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How good is the map? A multi-scale cross-comparison framework for global settlement layers: Evidence from Central Europe

M. Klotz [a,*], T. Kemper [b], C. Geiß [a], T. Esch [a], H. Taubenböck [a]

[a] German Aerospace Center (DLR), German Remote Sensing Data Center (DFD), Oberpfaffenhofen, 82234 Wessling, Germany
[b] European Commission, Joint Research Center (JRC), Institute for the Protection and Security of the Citizen, 21027 Ispra, Italy

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A B S T R A C T

Mapping of settlement areas from space is entering a new era. With the recently developed Global Urban Footprint (based on radar data from TanDEM-X) and the Global Human Settlement Layer (based on optical data), two new initiatives that promise to map complex settlement patterns at global scales and unprecedented spatial resolutions are about to enter the scientific and map user community. However, comparative studies on these layers' strengths and weaknesses, especially in terms of their potential added value with regard to existing lower resolution maps, as well as their assessed accuracy are still absent. In this regard, we introduce a multi-scale cross-comparison framework that uses the best existing urban maps as a benchmark. To paint a complete picture, we simultaneously address several components of map accuracy including relative inter-map agreement, absolute accuracies and pattern-based classification differences. This framework is applied to present regionally representative results from two Central European test sites. In this, we find that the new base maps bring decisive advancements in preserving the small-scale complexity of global human settlement patterns beyond urban core areas. Relative inter-map comparison exposes low density settlement regions traditionally under-represented by lower resolution maps that are now recognized. Absolute metrics such as the Kappa coefficient of agreement (K) show that accuracies of the new high resolution layers ($\overline{K} = 0.56$–0.58) nearly double those of existing products. Beyond, they feature substantial consistency between urban ($\overline{K} = 0.46$–0.50) and rural landscapes ($\overline{K} = 0.41$–0.45). Results from pattern-based exploration further reveal significant correlation of accuracies with physical pattern variations such as settlement density and mark a clear shift of accuracies from large to medium and small patch sizes. This differentiated view on classification accuracies shows that the new generation of urban maps constitutes a significantly enhanced spatial representation of large-scale settlement patterns.

1. Introduction

Global urbanization may well be the most important transformation that our planet will undergo in the 21st century. Even today, more than half or the world's population – approximately 54% – is living in urban areas, marking the dawn of the "urban century" (UN, 2014a). According to the United Nations' population projections, this share is expected to further increase to two-thirds in 2050 making cities the focal places of worldwide demographic growth. As our world progresses to demographically urbanize, the upcoming decades will bring along substantial changes with regard to size and spatial patterns of human settlements on our planet. New dimensions of urban landscapes such as mega-regions are increasingly being recognized (e.g., Florida, Gulden, & Mellander, 2008; UN-HABITAT, 2013; Taubenböck et al., 2014). Beyond, spatial complexity of urban transformation through e.g., peri-urbanization (e.g., Simon, 2008, Taubenböck, 2015), growth of urban villages and edge cities (Garreau, 1991; Anthrop, 2000), or the infrastructural delinking of rural areas located in the urban shadow (Main, 1993, Taubenböck & Wiesner, 2015) is constantly increasing. From a spatial perspective, the social, economic and environmental implications of global urbanization are not directly tangible. Nonetheless, the requirement of detailed, up-to-date, accurate and consistent information on the spatial patterns and dynamics of global settlements is today widely acknowledged (Potere & Schneider, 2007; Taubenböck et al., 2012; Esch, Marconcini, Felbier, Heldens, & Roth, 2014; Esch et al., 2012; UN 2014a, 2014b; GEO, 2014). In fact, it presents one key to understanding worldwide urbanization processes, and prerequisite to developing and supporting actions towards sustainable urban and rural development goals.

In this regard, satellite-based earth observation (EO) from space has long been recognized as an independent tool for the provision of area-wide spatial information on the location of settlement features and their spatial distribution from global (i.e., large-scale urban areas) to local scales (i.e., individual buildings). In the past decades, several initiatives coming from both government and academia have produced

* Corresponding author at: German Aerospace Center, German Remote Sensing Data Center:
E-mail addresses: martin.klotz@dlr.de (M. Klotz), thomas.kemper@jrc.ec.europa.eu (T. Kemper), christian.geiss@dlr.de (C. Geiß), thomas.esch@dlr.de (T. Esch), hannes.taubenboeck@dlr.de (H. Taubenböck).

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profound global maps on the size and spatial distribution of human settlements or related spatial attributes. This first generation of urban maps heavily relied on satellite sensors of relatively low geometric resolution (LR; ≥300 m acc. to EC-Copernicus, 2014). However, with the Global Urban Footprint (GUF) (Esch et al., 2013) and the Global Human Settlement Layer (GHSL) (Pesaresi et al., 2013), two new initiatives that promise to be capable of mapping fine-scale and complex human settlement patterns at unprecedented spatial resolutions and global scales are now becoming available. Knowledge on these layer's strengths and weaknesses in terms of their assessed accuracy, quality and overall agreement is however yet few and far.

In this regard, we present the first comprehensive cross-comparison that integrates these recent advancements in high resolution (HR; 4–30 m) settlement mapping into the portfolio of existing coarse resolution urban maps. To answer the call for a degree of confidence associated with the results from remote sensing-based land cover classifications (e.g., Richards, 1986; Congalton, 1991; Foody, 2002), our focus is on the capabilities of recently produced HR settlement maps respecting the best existing LR maps as a benchmark. To paint a complete picture, we develop and apply a comprehensive, multi-layered comparison framework that incorporates techniques of absolute accuracy assessment, analysis of relative inter-map agreement and exploration of pattern-based classification differences. We apply this framework for two large-scale test sites of varying landscape character in Central Europe. Within this setting, we present quantitative regional evidence on the mapping capabilities of the latest efforts in HR settlement mapping. In this, we address several specific research questions on the accuracy and validity of the respective layers under test:

(1) How and to which degree do new high resolution settlement layers correspond to existing global products of lower geometric resolution in a Central European setting?
(2) How accurate are different – high and low resolution – global geo-information layers in absolute terms regarding the representation of complex settlement features and their spatial configuration in Central Europe?
(3) How does the accuracy of these layers vary for structurally different areas, i.e., urban versus rural landscapes, in Central Europe?
(4) Does the accuracy of global settlement layers show spatial variation with regard to the physical configuration of human settlements, i.e., size or density, in Central Europe?

Building upon the presented framework, we aim at fostering the user-oriented assessment and definition of the novel products on the way to a global inventory of high resolution settlement information. The remainder of this work is organized as follows. The subsequent section presents relevant background information on past and present mapping and validation efforts followed by a review of techniques for meaningful accuracy assessment techniques. Section 3 depicts the layers under study from a technical perspective in combination with a brief description of the selected test sites, reference and ancillary data employed. The key methodological framework is summarized in Section 4 along with the scale-dependent steps of analysis taken. Section 5 presents the main results that are summarized and discussed in Section 6. Section 7 concludes with a final perspective and future directions.

2. Background & rationale

2.1. Overview of past and present global settlement mapping initiatives and their validation

Until the year 2000, only one dataset existed that aimed at representing the extent of the Earth's urban areas. The Digital Chart of the World (Danko, 1992; also known as Vector Map Level 0 (VMAP0)) was the predecessor to several global human settlement mapping initiatives since the millennium. These initiatives have produced an extended portfolio of ten global urban maps. Among these, six present urban areas as distinct human settlement outlines. In addition, four more layers model continuous physical features related to human settlement activity such as the degree of imperviousness of the land surface, the intensity of stable night-time illumination or the ambient local population. Satellite remote sensing data employed were mainly imagery from coarse resolution optical sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS), Satellite Pour l'Observation de la Terre (SPOT) or the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS). Table 1 gives a comprehensive overview of these layers including particular thematic and geometric specifications, data employed for map generation and their assessed accuracy according to Potere, Schneider, Angel, and Civco (2009).

Although these layers' usefulness and applicability for global analysis of larger urban areas are widely recognized, there are some problematic issues associated with their use: Heterogeneity in terms of geometric resolution (300 m–10 km), thematic representation (multi-category/binary/continuous information), and employed input data (EO/census/maps/data fusion) demands a high degree of expert knowledge by the map user. Beyond, the issue of a missing universally accepted, consistent and unambiguous definition of urban areas across these datasets is one of the major drawbacks with regard to their application (Schneider, Friedl, & Potere, 2010). Consequently, there is a large disagreement between the maps' total estimated shares of urban land at the global scale (Fig. 1). Beyond, inconsistencies between different scales of map representation (i.e., global vs. regional) are evident as indicated by the regional numbers for the city of Cologne, Germany. Further issues arise from low update frequencies, often data-dependent representation of human settlements (Schneider et al., 2010) as well as limited accuracy of the maps due to the spectral and spatial heterogeneity of built environments (Forster, 1983, 1985; Small, 2001, 2005). Ultimately, the coarse geometric resolution of EO data exploited so far does not embrace the full spatial complexity of large scale settlement patterns (Welch, 1982) and calls for novel HR layers that enable an enhanced spatial representation.

To answer this call, JRC and DLR have initiated the development of two new global products that promise to be a major leap forward regarding the derivation of spatially highly resolved settlement information on the global scale. The Global Urban Footprint (GUF) (Esch et al., 2012, 2013) builds upon the known capabilities of radar imagery for classification, monitoring and analysis of urban agglomerations at supranational levels (Henderson & Xia, 1997). It employs satellite imagery that is independent from weather, time-of-day and environmental conditions (Lewis, 1968). In contrast, the Global Human Settlement Layer (GHSL) (Pesaresi et al., 2013) initiative proposes a novel approach to map, analyze and monitor human settlements and ongoing urbanization processes in the 21st century. Exploiting high and very high resolution (HR/VHR) optical satellite imagery, GHSL is – although not globally available yet – up-to-date the largest and most complete known experiment based on optical EO data. Another promising approach that uses multi-spectral satellite imagery in combination with existing urban area maps is presented by Miyazaki, Shao, Koki, and Shibasaki (2013). It is, however, not subject to analysis in this work as the respective settlement layer only covers larger cities (>100.000 inhabitants) while disregarding other, lower density, settlement landscapes. Similarly, GUF and GHSL define urban areas based on distinct physical settlement features: Man-made vertical structures (GUF) or buildings (GHSL), respectively, mark the structuring elements for the derivation of generalized aerial representations of built-up areas (JRC, 2012; Esch et al., 2012). This eases the simultaneous assessment of these new high resolution geo-information products in the remainder of this work.

Despite these extensive efforts in global human settlement mapping now and in the past, comparative studies on these layers' strengths and weaknesses in terms of their assessed accuracy are still limited. Fig. 2 presents a comprehensive but non-exhaustive categorization of the published literature in this regard. While most studies relating to