Development of an algorithm for constructing a model of light pollution at a location using high-resolution visible satellite images

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Abstract

This article proposes a mathematical model for determining the relative level of light pollution in the night sky at a selected point in the area and the influence of a specific urban infrastructure object on it based on visible high-resolution satellite images. Statistical characteristics of the relative influence on light pollution of specific local objects were determined at an experimental local site. This model allows us to assess the degree of light pollution and its impact on various ecosystems, as well as develop strategies to reduce the negative impact of artificial lighting on nature.

1. Introduction

In the modern world, the problem of light pollution is becoming increasingly urgent. It has negative impacts on the environment, species and humans. Light pollution manifests itself as excessive illumination of the night sky by artificial light sources, which leads to disruption of natural cycles and changes in the behaviour of animals and plants.
Various methods and approaches are used to assess and monitor light pollution (Falchi and Bará, 2023; Popov,2021; Krause et al., 2019; Bara et al., 2020; Kocifaj, 2016; Flanders, 2008; Deverchère et al., 2022; Hölker et al., 2010).
A certain group of methods is associated with the construction of mathematical models of light pollution levels based on ground-based measurements of sky brightness levels using special instruments to obtain an accurate model of light pollution on the observed celestial sphere at a certain point in the area. Such methods are highly accurate, but are ineffective and costly for building models over a large area. However, with the help of online communities of amateur volunteers, this work can be distributed over relatively large areas.
Instrumental measurements of light pollution are point-linked to the terrain, whereas by means of space monitoring it is possible to obtain a continuous model.
One of them is the use of high-resolution satellite images. Such images make it possible to obtain detailed information about the distribution of light sources over large areas and analyze their impact on the environment.
This article proposes a mathematical model for determining the relative level of light pollution in the night sky at a selected point in the area and the influence of a specific urban infrastructure object on it based on high-resolution visible satellite images. This model will allow us to assess the degree of light pollution and its impact on various ecosystems, as well as develop strategies to reduce the negative impact of artificial lighting on nature.
Purpose of the study: to develop an algorithm that determines the relative value of the degree of light pollution from night-time space photography in the high-resolution visible range.
The proposed algorithm is unique in that it is able to determine the degree of influence on the level of light pollution not on the scale of a city as a whole, country or continent, but on a specific city block, individual building or industrial complex.
Information about the units of measurement used in the program
The main concepts that were used in the work:

- the power of luminous radiation (flux) from a light source
- luminous intensity
- illumination
- brightness

If such a concept as the power of luminous radiation is mentioned, then it means a specific source that an object has and shines with a certain power in all directions: a lamp in a street lamp, a lamp in a room, a flame from an oil refinery pipe, and so on. The power of the luminous flux is measured in lumens.
Luminous intensity is the same luminous flux from a source, but in a certain direction - a solid angle, measured in candelas (= lumen / steradian). Characterizes a device containing a source of light radiation, for example: a street lamp that shines in a certain direction, a glowing window of a shopping center, airport landing lights, car headlights.
When talking about the illumination of an object, they mean the luminous flux falling on a unit area of the object. It does not depend on the absorptivity of the object and its other properties, it only determines the light falling on it. It is measured in lux (1 lumen per square meter). There is an important property of illumination used in the application: it decreases proportionally to the square of the distance from the object to the light source.
The brightness of an object is a value that determines the amount of light emitted by the surface of an object and recorded by the human eye or a light-sensitive device (for example, a camera). It depends on the nature of the surface, its geometric and physical properties, the angle and location of observation, the properties of the environment located between the object and the observer. It is measured in candelas per square meter.
The brightness of the night sky is not a concept included in international systems, but is widely used in literature and in scientific communities. It is of direct importance in determining the level of light pollution. It has two components: natural brightness (the brightness of the Milky Way, planets, stars, moonlight) and anthropogenic brightness.
In this work we tried to estimate the luminous flux coming from the objects depicted in the photograph to the night sky, therefore we used units of brightness - lux as a characteristic of the relative influence of individual objects and their totality on light pollution in a local area.

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2. Description of the mathematical model of the algorithm. Basic settings and assumptions

The initial data for developing the algorithm are satellite images of the visible range of high (1-3 m per pixel) and ultra-high (up to 1 m per pixel) spatial resolution obtained in a multispectral shooting mode. Pictures that are a colour image taken at night.

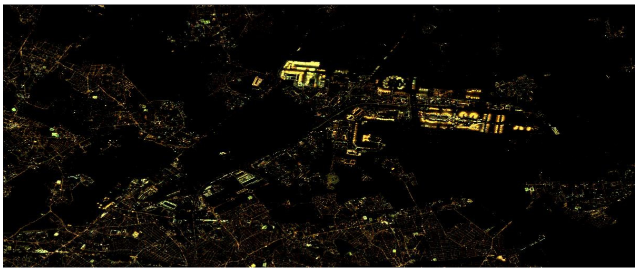


Figure 1. Multispectral image of the visible spectrum, taken from the Jilin-1 Gaofen-03C-02 spacecraft (Jilin-1 High Resolution-03C-02)

As an example for research, we chose an image (see Fig. 1) taken from the Jilin-1 Gaofen-03C-02 spacecraft (Jilin-1 High Resolution-03C-02) . The shooting was done in the suburbs of Paris, France. The spatial resolution of the image is about 1.5 m per pixel.

As a result of the algorithm, we need to get:

- ability to determine the image scale along two axes;
- ability to determine distances in any direction;
- the ability to georeference an image without orthorectification;
- determination of points of local brightness maxima over the entire area of the image;
- the ability to link the highest level of luminous flux of a light source to real values in lumens;
- calculation of the illumination model at each point of the image based on the distance to all local maxima, the magnitude of their luminous flux, and the brightness level of the points;
- the ability to transition from the illumination level of terrain points to the brightness level of the night sky in the area of the point, taking into account the general terrain model within the image, without taking into account the influence of objects located outside the image;
- graphical selection of polygons describing individual objects and storing their illumination levels in memory for statistical processing;
- displaying and saving a list of urban infrastructure objects with data on their type (name), average illumination of the object in lux; area in square meters; RMS deviation from the average illumination over the area of the object; total luminous flux from the object in lumens;
- the ability to transfer a list of objects to Excel spreadsheets.

To be able to measure distances from the image, the distances of the segments between the corresponding points on the image and a map available on the Internet were measured. The segments are grouped in two directions: along the X-axis of the image and along the Y-axis. Based on the average values, two scale factors are obtained (1, 2), which reflect the ratio of meters per pixel:

$$K_X = 1.65 * \frac{m}{px}; \quad (1)$$

$$K_Y = 2.2 * \frac{m}{px} \quad (2)$$

A formula (3) has been obtained for calculating distances from an image in meters, taking into account the directional angle of direction:

$$S_m = S_{px} * (K_X + ((K_Y - K_X) * \frac{abs(D_Y)}{S_{px}})), \quad (3)$$

where S_m is the distance in meters;
S_{px} is the distance in pixels;
$abs(D_y)$ – module of the difference between the ordinates of the points of the segment.

To determine pixel brightness levels, the original color image is converted to monochrome while preserving the perceived brightness Y according to formula (4)[1] :

$$Y = round(0.299*r + 0.587 * g + 0.144 * b), \quad (4)$$

where *r, g, b* are the brightness levels of the corresponding color channel of the pixel in 24-bit recording.

To determine local light sources, the image is divided into square areas, the sizes of which are selected experimentally and depend on the size of the image: for small images (up to 300x300 pixels) - 10x10 pixels, for medium ones 25x25, for large ones (from 3000x3000 pixels) about 80x80. In the developed program, the size of the search area for local maxima is adjusted. In each area there is a local maximum at the highest brightness level and is taken as a local light source, see Fig. 2.

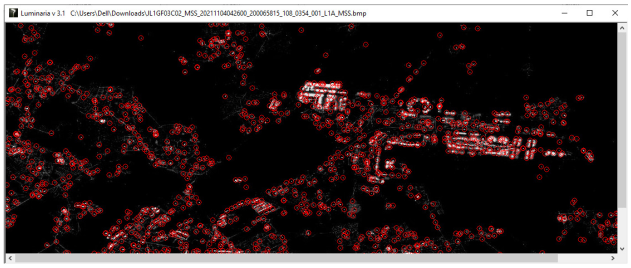


Figure 2. Determination of local maxima

The points of local maxima in the program, shown in the picture, are characterized by the amount of luminous flux (or the power of visible radiation), measured in lumens.

The binding of the value of the brightest light source is based on the assumption that modern urban infrastructure uses LED lamps corresponding to the power of 150-200 W incandescent lamps, which approximately corresponds to a luminous flux of 2200 lumens, of which approximately 30% is directed upward, including from the reflective surface[2].

By default, the power of the brightest light source in the image is 660 lumens, the value of which can be adjusted. The remaining local maxima of light sources are determined in proportion to their brightness levels in the image and are taken as sources emitting light flux evenly in all directions.

To build a model of illumination at each point of the image in lux, a well-known formula (5) was used to depend on the incidence of illumination on the square of the distance to the light sources.

1 Recommendation ITU-T T.871 05/2011

2 SP 52.13330.2016 Daylighting and artificial lighting. Updated version of SNiP 23-05-95* SP (Code of Rules) 07.11.2016 N 52.13330.2016 [in Russian].

$$E = \frac{I}{r^2} \quad (5)$$

In each pixel of the image, the distance to all local maxima is calculated; the illumination is determined and summed up (6). To the sum is added the own level of illumination at the point, determined by its gradation of brightness and reduced to a unit of illumination.

$$I_{xy} = \Sigma_{1..n}(I_i{*}R_i^2), \quad (6)$$

where n – number of local maxima.

To visualize the model, the range of illumination values is normalized to 1792 levels of a specially generated color scale (see Fig. 3), consisting of various combinations of changes in the component RGB color levels, a total of 7 combinations of 256 levels.

Figure 3. Logarithmic color scale of illumination levels from real experiment values, where the maximum illumination level value was 1096 lux.

To optimally display the visualization of a model consisting of significantly decreasing illumination values in accordance with the square of the distances, a logarithmic scale with a base of 2 is used. Thus, a visual display of illumination values in the region of small values is obtained (see Fig. 4).

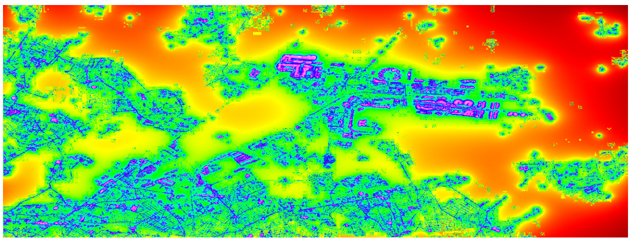


Figure 4. Illumination model obtained from the processed image

A detailed block diagram of the algorithm is shown in Fig. 5. Based on the block diagram, software has been developed to calculate a general model of the influence of the entire territory depicted in the image on light pollution at a certain point in the area (Fig. 4), as well as to determine the relative level of influence of individual, user-selected, urban or industrial infrastructure objects on the level of light pollution (Table 1).

3. Implementation of the algorithm in software.

The application was developed by the authors for photogrammetric and photometric processing of space and aerial photographs of the visible range, taken at night and displaying the brightness levels of objects of anthropogenic origin.

The main stages of the program, considered in the block diagram (Fig. 5):

1. Loading a color image of a space photograph into memory, displaying it on the screen.

2. Converting a color image into a monochrome one while preserving the perceived brightness Y according to formula (4), based on the different perception of color brightness by the human eye. To do this, we process each pixel of the original photograph in a cycle, find out the values of the R, G, B levels and replace three bytes of pixel color with three bytes of gray level: RGB to YYY.

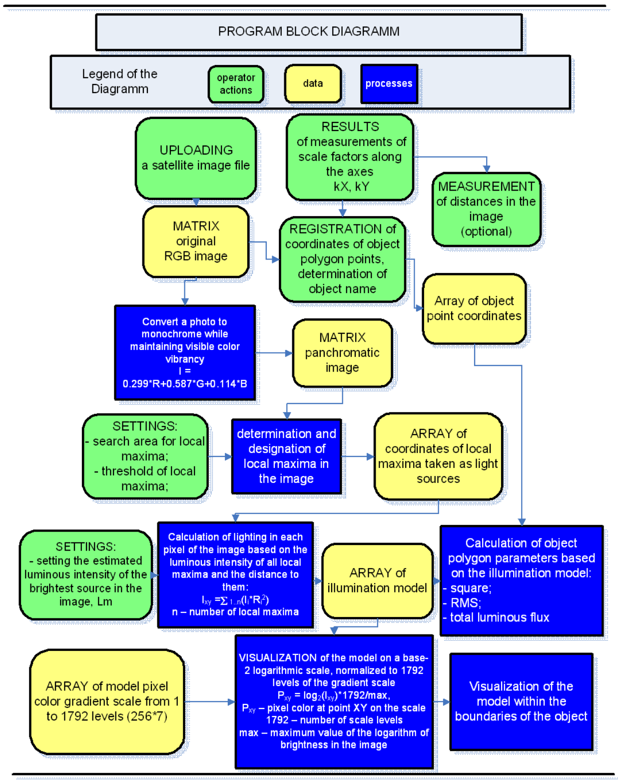


Figure 5. Block diagram of algorithm

3. For statistical processing of individual objects depicted in the image in order to determine their relative influence on light pollution, the user outlines the individual objects of interest with lines along their edges of the visible illuminated area (see Fig. 6).

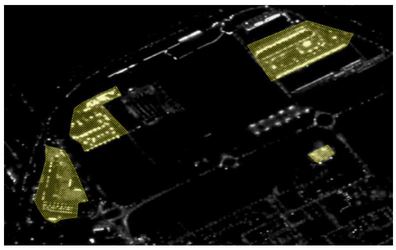


Figure 6. Vectorization of polygons of individual objects for statistical processing based on the illumination model

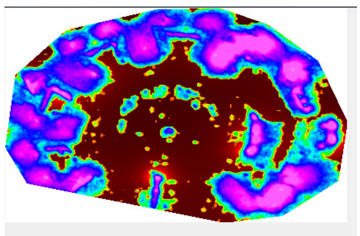
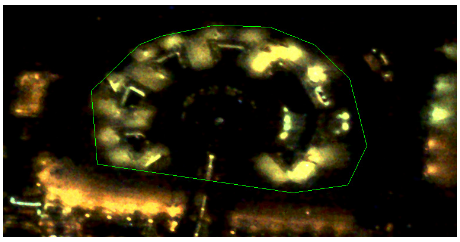


Figure 7. Obtaining images of polygons of objects from a model (Charles de Gaulle Airport Terminal 1, as an example)

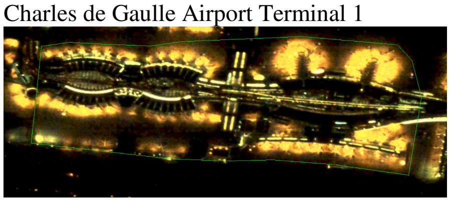
4. An array of object polygons is created with saved coordinates of vertices and their names.
5. The maximum and minimum values of the X, Y coordinates of the polygons in the coordinate system of the image are determined in order to limit the search areas in the large image, i.e. we create a rectangular matrix from the original image covering the polygon.
6. Then, in the cycle, the belonging of each pixel to the polygon is determined in order to form a set of polygon pixels and further processing.
There are several algorithms and methods used in computer graphics (e.g., Haines, Eric, 1994), based on the study of the intersection of rays emanating from the point under study with the boundaries of the polygon, calculating the values of the angles formed by the current point and the points of the polygon. There are also faster but more difficult to implement methods (Preparata 1985) based on the classification of polygon edges and the probability of their intersection by a ray emanating from the point in question. The authors developed a method based on the method of indexing polygon pixels (Hanrahan 1990). The method involves placing images of each polygon in a separate buffer, filling the polygon with any color different from the rest of the image. Our image is monochrome, so any color other than gray will do. We check the color of the pixel: if the bytes that make it up are equal to each other, then the point is outside the polygon, if they are not equal (that is, there is a color), then the point is inside the polygon. This method is implemented in the program by drawing on a pure white background (brightness level 255) the image of the polygon contours separately in any color with the creation of an array of coordinates of points belonging to a specific polygon. The points are checked by comparing their levels with 255, if less, then the point belongs to the polygon. The method is quite reliable, suitable for polygons of any shape. In addition, it can correctly process polygons that intersect each other.
The downside of this method is the increased use of computing resources, but on modern technology this is not a big problem.
7. Local maxima of light sources are determined (Fig.2). The size of their search area is determined depending on the size of the image, experimentally.
8. Processing each pixel of the image with the creation of an illumination model according to formula (6). The result is shown in Figure 4.
9. Visualization of the model based on a logarithmic scale (Fig. 3).
10. Statistical processing of object polygons (Table 1), obtaining images of polygons of objects from a model (Fig.7).

4. Results of an experiment to determine the relative level of influence of individual objects on the level of light pollution

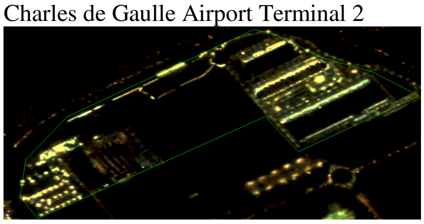
The final stage of this work was the processing of characteristic objects in the image. As examples (Fig. 8a - 8i), we tried to select the most characteristic objects for the infrastructure of the suburbs of a large European city: airport terminals, transport company buildings, shopping centers, residential areas, suburban streets, industrial facilities. The brightest objects and objects of normal brightness were selected for their comparison. According to comparative statistical data, it is possible to estimate the relative influence of individual "bright" objects on light pollution relative to "standard" ones, for example, residential areas of suburban low-rise buildings.



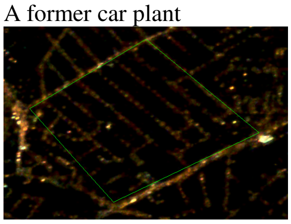
a) Charles de Gaulle Airport Terminal 1



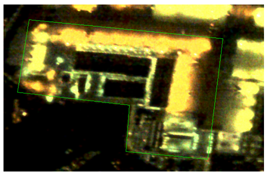
b) Charles de Gaulle Airport Terminal 2



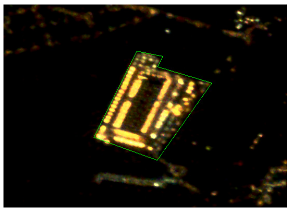
c) A former car plant



d) Suburban residential area

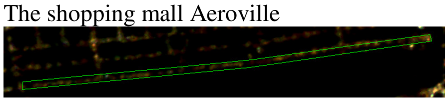


e) FedEx office

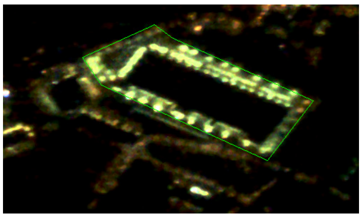


f) Logistics center of a transport company Colissimo

g) The shopping mall Aeroville



h) A suburban street



i) Garonor Business Park Building

Figure 8. Urban infrastructure objects selected for the study

The thin green line in Figure 8 is the boundaries of objects defined by the authors at their own discretion, focusing mainly on the boundaries of visible transitions from the dark surrounding background and neighboring objects, and not on their real (cadastral) boundaries. The real boundaries of the territories of objects may contain unlit areas that are not involved in statistical processing.

Table 1 presents statistical data on individual objects of urban and industrial infrastructure located in the coverage area of the original satellite image.

As a result of processing the polygons of individual local objects of urban or industrial infrastructure using the illumination model, it is possible to calculate the average illumination of the object in lux or the luminosity of the object, the standard deviation of the illumination of the object from the mathematical expectation (it shows the uniformity of the illumination of the object, the lower the value, the less deviations from the average, the illumination of the object is more uniform), the area in square meters and the total luminous flux in lumens from the object. The total luminous flux determines the relative influence of the object on the brightness of the night sky in the area of the object's location or light pollution.

The total luminous flux determines the relative influence of the object on the brightness of the night sky in the area of the object or light pollution.

The mathematical expectation does not always correctly reflect the brightness of the object, the maximum values and their share in the total number are needed, and sometimes it is better to use the median average. Therefore, other statistical operations can be performed on the array of points of a separate polygon: to construct a histogram of brightness level values to assess the distribution of illumination of an object, to find the median average to determine the basic illumination level without the influence of “outliers” and extreme values.

No	Polygon name	average illumination, Lux	Polygon area, m^2*10^3	RMS	total luminous flux, $Lm*10^6$
1	Charles de Gaulle Airport Terminal 1	124,85	349,68	695,1	43,66
2	Charles de Gaulle Airport Terminal 2	212,77	1167,97	907,3	248,51
3	FedEx office	277,79	366,11	1057,9	101,70
4	A former car plant	84,73	877,91	569,5	74,39
5	Suburban residential area	19,25	324,70	149,1	6,25
6	Logistics center of a transport company Colissimo	254,81	93,15	977,3	23,73
7	Suburban street	35,94	39,11	194,4	1,41
8	Shopping mall Aeroville	60,21	73,93	435,0	4,45
9	Garonor Business Park Building	184,78	105,62	885,9	19,52

Table 1. Statistical data on polygons processed in the image

4. Conclusions

The article showed how high-resolution satellite imagery can be used to determine the relative level of light pollution at a specific point in the area and the degree of influence of individual objects on the overall light pollution in a local area. The results obtained can be used to optimize the planning of urban infrastructure in order to prevent further deterioration of the situation with light pollution.

However, it is worth noting that the work did not take into account the influence of the relief and three-dimensional building models on the overall level of illumination at the selected point and, accordingly, the relative impact on the amount of light pollution can be clarified by taking these parameters into account. For a more accurate and detailed analysis of light pollution, it is recommended to use a combination of different monitoring and data collection methods.

Also, note that the work proposes a very simplified model of the distribution of urban lighting, which does not take into account many complex aspects of atmospheric optical properties and characteristics of ground-based light sources, multiple scattering of light and its spatial distribution in various conditions. Therefore, further research will be aimed at modeling the levels of light pollution at the observer’s point, taking into account the use of the modelling discussed in this work based on high-resolution satellite images and methods, such as two-stream approximation, iterative approach to Radiative Transfer Equation and Method of successive orders of scattering (Kocifaj M. A., 2016)

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