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Breaking new ground in mapping human settlements from space – The Global Urban Footprint

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ABSTRACT

Today, approximately 7.2 billion people inhabit the Earth and by 2050 this number will have risen to around nine billion, of which about 70% will be living in cities. The population growth and the related global urbanization pose one of the major challenges to a sustainable future. Hence, it is essential to understand drivers, dynamics, and impacts of the human settlements development. A key component in this context is the availability of an up-to-date and spatially consistent map of the location and distribution of human settlements. It is here that the Global Urban Footprint (GUF) raster map can make a valuable contribution. The new global GUF binary settlement mask shows a so far unprecedented spatial resolution of 0.4″ (∼ 12 m) that provides – for the first time – a complete picture of the entirety of urban and rural settlements. The GUF has been derived by means of a fully automated processing framework – the Urban Footprint Processor (UFP) – that was used to analyze a global coverage of more than 180,000 TanDEM-X and TerraSAR-X radar images with 3 m ground resolution collected in 2011–2012. The UFP consists of five main technical modules for data management, feature extraction, unsupervised classification, mosaicking and post-editing. Various quality assessment studies to determine the absolute GUF accuracy based on ground truth data on the one hand and the relative accuracies compared to established settlements maps on the other hand, clearly indicate the added value of the new global GUF layer, in particular with respect to the representation of rural settlement patterns. The Kappa coefficient of agreement compared to absolute ground truth data, for instance, shows GUF accuracies which are frequently twice as high as those of established low resolution maps. Generally, the GUF layer achieves an overall absolute accuracy of about 85%, with observed minima around 65% and maxima around 98%. The GUF will be provided open and free for any scientific use in the full resolution and for any non-profit (but also non-scientific) use in a generalized version of 2.8″ (∼ 84 m). Therewith, the new GUF layer can be expected to break new ground with respect to the analysis of global urbanization and peri-urbanization patterns, population estimation, vulnerability assessment, or the modeling of diseases and phenomena of global change in general.

1. Introduction

Global urbanization represents one of the most urgent present and future challenges. However, the real dimension of this phenomenon is still not completely understood – in particular with respect to a globally precise information basis on the location and distribution of human settlements in urban and – more specifically – in rural areas. Hence, this paper introduces a new inventory of human presence on Earth in form of the Global Urban Footprint raster map that reflects the human settlements pattern in a so far unique spatial resolution of 12 m. One of the most frequently referenced figures describing human settlements development is a simple graph composed of two lines representing the urban and rural percentages of the global population between 1950 and 2050. In 1950, the global rural population was twice as large as the urban population. Since then the rural population has been

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constantly decreasing, while the urban population has drastically increased. By around 2008 the urban population has exceeded the rural one for the first time in human history. This observation, commonly known as the global urban transition (UN, 2014), indicates that the majority of people on Earth inhabit some kind of urban environment. Arguments regarding the magnitude of global urbanization (UN, 2001, 2004, 2006; Birch and Wachter, 2011) have made clear to the global scientific and policy-making community that cities play a primary role as drivers of social, economic and environmental systems. Currently, there is considerable evidence that global urbanization impacts the entire spectrum of human and natural systems, in particular with respect to energy, water, food, biodiversity, climate or human health (Moore et al., 2003; Zhou et al., 2004; Kaufmann et al., 2007; Grimm et al., 2008; Tilman et al., 2011). The benefits and challenges of urbanization are comprehensively discussed in Daily and Ehrlich (1992), Johnson (2001), Cieslewicz (2002), Dye (2008), and Seto et al. (2011).

Beyond the global urbanization mantra, which is largely used to promote research agendas focusing on cities, fundamental questions still pertain to the knowledge about the spatial dimension of urbanization: Which proportion of the global land surface is covered with built-up area? What is the ratio between urban and rural settlements area? How many cities are on Earth? Many studies in fact share the view that estimations of the effects of human presence on Earth are strongly biased (Potere and Schneider, 2007; Potere et al., 2009) and that the dynamics of growth and its economic and social effects are poorly understood (Batty, 2008). Thereby the weak points regarding an objective view on global urbanization are clear: first, a shared definition of urban opposed to rural areas is missing. This is, in turn, reflected by a second critical issue - biased demography inventories on urban and rural population. Finally, a spatially detailed and up-to-date inventory of the entirety of urban and rural settlements on Earth does not exist so that any analysis on the global extent and development of human settlements is inherent to a certain bias. Meeting the third challenge regarding the lack of a detailed inventory of human settlements on Earth was the motivation for the GUF initiative and product, respectively. Earth observation (EO) imagery certainly represents an effective approach to overcome the lack of objective spatial information on the structure and spatiotemporal development of human settlements on Earth (Esch et al., 2010a). The global classification of human settlements is a very specific topic in urban remote sensing because of the necessary trade-off between spatial resolution of the available EO data and ability to collect a global coverage within a reasonable period of time.

A comprehensive overview of the available EO-based and EO-supported global geo-information layers on human settlements is provided by Potere et al. (2009), Gamba and Herold (2009) and Ban et al. (2015a). As they report, the majority of these data sets are generated from medium resolution (MR) optical EO data, as for instance the largely-established MODIS 500 (Schneider et al., 2010) and GlobCover 2009 (Bontemps et al., 2011) land cover maps with a spatial resolution of around 500 m and around 300 m, respectively. Although representing an important source of information, given their low resolution coupled with the existence of different definitions of urban areas, this first generation of global urban mapping products suffered from inaccuracy and considerable disagreements. For example, the results of a simple estimation of the total urban extent vary by an order of magnitude between VMAP0 and GRUMP, from 0.3–3.4 million km^2. Potere et al. (2009) report three main factors that cause such large inter-map differences: (i) the varying dates of the map production, (ii) different spatial resolution of the underlying data, and (iii) the varying definitions of urban land use. Moreover, their capabilities to accurately detect and delineate small and scattered villages and towns are quite limited. More recent initiatives aim to provide spatially more accurate human settlements layers based on high resolution (HR) EO data. NASA, for example, released in 2013 a new global night-time light product derived from imagery of the Visible Infrared Imaging Radiometer Suite (VIIRS) on board of the Suomi NPP satellite (NASA, 2012). The European Join Research Center (JRC) with the Global Human Settlements Layer (GHSL) presented a procedure for an automatic extraction of built-up areas by analyzing global Landsat coverage for several time steps (Pesaresi et al., 2016). Wieland and Pittore also proposed a method based on object based analysis and SVM to classify urban large areas from Landsat 8 (Wieland and Pittore, 2016). Miyazaki et al. (2013) propose a method based on the integrated analysis of ASTER satellite images and GIS data to produce a new global HR settlement mask. By means of Envisat-ASAR radar imagery, Gamba and Lisini (2012) and Ban et al. (2015b) derived a built-up area layer that aims at improving the GlobCover 2009 urban class.

In this publication we introduce a novel global settlements mask in a so far unique spatial resolution, the Global Urban Footprint (GUF), along with a description of the methodological framework deployed to generate this layer. Section 2 includes information about the underlying EO radar imagery collected in the TanDEM-X mission and a description of the Urban Footprint Processor (UFP) suite used to produce the GUF data set. After this technical section we focus on the characteristics of the new GUF product by providing a product specification, presenting the results of a quality assessment, giving a qualitative description of the main GUF characteristics, and showing first results regarding the global settlements statistics derived from the new GUF data. Finally, we draw the conclusions and provide an outlook on the future activities to support global urban observation and management with the GUF and planned add-on services and products.

2. The Global Urban Footprint framework

In 2007 and 2010 the German Aerospace Center (DLR) launched the EO radar satellites TerraSAR-X and TanDEM-X, respectively. In particular the ability to collect a global coverage of very high resolution SAR imagery within a comparably short period of time predestined the two missions to support global environmental monitoring activities. In previous studies we demonstrated the potential to delineate human settlements and basic land cover types based on SAR images by performing a combined analysis of speckle statistics and intensity information (Esch et al., 2010b, 2011). Encouraged by the promising outcomes of these studies, DLR's German Remote Sensing Data Center (DFD) started the internal Global Urban Footprint initiative. The goal of this activity was the development of a fully-automated processing framework to produce a world-wide map of human settlements in a so far unique spatial detail by analyzing a global coverage of TerraSAR-X and TanDEM-X images collected in the context of the TanDEM-X mission (Esch et al., 2012).

2.1. TanDEM-X mission

In June 2007, DLR launched its first EO radar satellite TerraSAR-X (TSX), followed by the identically constructed TanDEM-X (TDX) satellite three years later (Werninghaus and Buckreuss, 2010; Krieger et al., 2007). Both systems are part of the TanDEM-X mission which is the first bi-static, spaceborne SAR mission. The primary mission goal is the generation of a consistent global digital elevation model (DEM) with an unprecedented accuracy. It furthermore provides a highly reconfigurable platform for testing and demonstrating new SAR techniques and potential applications. Until mid-2014 TSX and TDX were flying in a unique formation