraction increases emission at horizontal polarization, while emission at vertical polarization is decreased. These instances imply that both impedance matching and refraction increase emission at horizontal polarization, while for vertical polarization the effects are partly compensatory. As proposed by Schwank et al. (2015), these emission processes offer the potential to use passive L-band observations to estimate the effective density ρ_S of the dry snow layer in contact with the ground. The thickness of this sensitive bottom layer is given by the lower limit of $\approx$10 cm where coherent effects can be disregarded for L-band observations. Although snow density may vary rapidly with increasing snow height, this novel remote sensing information on dry snow cover has the potential to improve satellite-based retrievals of SWE (e.g. Kelly, Chang, Tsang, & Foster, 2003; Takala et al., 2011) which currently rely on physical modeling or climatological values for snow density. In addition, the theoretical study of Schwank et al. (2015) indicates the significant impact of dry snow on retrieved ground permittivity ε_G. This has potential implications for current SMOS ground permittivity retrievals performed over areas covered with dry snow (Kerr, Waldteufel, Richaume, Ferrazzoli, & Wigneron, 2011).

In this investigation, we attempt to evaluate the feasibility of the approach proposed by Schwank et al. (2015) for the simultaneous retrieval of snow density (ρ_S) and ground permittivity (ε_G) from multi-angular (θ_k), dual-polarization (p = H, V) L-band brightness temperatures $T_B^p(\theta_k)$ as measured by SMOS. A near-continuous dataset of tower-based $T_B^p(\theta_k)$ measured with ESA's ELBARA-II radiometer (Schwank et al., 2010) are applied. With a focus on winter periods, the available dataset extends for six full seasons. Corresponding brightness temperatures $T_B^p(\theta_k)$ were measured over a dry mineral soil site located in a forest clearing as well as over an open wetland site representing organic soil. These two sites can be considered to represent common land cover and soil types in the northern boreal forest zone. A comprehensive dataset of both automated and manual in situ snow and soil observations are used to validate the two-parameter retrievals $\mathbf{P} = (\rho_S, \varepsilon_G)$ derived from the measured $T_B^p(\theta_k)$.

2. Datasets

2.1. Test site

Experimental data used in this study was collected at the Finnish Meteorological Institute Arctic Research Centre (FMI-ARC) in Sodankylä, Finland. The site is located in the northern boreal forest zone. The surrounding landscape is a mosaic of conifer-dominated forests (scots pine), forested and non-forested bogs (wetlands), and small lakes. Elevation above sea level varies between 180 and 240 m; however, small mountain regions (fjells) are typical of the surrounding region.

Tower-based observations of L-band brightness temperatures $T_B^p(\theta_k)$ at polarization p = H,V and incidence angle θ_k were collected from two test sites, representative of the two most common soil types in the region. The test sites were located $\approx$1 km apart from one another. Soil at the forest clearing test site consisted of sand (70%), silt (29%) and clay (1%), with a bulk density of 1300 kg m^{-3} and a thin organic surface-layer (2–5 cm) with sparse ground vegetation typical for northern latitudes, consisting mainly of lichen and heather. The wetland test site was located over an open bog exhibiting a thick and highly variable layer of organics (from 3 to 10 m of peat) on top of bedrock. Surface vegetation consisted of moss, grass and small shrubs, with occasional small trees (pine and birch). During autumn and spring months, the wetland site was typically inundated with water, with water levels often exceeding the height of local surface vegetation in some areas.

2.2. Microwave radiometer measurements

From October 2009 to August 2012, the L-band radiometer ELBARA-II was operated at the forest clearing site (Fig. 1a). It was deployed on a 4.1-meter platform allowing for elevation scans covering the range of incidence angles $35° \le \theta_k \le 180°$ (=zenith). However, our analysis uses $T_B^p(\theta_k)$ measured for the restricted range of incidence angles $40° \le \theta_k \le 65°$, because steep measurements $T_B^p(\theta_k < 40°)$ are expected to be influenced by the tower structure, and $T_B^p(\theta_k > 65°)$ measured for shallow angles θ_k were affected by the emission from trees facing the instrument.

The experimental setup was similar for the wetland site (Fig. 1b), where ELBARA-II was operated from August 2012 to February 2015. However, a modification of the platform design allowed a slight extension of the elevation scans to $\theta_k \ge 30°$. Analysis and retrievals based on observations $T_B^p(\theta_k)$ at the wetland site proved problematic in particular during late autumn, when the soil-surface in the radiometer field of view was partially saturated with water. Local-scale variability in the soil elevation and vegetation height caused the ELBARA-II footprints to include areas with open water (ponds) and areas with vegetation protruding above the local water level. These instances limited the usable incidence angles that provided $T_B^p(\theta_k)$ suitable for testing the retrieval at the wetland site.

At both sites, the ELBARA-II measurements $T_B^p(\theta_k)$ were composed of automated elevation scan sequences, fixed incidence angle observations, and zenith (sky) measurements for calibration purposes. At both sites elevation scans were made in 5° steps. During the first year of operation at the forest clearing site, elevation scans were performed every three hours. For the following years a four-hour interval was applied. At the bog site, a four-hour interval was used for the duration of the experiment. The measurement duration for each individual

Please cite this article as: Lemmetyinen, J., et al., Snow density and ground permittivity retrieved from L-band radiometry: Application to experimental data, *Remote Sensing of Environment* (2016), http://dx.doi.org/10.1016/j.rse.2016.02.002