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タイトル | 長期測定を用いた夜空輝度の観測 : 日本における観測データ (2009-2012)

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Abstract

To tackle the problem of light pollution, it is important to understand the current situation and its growth rate. The brightness of the night sky is an indicator for evaluating light pollution, because upward light from outdoor lighting fixtures induces a glow of the night sky through scattering by minute particles in the air. To measure it over a long period, Lightmeters have been operated since 2009 at three locations in Japan as part of a worldwide network observation. A preliminary analysis showed that the night sky brightness of Bisei and Yonago was almost constant over 2+ years. The estimated values of the brightness of very dark nights were 20.5, 18, 20 mag/arcsec² at Bisei, Setagaya and Yonago, respectively.

Keywords: Night sky brightness, Light pollution, Lightmeter, Environmental monitoring

1. Introduction

“Earth at Night” images taken by the NASA-NOAA satellites from ~824 km altitude show how much artificial light we are using in nighttime (NASA Earth Observatory and NOAA NGDC, 2012). Since the advent of electric light bulbs in the late 19th century, the amount of outdoor lighting has been increasing rapidly and it caused a drastic change of the nighttime environment on the earth. We have a lot of benefits from lighting, e.g. safety, convenience, comfortableness and expansion of activity time. On the other hand, it is known that lighting can cause various problems to the environment and humans.

One of the problems is a waste of energy. According to a recent estimation by the International Dark-Sky Association (2013), outdoor lighting accounts for 8% of total energy use of the whole world and approximately 60-70% of it is wasted; unnecessary, excessive, not dimmed, going upward and so on. This fact corresponds to 1.1 PWh of energy waste and 750 million tons of CO₂ emission annually. Other problems include an impact on the ecosystem (nocturnal animals, insects, birds, plants etc.), disturbance of our daily life (glare to pedestrians and drivers, intrusive light through windows etc.), adverse effects on human

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health (causing insomnia, depression, some kinds of cancer etc.) and a glow of the night sky (invisibility of stars). Comprehensive explanations about these problems can be found in Narisada & Schreuder (2004), Mizon (2012), International Dark-Sky Association (2012) and Yamamoto (2013).

This issue, caused by artificial light, is called ”light pollution”. It is regarded as one of environmental issues we are facing in this modern society. Although the problems are serious especially in big cities, the number of people who care about it is still very small. The author has been doing educational activities to raise public awareness about light pollution (Ochi, 2010).

To tackle this issue and to let people notice, it is important to know the current situation and its growth rate. An indicator for evaluating light pollution at a location is the brightness of the night sky. Upward light from outdoor lighting fixtures induces a glow of the night sky through scattering by minute particles in the air. There are some methods for measuring the night sky brightness, e.g. the Sky Quality Meter (Cinzano, 2005), the Lightmeter (Müller, 2011), a digital single-lens reflex camera (Onoma, 2009) and a satellite image (Cinzano, 2001). In this paper, data sets from three Lightmeter stations in Japan were used and compared each other, in order to monitor the night sky brightness.

2. Measurement

2.1 Detector

The Lightmeter is a small, weather-proof device equipped with a light sensor (solar cell) and a temperature sensor to measure the sky brightness continuously (Fig. 1). The dimensions are 92 x 92 x 15 mm and it is almost maintenance free (sand or snow accumulated on the device should be cleared). The sensor can measure illuminance from 50
μlx to 200,000 lx with very small contamination of noise (+/- 3 % at 200μlx-500 lx). It works properly in temperature from -25°C to 65°C; from severe winter to direct sunlight of hot summer, without a housing for protection (K2W Lights, 2013).

The sensor operates in a linear mode under dark environment and in a non-linear mode under environment brighter than the full moon. This enables us to measure the sky brightness over 11 orders of magnitude, covering the sun at the zenith and the darkest night of remote locations. Basically the sensor detects all wavelength that human’s eye can see from all angles above the detector’s surface.

A USB cable transmits data between the device and a personal computer (Windows/Linux) and supplies power to the device. The software automatically records the sky brightness data along with date, time and temperature once a second and creates daily data files.

The Lightmeter has been developed by a German research team since 2005, in order to form a global network of low-cost detectors which can monitor light pollution on the earth over many years (Wuchterl, 2009). Currently more than 160 Lightmeters are distributed over the world. All stations use equivalent detectors and software to collect data, which enables us to analyze and compare all data sets easily.

### 2.2 Stations

In this paper, data sets from three Lightmeter stations were used. Fig. 2 shows locations of the stations on a map of Japan. Table 1 shows a summary of the stations.
The Yonago station was located in Yonago City (population ~ 150k, density ~ 1.1k/km²), Tottori Prefecture in the western part of Japan. The population density (thus, the development of the city) is middle among the three stations. There are no highly-populated cities within 50 km. The detector was installed on the rooftop of a building of Yonago National College of Technology, which is located about 5 km from the center of the city. Environ of the campus are fields and detached houses. There are ~20 HID lamps in the campus and the density of street lamps (fluorescence, high pressure sodium) around the campus is not high (~1 per hundreds of square meters). The Lightmeter had been operated for about 2.3 years. Due to electric trouble, it was replaced twice; on April 28, 2010 (from Mark2.3, S/N908042.1402 to Mark2.3, S/N908098.1415) and on July 23, 2010 (to MarkPro2.4, S/N1040006.000). This station halted on March 9, 2012 and the detector was removed.

The Bisei station is situated in Bisei Town, Ibara City (population ~ 42k, density ~ 0.2k/km²), Okayama Prefecture, the north side of which abuts on Tottori Prefecture. This rural town is surrounded by mountains and the population density is very low. The night sky is quite dark, but a glow by light from Kurashiki City (23 km away, population ~ 480k) can be seen in the southeastern sky. The detector was installed on the rooftop of a building of Bisei Astronomical Observatory (BAO). This Lightmeter has been operating since May 15, 2010. It was replaced on August 20, 2010 (from Mark2.3, S/N908099.1397 to MarkPro2.4, S/N1040007.000) due to electric trouble.

The most important fact on the Bisei station is that Bisei Town established a light pollution prevention ordinance in 1989, the first one in Japan. In the ordinance, it is prohibited to use outdoor lighting fixtures which emit light above the horizontal and it is recommended to turn off outdoor lighting between 10 p.m. and dawn. The name of town “Bisei” means “beautiful star” in Japanese and this town is a popular spot for stargazing.

The Setagaya station is located in Setagaya Ward (population ~ 890k, density ~ 15k/km²), one of the 23 wards of Tokyo Metropolis. Since the population density is very high, there are a lot of street lamps in the ward. The detector was installed on the rooftop of a building of Setagaya Ward Education Center. It is in a residential area, but Shinjuku (the busiest district

<table>
<thead>
<tr>
<th>Station name</th>
<th>Yonago</th>
<th>Bisei</th>
<th>Setagaya</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Yonago City, Tottori Prefecture</td>
<td>Ibara City, Okayama Prefecture</td>
<td>Setagaya Ward, Tokyo Metropolis</td>
</tr>
<tr>
<td>Latitude</td>
<td>35° 27’ 21” N</td>
<td>34° 40’ 19” N</td>
<td>35° 38’ 16” N</td>
</tr>
<tr>
<td>Longitude</td>
<td>133° 17’ 21” E</td>
<td>133° 32’ 43” E</td>
<td>139° 38’ 40” E</td>
</tr>
<tr>
<td>Altitude</td>
<td>24 m</td>
<td>420 m</td>
<td>54 m</td>
</tr>
<tr>
<td>Oper. started on</td>
<td>December 8, 2009</td>
<td>May 15, 2010</td>
<td>June 7, 2012</td>
</tr>
<tr>
<td>Oper. stopped on</td>
<td>March 9, 2012</td>
<td>operating</td>
<td>operating</td>
</tr>
</tbody>
</table>
in Japan) and Shibuya (another very busy district) are only 8 km and 6 km away from the detector, respectively. Also, train stations, busy roads and shops exist within 1 km. The detector is the one used at Yonago station before (MarkPro2.4, S/N1040006.000) and has been operating since July 7, 2012.

2.3 Data Processing

Sky brightness data sent from the Lightmeter is recorded onto a PC storage every second. The data occupies about 3 MB/day. An output value of the Lightmeter corresponds to the number of electrons that are produced by incoming light. The data is uploaded to the German Astrophysical Virtual Observatory (GAVO) data center, where researchers analyze and calibrate data from worldwide stations by a standardized process. The processed data is written in a common format and the sky brightness is represented in the unit of W/m² (received energy per unit surface). The data of any station and any period can be downloaded from the database via the Internet.

They employ a homogeneous calibration process for all stations to ensure comparable data among different stations. In the process, radiation values from the sun, the moon and the twilight are calculated from specific models for a station location and time, as well as atmospheric extinction models. By comparing and fitting the output value of the Lightmeter to the calculation, calibration parameters are obtained. As a result, the energy flux density $X$ [W/m²] is calculated as:

$$X = c \left| b \left[ a \cdot \exp \left( \frac{n(1 + dT_c)}{a} \right) - 1 \right] + n \right|$$

where $n$ is the output value of the Lightmeter and $T_c$ is the temperature. This expression accounts for non-linear behavior and temperature-dependent sensitivity of the detector. The fit parameters $a$, $b$, $c$, $d$ obtained for each station are listed in Table 2. Details of the calibration process are described in Wuchterl (2010) and Müller (2011). By assuming that the solar constant 1368 W/m² corresponds to 130,000 lx, the illuminance $l$ [lx] can be calculated as:

$$l = 95.02X$$

There is another unit for representing the night sky brightness in astronomy, that is, magnitudes per square arc-seconds $m$ [mag/arcsec²]. According to Crawford (1997), $m$ can be obtained from illuminance as:

$$m = -14.0 + 2.5 \log_{10} l$$

Fig. 3 depicts a typical daily variation of the sky brightness and a fitted curve of the calibration process for a clear, moonless period (data: Setagaya, August 20-23, 2012). In the daytime, the whole shape of illuminance variation derived from the data fits well to the
smooth curve of the model calculation. There are also short fluctuations due to passing clouds. In the nighttime, the upward deviation of the data from the smooth curve is caused by artificial light.

### 3. Results and Discussion

As a preliminary result, data sets of the Bisei, Setagaya and Yonago stations, up to the end of 2012, were analyzed here.

The night sky brightness varies depending on various factors. In dark places, it primarily depends on the phase and altitude of the moon. In bright places, the quality and quantity of outdoor lighting fixtures around the location (and its on/off) is dominant. Other factors are clouds, mist, aerosol density in the air, and so on. Among them, fast variations (passing clouds, switching on/off of lighting fixtures etc.) and slow variations (the moon, decrease of city light towards midnight etc.) are intermingled. How to define a representative value of the night sky brightness of a certain location needs a deep examination. Here the sky brightness of 3 a.m. was used to check a long-term variation simply.

<table>
<thead>
<tr>
<th>Station name</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$ [W/m$^2$]</th>
<th>$d$ [1/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yonago_1</td>
<td>118810.0</td>
<td>0.012505</td>
<td>1.5932e-09</td>
<td>0.0023697</td>
</tr>
<tr>
<td>(Dec.2009-Apr.2010)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yonago_2</td>
<td>118500.0</td>
<td>0.008865</td>
<td>1.624e-09</td>
<td>0.005669</td>
</tr>
<tr>
<td>(Apr.2010-Jul.2010)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yonago_3</td>
<td>177600.0</td>
<td>0.003439</td>
<td>8.683e-09</td>
<td>0.004106</td>
</tr>
<tr>
<td>(Jul.2010-Mar.2012)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bisei_1</td>
<td>119300.0</td>
<td>0.0003681</td>
<td>5.636e-08</td>
<td>0.004575</td>
</tr>
<tr>
<td>(May2010-Aug.2010)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bisei_2</td>
<td>183782.0</td>
<td>0.0071977</td>
<td>7.87257e-09</td>
<td>0.00418979</td>
</tr>
<tr>
<td>(Aug.2010-)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Setagaya_1</td>
<td>194040.0</td>
<td>0.0048215</td>
<td>7.15e-09</td>
<td>0.0046223</td>
</tr>
<tr>
<td>(Jul.2012-)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 3 Example of a typical daily variation of the sky brightness and the calibration](image-url)
Long-term Measurement of the Night Sky Brightness

outdoor lighting fixtures around the location (and its on/off) is dominant. Other factors are clouds, mist, aerosol density in the air, and so on. Among them, fast variations (passing clouds, switching on/off of lighting fixtures etc.) and slow variations (the moon, decrease of city light towards midnight etc.) are intermingled. How to define a representative value of the night sky brightness of a certain location needs a deep examination. Here the sky brightness of 3 a.m. was used to check a long-term variation simply.

3.1 Bisei station

Fig. 4 shows long-term variation of the sky brightness at 3 a.m. of the Bisei station. The horizontal axis refers to the Modified Julian Day, while the vertical axis uses the unit of W/m². A monthly effect by the moon can be clearly seen, because the Bisei station locates in a very dark area. Over the 2.5 years, the brightness of moonless nights has been almost constant. The corresponding value in mag/arcsec² is about 20.5, which is consistent with a measurement by a digital camera (20.5 mag/arcsec² at BAO, 22:22 August 15, 2012) (Ministry of the Environment, 2012). There are no obvious effects by the season or artificial light in this figure.

Fig. 4 Long-term variation of the sky brightness at 3 a.m., Bisei station
Fig. 5 presents a histogram of the night sky brightness data for several conditions. 2011 data was used here. The horizontal axis is W/m² and the vertical axis is the number of measurements. All data (blue histogram) includes effects of the moon and/or clouds. The green histogram was derived by selecting moonless nights. By detecting passing clouds from the deviation of time series of the brightness data, the red histogram was drawn for clear, moonless nights. Lastly, data with below-zero temperature was removed to obtain the cyan histogram, in order to eliminate a possibility of ice on the detector. The red band in the figure corresponds to the brightness of a clear natural night sky; light comes only from stars, planets, zodiac light, and so on. When the condition is very good, the sky brightness at the Bisei station approaches that level.

Currently, the night sky of Bisei is kept very dark. However, it is needed to monitor the night sky brightness with special attention, because the use of bright LED street lamps has been spread in surrounding regions.

### 3.2 Setagaya station

Fig. 6 shows seven month data since the launch of the Setagaya station. The sky brightness at 3 a.m. was used here. Since there are many artificial light sources around this station, the variation is quite different from that of Bisei. The moon effect is obscured. At the darkest nights, the night sky brightness of Setagaya is about 18 mag/arcsec². A seasonal effect is not clear, but it might be seen after one or two years of continuous operation because the amount of artificial light is expected to vary in some periods of the year. Fig. 7 presents a histogram of the brightness data. The yellow vertical line corresponds to the brightness of the full moon in zenith. The night sky brightness at the Setagaya station
scatters around the full moon brightness, but there are some nights 15 times darker than that, which is still about 10 times above natural night sky level.

Another feature was found in data of clear nights. In Fig. 8, the variation of the brightness in a whole night is shown. Several steps, indicated by triangles between 18:00 and 24:00, mean rapid decreases of the brightness, presumably because of switching off of nearby light sources. This feature is quite different from the natural speed of a shift from day to night. It shows how much artificial light in the city is affecting the night sky.

3.3 Yonago station

Fig. 9 shows the whole period of measurement at the Yonago station. The sky brightness at 3 a.m. was used again. The moon effect can be clearly seen, but it is disturbed a little due to city light. Over the 2.3 years, the brightness of moonless nights was almost constant and it was about 20 mag/arcsec².
4. Conclusion

The night sky brightness was measured at three stations in Japan to study the current situation and a growth rate of light pollution. From 2009-2012 data, it was found that the night sky brightness at the Bisei station and the Yonago station was almost constant. Under very dark condition, the estimated night sky brightness was 18 mag/arcsec$^2$ at the Setagaya station, which was 6 times brighter than that of the Yonago station (20 mag/arcsec$^2$) and 10 times brighter than that of the Bisei station (20.5 mag/arcsec$^2$).

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de/Datenblätter/Sensor/MarkPro2.4.pdf (accessed on Nov. 29, 2013)


要 旨

ライトメーターを用いた夜空の明るさの長期観測：2009-2012 データ

越智信彦, Günther WUCHTERL

光害の問題について、その現状と進度を把握することは、この問題の啓発と解決に向けた重要なものである。光害を測定する指標の一つは、夜空の明るさである。屋外に設置された人工光源から出る上方光束は、大気中の微粒子によって散乱し、スカイグローを引き起こす。長期間にわたって夜空の明るさをモニタリングするために、国内3ヶ所にライトメーターを設置し、観測を行った。この観測は、ライトメーターによる世界規模の光害観測ネットワークの一部を成している。プレリミナリーな解析から、美星町と米子市の観測地では、2年以上にわたって夜空の明るさが安定していたことが見出された。美星町、世田谷区、米子市における、最も暗い条件のときの夜空の明るさは、それぞれ約 20.5, 18, 20 mag/arcsec² であった。