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Multi-temporal, multi-frequency, and multi-polarization coherence and SAR backscatter analysis of wetlands

Fariba Mohammadimanesh[a,*], Bahram Salehi[a], Masoud Mahdianpari[a], Brian Brisco[b], Mahdi Motagh[c,d]

[a] C-CORE and Department of Electrical Engineering, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X5, Canada
[b] The Canada Centre for Mapping and Earth Observation, Ottawa, Ontario K1S 5K2, Canada
[c] Department of Geodesy, Section of Remote Sensing, GFZ German Research Centre for Geosciences, 144173 Potsdam, Germany
[d] Institute of Photogrammetry and GeoInformation, Leibniz Universität Hannover, 30167 Hannover, Germany

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ABSTRACT

Despite recent research into the Interferometric Synthetic Aperture Radar (InSAR) technique for wetland mapping worldwide, its capability has not yet been thoroughly investigated for Canadian wetland ecosystems. Accordingly, this study statistically analysed interferometric coherence and SAR backscatter variation in a study area located on the Avalon Peninsula, Newfoundland and Labrador, Canada, consisting of various wetland classes, including bog, fen, marsh, swamp, and shallow-water. Specifically, multi-temporal L-band ALOS PALSAR-1, C-band RADARSAT-2, and X-band TerraSAR-X data were used to investigate the effect of SAR frequency and polarization, as well as temporal baselines on the coherence degree in the various wetland classes. SAR backscatter and coherence maps were also used as input features into an object-based Random Forest classification scheme to examine the contribution of these features to the overall classification accuracy. Our findings suggested that the temporal baseline was the most influential factor for coherence maintenance in herbaceous wetlands, especially for shorter wavelengths. In general, coherence was the highest in L-band and intermediate/low for both X- and C-band, depending on the wetland classes and temporal baseline. The Wilcoxon rank sum test at the 5% significance level found significant difference (*P-value* < 0.05) between the mean values of HH/HV coherence at the peak of growing season. The test also suggested that L-band intensity and X-band coherence observations were advantageous to discriminate complex wetland classes. Notably, an overall classification accuracy of 74.33% was attained for land cover classification by synergistic use of both SAR backscatter and interferometric coherence. Thus, the results of this study confirmed the potential of incorporating SAR and InSAR features for mapping Canadian wetlands and those elsewhere in the world with similar ecological characteristics.

1. Introduction

Wetlands are transitional zones between terrestrial and aquatic regions, which are permanently or temporarily covered with shallow water (Tiner et al., 2015). They are considered a desirable habitat for a variety of animal and plant species by providing food and shelter. Other wetland ecosystem services include flood storage, shoreline stabilization, and water-quality renovation. However, wetlands are increasingly degraded due to both natural processes, such as global warming, changing in precipitation patterns, and coastal erosion, as well as anthropogenic activities, including industrial runoff, road construction, and plant or animal collection and introduction (Tiner et al., 2015; Jaramillo and Destouni, 2015). Furthermore, the loss of wetland hydrological connectivity because of human activities leads to massive destruction of coastal wetlands (Jaramillo et al., 2018).

Wetland monitoring and management have recently gained more attention thanks to advancement in remote sensing technologies in a variety of subjects, including wetland hydrological monitoring (Wdowinski et al., 2008), change detection (Brisco et al., 2017), and classification (Mahdianpari et al., 2018). Importantly, the advent of Synthetic Aperture Radar (SAR) sensors has significantly influenced wetland restoration studies and management (Jiao et al., 2014; Jaramillo et al., 2018). This is because microwaves penetrate through soil, cloud, and vegetation and the sensors are not reliant on sun illumination, which means SAR sensors operate in all-weather day/night conditions. Thus, they have facilitated wetland monitoring especially in

* Corresponding author at: C-CORE, Captain Robert A. Bartlett Building, Morrissey Road, St. John's, NL A1B3X5, Canada.
E-mail address: f.mohammadimanesh@mun.ca (F. Mohammadimanesh).

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geographic regions with near-permanent cloud cover.

Hydrological monitoring of wetlands is crucial since they are water-dependent ecosystems. SAR images have been found to be efficient tools for wetland hydrological monitoring using both SAR backscatter signatures (Kasischke et al., 2003; Kim et al., 2014), and a more detailed and quantitative technique, Interferometric SAR (InSAR) (Wdowinski et al., 2008). The flooded and non-flooded statuses of vegetation in wetland environments have distinct differences in radar backscattering response, which plays an important role in sustainable hydrological monitoring of wetlands. In particular, a time series analysis of SAR backscatter signature has provided information about seasonal patterns of flooding in wetland ecosystems and has been examined in number of studies (Kasischke et al., 2003; Rebelo, 2010; Betbeder et al., 2014).

The potential of the InSAR technique for water level monitoring was first investigated in the Amazon floodplain using SIR-C in C- and L-band frequencies (Alsdorf et al., 2000). This study demonstrated that vegetation in or adjacent to the standing water backscatters the radar pulse towards the satellite sensor due to double-bouncing effect. This provided the possibility for monitoring water level changes in the phase data. Subsequently, the capability of the InSAR technique for water level monitoring has been further examined for a number of other places such as Florida Everglades (Wdowinski et al., 2008; Hong et al., 2010; Brisco et al., 2015), Louisiana coastal wetland (Lu and Kwoun, 2008; Kim et al., 2009; Oliver-Cabrera and Wdowinski, 2016), China wetlands (Xie et al., 2013; Zhang et al., 2016), and most recently the Cienaga Grande de Santa Marta (CGSM) wetland located in Colombia (Jaramillo et al., 2018).

In addition to hydrological monitoring of wetlands using InSAR, the interferometric coherence may be useful for discriminating different wetland vegetation covers. Currently, little is known about the capability of interferometric coherence for classifying different land cover types, which may provide information in addition to SAR intensity (i.e., the portion of the backscattered SAR signal from ground targets). This is because SAR intensity depends on the electromagnetic structure of the targets, while the interferometric coherence shows their mechanical and dielectric stability (Ferretti et al., 2007). Furthermore, SAR intensity is affected by speckle noise, while the speckle noise is averaged when two images are integrated to generate the interferometric product (Ramsey et al., 2006).

Ramsey et al. (2006) used ERS1/2 tandem image pairs to compare the potential of interferometric products (i.e., coherence and phase) and SAR backscatter images for land cover classification in the Big Bend coastal wetland, Florida. They found that intensity was less responsive to land covers and had high temporal variations. However, coherence had more variation in different classes and provided better discrimination, especially, during the leaf-off season. Kim et al. (2013) investigated the interferometric coherence of wetland classes using C- and L-band data in the Everglades wetlands. They reported that longer wavelengths and smaller incidence angles are better suited for wetland InSAR application. Zhang et al. (2015) used interferometric coherence obtained by ALOS data for classification of wet and dry marshes in the Liaoh River Delta, China. Brisco et al. (2015) looked at the interferometric coherence in the Everglades wetlands for different RADARSAT-2 products. They observed an adequate degree of coherence in all RADARSAT-2 products, while the coherence was better preserved for images with high spatial resolution and small incidence angle. Most recently, Brisco et al. (2017) evaluated the temporal variation of coherence in three wetland types, including swamp, marsh, and shallow open water classes using Spotlight RADARSAT-2 images during ice-off and ice-on seasons in Ottawa, Ontario. They reported a sufficient degree of coherence in both swamp and marsh during the periods of the ice-off season and noted the potential of coherence images for wetland change detection.

The majority of these studies have investigated the potential of InSAR products for wetland monitoring from a very specific point of view. Accordingly, studies attempting to address all influential factors for wetland InSAR applications are limited. For example, most of these researches applied only C- and especially, L-band data for coherence analysis, and mainly concentrated on HH polarization. However, the interferometric coherence of wetland classes using X-band SAR imagery, which may contribute to the success of InSAR for wetland applications due to high temporal and spatial resolution, has not yet been investigated. The selection of appropriate SAR wavelengths and polarizations are two influential factors for wetland monitoring using SAR imagery. Thus, the primary goal of this research study was to determine the capability of multi-frequency SAR imagery, including ALOS PALSAR-1 L-band, RADARSAT-2 C-band, and TerraSAR-X images in terms of coherence maintenance for different wetland classes. Specifically, the main objectives were: (1) to determine the most appropriate SAR frequency and polarization for hydrological monitoring of Newfoundland herbaceous wetlands; (2) to identify the most influential factors for coherence preservation of different vegetation types using a multi-temporal coherence analysis framework; (3) to assess the relationship between the variation of SAR backscatter and coherence in complex wetland ecosystems; and (4) to explore the contribution of the interferometric coherence to wetland classification results using an object-based Random Forest approach. Thus, this study advances towards an operational methodology for mapping Canadian wetlands, as well as those with similar ecological features and vegetation types, that builds upon the relationship between the flooding status of vegetation (i.e., wetland phenological cycle), SAR backscattering responses, and variation of interferometric coherence.

2. Methods

2.1. Study area and field data

This study was carried out within a 700 km^2 site located in the northeast portion of Newfoundland and Labrador, the Avalon Peninsula, in the Maritime Barren ecoregion (Fig. 1). This ecoregion is specified by an oceanic climate, having foggy, cool summers and relatively mild winters (Ecological Stratification Working Group, 1996). Mean annual precipitation varies between 1200 and 1600 mm and mean annual temperatures are approximately 5.5 °C (Marshall et al., 1996). Fig. 2 depicts the total precipitation (mm) for each month in 2016.

The study area contains a dense urban area to the north, where the capital city of St. John's and various closely associated towns and cities are located. Moving south, the urban cover becomes sparse, where balsam fir forests, heathland barrens, and expansive peatland (bog and fen) dominate (South, 1983). The patterns of forest stands separated by large barrens, common in and around the study area, are the result of frequent forest fires, partially a result of colonization (South, 1983; Ecological Stratification Working Group, 1996). The topography largely reflects past glacial activity in which retreating glaciers helped to form the numerous lakes and ponds across the rolling ground moraine land cover scattered by isolated rocks and boulders (Ecological Stratification Working Group, 1996).

This area has eight land cover classes, five of which are wetlands (see Table 1). In particular, all five class of wetlands categorized by the Canadian Wetland Classification System, including bog, fen, marsh, swamp, and shallow-water are found within the study area (National Wetlands Working Group, 1997); however, bog and fen are the most dominant wetland classes relative to the occurrence of swamp, marsh, and shallow-water. For this study, *in-situ* data were collected in the summers and falls of 2015 and 2016 over multiple field-visits during the leaf-on season, and Global Positioning System (GPS) locations were recorded. A total of 168 wetland sites were visited and categorized as bog (54), marsh (46), fen (29), swamp (24), and shallow-water (15).

Wetland boundary delineation was conducted using ArcMap 10.3.1 with the aid of aerial and satellite imagery, including a 50 cm resolution