The path to mapping the global urban footprint using TanDEM-X data

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Abstract – Global mapping of urban environments is a challenging task. Earth observation is probably the only source possibly providing a consistent and area-wide data set. With the German TanDEM-X mission two global coverages of high resolution radar data will be available for 2011 and 2012. While the main task of the mission is the derivation of a global digital elevation model, the collected data will additionally be used to classify urban areas. This paper gives an overview on the data sets, the method to derive urban footprints, the products and its accuracy.

Keywords: Remote Sensing, Urban Analysis, TanDEM-X, urban footprint, Classification

1. INTRODUCTION

According to United Nations predictions, by the year 2030 60% of the world's population will live in cities (UN, 2007). The inexorably process of urbanization, especially in developing countries, often results in a lack of up-to-date and area-wide knowledge for sustainable strategic development needed by politicians, urban planers, stakeholders or scientists. Often, there isn't even knowledge on the current extent of the city, the number of buildings or the population. Earth observation data provide the opportunity of independent views of the city in different spatio-temporal dimensions, in various scales.

Earth observation has been focused on mapping, monitoring quantifying and qualifying these urban phenomena for many years, with emphasis on local to regional scales. Global mapping is particularly challenging because of the spatial and structural heterogeneity of urban environments (Potere, 2009).

In 2011 and 2012 the German space mission TanDEM-X will acquire two coverages of the entire landmass of the world. This data set will be processed to a digital elevation model with 10 m posting (Huber, Younis, & Krieger, 2010). Mapping the global urban footprint will be based on this immense data source, too. This paper presents the idea of deriving a global urban footprint, including the data, the techniques, the product and its accuracy.

2. THE PATH OF MAPPING THE GLOBAL URBAN FOOTPRINT

Data

The TanDEM-X mission (TerraSAR-X add-on for Digital Elevation Measurement) comprises two almost identical earth observation satellites, TerraSAR-X and TanDEM-X. Both are equipped with a powerful modern Synthetic Aperture Radar (SAR). It permits observing the earth's surface not only in daylight but also when it is obscured by darkness and/or clouds.

The TerraSAR-X satellite provides different modes and incidence angles to scan the earths' surface. Available modes are ScanSAR (with a swath of 100km and an azimuth resolution of 16m), stripmap (30 km; 3m) and SpotLight (10km; 1m) (Herrman & Bottero, 2007). The standard mode for the DEM production is the 'Stripmap' single polarized mode with approximately 3 m spatial resolution. These data are input to the urban footprint extraction. The swath width is 30 km, one strip is up to several hundreds of km long. The input product for the mapping of the built-up area is the so called CoSSC, the single look complex format.

Method

The proposed methodology includes a specific pre-processing of the SAR data and an automated image analysis procedure. The pre-processing focuses on the analysis of local speckle characteristics in order to provide a texture layer that highlights built-up areas. In the context of a pixel-based image analysis this texture layer is used along with the original intensity information to automatically extract settlements (Esch et al., 2010).

The analysis of the local image heterogeneity C_S by means of the coefficient of variation (CoV) is an established and straightforward approach to define the local development of speckle in SAR data:

$$C_s = \frac{\sigma_s}{\mu_s} \qquad (1)$$

with μ_S giving the mean backscatter amplitude value and σ_S representing the standard deviation of the backscatter amplitude in the neighbourhood of the center pixel in the SAR image. Generally, the image texture C_S results from a combination of the true image texture - C_T - and the fading texture - C_F – representing the heterogeneity caused by speckle:

$$C_s^2 = C_T^2 C_F^2 + C_T^2 + C_F^2 \qquad (2)$$

Highly textured surfaces – e.g. urban environments or woodland - show various distinct structures, leading to an increase of directional, non-Gaussian backscatter. Hence, the texture for such regions results from C_T and C_F so that the measured image texture C_S takes comparably high values. In turn, homogeneous surfaces without any true structuring - such as grassland or non-cultivated bare soil -, show almost no true texture C_T, meaning that the measured image texture C_S more or less equals the fading texture C_F. Moreover, the backscatter is almost randomly distributed and C_S shows very low values.

In order to define a robust measure describing the true image texture C_T we make use of these characteristics. Thereby we determine the difference between measured local image heterogeneity C_S and theoretical scene-specific heterogeneity C_F

due to fully developed speckle. We assume that the local deviation from the fully developed speckle - the true local texture C_T - increases with a rising amount of real structures within the resolution cell. Accordingly, the local true image texture C_T is defined by:

$$C_T = \frac{C_S - C_F}{1 + C_F} \qquad (3)$$

Figure 2 shows the texture image C_T – called speckle divergence - derived from the TSX SM intensity image of Changsha, China. The brightest regions in the image correspond with urban areas, the medium gray values indicate woodland while a low speckle divergence characterizes open areas such as agricultural fields, grassland or water bodies.
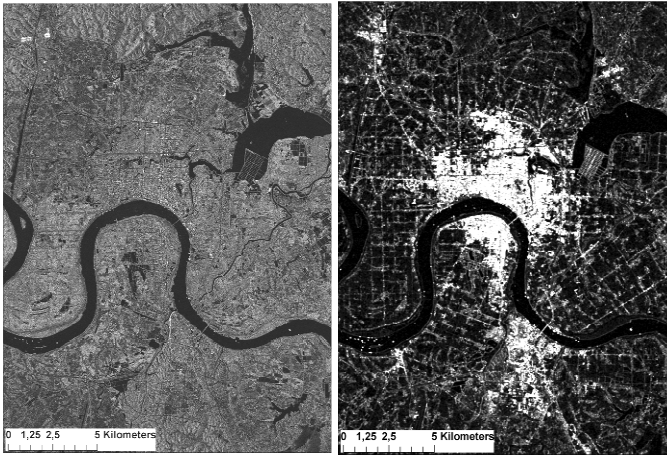

Figure 1: TerraSAR-X stripmap data and derived texture file showing the city Changsha in China

The speckle divergence texture file serves as input to the classification procedure. The classification starts with the comparison of the locally (15x15) and regionally (45x45) averaged C_T against two thresholds. In case that one of the thresholds is exceeded, the according image region is classified as a distinct backscattering cluster (DBC). The thresholds are set in a way that only pixels with a very high local or regional deviation from the scene-specific level of speckle-induced heterogeneity are assigned as DBC. In a second classification step all image regions showing both a certain amount of DBC in a neighbourhood of 99x99 pixels and a regionally increased C_T – defined by two additional thresholds – are assigned as built-up area (BA). Next, DBC are integrated into the class BA and all unclassified pixels are assigned as 'non-built-up area' (NBA). BA and NBA form a binary mask. The outcome represents the final urban footprint image (Fig. 2).

The product

The term 'urban footprint' is widely used in literature and basically refers to the spatial extent of urbanized areas on a regional scale; however, it is a fuzzy definition. Cahn (1978) understood the term 'urban footprint' as the land directly occupied by a particular structure. Thus, his definition is represented by a 'settlement mask', defined by buildings, streets and impervious surfaces. With an intended geometric resolution of 12 meters a concept behind classifying a pixel as 'urban' is as follows: Pixels of the classification refer to the landcover type urban, if a pixel is dominated by built environment, which includes human-construct elements, roads, buildings, runways and industrial facilities. When open land (e. g. vegetation, bare soil) dominates a pixel, these areas are not considered urban, even though they may function as urban space (Potere & Schneider, 2009).

Based on this theoretical concept, the definition for the intended 'urban footprint' product derived from TerraSAR-X and TanDEM-X data needs to come directly from the algorithm itself. As defined in section 2.2 the developed algorithm primarily detects vertical structures, which consist of buildings, but also cars, street signs, etc. These structures belong typically to the man-made urban environment. In addition, the subsequent generalization of the detected DBC by the algorithm allows identifying highly structured areas around these seed points. As a result, in line with the settlement mask defined above, the physically based definition of the 'urban footprint' is a logical consequence for our 'urban footprint' map. However, it has to be stressed that the 'urban footprint' therefore reflects the distribution of man-made structures with a vertical dimension – e.g. buildings, poles, traffic signs, etc.. In turn, flat areas such as streets, runways etc. are not included. Figure 2 shows the urban footprint derived for the city of Changsha, China.
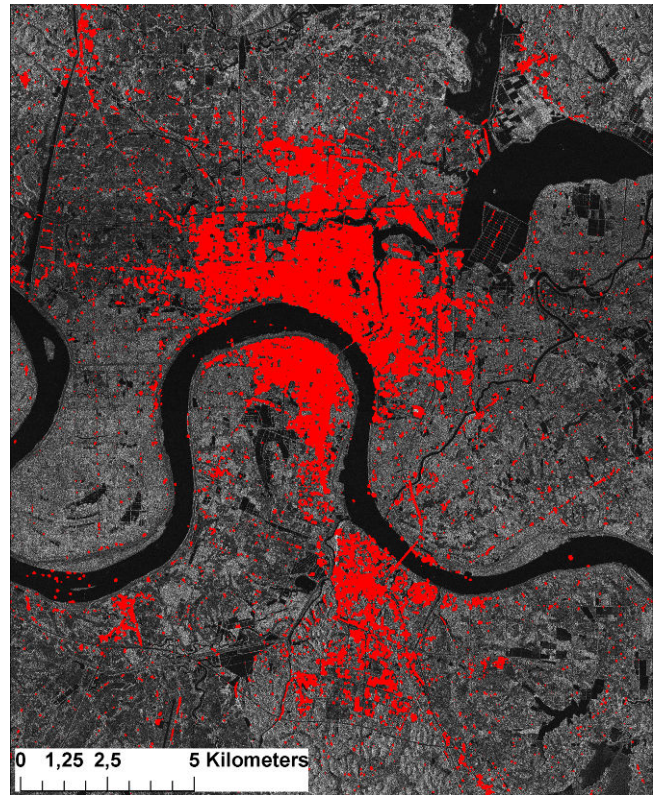

Figure 2: Urban footprint generated for region of Changsha, China

On a regional scale the urban footprint product provides insight into dimension, directions, patterns and location of the city. Recent applied research has used remotely sensed images to quantitatively describe the spatial structure of urban environments and characterize patterns of urban morphology on urban footprint

level. With methods like landscape metrics, gradient analysis or zonal statistics the urban patterns have been quantified (Jat, Garg & Khare, 2008; Sudhira, Ramachandra & Jagadish, 2003; Taubenböck et al., 2009). The consistent global data sets will also enable comparative studies between cities. Furthermore, multi-sensoral approaches have already been applied to analyse the spatial dimension and configuration over time.

Accuracy

The urban footprint is an abstract approximation of the particular city, as defined in section 2.3. Knowledge of the accuracy is essential for evaluation of fields of application and assessment of information value. As the intended global urban footprint product cannot be validated area-wide, the accuracy has been tested for different urban areas around the globe using manifold methods and reference data sets. In any assessment of map accuracy it is important to have a clear definition of the map attributes under review.

Esch et al. (2010) checked the classified urban footprint comparing the results to the original TerraSAR-X stripmap data by a visual verification process. Using a random distribution of check points the accuracy has been calculated for 12 structurally different cities around the globe (e. g. Buenos Aires, Munich or Padang). On average the overall accuracy came up to 90 %. Thus, the urban footprint proves high accuracy values on a regional scale.

However, in a different study the derived urban footprints have been compared to geometrically and thematically highly resolved reference data: a 3-D city model with a geometric detail of 1 meter and a thematic resolution of 8 land-cover classes, namely 'buildings', 'streets', 'sealed areas', 'grassland', 'forest', 'bare soil' and 'water' and an accuracy of 97 % is used (Taubenböck et al., 2009). With it, a multi-scale comparison between the regional urban footprint product and the high resolution 3-D city model was applied. The binary layer of the "urban footprint" was related to two different definitions of the urban footprint: First to the built-up areas consisting of buildings, streets and sealed areas (settlement mask). Second, to an alternative definition – the building mask only comprising vertical artificial elements. The square measures comparison reveals that the urban footprint derived from TerraSAR-X stripmap data relates closely to the spatial extension of the settlement mask. The overall accuracy resulted in 79.2 % to the settlement mask and 74.28 % to the building mask. This accuracy assessment allows defining in more detail the often unclear usage of the word 'urban footprint' (Taubenböck et al., 2011). The accuracy shows that due to the physical classification concept of the radar data an exact and direct reference to thematic classes as shown with the building mask or the settlement mask is partly misleading. However, the settlement mask derived from the 3-D city model proved to be a good approximation of what the urban footprint represents. With respect to the measured accuracy (cp. Section 2.3), the derived urban footprint classifies structured areas.

Furthermore, a dependence of the accuracy has been measured with respect to differing urban structures: E. g. with rising built-up densities the over-classification of the urban footprint increases as well. Thus, it is expected that the accuracy of the global product will not be consistent as the urban structures vary immensely around the globe.

3. CONCLUSION AND OUTLOOK

The new German satellite missions of TerraSAR-X and TanDEM-X allow a never before seen geometric capability for mapping urbanized areas on a global scale. Thus, the German Remote Sensing Data Center of DLR intends to provide a global urban reference data set for the year 2011. The term 'urban footprint' refers to a physical based definition.

The urban footprint map will allow analysis on the percentage of urbanized areas, their location and spatial configuration on a global, continental, national or regional level. With high accuracies, to date tested on sample cities across the world the urban footprint product will provide a reliable, independent, area-wide and up-to-date geo-information base.

The measurement and quantification of urban extents, urban corridors or spatiotemporal effects will indirectly allow interpreting causes of dynamic spatial growth. Thus, new scientific questions will arise: E.g. comparative studies will allow analysis of spatial urban trajectories across cities to identify similar effects. The indirect correlation of demographic data sets with the urban footprints will allow research for population assessment and up-dating of population numbers and spatial distribution.

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