Report of *Hong Kong Night Sky Brightness Monitoring Network* (ECF Project ID: 2009-10)

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Abstract

The *Hong Kong Night Sky Brightness Monitoring Network* (NSN) was established to monitor in detail the condition of light pollution in Hong Kong. Measurement stations of NSN had been set up throughout the city covering a wide range of urban and rural settings to monitor continuously the variation of night sky brightness. Since May 2010 till the end of the project in August 2012, nearly 2.9 million night sky measurements were collected from 18 distinct locations. This huge dataset, the largest one on sky brightness ever collected in the world, formed the backbone for studies of the temporal and geographical variations due to multiple natural and artificial factors that contribute to our light pollution problems. Findings from the project contribute to the overall environment of Hong Kong by promoting light pollution reduction and energy saving.

The exact sky brightness measured at a specific location depend on a multitude of factors, including the observing time, the nightly and seasonal changes in atmospheric conditions, and, last but not least, the commercial and public lightings in the vicinity. Nevertheless, concrete evidence is established in this study on how human lighting affects the natural environment — the mean night sky brightness in the 12 urban/suburban locations is on average almost 10 times brighter than that of the 6 rural locations. The result is highly dependent on the lighting environment: the brightest urban site in Tsim Sha Tsui is on average 33 times brighter than that of the darkest site in Eastern Sai Kung. In addition, the darkening effects of the switching-off of public and commercial lightings at 11:00pm, 12:00am, and 1:00am every night can also be observed in the data. By comparing the sky brightness measured at different times throughout the evening, it was found that the artificial lighting that could be turned off later in the evening contributed a significant fraction of the difference between in the night sky brightness observed in urban versus rural. In other words, reduction in light pollution could be achieved without sacrificing the essential safety functions provided by the night-time lightings.

In support of this project, the public website on light pollution http://nightsky.physics.hku.hk/ that was created for the previous ECF project (Project ID: 2007-01) had been totally revamped. Updated educational and academic materials on issues related to light pollution are presented in this one-stop forum to raise awareness of the public on this environmental problem. In addition, real-time night sky conditions at all observing stations around Hong Kong were available on the webpage to further engage the public for a deeper understanding of the problems. Findings from this project would not only support the importance of continuously monitoring of night sky in the future, but also strengthen the need for effective outdoor lighting guidelines or regulations in Hong Kong.

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1. Introduction

Outdoor lighting is an indispensable element of modern civilized societies for safety, recreation, and decorating purposes. However, poorly designed outdoor lighting system and excessive illumination level can lead to light pollution. The scattering of artificial lights by cloud, aerosol, and pollutants such as suspended particulates in the atmosphere spread the effects to distances beyond the position of the lighting source and could brighten the entire night sky (Benn & Ellison 1998). Light pollution is a form of environmental degradation in which excessive artificial outdoor lightings affect the natural environment and the ecosystem. Not only does it waste energy, money, and valuable earth resources, it also robs us of the beautiful night sky. Finally, the increase in the Night Sky Brightness (NSB hereafter) and the degradation of the quality of night sky in term of reducing the number of observable stars rob the cultural right for people to observe the stars.

Hong Kong is a metropolitan city famous for her spectacular city night lights, along with her notorious wasteful use of outdoor lightings. A recent photo taken from the space by the crews members onboard of the International Space Station in March 2012 (Figure 1) reveals that huge amount of light is not serving its function to illuminate people for their night-time needs, but rather shot up to illuminate the outer space. It was obvious that light pollution in Hong Kong is dominated by human activities.

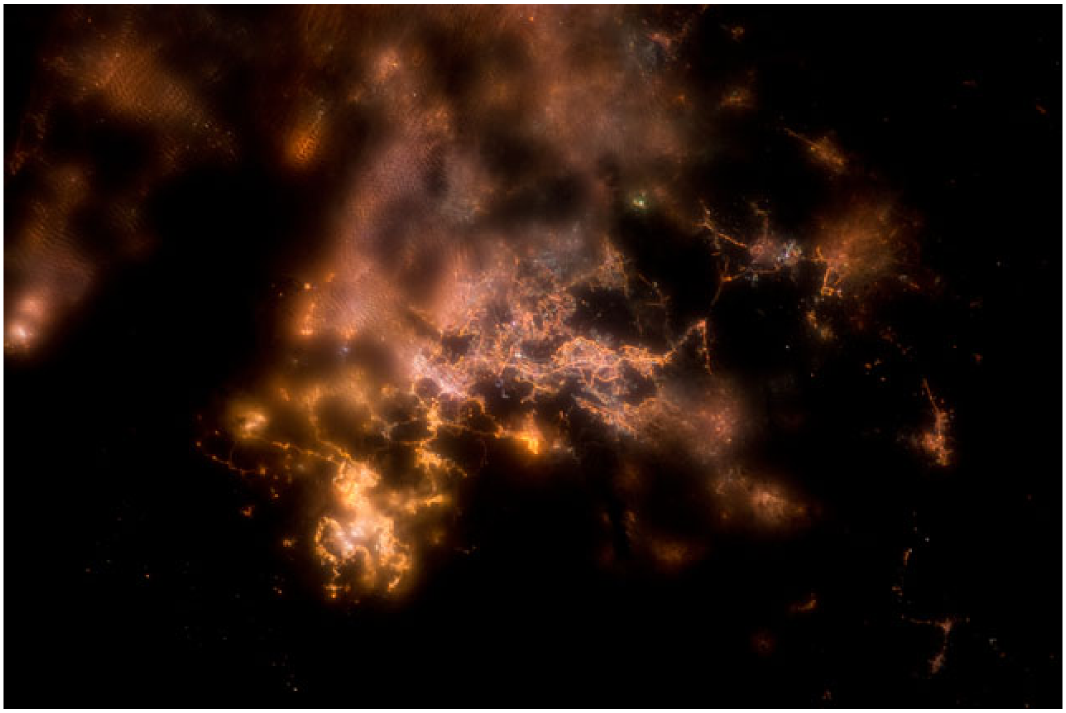

Fig. 1.— Raw image taken on orbit (∼300 km altitude) by the International Space Station when it flied over Hong Kong on 23 March 2012 at 00:38 local time. North is roughly orientated in the upper right. Urban centers in Hong Kong Island, Kowloon, and New Territories are clearly outlined by the upward human lightings. Lights in the far left and upper parts of the photo come from Macau and Shenzhen respectively. The irregular blur patches in the upper left that was believed to be mages of clouds. (image credit: NASA)

During 2007 to 2009, we conducted *A Survey of Light Pollution in Hong Kong* (refer as the last survey hereafter), with the support of an Environment and Conservation Fund (ECF) of the HKSAR Environmental Protection Department (EPD), and the Woo Wheelock Green Fund (ECF Project ID: 2007-01). From the near 2,000 data sets taken at almost 200 locations by over 170 volunteers during March 2008 to May 2009, it was concluded that light pollution in Hong Kong was severe, with large brightness contrast between the observed urban versus rural locations. Moreover, later night skies (at 11:30pm) were generally darker than at earlier time (at 9:30pm), which can be attributed to some public and commercial lightings being turned off late at night. For detailed descriptions of this survey, please refer to the *Report of A Survey of Light Pollution in Hong Kong*[1] and a research journal publication

[1]Obtainable from `http://nightsky.physics.hku.hk/file/ECF_2007_01_Final_Report.pdf`

(Pun & So 2012) which also elaborated the causes, effects, and previous studies of light pollution.

The last survey not only provided our first general understanding of light pollution situation in Hong Kong, but also spreaded the message of dark sky conservation and energy saving among students and the general public through actual observations of the environmental consequences of light pollution, and participated in hand-on sky brightness measurements. However, data from last survey were limited by the geographic distribution (volunteers made measurements usually within urban population areas), temporal resolution (volunteers made measurements usually once or twice every several nights), short monitoring time (volunteers were swapped every few months to allow for more participation), and subjected to human errors (volunteers may made mistakes during measurements and/or data reporting).

In this new survey, the range, depth, and accuracy of our data collection were optimized by setting up over a dozen automatic NSB measurement stations in multiple urban and rural locations around Hong Kong which can continuously monitor the variation of NSB in Hong Kong. All these stations were designed so that on-site long term (over than a year) NSB monitoring was possible, after securing long-term commitments from our partners (please refer to acknowledgment section for the full list). The temporal resolution of data collection was vastly improved and any possibility of human errors was eliminated by the use of fast-responding automatic light sensing devices. These ideas were incorporated in the project *Hong Kong Night Sky Brightness Monitoring Network* (NSN hereafter) as the successor or extension of the last survey. The methodology of the NSN was described in Section 2. Results and analysis can be found in Section 3 while conclusions are presented in Section 4.

The *Hong Kong Night Sky Brightness Monitoring Network* was funded by ECF (Project ID: 2009-10) of EPD. It was organized by the Department of Physics of The University of Hong Kong (HKU), with co-organizers the Hong Kong Observatory, Hong Kong Space Museum, the Hong Kong Astronomical Society (HKAS), Ho Koon Nature Education cum Astronomical Centre, and The Camping Association of Hong Kong, China, Ltd.

2. Methodology

2.1. Observing stations

To investigate the geographic variation of NSB, 18 locations that cover a wide range of population density and land usage for NSB monitoring were strategically chosen. Figure 2 shows the map of NSN stations while Table 1 listed their geographic details. Station codes in Table 1 will be used to refer to specific station(s) hereafter.

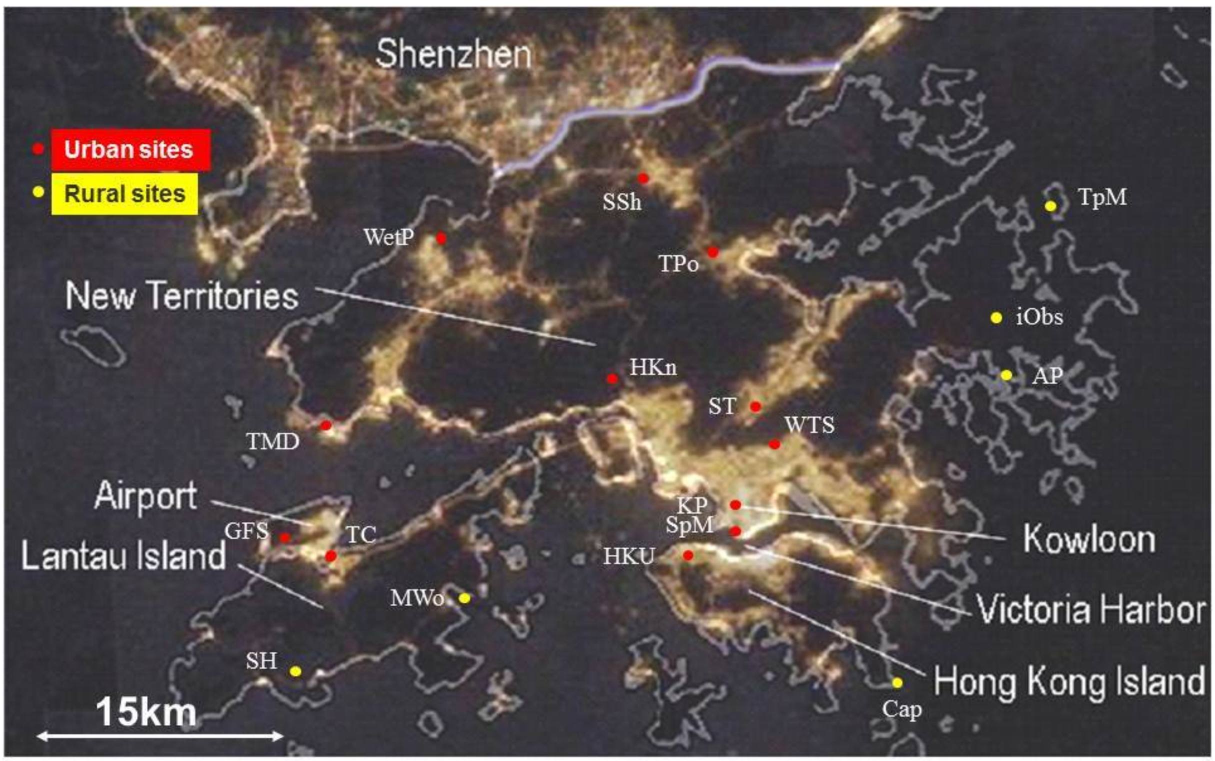

Fig. 2.— The geographic distribution of NSN stations, overlaid on the night time picture of Hong Kong taken from the International Space Station at 00:51 local time on 11 March 2003. (credit: NASA)

Table 1. Geographic details of the NSN measurement stations (sorted by the first date of operation)

Station code	Setting	District	Location	Organization	Installation location	First operation (DD-MM-YYYY)
HKU	urban	Central & Western	Chong Yuet Ming Physics Building, HKU, Pokfulam	The University of Hong Kong (HKU)	HKU Observatory	12-02-2010
KP	urban	Yau Tsim Mong	King's Park Meteorological Station	Hong Kong Observatory	near solar radiation measuring equipment	06-05-2010
TC	suburban	Islands	Tung Chung Health Centre, 6 Fu Tung Street, Tung Chung	Environmental Protection Department	Tung Chung Monitoring Station	11-08-2010
HKn	suburban	Tsuen Wan	101 Route Twisk	Ho Koon Nature Education cum Astronomical Centre	rooftop	28-08-2010
iObs	rural	Sai Kung	The Lady MacLehose Holiday Village, Pak Tam Chung	Hong Kong Space Museum	Sai Kung iObservatory	02-09-2010
SpM	urban	Yau Tsim Mong	10 Salisbury Road, Tsim Sha Tsui	Hong Kong Space Museum	rooftop	15-09-2010
SH	rural	Islands	Shui Hau	Hong Kong Astronomical Society	Shui Hau Observatory	15-10-2010
Cap	rural	Southern	Cape d'Aguilar, Shek O	HKU	The Swire Institute of Marine	11-11-2010
AP	rural	Sai Kung	West Sea Cofferdam, High Island Reservoir	Hong Kong Space Museum	Astropark	12-11-2010
TMD	suburban	Tuen Mun	Tuen Mun Government Depot, Mong Wing Street	Hong Kong Space Museum	Tuen Mun temporary observatory	16-11-2010
MWo	rural	Islands	30 Tung Wan Tau Road, Mui Wo	HKPA Silvermine Bay Camp	rooftop	26-11-2010$^{\#}$

Table 1—Continued

Station code	Setting	District	Location	Organization	Installation location	First operation (DD-MM-YYYY)
TPo	suburban	Tai Po	Tai Po Government Offices Building, 1 Ting Kok Road	Environmental Protection Department	Tai Po Monitoring Station	10-12-2010
WetP	suburban	Yuen Long	Wetland Park Road, Tin Shui Wai	Agriculture, Fisheries and Conservation Department	Hong Kong Wetland Park	21-12-2010
WTS	urban	Wong Tai Sin	3 Lung Fung Street	Our Lady's College	rooftop	21-12-2010
SSh	suburban	North	8 Ching Shing Road, Sheung Shui	Elegantia College (Sponsored By Education Convergence)	rooftop	21-03-2011
TpM	rural	Sai Kung	Tap Mun Police Post	Environmental Protection Department	Tap Mun Monitoring Station	12-11-2010
ST	suburban	Sha Tin	Lung Hang Estate	POH Chan Kai Memorial College	rooftop	30-03-2011
GFS	suburban	Islands	18 South Perimeter Road, Hong Kong International Airport	Government Flying Service	rooftop	31-05-2011

#shut down on 1 August 2011 due to closure of campsite

Apart from two stations which were installed within HKU properties, all the other stations were located at buildings which were properties of the project co-organizers (8), building facilities of the Hong Kong SAR government (5), and secondary schools (3). The stations were strategically chosen to cover a wide extent within the territory of Hong Kong, spreading over almost all four corners of the entire territory. It is therefore not a surprise that a wide range of lighting environments were included in this survey. The complex and diverse land use, along with a collection of many dense population centers, make the exact classification of each measurement site difficult. Nevertheless, a total of 6 (or one third) stations are classified to be in rural areas, while others are classifed as urban (4) or suburban (8). These classifications are difficult and admittedly subjective in nature, in particular with regard to the classication of urban (located near population centers in Hong Kong island and Kowloon) and sururban (located near population centers in New Territories) sites. However, it should be stressed that the classification scheme could change quickly when the lighting environment near the measurement stations change. On the other hand, there was no evidence of drastic change of settings in all our observing stations. All the stations except one are still intact for data taking in November 2012. The one exception, the Mui Woo (MWo) station was terminated in August 2011 due to the closure of the campsite of which the station was installed.

2.2. Data collection

The Sky Quality Meter - Lens Ethernet (SQM-LE) was the light sensing device used to make measurements at each NSN observing location (Figure 3). The SQM-LE measures the brightness of the night sky in unit[2] of mag arcsec^{-2}. An earlier version of this device, the Sky Quality Meter (SQM), was deployed in the last survey. Both the SQM and SQM-LE were fully calibrated by the manufacturer before shipment. Similar to the SQM, the light sensor of SQM-LE is covered by a near-infrared blocking filter so that the combined filter-sensor system would have similar sensitivity to that of a human eye. The SQM-LE units were all positioned to point towards the zenith (directly above the head) direction. The differences between the SQM and SQM-LE are that the newer units include capability

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[2] *Magnitude* (mag) is a logarithm scale international unit to measure the brightness of astronomical objects. A difference of 1 mag refers to an observed light flux ratio of $10^{-0.4} = 2.512$. *Arc second* (arcsec or ") is the unit of length on the celestial sphere. 1" = 1/3,600°. Suppose the measured NSB at site A is 20.0 mag arcsec^{-2}, then the brightness of the sky is equivalent to a celestial object of 20 mag filling up a patch of sky of area 1 arcsec × arcsec. Suppose the measure NSB at site B is 19.0 mag arcsec^{-2}, then the sky at site B is 2.512 times brighter than that at site A.

for transfer of data through internet and a narrower field of view (20° in Full Width Half Maximum [FWHM] for SQM-LE versus 40○ for SQM). With the advancements, remote stations can be established automatically with data transfer and collection taken over the internet. Moreover, the measured NSB results would be less affected by effects of stray lighting directly reaching the light sensor. For technique details of SQM-LE, please refer to the product webpage `http://unihedron.com/projects/sqm-le/`

Fig. 3.— A unit of Sky Quality Meter - Lens Ethernet. The view in the left shows the blocking filter in light blue. The semi-conductor sensor is mounted under the filter. The view in the right shows (from left to right) the power and Ethernet inlets, and a switch for calibration purpose. (image source: *Unihedron*)

To protect the SQM-LE from the wear and tear of the outdoor environments, each unit was fitted into a waterproof polycarbonate enclosure which has a transparent cover for light to reach the sensor of the SQM-LE. Configurations of the setup is shown in Figure 4[3]. The enclosures also store power supply adapters and network devices. In order to avoid direct human lights detected by the sensor, the measurement stations were usually installed at the rooftop of buildings. The rectangular enclosure was sat on a tailor-made frame made in stainless steel which mounted to a pole or railing. The whole enclosure and the frame are dispersible easily such that the enclosure together with equipment inside can be collected from site to our laboratory for maintenance. In addition, the lighting environment nearby were recorded at the beginning of the study and monitored regularly to ensure that the field of view of the sensors were not be blocked by any obstacle such as trees and other structures.

[3]The enclosure for almost all NSN stations are similar as the one shown in Figure 4, with a few slightly varied in terms of the size of the box. The one exception was the SH station in which the enclosure had a different design and was provided by the HKAS.

Fig. 4.— The WTS (urban, left) and iObs (rural, right) NSN monitoring stations. For the WTS station, a cylindrical light shield in black was applied to block direct lighting from nearby. For the iObs station, in addition to the night sky measurement module, two cloud sensors (narrow cylinders mounted on the right side of the rectangular box) were also mounted on the left-side pole, while an automatic weather station installed by the Hong Kong Space Museum on the right-side pole is also shown. Note that not all stations are equipped with cloud and weather observing equipments.

An electronic timer switch was applied to all stations, which turns the power supply on and off for the router and SQM-LE shortly before and after the actual operation of devices daily. The switch should allow electrical energy saving by turning off the system in day time, reduce heat generation and hence avoid heat damage to electronic components during hot day time, and perform daily reset to the system, so that in case of some software system failures, the entire system could sometimes be recovered in the next day automatically without manned on-site service maintenance. Each SQM-LE unit is connected to a commercial 3G router to access the Internet via a USB 3G modem. A computer server in HKU was programmed to request for carrying out NSB measurement simultaneously at all NSN stations, daily from 16:00 to 09:00 in the next day, for every predefined interval, which was 5 minutes during our early testing stage, and switched to 1 minute in late 2011. A database hosted in the server was responsible for logging and time-stamping all returned data according to the device location. The daily data collection performance (or successful rate) for all stations were closely monitored, with an overall successful rate of 92% for the survey. The reasons for down time for the survey include on-site maintenance work, power supply breakdown of station or server, cell phone network instability or failures, hanged software, and hardware failure. On rare occasions when the data collection dropped to below 50% for a prolonged duration, on-site visits were arranged to minimize the down time and to resume data collection as quick as possible.

For our long-term project, the long-term stability and reliability of NSB measurements were crucial. In particular, the efficiency of the light sensors, and the transparency of the enclosure need to be closely monitored to ensure accuracy of the data taken. All SQM-LE units were calibrated for their absolute sensitivities by the manufacturer before arrival. The absolute precision of any NSB measurement was claimed to be ± 0.10 mag arcsec^{-2}, or roughly $\pm 10\%$ in terms of light intensity. The SQM-LE units together with the enclosure were routinely collected from the outdoor to the testing facility in HKU at a frequency of roughly every 6 months for servicing. The optical properties of the measurement device were compared against standard units are placed indoor to check their performances. Most SQM-LE units were found to perform well during the 1.5 years duration of the project, with measurements consistent withat from the standard within the claimed precision. For two units, the transparencies of the filters were drastically reduced (by about 1 mag arcsec^{-2}). These units were shipped back to the manufacturer and the filters repaired with minimal disturbance to data collection. Unfortunately the exact pattern of the drop in performance of the sensor was not known and could not be traced. Therefore we decided just to mark these small amount of data in the database and in the subsequent analyses.

For the waterproof polycarbonate enclosure for the equipments, it was found that the transparent cover suffered from aging, leading to reduced transparency. This was likely to be due to UV radiation from sunlight after prolonged exposure. To deal with this problem, we took two remedies: first, all the polycarbonate covers were replaced with glass windows starting from February 2012; second, new units of the polycarbonate enclosure were installed for detailed outdoor testings to study in detail its drop in optical transparency over time. At the end, we were able to characterize and model the long-term aging effect of the polycarbonate cover and the replaced glass windows as a linear function of the number of days of sunlight exposure, with the decay rate at 0.3 and 0.2 mag arcsec^{-2} per year for the polycarbonate and glass windos respectively. These effects were fully accounted for and corrected in the database, which was important for long-term data analyses to be carried out, such as in Section 3.2.2.

3. Results and Analysis

3.1. Overall results

All the NSN stations are configured to be operating several hours before the sunset and after the sunrise daily. The light sensor captured also the change in sky brightness level near dusk and dawn (or *twilight* in astronomical term). Before any analysis, we filtered out sunlight-affected data taken early than 70 minutes after sunset and older than 70 minutes before sunrise. The choice of 70 minutes was concluded from our observations on the changes in sky brightness near summer and winter solstices at urban and rural stations.

In addition, there might be human activities happened very closed to our NSN stations at night sometime, e.g., star-grazing session carried out at the rooftop of iObs, SH or HKU. The duration of these activities was usually short (several hours). Although we believed that minimum outdoor lightings were switched on during these periods, we still excluded data taken during such activities.

A small subset of data taken during indoor maintenance or testing periods were also excluded for further studies. However, we have included data taken during raining or under other weather conditions, e.g., typhoon, thunderstorm, etc.

There were 4,089,239 individual data points collected from 18 monitoring stations since the first official operation of NSN in May 2010 to August 2012 (2 years and 4 months). 2,884,567 (about 70.5%) are real data in which 2,175,211 (about 75.4%) came from 12 urban station and 709,356 (24.6%) came from 6 rural stations. Figure 5 shows the grand total statistic from all stations. The data sample size varied according to the total number of station operated, data collection interval, maintenance schedule, station downtime, etc. Analyses and results presented hereafter considered real data only.

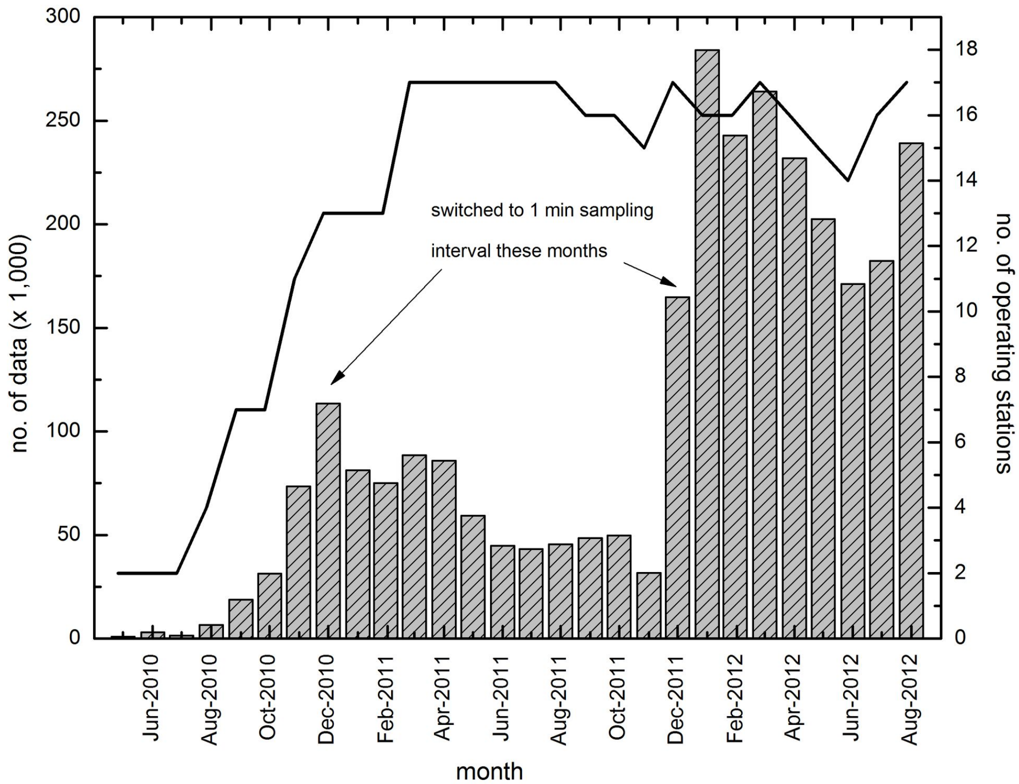

Fig. 5.— The monthly total number of individual data collected from all NSN stations till 31 August 2012. The height of the bar (left axis) represents the sample size of NSB recording the true sky variations. We switched the data taking interval from 5 minutes to 1 minute in HKU near November - December 2010 and for all stations since mid-December 2011 respectively, so that the sample size increased by about 5 times at those times. The line (right axis) shows the total number of stations operated each month.

The mode, average, and standard deviation for all data overall (regardless of land use) would be 16.0, 16.7, and 1.61 mag arcsec^{-2} respectively. These figures should be treated with care because the data were collected at vastly inhomogeneous conditions. Effects of factors such as time of observations, locations of study, meteorological factors, etc, will be studied and presented in the following sections. However they does present a characteristic figure of NSB in Hong Kong. Comparing the overall average value with the 21.6 mag arcsec^{-2} natural NSB level as suggested by the International Astronomical Union (IAU) for a good site for astronomical research (Smith 1979), the average Hong Kong night sky was about 4.9

mag arcsec^{-2} or almost 100 times[4] in light intensity brighter. In the last survey, we obtained 16.1 mag arcsec^{-2} as the overall average NSB in Hong Kong. Findings from two projects are similar and it is concluded that light pollution condition was mostly unchanged in the past several years.

The histograms of NSB recorded at urban and rural stations are shown in Figure 6. The mode (distribution peak in the histograms), average, and standard deviation are 16.0, 16.1, and 1.26 mag arcsec^{-2} for urban and 19.2, 18.5, and 1.13 mag arcsec^{-2} for rural respectively. Similarly, the general urban-rural NSB difference of 2.4 mag arcsec^{-2} refers to a flux ratio of 9.1 times in light intensity, which presents a characteristic figure of NSB in Hong Kong between urban and rural. Section 3.2 presents a detailed geographic analysis of light pollution.

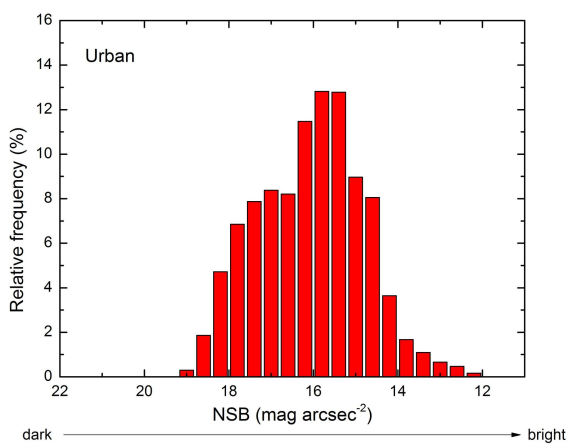

Fig. 6.— The histogram showing the percentage distribution of all real NSB recorded at the urban (red in left) and rural (blue in right) stations.

3.2. Temporal and geographical variations of night sky brightness

Sky brightness depends on both artificial and natural factors in which their properties and impacts on the night sky diverse. As we have huge datasets on NSB which were taken under a variety of conditions, we are able to choose specific subsets collected under predefined conditions then apply statistical treatments to analyze their relation with NSB for a

[4] A difference of 1 mag arcsec^{-2} refers to a light flux ratio of 2.512. Therefore a difference of x mag arcsec^{-2} refers to a flux ratio of 2.512^x.

particular issue. In this Section, we report findings from three preliminary studies which enriched our past understanding of light pollution while gave us new insights on the condition in Hong Kong.

3.2.1. Monthly variation of night sky brightness

To investigate the long term trend of light pollution condition in Hong Kong, the median value of NSB collected within a month at a specific station was computed. It was because, Moon, the major natural contributor of light pollution, completes its phase cycle roughly in a month. So it is expected that NSB at any station vary according to lunar phase, i.e. brighter than normal level near full Moon and darker near new Moon, regardless of the change in artificial lighting properties, in the period of a month.

Figure 7 shows the long term monthly variation (or *monthly profile* hereafter) of NSB[5] of all NSN stations. Light pollution properties in Hong Kong can be concluded from this figure:

[5]corrected for light attenuations due to aged cover of glass before analysis, as described in Section 2.2

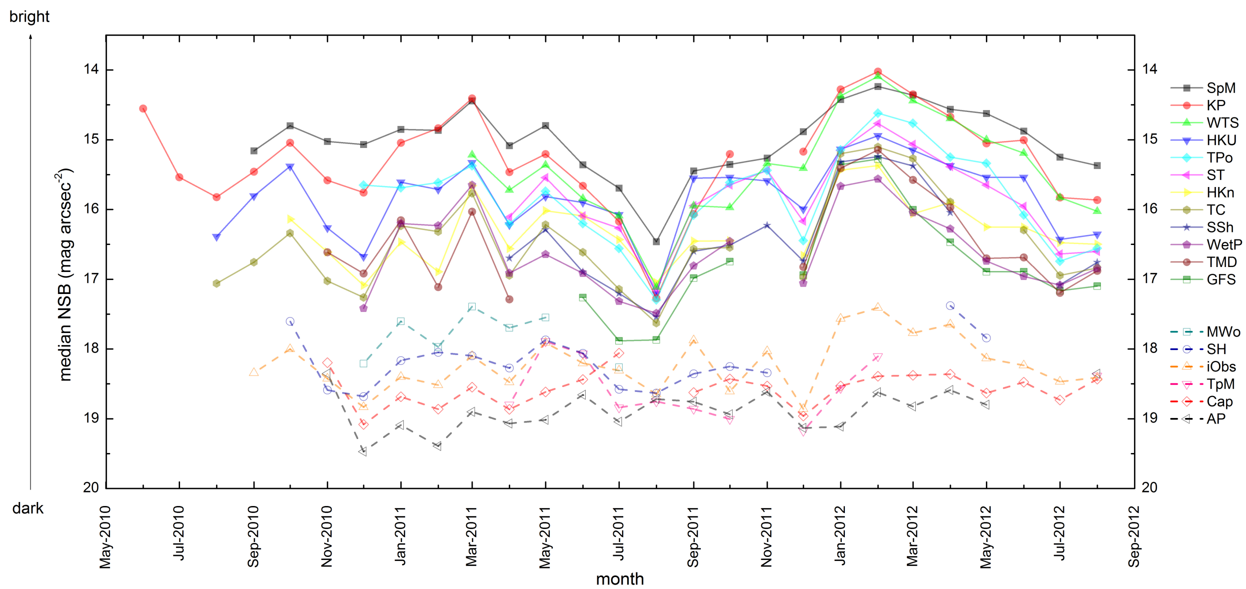

Fig. 7.— The monthly variation of NSB of all NSN stations from the start of the project to August 2012. The affect of sunlight on NSB had be avoided by selecting data subsets taken outside the sunlight lit periods. First operation dates of station are different so curves started at different month. Data points with monthly sample size less than half of the expected were excluded so curves may be broken. The geographic locations of urban (solid symbols and curves) and rural (open symbols and dashed curves) stations are marked in Figure 2 and listed in Table 1. GFS (semi-opened symbols) is located on the island of Chek Lap Kok Hong Kong International Airport where the outdoor lightings usage practice and hence light pollution conditions may not be the same from those in usual commercial or residential areas, urban or rural regions. The individual curve represents the change in atmospheric conditions and human influence on the night sky near specific station. See the texts for details.

- All NSB curves followed roughly the same waved pattern over the whole period. It was observed that summer skies were darker than those in winter in general over the past two years. Assumed the lightings usage practice at individual station remained largely unchanged throughout the study, we believed that monthly NSB trends manifested the monthly variations in atmospheric conditions (e.g., visibility, amount of cloud) which were assumed to be homogeneous across different locations in Hong Kong in general. For example, the decrease in NSB (or increase in numerical values) of most of the stations in August 2011, was probably caused by decrease in cloud amount and/or increase in visibility that month. On the other hand, the increase in NSB (or decrease in numerical values) of most of the stations in February 2012 was probably caused by increase in cloud amount and/or decrease in visibility that month. The relation between cloud amount and NSB will be discussed in Section 3.2.3;

- The NSB ripples discussed above were greater in urban stations (solid curves) than that of rural (dashed curves). By knowing the difference in outdoor lighting usage practice between urban and rural regions, a possible reason for such a deviation in ripples size would be similar to the study and discussions in Section 3.2.3;

- The relative ranking of NSB curves on this figure provided a solid comparison of light pollution condition across different locations in Hong Kong, independent of monthly change in atmospheric conditions which caused waved pattern: the top (brightest sky) three curves were kept as SpM, KP, and WTS in the dense Kowloon Peninsula, while the bottom (darkest sky) three would be AP, Cap, and iObs in remote edges (except North) of Hong Kong territory throughout the study period. In the view of changing atmospheric conditions at any time of the month while the ranking of NSB across 18 stations remained roughly the same, the plot reveals the fundamental difference in term of outdoor lightings usage practice, i.e. light pollution, in different regions in Hong Kong.

To answer how did the amount of light pollution vary around Hong Kong, the time scale of analysis was narrowed down from a month in this Section to a night in the next Section.

3.2.2. Nightly variation of night sky brightness

From last Section, there is no doubt that the use of outdoor lightings makes a great impact on the night sky. Apart from monthly change in atmospheric conditions, NSB is expected to be vary according to the change in outdoor lighting usages throughout the night. To study the nightly variation, NSB measured at each station every 5 minutes were averaged and plotted in Figure 8. Overall nightly variations of NSB at 12 urban and 6 rural stations were indicated by solid curves in the figure.

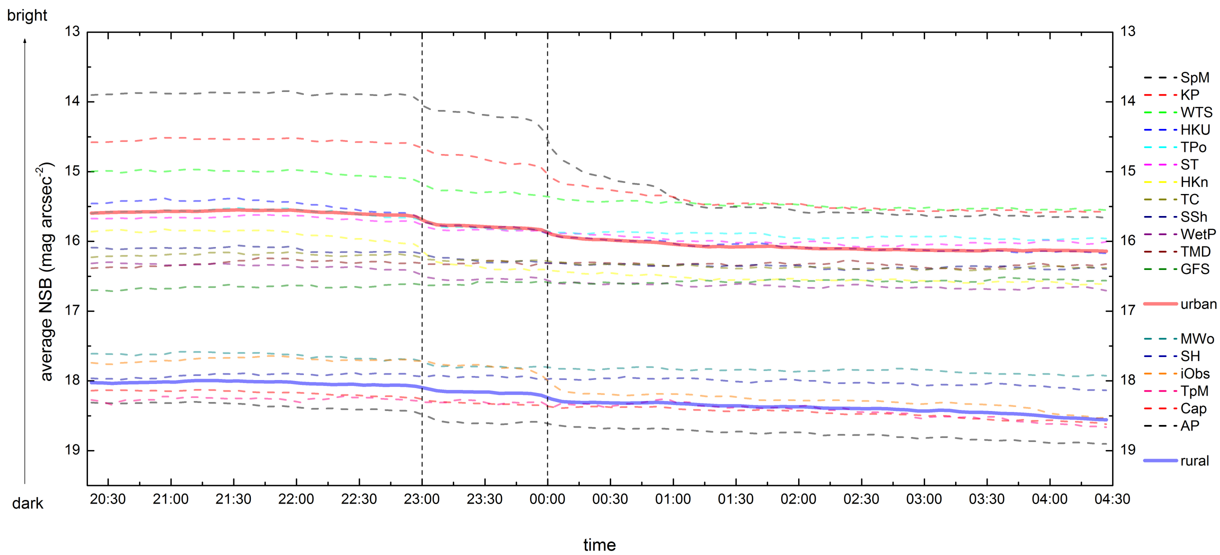

Fig. 8.— The nightly average profiles of each NSN station (dashed curve) sampled till 31 August 2012. The solid curves showed the averaged profiles for urban (red) and rural (blue) stations. Two vertical dashed lines were added on the plot to indicate 23:00 and 00:00 when there were major decreases in NSB for most of the stations. The affect of sunlight on NSB had be avoided by displaying the curves between 20:30 to 04:30 only. The geographic locations stations are marked in Figure 2 and listed in Table 1. Same color code was applied as on Figure 7. The individual curve clearly indicated the change in human influence on the night sky near specific station.

Observations related to light pollution properties of Hong Kong can be seem from the figure:

- The average NSB in the 12 urban and 6 rural locations were 15.9 and 18.3 mag arcsec^{-2} respectively. The difference in NSB was 2.4 mag arcsec^{-2}, meaning that the skies at urban locations was on average 9.1 times in flux ratio brighter than that of the rural locations;
- In particular, the brightest night sky was always found at SpM in the urban center Tsim Sha Tsui. On the other hand, the darkest sky can be found at AP in remote rural

area in Sai Kung at anytime of observation in a night. The brightest sky was on average 3.8 mag arcsec^{-2} or 33 times brighter than that of the darkest one. This property is one of the strong evidences that light pollution depends on geographic locations;

- NSB at early evening before 23:00 was flat for all stations, indicating that the light pollution conditions remained largely unchanged before 23:00;
- Almost all stations showed a sharp decrease in NSB near 23:00 and 00:00. It is believed that the switching-off of public and commercial lightings, e.g., floodlights in outdoor playgrounds and sport fields, illuminated signboard, lightings of corridors of public estates, etc, right at that times every night caused the observed change in NSB. In other words, NSB at early evening was generally brighter than that of late evening;
- NSB at late evening after 00:00 was also flat for all stations, indicating that the light pollution conditions remained largely unchanged after the end time of major commercial activities;
- The difference in NSB across individual urban stations became smaller at late evening. While the averaged urban-rural NSB flux ratio between 20:20-23:00 and 01:00-03:00 were 9.43 and 8.12 respectively. These observations implied that the source of light pollution may mostly concentrate at early evening;
- SpM light curve showed an additional turn near 01:00. So we believed that the lighting usage pattern may be slightly difference from others near Tsim Sha Tsui where three large groups of lightings turn off sequentially at 23:00, 00:00, and 01:00;
- The light curve of GFS is also special. The trend did not show obvious decrease in NSB at late evening, and GFS even turned slightly brighter after 01:00. As mentioned in the last section, GFS is located in the Chek Lap Kok airport which operates around-the-clock, its unique form of NSB light curve can be explained by knowing the special lighting usage practice in the airport, where lightings may remained turn-on throughout the night and even increase in illumination intensity at late evening to ensure safely.

To reject natural contributors which enhanced the sky brightness (or decreased the numerical value) in variety of time scales and magnitudes from the observational data, so that the human influence can be further sorted out, the second, third, and fourth darkest (largest in numerical value) NSB records measured at each station every 5 minutes were averaged[6]. We believed that such a *darkest profile* would represent the darkest possible

[6]The averaging smooth out short-term fluctuations. The first darkest values were not included as they usually polluted with abnormal large outlined NSB readings by unknown reason.

NSB at specific location, i.e. reflect both the absolute amount and the change in amount of artificial light pollution against time near specific location.

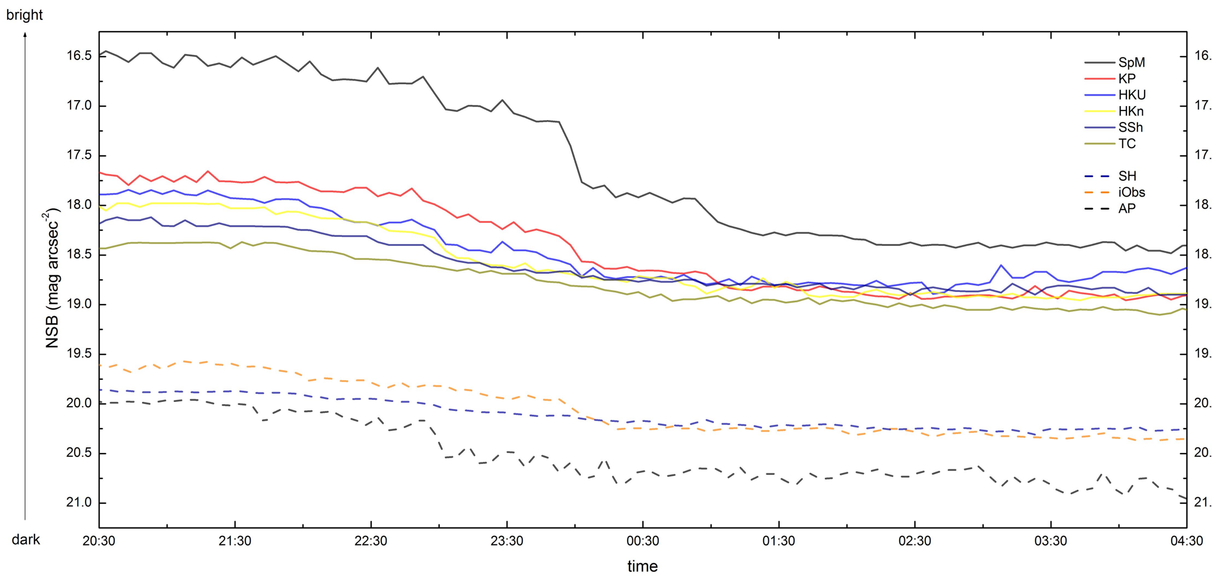

Fig. 9.— The darkest profiles of selected NSN stations sampled one year period since March 2011. The affect of sunlight on NSB had be avoided by displaying the curves between 20:30 to 04:30 only. The geographic locations of urban (solid curves) and rural (dashed curves) stations are marked in Figure 2 and listed in Table 1. Same color code was applied as on Figure 7. The individual curve represents the human influence on the night sky near specific station.

Figure 9 presented the darkest profile of selected NSN stations representing the period of March 2011 to March 2012. Although individual profiles have ripples sized larger than those in Figure 8, additional light pollution properties in Hong Kong can be concluded from this figure:

- The change in NSB at urban areas before and after 00:00 (so called "step size") was greater than that of rural in general. The size of the step more or less implied the percentage of outdoor lightings that turned off or can be turned off near 00:00. For example, it is believed that a greatest portion of lightings were turn off at SpM where it is located in within dense commercial areas, as seem from the greatest step size. While the change in lighting conditions kept minimum at SH where it is far from commercial clusters, as seem from its almost flat profile. It was found that the artificial lighting that could be turned off later in the evening contributed a significant fraction of the difference between in the night sky brightness observed in urban versus rural;

- The level of late evening (after 00:00) NSB in each station reflected roughly the minimum intrinsic amount of "always on" outdoor lightings, e.g. street lamps, security lightings, etc, in that area. In other words, the darkest possible NSB at TC, for example, cannot reach the NSB level of rural stations even though in late evening.
- The darkest NSB record measured at AP was 20.6 mag arcsec^{-2}. It was still a 1 mag arcsec^{-2} gap between the natural night sky (Smith 1979), suggesting that there are rooms for light pollution improvement even in the darkest location in Hong Kong.

The above analyses on the darkest profiles were preliminary. Further studies will be conducted for in-depth understanding of intrinsic sky background of Hong Kong.

3.2.3. Effect of cloud amount on night sky brightness

As seem in Section 3.2.1, NSB varied according to atmospheric conditions apart from human factors. One of the major atmospheric "brightening" contributors of NSB would be cloud. The present of cloud may dramatically increased the observed NSB by adding a patch of near-earth "reflective" layer that re-directs upward lights from the ground to the sky then back to ground (Garstang 2006, Lolkema et al. 2010, Kyba et al. 2011). From our past pilot studies and by knowing that light pollution properties in Hong Kong as discussed in the above Sections, it is believed that the NSB brightening effect due change in cloud amount should be easily observed.

To study the relation between cloud amount and NSB (cloud-NSB relation hereafter), we installed identical set of cloud observing device, namely Boltwood Cloud Sensor II[7], each at HKU (urban) and iObs (rural) stations to carry out simultaneous cloud-NSB observations since November 2010. Cloud emits infrared thermal radiation. The cloud sensor measured the amount of cloud by passively sensing temperature difference T_{s-a} (in degree Kelvin K) between the ambient ground level and effective infrared sky temperature every several seconds. The smaller the difference, the sky is more cloudy, and vice versa (Mallama & Degnan 2002). Note that information on spacial distribution of cloud, cloud base height,

[7]For additional details on the cloud sensor, please visit distributor's website at `http://www.cyanogen.com/fix.php`

cloud type and partial cloud amount (amount of sky covered by each type or layer of clouds), etc, and high cirrus made of ice crystals cannot be measured by the sensor.

Cloud-NSB[8] relation was observed on selected 41 dry and moonless (i.e., time periods near new moon) observational runs with over 320 hours of observations at each station. Table 2 shows the details on those runs. For each run, time series were plotted for preliminary preview of cloud-NSB relation. For those runs with possible relation, scatter plots of T_{s-a} against NSB were created. The Least Squares Linear Regression analysis between both quantities was also conducted for quantitative investigation.

[8]The darkest profile (see Section 3.2.2) of corresponding station acted as the artificial sky background was subtracted from the observed NSB light curves before cloud-NSN analysis, so that the cloud-NSB relation was consistent before and after mid-night.

Table 2. Observational conditions at selected nights

Observational run	Start date (dd/mm/yyyy)	Moon age	Start[a]	End[b]
01	08/11/2010	3	19:00	05:15
02	09/11/2010	4	19:00	05:15
03	10/11/2010	5	19:00	05:15
04	02/12/2010	27	19:00	05:30
05	03/12/2010	28	19:00	05:30
06	04/12/2010	29	19:00	05:30
07	05/12/2010	30	19:00	05:30
08	01/01/2011	27	19:15	05:45
09	02/01/2011	28	19:15	05:45
10	03/01/2011	29	19:15	05:45
11	04/01/2011	1	19:15	05:45
12	05/01/2011	2	19:15	05:45
13	06/01/2011	3	19:15	05:45
14	07/01/2011	4	19:15	05:45
15	08/01/2011	5	19:15	05:45
16	30/01/2011	27	19:30	05:45
17	31/01/2011	28	19:30	05:45
18	01/02/2011	29	19:30	05:45
19	02/02/2011	30	19:30	05:45
20	03/02/2011	1	19:30	05:45
21	04/02/2011	2	19:30	05:45
22	05/02/2011	3	19:30	05:45
23	06/02/2011	4	19:30	05:45
24	07/02/2011	5	19:30	05:45
25	01/03/2011	27	19:45	05:30
26	02/03/2011	28	19:45	05:30
27	03/03/2011	29	19:45	05:30
28	04/03/2011	30	19:45	05:30
29	05/03/2011	1	19:45	05:30
30	09/03/2011	5	19:45	05:15
31	31/03/2011	27	20:00	05:00
32	01/04/2011	28	20:00	05:00
33	02/04/2011	29	20:00	05:00
34	03/04/2011	1	20:00	05:00
35	04/04/2011	2	20:00	05:00
36	05/04/2011	3	20:00	05:00
37	06/04/2011	4	20:00	05:00
38	07/04/2011	5	20:00	05:00
39	30/04/2011	28	20:15	04:30
40	01/05/2011	29	20:15	04:30
41	02/05/2011	30	20:15	04:30

[a]astronomical twilight avoided

[b]astronomical twilight avoided, the time of the next date

Different relations on cloud-NSB were found. Strong linear cloud-NSB relation was generally observed. Figure 10 show a typical run #23. At that night, both stations recorded stable NSB levels at early night (~18.8 mag arcsec^{-2} before 23:00 in the urban station; ~20.3 mag arcsec^{-2} before 00:00 in the rural station). It may due to the stable clear sky conditions as indicated by the flat T_{s-a} curves at small values. The skies gradually became significantly overcast (increasing T_{s-a}) starting from near mid-night, at the same time, the skies gradually became ~2.2 (~7.5 times in flux, same below) and ~0.9 mag arcsec^{-2} (~2.3 times) brighter at the urban and rural stations respectively. The skies finally "landed" on the brightness levels of ~16.6 and ~19.4 mag arcsec^{-2} at late night at the urban and rural stations respectively when the cloudy conditions maintained, except that the clouds above the rural station were starting dissipated at around 05:00. Good linear correlations, R^2 (Coefficient of Determination) equaled to 0.98 and 0.90 for the urban and rural stations respectively, were recorded for that run.

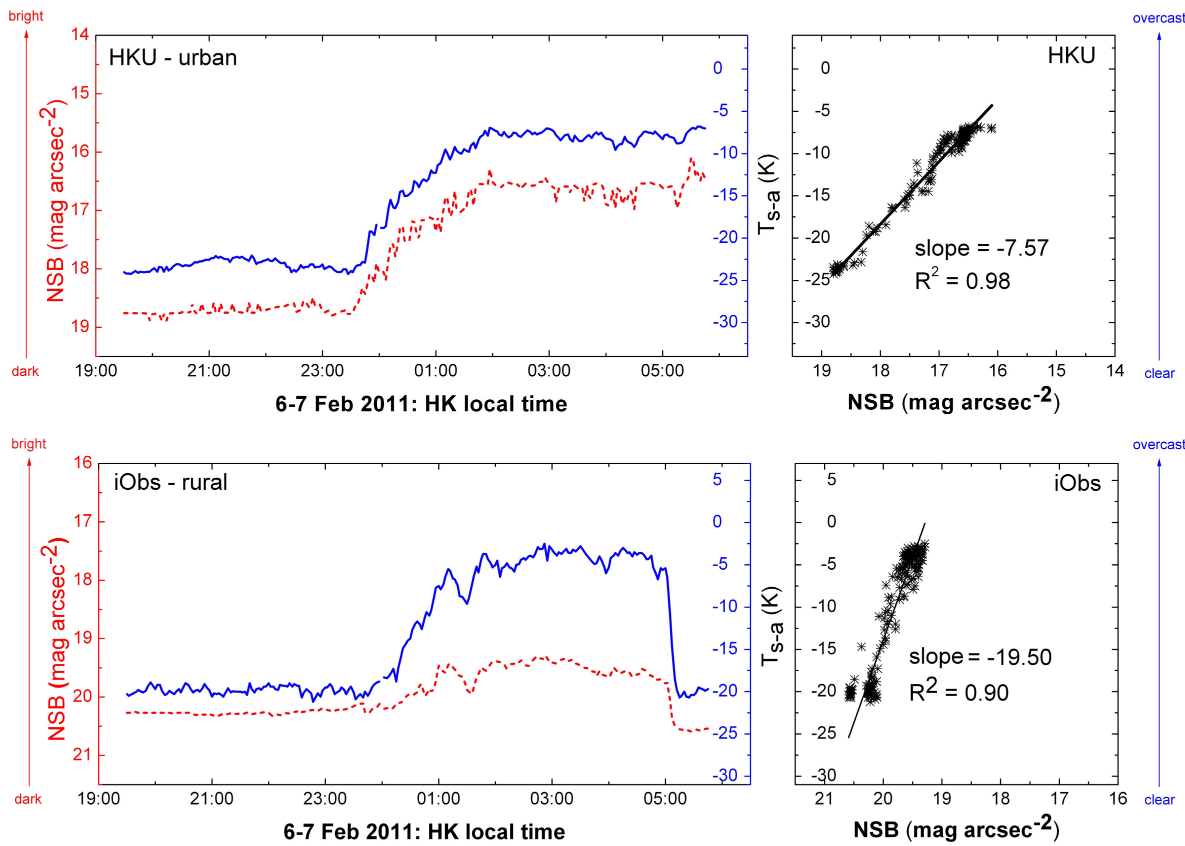

Fig. 10.— This figure describes a typical observational run #23 which had a noticeable cloud-NSB relation. *Left panel:* time series of NSB (red dashed curves, left red axis) and cloud amount in term of T_{s-a} (blue curves, right blue axis) measured simultaneously at the urban (upper panel) and the rural (lower panel) stations. *Right panel:* the corresponding scatter plots of T_{s-a} vs. NSB. The numbers near the fitted straight lines are their slopes in K/mag arcsec^{-2} and Coefficients of Determination R^2.

A very weak linear cloud-NSB correlation would be observed when the change in cloud amount or T_{s-a} was small. For examples, during observational runs #21 as seemed in Figure 11, T_{s-a} kept at relatively small values at both stations, indicating that the sky was clear throughout the observational runs, while NSB showed no noticeable variation throughout the runs.

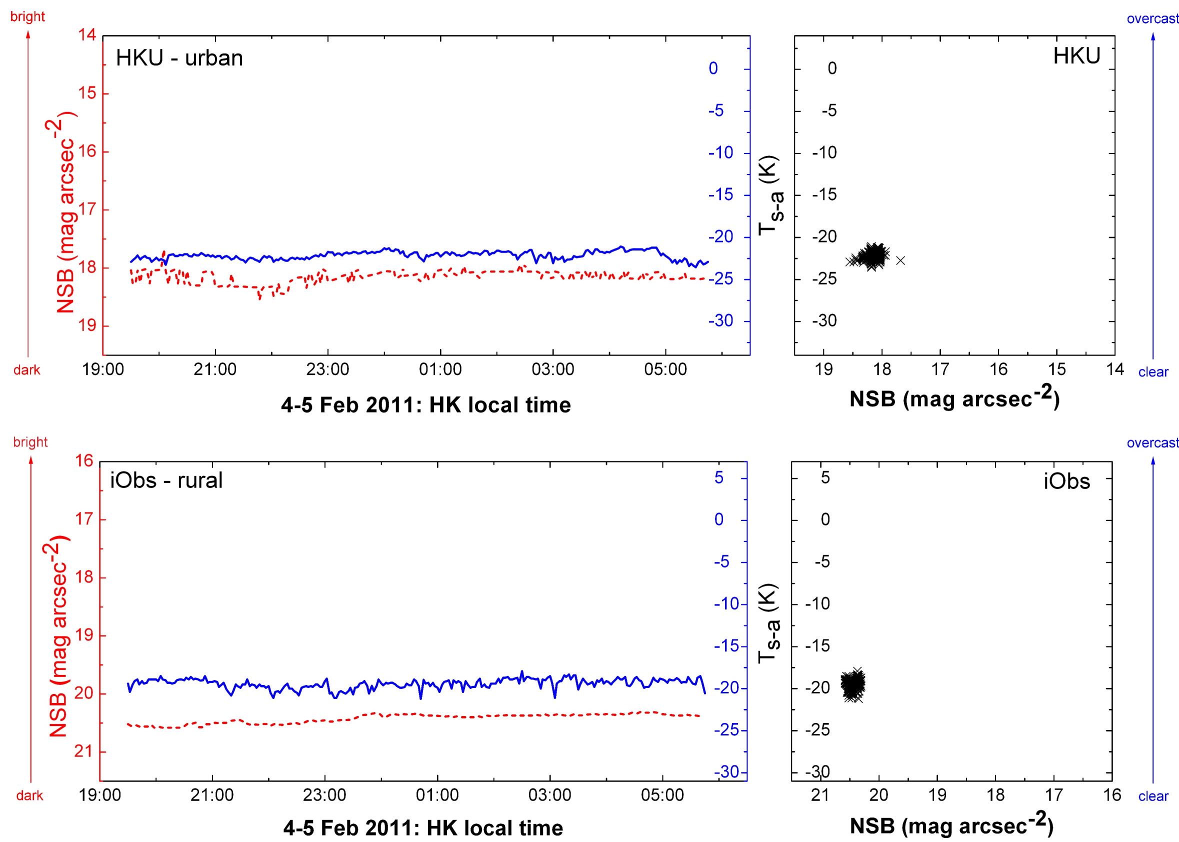

Fig. 11.— Same as Figure 10 for the observational run #21 which did not have a noticeable cloud-NSB relation.

Several general observational properties can be noticed when seeking for cloud-NSB linear relationship. Firstly, from Figure 12 where the histogram of R^2 of all runs which show clear cloud-NSB relation was presented, the proportion of run showing the noticeable ($R^2 \geq 0.30$) linear relation at the urban (29 out of 40 runs, or 72.5%) was greater than that at the rural station (19 out of 38 runs, or 50.0%). In term of observational hours, the numbers were 63.0% and 44.8% respectively.

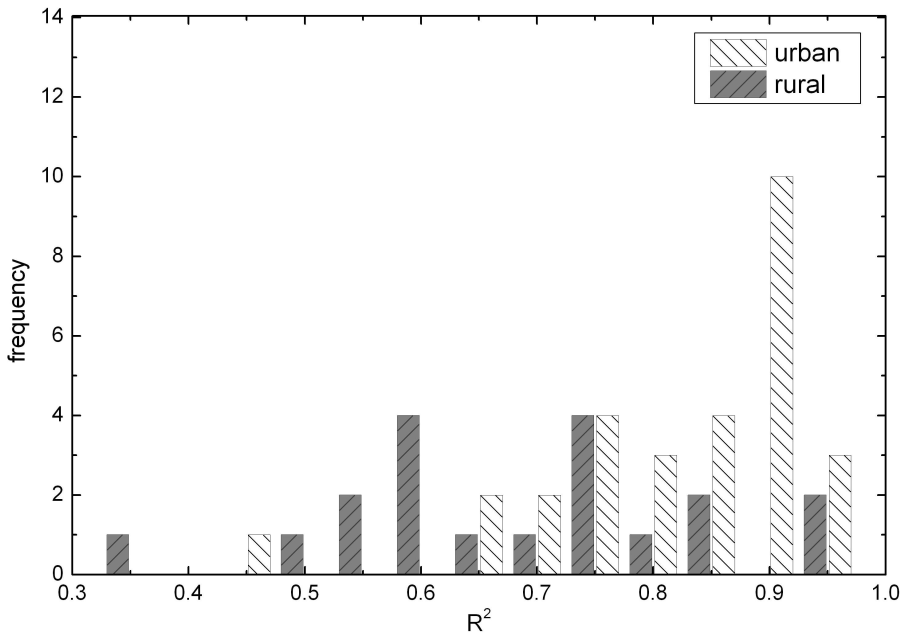

Fig. 12.— Histogram of the Coefficient of Determination R^2 of the cloud-NSB linear fittings

Secondly, the strength of linear correlation or the size of R^2 of those runs showing noticeable cloud-NSB relation was greater at the urban (0.84 on average) than that at the rural station (0.65 on average). Assumed the same cloud properties at both stations, comparing with the NSB responses against cloud amount change recorded at the rural station in which the changes in NSB were less noticeable in general, and hence smaller R^2, the effect of light pollution at the urban station was demonstrated.

Thirdly, from Figure 13 where the histogram on the values of the best fitted slopes was presented, the median values of slope measured at the urban and rural stations were -7.57 and -12.40 K/mag arcsec^{-2} respectively. Similarly, assuming the clouds over both stations were identical, and we were able to compare the slope values across both stations within the same night, we found that the slopes of the urban station were always greater (less negative) than that of the rural station, except a small portion (or 17.6%) of observational runs. By knowing that the slope is the *measurement of the rate of change in cloud amount as a function of the change in NSB*, assumed clouds were illuminated (in visible range) solely due to artificial outdoor light sources, the slope is therefore the measurement of light pollution at specific station, i.e. if there were more artificial lights emitted to the sky at a station, the clouds over there would be brighter, leading to the larger change in NSB against the variation of cloud amount, and vice versa. The observed general trend of greater slopes measured at the urban station matched this expectation.

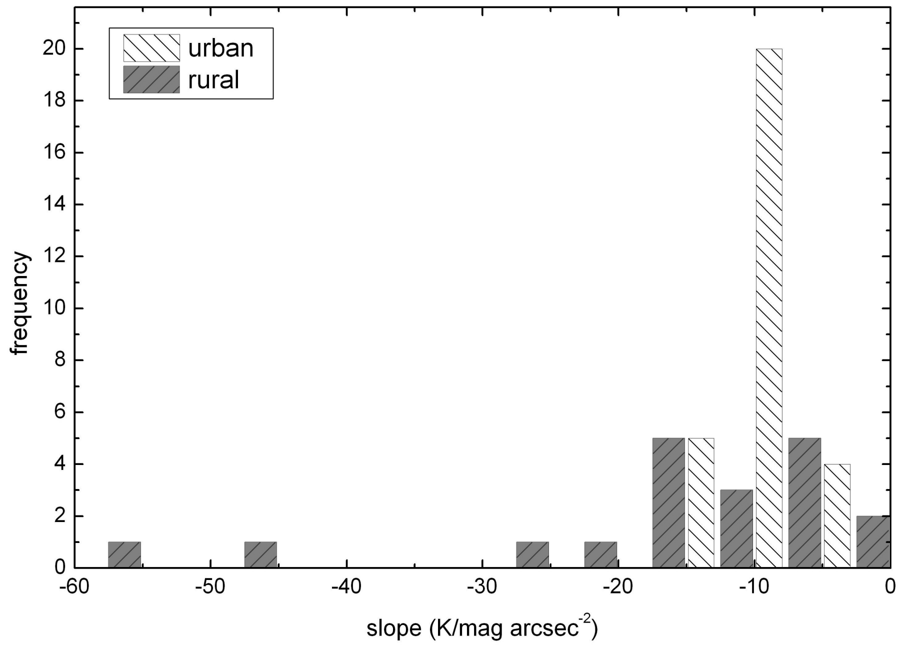

Fig. 13.— Histogram of the best fitted slope of the cloud-NSB linear fittings

3.3. Project outreaches

We launched a website as the main outreach media for publicizing the project in October 2011. The URL address is `http://nightsky.physics.hku.hk`. The index page presents a *Google Maps* (Figure 14) which shows the nightly and hourly overall median value of NSB recorded per station last night and/or real-time 15 minutes median value of NSB recorded per station (if visit the page in night time).

Fig. 14.— The NSN website is showing the light pollution condition in Hong Kong in *Google Maps*.

Since the first month of launch (October 2011), the website has been ranked within the top 5th in the results from local major search engines for Chinese and English keywords similar to "light pollution". Visitor statistics of the website were tracked by the free service *Google Analytics*. There were totally 9,157 visitors (about half of them were new visitors) and 38,992 page views for the period October 2011 to August 2012. There was about 900 visitors and 3,810 views per month on average. For the locations of visitors, almost 90% came from Hong Kong. The remaining 10% mainly came from the Chinese speaking regions, namely Taiwan (2.8%) and Mainland China (1.7%). Other main traffic sources were America (2.1%) and Europe (1.6%).

Thanks to the high ranking by search engines, students who were seeking information on local light pollution most probably reached our website. There were totally 7 groups of secondary school students and 3 groups of university students approached us for requesting information, statistic, interviews, and comments on the issues related to local light pollution problem during the project period. Our website and data showed on it nicely facilitated students' school projects, mostly on Liberal Education. In particular, a unit of hand-held Sky Quality Meter (SQM-L) was lent to a student from the Chinese Y.M.C.A. Secondary School for her project in Liberal Education examination. Two units of SQM-L were lent to a group of students from The Chinese Foundation Secondary School for their report on UNDESD Project Hong Kong Award Scheme ESD Programme 2011-2012. In addition, the project team members were interviewed by reporters from iCable news channel for a TV program[9], South China Morning Post for a news article (dated 27 March 2012), and a local web magazine titled CityReborn.com for an article[10].

Finally, the project team members were invited to conduct two oval presentations, titled *Night Sky Brightness Monitoring Network in Hong Kong*, during the 11th European Symposium for the Protection of the Night Sky which held in Germany in October 2011, and *The Night Sky Monitoring Network in Hong Kong*, during the 28th General Assembly of the International Astronomical Union (IAU XXVIII) which held in Beijing in August 2012. A poster presentation, titled *Effects of moonlight and cloud amount on the night sky brightness*, and two proceedings articles, titled *The Night Sky Monitoring Network in Hong Kong* and *Effects of cloud amount on the night sky brightness* were also contributed to IAU XXVIII. The copies of proceedings and poster can be found from our website[11].

4. Conclusions

Outdoor lighting is an integral and indispensible part of modern societies. The acoompanying issue of light pollution has just begun to arouse the attention of a wide spectrum of the general public, including ecologists, medical professionals, astronomers, and energy conservationists. This is an growing environmental problem that we have to face squarely and globally, and was included as one of the Global Projects titled *Dark Skies Awareness*[12] during the International Year of Astronomy 2009 (IYA2009). In the view of raising public

[9]See http://cablenews.i-cable.com/webapps/news_video/index.php?news_id=376484

[10]See http://cityreborn.com/node/1057

[11]See http://nightsky.physics.hku.hk/reference-local.php

[12]See http://www.astronomy2009.org/globalprojects/cornerstones/darkskiesawareness/

awareness on the improper use of outdoor lights which leads to significant light pollution problems, an earlier study (ECF Project ID: 2007-01) provided a snapshot survey of the severe extent of the problem, clearly revealing that human outdoor lighting usage contribute to this environmental degradation. In order to understand the extent and cause of this environmental issue, the *Hong Kong Night Sky Brightness Monitoring Network* (NSN) project was proposed to set up long-term monitoring stations of light pollution, similar as those measuring other environmental indicators such as toxic gas and particulate concentration maintained by the Environmental Protection Department.

The NSN monitored the changes in Night Sky Brightness (NSB) as a function of time, location, and others environmental factors by the use of 18 automatic light sensing devices around Hong Kong. Over 2.9 million individual NSB measurements were recorded under all possible environmental conditions over the past 2 years. This represents the largest data set ever collected around the world on night sky brightness of a single city. With such a huge dataset with high temporal resolution collected, we are able to on one hand consolidate our past understanding of the light pollution conditions in Hong Kong, while on the other hand discover new insights on connections between sky brightness and various artificial and natural factors.

This report summarized the main findings from the survey for results taken between the begining of the project in May 2010 to the end of project at August 2012. First, the overall average brightness level of the Hong Kong night sky was 16.7 mag arcsec^{-2}, implying a brightness level 100 times brighter than that of the moonless pristine night sky background as defined by the International Astronomical Union . Among the 18 locations studied, the brightest one is Tsim Sha Tsui, which averages 510 times brighter than that background, while the darkest one is Sai Kung East Country Park, which averages 15.4 times the standard. This suggests that even in the case for the darkest location, located deep inside the Sai Kung Country Park, the night sky is severely affected by the manmade lighting usage in the surrounding areas.

Second, by studying the average NSB observed in each station, we determined that the land utilization (urban or rural) in the vacinity of the monitoring station had significant effects on the brightness level of the night sky observed. On average, the night sky brightness in the 12 urban/suburban locations is almost 10 times brighter than that of the 6 rural locations. In particular, the brightest urban site in Tsim Sha Tsui is on average 33 times brighter than that of the darkest one in Sai Kung East Country Park. In addition, a detailed analysis of the average nightly profile of the night sky brightness reveal the strong effects of the outdoor lightings in the urban/suburban areas. It was found that significant darkening could be observed at 23:00, 00:00, and 01:00, which closely resemble the pattern of light usage of manmade public and commercial lightings. Moreover, the drop of NSB in urban locations is greater than the rural ones, possibly suggesting that a higher fraction of decorative or commercial lightings (as reflected in our measurements between 20:30 and 23:00) versus the essential lightings (as indicated in our late-night readings after 01:00) in these places (Section 3.2.2).

Third, the monthly variation of the averaged NSB for each stations revealed that the relative ranking of the NSB levels between different monitoring statiosn remain roughly constant. The top three brightest regions are all located in the dense Kowloon Peninsula while the darkest skies are in remote East, South, and Southwest edges of Hong Kong. This is consistent with our visual estimate that the amount and pattern of artificial lighting usage in each location stay fairly steady during the survey period. Our result once again confirms that the outdoor lighting usage practices in different regions is the key element in determining the brightness of the night sky in a particular location. On the other hand, the survey also indicates that the actual NSB measured in a particular night could be influenced by many factors, including variations in meteorological factors such as humidity, atmospheric conditions such as cloud amount and visibility, or astronomical factors such as moon phase and location. This is reflected in the large variation of the month-to-month average of the NSB measured over the duration of the survey in every location we studied (the moon effect is roughly averaged in the monthly statistics). The profile provided a solid comparison of light pollution condition across different locations in Hong Kong for the first time. (Section 3.2.1)

Finally, from the simultaneous observations of cloud amount and NSB in one urban and one rural location, it is demonstrable that the variation of NSB can be highly affected by changes in the cloud amount. A higher cloud amount would generally imply a brighter nightsky, with identical cloud amount variation leading to a larger change in the observed NSB in the urban location compared to that for the rural site. The observed correlation between the cloud amount and the NSB can be explained by the back-scattering effects of upward-directing light back down to Earth. Therefore the net effect is that clouds can make the light pollution effects more severe (Section 3.2.3).

Further investigations of this huge database of the NSN will focus on establishing a long baseline archive of the light pollution conditions in Hong Kong. The project team plans also to participate in the international network of light pollution monitoring stations to join this world-wide effort to combat this growing environmental problem. Possible further analysis of the data archive include studies of the relations between NSB and other factors including the brightness of the Moon, change in visibility, and concentration of air pollutants, etc.

The NSN project had developed a popular website which serve both to provide real-time measurements to concerned professionals and citizens, and to educate the general public about the background on light pollution. This webpage would remain as the real-life educational platform and resource center for those interested in the problem of light pollution even after the completion of the project, especially its effect on the natural night sky. The public knowledge exchange aspect of the project will be continued through an Impact Project *Community Light Pollution Reach-out Project* with the support of the Knowledge Exchange Funding of the University of Hong Kong (HKU)[13]. A series of workshops in schools and community reach-out events in public places will be organized to promote awareness of light pollution, to engage students to study and understand light pollution scientifically, to inform the public of the results from the NSN, and to contribute to the reduction of light pollution.

The *Guidelines on Industry Best Practices for External Lighting Installations*[14] issued by the Environment Bureau of the HKSAR Government in January 2012 represents a significant first step in terms of improving the light pollution conditions in Hong Kong. This set of guidelines is the first-ever list of suggestions which aim at minimizing the nuisance and energy wastage that may be caused by external lighting in Hong Kong. It is envisioned that the Task Force on External Lighting of the Environmental Protection Department may submit recommendations in terms of additional steps that the government and the community can take to ease this problem.

One way to assess the successfulness or effectiveness of these and future guidelines would rely on sustaining the light pollution monitoring. Indeed, from international experiences, yearly long-term NSB monitoring is essential for constructing the relationships between light pollution (or airglow) and human factors like lighting ordinances and population growths, as well as natural factors like climate and solar activities (Lane & Garrison 1978, Benn & Ellison 1998, Sanchez et al. 2007, Neugent & Massey 2010). Therefore a long-term monitoring extending beyond the current study would be greatly desired.

Moreover, our current study was only designed to measure the brightness of the night sky, but not the *source* of these lights. The NSN light sensors record the integrated light from the sky originated from different types and models of outdoor lightings (e.g., metal halide, high pressure sodium, low pressure sodium, mercury vapor, incandescent, and fluorescent lamps, etc), together with natural emissions from the moon, atmospheric gases, and molecules. Important questions such as how much of the light from the night sky is actually natural and how much is from manmade lightings cannot be answered.

One possible study to answer this question is to monitor *both* the intensity and the origin

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[13]`http://www.ke.hku.hk/`

[14]See `http://www.enb.gov.hk/en/resources_publications/guidelines/index.html`

of the night sky in Hong Kong. The identity of the source of light pollution can be traced with its spectroscopic signature, which is different for different kinds of lighting. A system which includes both a series of monitoring stations (similar to that of NSN) and a handful of spectrometers placed alongside at strategic locations could go a long way in identifying key areas to address in terms of easing the light pollution situations in Hong Kong. With the natural airglow components filtered out, it is expected that such system could provide a more accurate picture of light pollution conditions in Hong Kong.

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