Proceedings of the Asia-Pacific Advanced Network ***2011*** *v. 31, p. 79-90.*
http://dx.doi.org/10.7125/APAN.31.9
ISSN 2227-3026

Relationships between Nighttime Imagery and Population Density for Hong Kong

Qing Liu [1*], Paul C. Sutton [1], Christopher D. Elvidge [2]

1 Department of Geography, University of Denver, Denver, CO 80208.

2 National Geophysical Data Center (NGDC), National Oceanic and Atmospheric Administration (NOAA), 325 Broadway, Boulder CO 80305, USA.

E-Mails: qing.liu@du.edu; paul.sutton@du.edu; chris.elvidge@noaa.gov

* Author to whom correspondence should be addressed; Tel.: +1-850-443-4719

Abstract: Nighttime imagery is an unusual remote sensing data source that offers capabilities to represent human activities on the Earth's surface through the observation of artificial lighting at night. Previous analyses of images of the earth at night derived from the Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS) have revealed a striking correlation between city-lights and human population density. Nighttime light photographs taken by astronauts aboard the International Space Station (ISS) may have the potential of offering more sophisticated representations of population density with finer spatial and spectral resolution than the DMSP-OLS imagery. The objective of this study is to analyze and map the relationships between the city lights of Hong Kong, China, and representations of population and population density, through comparing two types of nighttime imagery (DMSP-OLS satellite image and ISS photograph) to census population and population density derived from the LandScan population dataset.

Keywords: Population density, DMSP-OLS Nighttime satellite imagery, ISS photographs, LandScan population dataset

---

1. Introduction

Nighttime imagery as an unusual remote sensing data source offers capabilities to represent human activities on the Earth's surface through the observation of artificial lighting at night. Previous analysis of nighttime light image data products derived from the Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS) have revealed striking correlation between city-lights and human population density. With finer spatial and spectral resolution than the DMSP-OLS imagery, nighttime light photographs taken by astronauts aboard the International Space Station (ISS) may have the potential capable of offering more sophisticated representation of population density.

Population studies have a long history in remote sensing. Researchers have used many sources of remote sensing data to estimate human population. In late 1960s, Tobler (1969) demonstrated that human population could be estimated at a high degree of accuracy by measuring the size of human settlements observed from satellite imagery. Empirical relations were developed for estimating population by modeling settlements as circular areas. Instead of using high spatial resolution imagery to identify human settlements, the population can be more effectively estimated with nocturnal light intensity derived from nighttime imagery. The strikingly apparent correlation between nighttime imagery and population density was explored for a global extent (Elvidge et al. 1997a, Doll and Muller 1999, Sutton et al. 2001), the continental United States (Sutton et al. 1997) and some metropolitan areas in the United States (Sutton et al. 2003, Anderson et al. 2010), as well as for China (Lo 2001, Cheng et al. 2007). Some studies suggested that the correlation between the nighttime imagery and the pixel value of population or population density is low and not statistically significant. Doll and Muller (2000) pointed out a spatial mismatch between the location of brightest lights and highest population densities for London. Elvidge (1997b) also indicated that the use of night-time light imagery was dropped as a model input due to the effect of economic development on the brightness and intensity of nighttime lighting. One explanation for the low correlation or the mismatch is the fact that the DMSP saturates in most of the areas of high population density. With finer spatial resolution (estimated to be 6m per pixel), photographs taken by astronaut aboard International Space Station (ISS) provide more nighttime lights information than DMSP-OLS imagery (roughly 1km spatial resolution). It is expected that the ISS photograph will produce a better model to estimate population for an area with high population density and highly developed economy, such as Hong Kong.

A recent study of characterizing relationships between population density and nighttime imagery has been conducted for Denver (Anderson et al. 2010). The study suggested that the DMSP-OLS imagery had higher correlation with LandScan population density than ISS photograph, and that the finer resolution ISS photograph did not produce models of population or population density that were better than pre-existing models using DMSP-OLS imagery. Hong Kong is one of the two special administrative regions of the People's Republic of China (PRC) situated on China's south coast. With a land area of 1,104 km^2 (426 mi^2) and a population of about seven million people, Hong Kong is one of the most densely populated areas in the world. For a sea-based city like Hong Kong with such high population density, whether there will be similar relationships between nighttime imagery and population density as for Denver is expected to be investigated.

To understand the relationships between nighttime imagery and population density for Hong Kong, this study aims to answer the following questions:

a. Does nighttime light intensity positively correlate with the population density?

b. Specifically, what is the relationship between integration of nighttime lights within a district polygon and the total population of the district?

c. Will ISS imagery produce better model than DMSP-OLS for estimation of population in areas with high population density?

The objective of this research is to analyze the correlation between the nighttime city lights of Hong Kong and the population density, through comparing two types of nighttime imagery to population density. It is also expected to produce models to estimate population with nighttime city lights. The results of this research is expected to provide more information about the problems and limitations of using nighttime imagery in estimating population in areas with high population density, and whether finer spatial resolution nighttime imagery will be necessary to overcome these problems and limitations.

2. Methods

2.1. Data: Nighttime Lights, Landscan, and Census Population

The basic methodological approach we used was to compare two types of nighttime light imagery with the population density derived from LandScan population grid dataset, and to predict the total population of each district using the sum of nighttime lights within the district polygon. A pixel in both the Landscan and the DMSP-OLS dataset is a 30 arcsecond grid cell (roughly 1 km^2). ISS photograph was mean aggregated to match the spatial resolution of the

DMSP-OLS and LandScan dataset. The variables used for the analysis were the nighttime lights DN values from nighttime imagery (DMSP-OLS, ISS red, green, blue bands, and first-principal component of ISS photograph), the grid value of population density from LandScan, and the census population for each district.

The nighttime imagery used in this research including DMSP-OLS global radiance calibrated nighttime lights data product for year 2006 obtained from National Geophysical Data Center (NGDC) of National Oceanic and Atmospheric Administration (NOAA). The nighttime imagery used is a cloud-free composite derived from DMSP-OLS data collected at low, medium and high gain settings. The spatial resolution is 30 arc-second grid or approximately 1 km^2 at the equator. “Hong Kong at Night” photograph taken by astronaut from ISS in 2003 was obtained from “The Gateway to Astronaut Photography of Earth” entry on NASA website. Spatial Resolution of the ISS photograph is estimated to be 6 meters per pixel, and approximately 90 meters for the image of Hong Kong area. Population density was derived from LandScan 2008 Global Population Dataset produced by Oak Ridge National Laboratory. The spatial resolution is approximately the same as DMSP-OLS image in 1 km^2 grids. Hong Kong population in 2006 at administrative district level obtained from Hong Kong Census and Statistics Department was used as the actual population for each administrative district. In need of a single-band image that represents the most variability of ISS photograph that can be used in this analysis, a first principal-component image was derived from the ISS image which contains 95% of the variability in the red, green and blue bands of the ISS photograph of Hong Kong.

2.2. Pixel-based Correlation Analysis

We used a pixel-based correlation analysis to measure the strength of the relationships between population density and nighttime imagery. The variables used in the analysis were population density values derived from LandScan data in 1 km^2 grid, pixel DN values derived from DMSP-OLS image also in 1 km^2 grid, and pixel DN values derived from ISS image bands of visible red, green, blue and first principle component, which were mean aggregated to 1 km^2 grids to match the spatial resolution of LandScan population grid data and DMSP-OLS image. Images used are shown in Figure1.

By excluding the pixels out of the boundary of Hong Kong and pixels with no data value in all the six images, we extracted samples of pixel values form the input images. The six groups of values were matched with the same pixels as the observed units. Pearson’s product-moment correlation coefficient was used as the measure of correlation to assess the correlations among different nighttime imagery datasets, as well as between nighttime lights and population density.

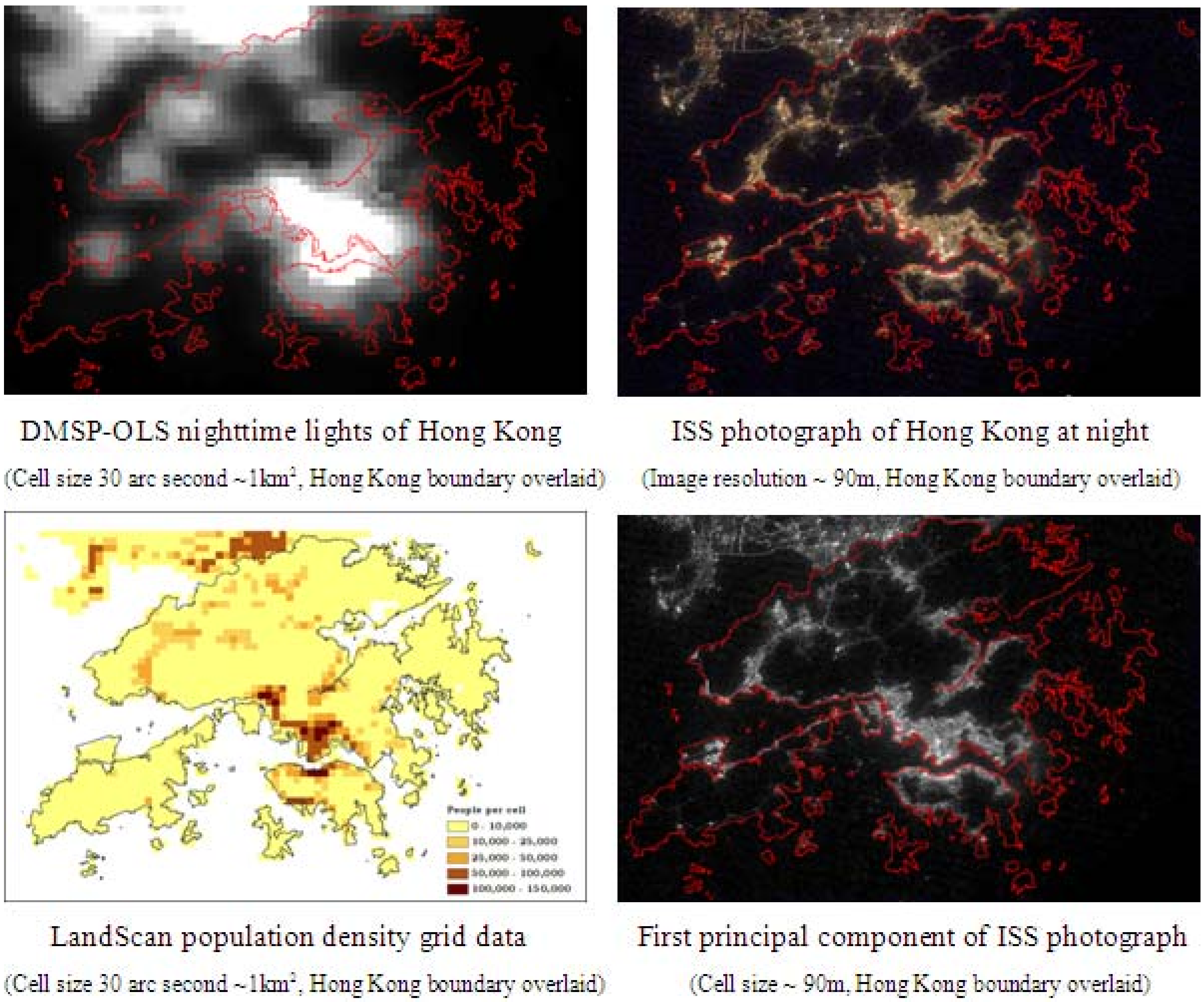

Figure 1: Nighttime Imagery for Hong Kong and LandScan Population Density Gird

2.3. Polygon-based Regression Analysis

We used a polygon based approach to predict the total population for each district with sum of lights within the district polygon derived from DMSP-OLS and ISS photograph. Regression analysis was used to specifically measure the nature of the relationships between nighttime lights and population for each district. Variables being analyzed were census population of the 18 administrative districts of Hong Kong and the sum of lights within each district polygon. DN values of the ISS first principal component imagery were summed within district polygons to predict the total population of each district. Population for each district were derived from Hong

Kong census data and assigned as attributes to the corresponding district polygons. Sum of lights for each district were obtained by running Zonal statistics using ISS first-principle component image for each district polygon.

Ordinary Least Squares (OLS) regression was conducted using total population of each district as the dependent variable and sum of lights within each district polygon as the independent variable. The regression model was then assessed through observing the correlation coefficient of DN values and population, the coefficient of determination, and the standard error of regression. Graphical diagnostics and plots of residuals were analyzed to assess the results of OLS regression model. Errors in estimates of population were mapped for interpreting any possible spatial pattern for the distribution of residuals.

3. Results

3.1. Results of Correlation Analysis

Shown in Figute2 are matrix of Pearson's correlation coefficients and the scatter plot matrix of all variables under analysis. As we would expect, both the DMSP-OLS imagery and ISS imagery strongly and positively correlated with the LandScan population density, with correlation coefficients around 0.6. We noted that DMSP-OLS had the highest correlation with LandScan population density, which was unexpected. Of the ISS data, the green band correlated the most strongly with LandScan, and all the ISS bands correlated strongly with the DMSP-OLS imagery. However, the ISS photograph did not provide a higher correlation between nighttime lights and population density than DMSP-OLS imagery at the spatial resolution of LandScan. The scatterplot matrix represented the correlations graphically. Identifiable correlations between LandScan population density and nighttime images were found in the matrix. Also, all the ISS bands had very strong linear relationships with each other.

Based on the correlation analysis, we found that the pixel values of the nighttime imagery were positively correlated with the pixel values in the population density data. Thus, we concluded that nighttime light intensity positively correlates with the population density at the spatial resolution of approximately 1 km^2.

Correlation Coefficeints

	ISS PC1	ISS R	ISS G	ISS B	DMSP-OLS	LandScan
ISS PC1	1.0000	0.9988	0.9989	0.9851	0.7706	0.6118
ISS R	0.9988	1.0000	0.9976	0.9768	0.7677	0.6116
ISS G	0.9989	0.9976	1.0000	0.9796	0.7709	0.6127
ISS B	0.9851	0.9768	0.9796	1.0000	0.7618	0.5976
DMSP-OLS	0.7706	0.7677	0.7709	0.7618	1.0000	0.6239
LandScan	0.6118	0.6116	0.6127	0.5976	0.6239	1.0000

Scatterplot Matrix

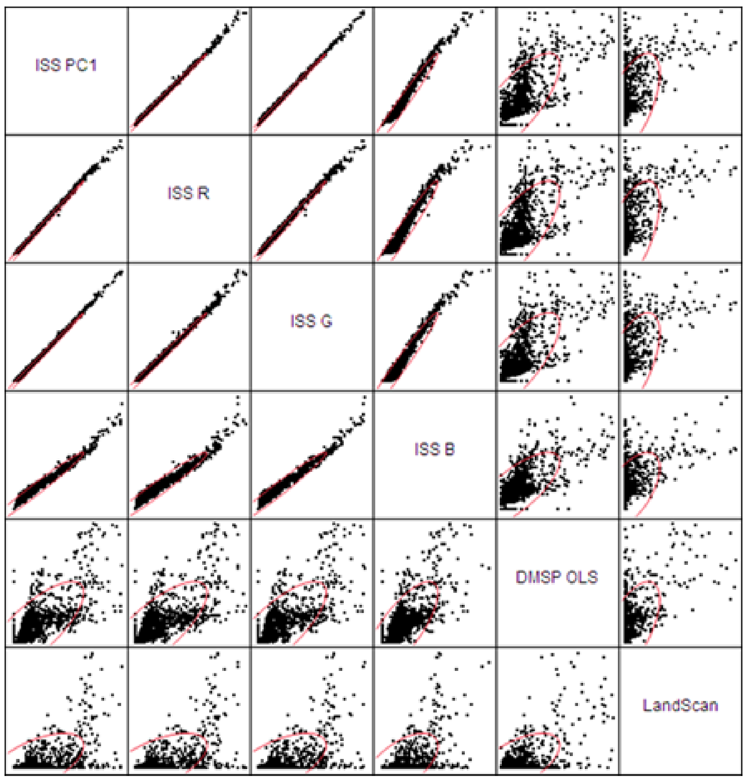

Figure 2: Correlation Matrix of Nighttime Imagery and LancScan Population Density

3.2.Results of Regression Analysis

Figure 3 showed the results of the regression analysis for estimation of population using sum of lights derived from both DMSP-OLS and ISS PC1 image. In the left plot of Figure3, the regression line showed a relatively large slope. Though not statistically significant, it represented a positive linear relationship between district population and DMSP-OLS sum of lights.

However, the R square was 0.15, indicating a poor fit of the regression model to the data under analysis. By plotting the residuals against predicted values of population, the results showed that the residuals are normally distributed, indicating the assumption of the normality of the error components of the linear regression held.

The plot on the right in Figure 3 shows the results of the regression using sum of lights derived from ISS first principle component image to estimate population. The regression line showed a smaller slope compared to the model using DMSP-OLS sum of lights. The linear relationship between the two variables was weak and not statistically significant. The R square was about 0.04, indicating a very poor fit of the regression model to the data. However, it also showed a positive linear relationship between district population and sum of ISS lights within the district polygon. Same as the previous model, the residuals were normally distributed; all the assumption of the linear regression held; so the least squares regression provided unbiased estimators of all model parameters.

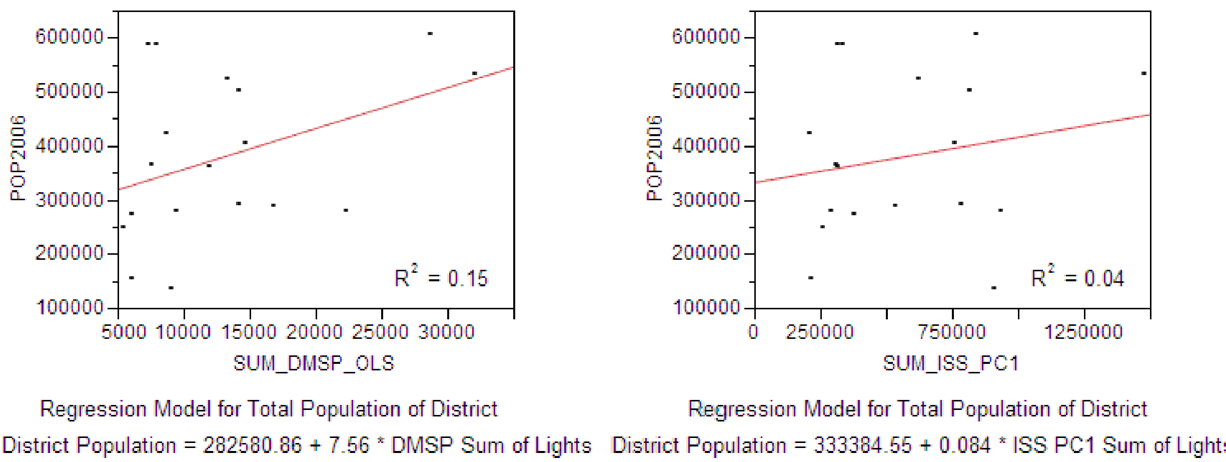

Figure 3: Regression Models Predicting District Population

In addition to the traditional non-spatial evaluation of the regression fit, a spatial biased performance evaluation was used with the residual maps. The maps in Figure 4 showed the percentage error in estimates of population for each district using DMSP-OLS and ISS images. Overestimated districts were represented in red tones while underestimated districts were in blue tones. The overall performance of the regression model is not satisfying with large percentage of residuals. Most of the districts were either overestimated or underestimated by the sum of lights derived from nighttime images. A few districts were reasonably estimated with percentage of errors between -20% and 20%.

Estimations of district population using the two types of nighttime imagery had some patterns in common. Districts including airport, commercial areas, and new town residential areas with high-income and well-educated residents tend to be overestimated by the sum of lights. Those districts were distributed in the Islands district, western areas around Victoria Harbor and the north portion of the New Territories. On the other hand, districts including large residential areas and industrial areas with low-income and less-educated residents tend to be underestimated, such as the new towns in New Territories and industrial areas in Kowloon. Those districts including relatively low density residential areas tend to be reasonably estimated, such as the Southern district in the south portion of the Hong Kong Island. Unfortunately, the ISS image did not estimate the total district population better than DMSP-OLS. The percentage of error was generally higher than DMSP-OLS, and fewer districts were reasonably estimated.

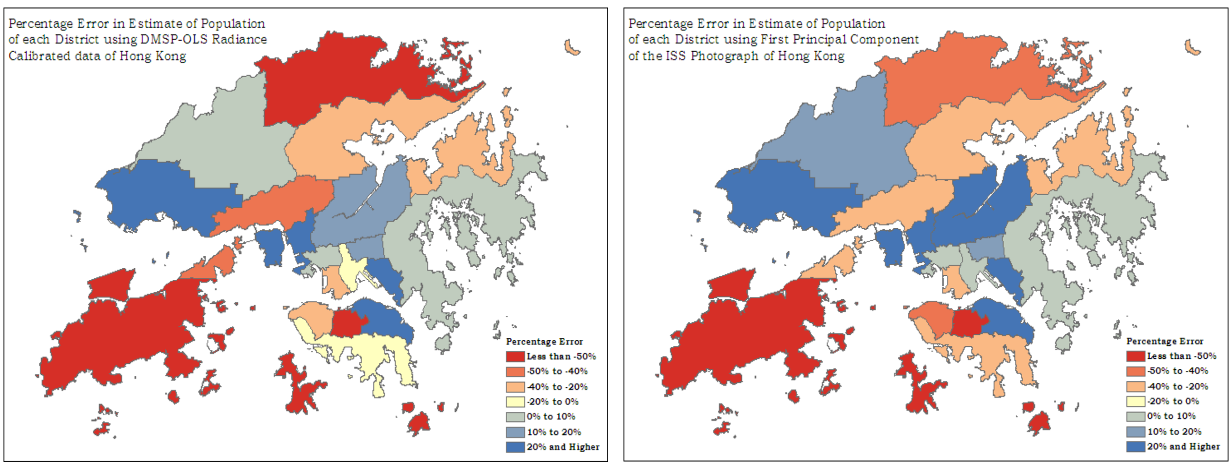

Figure 4: Residual Map for DMSP-OLS and ISS image versus Census Population

4. Discussion and Conclusion

In this study, we used both pixel-based and polygon-based approach to analyze the relationships between nighttime imagery and population density for Hong Kong. The results indicated that nighttime light intensity positively correlated with the population density. However, the ISS photograph with finer spatial resolution than DMSP-OLS image did not increase correlations between nighttime lights and measures of population density at the spatial resolution of LandScan grid (about 1 km^2). From the polygon based perspective, the sum of lights within district polygon derived from both DMSP-OLS and ISS images had positive linear relationships with the total census population for the district. Unfortunately, the ISS photograph is no better than the DMSP-OLS imagery at predicting residence-based population at district level for Hong Kong. Areas of high ambient population density that are not residential tend to emit more lights than residential areas.

One explanation of the lower correlation between finer-resolution ISS photograph and population density than DMSP-OLS image might be that DMSP-OLS had approximately the same spatial resolution (and so the cell size) as the LandScan population density grid data. ISS photograph was mean aggregated at a factor of 11 to the coarser resolution of 1 km^2. When mean-aggregating the ISS image, lots of details of the nighttime city lights were eliminated. The mean of the nighttime light values within a 1 km^2 grid may not be representative of all the pixel values within the extent of the grid, which can weaken the correlation between the ISS pixel values and the LandScan population density grids. A method of sum-aggregation of ISS image can be applied in future studies to see whether better correlation between ISS image and population density will be found.

The sample size for the regression analysis was very small (18 districts), due to that the finest official census data for Hong Kong is at administrative district level. From a statistical perspective, the regression model did not violate any of the assumptions of the linear regression, but the OLS regression model may not be the best fit model for estimating the district population with nighttime imagery. From the regression results, we can conclude that nighttime lights alone may not be the best predictor for the estimation of population. Other potential measures of population can be taken into consideration as one of the predictors for the total district population. In addition, due to the limitations in data acquisition, ISS photograph taken in 2003 were used to predict the district population in 2006 in this study. The mismatch in the time period of the data acquisition might also affect the results of the regression model. Additionally, due to the small sample size, the sampled data of the dependent variable and the two independent variables for the two regression models are strongly skewed. The logarithm transformations for either of the variables or both of them were used to transform the sample data into a more normal distribution. However, none of the transformation improved the fit of the OLS regression model to the data. For further studies, we can explore other regression models to predict population with nighttime lights other than the OLS models used in this study. Other predictors besides sum of lights can be explored for a better prediction of population.

References

Anderson, S. J., Tuttle, B.T., Powell, R.L., Sutton, P.C. (2010) *Characterizing relationships between population density and nighttime imagery for Denver, Colorado: issues of scale and representation.* International Journal of Remote Sensing, 31(21), 5733 – 5746.

Cheng, L., Zhou, Y., Wang, L., Wang, S., Du, C. (2007) *An estimate of the city population in China using DMSP night-time satellite imagery.* Geoscience and Remote Sensing Symposium, 23-28, 691-694.

Doll, C.N.H. and Muller, J-P. (1999) *An evaluation of global urban growth via comparison of DCW and DMSP-OLS satellite data.* In: Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS'99). Hamburg, Germany 28 June – 2 July. 1134-1136.

Elvidge, C.D., Baugh, K.E., Hobson, V.R., Kihn, E.A., Kroehl, H.W., Davis, E.R. and Cocero, D. (1997a) *Satellite inventory of human settlements using nocturnal radiation emissions: A contribution for the global toolchest.* Global Change Biology, 3 (5), 387-395.

Elvidge, C.D., Baugh, K.B., Kihn, E.A., Kroehl, H.W., and Davis, E.R. (1997b) *Mapping city lights with nighttime data from the DMSP operational Linescan system.* Photogrammetric Engineering and Remote Sensing, 63:727-734

Lo, C.P. (2001) *Modeling the population of China using DMSP operational linescan system nighttime data.* Photogrammetric Engineering & Remote Sensing, 67:1037–1047.

Sutton, P.C. (2003) *Estimation of human population parameters using night-time satellite imagery.* In: Mesev, V. (Ed.) Remotely Sensed Cities. Taylor & Francis: London, UK, 301-334.

Sutton, P.C., Roberts, C., Elvidge, C. and Meij, H. (1997) *A comparison of nighttime satellite imagery and population density for the continental united states.* Photogrammetric Engineering and Remote Sensing, 63 (11), 1303-1313.4.2.

Tobler, W. (1969) *Satellite confirmation of settlement size coefficient.* Area 1(3), 30-34.

Data Sources

1. DMSP-OLS global radiance calibrated nighttime lights data product

   http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html

   From: National Geophysical Data Center (NGDC) of National Oceanic and Atmospheric Administration (NOAA)

2. "Hong Kong at Night" photograph taken by astronaut from ISS in 2003

   http://eol.jsc.nasa.gov/scripts/sseop/photo.pl?mission=ISS006&roll=E&frame=36854&QueryResultsFile=130504459047002.tsv

   From: "The Gateway to Astronaut Photography of Earth" entry on NASA website

   Geo-referenced ISS photograph of Hong Kong:

http://www.ngdc.noaa.gov/dmsp/ISS_Hong_Kong.html

3. LandScan 2008 Global Population Dataset

   http://www.ornl.gov/sci/landscan/

   Produced by: Oak Ridge National Laboratory

4. Hong Kong population in 2006 at administrative district level

   http://www.censtatd.gov.hk/hong_kong_statistics/statistics_by_subject/index.jsp

   From: Hong Kong Census and Statistics Department

Submitted March 11, 2011.
Accepted May 5, 2011.