High resolution map of light pollution over Poland

Henryka Netzel[1]

Astronomical Observatory, University of Warsaw, Poland

Paweł Netzel[2]

Space Informatics Lab, University of Cincinnati, OH, USA

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-meter 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.

Keywords: light pollution, modeling, GIS

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

[1]henia@netzel.pl
[2]netzelpl@ucmail.uc.edu

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 km x 8 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 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 arc second 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 100m. Each cell in the GHSL raster contains percentage of built-up area coverage per spatial unit. Our method is based on the 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 meters 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 $0 - 1$. 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 meters 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 Wroclaw, 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

The 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

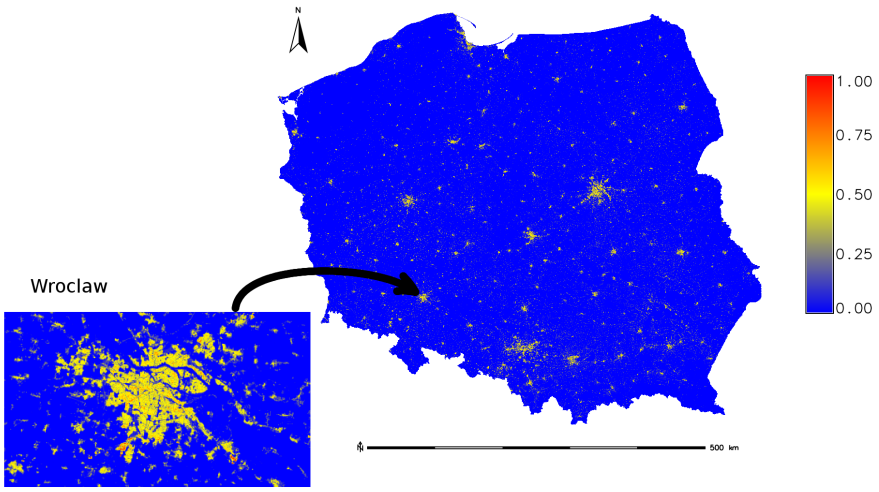

Figure 1: Global Human Settlements Layer for Poland. Values of GHSL are indicated with colors: from blue, through yellow to red. Blue corresponds to value 0 and red - to value 1.

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 kilometers from Wroclaw. Observational sites were chosen inside cities and far from cities. Locations of these sites are presented in Fig. 2. Observations were carried out during a road-based surveys. Observations were collected exclusively during nights with good observing conditions. Requirements were: no moon, low humidity, no clouds or fog. Observations were carried out on six nights during spring of 2014 and 2015. Measurements from two nights were rejected, because of high clouds (cirrus) present during these nights, which resulted in increased brightness of night sky. Altogether there are 65 observational sites. For each site we took five measurements in zenith and take an average value. We used these for re-calibrating and validating the model. Majority of these measurements were obtained with the Sky Quality Meter (SQM). SQM used for observations was the SQM-L model. Each value of brightness was obtained from averaging five measurements.

At five sites the observations were carried out with a digital camera Olympus E-450. We used only RAW images in G filter. Data reduction was carried out using standard procedures in IRIS program (`http://www.astrosurf.com/buil/us/iris/iris.htm`). In order to translate instrumental sky background to physical units we used standard stars. As standard stars we used bright stars in the field with magnitudes in V filter from the NOMAD Catalog [12]. The method is described in details in [7] and was presented during IAU XXIX General Assemly.

Results from both methods were similar for the same observational sites. Both method were used simultaneously at three sites only and they gave following results: 17.63 mag arcsec^{-2} (SQM) and 18.23 mag arcsec^{-2} (photographic method); 19.22 mag arcsec^{-2} (SQM) and 19.16 mag arcsec^{-2} (photographic method); 19.81 mag arcsec^{-2} (SQM) and 19.88 mag arcsec^{-2} (photographic method). Error of the photographic method is

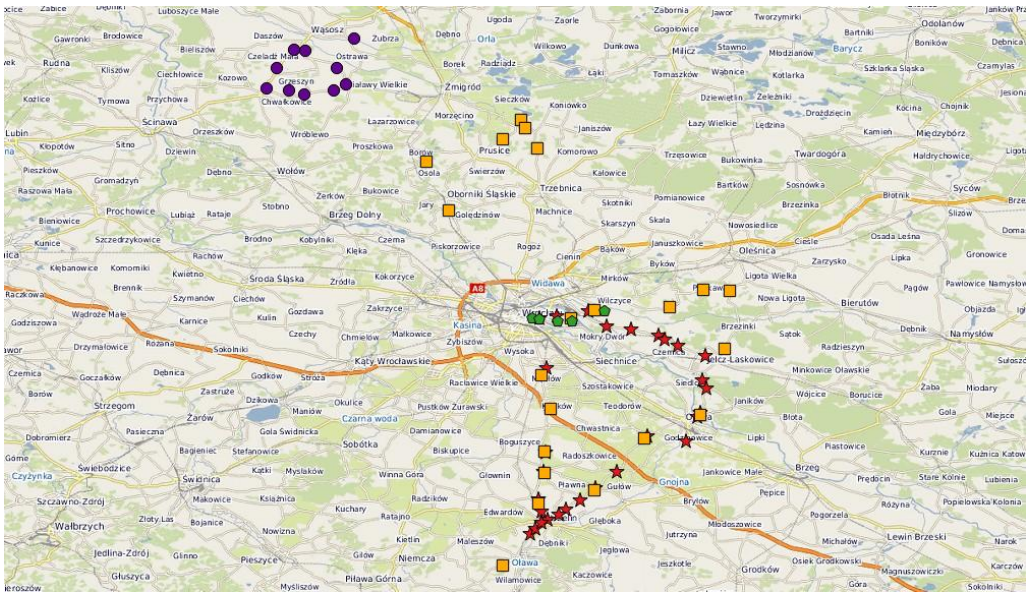

Figure 2: Locations of sites where observations were carried out. Only measurements taken to validate the model are presented. Observations from each night are marked with different symbols: 4.04.2014 (SQM) - red asterisks; 3.04.2014 (photographic method) - green pentagons; 17.03.2015 (SQM) - blue squares; 18.03.2015 (SQM) - blue circles.

on average 0.5 mag arcsec^{-2}. Error of the SQM measurements is on average 0.1 mag arcsec^{-2}. The photographic method is less accurate, but does not require any special equipment like the SQM. Therefore measurements can be collected by amateurs.

The brightest observed sky has brightness 17.63 mag arcsec^{-2}, while the darkest - 21.33 mag arcsec^{-2}. Average sky brightness is 20.45 mag arcsec^{-2}, standard deviation is 0.79 mag arcsec^{-2}.

2.3. Model of light pollution

Original Berry's model is described by Eq. 1, that describes contribution to the brightness at zenith, B (in tenth-magnitude star per square degree, S_{10}, units), of the single light spatial source of population P at a distance D (in kilometers).

$$B(D) = a\sqrt{P}\left(\frac{U}{D^2+h^2} + \frac{V}{\sqrt{D^2+h^2}}\right)\exp\left(-k\sqrt{D^2+h^2}\right) \tag{1}$$

Light sources in the original model were exclusively cities. In contrary to Berry's model, we assumed that all terrain surface can be a source of light. We use raster model of surface and our source is a raster element - cell. Emission of light depends on a percent of built up area in a given cell, which replaced population P in Eq. 1.

In order to obtain total brightness at a given point one needs to add contributions from all nearby cells. In this model there are five free parameters: a, U, V, h, k. These were determined by fitting the model to observational data.

Parameter	Berry (1976)	This analysis	Physical interpretation
a	50	2.5	luminosity constant
U	2.59 km^2	2.55 km^2	
V	0.08 km	0 km	
h	2.4 km	1.3 km	scattering height
k	0.026 km^{-1}	0.031 km^{-1}	absorption coefficient

Table 1: Five constants present in Berry's model determined by Berry and in this analysis.

This model assumes that cells, similarly to cities in Berry's model, emit light uniformly in every direction. Light reaching a thin layer above the observer is scattered down at a certain height, h. Atmosphere is homogeneous. It absorbs light uniformly and scatters in the forward direction over a small angle.

Because we modified original Berry's model and changed input data, we need to recalibrate the model, i.e. redefine five constants present in Eq. 1. In order to do that we used observational data. Model was calculated for vicinity of Wroclaw with different constants. Model with the lowest mean squared error was chosen.

In Tab. 1 constants determined by Berry [3] and determined during this analysis are compared. Last column contains physical interpretation of these constants.

2.4. Calculation of the map

```
r.skylight input=name output=name [a=value] [U=value] [V=value]
  [h=value] [k=value] [--overwrite] [--help] [--verbose] [--quiet]

Flags:
 --o   Allow output files to overwrite existing files
 --h   Print usage summary
 --v   Verbose module output
 --q   Quiet module output

Parameters:
  input   Name of input raster map
 output   Name for output raster map
     a   Parametr a
         default: 2.5
     U   Parametr U
         default: 2.55
     V   Parametr V
         default: 0.0
     h   Parametr h
         default: 1.3
     k   Parametr k
         default: 0.031
```

Figure 3: Module *r.skylight*. It is dedicated for calculation of night sky brightness in a given area based on Berry's model.

Main engine for our calculations was GRASS software (Geographical Resources Analysis Support System, `http://grass.osgeo.org/`). It is an open source system dedicated for spatial data analysis and management [8][9]. One of the advantages of GRASS is that it has modular architecture, which means that it consists of separate modules. Therefore it is easy to extend GRASS by adding modules which are dedicated for particular

operations. We created the module dedicated for calculating a sky brightness map. The module is called *r.skylight*. It is written in ANSI C and its usage is presented in Fig. 3. A raster map of light sources is used as input data. We used the GHSL layer for this purpose. We also used parameters determined during our analysis. However, it is possible to use any data as input data and to change these parameters. Map of night sky brightness in standard units (mag arcsec^{-2}) is generated as an output map. Since the total brightness of the night sky is a sum of all contributions, effective region of an output map is lower than for the input map. For a given point we added contributions of light sources within a square of 120 km In the module the brightness of a natural night sky is included. It is set permanently for 250 S_{10} units (21.79 mag arcsec^{-2}). Map is created with Berry's model. Constants determined in our analysis are default, but it is possible to run the module with different constants.

The map of light pollution presented in this paper has 100-meter resolution. Contribution of light from light sources outside Poland is included. Natural night sky brightness is automatically included in the module. Output map is in magnitudes per arc second squared. Hardware used for calculations: Dell Power Edge, two Xeon 3.1 GHz, 256 GB RAM. Calculations were performed on 14 threads. Time of calculations is 82 minutes and 32 seconds.

3. Results

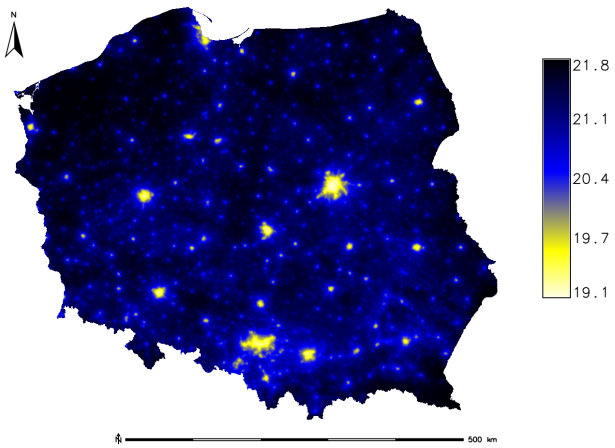

Figure 4: Resultant map of night sky brightness over Poland. Resolution is 100 meters. Scale of the map is marked on the bottom of the figure. Night sky brightness is marked with colors, from black (darkest sky) to white (brightest sky).

In Fig. 4 the map of night sky brightness over Poland is presented. Night sky brightness on the map is a sum of natural and artificial brightness. It is color-coded from black, through blue, yellow to white. Resolution of the map is 100 meters. It means that the output raster map consists of 73 610 720 cells. Darkest areas have brightness 21.8 mag

arcsec^{-2}. Darkest areas are situated mainly in the north part of Poland. In the center of Poland areas are not so dark, because of light emission from villages and satellite cities. The brightest areas are cities. The brightness in city centers on the map is around 19 mag arcsec^{-2}. Complex shapes of cities are very realistic. Visible bright structures agree with buildings inside cities, with shopping malls and roads. Resolution of the map allows to observe even individual districts.

In the southern part of Poland there are mountains. Mountain areas have darker night sky. One reason is that these areas are less populated. The other factor is shadowing effect. Then the light emission from nearby light sources is blocked by terrain. The shadowing effect is not included in the Berry's model. Therefore dark areas in the southern part of Poland are not well reproduced in the map.

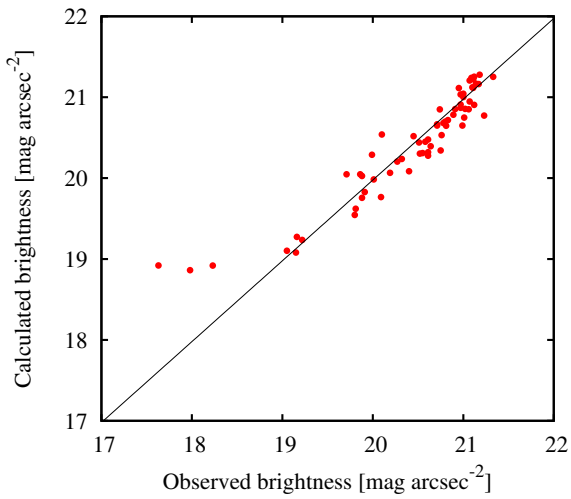

Figure 5: Comparison between observed and calculated values of night sky brightness at selected observational sites.

Calculated night sky brightness is compared with measured values at chosen sites. The comparison is shown in Fig. 5. Values from 19 mag arcsec^{-2} to 22 mag arcsec^{-2} are in a very good agreement. There is a discrepancy between calculated and measured values for the brightest sky. Calculated values for these sites are still around 19 mag arcsec^{-2}, while measured values are between $17 - 18$ mag arcsec^{-2}. As a result, brightness in city centers are underestimated by the model. Line in Fig. 5 is a linear fit to the data, which is $m_{calculated} = 0.998822 \cdot m_{observed}$. The regression coefficient $R^2 = 0.999813$.

Measured values of night sky brightness are a test for the model. However these measurements are available only in limited number and for limited sites. Another way to check whether the model describes the night sky brightness correctly is to compare the resultant map of night sky brightness with images of Earth at night. Image of the light emission over Poland is presented in Fig. 6. The image is a composite assembled from data collected by the Suomi National Polar-orbiting Partnership (Suomi NPP) satellite. Data collection took altogether 22 days in 2012. Image is made with the Visible Infrared Imaging Radiometer Suite (VIIRS).

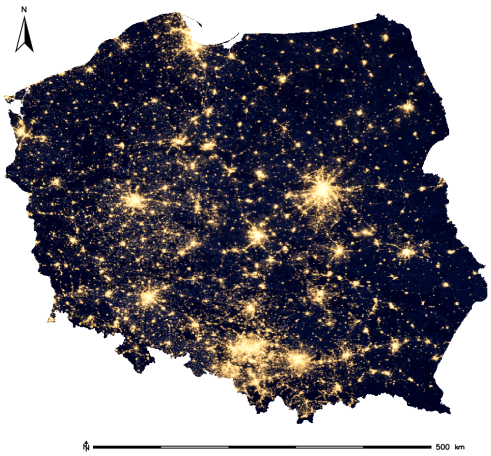

Figure 6: Image of night light emission observed from a satellites (data downloaded from `http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=79765`)

VIIRS data (Fig. 6) and model (Fig. 4) results describe different light paths through atmosphere. Moreover, these data represent phenomena with different resolution and scale. VIIRS contains information about light emitted upward from terrain and transformed by atmosphere. Spatial resolution of VIIRS data is around 1 square km. The data are smoothed spatially because of dispersion in atmosphere. On the other hand, the results of presented model are a measure of dispersion and reflectance of light in atmosphere. Spatial resolution of the model is 100m. Correlation coefficient between VIIRS and smoothed model results (in S10 units) is 0.68. Model results were smoothed to compare the data at the same spatial scale i.e. 1 square km. Unfortunately, the correlation depends on smoothing parameters and changes from 0.54 to 0.70 for different averaging radii.

Instead we can focus on comparison between structures observed in Fig. 4 and Fig. 6. Similarity between two maps is very good. Brightest cities are situated in the same places. Also shapes of cities are similar. Smaller cities are very well visible. Their positions are in a good agreement on both maps. Smaller light emission in the satellite image is visible in the northern part of Poland and in the small are in south-east.

To investigate in more detail similarities and differences between the input data, out model and night light emission we present in Fig. 7 these three different data sets for the same area - Wrocław, a very populated region. The GHSL raster map in on panel 'a'. Our model is on panel 'b' and night light emission is on panel 'c'. Fig. 8 is the same representation of three data sets for a less populated region in Poland. Note that units do not match for these three different data sets. Also the resolution of the image in last panel is lower than for the first two.

Sky brightness and the GHSL NS profile across Wrocław and surroundings is presented in Fig. 9. The model is marked with red line, measured sky brightness is marked with green circles and values of the GHSL are marked with blue bars. Clusters of blue

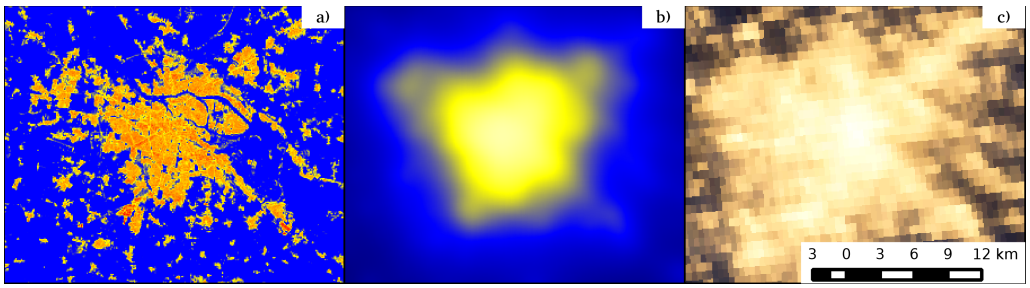

Figure 7: Zoom in for Wrocław for three different data sets. The GHSL raster is on panel 'a', model presented in this analysis is on panel 'b' and night light emission is on panel 'c'.

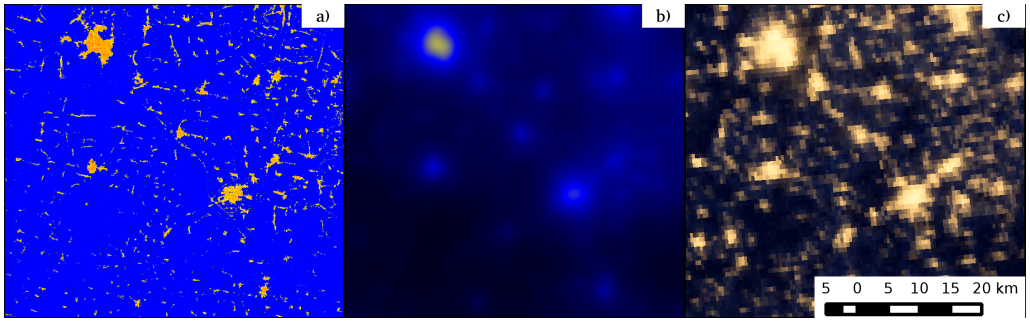

Figure 8: Zoom in for a sparsely populated region in Poland for three different data sets. The GHSL raster is on panel 'a', model presented in this analysis is on panel 'b' and night light emission is on panel 'c'.

bars correspond to cities. Light emission from cities is reflected in the shape of the model. Our model underestimates sky brightness.

4. Conclusions

Modeling light pollution is a complex task. Many factors need to be taken into account. Complicated models describe physical situation in more details, but these are limited to small areas, because of limited computational power. We proposed a new method to investigate the light pollution on large areas in high resolution. Good quality, high resolution data and simple model are used instead of models with complex physics. With this method we created a map of night sky brightness over Poland in resolution of 100 meters. Calculated values of light pollution are in a good agreement with values of night sky brightness measured by us in Poland. Therefore, the proposed method can be a convenient way of estimating the light pollution without hampering the calculations.

The proposed method is based on Berry's model. We used high-resolution data describing percentage of built-up area coverage - the Global Human Settlements Layer. These data allowed to obtain 100-meter resolution of the resultant map in a short time of calculations (less than two hours). Structures visible in the created map are in a good agreement with light emission observed by satellites. Shapes of cities, visible in satellite images, are preserved on the map of sky brightness. In larger spatial scales we can see

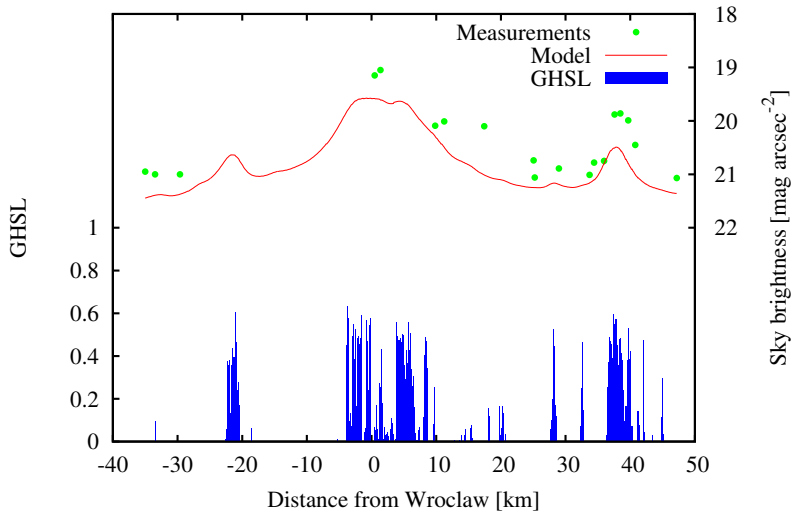

Figure 9: Sky brightness and the GHSL NS profile across Wrocław and surroundings. Distance from the center of Wrocław is on X axis. Zero marks the center of the city. Negative values are in N direction.

that northern part of Poland is in general darker than the southern part. It is due to smaller light emission visible on the satellite image. At first glance, there is also a good agreement between calculated and measured values of night sky brightness for darker sky, with brightness over 19 mag arcsec^{-2}. For brighter sky, model underestimates the brightness.

The agreement between observations and calculations suggests that very simple model with better data, can be an accurate way to estimate the light pollution over large areas. High population density results in complicated structures of night sky brightness. In a city center, where light emission is high, these complicated structures mostly probably average out. However, further from a city center light emission is less homogeneous. Sky brightness depends in these areas more on small light sources. Originally Berry's model was created to estimate night sky brightness far from cities. Nowadays in Poland there are many villages and satellite cities. Light contribution from these sources are relevant. With high resolution data it is possible to track changes in brightness due to small cities and small light sources outside the city centers.

One of the assumptions in Berry's model is that the luminosity constant 'a' is the same for the whole region. Physical interpretation of this assumption is that the light emission characteristics is the same in that region. In reality the amount of light emitted upwards depends on many factors e.g. albedo of the surface, type of lamps, different lighting policy. The luminosity constant was determined using observations collected in a certain area. Therefore the presented map needs further validation. It can be done by collecting more measurements from different urbanization areas. Calculations for different countries, in which urbanization is different from Polish, may also be an important test for the model. The topography should be included in the model in order to obtain more reliable brightness of the night sky. The shadowing effect is important factor important in mountainous terrain. In urban areas very important is blocking of

light by building and trees.

Acknowledgments

We acknowledge the Space Informatics Lab, University of Cincinnati, for providing computing resources. We also want to thank dr Sylwester Kołomański and dr Tomasz Mrozek for help with data collection.

References

[1] Aubé M., Franchomme-Fossé L, Robert-Staehler P., Houle V., Light pollution modeling and detection in a heterogenous environment: toward a night time aerosol optical depth retrieval method, 2005, Proc. SPIE, 5890, 248

[2] Aubé M., Kocifaj M., Using two light-pollution models to investigate artificial sky radiances at Canary Islands observatories, 2012, Monthly Notices of the Royal Astronomical Society, 422, 819

[3] Berry R. L., Light Pollution in Southern Ontario, 1976, Journal of the Royal Astronomical Society of Canada, 70, 97

[4] Cinzano P, Falchi F., Elvidge C. D., Baugh K. E., The artificial night sky brightness mapped from DMSP satellite Operational Linescan System measurements, 2000, Monthly Notices of the Royal Astronomical Society, 318, 641

[5] Cinzano P., Falchi F., Elvidge C. D., The first World Atlas of the artificial night sky brightness, 2001, Monthly Notices of the Royal Astronomical Society, 328, 689

[6] Garstang R. H., Model of artificial night-sky illumination, 1986, Publication of the Astronomical Society of the Pacific, 98, 364

[7] Mrozek T., conference materials from II Polish Conference on Light Pollution, 2014, (in Polish), `http://www.astro.uni.wroc.pl/ludzie/mrozek/publikacje/`

[8] Neteler, M., Mitasova, H., 2007. Open source GIS: a GRASS GIS approach, 3rd Edition. Springer, New York

[9] Netzel P. (ed.), 2011, Spatial analysis with GRASS, Scientific Dissertations of the Institute of Geography and Regional Development 15, University of Wroclaw, Wroclaw, (in Polish)

[10] Pesaresi M., Huadong G., Blaes X., et al., A Global Human Settlement Layer From Optical HR/VHR RS Data: Concept and First Results, 2013, Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 6, 2102

[11] Treanor P. J., A simple propagation law for artificial night-sky illumination, 1973, The Observatory, 93, 117

[12] Zacharias N., Monet D. G., Levine S. E., Urban S. E., Gaume R., Wycoff G. L., The Naval Observatory Merged Astrometric Dataset (NOMAD), 2004, American Astronomical Society Meeting, 205, 4815