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Response of L-Band brightness temperatures to freeze/thaw and snow dynamics in a prairie environment from ground-based radiometer measurements

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ABSTRACT

Land surface freeze/thaw (F/T) dynamics impact the surface energy balance, carbon fluxes, and hydrologic processes. Recent and on-going L-Band (≈1.4 GHz) spaceborne missions have the potential to provide enhanced information on F/T state over large geographic regions with rapid revisit time. However, the low spatial resolution of these spaceborne observations (≈45 km) makes it difficult to isolate the primary contributions to the F/T signal, including the soil, snow, and vegetation states. A ground-based L-Band radiometer measurement campaign was conducted in Saskatchewan, Canada during the winter of 2014–2015 to evaluate brightness temperature sensitivity to F/T processes, snow, liquid water in snow and assess theoretical retrievals of soil permittivity (ε_G), and snow density from experimental data. The ground-based radiometer was run in multiple configurations. First, temporally continuous measurements were conducted through the winter over an agricultural field, with a comprehensive network of reference snow and soil observations characterizing the F/T state of the soils within or adjacent to the radiometer footprint. Secondly, weekly multi-angular L-Band measurements were made at an undisturbed site of naturally accumulating snow cover, over a site that was kept snow free, and a site with artificially compacted snow. Results from the assessment of the land surface F/T retrieval algorithm showed that L-Band measurements are sensitive to the near surface F/T state of the soil, with the highest level of agreement found between the near surface (2.5 cm) F/T reference measurements of soil temperature and ε_G (accuracies of 91.1% and 92.9%, respectively). Several mid-winter melt events with air temperatures (T_{air}) above 0°, and soil temperatures below 0 °C, illustrated that liquid water within the snow dramatically increase the T_B, resulting in false retrievals of soil thaw events using existing L-Band F/T retrieval algorithms. However, T_{air} was also shown to have a high commission errors compared to radiometer observations in detecting snow melt, because of the delay between $T_{air} > 0$ °C and the onset of melt resulting in a measurable wet snow signal at L-Band. The retrieval of snow density (ρ_s), of the bottom 10 cm of the snowpack tended to underestimate high ρ_s (>400 kg m^{-3}), and agreed well for lower ρ_s (<400 kg m^{-3}). The paper gives important information on different contributions to the L-Band F/T signal in a prairie environment, which will help improving satellite-based F/T retrieval algorithms.

1. Introduction

Snow and frozen ground play a crucial role in climatological and hydrological processes, and are key factors in modulating energy, water, and carbon and nitrogen cycle processes and budgets. The stability of the soil carbon pool in boreal forests, which is strongly related to the annual photosynthetic period, is sensitive to the depth and duration of thaw (Kurganova et al., 2007; Goulden et al., 1998). Moreover, in

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high-latitude ecosystems the continued thawing of permafrost in response to increasingly warmer temperatures induces major changes in hydrological processes (Gouttevin et al., 2012) and could initiate positive carbon cycle feedbacks (Schaefer et al., 2011) and high nitrous oxide production (Elberling et al., 2010). In the prairies, the freeze/thaw (F/T) state of the soil significantly impacts the surface runoff and infiltration rates during snowmelt (Gray et al., 1985; Fouli et al., 2013). Comprehensive observational long-term data sets for snow and soil state characteristics across terrestrial environments are limited or inadequate. In particular, spatially and temporally continuous information on soil freezing depth is lacking, both for the regions of seasonal frozen ground and permafrost.

Passive microwave measurements have been used previously to monitor the landscape F/T primarily at 37 GHz (Kim et al., 2012). However, the high Ka-Band incorporates effects of e.g. snow cover and vegetation in the retrieved F/T estimate. Compared to higher frequencies, L-Band signatures exhibit deeper penetration in the soil vegetation as well as snow cover in winter. Recent investigations have demonstrated the feasibility of using tower-based remotely sensed L-Band (1–2 GHz) radiometry for F/T monitoring of the surface soil layer in the boreal forest (Schwank et al., 2004; Rautiainen et al., 2012; Rautiainen et al., 2014). L-Band sensitivity to F/T state is also present at the satellite scale, illustrated with measurements from the ESA Soil Moisture Ocean Salinity (SMOS) and NASA Satellite de Aplicaciones Cientificas (SAC-D) Aquarius missions and NASA Soil Moisture Active Passive (SMAP) radiometer mission data (Rautiainen et al., 2016; Roy et al., 2015). L-Band spaceborne missions have the potential to provide enhanced information on the surface F/T state over large geographic regions which are important for studies of terrestrial hydroclimatology in northern regions (Rawlins et al., 2010; Lawrence and Slater, 2010) and for assimilation, initialization and evaluation of land surface models in operational prediction systems (Farhadi et al., 2015; Decharme et al., 2016). Even as results obtained with Aquarius and SMOS observations show a clear seasonal signal in L-Band T_B that is well correlated with air and soil temperature-derived land surface F/T information, the low spatial resolution of spaceborne observations (~45 km) make it difficult to isolate potential contributions to the F/T signal from different landscape components including soil, snow, and vegetation properties. Previous studies have outlined spaceborne L-Band sensitivity to liquid water in snow over lake ice that produces a signal similar to landscape soil F/T signal in spring (Roy et al., 2015) and the influence of snow density and soil permittivity on the L-Band brightness temperature (Schwank et al., 2015; Lemmetyinen et al., 2016). Hence, ground-based measurements, where the radiometer footprint can be comprehensively monitored through supplementary measurements, could help to isolate the different landscape contributions to the signal. Ground-based measurements also provide high temporal resolution compared to satellite (2–3 days between passes), which is an important advantage for F/T investigations considering that F/T state changes can occur across short time periods.

Knowledge of the land surface state could also improve the mapping of snow mass (snow water equivalent, SWE) by microwave radiometers at higher frequencies (19 and 37 GHz) because state of the art SWE retrieval techniques do not currently consider the dynamic state of the background soil underneath the snow pack (Takala et al. 2011). Additionally, there is potential for L-Band radiometry to provide estimates of snow density for the bottom 10 cm of the snowpack, but more in situ observations are required for validation, and development of approaches to relate the lower layer snow density to the bulk snowpack properties (Schwank et al., 2015; Lemmetyinen et al., 2016).

Near continuous L-Band ground-based radiometer measurements were acquired in a prairie environment in Saskatchewan, Canada between October 2014 and April 2015 to evaluate brightness temperature sensitivity to soil and snow characteristics for potential application to SMAP and SMOS measurements. The objective of this paper is to evaluate and better understand the role of soil surface F/T processes, snow, and liquid water in snow, on L-Band T_B for F/T retrieval algorithm development/validation in a prairie environment. First, we describe the dataset gathered during the campaign. Next, we evaluate the different contributions (soil, snow, liquid water in snow) to the F/T signal, and assess the applicability of the snow density and soil permittivity retrievals developed by Schwank et al. (2015) using our experimental data.

2. Method and data

2.1. Radiometer

L-Band measurements were acquired by a unique surface-based/airborne, hyperspectral, 385 channel, dual polarization, L-Band Fourier transform, radio frequency interference (RFI) detecting radiometer designed with a frequency range from 1400 through ≈1550 MHz. Toose et al. (2016) demonstrates a method for separating the thermal signal from RFI-contaminated channels. To find an RFI-free T_B value representative of the observed spectrum, a 3rd order polynomial of sort-rank versus T_B is calculated, and the 2nd derivative of the slope of this cubic polynomial is derived. The RFI-free T_B value of the scene is the T_B at the inflection point where the 2nd derivative goes from negative to positive. The inflection point T_B become less representative of an RFI-free scene as the spectrum being analyzed becomes exceedingly contaminated with RFI (within ≈2 K for a spectrum contamination of up to ≈9%). The radiometer antenna is a 19 element air loaded conformal muffin tin design that has a 30° half-power beamwidth (−3 dB), but is only 51 × 51 × 6.5 cm and weighs ≈5 kg. During ground deployment, the incidence angle is adjusted manually with a hand-crank and a digital level from 30° off nadir to 180° (zenith). For this campaign, the radiometer system was mounted on a mobile manual forklift in order to be moved easily between sites, with the ability to adjust the height above ground at to a standard acquisition height of 2.75 m above the surface at each measurement site. This produced four different footprint sizes dependent on the acquisition incidence angle (Table 1). The integration time of the radiometer was set to acquire 1 measurement every ≈3.9 s for all 385 channels at each polarization.

During the campaign, 16 three-point calibrations were conducted to calibrate the radiometer including the measurements of: sky at zenith (estimated at ≈5 K: Pellarin et al., 2016; Lemmetyinen et al., 2016), an ambient black body target and a heated warm black body target (≈340 K). Independent sky and calibration target measurements (91 in total), show that the mean absolute error of the calibration accuracy (MAE) was between 1.0 and 1.5 K over the course of the entire campaign (Toose et al. 2016). This is a small amount of uncertainty in comparison to the frozen versus thawed T_B difference of both soil and snow which can exceed 40 K at L-Band, horizontal polarization (see Section 3.1.1).

2.2. Study area and dataset

2.2.1. L-Band ground based radiometer measurements

Continuous L-Band radiometer and coincident meteorological measurements including air/soil/snow temperature, snow depth, wind speed and hourly photographs of the soil surface were recorded between October 23rd 2014 and April 24th 2015. These measurements were made at the Kernen Crop Research Farm (KCRF) in Saskatoon

Table 1
L-Band radiometer −3 dB half-power beamwidth footprint sizes for each incidence angle.

Incidence angle (degrees)	Height above ground (meters)	Width (m)	Depth (m)
30	2.75	1.74	2.01
40		2.03	2.65
50		2.56	3.97
60		3.79	7.51