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Observations of urban and suburban environments with global satellite scatterometer data

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ABSTRACT

A global and consistent characterization of land use and land change in urban and suburban environments is crucial for many fundamental social and natural science studies and applications. Presented here is a dense sampling method (DSM) that uses satellite scatterometer data to delineate urban and intraurban areas at a posting scale of about 1 km. DSM results are analyzed together with information on population and housing censuses, with Landsat Enhanced Thematic Mapper Plus (ETM+) imagery, and with Defense Meteorological Satellite Program (DMSP) night-light data. The analyses include Dallas-Fort Worth and Phoenix in the United States, Bogotá in Colombia, Dhaka in Bangladesh, Guangzhou in China, and Quito in Ecuador. Results show that scatterometer signatures correspond to buildings and infrastructures in urban and suburban environments. City extents detected by scatterometer data are significantly smaller than city light extents, but not all urban areas are detectable by the current SeaWinds scatterometer on the QuikSCAT satellite. Core commercial and industrial areas with high buildings and large factories are identified as high-backscatter centers. Data from DSM backscatter and DMSP nighttime lights have a good correlation with population density. However, the correlation relations from the two satellite datasets are different for different cities indicating that they contain complementary information. Together with night-light and census data, DSM and satellite scatterometer data provide new observations to study global urban and suburban environments and their changes. Furthermore, the capability of DSM to identify hydrological channels on the Greenland ice sheet and ecological biomes in central Africa demonstrates that DSM can be used to observe persistent structures in natural environments at a km scale, providing contemporaneous data to study human impacts beyond urban and suburban areas.

1. Introduction

The state of the world's urban and suburban environments, consistently inventoried at fixed periods in time, is fundamental in addressing and solving many pressing policy questions grounded in the social and environmental sciences. A globally and temporally consistent dataset, delineating and characterizing land use and its change in urban and suburban environments, does not exist at the present time. Census data everywhere are collected according to irregular administrative or enumeration units. In the data-rich United States (US), census results are obtained once per decade, and are not intended to capture spatial dimensions of urban change processes. Globally, such data are less frequent, coarser, inaccurate, often non-accessible, or even nonexistent in many areas. An understanding of urban change becomes more imperative not only as the world becomes more urban than rural, but also as more urban dwellers live in coastal zones (McGranahan et al., 2007); many have been at an increasing risk of extreme weather events, such as Hurricanes Katrina and Rita in 2005.

The Night-Light (NL) dataset obtained by DMSP-Operational Line Scanner (DMSP-OLS) has been used as a proxy indicator of urban areas (Elvidge et al., 1997, 2001; Sutton et al., 1997, 2001; Owen et al., 1998; Balk et al., 2005). While it represents an important step in the right direction, the light data have limitations: the level of night illumination depends on local lighting sources, atmospheric conditions, and surrounding land cover; only very limited intraurban or suburban differentiation can be determined with DMSP NL; and changes in lighting technology

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may change the detected NL without any correspondence to change in population or built-up areas within a city. The primary limitation of the DMSP-OLS sensor is related to persistent "overglow", the area from which detected light is significantly larger than the built area (Elvidge et al., 1997). While some analyses attempt to reduce the spatial extent of the overglow by imposing a detection frequency threshold (Imhoff et al., 1997), comparisons of lighted areas with global Landsat imagery (Small et al., 2006) indicate that there is no single threshold that provides consistent results for multiple cities. Imposing high detection frequency thresholds to reduce overglow around large cities also eliminates most of the unique information content of the light data by attenuating most of smaller settlements entirely (Small et al., 2006).

Moderate resolution sensors like Landsat, Spot, and Aster provide the longest running observations of cities and the most consistent source of imagery. While these sensors lack the spatial resolution to discriminate individual components in the urban mosaic, they do have sufficient swath width to image an entire city simultaneously. This is critical because it eliminates the cost and complexity of acquiring and mosaicing multiple images to cover an entire city. The Landsat Thematic Mapper (TM) and ETM+ sensors are particularly well suited to synoptic urban imaging because of their 185 km wide swath and their thermal and short-wavelength infrared (SWIR) imaging capability spanning over 25 years. However, comparative analyses of urban Landsat imagery reveal considerable intraurban and interurban spectral heterogeneity (Small, 2005). As a result, traditional thematic classifications generally fail to produce accurate results when applied to moderate resolution imagery of urban areas. Continuous field approaches like Spectral Mixture Analysis (Adams et al., 1986; Smith et al., 1985, 1990) are able to accommodate the spectrally mixed pixels that are characteristic of urban areas and represent urban land cover in terms of their physical constituents. However, the pervasive spectral diversity of urban mosaics so far precludes a single universal approach to mapping global urban extent from moderate-resolution optical imagery.

Optical sensors with a high spatial resolution (<10 m) offer considerably more information because they can resolve individual components of the urban mosaic (Welch, 1980; Small, 2003). However, the high-resolution capability of these instruments is also a limitation because only a very small fraction of the Earth's surface is imaged at a high resolution in a single instant. For example, Bogotá in Colombia, an extended urban area of 15 million people with a population growth of almost 5 million people over the last decade, did not have any cloud-free Landsat data acquired for a period of 10 years prior to 2005.

Synthetic Aperture Radar (SAR) data have been used for urban characterization with encouraging results (Henderson and Xia, 1998; Dell'Acqua and Gamba, 2006; Böhm and Schenkel, 2006). SAR data can have high resolution ranging from 10 to 100 m without the problem of clouds obscuring the target. SAR data have been collected piecewise at different times over different areas of the world. An exception is the global SAR dataset from the Shuttle Radar Topography Mission (SRTM) collected between 60° S and 60° N in February 2000, which has a potential use for global infrastructure mapping (Nghiem et al., 2001). However, there has been no consistent collection of global SAR data at repeated time intervals since the SRTM dataset obtained about 9 years ago. The community of users who wish to detect change in urban areas needs to be able to observe unbiased changes at regular periodic intervals, and perhaps even annually for rapidly changing areas. New data and methods will be required to address these issues on a global scale.

In this paper, the objectives are to demonstrate the capability of DSM using satellite scatterometer data to observe global urban and suburban environments, to show how DSM can provide a tighter delineation of city extent compared to NL results, and to investigate the relationship between DSM urban typology and socioeconomic and demographic characteristics.

2. Approach

We present a new approach to observe urban and suburban areas, with a particular attention on intraurban detection, drawing on a set of case-study cities. Using radar backscatter data acquired by the SeaWinds scatterometer on the QuikSCAT satellite (QSCAT), DSM is applied to determine the fundamental characteristics of a dense ensemble of data samples in the identification and mapping of high-resolution surface features at a posting of approximately 1 km. The trade-off is that the daily or near daily temporal resolution of QSCAT is reduced to a yearly or multi-year time scale, which is still appropriate to map urban and suburban areas and to identify interannual changes. A single azimuth look may identify only a city sector having a specific preferential alignment direction of buildings. The multi-azimuth looks of QSCAT allow all parts of a city to be detected regardless of the building directional alignment. In the subsections below, the DSM concept is formulated mathematically and a simulation is presented to illustrate the capability of scatterometer data in characterizing urban and suburban environments.

2.1. QuikSCAT scanning scatterometer

A satellite scatterometer, a stable and accurate radar such as QSCAT, collects data with a scanning pencil-beam antenna across a large swath as wide as 1800 km over the Earth's surface as the satellite moves along its orbit around the Earth (Tsai et al., 2000). QSCAT acquires global data covering 90% of the global surface each day since 1999 (Jet Propulsion Laboratory, 2006). QSCAT footprint (two-way, half-power, full beamwidth) has an elongated or 'egg' shape of about 25 km in azimuth by 37 km in range. Moreover, the transmitted radar pulse is modulated (chirped), and the received pulse is Doppler compensated before it is processed through a fast-Fourier-transform stage to achieve a sub-footprint resolution. This linear frequency modulation chirp function is capable of generating sub-footprints or thin 'slices' of 25 km in azimuth with a commendable variable range resolution of approximately 2 to 10 km with a nominal value set at 6 km (Jet Propulsion Laboratory, 2006).

If a satellite is kept constrained in exact repeat orbits, measurements can only be made at a limited range of azimuth directions. At the beginning of the mission, QSCAT had exact repeat orbits; however, the orbits have been allowed to drift since year 2000 to save satellite fuel. With the scanning antenna along drifting orbits, radar measurements are made with more complete azimuth diversity at each location. These radar measurement geometries will be accounted for in the formulation of the DSM.

2.2. Dense sampling method

Consider an x–y coordinate surface where the center of a radar footprint is located at (x_k, y_k). In the formulation below, we set (x_k, y_k) at (0, 0) for simplicity without loss of generality, and all backscatter quantities are in the linear domain (as opposed to the decibel or dB domain that is logarithmic and non-linear). We model the radar gain pattern approximately with an elongated Gaussian beam tilted at an azimuth angle of ϕ_i as defined by the following expression

$$G(\phi_i, x, y) = \exp\left[-\left(\frac{x\cos\phi_i + y\sin\phi_i}{a}\right)^2 - \left(\frac{-x\sin\phi_i + y\cos\phi_i}{b}\right)^2\right] \quad (1)$$