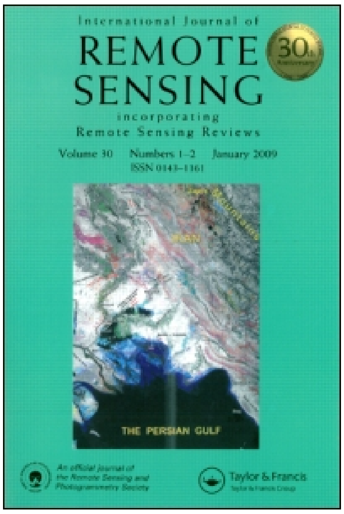

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Characterizing relationships between population density and nighttime imagery for Denver, Colorado: issues of scale and representation

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Characterizing relationships between population density and nighttime imagery for Denver, Colorado: issues of scale and representation

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This paper maps and characterizes the correlation between population density and nighttime imagery over Denver, Colorado. Photographs taken at night from the International Space Station (ISS) have finer spatial and spectral resolution than existing nocturnal observing satellites such as the Defense Meteorological Satellite Program's Operational Linescan System (DMSP OLS). We determined the correlation between the city lights of Denver, Colorado, and several representations of population and population density derived from census data. The DMSP OLS proved to have a stronger correlation than any of the finer resolution ISS photograph bands. This study suggests that exclusive use of nighttime images with finer spatial and spectral resolution will not necessarily improve our ability to use nighttime imagery for modelling traditional representations of population. However, analysis of the spatial patterns of error indicates that finer resolution imagery may be a good proxy of conceptualizations of population density that account for human spatial behaviour. Future research may demonstrate that imagery such as the ISS photographs may prove to be uniquely capable of informing more sophisticated representations of complex phenomena such as ambient population density, land-use intensity and impervious surface.

1. Introduction

Nighttime images of the Earth from space present a dramatic and striking portrait of human activity across the globe. Analyses of nighttime image data products derived from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP OLS) have demonstrated that these patterns of light have many potential applications including: (1) mapping urban extent and impervious surface (Imhoff *et al.* 1997, Lo 2002), (2) estimating urban populations and intra-urban population densities (Sutton 1997, 2003, Sutton *et al.* 1997), (3) modelling disaggregate gross domestic product (Sutton and Costanza 2002, Sutton *et al.* 2007) and (4) estimating and mapping economic activity, CO_2 emissions, poverty and ecological footprints (Doll *et al.* 2000, Elvidge *et al.* 2007, Sutton 2003, Doll 2008). Nonetheless, these DMSP OLS-derived data products are of coarse spatial resolution ($\sim$1 km^2) and are derived from only one panchromatic visible–near infrared band (Elvidge *et al.* 1999). Many efforts at intra-urban population and population density estimation have been performed at moderate spatial resolutions using daytime imagery (Chen 2002, Harvey 2002, Wu *et al.* 2005).

Photographs of cities at night taken by astronauts on the International Space Station (ISS) raise interesting questions as to how improved spatial and spectral

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resolution might improve these applications (Evans and Stefanov 2008). These images of ‘cities at night’ capture the location of over half the World’s population, and this proportion is expected to grow to 75% in the coming decades (Weeks 2005). The World’s population and how it is geographically distributed are important influences on the environment, both in terms of sheer numbers and in terms of patterns of consumption (Newton *et al.* 2001). As the World’s population and economy grows, measuring, mapping and monitoring the number, behaviour and spatial distribution of the global population are increasingly difficult and expensive (Lo 1995); however, information of this nature is vital to policies related to sustainability. The atmospheric CO_2 data gathered at Mauna Loa by Keeling and Whorf (2004) is, in one sense, a globally aggregate time-series proxy measure of anthropogenic impacts that are measured on the Earth. A time series of satellite images of the Earth at night is, in another sense, a spatially explicit map of ostensibly the same anthropogenic impacts measured in the aggregate at Mauna Loa (Sutton *et al.* 2009).

A proposed satellite mission designed to make nocturnal observations of the Earth (the NightSat mission concept) could provide proxy measures of many socio-economic variables relevant to issues of sustainability (Elvidge *et al.* 2007). A NightSat mission is likely to provide global coverage of nighttime satellite imagery at spatial and spectral resolutions comparable to the ISS photographs taken by astronauts. Here, we analyse an ISS photograph of Denver, Colorado, to improve our understanding of the potential of a NightSat or comparable mission for mapping and estimating intra-urban population density.

2. Methods

The two basic hypotheses involved in this investigation use two approaches: (1) a pixel-based approach: here, nocturnally emitted light intensity will positively correlate with the average population density of a polygon and (2) a polygon-based approach: integrations of light intensity over variably sized and populated polygons will positively correlate with the total population of those polygons. The pixel-based approach is a classic manifestation of the areal interpolation problem and compares light-intensity values to population density of polygons (Langford *et al.* 1991). The polygon-based approach integrates the values of pixels in a given polygon and estimates the total population of that polygon. The goal of this analysis was to quantify the correlation between two types of nocturnal imagery and several representations of population. In addition, we wanted to map the variability of the strength and nature of these relationships. Our approach was to compare the nighttime imagery (both DMSP OLS and the ISS photo) to population and population density as represented in three ways: (1) LandScan (at $\sim$1 km^2 pixels) (Bhaduri *et al.* 2002), (2) the 2000 census data at the spatial resolution of tracts, block groups and blocks and (3) a rasterization of the census-block data at the spatial resolution of the ISS photograph itself ($\sim$50 m $\times$ 50 m pixels).

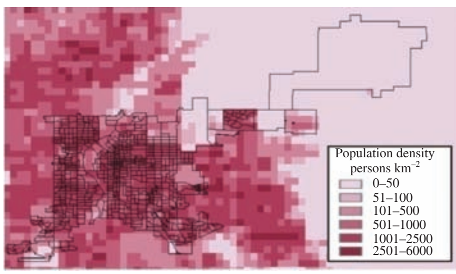
We obtained and georeferenced a photograph of the city of Denver, Colorado, taken from the ISS. The ISS is approximately 278 km above sea level, and these photographs capture light that is emitted from urban areas including streetlights, automobile headlights and light from buildings. The colour visible photograph (red, green, blue; RGB) was taken with a digital camera with a spatial resolution of approximately 50 m. The image was accessed via the National Aeronautics and

Space Administration (NASA) website, and was named ESC_large_ISS016_ISS016-E-26 150 (Evans and Stefanov 2008). We co-located this ISS photograph with United States census data at the block, block group and tract level of aggregation, LandScan population data at ~1 km^2 spatial resolution (Dobson *et al.* 2000) and a city lights data product derived from the DMSP OLS, also at a nominal resolution of 1 km^2 (figure 1). We needed a single-band image that contained most of the variability in the intensity of the ISS photograph to use in the analysis. To this end, we generated a first principal-component image (PC1) using the red, green and blue bands of the ISS image. This PC1 captured 95% of the variability in the red, green and blue bands of the ISS photograph of Denver.

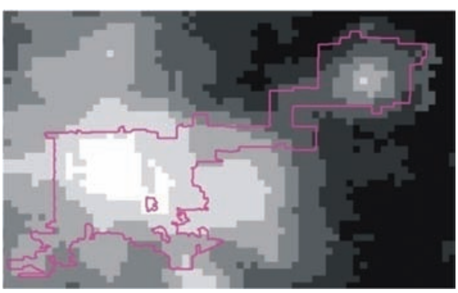
To investigate background light levels, we examined a National Agricultural Imagery Program (NAIP) photograph mosaic of the Denver metropolitan area and compared it to the ISS nighttime image. Here, we noted that lakes, golf courses and other presumptively 'dark' areas of the city nonetheless showed up as having some light levels in the ISS photograph. We removed this background light level of noise in the ISS photograph before proceeding. We measured the mean and standard deviation of lakes in the metro area and set all pixels with digital number (DN) values less than two standard deviations above the mean of the lake pixels to zero (DN values of 74 and below) (figure 2).

For the LandScan representation of population, we simply assessed the correlation matrix of the LandScan, DMSP OLS, ISS Red, ISS Blue, ISS Green and ISS PC1 datasets (figure 3). These correlations are derived from the comparison of the DN values of pixels of approximately 1 km^2 spatial resolution. We used mean aggregations of the ISS images for this analysis. These image-to-image correlations are based on 100% sampling of the pixels. We include the coarse-resolution LandScan dataset to

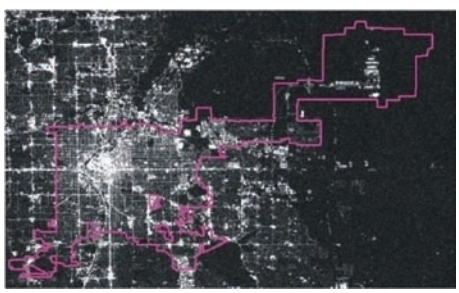
RGB digital photo taken from international space station
(Image resolution~ 50 m × 50 m, census tract boundaries overlaid)



Landscan population density from oak ridge national lab
(Cell size 30 arc second × 30 arc second, block group boundaries overlaid)



DMSP OLS city lights data product
(Cell size 30 arc second × 30 arc second, country of denver boundary overlaid)



First principal component of space station photograph
(Cell size ~50 m × 50 m, country of denver boundary overlaid)

Figure 1. Source data for the Denver area. Darker pixels are low light areas.

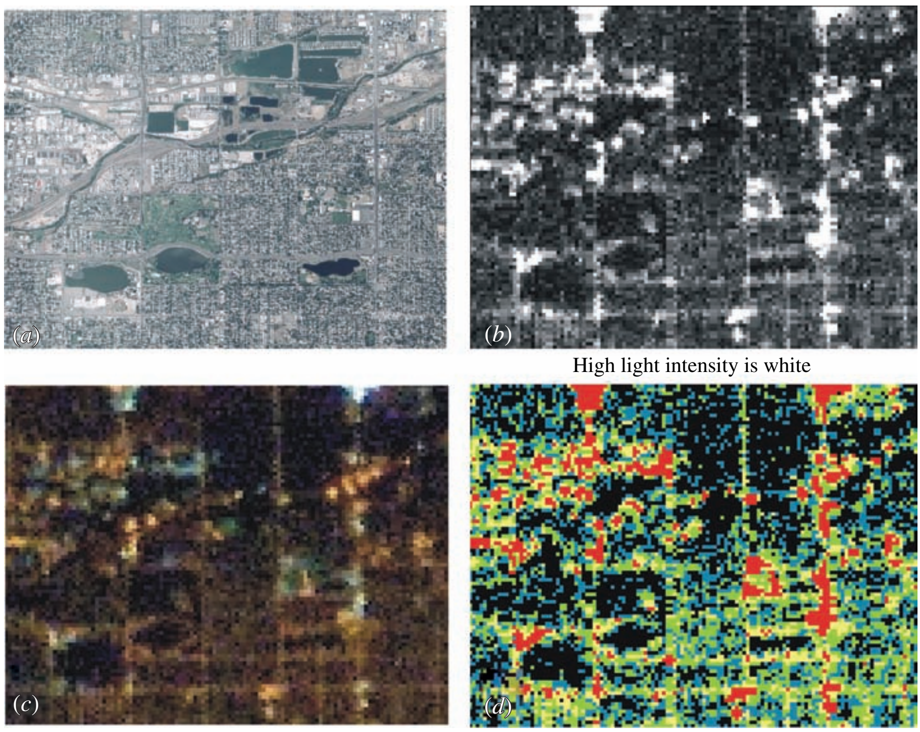


Figure 2. Noise thresholding of ISS PC1. Diverse land-use region in north Denver. Area includes water bodies, golf courses, bare soil, riparian environments, interstate, commercial, industrial and residential areas. (*a*) NAIP aerial photograph; (*b*) 1st principal component (PC) ISS photo; (*c*) RGB composite of ISS photo; (*d*) Threshold classification of PC1.

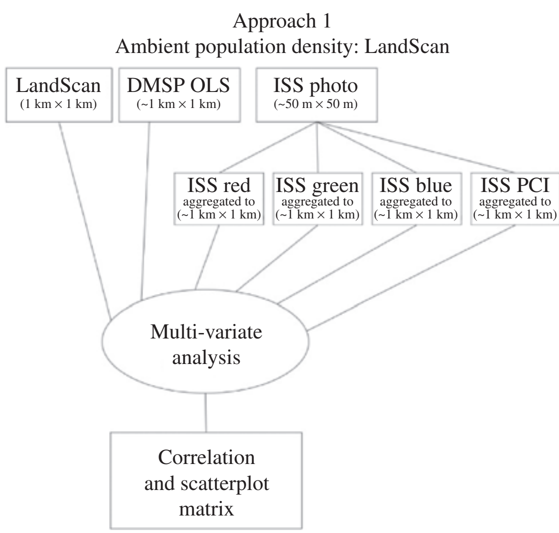


Figure 3. Flowchart of procedure 1.

provide some variation in both spatial resolution and nature of representation. Keep in mind that LandScan attempts to represent an ambient rather than residence-based measure of population density. The ambient population density that LandScan attempts to represent is a temporally averaged map of human spatial behaviour (e.g. work, recreation, travel and residence).

For the three spatial resolutions of census polygons, we summed the DN values of the ISS first principal-component image, both with and without the noise threshold applied, to predict the total population of each polygon. An ordinary least squares regression was performed, in which the independent variable was the sum of ISS PC1 lights, and the dependent variable was the total population for the polygons in the tracts, block groups and blocks datasets (figure 4).

Our third approach involved generating a 50 m $\times$ 50 m representation of population density from the 2000 census-block data. The 2000 census-block polygons are the only ones with fine enough spatial resolution to represent as a 50 m $\times$ 50 m grid. First, we rasterized the block polygons to 5 m $\times$ 5 m resolution of population density. Then, we mean aggregated this dataset up to 50 m $\times$ 50 m resolution to match the resolution

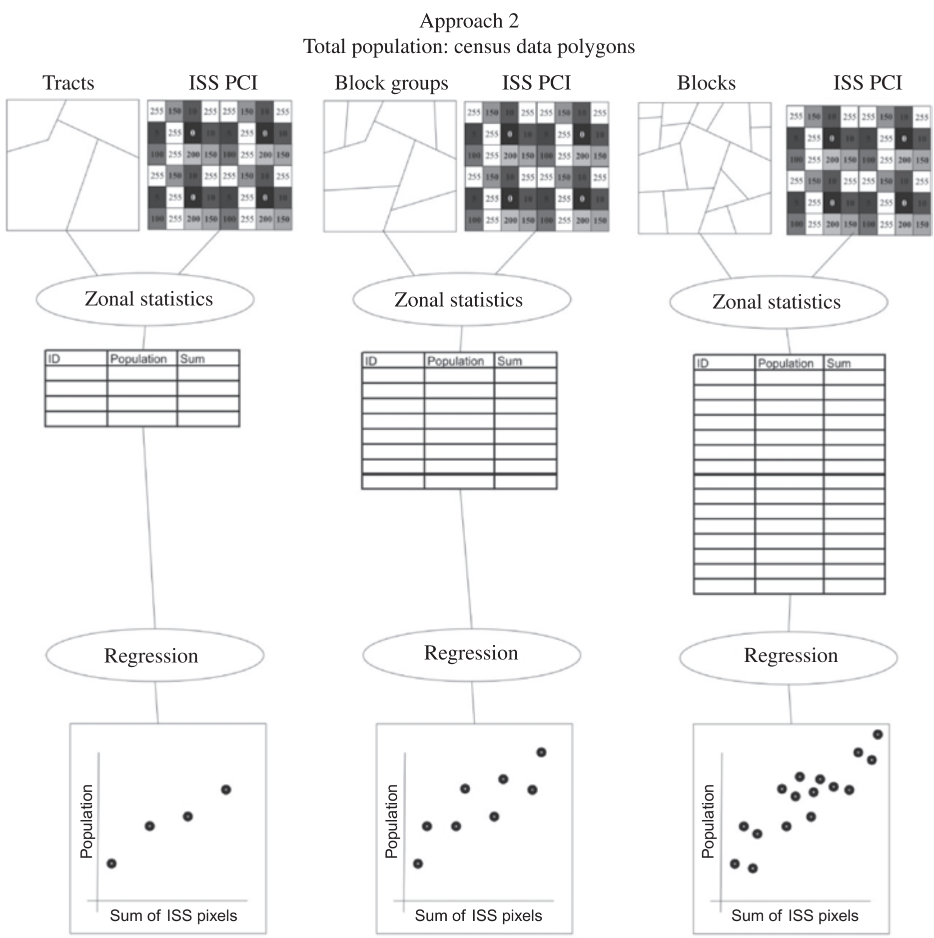


Figure 4. Flowchart of procedure 2.

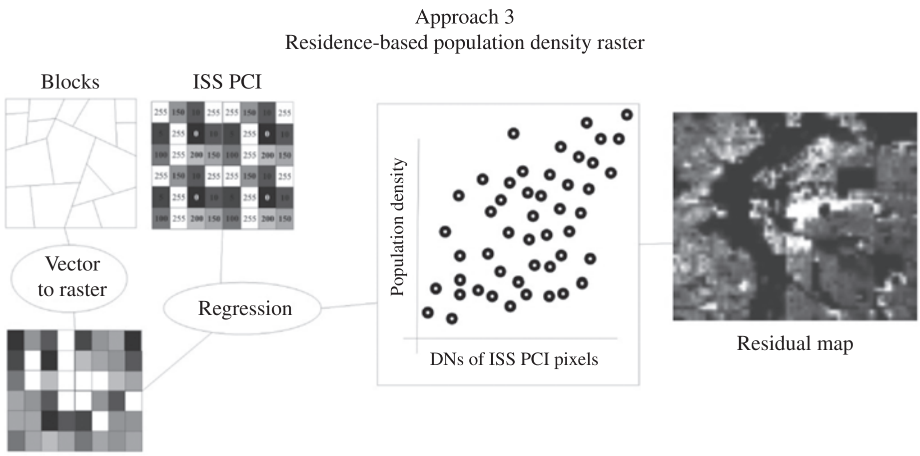


Figure 5. Flowchart of procedure 3.

of the ISS-derived data products (figure 5). Again, we performed an ordinary least squares regression using the ISS PC1 DNs as the independent variable to predict the population density pixels (dependent variable) derived from the 2000 census blocks.

3. Results

We assessed three approaches to representing intra-urban population and population density using both raster and vector data models at several spatial resolutions using both zonal and pixel-based regression models (Wu and Murray 2007). Each approach involved robust and commonly used simple linear regression methods.

3.1 *Approach 1: population representation via LandScan*

LandScan differs from census data in that it represents ambient population density (Dobson *et al.* 2000, Sutton *et al.* 2006). In addition, the finest spatial resolution at which LandScan represents population and population density is at $\sim$1 km^2. In testing the idea that nocturnal emitted light intensity correlates with ambient population density, we compared the three ISS bands, the first principal component of those three bands and the DMSP OLS to the LandScan population values and each other on a pixel-by-pixel basis. An unexpected result was that the DMSP OLS had the highest correlation with LandScan (Pearson product-moment correlation coefficient, $r = 0.60$). Of the mean aggregated ISS data, the red correlated the most strongly with LandScan ($r = 0.53$) (figure 6). The aggregated ISS bands correlate strongly with the DMSP OLS imagery, as we would expect. However, they were no better than the DMSP OLS imagery at predicting population density at the spatial resolution of LandScan. The coarse spatial resolution of LandScan is not particularly useful for intra-urban applications; however, we used LandScan to provide a broader variation of spatial resolution.

3.2 *Approach 2: population represented as census 2000 polygons*

This approach used the 'population' attribute of census polygons, which is a simple count of persons. We used the three spatial 'resolutions' of census data: tract, block group and block. The summed DN values of the first principal component of the ISS

Correlations

	PCA1	ISSred	ISSgrn	ISSblu	DMSP	LandScan
PCA1	1.0000	0.9787	0.9965	0.8950	0.8109	0.4937
ISSred	0.9787	1.0000	0.9762	0.8135	0.8258	0.5282
ISSgrn	0.9965	0.9762	1.0000	0.9061	0.7991	0.4748
ISSblu	0.8950	0.8135	0.9061	1.0000	0.6373	0.3266
DMSP	0.8109	0.8258	0.7991	0.6373	1.0000	0.5965
LandScan	0.4937	0.5282	0.4748	0.3266	0.5965	1.0000

Scatterplot matrix
data model: raster cells at 1 km x 1 km

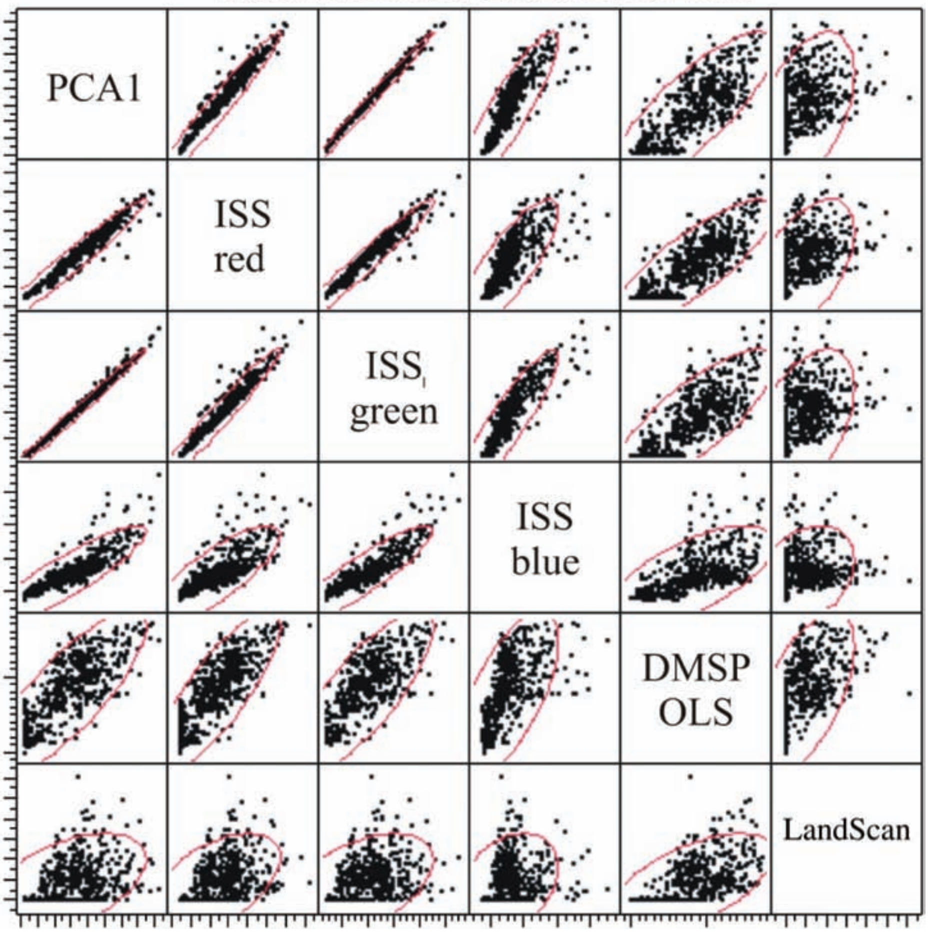


Figure 6. Correlation matrix of images relative to LandScan.

image within each census polygon were used to predict the population of that polygon. The correlations were not very strong and did not change substantially when the noise threshold was applied to the ISS PC1 image (figure 7). The correlations were highest at the finest spatial resolution of census blocks ($r = 0.21$), suggesting that finer

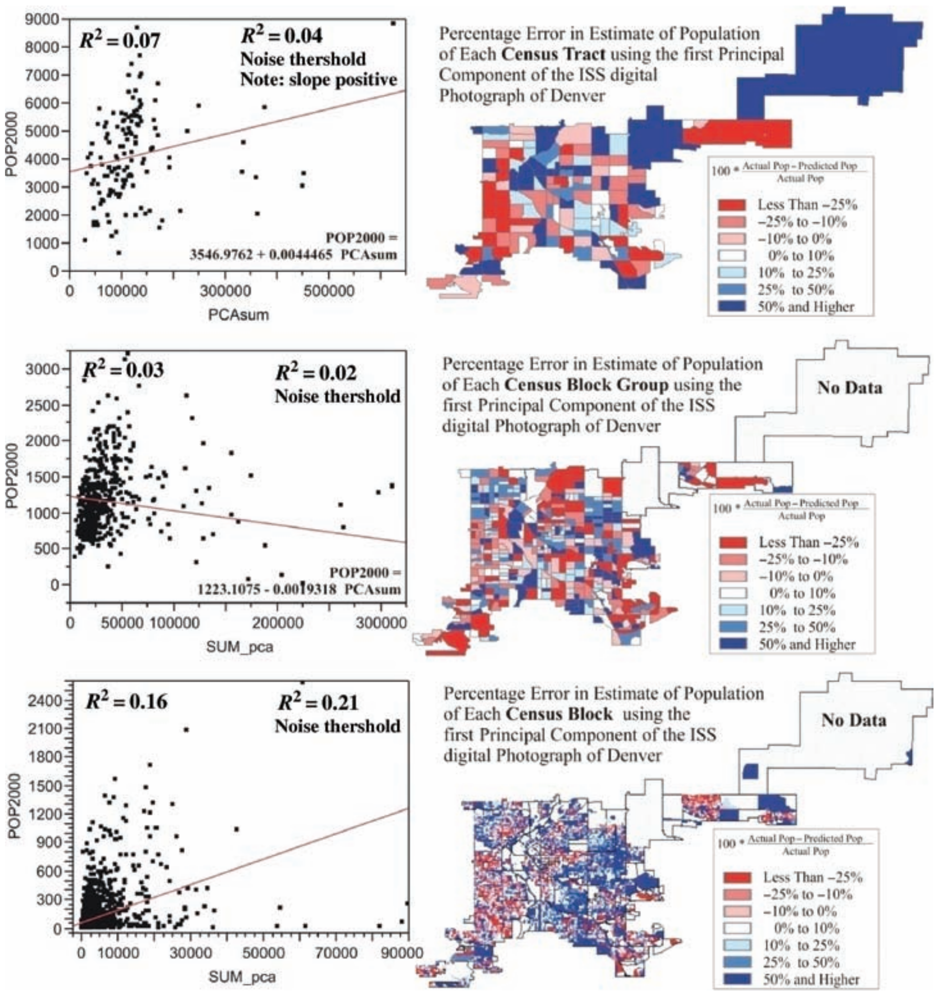


Figure 7. Regression and residual maps for ISS versus census data. R^2 is the coefficient of determination.

spatial resolution nighttime imagery may have potential applications for population estimation. An analysis of the residuals from these regressions shows that we overestimate population in highly industrialized and commercial areas such as Denver International Airport and the South Platte river corridor. These areas have high ambient population densities that are not captured in traditional census-based measures of population. However, the patterns in the residual maps diminish as the spatial resolution progresses from tracts to block groups to blocks (i.e. from coarser to finer spatial resolution).

3.3 *Approach 3: population density gridded from census 2000 block polygons*

This approach involved preparing a gridded representation of population density that matched the spatial resolution of the ISS photograph. A pixel-to-pixel regression of light intensity as measured by the PC1 to predict population density as derived from census data showed a significant regression (slope $\neq 0$; probability, $p < 0.0001$) (estimated population density (persons km^{-2}) = 1821 + 18.3PC1); however, the R^2 was only 0.05 (figure 8). Mapping and analysis of these pixel-based residuals showed the same pattern we found in the census polygon analysis. Commercial and industrial areas associated with census blocks that had population densities of zero were overestimated (coloured red in figure 8). These overestimated areas include parks, golf courses and large shopping centres. Underestimated areas tended to be densely populated urban residential neighbourhoods (coloured blue in figure 9). Unfortunately, the 'reasonably' estimated yellow pixels constitute the smallest area in this image, and they are defined as within ± 50% of the true population-density values. The reasonable estimates seem to be randomly interspersed in the urban residential areas, with some concentration at the periphery of the city. This may be an artefact of these peripheral areas being at a distance that exhibit classic

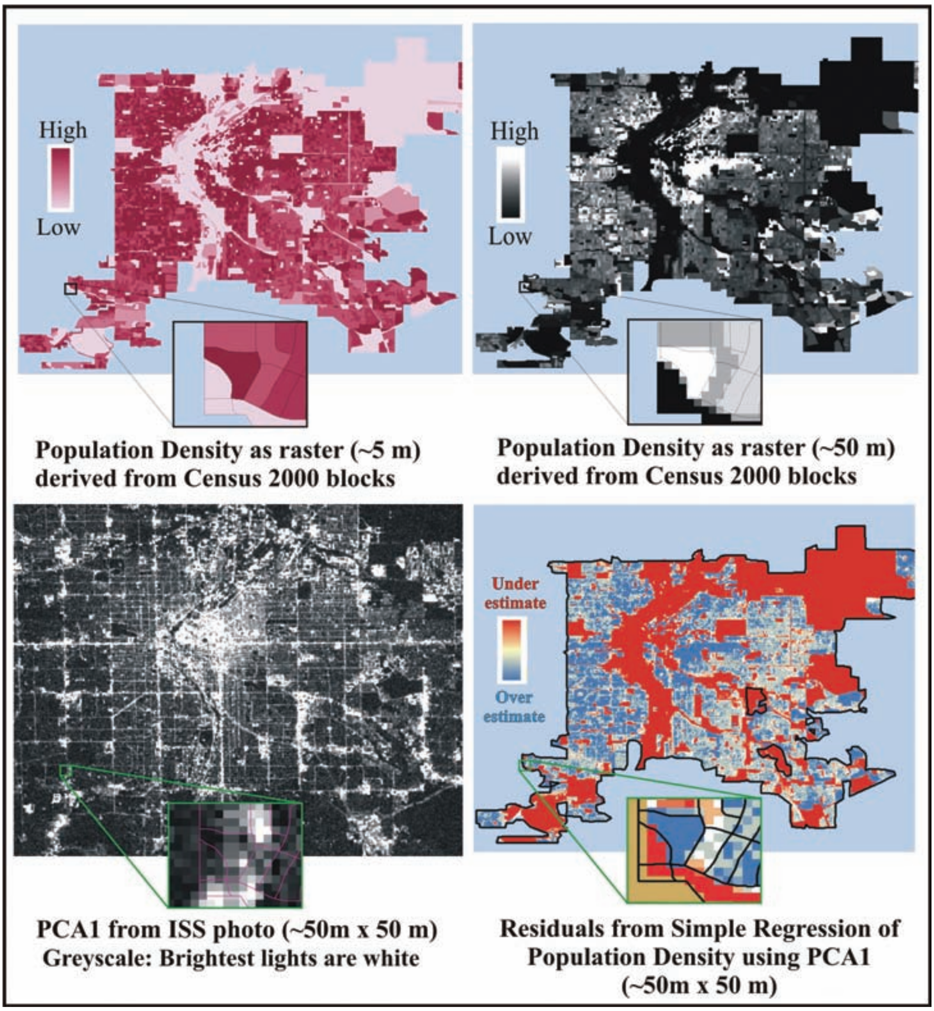


Figure 8. Preparation of raster population density at the spatial resolution of the ISS.

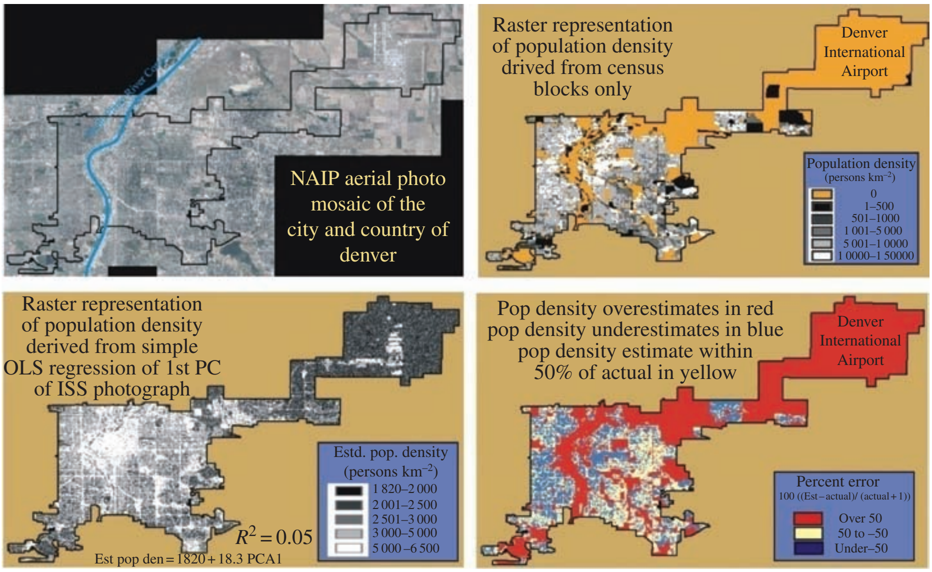


Figure 9. NAIP aerial photo mosaic and raster of ISS model residuals.

levels of exponential population-density decay (Clark 1951). Poor prediction in the areas of very low or very high population density is common for pixel-based estimation of urban populations (Hardin and Shumway 2008).

4. Discussion

This investigation was motivated by the hypothesis that the finer spatial and spectral resolution of the ISS photographs would increase correlation between measures of population density and nighttime imagery. Our results do not support this hypothesis. However, at intra-urban spatial scales, the spatio-temporal variability of human population and population density are difficult to represent, even with perfect data, let alone *estimate* with static satellite imagery.

Residence-based representations of population density as provided by census data will not be well modelled by nighttime satellite imagery alone. Other areas of high ambient population density that are not residential (airports, football stadiums, commercial and industrial areas, etc.) often emit more light than residential neighbourhoods. The finer spatial resolution of the ISS photographs magnifies many of these disparities that are aggregated in the larger pixels of the DMSP OLS. However, finer spatial and spectral resolution nighttime images of urban areas used in conjunction with land-cover datasets may prove useful for improving land-use information about intra-urban areas. A study by Sutton *et al.* (2006) identified areas of exurban development using a combination of low light levels in nighttime imagery (DMSP OLS) and non-urban land cover that was primarily classified as forest from Landsat. Obtaining good land-use information in urban environments has been an elusive and challenging problem for the remote-sensing community (Cowen and Jensen 1998, Donnay *et al.* 2001). Measuring, mapping and modelling the complex urban environment will likely require a data model that is substantially more sophisticated than a raster of industrial, transportation, commercial and residential grid cells.

Urban environments represent a small fraction of the Earth's surface yet house more than of half of the human population. Improved methods of intra-urban population estimation will contribute to the need for new multi-dimensional classifications of the heterogeneity of urban areas. The long-used classifications of residential, industrial and commercial are increasingly inadequate for understanding the complex, mixed-use and multi-cultural patterns of human-dominated ecosystems (Grimm *et al.* 2000). A greater understanding of the dynamics of these environments is a vital challenge to the development of policies related to sustainability. Remote sensing can contribute to many potential inputs into models that attempt to capture these complexities such as: land-use intensity and/or ambient population density, impervious surface, carbon emissions, heat island effects, tree-canopy cover and related evapotranspiration and energy consumption (Hawkins *et al.* 2004, Doll 2008, Chand *et al.* 2009). The challenge to the remote-sensing community with respect to contributing to sustainable policy development remains multi-faceted (Gatrell and Jensen 2008). We need to address relevant questions and provide data products and models that are used and accepted by researchers and policy makers.

An interesting example is a study by Agnew *et al.* (2008), in which they used nighttime imagery from the DMSP OLS to investigate whether or not the military 'surge' in Baghdad was effective or not. They found that the 'surge' had produced no observable benefit from the 'eyes' of the DMSP OLS sensor. The basic idea being that the DMSP OLS imagery would be able to measure a stable or improved quality of life by an increased or stable light signature of the city. The almost real-time empirical evidence provided by satellite imagery is becoming increasingly sophisticated and increasingly available and easy to display in software such as Google Earth. It will be interesting to see if satellite observations of highly politicized phenomena such as the 'surge' in the Gulf War will be increasingly used by the media, the public and politicians in the development and discussion of various policies.

5. Conclusion

Our analysis of a single space station photograph over Denver, Colorado, did not produce models of population or population density that were better than pre-existing models using coarser spatial resolution imagery such as those derived from the DMSP OLS. However, we constrained our study to narrowly defined representations of population and population density. United States census data produces a static representation of where the human population sleeps. The ISS imagery has high DN values in many places where census data records low or zero population density (airports, commercial and industrial areas, etc.). It is likely that the overall brightness of the ISS imagery does serve as a proxy measure of a representation of population density that captures temporally averaged human spatial behaviour as LandScan attempts to capture. However, the mismatch of spatial resolution between the ISS photograph and LandScan precluded the demonstration of the potential of the ISS image as a proxy measure of ambient population density at the finer resolution of the ISS imagery. Future research involving finer spatial resolution representations of population density that capture human behaviour at airports, football stadiums, shopping malls, and so on may prove the utility of finer spatial resolution nighttime imagery as a proxy of population density. A temporally averaged representation of human spatial behaviour could be produced with global positioning system (GPS), radio-frequency identification (RFID) or cell phone technologies. Whether or not we want to use such measures remains a highly contested moral and ethical question (Dobson and Fisher 2003).

Images of the Earth at night are a fascinating proxy measure of human impact on the environment. While the ISS photos may not be an ideal means for making intra-urban population and population-density estimates, this is not because the ISS images lack vital and useful information. In many respects, our conceptualizations and representations of the population and population density we are trying to model are perhaps antiquated. We believe that global mosaics of nighttime imagery (from DMSP OLS, NightSat or space station photographs) will prove to be as provocative and informative as the time-series measurements of CO_2 made by Keeling and others at Mauna Loa. The fundamental advantage of these nighttime image mosaics is that they constitute a spatially explicit measurement and documentation of myriad human impacts on the Earth's surface.

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