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Research paper

Investigation on the separability of slums by multi-aspect TerraSAR-X dual-co-polarized high resolution spotlight images based on the multi-scale evaluation of local distributions

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ABSTRACT

Following recent advances in distinguishing settlements vs. non-settlement areas from latest SAR data, the question arises whether a further automatic intra-urban delineation and characterization of different structural types is possible. This paper studies the appearance of the structural type “slums” in high resolution SAR images. Geocoded Kennaugh elements are used as backscatter information and Schmittlet indices as descriptor of local texture. Three cities with a significant share of slums (Cape Town, Manila, Mumbai) are chosen as test sites. These are imaged by TerraSAR-X in the dual-co-polarized high resolution spotlight mode in any available aspect angle. Representative distributions are estimated and fused by a robust approach. Our observations identify a high similarity of slums throughout all three test sites. The derived similarity maps are validated with reference data sets from visual interpretation and ground truth. The final validation strategy is based on completeness and correctness versus other classes in relation to the similarity. High accuracies (up to 87%) in identifying morphologic slums are reached for Cape Town. For Manila (up to 60%) and Mumbai (up to 54%), the distinction is more difficult due to their complex structural configuration. Concluding, high resolution SAR data can be suitable to automatically trace potential locations of slums. Polarimetric information and the incidence angle seem to have a negligible impact on the results whereas the intensity patterns and the passing direction of the satellite are playing a key role. Hence, the combination of intensity images (brightness) acquired from ascending and descending orbits together with Schmittlet indices (spatial pattern) promises best results. The transfer from the automatically recognized physical similarity to the semantic interpretation remains challenging.

1. Introduction

1.1. Thematic introduction

About 827 million people across the globe live in conditions that UN-HABITAT (UN-HABITAT, 2010) classifies as slums. Future projections suggest that by 2050 about two billion people will additionally live in self-built neighborhoods resulting from informal occupation and construction of precarious environments (UN-HABITAT, 2010; Werthmann and Bridger, 2016). The magnitude of these numbers reveals that informal city building is not a fringe phenomenon. Still, conventional data sources such as the census, maps or geodata on such locations are often outdated, incomplete, not reliable or missing completely. In consequence, spatiotemporal information on slums is scarce at the city scale. A global or at least large area inventory of informal settlements locations, extents or their morphology is inexistent (Kuffer et al., 2016). Consequently, the numbers on slum population presented above are of high uncertainty (Taubenböck and Wurm, 2015).

Remote sensing is able to provide the only consistent and area-wide data set that allows realizing local, regional or global knowledge on slum locations and structural characteristics. Unfortunately, the only indicator from UN-Habitats slum definition allowing the usage of earth observation data is the “durability of housing conditions”. Hence, recent studies try to relate this indicator to physical information present in EO-data in order to develop appropriate target classification approaches (Kuffer et al., 2016). The most frequently used characteristics are high building density, small building sizes, and irregular, organic patterns (Kohli et al., 2012a; Owen and Wong, 2013; Taubenböck and Kraff, 2014). A survey of current literature on classification techniques reveals that predominantly very high resolution optical satellite images have been exploited in slum mapping. Spectral as well as textural features within object-based image analysis in knowledge-based

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frameworks are dominating the developments (Niebergall et al., 2008; Hofmann et al., 2008; Hofmann, 2014; Shekhar, 2012; Kohli et al., 2013; Engstrom et al., 2015; Sandborn and Engstrom, 2016; Kuffer and Barros, 2011). Studies using synthetic aperture radar (SAR) techniques for the detection of morphologic slums are rare. SAR data are of high relevance in this domain because of their capability to provide a stable data set independent from atmospheric conditions or day-time. This is an important advantage compared to data sets acquired by optical sensors especially with regard to tropical regions in which many of cities with a large share of slum structures are located. Furthermore, the detection of urban settlements by means of polarimetric SAR acquisitions is shown to be possible (Ferro-Famil et al., 2001; Marino et al., 2012). However, the discrimination of different settlement types by SAR data sets is still challenging. The texture of the acquired images is a key feature for the separation between different settlement types due to the complexity of urban environments. The fundamental problem in the description of texture is the great variety of different texture measures from simple local statistics (Ulaby et al., 1986) to grey-level co-occurrence matrices (Habermeyer and Schmullius, 1997) and their interpretative derivations (Wen et al., 2009). Former studies search for the optimal descriptor, i.e. the (derived) SAR feature that shows the highest correlation with building density (Dell'Acqua and Gamba, 2003). While former classification algorithms were designed for the use of a low number of distinct layers, recent studies try to include the whole entity of multifaceted descriptors by using self-learning approaches like the random forest method for classification of slums (Wurm et al., 2017). Though the classification from hundreds of feature layers is not a problem any longer, the calculation of those layers still is time and memory consuming. Hence, simple approaches are preferred for the classification of large areas, e.g. the global urban footprint (Esch et al., 2013). Therefore, this study investigates the characteristics of slums in high resolution SAR images by their radiometric and spatial signature to distinguish between different settlement types. The data sets for this study are acquired by TerraSAR-X in the dual-co-polarized high resolution spotlight mode. Upcoming SAR satellite missions like the “Radarsat Constellation” (Canadian Space Agency, 2017) or the “High Resolution Wide Swath” mission (Krieger et al., 2010) will probably be able to provide suitable image data with comparable radiometric resolution, but a much larger coverage.

1.2. Methodological introduction

TerraSAR-X images show a very high spatial resolution up to 1 m though imaged from space. A large set of measurements hence is available per point of interest. Hence the number of pixels within an area of interest is much higher compared to former SAR sensors with a lower spatial resolution of e.g. 30 m. The mapping unit of one hectare formerly covered by roughly eleven pixels – which are necessary for the initial multi-looking prior to the polarimetric decomposition – contains about 10,000 pixels when acquired by TerraSAR-X. Consequently, the traditional pixel-based estimation and classification of the backscattering mechanisms by very sophisticated polarimetric decompositions (Rodrigues et al., 2003) is not appropriate for these data sets. Thus, it is reasonable to investigate agglomerations of measurements in the range of the mapping unit instead of dealing with isolated pixels.

Segment-based classification (Novack and Stilla, 2014) represents one possible approach for this investigation introducing geometric features, as e.g. shape, size and context parameters of the segments. This requires a high quality of the initial segmentation which is challenging with respect to SAR data (Hänsch and Hellwich, 2008). The segmentation algorithms applied to optical data assume a similarity of pixels which belong to the same segment and therewith, representing one object. In contrast, an object imaged by SAR generally appears as a collection of different backscattering effects, e.g. a residential house is characterized by the overlay of façade and forecourt, the roof, and the shadow behind. Even if highly accurate segment geometries from cadastral data (e.g. block units) are used, the imaging effects of SAR still impede a perfect match. Thus, we introduce a region-based evaluation as middle course between the pixel-based and the segment-based approach. The region-based strategy is partly pixel-based since the evaluation is performed at any position in the image and partly segment-based because a locally variable environment around the corresponding pixel is considered.

There are mainly two ways to investigate this large entity of measurements per evaluation point. First, a theoretical distribution function is adopted and its parameters are estimated from the samples (Tison et al., 2004). In the simplest case of a normal distribution, the number of parameters reduces to the mean and the standard deviation. With respect to SAR images of urban environments the definition of an encompassing distribution, i.e. one statistical distribution that is valid for all settlement types, is not feasible, because different settlement types actually show different kinds of distribution (Majd et al., 2012). Hence, the theoretical distribution is commonly chosen from a distribution family and adapted to the local image (Freitas et al., 2005). Second, the empirical distribution is accepted as it is and evaluated by so-called non-parametric approaches (Jäger et al., 2014). The latter approach is free from assumptions on the underlying statistics. In general, the computation of such algorithms is very expensive in terms of memory and time because of the usually high sampling rate which is required. The empirical probability density is commonly expressed by histograms. At this point, data preparation can help to reduce the number of bins of the histograms, i.e. the radiometric sampling rate, from several hundreds to just a few by a sophisticated and consistent scaling of the input data. The computing demand thus decreases considerably and the implementation becomes feasible with view to practical applications for the first time. One possible solution is provided by the TANH scaling implemented in the MultiSAR framework of DLR which will be introduced in the following and used as preprocessing environment for our SAR data sets.

2. Study area and data set

2.1. Reference data

For our experiments, we select three cities – Cape Town (South Africa), Mumbai (India), and Manila (The Philippines) – because of the following reasons: First, all three cities contain a significant share of slums, e.g. more than 50% of the population lives in slums in Manila. Morphologically these morphologic target areas are in line with the typically physical characteristics (small building extents, complex alignment of buildings, etc.) identified by an expert group (Sliuzas et al., 2008) as well as with the enhanced ontology presented by (Kohli et al., 2012b). Second, all three cities are very large cities featuring a diverse mixture of different structural types across the city, but at the same time the structural configuration is varying across these cities. The Cape Town test area comprises Khayelitsha which represents a mixture of formal settlements, townships (generally planned settlements, but with very low living conditions), and slums. Further land cover classes in the image are bare soil and vegetation. The Manila test site is characterized by high-rise buildings in the central business district, a large amount of formal residential buildings, the harbor zone with industrial buildings, and several rather small-sized slums. Water and park areas like the Manila Cemetery are the main non-settlements classes. The Mumbai test ground is a very diverse landscape consisting of water, bog, grassland, bare soil, railroads, highways, the airport, and settlements. The built-up area is composed out of chemical factories, the central business district, the Mumbai university campus, formal residential buildings, and large slums like Dharavi.

Thus, this setting allows evaluating transferability of the methodology across structural types of cities. Third, the availability of reference information on slum locations and extents is very scarce which limits the possible selection for test areas. Thus, we take advantage of