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High resolution map of light pollution over Poland

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ABSTRACT

In 1976 Berry introduced a simple mathematical equation to calculate artificial night sky brightness at zenith. In the original model cities, considered as points with given population, are only sources of light emission. In contrary to Berry's model, we assumed that all terrain surface can be a source of light. Emission of light depends on percent of built up area in a given cell. We based on Berry's model. Using field measurements and high-resolution data we obtained the map of night sky brightness over Poland in 100-m resolution. High resolution input data, combined with a very simple model, makes it possible to obtain detailed structures of the night sky brightness without complicating the calculations.

1. Introduction

The idea behind modeling of light pollution is to calculate brightness of night sky caused by artificial lighting. To build a model of light pollution, it is necessary to do many simplifications and assumptions. Modeling of light propagation through an atmosphere needs information or assumptions about the state of an atmosphere (in particular state of the boundary layer of an atmosphere) and environment (e.g. albedo of surface). Additionally it is necessary to add extra restrictions to made the model calculable within reasonable time.

First models of light pollution were very simple. One of the first models is the model introduced by Treanor in 1973 [11]. He used simplified formula for light propagation through an atmosphere. Light sources are exclusively cities and they are assumed to be point sources. Brightness is proportional to the population of a city. In Treanor's model, atmosphere is homogeneous. Light coming from a city obey inverse square law with distance and atmospheric extinction. Light beam reaching zenith above an observer is a sum of two beams: direct beam coming from a city and second beam subjected to scattering limited to a cone of small angle. A portion of the total beam is scattered down to the observer.

In 1976, Berry [3] modified Treanor's model and created the map of night sky brightness over Ontario in Canada. This map has resolution $8\ \text{km} \times 8\ \text{km}$. He assumed that output light of a city is proportional to square root of its population, instead of direct proportionality assumed by Treanor. The square root proportionality was in a better agreement with Berry's observations. Square root proportionality increases importance of satellite cities. Berry also assumed that downward scattering takes place at a given height above an observer.

These two models are based on the assumption that all light comes from urban areas. Input data for calculations are position and population of cities which are considered to be points. This is the main reason of discrepancies between calculated values of brightness and observations. Light emission of cities is not exactly proportional to their population. In these models, light sources other than habitable zones are neglected. In large scale maps of artificial brightness it is a good approximation, but when we

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go into smaller scales and more detailed maps this description is inadequate.

Current trend in modeling of light pollution is to obtain better description of light propagation in an atmosphere. Also a breakthrough was when satellite data became available. Measurements obtained from ground, which were used in Treanor's and Berry's model, are available only for limited sites. Also these are spread over a certain time range. An alternative for ground-based measurements are data of an irradiance on top of an atmosphere measured by satellites. Cinzano [4] used data from the US Air Force Defense Meteorological Satellite System (DMSP) Operational Linescan System (OLS) to create a global map of artificial night sky brightness [5]. The method of calculation of light propagation was similar to the method introduced by Garstang [6]. Scattering on molecules and aerosols, atmospheric extinction and Earth curvature were taken into account. State of an atmosphere (e.g. content and distribution of molecules and aerosols) must be assumed for computations of light propagation. Resultant map has 30 arcsec resolution, which is 0.927 km at the equator.

It is necessary to take into account many conditions to obtain realistic description of light pollution at certain area. Such detailed modeling is implemented in ILLUMINA [1]. ILLUMINA simulates the contribution of artificial light source to the total night sky brightness at given wavelengths. The model takes into account both 1st and 2nd order molecular and aerosol scattering and aerosol absorption. It also takes into account shape of a city and distribution of light inside it, which might not be homogeneous. Information about topography of a terrain is used. In this way, the shadowing effect – important factor for complex topography – is included in the model. Necessary input data for the software are light luminosity and angular photo-metric functions at given wavelength, lamp heights, elevation map, ground albedo for the same wavelength, aerosol optical depth, cross-sections for aerosol scattering and absorption [2]. Such detailed analysis needs a lot of computational power. This is the model dedicated for studying light pollution at selected small areas – a case study rather than a large-area survey.

We present a solution, which allows to create a map of night sky brightness for a large area in reasonable computing time. In our solution, we use high-resolution map of human settlements and urbanization (GHSL) as input data. The GHSL is available as a raster map with spatial resolution of 100 m. Each cell in the GHSL raster contains percentage of built-up area coverage per spatial unit. Our method is based on Berry's model. The simple form of the model is preserved, but we have introduced different assumptions. Instead of using cities and its populations as input data, we used values of each cell of the GHSL. Therefore resolution increases, but simplicity of calculations remains.

The result of using our model is the map of light pollution over Poland. Calculated values are in a good agreement with observational data collected with Sky Quality Meter. Comparison with satellite data 3 reveals that such solution is a very promising method for large-scale calculations. Additionally, we have created a software module which implements our approach. The module can be used as an extension of GRASS (Geographic Resources Analysis Support System). GRASS is the GIS (Geographical Information System) software which has been used to calculate the map of light pollution.

2. Data and method

2.1. Global human settlements layer

Instead of using population data, according to the original Berry's assumptions, we used the Global Human Settlements Layer – GHSL [10]. The GHSL is a raster map, which contains information about percentage of built-up area per spatial unit. The GHSL was created by the European Commission, Joint Research Centre, Institute for the Protection and Security of the Citizen, Global Security and Crisis Management Unit (http://ghslsys.jrc.ec.europa.eu/).

Panchromatic and multi-spectral satellite images are used to create the GHSL. Data were collected with satellites SPOT 2, SPOT 5, RadpisEye, CBERS-2B, QuickBird-2, GeoEye-1, WorldView 1 and WorldView 2. Spatial resolution of these images is 10 m or better. Reference data sets used in the work are TerraColor, Landsat, MODIS500 and LandScan (for details see [10] and references therein).

The GHSL data for Poland are presented in Fig. 1. Values in cells are from a range 0 to 1. This value represents a fraction of cell covered by built-up area. Additionally, empty cells have value -1. Value -2 corresponds to water (ponds, rivers, lakes). For the analysis, we changed values -1 and -2 to 0, which means that these cells do not have any contribution to the night sky brightness. The GHSL has spatial resolution of 100 m and is in Lambert Azimuthal Equal Area projection (EPSG:3035). We have used the GHSL values instead of population P in Eq. (1).

In Fig. 1 the GHSL data for surroundings of Wrocław, the Polish city, are zoomed in. Blue color corresponds to zero value – no data or water. A river, flowing through the city, and parks are in blue color on this map. Streets have lower values of built-up are coverage, so are more yellow than surroundings. Therefore streets are visible as a net of yellow lines. Interestingly, big shopping malls have high values in the GHSL map. They give a significant contribution to sky brightness. This contribution would be neglected if we used only population data.

2.2. Field measurements

Berry's model is semi-empirical. Berry used measurements of night sky brightness, collected in Canada, in order to determine five constants present in the model. The original model did not fit to values of night sky brightness measured in Poland. We also changed input data for the model: from cities to geometry of raster cells, from population to GHSL. Therefore we need to re-calibrate the model to fit measurements collected in Poland.

Observational data were collected in the Lower Silesia in Poland up to 80 km from Wrocław. Observational sites were chosen inside cities and far from cities. Locations of these sites are presented in Fig. 2. Observations were