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Three years of L-band brightness temperature measurements in a mountainous area: Topography, vegetation and snowmelt issues

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ABSTRACT

L-band passive measurements (1.4 GHz) over continental areas are known to be related to surface soil moisture. Two satellite missions were recently launched to measure land surface emissions at this frequency band (SMOS-Soil Moisture and Ocean Salinity in 2009 and SMAP-Soil Moisture Active/Passive in 2015). In order to improve soil moisture retrievals from satellite data, ground-based radiometer systems operating at the same frequency were deployed over specified areas to investigate the L-band emission of various land covers under various climatological conditions. In this study, three years of L-band passive measurements from a radiometer installed on top of a steep mountain in the French Alps were analyzed and compared to L-band passive simulations. The innovative radiometer location led to large footprints due to the distance between the radiometer and the area under study. This experiment also produced microwave measurements affected by various potential difficulties typically encountered in SMOS/SMAP satellite missions: topography, heterogeneous footprints, dry/wet snow events, dew and vegetation litter. Based on *in situ* and modeling data, this paper investigates the potential of a radiative transfer model (L-band Microwave Emission of the Biosphere, L-MEB) to simulate L-band measurements and analyzes the differences with ELBARA observations. First, it was found that the topography generated a mixing of the horizontal and vertical polarizations. In addition, a large positive bias was found on ELBARA measurements (31 K and 12 K in horizontal and vertical polarizations respectively). Investigations showed that the sky reflection measured by the radiometer was partially substituted by land reflection coming from the surrounding topography. Second, the low-vegetation emission was investigated and highlighted the inability of the MODIS NDVI product to correctly represent the vegetation dynamics. Finally, dry snow conditions were found to have non-negligible impact at L-band and a particular signature was found during snow melting periods, with potential applications at the SMOS/SMAP spatial scales (~40 km).

1. Introduction

Since the launch of the European Space Agency (ESA) SMOS satellite mission (Soil Moisture and Ocean Salinity, Kerr et al., 2010) in November 2009, numerous studies have been devoted to assessing the performance of the Level 2 and 3 SMOS soil moisture products using *in situ* soil moisture stations at various locations (Peischl et al., 2012; Bircher, Skou, Jensen, Walker, & Rasmussen, 2012; Jackson et al., 2012; Louvet et al., 2015). To make more advanced assessments, some experimental sites were also designed to measure brightness temperature and soil moisture in order to evaluate the representativeness of SMOS soil moisture retrievals at a smaller spatial scale than that actually used in the mission. In this context, various long-term experiments were carried out using tower-based L-band radiometers. One year before the SMOS launch, ESA proposed the setting up of three L-band radiometers (ELBARA-II systems) for land or sea, local, long-term observations. In 2009, three ELBARA-II systems were installed. The first (Schwank et al., 2010) was near Valencia, Spain (Wigneron et al., 2012 and Schwank et al., 2012), on a site with mainly natural Mediterranean vegetation, including vineyards and other agricultural fields; the second was deployed in the boreal and subarctic region (Finland) to study the effects of the soil freeze/thaw process on the L-band signature (Rautiainen et al., 2012; Lemmetyinen et al., 2015; Rautiainen et al., 2015); and the third was on an experimental farm in southern Germany over a temperate agricultural area (Schlenz, dall'Amico, Loew, & Mauser, 2012; dall'Amico, Schlenz, Loew, & Mauser, 2012). Other L-band radiometers

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were also deployed in various locations, such as Antarctica (Macelloni et al., 2013), the South-West of France (de Rosnay et al., 2006), Belgium (Jonard et al., 2011) and Germany (Jonard et al., 2015). Lastly, various L-band airborne radiometric experiments were conducted (Zribi et al., 2011; Albergel et al., 2011; Bircher Skou & Kerr, 2013; Skou, Misra, Balling, Kristensen, & Sobjaerg, 2010; Rudiger, Walker, & Kerr, 2011).

Ground-based radiometer experiments provided brightness temperature measurements over a relatively small area (usually 5 to 20 m^2) due to the proximity of the radiometer (tower of 5 m in Finland and 17 m in Valencia) and the antenna field of view (≈24° at −10 dB sensitivity, ELBARA-II). These experiments were dedicated to analyzing specific soil and vegetation microwave emissions in some particular climatic regions. In contrast, airborne radiometric experiments were able to acquire microwave measurements over large areas in order to investigate the spatial variability of the soil moisture within an SMOS pixel (about 43 km). The main drawbacks of airborne experiments are their almost prohibitive cost compared to ground-based experiments, and the usually restricted possibilities for verifying the statistics obtained for the overflown footprints due to the limited availability of *in situ* information.

An alternative to airborne experiments is to install a radiometer on top of a steep mountain in order to obtain continuous measurements over a large footprint area (comparable in size to that of airborne experiments). In 2011, one ELBARA-II radiometer was installed in the Vercors region of the French Alps at 1585 m above sea level in order to acquire L-band passive measurements of an area located 600 m below. The area studied was composed of grassland, and broadleaf and coniferous forests. It offered various climatological conditions such as dry/wet snow events, soil freezing and dew events. In addition, the selected site was strongly affected by the topography.

This experiment was also designed to investigate potential improvements of the SMOS L2SM algorithm since the current version is designed to retrieve soil moisture over the dominant kind of land cover at the pixel scale (Kerr et al., 2010). In addition, there is currently no SMOS soil moisture retrieval on topographic areas and under snow conditions (these areas are masked prior to the retrieval process).

The objective of the present paper is to analyze three years of L-band passive measurements together with coinciding *in situ* measurements and modeling data and to focus on three main topics: the topography, which plays a significant role in passive microwave remote sensing (Utku & Le Vine, 2011); the dynamics of the two main vegetation land covers on this site (grassland and forest); and the impact of snow cover on the brightness temperature measurements at L-band, particularly during snow melting periods.

2. Experimental setup and measurements

The Vercors region is located in the western part of the French Alps near the city of Grenoble. This mountainous, limestone region has many vertical cliffs. One of these was chosen in 2011 to receive the ELBARA-II system. This site was also selected in order to allow rapid access to the radiometer location at all times, either by car (most of the year) or by using the ski resort facilities in winter. The radiometer coordinates were 45.1304°N, 5.4913°E, alt = 1585 m. Five *in situ* soil moisture stations were installed in the target area in 2009, followed by a meteorological station in 2010.

2.1. ELBARA-II measurements

The ELBARA-II system is a Dicke-type radiometer operating at 1400–1427 MHz (L-band). It is equipped with a Pickett-horn antenna with two ports, one for horizontal (H) and one for vertical (V) polarization (Schwank et al., 2010). The antenna diameter is 1.4 m and its length is 2.7 m. The beam widths are ±6° around the main antenna direction at −3 dB, ±9° at −6 dB, and ±12° at −10 dB.

The ELBARA-II radiometer was installed at its operational location in the Vercors site on June 24th, 2011 and the experiment ended on December 12th, 2014. After a short test period of the three solar panels, the operational experiment started on August 20th, 2011. Brightness temperature measurements at horizontal and vertical polarizations were obtained every 30 min for five observation angles (55°, 60°, 65°, 70°, 75°) relative to the nadir (Fig. 1). The footprint of measurements ranged from 120,800 m^2 to 166,000 m^2 (at 3 dB) depending on the angle of incidence. In addition, once a week, external calibration sky measurements were performed for one hour, starting at 12:00 UTC at 135° relative to nadir (West direction) to recalibrate the Active Cold Source (ACS) and to check the "health" of the radiometer. Analysis of the sky measurements confirmed the excellent temporal stability of the ELBARA-II radiometer during the approximately three-year campaign performed at the Vercors site (Fig. 2). The average values were 4.44 and 4.46 K respectively for H and V polarizations and the standard deviation values were 0.27 and 0.29 K.

Similarly, problems internal and external to the instrument and affecting the quality of the measured brightness temperature were analyzed in detail by Schwank, Wiesmann, and Wegmüller (2014), in order to identify and eliminate outlying brightness temperature measurements from the time-series. Instrument internal distortions could occur because of deficient stabilization of the actual radiometer internal temperature with respect to the corresponding set-point temperature. These events were present during times of little incident solar radiation, when insufficient electrical power was generated to accurately stabilize the instrument temperature. External distortions were associated with non-thermal emissions of the scenes observed (radio frequency interferences, RFI). This procedure resulted in about 25% of the ELBARA-II measurements being rejected.

2.2. In situ measurements

The target area is presented in Fig. 3-a with a picture taken from the radiometer location. The target area has three kinds of vegetation: grassland and coniferous forest located on the East side of the valley and broadleaf forest on the west. *In situ* soil moisture and soil temperature measurements were set up prior to the ELBARA-II radiometer installation at various locations in the target area. Four stations were installed in the grassland area and one in the broadleaf forest. Micro-acquisition stations were Onset HOBO H21 002 with four inputs. Soil moisture probes were Decagon impedance sensors type ECH2O EC20 (Fig. 3-b). On each of the five sites, two soil moisture probes were installed at 5 cm depth. The other two inputs were used to record either soil temperature at 10 and 40 cm depth or soil moisture at 20 and 50 cm depth. Finally, meteorological measurements were obtained at the Grassland2 site (air temperature, air specific humidity, atmospheric pressure and precipitation since November 2011 (Fig. 3-c)).

2.2.1. Soil moisture

Soil moisture measurements were automatically obtained at a 30-min time step. Fig. 4 presents the evolution of the surface soil moisture (5 cm depth) during the ELBARA-II Vercors experiment from June 2011 to December 2014, and daily rainfall measurements since the installation of the meteorological station in November 2011. All soil moisture sensors located at 5 cm depth are plotted in Fig. 4 (i.e. min/max and mean) separately for the grassland (gray) and forest (green) sites. The averaged values (black curves) for the grassland and the forest site are plotted separately and the overall variability of the two time-series is presented with the minimum and maximum values of all sensors. It can be observed that soil moisture is generally 10% lower under broadleaf forest than under grassland except during some short periods in summer. This is mostly due to the rain being intercepted by the vegetation (over- and

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