A COMPARISON OF DIFFERENT TECHNIQUES APPLIED TO THE UK TO MAP SOCIO-ECONOMIC PARAMETERS: IMPLICATIONS FOR MODELLING THE HUMAN DIMENSIONS OF GLOBAL CHANGE

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KEY WORDS: Global Change, Mapping, Interferometry, Remote Sensing

ABSTRACT

This paper focuses on the potential of remotely sensed imagery to map the parameters important to aid our understanding and modelling of the interactions between anthropogenic activity and the natural environment. Urban areas are nodes for commerce, industry, habitation and the exchange of ideas. As such they are areas which are of greatest importance to scientists studying human induced global change. Urban areal extent is one parameter that is readily mapped from remote sensing data, and is already a component of global land use maps. This paper considers to what extent remote sensing can provide information on other parameters, and how different techniques may compliment each other.

Night-time imagery over the UK has been analysed with respect to a number of other datasets. Street lighting is hypothesised to be a major contributor to night-light data, so a detailed map of the road network was used to analyse which road types were the largest contributors to “light pollution” over the UK. The UK is highly visible from space at night, urban centres being clearly visible as foci of bright light. A 1km land-use map provided by the Institute of Terrestrial Ecology (ITE) was used as a more quantitative measure of correlation between light and land cover class. Varying proportions of urban/suburban cover against radiance were tested to establish the threshold radiance for different land cover proportions. Night-light data has been previously demonstrated to be useful for estimating urban population (84% accurate for the UK). A 200m gridded census map was resampled and summed to 1km and used to better understand the radiance-population relationship. Features such as airports were found to affect the correlation of light to population. Night-time light imagery is limited however, in that the light emissions are used as a proxy for the underlying built environment. SAR interferometric composite images of phase coherence, amplitude, and difference in amplitude and its urban classified component may also be used to elucidate the night-light data and assess the accuracy of the built environment components of the ITE land use map. A preliminary example of this is shown here.

1 INTRODUCTION

Apart from natural hazards, human activity has the greatest potential to inflict unplanned changes on the natural environment. However, the feedbacks between human activity, the natural environment and the climate system are so complex, it is one of the least well understood aspects of the subject despite being a major (if not the primary) driver for global change. There is a dearth of suitable datasets to link the effects of human activity to the well-established biogeochemical processes leading to global change.

Conventional optical imagery is not well suited to urban area detection and delimitation as it suffers from mixed signals arising from the heterogeneous land-cover, particularly due to green spaces within the urban fabric, which is a feature of these areas. Night-time imagery overcomes this problem by solely considering light emissions from the ground. In the absence of industrial processes such as gas flare burn off, this contribution is primarily from cities and transport networks; the hubs of human concentration.

1.1 Night-time Imagery

Night-time imagery has great potential not only for mapping urban areas, but also deriving other socio-economic parameters. (Doll et al., 2000) have demonstrated its utility for mapping Carbon Dioxide emissions, economic activity and, estimating national populations (Doll & Muller, 1999). A radiance calibrated image of the UK at 30” (~1km) captured by the Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) was processed and supplied by Chris Elvidge at NOAA-NGDC. The radiance-calibrated night-time light product supercedes the frequency composite dataset acquired between October 1994 and March 1995 from which a ‘stable lights’ dataset was created. Stable lights refer to light sources that are spatially and temporally stable throughout the period of observation. In this way city lights may be distinguished from transient features such as bush fires. The OLS channel used to acquire the images is a broad band visible – near infrared (0.4-1.1μm) capable of sensing light emissions down to 10^{-9} $W.cm^2sr^{-1}.\mu m^{-1}$. Clouds were screened via use of the thermal channel of the OLS sensor. The DN value associated with a pixel refers to the percentage frequency with which lights were detected during cloud free overpasses (Elvidge et al., 1997). This was thresholded to minimise the effects of reflection from adjacent water bodies (blooming).

The radiance-calibrated dataset was collected during the period March 1996 and January-February 1997. It differs from the preliminary stable-lights product in that a variable gain control was used to acquire the constituent images. Previously high gain settings were used to amplify the signal from faint light sources. This also had the effect of saturating the data received from much brighter cities. In order to accommodate the wide range of light intensities encountered, a variable gain of 24dB and 50dB was used and then the individual images composited (Elvidge et al., 1999). All data were taken when lunar illumination was low so as to minimise its effects, especially over water bodies close to terrestrial light sources. By conducting an initial variable gain experiment, thresholds of minimum detectable light were established and used to calibrate the output from the sensor. Work done by Chris Elvidge at NOAA-NGDC based in the US, suggests that towns of only 150 inhabitants can be detected (Elvidge, pers. com.)

1.2 Other Datasets

Studies up until now have concentrated on night-time lights at a global scale and have been used to infer parameters like population via derivation of areal, and areal-radiance log-log relationships. An aim of this paper is to establish to what degree night-time imagery represents light sources on the ground, and how well the coarse resolution of the imagery compares to the expected classes found in land use maps (namely, the urban and suburban classes) and gridded census data. The UK was selected for this study, as there were many ancillary datasets available and almost all similar previous work has only focused on the US. The UK offers a European perspective, and access to comparative data was easily available from the Manchester Information and Associated Services website [1].

City-lights over the UK was compared against the following datasets which are described in more detail below:

- Bartholomew’s 1:250,000 road network
- Institute of Terrestrial Ecology’s 1km land-cover map
- 1991 Population census data gridded to 200m (SURPOP)

1.2.1. The ITE Land Cover Map. The map used was produced by the ITE and is itself derived entirely from satellite data, specifically a mosaic of 46 Landsat TM images taken between 1987 and 1990. The product was produced on a 25m grid and there is also a 1km ‘summary’ dataset. In resampling from 25m to 1km, the relative % coverage of each of the 25 classes is represented in each 1-km cell. Each land cover class is represented as an ArcView coverage, thus the urban layer is essentially a map of the UK with the % urban value in each cell. A realistic assessment of accuracy for the Land Cover map is put at between 80-85% (Fuller, 1995)

The format of the landcover map was such that it could be used with the radiance calibrated night-time data to test whether there is any obvious relationship between radiance and land cover exist for the UK. In particular since urban and suburban classes are distinct, there is a good opportunity to examine how these two individual classes affect night-time light emissions. It is hypothesised that light should only come from cells that have some component of urban or suburban infrastructure therein and that radiances are higher where urban infrastructure predominates. As a point of note, the urban class is defined as *‘all developments which are large enough to fill individual pixels* [at 25m]*, to the exclusion of significant quantities of permanent vegetation’* (Fuller, 1995). The suburban/rural development category includes *‘all land where pixels of the Landsat image have recorded a mixture of built-up land and permanent vegetation’* (Fuller, 1995). However, this study is only concerned with which part of the built environment is covered by lights. In this case, one need not make the distinction too rigorously.

1.2.2 Gridded Census Data. A complementary element of the analysis involves a gridded dataset of the census taken in 1991. Census data is collected at the smallest level, by enumeration districts (ED, ~200 households in 1991) of irregular shape and size. This data was then gridded to 200m via identifying the centroids of each ED and then running a re-distribution algorithm that generates a distance decay function, whose extent is determined by the local density of centroids. Weights are assigned to the surrounding cells, which receive a proportion of the count at the centroid [2]. The initial dataset has a resolution of 200m, though this was aggregated to 1km so as to match with the other datasets.

2 NIGHT-LIGHTS AND THE UK ROAD NETWORK

Street lights generate most of the urban light observed at night. The Bartholomew's road network at 1:250,00 is available as an ArcView coverage from MIMAS. Arcs (roads) were assigned identification numbers based on road classes (single/dual carriageways, tunnels etc). These in turn could be grouped into the major road types displayed in road atlases namely; A-roads; B-roads; motorways; and minor roads. These categories were overlaid onto a greyscale night-time image map of the UK, using the standard colour map from OS maps (Figure 1). The distance of each road type was calculated for the range of radiances occurring with mainland Britain.

2.1 Methodology

Processing of the data was done using ArcInfo. The arc line coverage was split up into separate route topologies using the ***ARCROUTES*** command that splits an arc topology up into separate routes according to a given attribute within the attribute table. The id-code codes for the road types were selected enabling the GIS to recognise different road types. The night-light grid was vectorised such that each square grid cell was made into a discrete polygon. By vectorising the satellite data, it effectively reduces the problem to calculating the length of an arc within a polygon. The ***POLYGONEVENTS*** command was invoked to compute the geometric intersection of a polygon coverage (the night-lights) and a route system (the roads). Roads were processed by four regions, depending on the prefix of the UK grid tiles used to split up the Great Britain National Grid system. The tables written out by the ***POLYGONEVENTS*** command were merged and road lengths (classified by road types) were collated. A new table of total road length radiance and area was created. Finally total road length was normalised by area so road density for each road type could be plotted against radiance.

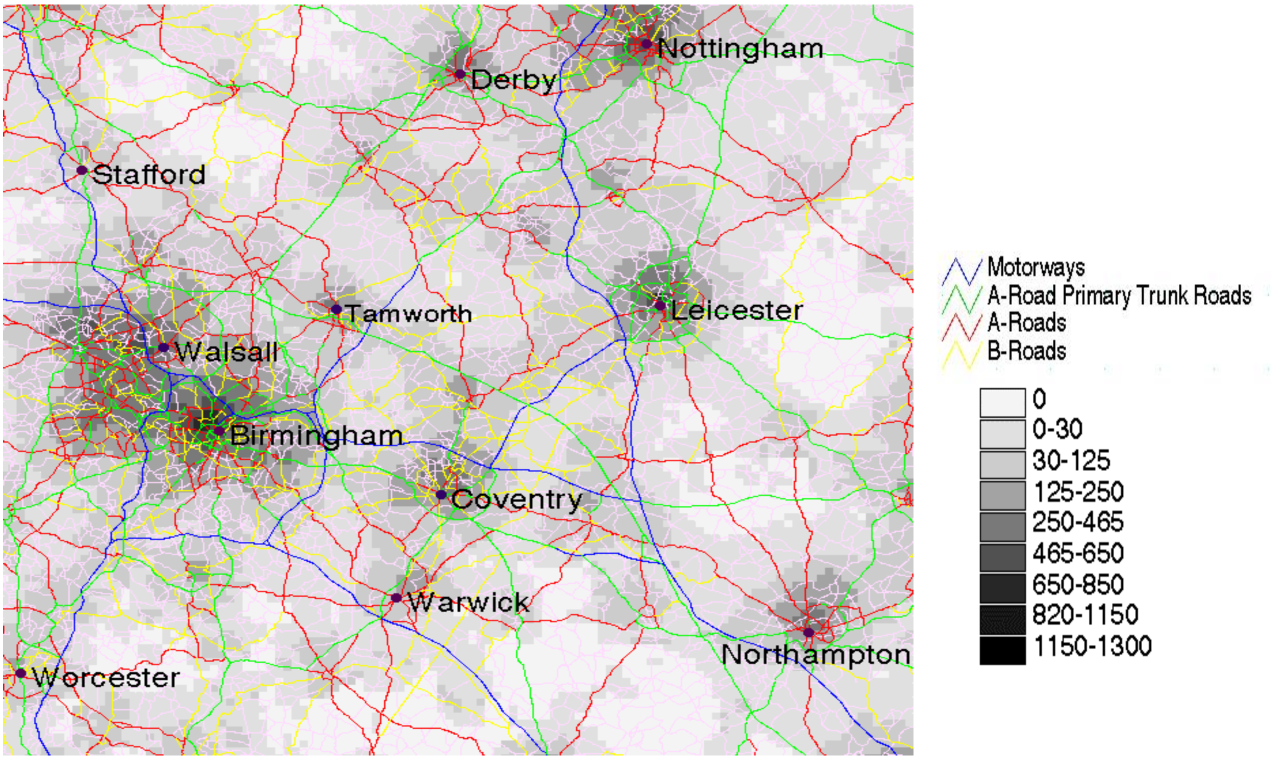


Figure 1. Greyscacle Night-time light polygons with Road Network overlaid for the Midlands. (Radiance; $x10^{-10}$ $W.cm^2.\mu m^{-1}$)

2.2 Results

Figure 2 shows how road density over mainland Britain varies as a function of road type. Road density is expressed as metre lengths per square kilometre and the data has been smoothed by a 10 DN (~32 W.cm^2.um^{-1}.sr^{-1}) running average to make the data more readily understandable. Non primary A-roads dominate the plot and are observed to linearly increase up to around 560x10^{-10} W.cm^2.um^{-1}.sr^{-1} where upon the road density increases rapidly until it reaches 800 W.cm^2.um^{-1}.sr^{-1}. A further peak occurs at the highest radiances in the UK at over 1000 W.cm^2.um^{-1}.sr^{-1} which only occurs over London. Minor roads are densest over the lower range of radiances (0-350 W.cm^2.um^{-1}.sr^{-1}). Minor roads are the densest of all roads in low radiance polygons and have a fairly constant density of around 700 m.km^{-2} until they drop rapidly to around 50 m.km^{-2} at 640 W.cm^2.um^{-1}.sr^{-1} and cease to feature beyond 850 W.cm^2.um^{-1}.sr^{-1}. Motorways have a constant low density throughout the radiance range of around 75-100 m.km^{-2}. Trunk roads and primary dual carriageways linearly increase to around 400 m.km^{-2} at 550 W.cm^2.um^{-1}.sr^{-1} where it stabilises throughout the higher radiances. Meanwhile B-roads increase very gently in density (200-300 m.km^{-2}) until they experience a broad peak of 600 m.km^{-2} through the 810-920 W.cm^2.um^{-1}.sr^{-1} radiance range, suggesting that these roads are most common in the centre of towns.

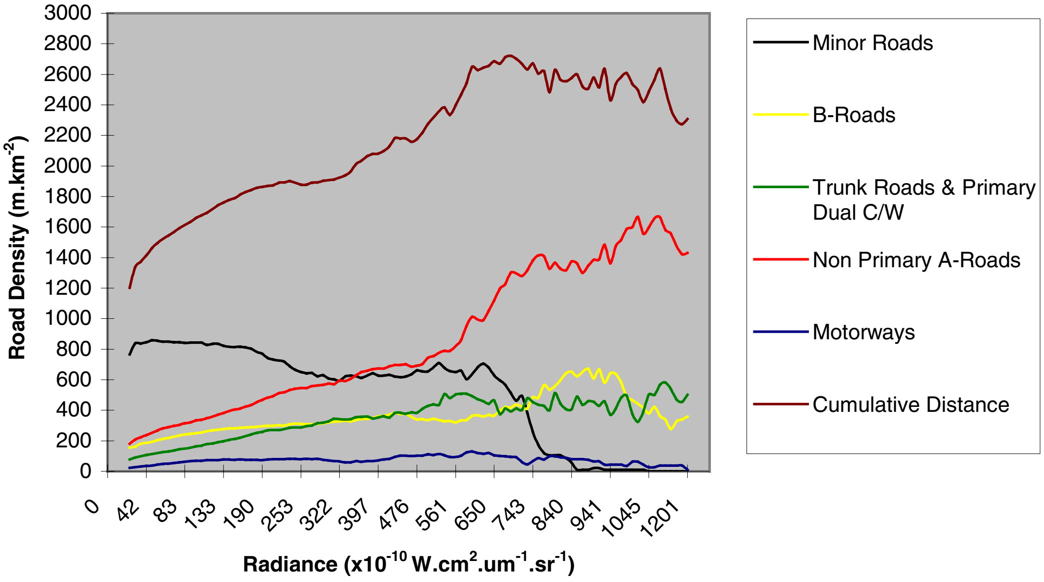


Figure 2. Average Road Density as a function of Radiance for Mainland Britain

2.3 Discussion. The cumulative distance trace is most akin to the non-primary A-roads, showing it is the most dominant of all the road types displayed. Cumulative distance increases roughly linearly with radiance until it reaches a peak of 2700 m.km^{-2} at 600 W.cm^2.um^{-1}.sr^{-1} beyond which road density gently falls to around 2400 m.km^{-2}. It is therefore true to say that overall, night-time light imagery and the road network, taken as a proxy for street lighting are correlated. However there is variation within different road classes. The dominance of non-primary A-roads in the higher radiance range (>620 W.cm^2.um^{-1}.sr^{-1}) suggests that these road sections are concentrated in urban areas, and as such are a major source of street lighting. This study assumes that all roads are lit throughout the entire road network. This is not the case, especially in rural areas. Motorways are only lit around towns (e.g. within the M25 region in London). There exists no comprehensive list of lit road sections for the UK as this is under the control of individual Route Managers (D.Ryall, Highways Agency, personal communication). Thus, it is not immediately clear what are the quantitative effects of road network on the night-time image over Britain.

3 NIGHT-LIGHTS, LAND COVER & POPULATION

The night-light map of Great Britain is observed to have a wide covering of low intensity lighting with urban centres lying within distinguished by their higher radiances. Low level light is far more widespread in this version of the night-time light product than in the frequency composite product produced some 18 months to two years earlier. This is not to say urban area has increased during this time interval, rather that the incorporation of low–gain imagery has identified many more faint light sources which are non-urban, and as such raw night-time imagery cannot be taken as an absolute measure for urban area. The contribution of low radiance light around the urban periphery is of great importance in its interpretation for global urban land cover mapping. In order to assess this situation for mainland Britain, the land cover map was required to identify; firstly if there was a radiance threshold which corresponded to the urban (and suburban) classes of the land cover map.

3.1 Results and Discussion

The first item to be tested was whether there can be a proportion of the built environment, which can be said to be urban. At a first attempt the DCW (Denko, 1992) populated places polygons were used as the urban layer (as opposed to the night-lights). This was tested against proportions of the built environment as defined by a threshold of summed urban and suburban land cover. Assessments were made both visually and with respect to cell counts.

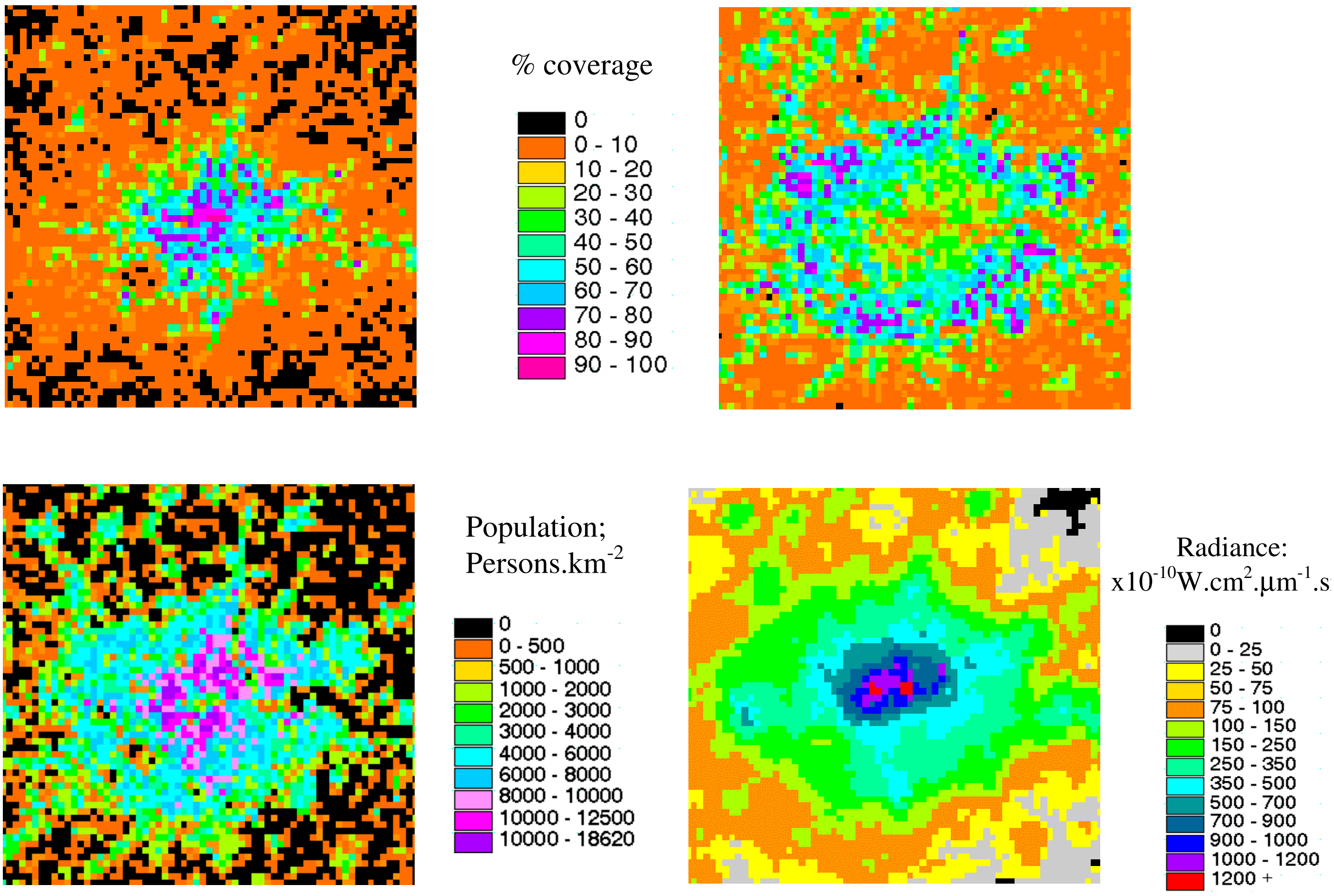
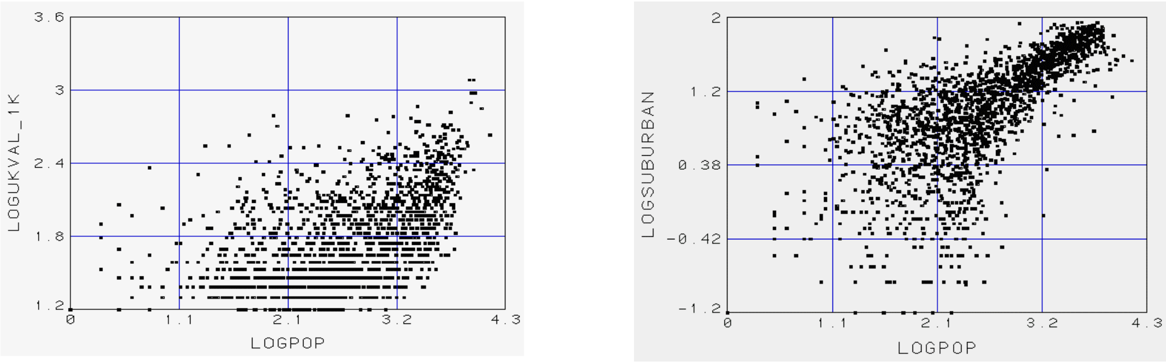

(a) (b) (c) (d)

Figure 3. Different Datasets over London, Urban land cover (a), Suburban land cover (b), and Population (c) as compared to the Radiance Calibrated Night-time lights Imagery (d). Image 65 x 60 km.

Urban areas are characterised in the land cover map by a core of high percentage urban cover surrounded by a ring of high percentage ‘suburban/rural development’ (Figure 3 a,b). Population (Figure 3c) can be observed to follow a similar pattern though in London, the ring of high population density is much closer to the centre. The night-lights image (Figure 3d) has much less detail even though it has the same 1km resolution. This is partly due to the image having been resampled from a nominal resolution of 2.7km. A threshold of 43% for combined urban+suburban land cover was found to be consistent with the DCW urban polygons. This also approximated to a population density of 2000 people.km^{-2}. However, no single radiance threshold could be easily determined in the same way. One reason for this is illustrated in Figures 3c and 3d. The bright patch in the radiance image towards the west of London is Heathrow

Airport, though it has no *recorded* population. The fact that light-sources may be attributable to human activity other than habitation results in the poor correlation between radiance and population (Figure 4a). A given radiance threshold was found to overestimate the area for some settlements, and underestimate for others. In some cases settlements were totally omitted. The spread of population at low radiance values in the scatterplot supports this. Smaller settlements and urban fringes are noted to be omitted when invoking a single threshold. This suggests an adaptive threshold approach whereby the radiance threshold is a function of settlement size, though not helpful in the London Airport case, would generally help to elucidate a relationship between these two parameters. Population was found to be better correlated with suburban land cover (Figure 4b) than with the urban land cover class. Summing urban and suburban land cover helps to define the built environment, but effaces (?) the correlation between a 'built' cover percentage and population. The DCW urban polygons intersected with 33.4 million people out of a total 54.45 million from the 1991 census, giving a 61.3% urban percentage compared with 89% from the WRI. The WRI urban population figure for 1995 (WRI, 1996) for the UK is 52.1 million.



(a) (b)

Figure 4. Scatterplot of Log population and Log radiance (a), and Log Suburban land cover (b)

The gridded population dataset has the potential to identify the population morphology outlined as being a key component of accurate population estimation in the previous section. Once a criterion for urban area delimitation has been agreed, the population morphology within these areas can be assessed and used in population estimation models. The lack of such census datasets for most other parts of the world is a disadvantage for ascertaining how population morphologies differ and to what extent they can be generalised for global mapping.

4 INTERFEROMETRIC COMPOSITES

Imaging radar can offer distinct advantages over optical sensors when considering the mapping of urban area. The inherent nature of radar imagery being more related to the physical properties of the target as opposed to the molecular resonances of surface materials more akin associated with optical imagery (Henderson & Xia, 1997). The structural/physical nature of radar imagery has meant that the backscatter in an image is dependent on the geometric relationship between the look angle of the antenna, and the orientation of the buildings (targets) (Bryan, 1979). In this respect the use of interferometric SAR is particularly valuable for urban mapping. Since urban areas are highly coherent land surfaces when compared to the surrounding area, they tend to appear as bright patches on the image. Studies have shown that urban surfaces can remain relatively coherent since surrounding vegetation will necessarily decorrelate with time as the seasonal vegetation cover alters the scattering characteristics of the target. Significant decorrelation can occur in rural areas due to changes in moisture and wind effects even at short temporal baselines (Grey & Luckman, 1999).

ERS1/2 tandem data was acquired as part of the LANDMAP project (Muller et al., 1999, Morley et al., 2000) was processed and used to create colour composites according to the methodology proposed by Wegmuller & Werner (1995). According to the colour scheme the three bands are assembled into a RGB colour composite as phase coherence (red), amplitude [backscatter] (green) and difference in amplitude (blue). In this way urban areas distinguish themselves as yellow pixels since there is little magnitude in the blue band and coherence and backscatter are high. One strip was processed running diagonally across the British Isles from NE-SW. An example of the 3 band colour composite is shown in Figure 5. Urban areas are easily distinguished on the image despite the very short temporal baseline. Other high coherence areas include fields and ridges. An unsupervised classification could not adequately resolve these features, however a Mahalanbois Distance supervised classifier (Figure 6) was found to markedly improve the extraction of urban features from the 3 band composite. Two supervised urban classes were identified. Both were found to contribute to urban cover in the classification, though one (yellow) was noted to also misclassify some 'bright' pixels on the crest of hills.

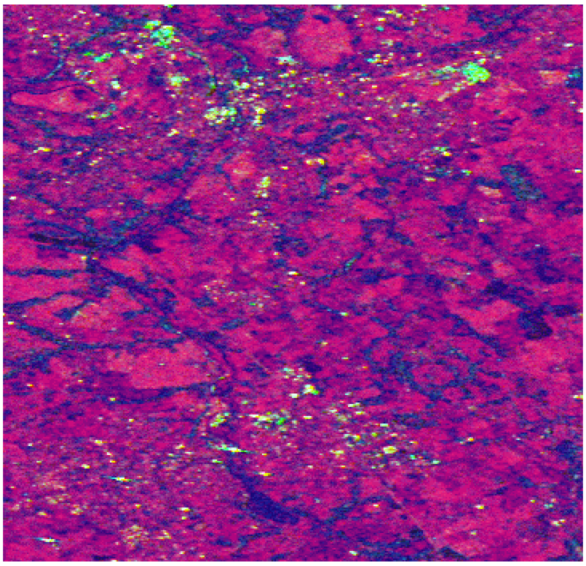


Figure 5. Section of the three-band colour composite phase coherence (red), amplitude (green) and phase difference (blue)

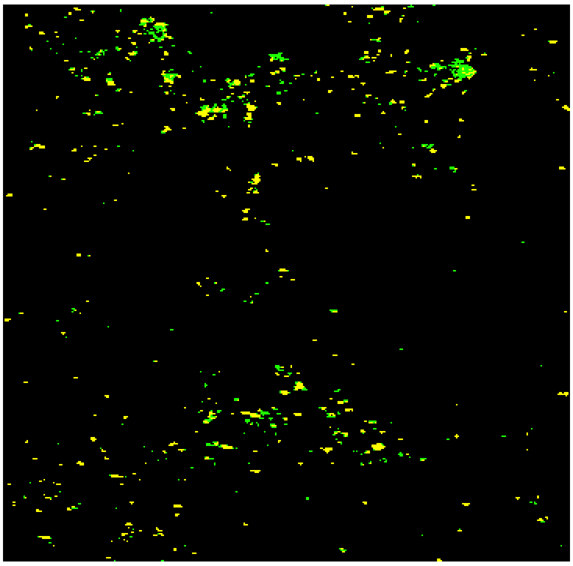


Figure 6. Classified urban layers (2) from the Figure 5. (Mahalanbois distance supervised classification (8 classes)

Urban areas are very apparent on the image at all scales, though the supervised classification still misclassifies some pixels belonging to other high coherent features at this temporal baseline. The result is expected to significantly improve with use of interferometric data with a longer temporal baseline. The higher resolution of this imagery (1 arc second pixel size) has many useful applications with respect to the other datasets used in this study. The lack of a one-to-one correspondence between population and radiance means that there needs to be a more subjective investigation into what the effective ground conditions are to produce a given radiance. The adaptive threshold approach mentioned in the previous section would benefit from the incorporation of a high-resolution urban layer, since pixels of equal radiance but in different positions (i.e. isolated or part of a large cluster). This new layer would also provide a source of validation for the urban components in the ITE land use map, given that interferometric techniques are more reliable than classifications from optical data as displayed in the land cover map.

Aside from the potential to classify night-time data, it is highly valuable in areas where settlements are not reliably detected by night-time imagery. Doll & Muller (1999) used night-time imagery to estimate the urban component of population, but considered the data to be unrepresentative of total settled areas. IfSAR's ability to map the built environment should be of great potential to map urbanisation in the developing world. In addition, since there is urban areas can stay coherent over very long time periods, it also provides a useful tool for change detection analysis as has been attempted by Grey and Luckman (1999) for an area over Cardiff.

5 SUMMARY & CONCLUSIONS

Population, and land cover have been combined with night-time radiance data over mainland Britain to analyse the relationship between these parameters which have, up until now been considered individually. The radiance-calibrated night-light image is over-sensitive to urban land cover. Unlike the land cover data, there appeared to be no single radiance threshold that corresponds to the urban delimitation as described by DCW map layer. This was attributed to the lack of a one-to-one correspondence between population density and radiance for low radiance values. It is hypothesised that this is can be modelled by analysing the population morphology within an urban area, which may be dependent on the size of the settlement in question. The SURPOP dataset will be used to test this hypothesis, along with the previous city lights polygons will be used to test this hypothesis. Higher resolution classified interferometric composites of urban area may be combined to assess how much of the built environment is present to produce a night-light pixel of a given radiance and also to assess the urban layers of the land cover map. The preliminary results presented here are positive and set to become more so with the use of longer temporal baselines for increased delimitation of urban areas.

ACKNOWLEDGEMENTS

The authors acknowledge and wish to thank Alec Walker from the Department of Geomatic Engineering, UCL, for processing the SAR data as part of the LANDMAP project. The authors also wish to thank Chris Elvidge and Kimberly Baugh of NOAA-NGDC for processing and supplying the night-time lights datasets. All processing was done at the Manchester Computing Facility, MIMAS. We thank Dr. Kamie Kimitto for provision of the computing facilities. This work is supported by the NERC studentship GT 04/98 188/TS.

REFERENCES

Bryan, M. 1979. The Effect of Radar Azimuth Angle on Cultural Data. Photogrammetric Engineering and Remote Sensing, 45, 1097-1107

Denko, D.M. 1992. The Digital Chart of the World Project. PERS 58(8): 1125-1128

Doll, C.N.H., Muller, J-P., Elvidge, C.D. 2000. Night-time Imagery as a Tool for Global Mapping of Socio-Economic Parameters and Greenhouse Gas Emissions. AmbioVol.29 No.3 159-164.

Doll, C.N.H. and Muller, J-P. 1999. The Use of Radiance Calibrated Night-time Imagery to Improve Remotely Sensed Population Estimation. Proc. RSS99, Cardiff, 8-10th Sept. 1999 pp.127-133

Elvidge, C.D., Baugh, K.E., Kihn, E.A., Kroehl, H.W., Davis, E.R. 1997. Mapping City Lights with Nighttime data from the DMSP-OLS. *Photogrammetric Engineering and Remote Sensing 63 (6): 727-734*

Elvidge, C.D., Baugh, E., Dietz, J.B., Bland, T., Sutton, P.C., Kroehl., H.W. 1999. Radiance Calibration of DMSP-OLS Low-Light Imaging Data of Human Settlements. *Remote Sensing of Environment* 68: 77-88.

Fuller, R.M., 1995. The Land cover Map of Great Britain – A Description, Annex A. Pub. ITE Monks Wood, Abbots Ripton, Huntington, Cambs. PE17 2LS.

Grey, W.M.J., Luckman, A.J., 1999. Using SAR Interferometric Phase Coherence to Detect Urban Change. Proc. RSS99, Cardiff, 8-10th Sept. 1999. 457-464.

Henderson, F.M., and Xia, Z-G. 1997. SAR Applications in Human Settlement Detection, Population Estimation and Urban Land Use Pattern Analysis: A Status Report. IEEE Transactions on Geoscience and Remote Sensing, Vol.35. No.1 79-85

Morley, J.G., Walker, A.H., Muller, J-P., Kimitto. K, Mitchell., K, Chagani, K., Smith., A., Barnes, J., Cross. P.A., Dowman, I.J. 2000. LANDMAP: Creating a DEM of the British Isles by SAR interferometry. ISPRS 2000. Amsterdam.

Muller, J-P, Morley, J.G., Walker, A.H., Barnes, J., Cross, P.A., Dowman, I.J., Mitchell, K., Smith, A, Chagani, K, Kimitto, 1999. The LANDMAP Project for the Creation of multi-sensor Geocoded and Topographic Map Products for the British Isles based on Tandem Interferometry. Fringe '99 ESA Workshop, Liege 10th Sept. – 12th November 1999. www.esa.int/fringe99.

Wegmuller, U., Werner, C.L. 1995. Land Surface Analysis using ERS-1/2 Tandem Data. ESA Bulll. No.81, Feb. 1995. 30-37.

World Resources 1996-97, 1996. A Guide to the Global Environment. Joint Publication by; The World Resources Institute, UNEP, UNDP, The World Bank, *OUP.*

URL References

[1] http://www.mimas.ac.uk
[2] http://census.ac.uk/cdu/surpop/