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Review

Inverting surface soil moisture information from satellite altimetry over arid and semi-arid regions

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ABSTRACT

Monitoring surface soil moisture (SSM) variability is essential for understanding hydrological processes, vegetation growth, and interactions between land and atmosphere. Due to sparse distribution of in-situ soil moisture networks, over the last two decades, several active and passive radar satellite missions have been launched to provide information that can be used to estimate surface conditions and subsequently soil moisture content of the upper few cm soil layers. Some recent studies reported the potential of satellite altimeter backscatter to estimate SSM, especially in arid and semi-arid regions. They also pointed out some difficulties of such technique including: (i) the noisy behavior of the backscatter estimations mainly caused by surface water in the radar foot-print, (ii) the assumptions for converting altimetry backscatter to SSM, and (iii) the need for interpolating between the tracks.

In this study, we introduce a new inversion framework to retrieve soil moisture information from along-track altimetry measurements. First, 20Hz along-track nadir radar backscatter is estimated by post-processing waveforms from Jason-2 (Ku- and C-Band during 2008–2014) and Envisat (Ku- and S-Band during 2002–2008). This provides backscatter measurements every ~300m along-track within every ~10 days from Jason, and every ~35days from Envisat observations. Empirical orthogonal base-functions (EOFs) are then derived from soil moisture simulations of a hydrological model, and used as constraints within the inversion. Finally, along-track altimetry reconstructed surface soil moisture (ARSSM) storage is inverted by fitting these EOFs to the altimeter backscatter. The framework is tested in arid and semi-arid Western Australia, for which a high resolution hydrological model (the Australian Water Resource Assessment, AWRA model) is available. Our ARSSM products are also validated against Soil Moisture and Ocean Salinity (SMOS) L3 products, for which maximum correlation coefficients of bigger than 0.8 are found. Our results also indicate that ARSSM can validate the simulation of hydrological models at least at seasonal time scales.

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1. Introduction

Soil moisture storage is the main driver of the outgoing hydrological fluxes, such as evapotranspiration and (sub-)surface runoff (Katul et al., 2012), two important components of the terrestrial water cycle. Therefore, quantifying spatio-temporal variability of soil moisture is essential for modeling and understanding the water cycle, including land–atmosphere interactions, as well as for simulating present day and future climate change, and for flood and drought prediction (see, e.g., Rötzer et al., 2014). Nowadays, soil moisture remote sensing has attracted growing interest to complement the sparse available in-situ networks. The contribution of remote sensing techniques is in particular in monitoring of the top soil layer (first few centimeters).

Starting with the C-Band (5 GHz) wind-scatterometers on-board of the European Remote Sensing satellites ERS-1 (launched 1991) and ERS-2 (launched 1995), it was demonstrated that the scatterometer data could be applied to estimate vegetation and soil characteristics over continental land surfaces (Mougin et al., 1995). In fact, the backscattered signal energy is linked to the soil water content via the dielectric constant (Ulaby et al., 1982). In 2002, the National Aeronautics and Space Administration (NASA) launched the Aqua satellite mission that carried the Advanced Microwave Scanning Radiometer (AMSR-E) to observe (passive-mode) brightness temperatures at six dual polarized frequencies (Njoku et al., 2003). Lower microwave frequencies (e.g. C- or X-Band) allow a better monitoring of the upper few centimeters of the Earth's surface (Njoku et al., 2003) with reduced sensitivity to vegetation cover and surface roughness (Draper et al., 2009). To continue the coverage provided by the ERS missions, the Advanced Scatterometer (ASCAT) was launched in 2006 on-board a Meteorological Operational (METOP) satellite (Bartalis et al., 2007).

The Soil Moisture and Ocean Salinity (SMOS) satellite, a dedicated soil moisture monitoring mission, was launched in 2009 to provide brightness temperature and soil moisture products on a three-daily basis (Delwart et al., 2008; Montzka et al., 2013). Additionally, the Soil Moisture Active Passive (SMAP) mission (Entekhabi et al., 2010), launched in early 2015, has been monitoring continental soil moisture changes with its passive radiometer and active L-Band scatterometer. However, the active instrument failed after six month of operation. Table 1 provides a short summary on the individual missions.

Dedicated satellite altimetry missions (e.g., Envisat, Topex/Poseidon and its follow-on Jason 1, 2, and 3) have been originally designed to measure sea surface height over the oceans (Shum et al., 1995). Over land, the measured backscatter is closely related to soil characteristics at the satellite nadir (Papa et al., 2003; Blarel et al., 2015). Ridley et al. (1996) and Fatras et al. (2012) found high correlation between in-situ soil moisture measurements and altimetry backscatter from the Topex/Poseidon and Envisat missions. Fatras et al. (2015) extended these investigations to different land cover regions, such as desert, savanna and forests. They compared Jason-2 backscatter with side-looking scatterometers (QuickSCAT and ASCAT) over the arid regions of West Africa and found altimetry results to be more sensitive to soil moisture variations and considerably less to vegetation effects, due to the nadir-looking instrument on-board of the satellite. Ka-Band measurements of the Satellite with Argos and Altika (SARAL) mission were assessed by Frappart et al. (2015) to relate the backscatter estimates to spatio-temporal changes in surface roughness, land cover, and soil moisture changes over West Africa. Their study indicates that Ka-Band measurements are able to penetrate underneath the canopy of tropical forests in non-inundated areas. In Table 2, relevant studies that utilize altimetry for soil moisture studies are summarized. We believe that altimetry missions (1) provide high resolution along-track measurements ($\sim$300 m) of backscatter with (2) low sensitivity to vegetation in combination with (3) more than two decades of continuous measurements which makes altimetry a valuable and independent tool for measuring surface soil moisture. However, due to the limited (across-track) spatial and temporal resolution (Table 1), the range of applications for altimetry based soil moisture monitoring might be limited and the data should be utilized in combination with the existing dedicated soil moisture missions.

Estimating surface soil moisture (SSM) from brightness temperatures as measured by dedicated soil moisture missions, or from backscatter observations as measured by altimetry, is challenging. Several previous studies formulated this conversion based on a linear change detection approach (Wagner et al., 1999) and applied to SMOS observations. For example, Liu et al. (2011) combined active (ASCAT) and passive (AMSR-E) products and rescaled them against the simulation of the Global Land Data Assimilation System (GLDAS, Rodell et al., 2004). In Piles et al. (2011), SMOS products were combined and downscaled to 1 km using high resolution VIS/IR MODIS observations. Al-Yaari et al. (2015) applied a multiple-linear regression approach to minimize the differences between AMSR-E and SMOS soil moisture products. An artificial neural network was used to estimate soil moisture from simulated brightness temperatures as in Liou et al. (2001), Angiuli et al. (2008), and Chai et al. (2010). Recently, Rodríguez-Fernández et al. (2015) applied a neural network to identify the statistical relationship between a reference soil moisture data set and a variety of information from SMOS brightness temperatures, C-Band backscatter coefficients from ASCAT and MODIS derived Normalized Difference Vegetation Index (NDVI) data.