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A new scheme for urban impervious surface classification from SAR images

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ABSTRACT

Urban impervious surfaces have been recognized as a significant indicator for various environmental and socio-economic studies. There is an increasingly urgent demand for timely and accurate monitoring of the impervious surfaces with satellite technology from local to global scales. In the past decades, optical remote sensing has been widely employed for this task with various techniques. However, there are still a range of challenges, e.g. handling cloud contamination on optical data. Therefore, the Synthetic Aperture Radar (SAR) was introduced for the challenging task because it is uniquely all-time- and all-weather-capable. Nevertheless, with an increasing number of SAR data applied, the methodology used for impervious surfaces classification remains unchanged from the methods used for optical datasets. This shortcoming has prevented the community from fully exploring the potential of using SAR data for impervious surfaces classification. We proposed a new scheme that is comparable to the well-known and fundamental Vegetation-Impervious surface-Soil (V-I-S) model for mapping urban impervious surfaces. Three scenes of fully polarimetric Radsarsat-2 data for the cities of Shenzhen, Hong Kong and Macau were employed to test and validate the proposed methodology. Experimental results indicated that the overall accuracy and Kappa coefficient were 96.00% and 0.8808 in Shenzhen, 93.87% and 0.8307 in Hong Kong and 97.48% and 0.9354 in Macau, indicating the applicability and great potential of the new scheme for impervious surfaces classification using polarimetric SAR data. Comparison with the traditional scheme indicated that this new scheme was able to improve the overall accuracy by up to 4.6% and Kappa coefficient by up to 0.18.

1. Introduction

1.1. Scientific significance of urban impervious surfaces

Among urban land covers, urban impervious surfaces mainly refer to the built-up areas, including pavements and rooftops, that can be made up of diverse materials, such as asphalt, concrete, plastic and metal materials. Conventionally, urban impervious surfaces have been identified as a critical indicator for the process of urbanization and for the environmental impacts of urbanization (Arnold and Gibbons, 1996; Weng, 2001; Wu and Murray, 2003; Zhang et al., 2015). They were commonly used in lots of studies on environmental consequences of urbanization (Arnold and Gibbons, 1996; Bannerman et al., 1993; Schueler, 1994; Sleavin et al., 2000), hydrological, atmospheric and environmental models to simulate and study the urban hydrological process (Arnold et al., 1982; Espey et al., 1966; Jacobson, 2011; Seabum, 1969; Yang et al., 2010), urban atmospheric process and urban climate change (Hu et al., 2014; Ooi et al., 2017), urban solar energy balance, urban land surface temperature and the urban heat island (Lu and Weng, 2006; Schueler, 1994; Slonecker et al., 2001; Weng et al., 2006; Yuan and Bauer, 2007), as well as socio-economic studies such as measurement of urban growth, estimation of population distribution, and variation of housing prices (Wu and Murray, 2003).

1.2. Urban land cover classification from synthetic aperture radar (SAR) data

Numerous studies have focused on the urban land use and land cover (LULC) mapping using various polarimetric SAR data. Since

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the active and side-looking SAR is sensitive to the dielectric and geometric properties of urban land surface such as structure and surface roughness, SAR data provided complementary information for LULC (Calabresi, 1996; Henderson and Xia, 1997; Stasolla and Gamba, 2008; Zhang et al., 2012; Zhang et al., 2014). With a number of studies exploring SAR data using their backscattering and polarimetric information, the diversity and complexity of LULC were identified and reported (Dekker, 2003; Gamba and Aldrighi, 2012; Guo et al., 2014; Hu and Ban, 2012; Majd et al., 2012; Niu and Ban, 2013; Tison et al., 2004; Voisin et al., 2013; Zhang et al., 2012; Zhang et al., 2016; Zhang et al., 2014). For instance, different backscatters in the urban environment were analyzed to examined the single, double and triple bounce scattering mechanism in urban areas and concluded that dominant urban scatters are single bounce from roofs and double bounce from ground-wall structures (Dong et al., 1997). Various LULC classes were analyzed in urban areas using polarimetric SAR data (Gamba and Lisini, 2013; Li et al., 2010; Niu and Ban, 2013), with different polarimetric decompositions including Pauli, Freeman, Touzi, Cloud-Pottier and H/A/alpha decompositions (Bhattacharya and Touzi, 2011; Hariharan et al., 2016; Niu and Ban, 2013; Park and Moon, 2007; Pellizzeri, 2003). Different classification methods were employed to conduct the LULC classification such as the maximum likelihood based methods (Li et al., 2010; Wu et al., 2008), support vector machine (Zhang et al., 2010), adaptive Markov random field (Niu and Ban, 2014) and fuzzy classification (Park and Moon, 2007). Nevertheless, impervious surfaces were seldom focused in previous studies, with only a few studies using polarimetric SAR. Fully polarimetric Radarsat-2 data were combined with SPOT-5 data to extract impervious surfaces using C5.0 decision tree algorithm in Beijing, China (Guo et al., 2014). Dual polarimetric SAR data (e.g. ALOS/PALSAR) and single polarimetric SAR data (e.g. ENVISAT ASAR and TerraSAR-X) were also employed to extract impervious surfaces with the support of different optical satellite data (e.g. Landsat TM/ETM + and SPOT-5) in the metropolitan regions of the Pearl River Delta (Zhang et al., 2016; Zhang et al., 2015; Zhang et al., 2012; Zhang et al., 2014). Nevertheless, most of these studies followed the conventional scheme (i.e., vegetation, bright and dark impervious surfaces, bare soil and water surface), which does not consider the dielectric and geometric properties of urban land surface, which are the determining factors in SAR remote sensing data.

1.3. Previous scheme of impervious surfaces classification

Given its importance and wide applications, impervious surfaces classification (ISC) has been intensively studied using various types of space-borne and airborne remote sensing data. The first attempt can be dated back to the Vegetation-Impervious surface-Soil (VIS) conceptual model, where Ridd analyzed the composition of urban land covers and divided them into vegetation, impervious surface and bare soil, after masking out the water surface, which was considered to be relatively easily identified (Ridd, 1995). This study set up a theoretical model for ISC from remote sensing data. Following the VIS model, spectral mixture analysis (SMA) was employed to implement this conceptual model to estimate impervious surfaces at the sub-pixel level from satellite data. Wu and Murray (2003) applied this SMA method with the VIS model and further divided impervious surface into bright impervious surface and dark impervious surface after considering the significant differences in their spectral reflectance. This contribution provided the community with a better understanding of the composition of urban covers. A number of later studies have been conducted at the sub-pixel level, per-pixel level and segmented object level (Deng and Wu, 2013; Hu and Weng, 2009, 2011; Van de Voorde et al., 2011; Weng and Hu, 2008).

However, the composition of impervious surfaces in SAR data and their dielectric and geometric properties were insufficiently addressed in previous studies regarding the classification of urban impervious surfaces. This study aimed to develop a new scheme for impervious surfaces classification by investigating and understanding the composition of urban impervious surfaces in polarimetric SAR data. The compositions of land covers in the VIS model were re-examined under the context of their polarimetric mechanism in the SAR data, and thus various subclasses of each land cover class were identified to form the new scheme of ISC in polarimetric SAR data.

2. Study area and data sets

2.1. Study sites

The Pearl River Delta (PRD) has witnessed the most dramatic urbanization process in the world in the past four decades under the implementation of the *reform and opening* policy of the Chinese Government. Additionally, the PRD is a special metropolitan area because it includes three different urban planning and development policy bodies, Mainland China, Hong Kong and Macau. In PRD, numerous areas of urban impervious surfaces have been produced and have resulted in a wide range of environmental issues, such as urban flooding and air and water pollution. These impacts have been threatening the health of the environment and human beings in the whole PRD region, including Mainland China, Hong Kong and Macau. Continuous or timely monitoring of the urbanization dynamics using satellite remote sensing technology is important. However, the whole region is located in a subtropical climate zone, which is characterized by rainy and cloudy weather throughout the whole year. This weather brings great difficulties for optical remote sensing technology. Therefore, with the capability of penetrating clouds and rain, SAR remote sensing provides an ideal approach for monitoring the PRD area over a regional scale. In this study, three sites were carefully selected, including Shenzhen City from Mainland China, Hong Kong and Macau. The geographic locations of the study sites in the PRD are showed in Fig. 1. The Macau site actually includes a part of Zhuhai City (Wang Kam Island) from the Mainland.

2.2. Satellite data

Three scenes of fully polarimetric Radarsat-2 data at a fine resolution of 8 m were collected for the three study sites. The acquisition dates for the three Radarsat-2 data are listed in Table 1. These polarimetric SAR data were first calibrated using the Sentinel Application Platform (SNAP) toolbox provided by the European Space Agency (ESA). Various polarimetric decomposition methods were applied using SNAP. Detailed information about the decomposition methods were provided in Section 3.1. Finally, both the original SAR data and the polarimetric features were geocoded under the geo-reference systems of WGS 1984 and UTM projection system at Zone 49 N. Moreover, very high resolution optical satellite data from Worldview-2 and Google Earth at a spatial resolution of 2 m were used as the reference data. As shown in Table 1, the acquisition dates were very close to the acquisition dates of Radarsat-2 data in the three study sites. More details about the reference data are provided in Section 3.4.

3. Methodology

The methodology of this study is illustrated in the flowchart in Fig. 2, showing the proposed impervious surface classification scheme (within the dashed rectangle) and the working flow to