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Impervious surface detection with nighttime photography from the International Space Station

Andrzej Z. Kotarba *, Sebastian Aleksandrowicz

Space Research Centre, Polish Academy of Sciences, Bartycka 18A, 00-716 Warsaw, Poland

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ABSTRACT

For over two decades nighttime satellite imagery from the Operational Linescan System (OLS) has been used to detect impervious surfaces. However, OLS-based maps suffer from the sensor's coarse resolution (2.7 km/pixel), overglow, and saturation in urban areas, resulting in inaccurate estimates of the extent and degree of impervious surfaces. In order to provide more reliable estimates of impervious surface extent, we used high resolution (~10 m/pixel) nighttime photography from the International Space Station (ISS). Focusing on the city of Berlin in Germany, we produced a map of the extent of impervious surfaces. Our classification was 85% accurate for both user and producer measures. Impervious surfaces omitted by ISS photography were mainly transit roads and airport runways, while green areas and water bodies within the city were falsely identified. An analysis based on ISS imagery classified 55.7% of the study area as impervious, which is only 3.9% less than ground truth (while the OLS-based estimate was 40% higher than ground truth). ISS imagery failed to provide reliable information about the degree of imperviousness for individual pixels (±20% errors); nevertheless it accurately estimated the spatially-averaged degree of imperviousness for the whole study area (30.2% vs. the reference value of 30.1%). These results show that ISS photography is an important source of nighttime imagery for mapping the extent of impervious surfaces, and represents a considerable improvement over OLS capabilities.

1. Introduction

An impervious surface is defined as a surface that prevents or impedes the infiltration of water into the underlying soil. This implies that impervious surfaces play an important role in the hydrological regime, which is supported by work such as Arnold and Gibbons (1996) that showed that if a river drainage basin is covered by ~30% or more of impervious surfaces, a stream can be considered as degraded. Modification of hydrological processes through soil sealing can manifest in, for example, flood dynamics (Jacobson, 2011; Mejia & Moglen, 2009; Miller et al., 2014; Ogden, Pradhan, Downer, & Zahner, 2011). The transformation of natural or semi-natural surfaces into impervious areas (roads, parking lots, buildings, etc.) also has consequences for the radiation budget, resulting in an increase in the local surface and air temperature (Myint, Brazel, Okin, & Buyantuyev, 2010; Weng & Lu, 2008; Xiao et al., 2007; Yuan & Bauer, 2007). Since soil sealing is a consequence of human activity, the examination of impervious areas makes it possible to monitor the urbanization process (Liu, He, Zhang, Huang, & Yang, 2012; Ma, Zhoua, Pei, Haynie, & Fan, 2012; Sutton, 2003) as well as its impact on the environment (Imhoff, Lawrence, Elvidge, et al., 1997; Milesi, Elvidge, Nemani, & Running, 2003).

One of the most effective ways to obtain surface imperviousness data (its degree and/or spatial extent) is satellite remote sensing. There are many approaches to the detection of impervious surfaces based on optical and radar imagery at different spatial resolutions. For example Mohapatra and Wu (2010) used Landsat-7 and Ikonos data in order to detect impervious surfaces with regression tree approach, Weng and Hu (2008) focused on Terra/ASTER and Landsat-7 data analyzed with neural network and spectral mixing techniques, Wu and Murray (2003) investigated Landsat-7 data with spectral mixing techniques, Deguchi and Sugio (1994) classified build-up areas with Landsat/MSS and SPOT/HRV imagery, and Yang (2006) processed Landsat-7 observations with multivariate statistical model. See also Parece and Campbell (2013) and Chabaeva, Civco, and Hurd (2009) for more extensive summaries of studies dedicated to detecting the impervious surfaces with satellite imagery. Of special interest are mapping efforts that aim to cover large spatial domains: notably, the High Resolution Layer — Imperviousness (HRL-I) system developed for the European Union (Kuntz, Schmeer, Jochum, & Smith, 2014), and the Percent Developed Impervious surface layer, developed as a part of the National Land Cover Database (NLCD) in the United States (Homer, Huang, Yang, Wylie, & Coan, 2004). Both of these datasets report the degree to which the surface (soil) is sealed, ranging from 0 to 100%, at a spatial resolution of 20 m/pixel (HRL-I) and 30 m/pixel (NLCD). The European dataset is based on imagery collected with IRS,

* Corresponding author.
E-mail address: akotarba@cbk.waw.pl (A.Z. Kotarba).

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SPOT and RapidEye satellites, while the United States data were produced with Landsat observations.

An approach that has emerged from mapping impervious surfaces with satellites is the use of optical imagery in the visible range of the electromagnetic spectrum, collected at night. Nocturnal light emissions predominantly originate from artificial sources (Sullivan, 1989), and therefore directly indicate potential impervious areas. Since 1977, nighttime data has been collected using the OLS installed onboard satellites belonging to the United States Defense Meteorological Satellite Program (DMSP). Although nighttime imagery was first recognized as useful for studies of human activity in the 1970s (Croft, 1978), it was not until the late 1990s that digital archives of OLS images were established, enabling quantitative studies of nocturnal light. See Huang, Yang, Gao, Yang, and Zhao (2014) for a comprehensive overview of OLS data applications.

From the perspective of urban mapping, daytime imagery allows the direct observation of impervious surfaces, while at nighttime they are only indirectly suggested by artificial illumination. The number of spectral bands means that daytime imagery can discriminate between various types of land use/cover, while OLS nighttime imagery only provides single-channel observations and information about a light source's location and relative intensity. The latter requires a more sensitive instrument, as well as a wide dynamic range of radiances, in order to avoid data saturation. Nighttime imagery is important for urban studies since the signal only originates from artificial sources, while radiances collected during the daytime are a complex mix of spectral responses coming from both artificial and natural surfaces. In this case, the spectral signatures overlap, making accurate land use mapping complicated.

OLS-based studies by Imhoff, Lawrence, Stutzer, and Elvidge (1997), Sutton (2003), Henderson, Yeh, Gong, Elvidge, and Baugh (2003), Lu, Tian, Zhou, and Ge (2008), He et al. (2006), Small, Pozzi, and Elvidge (2005), and Elvidge et al. (1997) found a good correlation between the actual extent of urban areas and OLS models. Further analysis of OLS imagery by Elvidge, Tuttle, et al. (2007) and Sutton, Elvidge, Tuttle, and Ghosh (2009) identified and explored the relation between light intensity and the degree of imperviousness. The above-mentioned studies, however, also revealed a limitation of the OLS sensor: the extent of the impervious area was found to be overestimated. This was due to a combination of low spatial resolution data (1–2.7 km/pixel, depending on the processing path) and the sensor's high sensitivity, which resulted in the spatial overextension of lighted areas, an effect sometimes called "blooming" (Letu, Hara, Tana, & Nishio, 2012; Lu et al., 2008).

These limitations are partially eliminated by the OLS successor — the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi-NPP satellite. Since late 2012, VIIRS has offered high-quality, radiometric calibrated imagery of nighttime lights at a spatial resolution of 750 m/pixel (Miller et al., 2013). The global VIIRS mosaics have been used by Shi et al. (2014) to detect urban areas in China. The authors found that VIIRS data produced maps that were only 1.2% (on average) more accurate (in term of overall accuracy) than maps derived from OLS mosaics. This was partially due to the preliminary nature of VIIRS global datasets, notably the unassessed quality of mosaics. Nevertheless, it is important to note that any future VIIRS products will continue to be at a moderate resolution (~750 m/pixel).

The goal of this study is to investigate the accuracy and reliability of measurements of the degree and extent of impervious surfaces, estimated from nighttime imagery acquired by a sensor that collects unsaturated (not overexposed) data with a spatial resolution that is comparable to that of "daytime" sensors, e.g. Landsat (30 m/pixel). The fundamental limitations of the OLS sensor were overcome using high resolution (~10 m/pixel) nighttime photography taken by an astronaut onboard the ISS. Such data has already been used in demographic and socio-economic research (Anderson, Tuttle, Powell, & Sutton, 2010; Kyba et al., 2015; Levin & Duke, 2012), but not for impervious surface detection. The study area focuses on the city of Berlin, Germany. Unlike most satellite data, ISS photography is not the result of radiation registration with a typical push-broom or a whisk-broom scanning instrument. Instead it is a form of digital photography that can be taken with an off-the-shelf digital camera, either hand-held or mounted on a tripod. To the best of our knowledge, this is the first time that ISS nighttime photography has been used in a quantitative investigation of impervious surfaces.

2. Data and methods

In the study we used two kinds of data: light intensity, based on ISS photography (Section 2.1) and land use/land cover data for the study area (Section 2.2). HRL-I data served as a baseline for assessing the ISS-based products, while CORINE Land Cover and Urban Atlas classifications allowed us to investigate errors of omission and commission. All of our land use/land cover datasets were provided by the European Environmental Agency via the Land Monitoring Services of the Copernicus Program.

2.1. ISS photography

ISS photography of Berlin, Germany was acquired during the space station pass over Europe on April 6, 2013, 22:37 UTC and covered an area of 28 km × 40 km (Fig. 1a), which defines the area of interest in this study. Although the photography is slightly oblique, the sub-satellite point lies only 140 km from the center of the image, hence the geometry is comparable with a typical Landsat scene (Fig. 1b). Visual inspection of the photography confirmed no cloud cover over the city. The Sun. and the Moon were below the horizon by 31° and 37° respectively.

The photography was obtained with a 12.1-megapixel Nikon D3S digital still camera equipped with a 400-mm AF-I Nikkor lens. Detailed exposure parameters are as follows — shutter speed: 1/30, aperture: 2.8, ISO equivalent sensitivity: 51 200. The camera's CMOS sensor produced RGB photography archived as a NEF file, which is Nikon's proprietary lossless compression standard for raw digital imagery. This was converted into TIFF format (16 bits per channel, as in the original NEF file).

In order to produce a spatially-adjusted TIFF file, we geo-referenced the photography using the UTM spatial reference frame (Zone 33 N) and a third order polynomial fit. The best solution for the model was based on 99 ground control points, and resulted in a total root mean square error of 16.95 m. The actual geometric spatial resolution of the projected data was found to be 9.6 m/pixel.

Pixels were assigned digital numbers (DN) that represented uncalibrated light intensities in three spectral channels (red, green, blue). We decided to sum red, green and blue values and synthesize a pseudo-panchromatic light intensity, therefore making the ISS photography more similar to OLS data. After summing the three, 16-bit channels the range of possible DN values become wider: from 0 to $3\times(2^{16}-1)=196\,605$.

ISS data was obtained from NASA's "Gateway to Astronaut Photography of Earth" database, maintained by the Lyndon B. Johnson Space Center (NASA image ID: iss035e017202). Further information on ISS Earth photography – including nighttime imagery – can be found in papers by Robinson, Liddle, Evans, and Amsbury (2002), Gebelein and Eppler (2006) and Elvidge, Cinzano, et al. (2007) and references therein.

2.2. Land use/land cover data

2.2.1. High resolution layer — imperviousness

HRL-I data reports one type of land cover information: the degree to which the surface is impermeable. This varies from 0 to 100%, and is considered "continuous" when it exceeds 80% (otherwise it is "discontinuous").