Mapping night-time light emissions in the EU using satellite observed visible-near-infrared emissions as a policy tool: The MANTLE Project

M. Tang & G.C. Deane  
HTS Development Limited, Hemel Hempstead, United Kingdom

D.J. Briggs  
Imperial College of Science, Technology and Medicine, London, United Kingdom

C. Conese  
Istituto per l’Agrometeorologia e l’Analisi Ambientale applicata all’Agricoltura, Firenze, Italy

M. Benvenuti  
Centro di Studio per l’applicazione dell’ Informatica in Agricoltura, Firenze, Italy

M. Petrakis  
Institute of Environmental Research & Sustainable Development, National Observatory of Athens, Greece

Keywords: remote sensing, night-time visible-near-infrared (VNIR) radiance, DMSP OLS data, GIS, mapping, socio-economic indicators, urban typology, light pollution

ABSTRACT: Night-time light emissions maps derived from coarse resolution satellite imagery provide a means to obtain continent-wide or even global estimates of the area covered by human settlements. Such night-time light emissions maps can also be regarded as a surrogate measure for a range of other socio-economic and environmental indicators, notably population number & density, GDP, energy consumption & wastage, skyglow and tranquil areas. The MANTLE project builds upon a project definition phase incorporating a state of the art review and user-requirements survey carried out across the EU to define, produce and present a range of information products derived from night-time satellite imagery that are of value to national and international users.

MANTLE uses reduced gain data from the Defense Meteorological Satellite Program’s Operational Linescan System (DMSP OLS) to derive country and EU-wide night-time light emissions mosaics. Regression-based modelling techniques have demonstrated that strong relationships exist between these DMSP OLS data and such parameters as population, GDP, road lighting, energy wastage and total energy consumption. This paper describes some of the analyses carried out during the MANTLE project and presents preliminary versions of some potential MANTLE products.

1 INTRODUCTION

Night-time light emissions maps derived from coarse resolution satellite imagery provide a potentially important data source, from which to obtain continent-wide or even global estimates of the area covered by human settlements, both for policy support and research. On the one hand, light emissions are a significant form of environmental pollution; on the other hand they provide a valuable socio-economic and environmental indicator. The MANTLE project is aimed both at exploring the potential of this data source and developing and testing methods for using the results in support of EU policies.

2 SOURCES OF NIGHT-TIME LIGHT EMISSIONS

Information on the total level of night-time light emissions within the EU is lacking, despite the prevalent use and increasing levels of lighting in almost all urban areas in response to a range of social and economic influences. Data are not available for the EU, but a recent survey in the USA showed that skyglow was increasing annually by up to 30 per cent in some cities (quoted by Shaflik, 1997).

Major incremental factors are:
- the increasing power of many light sources;
- increased road lighting (as a result of expansion of urban road networks and for enhanced road safety);
- increasing night-time traffic flows;
- increased use of security lighting (commercial and domestic premises);
- the development of the ‘24 hour city’, with all-night provision of entertainment and shopping facilities;
- increasing use of night-time lighting for advertising and promotional purposes, and
Figure 1. DMSP-OLS coarse data with NUTS3 borders
• general increases in wealth and disposable income.

Today, roads represent a major source of lighting, both from fixed street-side lighting and the headlights of vehicles (Shaflik, 1997). Most of the remainder derives from buildings, much of which is associated with security and/or promotional commercial lighting. Industrial lighting also comprises a significant proportion of the total, though the character of this source has changed greatly in the EU over recent years as heavy industry has given way to light and retail industry. Nevertheless, many industrial areas, including manufacturing plants, transportation depots and warehouses remain as important sources of urban light emission. Other sources of increasing importance are domestic premises (where security lighting, in particular, has become both more powerful and more common) and sports and leisure centres (e.g. sports grounds/halls, clubs) with outdoor and evening facilities.

2.1 The importance and potential of night-time light emissions

The relationship between urban light emissions and population level is already widely recognised. In the USA, a relationship, referred to as Walker’s Law (IDSA 1996b), has been determined from measurements of skyglov around Californian cities. Based on this, it has been suggested that satellite-derived measurements of urban light emissions may be used as a potential indicator of population distribution (e.g. Welch, 1980; Foster, 1983; Sullivan, 1989; Elvidge et al., 1997a). Elvidge et al. (1997a), for example, found a highly significant relationship ($r^2 = 0.85$) between urban population size and area lit for 21 countries across the world.

Data on urban light emissions might equally be expected to provide an important surrogate for a range of other socio-economic and environmental indicators. Elvidge et al. (1997a) found strong and consistent relationships between the national area lit and both Gross Domestic Product ($\text{billion GDP}$; $r^2 = 0.97$) and level of energy consumption (measured as Gigawatt hours; $r^2 = 0.96$) for 21 countries examined world-wide. Similar relationships might also be expected with a range of other socio-economic and environmental conditions.

In the same way, data on light emissions might be used as an important environmental indicator. At its simplest, it could provide a simple means of mapping urban areas, and thus of tracking changes in the area of built-up land as a result of urban development. The distribution of urban light emissions might also give some insight into the internal structure and layout of towns, and thus provide a useful indicator of urban morphology. Since light emissions are a form of waste (and are likely to be correlated with overall levels of energy usage), they may also offer a means of estimating levels of energy consumption and wastage. In addition, the geography of light emissions around larger towns (including patterns of connection and juxtaposition) may be valuable indicators of the wider environmental footprint of these urban areas, and of the spatial interdependencies between them. More generally, because of these various associations, light emissions might be an especially effective basis for sampling and survey/statistical stratification, and a valuable covariate for use in the mapping and interpolation of population and socio-economic activities.

2.2 Light emissions as a socio-economic and environmental indicator

As a result of their inherent association with human activity, data on light emissions offer a basis for constructing a range of widely applicable socio-economic and environmental indicators. If night-time light emissions can act as a marker for human activity, they may be useful, if analysed appropriately, for providing valuable information on socio-economic and demographic conditions and trends. Light emissions may thus provide a basis for developing useful indicators for policy support. The MANTLE project aims to build, produce and present a range of information products derived from night-time satellite imagery that are of value to national and international users.

3 METHODOLOGICAL DEVELOPMENT AND TESTING

Several satellite data sources were considered and used for this purpose. The most important was the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS), as used in previous studies on mapping light emissions (e.g. Elvidge et al., 1997a, 1997b). DMSP OLS imagery has the advantage of enabling faint sources of light emission to be detected on the Earth’s surface: the sensor is reported to be four orders of magnitude more sensitive than other, currently available, satellite sensors. It also provides continuous coverage of 3000km during daytime and night-time conditions. The data are initially collected at a spatial resolution of 0.56km (referred to as “fine”), but on-board averaging produces “smoothed” data with a nominal resolution of 2.7km. Most of the data received by the NOAA National Geophysical Data Centre (NGDC) is in the smoothed resolution mode.

Mapping night-time light emissions in the EU using satellite observed visible-near-infrared emissions as a policy tool: The MANTLE Project
3.1 **Image Processing**

To understand the information contained in the DMSP OLS data it has been necessary to create a "composite" image of the data, using a procedure to calculate the 'Weighted Sum Intensity' for DMSP OLS images. The reason for creating a "composite" image is that:

- the DMSP OLS sensor set at low-gain (L) is able to capture only very bright targets and cannot sense very low light;
- the DMSP OLS sensor set at medium-gain (M) is reliable only in sensing targets with mean intensity, and is saturated by very bright targets and, as for low-gain images, cannot sense very low light;
- the DMSP OLS sensor set at high-gain (H) can reliably sense very low lights, but, again it is saturated by brighter targets.

The basic concept behind the "composite" image is that DMSP low-, medium- and high-gain images are combined into a single 16-bit representative image. An example of this image is shown in Figure 1.

3.2 **Modelling and Analysis**

Modelling of population, GDP and energy consumption has been undertaken at EU, national and regional levels. All referenced data sets were integrated into a GIS (at an appropriate spatial scale) in order to allow processing and manipulation, and spatial modelling.

MANTLE used DMSP OLS data to derive country and EU-wide night-time light emissions mosaics. The study has analysed the relationships between DMSP light emissions and CORINE land cover, light pollution modelling and assessed socio-economic indicators based on DMSP and CORINE land cover data. Regression-based modelling techniques, used with other statistical methods, have demonstrated that strong relationships exist between these DMSP OLS data and such parameters as population number and density, GDP, road lighting, energy wastage and total energy consumption. Figure 2 shows some results from simple regression analyses.

Development and testing of these methods has been carried out at three linked scales: locally (in a series of 'test' areas), in one or more selected trans-frontier areas, and at EU level. The purpose of the test areas is to enable specific relationships between light emissions and other factors of interest to be explored in detail (if necessary through field investigation). Test areas have been selected to provide contrasting study areas, in terms of their urban form, topography, socio-economic activities, climate and other characteristics (all factors likely to affect light emissions). Figure 3 and Figure 4 show population and energy consumption compared with lit areas in one test area on the island of Crete.
Analysis within the selected transfrontier area is designed to allow issues of data consistency and spatial structure to be investigated. In this context, one of the main problems is what is known as the Modifiable Areal Unit Problem (MAUP) (Openshaw, 1984). Census data, for example, typically relate to administrative units which vary greatly in size and shape from one country to another, making it difficult in many cases to interpret underlying population patterns, or to compare data from different regions. Moreover, the administrative units typically do not conform closely to the actual boundaries of urban areas, producing considerable uncertainty and fuzziness in population maps. This may mask significant local patterns and changes, and lead to significant errors when attempts are made to link population data to other data sets (e.g. environmental or health data). An important part of the analysis will therefore be to explore the capability of using light emission data to model socio-economic factors across transfrontier regions, as a basis for deriving spatially more consistent data. Equally important, however, will be testing the robustness of the models developed to interpret light emissions for one area in other, adjacent, areas.

Analysis at EU-level is intended to extend these methods to the wider scale. At this scale, of course, variations in the relationships between light emiss-

\[
\log(\text{Energy Consumption}) = A \times \log(\text{Area Lit}) + B
\]

Summer and winter DMSP data show similar linear relationships with energy consumption by prefecture. NB energy data only available as annual total.

During the summer a significant percentage of this energy is consumed for air-conditioning purposes. This is possibly the reason for the higher intercept that appears in the summer linear relation (the same Area Lit corresponds to more energy consumption).

Figure 3. Winter and summer correlations with lit areas on Crete

Figure 4. Energy consumption for lit areas on Crete
tions and socio-economic and environmental characteristics are likely to be especially important. The question of whether specific models are needed for different countries or geographic regions, will have to be addressed. This is likely to be the situation for areas outside the EU, where problems of data consistency and availability are also likely to be significant, especially at lower levels of aggregation (e.g. Nomenclature des Unités Territoriales Statistiques levels NUTS 3, NUTS 5), for which data sets may be incomplete. The outcome of the EU-wide study will be an assessment of how far the MANTLE approach could be used to enhance or complete data sets of variable quality in areas of interest beyond the EU.

4 EU APPLICATION AND MAPPING

The first phase of the study involved a detailed evaluation of user needs, both for light emission data per se and for derivative data sets (e.g. on socio-economic indicators). The final phase of the work will be to apply the methods developed during the study to derive a set of socio-economic and environmental indicators across the EU. The extent to which this will be possible – and the accuracy of the resulting indicators – will clearly depend on the success or otherwise of the preceding work. The target indicators are, however, listed in Table 1. These indicators will be distributed to potential users for review and evaluation, before being made publicly available (e.g. via the Web).

<table>
<thead>
<tr>
<th>Core Indicators</th>
<th>Urban Area</th>
<th>Population size/density</th>
<th>Total energy consumption</th>
<th>Energy Wastage</th>
<th>Gross Domestic Product</th>
<th>Urban Typology</th>
<th>Urban Footprint</th>
<th>Rural Tranquility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ancillary Indicators</td>
<td>Urban area/green space</td>
<td>Night-time noise</td>
<td>Urban air pollution</td>
<td>Light-induced health risks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Target socio-economic and environmental indicators

CONCLUSION

DMSP OLS data has potential as an important data source in providing valuable information both for policy support and research. The association between light emissions and human activity as demonstrated by the MANTLE Project can be exploited to provide valuable information on socio-economic and demographic conditions and trends, and environmental indicators as a basis for policy support. Further research is required, and is currently on-going to model policy-related socio-economic indicators to monitor urban development and population change and to map tranquility. Scope exists for enhancement and wider applications, such as extending the research to investigate associations between DMSP data and other human related activities, for example, with air pollution and noise modelling.

Much of this research has so far been carried out using coarse resolution data, and further studies of DMSP data are required in order to understand and analyse the data fully. Obtaining timely acquisition of DMSP OLS data would improve this process, as well as increase the potential for commercial uptake for the data. The MANTLE Project has so far demonstrated that DMSP OLS data is a valuable data source that can be used to support policy related measures. Light emissions data from their inherent association with human activity, can also be a surrogate measure for a range of other socio-economic and environmental indicators.

ACKNOWLEDGEMENTS

The MANTLE Project is funded under the EC-IST supported Shared-cost RTD (2000-2002) programme of the European Union and is being carried out by a total of eight partner organisations based in four EU Member States. HTS Development is the co-ordinating partner. The authors of this summary paper acknowledge the contributions also made by the following members of the consortium:

Science Systems (Space) Limited, Chippenham, UK
Rasmussen & Witthoff, Frederiksberg, Denmark
Regione Liguria, Italy

REFERENCES
