High-Resolution Global Monitoring of Urban Settlements

Mattia Marconcini, Thomas Esch, Andreas Felbier, Wieke Heldens

(Dr. Mattia Marconcini, German Aerospace Center, Wessling, Germany, mattia.marconcini@dlr.de)
(Dr. Thomas Esch, German Aerospace Center, Wessling, Germany, thomas.esch@dlr.de)
(Andreas Felbier, German Aerospace Center, Wessling, Germany, andreas.felbier@dlr.de)
(Dr. Wieke Heldens, German Aerospace Centre, Wessling, Germany, wieke.heldens@dlr.de)

1 ABSTRACT

Since the beginning of the 21st century, more than half of the global human population is living in urban environments and the dynamic trend of urbanization is expected to grow incredibly fast, with the number of urban dwellers currently increasing by about 180.000 people every day. In this framework, an effective monitoring of urban sprawl represents a key issue to analyse and understand the complexity, cross-linking and increasing dynamics of urban environments in order to ensure a sustainable development of urban and peri-urban areas. To this purpose, in the last decades satellite Earth observation (EO) has proved to be a promising tool in combination with widely automated methods of data processing and image analysis for providing up-to date geo-information on urban settlements at global scale; nevertheless, the geometric resolution of the current EO-based geo-information products is limited to 300-500 m, thus often resulting in poor accuracy to support decision makers and urban planners.

TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) is a German radar satellite mission aiming at the provision of a global digital elevation model (DEM) at 12 m spatial resolution. Besides this primary goal, the global coverage with very high resolution (VHR) TerraSAR-X (TSX) and TanDEM-X (TDX) imagery collected in 2011 and 2012 can be used to characterize settlement patterns worldwide in a so far unique spatial detail. Accordingly, the German Remote Sensing Data Center (DFD) of the German Aerospace Center (DLR) has implemented a fully-automated processing system that detects and extracts built-up areas from the global TSX/TDX imagery acquired in the context of the TDM. The output of this approach is a global binary settlement mask that outlines urban and non-urban areas at the unprecedented spatial resolution of ~0.4 arc sec (i.e., ~12 m). The intended, world-wide data set is called Global Urban Footprint (GUF) and a public domain version of it will be made available at ~3 arcsec (i.e., ~50-75m) spatial resolution. With its global coverage and the enormous spatial detail, this initiative represents a promising contribution to global analyses of urban and peri-urban areas.

2 INTRODUCTION

Urbanization is one of the most pressing global challenges; indeed, according to the United Nations Development Program (UN 2011), almost two-thirds of the world's population will live in cities by the year 2030 (as an example, in China and India the number of new cities with more than one million inhabitants will come up to 30 and 26, respectively, just within the next 20 years). It is approximated that urban areas cover about 2% to 3% of the Earth's surface. However, despite this rather marginal significance in terms of spatial coverage, metropolitan areas represent the focal points of human activity. Therefore, the impacts of urbanization on the natural and human environment are much more far-reaching at all geographic and socio-economic scales than the purely area-related perspective might imply. In this framework, regional to global analyses of urban growth patterns and the interrelation between urban areas and natural or anthropogenic processes have only just begun. Hence, there is much work remaining to provide spatially detailed, accurate and up-to-date geo-information on the patterns and processes within the urban and peri-urban environment. A key technology to provide the required data and information is satellite Earth Observation (EO), which in the last few years has proved being an effective tool for providing global geo-information on the location, spatial extent and distribution of urban areas. A comprehensive review of the available state-of-the-art EO-based and EO-supported global human settlements layers (GHSL) is given in (Gamba & Herold 2009, Potere & Schneider 2009). In particular, both papers highlights that the currently existing GHSL are mainly derived from medium resolution (MR) optical EO data, hence exhibiting a comparably coarse spatial resolution (i.e., at least a few hundred meters). Nowadays, the MODIS 500 (Schneider et al. 2009) and GlobCover (Bontemps et al. 2011) layers are considered to be the most accurate urban data sets provided on a global level; nevertheless, their limited spatial resolution (i.e., 463 m for MODIS 500 and 309 m for GlobCover) do not allow a precise characterization of urban settlements, especially in rural and peri-urban areas (which are

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characterized by small and scattered villages and towns). Accordingly, some recent initiatives aimed at improving the current GHSL by developing efficient processing techniques for delineating settlement extents based on high resolution (HR) and VHR EO data. In this context, most promising approaches are based on: the analysis of a new global nighttime lights product derived from imagery of the Visible Infrared Imaging Radiometer Suite (VIIRS) (NASA 2012), the use of HR/VHR optical imagery (Pesaresi et al. 2011), and the employment of HR/VHR SAR data collected by the latest generation of radar satellite sensors (i.e., Envisat-ASAR, ALOS-PALSAR, Radarsat-1/2, TerraSAR-X, TanDEM-X, COSMO-Skymed).

The latter type of approaches looks particularly promising as, with respect to optical sensors, the weather-independent, day-and-night data acquisition capability and the low sensitivity towards atmospheric effects of SAR systems make them particularly suitable to provide temporally and radiometrically consistent global data coverages. In this framework, the authors yet explored and assessed the capabilities of the German TanDEM-X mission (TDM) (Krieger et al. 2007) to monitor built-up areas at very high resolution (Esch et al. 2012). With two global coverages of VHR SAR data acquired at 3m spatial resolution and collected within a period of about one year, the German TDM is predestined to be included to the new initiatives aiming at the provision of innovative GHSLs. Accordingly, the German Remote Sensing Data Center (DFD) of the German Aerospace Center (DLR) has developed and implemented the Urban Footprint Processor (UFP), i.e. a fully-automated, operational image processing and analysis procedure that detects and delineates built-up areas from the global TDM data. The outputs of the UFP are binary settlement masks – the Urban Footprint (UF) masks – indicating built-up and non-built-up areas at a spatial resolution of 0.4 arcsec (~12 m). The global coverage of UF data sets will then be used to generate a world-wide inventory of human settlements – the Global Urban Footprint (GUF) layer – that is also intended to be publicly provided at a spatial resolution of ~3.0 arcsec (i.e., ~50-75m).

3 URBAN FOOTPRINT PROCESSOR

The basic methodological components for detecting built-up areas from TSX/TDX data have been already introduced by the authors in (Esch et al. 2012). However, to effectively process the huge TDM mass data set of about 300 TB (one coverage comprises ~180,000 complex SAR images with each image having an average size of ~50,000 × 40,000 pixels), the abovementioned approach has systematically been enhanced and transformed into a fully-automatic processing chain with several additional modules and functionalities (Esch et al. 2013), namely the UFP. This processing chain takes single look slant range complex (SSC) Stripmap data of one TDM coverage (2011/2012) as input. The image analysis and classification module consists of three main components, namely feature extraction, classification stage, and mosaicking and post-editing. Each of them is described into details in the following.

3.1 Feature Extraction

The aim of the first module of the UFP is to extract the“speckle divergence” (Esch et al. 2010), an effective texture feature capable of highlighting areas characterized by heterogeneous and highly structured built-up. In particular, due to the strong scattering from double bounce effects in urban areas typical of SAR data, the attention is focused on the analysis of the local speckle and its development is estimated accounting for the local image heterogeneity $\mathcal{H}$ (Esch et al. 2012) defined as:

$$\mathcal{H} = \sigma_{\mathcal{A}} / \mu_{\mathcal{A}} \tag{1}$$

where, $\sigma_{\mathcal{A}}$ and $\mu_{\mathcal{A}}$ represent the standard deviation and mean, respectively, of the original backscattering amplitude image $\mathcal{A}$ (stored inside a Single Look Slant Range Complex image product, SSC) computed in a local neighborhood. The image heterogeneity $\mathcal{H}$, the fading texture $\mathcal{F}$ (which represents the heterogeneity caused by speckle) and the true image texture $\mathcal{T}$ are related as follows (Potere et al. 2009):

$$\mathcal{H}^2 = \mathcal{T}^2\mathcal{F}^2 + \mathcal{T}^2 + \mathcal{F}^2 \tag{2}$$

Accordingly, it is then possible to demonstrate (Esch et al. 2010) that (when considering radiometrically unenhanced SSC products as in our case) a reliable estimate $\hat{\mathcal{T}}$ (i.e., the speckle divergence $\mathcal{S}$) of the local true image texture is given by:

$$\hat{\mathcal{T}} = \mathcal{S} = (\mathcal{H} - 0.5)/1.5 \tag{3}$$

To reduce the amount of data (due to technical restrictions) the multi-looking described in (Eineder et al. 2004) is finally performed for rescaling both $\mathcal{A}$ and $\mathcal{S}$ to a spatial resolution of ~0.4 arcsec (~12 m).

3.2 Classification

The second module of the UFP is dedicated to the production of a binary settlement layer (built-up, non-built-up) for the investigated scene once provided as input with the backscattering image $\mathcal{A}$ and the corresponding speckle divergence $\mathcal{S}$ and implements the technique described in (Marconcini et. al 2013). Generally, pixels associated with high values of $\mathcal{S}$ correspond to urbanized areas, while those exhibiting lower values correspond to non-built-up structures. Accordingly, for each investigated scene the objective is to determine a specific optimal threshold for $\mathcal{S}$ capable of effectively discriminating between built-up and non-built-up areas. Initially, all the pixels showing a backscattering amplitude lower than the prefixed threshold $Th^{\mathcal{A}} = 100$ are marked as non-urban, since they always correspond to information classes not belonging to built-up areas (e.g., water bodies, surfaces with a smooth meso-scale roughness). A set of M candidate thresholds for $\mathcal{S}$, $Th_1^{\mathcal{S}} > \ldots > Th_M^{\mathcal{S}}$, is then determined based on the specific image dynamics. For each of them, pixels are categorized into urban ($\mathcal{U}_m$) or non-urban ($\mathcal{L}_m$) candidates depending on whether the corresponding speckle divergence value is greater or lower than $Th_m^{\mathcal{S}}$, respectively. Afterwards, we compute the Jensen-Shannon divergence $D_{JS}[U_m \| L_m]$ (Lin 1991) accounting for both $\mathcal{A}$ and $\mathcal{S}$, which allows to estimate the "distance" between U_m and L_m (i.e., the probability distributions of $\mathcal{U}_m$ and $\mathcal{L}_m$, respectively). The higher the divergence, the higher is the distance between the two distributions and vice-versa. $D_{JS}[U_m \| L_m]$ assumes high values for higher values of $Th_m^{\mathcal{S}}$, while it decreases as the threshold gets lower. As soon as the two distributions U_m and L_m start to significantly overlap, then there always occurs a consistent fall in $D_{JS}[U_m \| L_m]$. When this happens, the corresponding threshold $Th_{m*}^{\mathcal{S}}$ is selected as optimal for the specific image under analysis and the subset $\mathcal{U}_{m*}$ is employed for training a one-class classifier based on support vector data description - SVDD (Tax and Duin, 2004). This approach allows increasing generalization and obtaining a more consistent and reliable final UF map $\mathcal{G}_{m*}$.

3.3 Mosaicking and Post-editing

The last module of the UFP implements automated mosaicking and post-editing operations to further improve the quality of the generated UF products. The criterion adopted for selecting the optimal threshold for $\mathcal{S}$ generally proved effective and robust. Nonetheless, it might happen that one or few UFs exhibit slight under- or over-estimation of urban areas with respect to corresponding neighboring UFs when mosaicking multiple images. To solve this problem we implemented a simple but effective technique, which accounts for the partial overlap occurring between neigbouring TDX/TDM scenes. In particular, by comparing the amount of samples categorized as urban falling in the intersections we can identify which UFs need to be improved and whether under- or over-estimation occurs and we then modify the threshold accordingly (i.e., we select the one resulting in the the lowest difference with respect to the neighboring UFs in terms of number of urban samples). It is worth noting that, sometimes highly mountainous areas could be wrongly categorized as built-up regions as they exhibit high values for both $\mathcal{A}$ and $\mathcal{S}$ as an effect of the particular topography. In order to solve this problem a dedicated mask has been implemented by taking into consideration the ASTER Global DEM (NASA 2013) and marking all those pixels showing a slope (i.e., the maximum rate of height change between each pixel and its closest eight neighbors) higher than 20 in the neighborhood of a local peak as non-urban. This approach allowed minimizing this type of error and to preserve urban settlements on the side of the mountains.

4 URBAN FOOTPRINT SETTLEMENT MASK

So far, the UFP has yet produced both $\mathcal{A}$ and $\mathcal{S}$ for a total of 140,000 scenes acquired in the context of the first TDM coverage (2011/2012) with each scene covering an area of ~50 × 30 km. Moreover, a number of globally distributed test runs for the final GUF generation have been performed investigating either single scenes or extensive mosaics consisting of several hundred images. An accuracy assessment of the corresponding results showed that the overall accuracies mostly lie in a range of 70 - 90 %. These results are in line with the outcomes of earlier studies investigating the methodological precursors of the UFP technique (Esch et al. 2010, 2012). Figure 1 reports optical data from Google Earth, TDM backscattering amplitude $\mathcal{A}$, speckle divergence $\mathcal{S}$, urban footprint and corresponding GlobCover 2009 urban class map for four representative cases, namely the cities of Accra (Ghana), Dar es Salaam (Tanzania), Baghdad (Iraq), and Amsterdam (The Netherlands). The different scales of the given examples allow to assess the capabilities of the GUF to see the large area settlement patterns in their spatial configurations with e.g. Accra or Dar es Salaam

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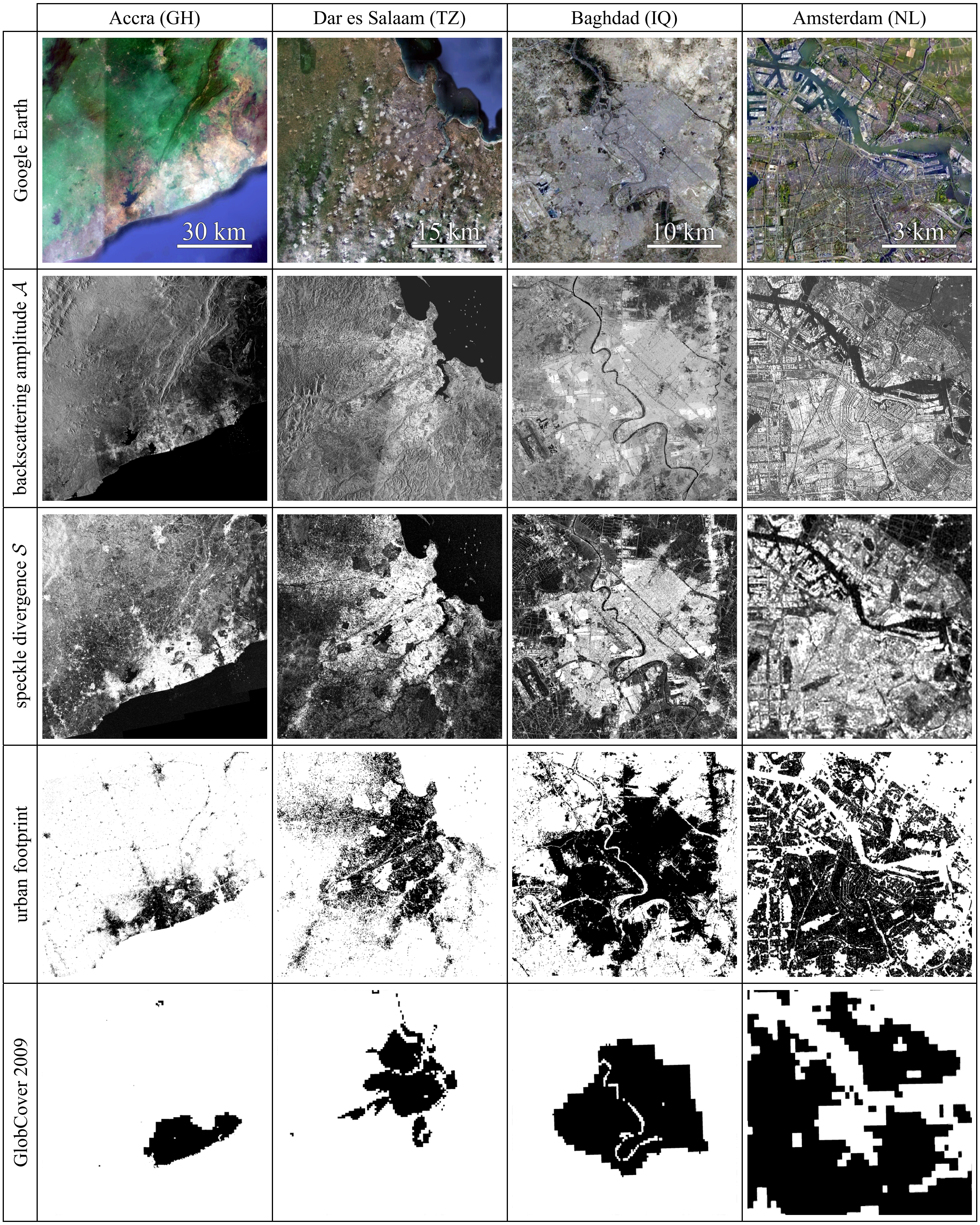

Fig. 1 – Optical data (from Google Earth), TDM backscattering amplitude $\mathcal{A}$, speckle divergence $\mathcal{S}$, urban footprint and corresponding GlobCover 2009 urban class map for the cities of Accra (GH), Dar es Salaam (TZ), Baghdad (IQ), Amsterdam (NL).

as dominating urban centers and a hierarchical system of smaller urban centers or low density rural settlements. At the same time, structural details of cities are captured as the examples of Baghdad and Amsterdam. The capability of the algorithm to even ignore open spaces without any vertical structures such as buildings etc. or green belts within the urban centers becomes obvious. The examples stress that the settlement patterns can be extracted and characterized for diverse geographical regions and landscape types by means of TDM imagery and the UFP system.

5 CONCLUSION

In this paper we presented DLR's Global Urban Footprint (GUF) initiative along with its technical implementation, i.e. the fully-automatic processing and image analysis system of the Urban Footprint Processor (UFP). Using the already acquired TDM data of the first coverage (~140.000 images over ~180.000), we could yet test the performance of the processing chain and assessed the resulting built-up mask on the basis of several thousand globally distributed images. The results of these tests demonstrate the high potential of the GUF approach to provide a spatially detailed map of global settlement patterns for urbanized areas as well as for rural regions. With the described characteristics, the GUF (whose first completion is envisaged for 2014) will provide a unique data set that is to some extent complementary to the existing GHSLs derived from medium (MR) or high resolution (HR) optical imagery. Moreover, in addition to the full-resolution 12 m product also a public domain version downscaled at ~3 arcsec (i.e., ~50-75 m) will be generated.

Considering the challenges of the GUF production, we still investigate in the potential to improve the classification stage of the UFP. In particular, we intend to identify potentially existing, systematic weaknesses of the UFP that might not have been discovered so far and at the same time we gain more precise knowledge on the performance and optimal tuning of the algorithms for the classification and mosaicking stage. Regarding follow-on research and development, it is planned to adapt the UFP to all TSX/TDX imaging modes (ScanSAR, SpotLight) as well as to other SAR satellites such as Sentinel-1 or Radarsat-2. Moreover, the calculation and consideration of long-term coherences will be investigated. First studies have also shown the potential to characterize building structures and estimate building densities based on texture measures or the modeling of building volume on building block level using the VHR DEM data generated on the basis of TDM imagery.

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