Report of *A Survey of Light Pollution in Hong Kong* (ECF Project ID: 2007-01)

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Abstract

With the support of an Environment and Conservation Fund (Project ID: 2007-01), we completed the first light pollution survey in Hong Kong. Findings from the project contribute to the overall environment of Hong Kong by promoting light pollution reduction and energy saving. Using a portable light sensing device called the Sky Quality Meter, the night sky brightness was measured and monitored around Hong Kong over a 15-month period (2008 March − 2009 May) with the assistance of 171 volunteering participants, comprising secondary school students, camp site workers, and astronomy enthusiasts. A total of 1,957 data sets were taken at 199 distinct locations, including urban and rural sites covering all 18 Administrative Districts. In support of this project, a public website was created which served both as the interface for data input and to educate the public about issues related to light pollution and to raise public concerns.

The survey shows that the light pollution in Hong Kong is severe – urban night skies are on average 100 times brighter than at the darkest rural sites, indicating that high population and thus high lighting densities in dense urban areas can cause severe light pollution. In the worst polluted urban areas such as Wan Chai and Mong Kok, the night sky is at least 500 times brighter than the darkest sites in Hong Kong such as eastern Sai Kung and southern Lantau Island. Moreover, later night skies (at 11:30pm) are 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. We failed to establish any conclusive correlation of night sky brightness with different meteorological and air quality factors due to insufficient data coverage. Results from this survey will serve as an important database for the public to assess whether new rules and regulations are necessary to control the use of outdoor lightings in Hong Kong.

Contents

1. Introduction

Outdoor lighting is an indispensable element of modern civilized societies for safety, recreation, and decorating purposes. However, poorly designed lighting system and excessive illumination level lead to a huge waste of energy and money. Any misuse of electric lighting not serving its originally intended purposes means a huge waste of energy and resources of the Earth. It is not uncommon to find poorly designed outdoor security light not using a lamp shade so that only a small fraction of light generated is directed to the ground, with a majority of light directed upwards towards the sky. These poorly designed outdoor lightings not only waste energy, money, and valuable earth resources, but also rob us of our beautiful night sky. The saved electricity from improper outdoor lighting would also means less air pollution, which can then reduce global warming caused by the power generation process.

According to the International Dark-Sky Association (IDA)[1], light pollution refers to any "adverse effect of artificial light including sky glow, glare, light trespass, light clutter, decreased visibility at night, and energy waste". Excessive artificial outdoor lightings, such as street lamps, neon signs, and illuminated signboards, can lead to environmental degradation and affect the natural environment and the ecosystem. The wasteful light emitted directly by or reflected from the artificial sources pointing upwards can be scattered by clouds, frogs, and pollutants like suspended particulates in the atmosphere (Benn & Ellison 1998). Therefore the night sky brightness (NSB) is the key environmental indicator to reflect upon the condition of light pollution.

Light pollution is quickly becoming a severe environmental problem worldwide. Satellite images of the earth at night show that few regions are truly dark (Figure 1) and the dark sky is an endangered natural resource (Bakich 2009). It is entirely possible that the Moon is the only celestial object youngsters would ever see with their naked eyes their whole life in the big cities. Therefore, in year 2009, designated as the *International Year of Astronomy 2009* (IYA2009) by the United Nation, the International Astronomical Union (IAU) has put *Dark Skies Awareness* as one of the cornerstone projects of IYA2009[2]. The IAU aims to raise the level of public knowledge about adverse impacts of excess artificial lighting on local environments, and to help people to appreciate the ongoing loss of a dark night sky for much of the world's population.

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[1]http://www.darksky.org/

[2]http://www.darkskiesawareness.org/

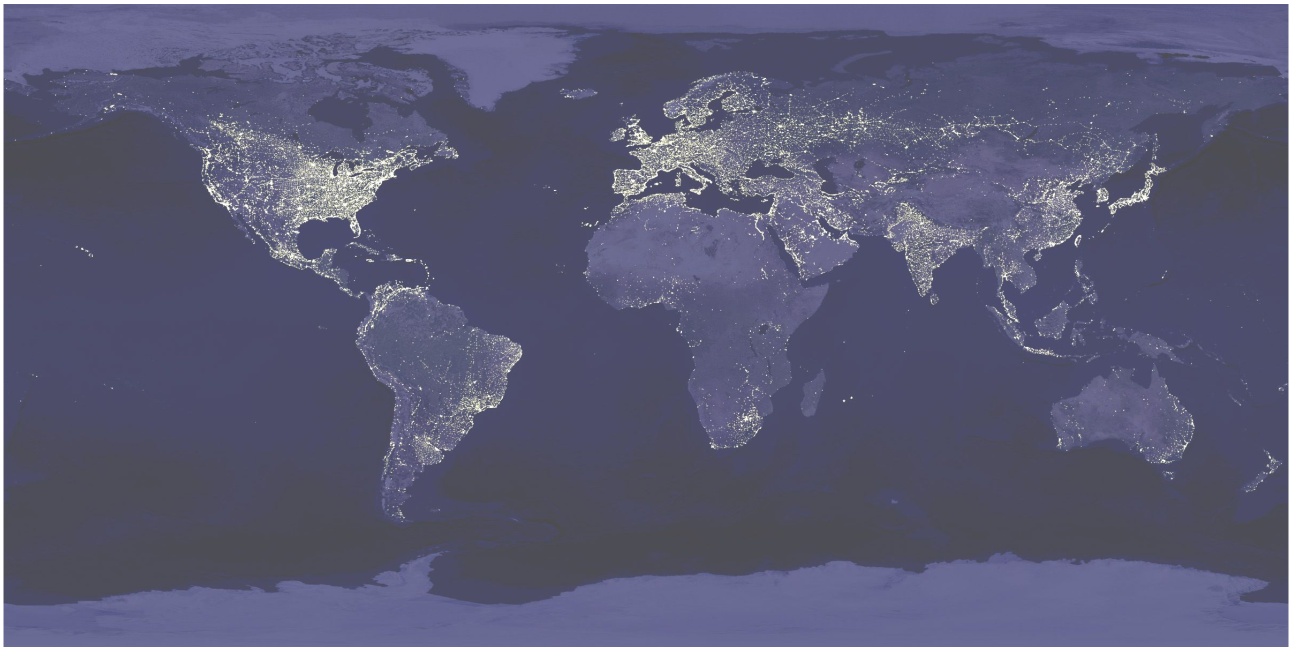

Fig. 1.— Satellite image of the Earth at night (Credit: C. Mayhew & R. Simmon (NASA/GSFC), NOAA/NGDC, DMSP Digital Archive).

Hong Kong is a metropolitan city famous for her spectacular city night lights. With highly mixed land utilization within a small area, along with a complex geological landscape and robust human activities, the night sky condition of Hong Kong makes for an interesting case study for the effect of human activities on the quality of night sky. Hence we carried out the first large-scale survey of the condition of light pollution in Hong Kong by measuring the NSB using standard astronomical photometry techniques widely adopted worldwide as a reliable method to study the problem. This survey has been highlighted by the *Dark Skies Awareness* working group as a sample project for other countries[3].

For a 15-month period from March 2008 to May 2009, a total of 171 volunteers, making up of secondary school students, campsite workers, and amateur astronomers, participated in the survey and measured the NSB using a small and easy-to-use light sensor called Sky Quality Meter (SQM). These volunteers contributed 1,957 sets of NSB data from 199 distinct observation sites all around Hong Kong. Armed with this important database, we generated the first Hong Kong light pollution map detailing the overall geographical variations of NSB

[3]http://www.darkskiesawareness.org/lp-in-hk.php

in Hong Kong. Moreover, many NSB data were taken simultaneously from different locations so that snapshots of the regional variation of the light pollution at a particular time could be identified. In addition, long term variation of the NSB, and the relation between NSB and meteorological and natural factors, including cloudiness, visibility and air quality, were also investigated.

Another important goal of this project is that, throughout the survey, participants could be introduced with the problem of light pollution, and all its damaging consequences. This was achieved in two ways, first, we invited a large group of volunteers to participate in this survey, in particular secondary school students, so that they could experience first hand the light pollution situation and conduct scientific research first hand. Second, a website dedicated to this survey was created[4] which acted both as an educational resource on topics related to light pollution and as an interface for participants of the survey to submit their NSB measurements.

A Survey of Light Pollution in Hong Kong was funded by the Environment and Conservation Fund (ECF) (Project ID: 2007-01) of the HKSAR Environmental Protection Department (EPD), and the Woo Wheelock Green Fund. It was organized by the Department of Physics of The University of Hong Kong and co-organizers were the Hong Kong Space Museum, the Sky Observers' Association (Hong Kong), Ho Koon Nature Education cum Astronomical Centre (Sponsored by Sik Sik Yuen), and The Camping Association of Hong Kong, China, Ltd.

2. Light Pollution

2.1. Cause of Light Pollution

Light pollution is caused by many sources. Obtrusive light is defined to be any luminary that is operating at inappropriate location and/or during inappropriate time. As illustrated by Figure 2, in many cases, even though there is only a specific area on the ground originally intended to be illuminated, in reality light from the luminary spills out to a much larger area due to poor light shielding. These spill light sources can then cause light trespass that directly impacts the surrounding areas. To make matter worse, these poor lighting designs can also lead to light that is directed upward to pollute the sky. Another important source

[4]http://nightsky.physics.hku.hk/

of light pollution is the reflected light from both the intended and unintended illuminated areas on the ground. Therefore in addition to bad design of external lighting elements, excessive amount of lighting used also contributes to the pollution of our night sky. Finally, the exact pattern and mode of the outdoor lighting usage can also affect people: for example, short-term flashes used in some commercial and residential external architecture can cause discomfort in people living nearby.

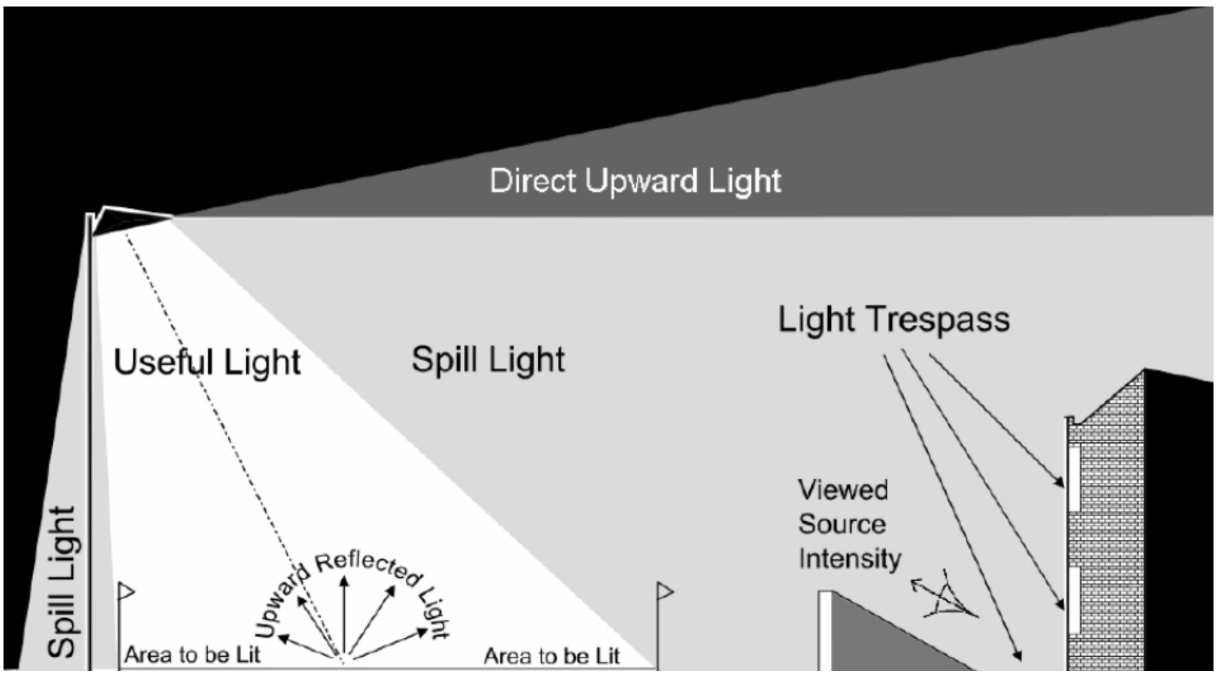

Fig. 2.— Types of obtrusive light defined and sources of light pollution. Source: *Guidance notes for the reduction of obtrusive light*, The Institution of Lighting Engineers, 2005.

To study light pollution quantitatively and scientifically, astronomers measure the brightness of the night sky, which reflects upon the amount of sky glow. Sky glow is the brightening of the night sky by the scattering by the molecules and aerosols (suspended fine solid particles or liquid droplets such as smoke and smog) in the atmosphere of the artificial light directly emitted or reflected from the ground. The extent of sky glow, hence the measured NSB, thus depend on both the amount of artificial light sources and on natural factors, such as moonlight (Krisciunas 1991), optical thickness of air (or *airmass*) (Taylor et al. 2004, Sanchez et al. 2007), cloud coverage (Garstang 2006), ozone (Garstang 1989), and dust layers (Garstang 1991). However, in a metropolitan city like Hong Kong, we expect human contributions to be the dominating factor, which means that the extent of human activities and the lighting practices can largely determine the night sky properties observed.

2.2. Effects of Light Pollution

A direct effect of light pollution is the decrease of the number of stars visible in the night sky. The light scattered by tiny aerosol molecules in the atmosphere brightens the entire night sky, and reduces its brightness contrast. Therefore an increase of light pollution or NSB would lead to an increase in the limiting visual magnitude[5], thus reducing the number of star visible (see Table 1).

The reduction in the number of star visible severely affects stargazing activities. With the subject of Astronomy soon to be included as part of the New Secondary School curriculum of Physics, we need our night sky now more than ever as a scientific teaching-aid for our next generation to educate them the science of the heavens. However, on a night sky that is heavily polluted by artificial lights, only the brightest stars are visible and even the most common and the brightest star constellations, such as the Sagittarius and Orion, can hardly be recognized. Even the two stars Altair and Vega, representing the two main characters in the famous Chinese legendary story "*Qi Xi* (The Night of Sevens)," are frequently engulfed up by the serious light pollution in Hong Kong. The Milky Way, poetized as a celestial waterfall pouring down from heaven, is also constantly deemed invisible by light pollution in Hong Kong. The starry night is quickly losing its status as an educational tool to link our next generation to the traditional legendary stories, and as a great object of imagination for our youngsters. The incredible starry night together with the stories behind the stars could soon disappear forever.

In addition to astronomical observation, excessive lighting also brings significant ecological consequences. In the worst scenario, it could influence the entire ecological balance of the local living environment. Owing to abused lightings, normal activities and behaviors of nocturnal animals could be disrupted as most living species depend on the daily light and dark cycles for their ways of life (Rich & Longcore 2005, Klinkenborg 2008). A simple example is that billions of moths and other nocturnal insects are killed each year at lights, upsetting the ecological systems. Nocturnally migrating birds could also be disoriented and entrapped by lights at night. Once a bird is within a lighted zone at night, it may become

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[5] The limiting visual magnitude is dimmest celestial object that can be observed by unaided eyes. *Magnitude* (mag) is an astronomical unit to describe the brightness of objects. The brighter an object, the smaller is the magnitude and vice versa. This unit is in logarithmic scale, meaning that 1 unit difference implies a brightness ratio of about 2.512 while difference of 5 magnitudes is defined to imply a brightness ratio of exactly 100.

"trapped" and will not leave the lighted area. Changes in light level may disrupt orientation in nocturnal animals. The range of anatomical adaptations to allow night vision is broad and rapid increases in light intensity can blind animals.

On the human side, there have been increasing media reports about lives of people living in the immediate vicinity of fully lit neon signboard and improperly designed flood lights (from say outdoor parking lots and playgrounds) to be severely affected by the excessive illumination. These people are forced to surround their living environments with thick curtains or else they cannot get a proper sleeping environment in their own home. EPD currently receives about 30-40 complaints on abuse of lightings each year. The number of persons affected may increase in the future due to the growing use of outdoor lighting and due to the increase awareness of the public on the issue of light pollution. In addition, there have been some scientific reports linking the excessive exposure of light at night by women and the chance to develop breast cancer (Davis et al. 2001, Blask et al. 2005, Stevens 2006). On the other hand, there is yet a comprehensive series of research to study the full range adverse effects of light pollution on human physiology.

Poorly designed lighting system and excessive illumination level lead to a huge waste of energy and money, although lighting is an indispensable element of modern civilized societies for safety, recreation, and decorating purposes. According to the 2004 statistics from the HKSAR Electrical and Mechanical Services Department, 20% of the total electrical consumption in Hong Kong was spent on lighting. Since electrical production is widely regarded as one of the major source of air pollutants, any misuse of electric lighting not serving its originally intended purposes means a huge waste of energy, and indirectly, generating air pollution. It is not uncommon to find poorly designed outdoor security light not using a lamp shade so that only a small fraction of light generated is directed to the ground, with a majority of light directed upwards towards the sky. Not only does this light provide no useful illumination, it also becomes a source of pollution to our night sky. IDA estimated that about US$2 billion, or equivalent to six million tons of coal, was spent in the US each year on wasteful lightings. Therefore light pollution not only means wasting energy and money, but also enhancing air pollution and global warming.

2.3. Previous Studies of Light Pollution

Around the world, astronomers have taken active roles in studying the quality of the night sky because brightened night sky background has adverse effects on ground-based optical astronomical observations, in term of increasing the limiting magnitude and hence degrading the night sky quality. A suitable astronomical observatory site should be dark enough for the observations of very faint objects (Isobe 1997). Monitoring the night sky brightness is hence important and essential for both potential and existing astronomical sites (see for examples Krisciunas 1987, Walker 1988, Pilachowski et al. 1989, Krisciunas 1990, Leinert et al. 1995, Mattila et al. 1996, Krisciunas 1997, Leinert et al. 1998, Benn & Ellison 1998, Patat 2003, Taylor et al. 2004, Sanchez et al. 2007, Krisciunas et al. 2007, Stalin et al. 2008, Patat 2008). These measurements have been done with professional astronomical equipments and astronomical photometry techniques. Furthermore, there have been increasing concerns of the effects of light pollution in outdoor environments such as big national parks in the US (Duriscoe et al. 2007).

In addition to studies by professional researchers, a variety of educational citizen-science programs had been organized to survey the night sky with just unaided eyes or with simple equipments. For example, the *Star Watch* campaign organized by the Japanese National Astronomical Observatory used unaided eye estimates and astronomical photographs to measure the NSB level of Japan. Nearly 10,000 people in 270 towns contributed measurements, resulting in a detailed map of light pollution (Kosai et al. 1992, Burton & Gural 1996). Similar large scale surveying campaign, namely *Project Orion*, had been organized by the Northern Virginia Astronomy Club to provide a unaided-eye limiting magnitude contour map of the Washington, D.C. area in the US (Burton & Gural 1996). A recent major international effort was *GLOBE at Night* (GaN), the Global Learning and Observations to Benefit the Environment project[6]. Primary and secondary school students worldwide were invited to report on the limiting magnitude of stars in the constellation Orion throughout the month of March in 2006 − 2009. These projects not only mapped the global night sky conditions, but also rose the awareness of the public on the night sky protection.

In Hong Kong, the authors of this report have been working on projects to measure the NSB of Hong Kong since 2003, using technique of astronomical photometry, the international standard method employed by professional research observatories from around the world. Pictures of the night sky were taken with telescopes and astronomical CCD cameras. We have measured the brightness of the night sky in the The University of Hong Kong (HKU) Pokfulam Road campus, an urban setting, and in two rural settings at the Sai Kung High Island Reservoir and at Shui Hau in southern Lantau. A total of 40 nights of data

[6]http://www.globe.gov/GaN/

were taken over 4 years. The results indicated that the darkest urban night sky observable at HKU was at least 30 times brighter than the rural counterpart. This indicated that the heavy use of lighting in the city was indeed polluting the night sky. It was also found that the night sky was significantly brighter in early evening before 12am than in late night after 12am within the same night of measurement, reflecting the effects of human activities.

These previous activities were all essential in establishing our basic understanding of the condition of light pollution in Hong Kong and around the world. However, there were a few limitations to these previous studies. For example, the detailed measurements at research astronomical observatory were indeed comprehensive in nature but were limited to only a handful of locations. Moreover, many of the large scale citizen-science projects such as GaN relied on subjective reports from participants' own vision and could suffer from inaccuracies and errors. Finally, our previous studies in Hong Kong were limited by the small number of measurements taken and the few locations covered. These low data collection rate was due to a few factors: difficulties in transporting the bulky observing equipments to remote locations, the large amount of time needed to set up the astronomical telescopes and CCD cameras, and the small number of personals who have the expert skills to conduct the measurements. Therefore in order to fully comprehend the conditions of light pollution in Hong Kong, we would need a large scale and long-term study which includes a large team of participants measuring the NSB using a portable and simple-to-use scientific equipment so that accurate data can be taken at multiple locations by lightly-trained personnels. The project *A Survey of Light Pollution in Hong Kong* is the first attempt at such a study and the details will be described in the article below.

Table 1. Limiting visual magnitude and the number of star visible

Limiting visual magnitude	NSB (mag arcsec^{-2})[a]	Approximate number of star visible with naked eye [b]
1	≈14.7	7
2	≈15.8	20
3	≈16.9	50
4	≈18.0	250
5	≈19.3	800
6	≈20.8	2,500
7	≈22.9	6,000

[a]Based on the formula from Schaefer (1990).

[b]The total number of star simultaneously visible to unaided eyes under a totally moonless night in theory (Roach & Gordon 1973).

3. Methodology

3.1. Outline of the Survey

The contributions of NSB data from volunteers was a key element of our survey. The drafting of volunteering participants served two purposes. First, we were able to vastly expand the geographical coverage of the survey to many locations. Second, we saw the survey as an opportunity to engage the community with the problem of light pollution. Throughout the survey, participants were introduced with the cause of light pollution, and all its damaging consequences to the environment. In order to obtain accurate data from the volunteering team of observers, many of whom did not have sufficient training to carry out complicated scientific experiments, we decided upon using a small and easy-to-use tool called the Sky Quality Meter (SQM) for making NSB measurements. The SQM gives an instantaneous reading of the NSB in units of *magitude per arc second square* (mag arcsec^{-2} for short), the international standard for measuring sky brightness[7]. Technical information of the SQM will be presented in Section 3.2.

3.1.1. Observation time

The survey started on 2008 March 15 and completed in 2009 May 31. The 15-month duration of the survey was divided into four phases, each of which lasted for roughly 3 to 4 months, with the starting and ending dates tabulated in Table 2. Breaking down the long survey period into phases not only give more interested parties the opportunities to participate in the survey, but also allow us to check and calibrate the SQMs regularly for their accuracies. Before the start of each phase, we organized briefing sessions for interested participants to introduce to them issues on light pollution and to demonstrate the proper procedures to use the SQMs to take NSB data. Briefings were held at the HKU Department of Physics on 2008 March 15, 2008 June 28, 2008 September 27, and 2009 February 7 (Figure 3). Detailed instructions for data taking and data reporting were also distributed at the briefing (Appendix A). All briefing materials were posted on the survey website so that participants who have missed the briefing session could also access them.

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[7]Suppose the measured NSB at site A is 20 mag arcsec^{-2}, then the brightness of the sky is equivalent to a celestial object of 20 magitude (mag) (cf Section 2.2) filling up a patch of sky of area 1 arcsec × 1 arcsec. Suppose the measured NSB at site B is 19 mag arcsec^{-2}, then the sky at site B is 2.512 times brighter than that at site A. The unit *arc second* (arcsec) is the unit of length on the celestial sphere. 1 arcsec = 1/3,600 degree.

In order to regularly monitor the full picture of NSB across Hong Kong, while not overworking our volunteering workforce, we decided to ask participants to take NSB readings at predefined *Survey Time*, which was defined to be 9:30pm and 11:30pm (± 5 minutes) on the 5th, 10th, 15th, 20th, 25th, and (if available) 30th day of the month local time. The first observing time of 9:30pm was selected to be at least two hours past the sunset time in Hong Kong so that the results will not be affected by twilight. Two observations taken on the same night allowed us to investigate effects of artificial lightings on NSB as many public and private outdoor lights were turned off in late evenings. Finally, observations were taken roughly every 5 days so that artificial weekly or weekday/weekend effects can be studied. For safety reasons, we asked participants not to take data when typhoon or lightning warning signals were issued, and not to take data during rainfall for fear of damaging the equipments. On the other hand, data collected on cloudy or full-moon nights were acceptable.

Table 2. Durations of phases of the survey

Phase	Start	End	Number of days[a]
1	15-Mar-08	31-May-08	78
2	28-Jun-08	30-Sep-08	95
3	1-Oct-08	31-Dec-08	92
4	7-Feb-09	31-May-09	114

[a]start and end dates inclusive

Fig. 3.— Briefing before the fourth phase of survey on 2009 February 7 at the Department of Physics, HKU.

3.1.2. Observation sites

One of the main strength of the survey was the deployment of many observers so that NSB readings can be taken simultaneously from many locations across the city. All observers were instructed to take data from at least one location of their own choosing. The following guidelines were issued to the observers in assisting them to select a proper site:

- Do not take data at a site with excessive street lamps or artificial lightings from outdoor buildings or light-emitting signboards nearby;
- Select an outdoor site which is easily accessible, safe, open, and has a wide field of view (that is, view of the night sky not blocked by buildings and structures), such as building rooftops, parks, or playgrounds;
- If there are artificial lightings nearby, measurements should be taken at least 10 meters from any individual light source.

Participants were instructed to take data at locations of their own choosing. In the majority of cases, these locations are either close to their home (e.g., the secondary school students), their work place (e.g., the Camping Association members), or areas of special interest (e.g., the amateur astronomers).

3.1.3. Data taking and reporting

In order to ensure data of sufficient reliability and accuracy, all observers were required to follow identical procedures. For each data set, each observer was requested to take 5 consecutive readings of the NSB with the SQM so that short-term electronic glitches and short-term malfunction of the SQM can be avoided. In addition to the NSB readings from the SQM, each observer was also requested to record the date, time, location, and temperature (read from the SQM) of the observation. Moreover, they were asked to estimate the cloud coverage (choose between 100%, 75%, 50%, 25%, 0%) and the haze condition (choose between heavily hazy, hazy, not hazy) during the observing time. A data report sheet was provided for all participants to record the observation results (Appendix B).

To maintain a speedy and accurate reporting of results, we created a on-line data reporting system accessable through the project webpage. Each participant was given a unique username and password to report the data of the survey. The first thing the observers had to do was to to register their site(s). Observers were asked to provide details about the site, such as address and the Administrative District of which the site belonged to. Moreover, the observers were asked to evaluate the lighting distribution (whether it was dense, moderate, or rare) and the field of view (whether it was wide, moderate or narrow). Participants were also required to provide the detailed latitude and longitude of each site to our data base so that all observation locations would be uniquely identifiable. That information could be found from public domain software such as *Google Earth*[8]. Finally, observers were recommended to upload day-time and night-time photographs of the nearby environment of each site so that we could evaluate the feasibility of the site for taking NSB data.

In the project webpage portal, we created simple online reporting forms so that observers, after logged on with their usernames, could report all data related to each observation (SQM readings, date, time, location, temperature, cloud coverage, and haze condition) to our data base. Observers were encouraged to report the data to us as soon as they have

[8]http://earth.google.com/

taken the measurements to minimize the opportunity of lost report sheets, even though we did allow late reporting from observers.

A total of 171 volunteers participated in the survey. The majority of them (148 or 86.5%) are secondary school students from 28 schools. The next biggest group are members of the Camping Association who work on the various campsites around the city. The statistics of the participants are tabulated in Table 3. It should be noted that we might have underestimated the number of participants because many of the observers at the camping sites worked as a team and used the same username to report observations taken at the same location.

3.2. Sky Quality Meters

The Sky Quality Meter (SQM) is a device that can measure the brightness of the night sky in units of mag arcsec^{-2} , the international unit used for measuring NSB (Figure 4). We selected the SQM for this project because of its portability (roughly about that of a deck of playing cards operating on a 9V battery) and its ease-of-use. It is manufactured in Canada by Unihedron[9] at a price of ∼USD 100 each. The light sensor of SQM is the TAOS TSL237 High-Sensivity Light-to-Frequancy Converter[10], which is covered by a near-infrared blocking Hoya CM-500 filter[11] to so that the combined filter-sensor system would have similar sensitivity to that of a human eye.

[9]http://www.unihedron.com/

[10]http://www.taosinc.com/

[11]http://www.hoyaopticalfilters.co.uk/

Table 3. Statistics on the participants of the survey

Participating volunteers	Number of participants
Secondary school students	148[a]
Camping Association members	14[b]
Amateur astronomers	9

[a]Representing a total of 28 schools

[b]In some campsites, data are taken by more than one observer

Fig. 4.— The Sky Quality Meter: the light sensor is located on the side of the near-infrared filter next to the display.

To properly use the SQM to measure the NSB, an observer needs to point the sensor-side of the SQM directly to the zenith (the highest point in the sky direction above one's head) and press a button. Readings of the NSB in units of mag arcsec^{-2} (with two decimal places) and the ambient temperature will be displayed in about one second. There are currently two versions: the original SQM and the SQM-L, which is modified from SQM with a lens in front of the sensor. Both versions of the SQM are sensitive only to a narrow cone of the sky directly in front of its sensor. The width of light cone measured in HWHM[12] for SQM is measured about 42° while that of SQM-L is about 10° (Cinzano 2005, 2007). As shown in Figure 5, the sensitivity of the SQM drops sharply beyond the width of the sensor. This is important because we do not want the NSB measurements to be directly affected by surrounding lightings from other sources. A total of 39 SQM units and 4 SQM-L units were used in the survey and we did not distinguish readings from the two different kinds of meters. Hereafter we use "SQM(s)" to represent both SQM and SQM-L.

Before arrival, all SQMs were calibrated for their absolute sensitivities by the manufacturer, who claimed an absolute precision of any NSB measurement to be ± 0.10 mag arcsec^{-2},

[12]Half Width Half Maximum (HWHM) is the angular size at which the sensitivity falls by half.

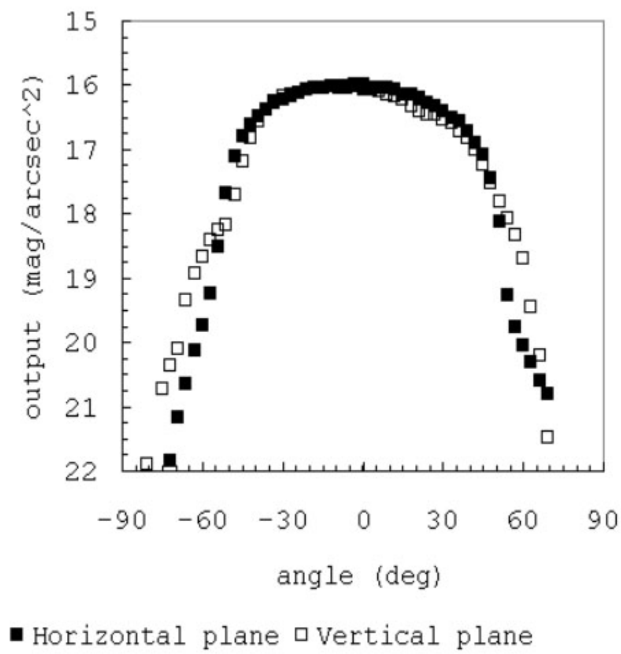

Fig. 5.— Angular dependence of the sensitivity of the SQM (Cinzano 2005).

or roughly ±10% in terms of light intensity. For our 15 month survey, the long-term stability and reliability of measurements were crucial. Therefore, as mentioned in Section 3.1.1, we have divided the entire duration of the survey into four phases so that we would collect the SQMs from the observers roughly every 3 to 4 months. We checked these collected SQMs with experimental setups in HKU for battery level, absolute sensitivity, and detector linearity after every phase. The angular acceptance of all SQMs were checked before the first phase and after the last phase. We did not notice significant drop in performance of the SQMs over time and therefore we did not have to modify any of the measurements collected from the observers throughout the survey.

3.3. Sources of meteorological data

One aim of our survey is to investigate whether any correlation exists between the brightness of the night sky and the meteorological conditions. Observers were asked to estimate and report the amount of cloud coverage (choose between 100%, 75%, 50%, 25%, 0%) in the sky during the observating time. We believed that while the cloud coverage data reported by observers were subjective, they more or less reflected the local situations.

Moreover, in additional to visual estimates from observers, we also obtained hourly cloud coverage and visibility data taken by the Hong Kong Observatory (HKO) at its headquarter in Tsim Sha Tsui (HKOH) and at the Hong Kong International Airport (HKIA) in Chek Lap Kok for comparison. Estimates of cloud coverage in the HKO data were measured by professional meteorological observers in units of *okta*, which described how many eighths of the sky were covered by cloud. For example, 0 okta represents a completely clear sky while 8 oktas represents a completely overcast sky. On the other hand, visibility readings in kilometers were made by professional observers at HKOH and by visibility meters at HKIA[13]. Meteorological data taken from the start of the survey until 2008 September 30 were obtained.

3.4. Sources of air quality data

We also asked our observers to estimate and report the haze condition (choose between heavily hazy, hazy, not hazy) during the observation time. We believed the haze condition could reflect of the quality of the air that night. However, since it was difficult for untrained observers to accurately determine whether a night sky was hazy or not, we decided to download Air Pollution Index (API) data[14] and air pollutant concentrations values[15] from the EPD website. The API, in a scale of 0 to 500, is the conversion of the ambient respirable suspended particulate (RSP), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and nitrogen dioxide (NO_2) concentrations measured by the air quality monitoring network of EPD. An API level of 100 corresponds to the short-term Hong Kong Air Quality Objectives below which there is no adverse acute health effect while a level of 500 can lead to significant harm to human health. The concentrations of air pollutants are measured every hour from the 11 general stations and 3 roadside monitoring stations around Hong Kong[16]. It should be noted though that the air monitoring stations are usually not located near any NSB observing sites (Figure 6). The sampling period of the EPD air quality data was 2008 March 15 to 2008 September 30.

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[13]for details, see: *Summary of Meteorological and Tidal Observations in Hong Kong 2007*, Hong Kong Observatory

[14]http://www.epd-asg.gov.hk/english/pastapi/pastapie.php

[15]http://epic.epd.gov.hk/ca/uid/airdata/p/1

[16]http://www.epd-asg.gov.hk/english/backgd/quality.php

Fig. 6.— The air quality monitoring network of HKSAR Environmental Protection Department (EPD), with the locations of 11 general stations and 3 roadside stations shown (Credit: EPD).

4. Results and Analysis

4.1. Overall results of Hong Kong

With contributions from 171 volunteer participants, we received a total of 1,957 sets of NSB data collected at 199 distinct observation sites during the entire duration of the survey from 2008 March 15 to 2009 June 1. The histogram of all the NSB readings collected are shown in Figure 7. The distribution peaks at around $15.5-16.5$ mag arcsec^{-2} with the highest NSB value (darkest sky) reported at 20.8 mag arcsec^{-2} (measured in Shui Hau, Lantau Island) and the lowest NSB (brightest sky) reported at 8.5 mag arcsec^{-2}. We believed that while the highest NSB values recorded were probably correctly measured, the NSB readings smaller than 12 mag arcsec^{-2} could probably be due to either incorrect data input (human error during data reporting on the web), incorrect usage of SQM (such as not orienting the SQM light sensor along the zenith), or improper site selection (that is, measuring at sites with external lightings directly entering into the detection cone of the SQM light sensor).

The overall average NSB reading we obtained in this survey is 16.1 mag arcsec^{-2}. How-

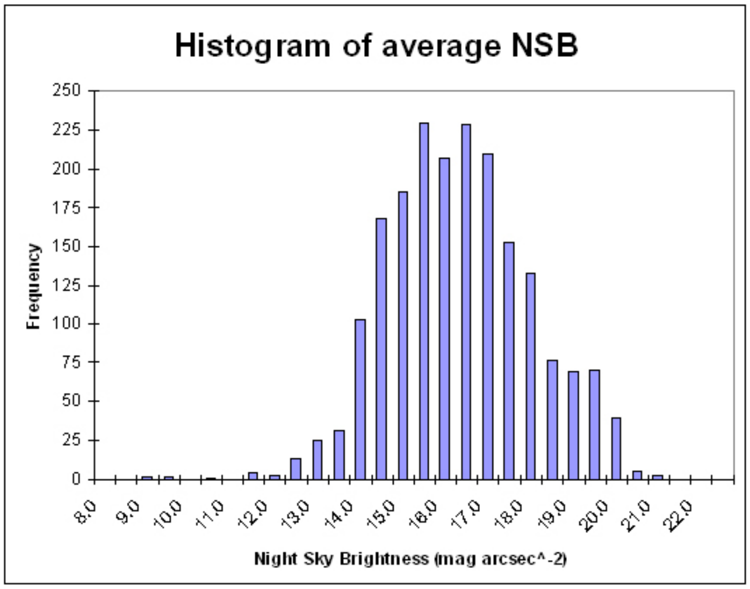

Fig. 7.— Histogram of the brightness of the night sky collected in the survey.

ever, this figure 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, and air quality factors will be studied and presented in the following sections. On the other hand, this figure does present a characteristic figure of NSB in Hong Kong for comparison with the figure measured elsewhere. Comparing this figure with the 21.6 mag arcsec^{-2} natural NSB level as suggested by the IAU for a good site for astronomical research (Smith 1979), the average Hong Kong night sky is about 5.5 mag arcsec^{-2} or 159 times in light intensity brighter[17]. On the other hand, the darkest sites in Hong Kong at 20.8 mag arcsec^{-2} remain to be reasonably good sites for astronomy despite the heavy urbanization in many parts of the city and it is essential that efforts should be made for these locations to remain so.

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[17]The magnitude is a log-scale unit and a difference of 1 mag arcsec^{-2} refers to a light flux ratio of 2.512. Therefore a difference of 5.5 mag arcsec^{-2} refers to a flux ratio of $2.512^{5.5} \approx 159$.

4.2. Geographic variation of night sky brightness

4.2.1. Observing locations

One key factor affecting the measured NSB is the observing location. This is expected because of the vastly different outdoor lighting environment and practices in different areas in Hong Kong. There were totally 220 individual sites correctly registered by the participants of the survey, of which 21 did not have any reported data and were discarded. The remaining 199 sites covered all of the 18 Administrative Districts of Hong Kong and their locations were presented in Figure 8. These sites covered a wide range of land utilizations, including dense urban residential areas, mixed commercial and residential areas, new town regions, rural residential areas, campsites within country parks, and remote rural areas. Without referring to the exact land utilization of each observation site, we roughly classified all sites to be either under *urban* or *rural* categories. Major criteria considered for the classification include the location and the population density of the surrounding areas, which could be estimated from inspections of the neighborhood environments with software such as *Google Earth*, and the site photos uploaded by the observers.

A majority of the sites in our survey (represented by circle symbols in Figure 8), totaling 171 sites or 85.9% of total, are classified to be urban, while the remaining sites (28 sites or 14.1% of total, represented by diamond symbols in Figure 8) are from rural locations. The bias towards urban sites in our survey is probably due to the fact that 86.5% of our survey participants are secondary school students and they opt more frequently to take NSB measurements near their home. In a crowded city like Hong Kong, it is difficult to entirely avoid lightings from street lamps, neon signboards, and buildings in urban or even rural areas. Although we had provided guidelines to observers to choose a relatively dark site with no direct external lighting shining at the light sensors of the SQMs (Appendix A), we found from the coordinates of the reporting locations and the uploaded photos of the surrounding that a small percentage of observers could have collected data under direct lighting and/or at sites with a very narrow field of view. This could have led to some of the abnormally bright night sky (NSB < 12 mag arcsec^{-2}) observed (cf Section 4.1). However, for the completeness of the study, we have included all the survey results in our analyses.

Of the 1,957 data sets of NSB received, 41.8% of the data sets were from rural sites while the remaining were from urban sites. The higher representation of rural data sets compared to the number of rural sites involved implied that we obtained on average a higher number of data set from rural sites (29.2 per site) than from the urban locations (6.7). This could be explained by our strategy of rotating the meters among student participants from different schools for each of the four phases of the survey while leaving some SQMs to selected camp site participants for the entire duration of the entire survey for long-term studies. Moreover, the high data report rates from camp site participants could also probably be due to the relative ease for them to go from their work place to the observation sites compared to the relative inconvenience for students to have to go from their home to the outdoor observation sites in the evening.

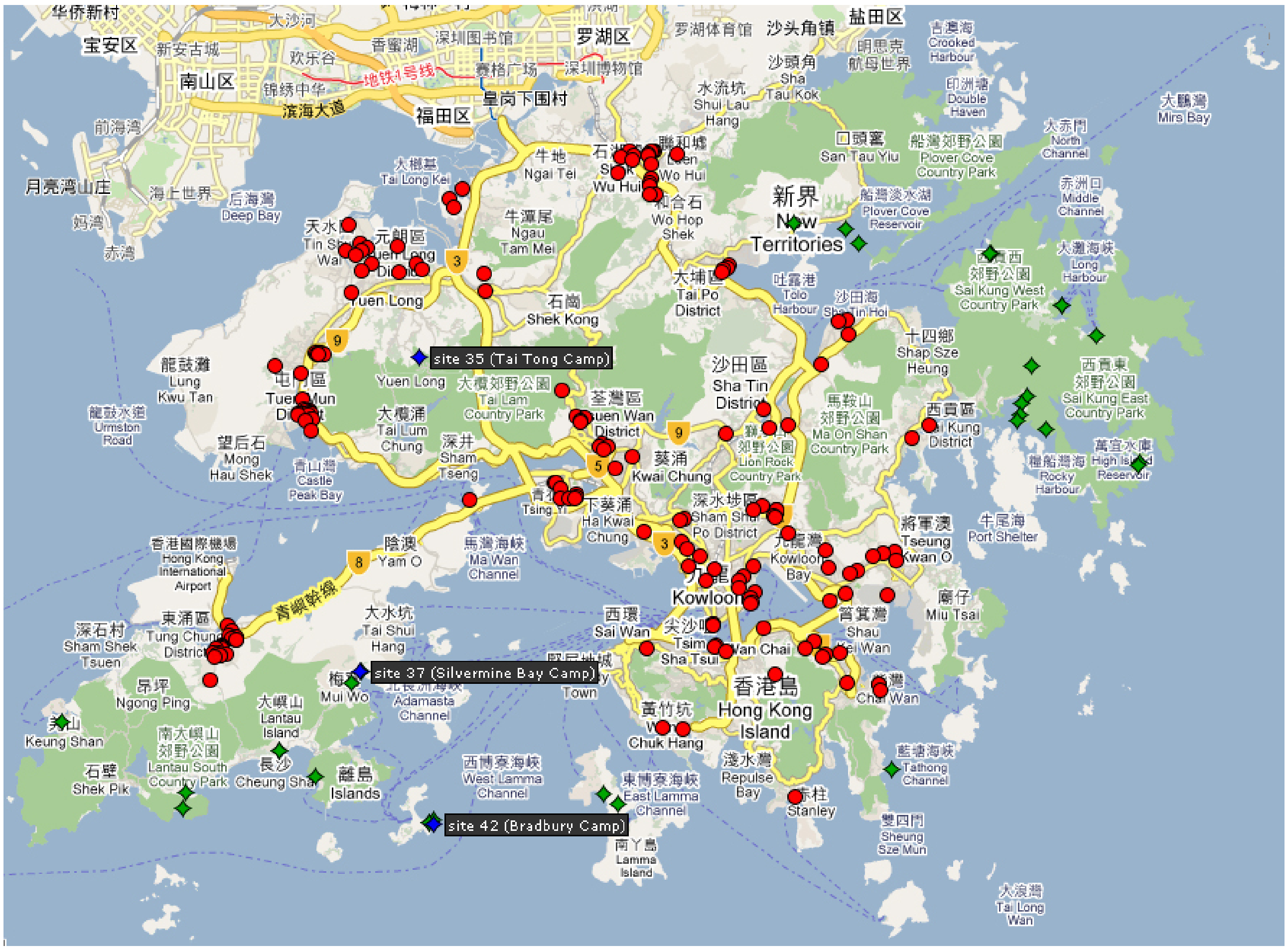

Fig. 8.— Geographic distribution of the observation sites. The urban (red circles) and rural (green diamonds) sites are represented with different symbols. The three campsites from which long-term data are studied, Tai Tong Camp in Yuen Long (site 35), Silvermine Bay Camp in Mui Woo (site 37), and the Bradbury Camp in Cheung Chau (site 42), are also shown (blue diamonds, see Section 4.3 for details).

4.2.2. The Hong Kong Light Pollution Map

We present the geographical dependence of the brightness of night sky in Hong Kong by constructing the "Hong Kong Light Pollution Map" (Figure 9). For each observing site, the average value of all observations taken from that location was taken. A map was then generated by representing the average NSB at each location with different color symbols. The map shown in Figure 9 was generated using the software *Google Maps*[18]. An online version of the light pollution map is also available on our survey website, with which visitors can zoom in on their neighborhood of interest and check the average NSB of these locations.

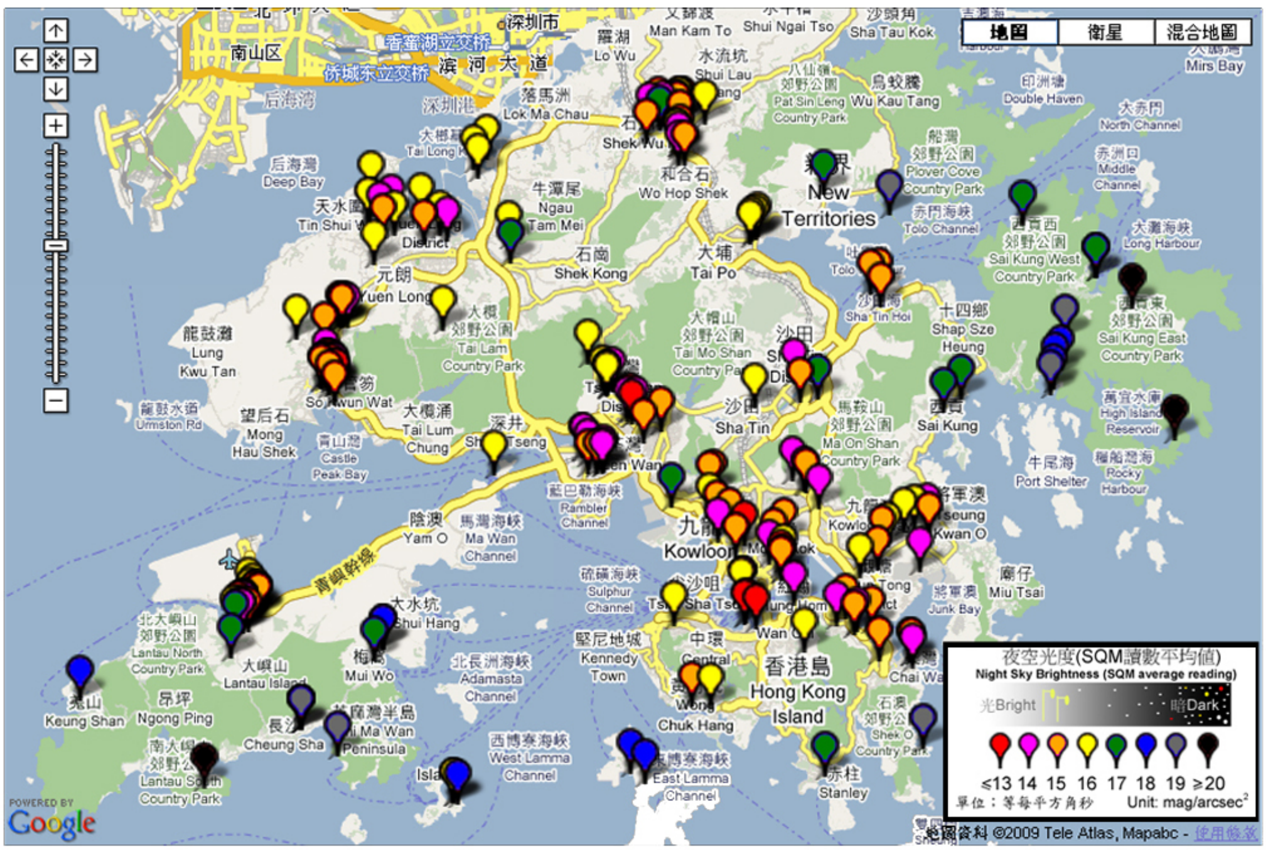

Fig. 9.— The Hong Kong Light Pollution Map. Color of the icon represents the averaged NSB measured for that site.

The map in Figure 9 showed that the measured NSB generally matched the amount

[18]http://maps.google.com/

of lighting usages at individual sites with different land utilizations among rural and urban areas. The brightest sites recorded in this survey were two locations Mong Kok and Wan Chai, both yielding averaged NSB readings of 13.2 mag arcsec^{-2}. The darkest night skies with averaged NSB readings of 20.1 mag arcsec^{-2} were recorded at Shui Hau in southern Lantau Island and at the East Dam of the High Island Reservoir in eastern Sai Kung. The difference of 6.9 mag arcsec^{-2} in NSB measured suggested that the brightest night sky in Hong Kong can be over 550 times brighter than that at the most pristine starry dark sky available. On average, the NSB value for all the 171 urban sites was 15.0 mag arcsec^{-2}, suggesting that the average urban night sky was 100 times polluted by outdoor lightings compared to the darkest night sky observable in Hong Kong.

Our study indicated that the quality of night sky in Hong Kong strongly correlated with the human presence and human activities. High population and thus high lighting densities in dense urban areas caused severe light pollution. An example could be found in Sai Kung in which we observed a general trend of darkening of the night sky as we moved to towards the eastern part of the region which was further away from the population center to her western side. Another trend observed was the similar NSB level observed in the mixed residential-commercial areas such as Kowloon and northern Hong Kong Island with the more residential areas such as Tuen Mun and Sheung Shui in the New Territories. This result seemed to indicated that there was not much difference between residential and commercial activities when it came to polluting the night sky, and the presence or absence of human activities was the key factor.

Special care should be taken when interpreting the light pollution map presented in Figure 9. First, the confidence level of the average NSB shown varied significantly, ranging from the high level of confidence for sites with large number of observations (e.g., 187 data sets for the site 35 Tai Tong Camp), to the lowest level of confidence for the 38 sites with one single reported observation. Second, as shown below in Section 4.3, in addition to the observation location, the measured NSB at a particular site also depended on the date and time of the observation. Therefore we did not believe that the light pollution map presented here would be an accurate predictor of the NSB of any specific location on a certain night, nor did we put high significance on all the detailed distribution of NSB within a small region, particularly for cases where large NSB differences were observed for adjacent sites because data from adjacent sites could be taken from different nights under different conditions. On the other hand, with a large number of data sets received covering large fractions of land area, we believe the light pollution map does provide a general overview of the light pollution situation in Hong Kong and can serve as a starting point for our understanding of the problem.

4.2.3. Snapshots of the night sky in Hong Kong

Throughout the survey, we encouraged users to take data during the designated *Survey Time* (cf. Section 3.1.1). These observations provided opportunities for data to be taken simultaneously under supposedly homogeneous natural conditions, such as meteorological, air pollution, and moonlight. In order to understand the detailed geographical distribution of the night sky condition in Hong Kong, we selected two *Survey Time* slots with relatively large number of data sets taken within a single night, dated 2008 March 25 and 2008 April 5. The plots of NSB verses sites were presented in Figures 10 and 11 respectively. In the figures, the top plot showed the NSB of that night at the various observing sites, the exact locations of which were shown in the map below. The sites, as described in Section 4.2.1 above, were classified into urban and rural sites and were represented respectively by circle and diamond symbols. The NSB readings taken at the two survey time, 9:30pm and 11:30pm, were represented with red and green icons respectively. The error bars shown in the plot were the standard deviations of the 5 SQM readings reported by the observers for every data set.

Benefited from the advantage that the observations were taken under similar conditions, we could get a more realistic snapshot of the condition of the night sky in Hong Kong from Figures 10 and 11 compared to the general Hong Kong light pollution map presented in Figure 9. Some observations are as follows:

- The observed NSB could signficantly vary among different locations in Hong Kong. On 2008 March 25 (Figure 10), the brightest observed night sky at 9:30pm, site 55[19] at 14.4 mag arcsec^{-2}, was 3.5 mag arcsec^{-2}, or 25.1 times in light intensity, brighter than the darkest location, site 41[20] at 17.9 mag arcsec^{-2} (We excluded the result from site 35 taken at 9:30pm here, please refer to bullet below). Site 41 is located inside the Sai Kung East Country Park and the observation site has a wide field of view and is far away from street lamps. On the other hand, from the submitted photograph of the site, we notice that site 55 has a narrow field of view partially blocked by the surrounding tall

[19]outside a village house, Yuen Long, location: 22°27'11"N, 114°01'49"E

[20]The Boys' and Girls' Clubs Association of Hong Kong Bradbury Camp, Sai Kung, location: 22°23'30"N, 114°19'07"E

residential buildings. Similarly, on 2008 April 5 (Figure 11) at 9:30pm, the brightest observed night sky, site 68[21] at 13.8 mag arcsec^{-2}, was 5.0 mag arcsec^{-2}, or 100 times in light intensity, brighter than the darkest location, sites 41 at 18.8 mag arcsec^{-2} (We excluded the result from site 74 as the measured NSB was much brighter than from the surrounding locations of sites 68, 70, 72, and 73.) The huge difference observed in different locations in Hong Kong suggests that the surrounding environment of the observing site can have significant effects on the quality of the night sky.

- On both nights of the snapshot survey, the brightness of the night sky at all the urban sites (circles) were almost all brighter than that observed at rural sites (diamond symbols), with the results from site 35 as the only major exception[22]. This strongly implied that human activities in urban areas were hugely important on the quality of the night sky, and the extent of these activities was the key factor in determining the wide ranges of the NSB observed in different locations around Hong Kong at the same time.

- For some of the observing sites, there were data taken on both 9:30pm and 11:30pm. In a majority of the sites (8 out of 10 on 2008 March 25, and 7 out of 11 on 2008 April 5), the night sky in 11:30pm was dimmer than that at 9:30pm. It was consistent with the earlier observation of human influence on the night sky, as more artificial lightings were turned off in the later evening at 11:30pm. The observed NSB difference was not very big and was mostly in the range of around $0.1 - 1.0$ mag arcsec^{-2}, implying a flux difference of less than a factor of 2. We believe it is because many external lightings remain turned on by 11:30pm and are not turned off until later in the evening, say by 1am.

[21]outside tall residential buildings in a public estate, Tuen Mun, location: 22°24’47"N, 113°59’10"E

[22]On 2008 March 25, the 9:30pm observation was actually the brightest NSB observed that night in Hong Kong. However, we suspected the authenticity of this data point as the result of 11:30pm from the same site was almost 2 mag arcsec^{-2} dimmer, a much bigger same-night difference observed than from all other locations. Similar argument could be made for the 11:30pm result from 2008 April 5, which was 1.5 mag arcsec^{-2} *brighter* than the 9:30pm data.

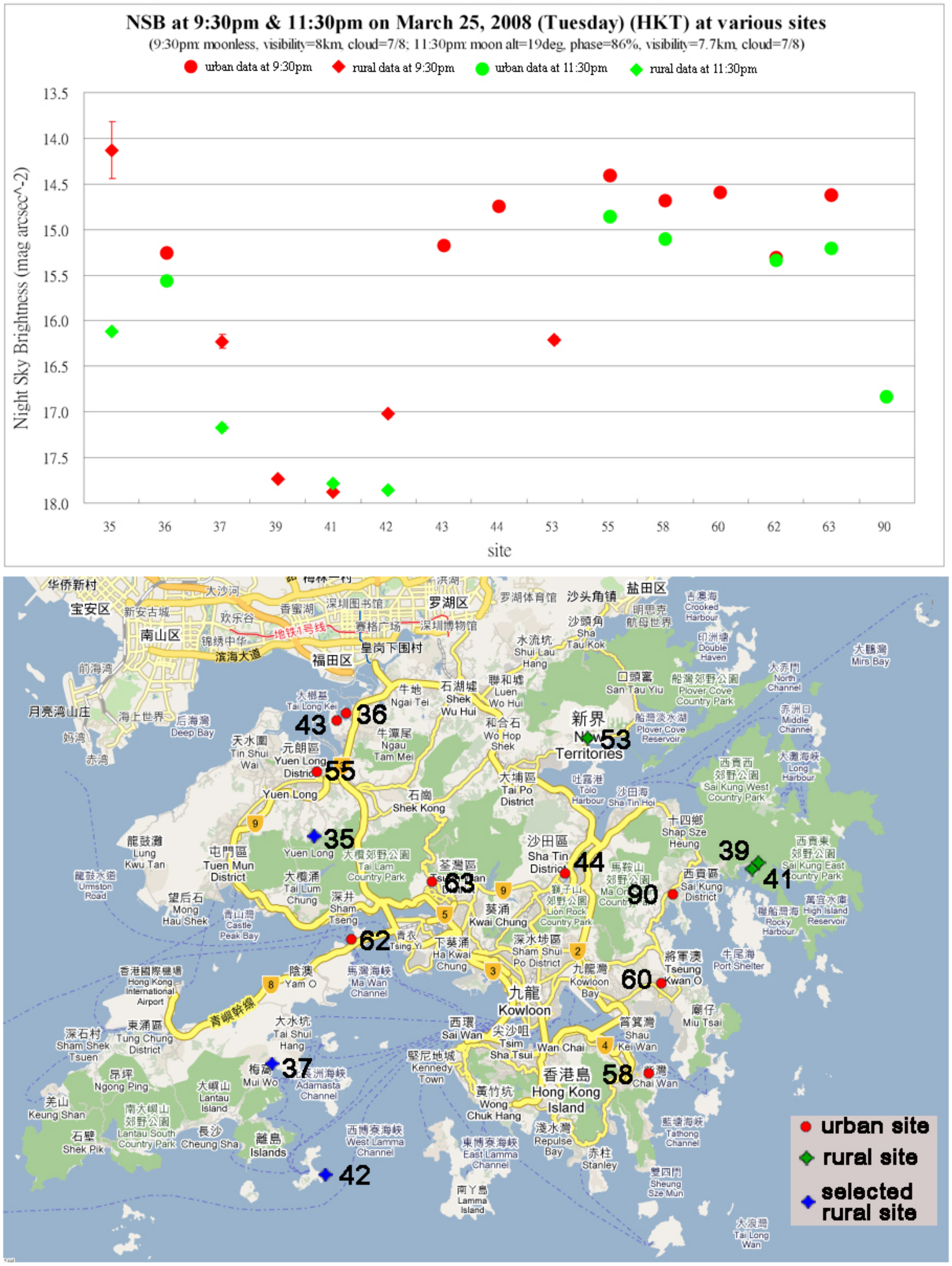

Fig. 10.— Snapshot survey of NSB in Hong Kong on 2008 March 25. Simultaneous NSB measurements taken at different observing sites are plotted in upper figure, with the exact locations of the sites shown in the lower figure. The data from urban and rural sites are represented with circle and diamond symbols respectively, with the NSB readings taken at 9:30pm and 11:30pm marked in red and green respectively in the upper figure.

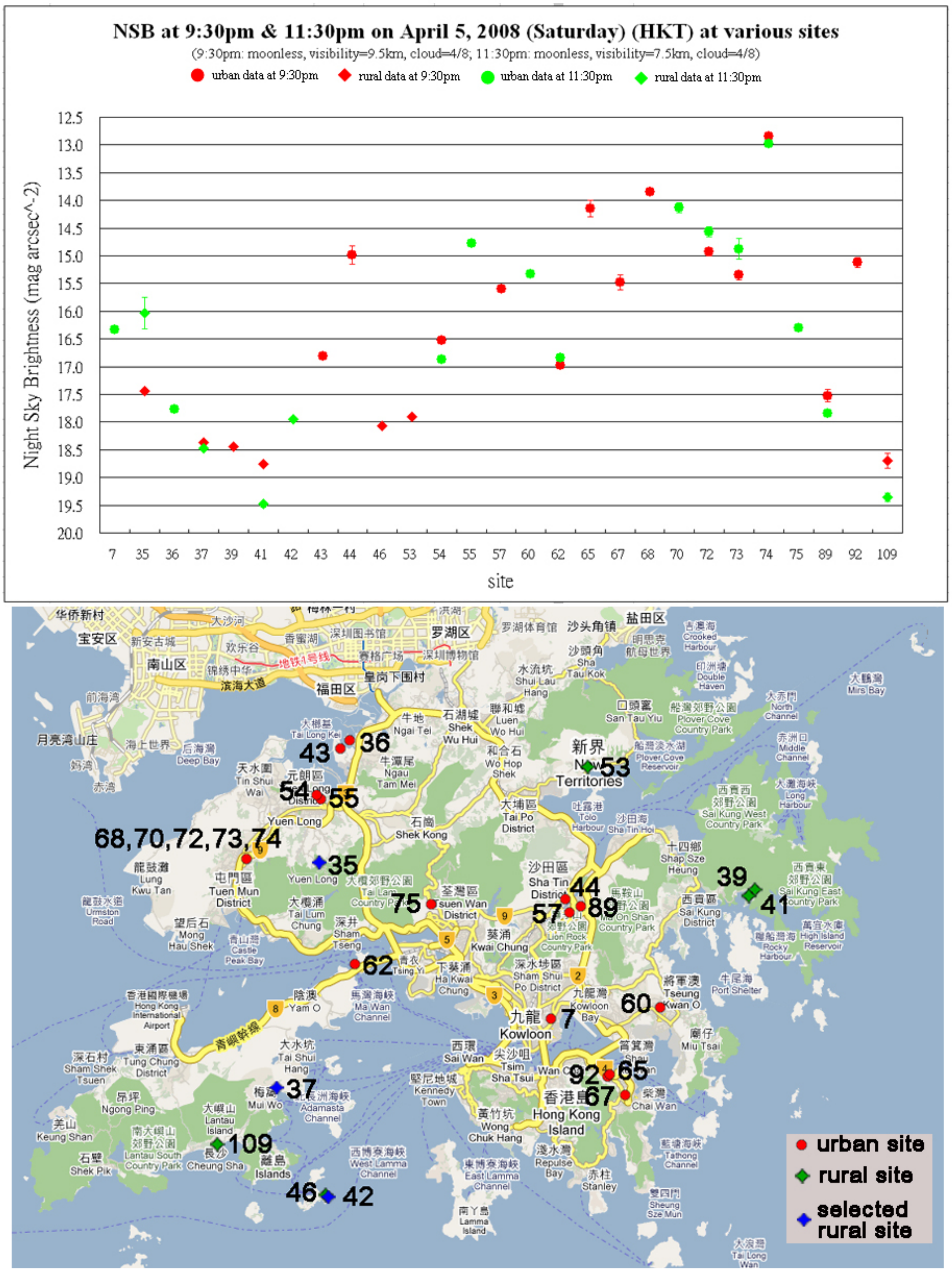

Fig. 11.— Same as Firgure 10, for the snapshot survey taken on 2008 April 5.

4.3. Time variation of night sky brightness

4.3.1. Observing time

Another important factor that could affect the observed NSB was the observing time of the survey. The amount of data sets received in each month of the survey was shown in Figure 12. Apart from the few months (2008 June and 2009 January) when we collected the SQMs for calibration at the end of each phase of the survey and thus resulting in lower data report rates, we consistently received over 100 data sets each month throughout the entire duration of the survey.

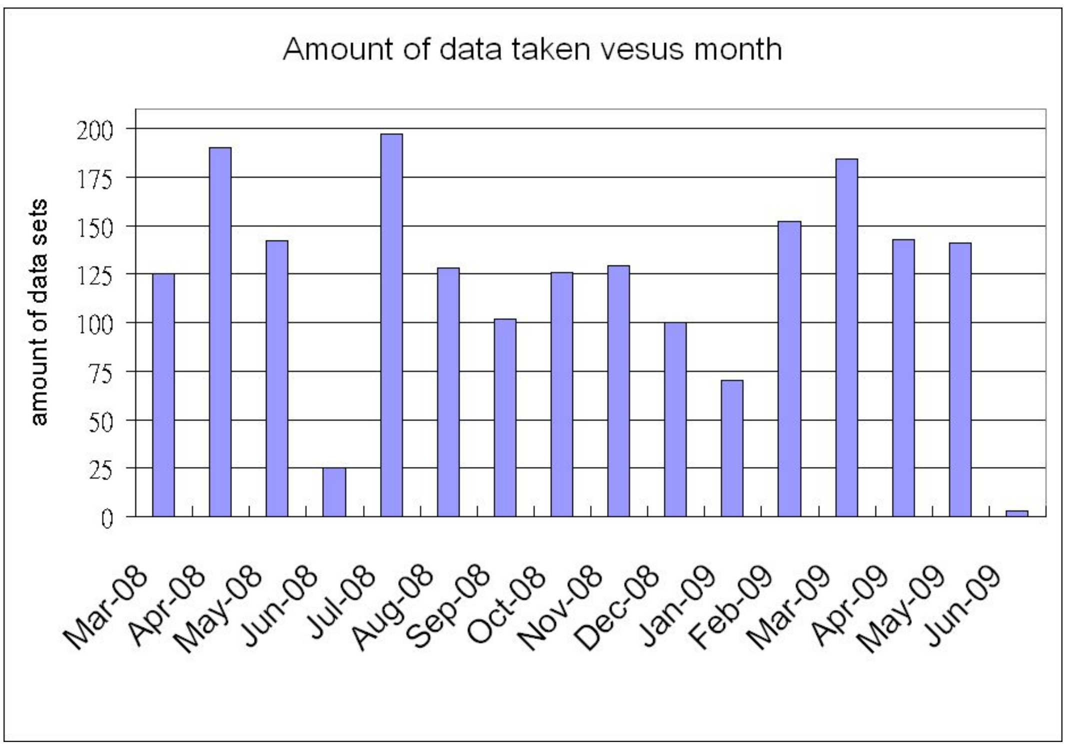

Fig. 12.— Amount of data sets taken versus month.

As discussed in Section 3.1.1, the survey volunteers were encouraged to make observations at the designated *Survey Time* of 9:30pm and 11:30pm on the 5th, 10th, 15th, 20th, 25th, and (if available) 30th day of each month so that observations taken under similar conditions can be compared. Of the 1,957 data sets collected, 1,023 (52.3%) were indeed taken at the specified *Survey Time*. Within that data subset, the ratio between the number of data sets taken at 9:30pm and 11:30pm time slots was 1.32:1, reflecting the lower data collection during late hours from the student participants. For the data set not taken at the specified *Survey Time*, the observation time ranged from 6:30pm to 7:30am. Even though a small portion of NSB results could be taken too close to the sunset and sunrise hours of the day, we did not remove any data from our analysis for completeness of the survey.

The NSB of Hong Kong at 9:30pm averaged from 766 sets of data (include urban and rural sites) was found to be 16.1 mag arcsec^{-2}, while the average NSB at 11:30pm from 605 data sets was 16.7 mag arcsec^{-2}, implying a difference of 0.6 mag arcsec^{-2}. On the other hand, the respective numbers for urban-only and rural-only sites were 0.1 and 1.1 mag arcsec^{-2} respectively, corresponding to the averaged 9:30pm night sky to be 1.1 and 2.8 times brighter in 9:30pm than 11:30pm in terms of light intensity. The small difference between the NSB measured at the two specified time for the urban sites is probably due to the many public and private lightings that remained lit up in the city at 11:30pm. On the other hand, it is encouraging to learn that in the rural areas, the larger contrast of observed NSB readings between 9:30pm and 11:30pm could probably be due to more external lightings being turned off in later evenings.

4.3.2. Long-term variation of night sky brightness at selected sites

One objective of this 15-month survey is to study the long-term variation of the NSB in Hong Kong. We selected three rural sites with the most pairs of NSB data taken at both 9:30pm and 11:30pm to investigate whether any seasonal variation of NSB could be detected. The three sites are site 35 (Po Leung Kuk Jockey Club Tai Tong Holiday Camp) in Yuen Long, site 37 (Hong Kong Playground Association Silvermine Bay Outdoor Recreation Camp) in Mui Woo, and site 42 (The Salvation Army Bradbury Camp) in Cheung Chau. Detailed information about these sites are tabulated in Table 4 while their geographic locations are indicated by blue diamond symbols in Figure 8. We interviewed the observers responsible for reporting the NSB data in each of these three sites and they confirmed that the lighting environments in the immediate vacinity of the observing sites, including the number of external lightings, lighting distributions, turn-on and turn-off time of lightings, and the lighting intensity did not significantly vary throughout the period of this survey.

The long-term variations of NSB over time for sites 35, 37, and 42 were plotted in Figures 13, 14, and 15 respectively. In these figures, the measured NSB at 9:30pm (red triangles) and 11:30pm (green squares) were shown separately, along with the survey-average NSB level of each site measured at 9:30pm (red dotted line) and 11:30pm (green dashed line) for comparison. The variations of NSB in all three sites over the entire survey period were found to be of the order of 3 to 4 mag arcsec^{-2}. As discussed above, these observations were taken under almost identical artificial lighting environments at the same time in each day and were considered to be the most "identical" data sets in our entire survey. We believed the fluctuations could be due to the following factors:

- Meteorological and environmental factors such as temperature, humidity, haze condition, and air pollution. Seasonal variation of these factors could affect the observed NSB. These factors will be studied below in Section 4.4.
- Astronomical factors such as light from bright stars and planets. The most important factor would be the variation of moonlight due to varying moon phase within a month.
- Instrumental errors of SQMs or human errors, as suspected of the very bright night skies recorded at site 35 at the beginning of the survey (Figure 13).

Similar to the snapshot survey results in Section 4.2.3, we found the general trend of a darker night sky at 11:30pm than that of 9:30pm (71% of the time for site 35, 64% for site 37, and 73% for site 42). The darkening of NSB later in the evening should partly be due to the usual lighting practice of many public lights under the administration of the government: many of the high-intensity floodlights which contributed significantly to the NSB used in outdoor areas and public playgrounds were turned off at 11:00pm every night. Our study suggested that the light from outdoor lightings indeed contributed to the brightening of our night sky. This kind of study with a large amount of data collected at some seleced sites allowed for a detail study of the light pollution conditions. Finally, while the NSB readings taken at one single site were taken under almost identical conditions, the environment around each of the three sites could be quite different from each other. The night sky measured in site 35 was generally brighter than the other two sites, probably due to its relative proximity to developed areas and the flat landscape nearby in Yuen Long.

Table 4. Details on sites selected for studying the time variation of NSB

Site ID	Abbreviation	Latitude	Longitude	Data set pairs at 9:30pm and 11:30pm
35	Tai Tong Camp[a]	22°24’42"N	114°01’52"E	80
37	Silvermine Bay Camp[b]	22°16’23"N	114°00’12"E	70
42	Bradbury Camp[c]	22°12’20"N	114°02’17"E	41

[a]Data taken at an outdoor car park, lights from lamps were avoided.

[b]Data taken at an outdoor playground, some lightings turned off at 11:30pm.

[c]Data taken at the rooftop. Floodlights about 3 meters away turned off at 11:00pm.

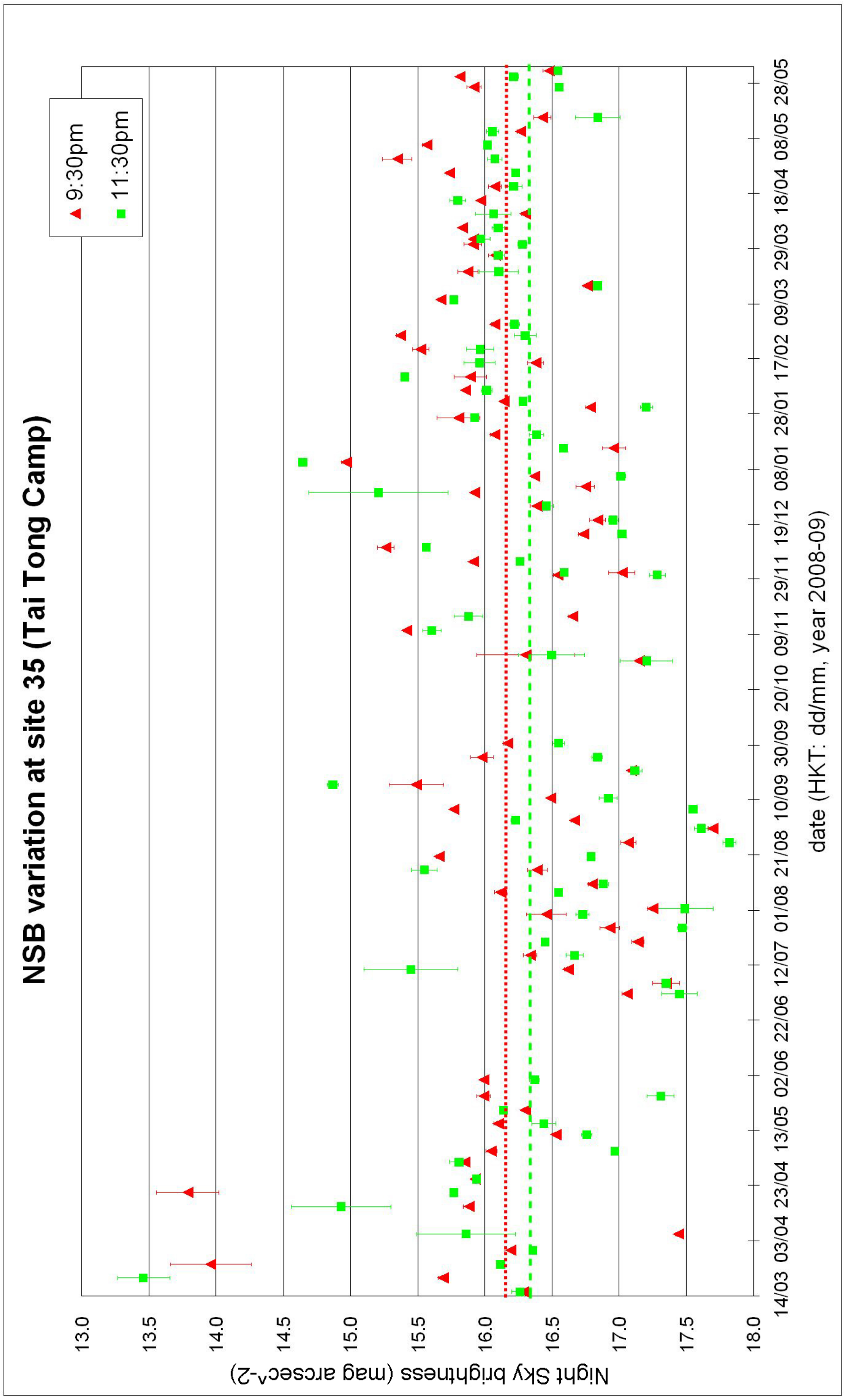

Fig. 13.— Time variation of NSB at site 35 (Tai Tong Camp, Yuen Long). The measured NSB at 9:30pm (red triangles) and 11:30pm (green squares) are shown separately. The survey-average NSB level at this site measured at 9:30pm (red dotted line) and 11:30pm (green dashed line) are also plotted for comparison.

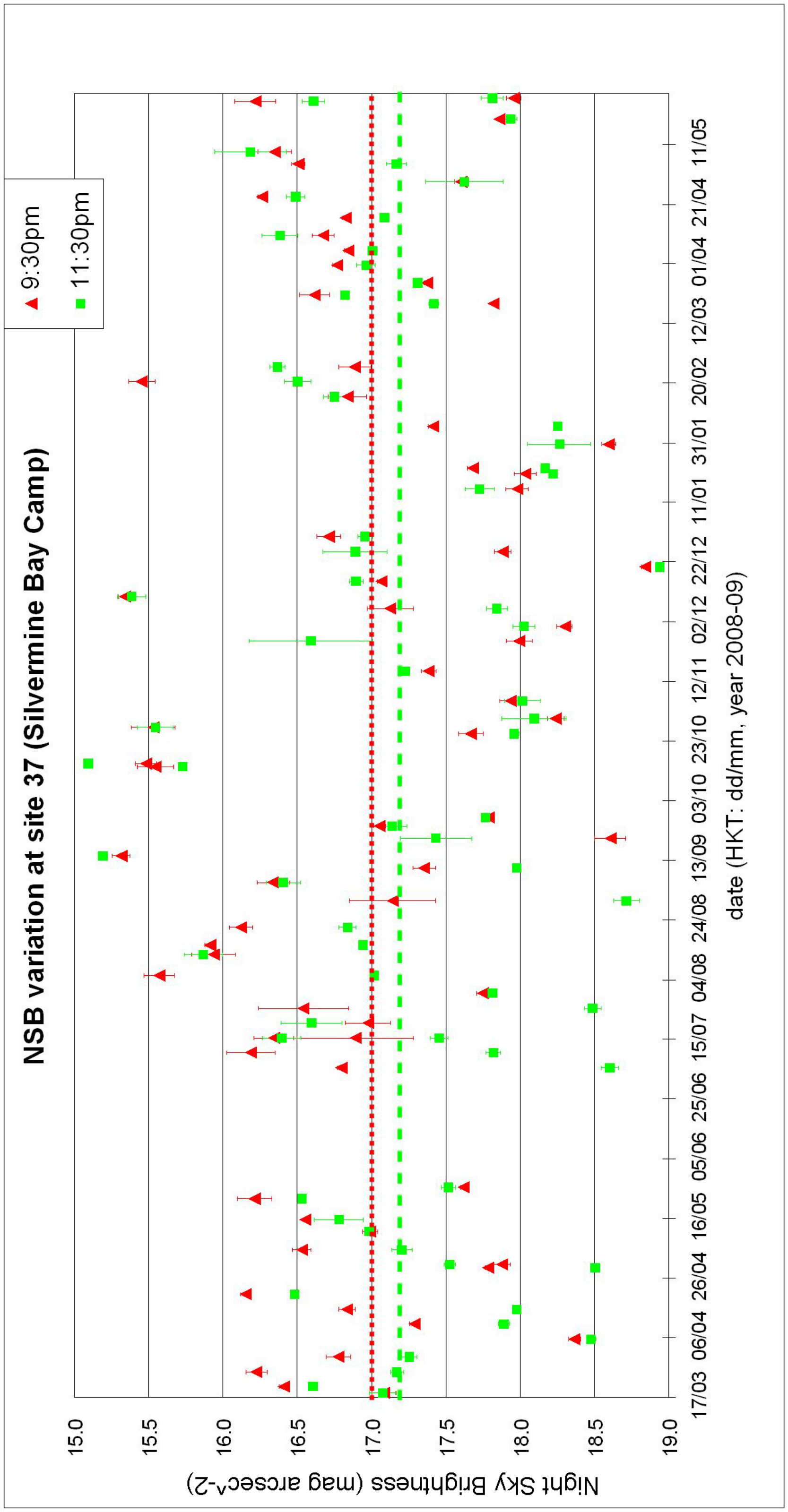

Fig. 14.— Same as Figure 13 for site 37 (Silvermine Bay Camp, Mui Woo).

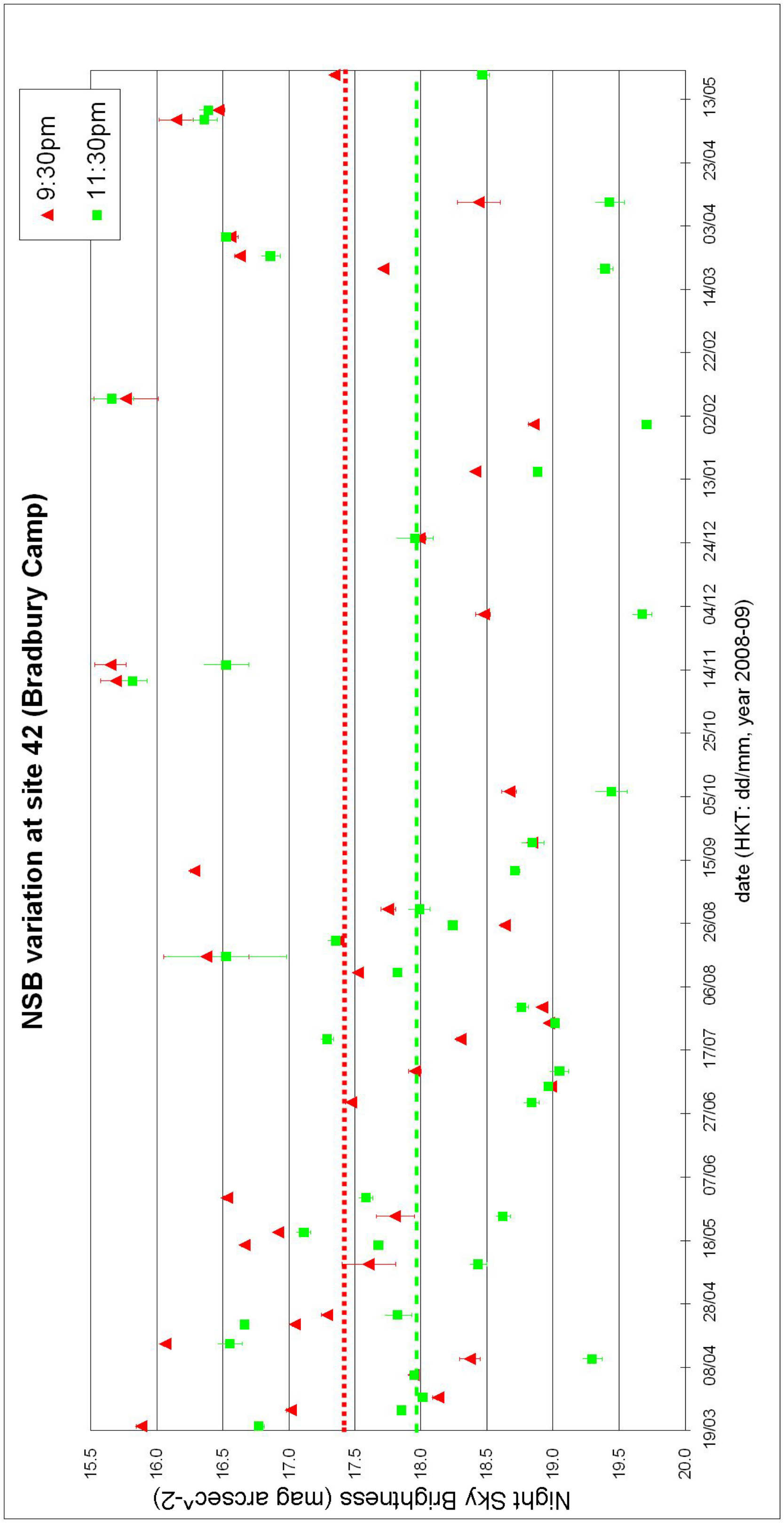

Fig. 15.— Same as Figure 13 for site 42 (Bradbury Camp, Cheung Chau).

4.4. Night sky brightness variation against meteorological and air quality factors

4.4.1. Cloud coverage

In our survey, the SQM measured the amount of light reaching its sensor from the night sky near the zenith. The amount of cloud present near the zenith could have an effect on the NSB measured as it could reflect and scatter the light originating from the Earth's surface, thus brightening the night sky. We tried to study the correlation between the measured NSB and the amount of cloud coverage. Even though we have asked the volunteering observers to estimate and report the amount of cloud presence, we decided at the end only to use data taken by experienced meteorologists of the HKO (cf Section 3.3). The major shortcoming of the HKO data was the limited geographical coverage to two locations: the HKO headquarter in Tsim Sha Tsui (HKOH), and the HK Airport station in Lantau Island (HKIA). We compared the NSB measured at the location nearest to either of these two stations, the Silvermine Bay Camp in Mui Woo, Lantau Island (site 37). NSB Data taken at 9:30pm and 11:30pm were plotted against the cloud coverage data (in *okta* scale, with 0 being completely clear sky and 8 being completely cloudy) measured at HKIA in Figure 16. Since the HKO cloud coverage data were taken every hour at the hour, we averaged the two values before and after the 9:30pm and 11:30pm observing time for comparison with the NSB measurements.

From Figure 16, no concrete relation between the observed NSB and cloud coverage could be established. One limit of this study was that the NSB and the cloud coverage data were not taken at the same place. Moreover, the overall cloud condition of the entire sky measured in the HKO data might not reflect the condition of the night sky directly above the zenith, of which the SQMs were sensitive to. Moreover, other natural factors such as moonlight that could affect the measured NSB were not considered in the comparison.

4.4.2. Visibility

Another factor that could affect the NSB measured is the visibility (or haziness) of the night sky. The presence of fog, mist, dust, and aerosol molecules in the atmosphere could reduce transparency of air and could scatter light originating from the Earth's surface, thus brightening the night sky. Similar to the cloud coverage study in the previous section, even though we asked the volunteering observers to estimate and report the amount of haziness, we decided to rely only on data taken by experienced meteorologists and visibility meters of

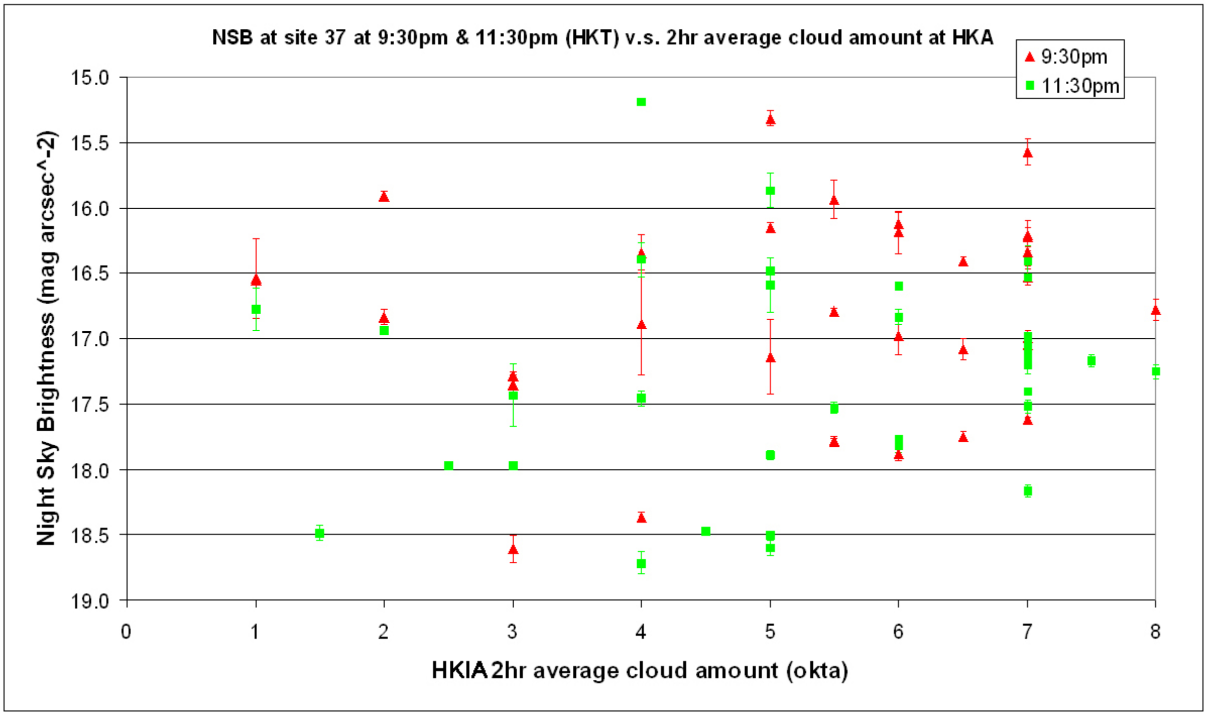

Fig. 16.— NSB at Silvermine Bay Camp (site 37) plotted against the cloud coverage measured at the HKO observation station at the airport (HKIA) between 2008 March 15 to 2008 September 30.

HKO (cf Section 3.3). Unfortunately, the visibility data were also only available in the same two locations as the cloud coverage. Therefore we decided to compare the NSB measured at the Silvermine Bay Camp in Mui Woo, Lantau Island (site 37) with the visibility values measured at HKIA in Figure 17. Similar to the cloud coverage data, the HKO visibility data were taken every hour at the hour and the two values before and after the 9:30pm and 11:30pm observing time were averaged for comparison with the NSB measurements.

Similar to the cloud content data, no concrete relation between the observed NSB and visibility could be established from Figure 17. This study was limited again by the different locations the NSB and the visibility data were taken. In addition, visibilities of the night sky were measured along the horizon and that might not reflect the actual transparency of the atmosphere directly above the zenith.

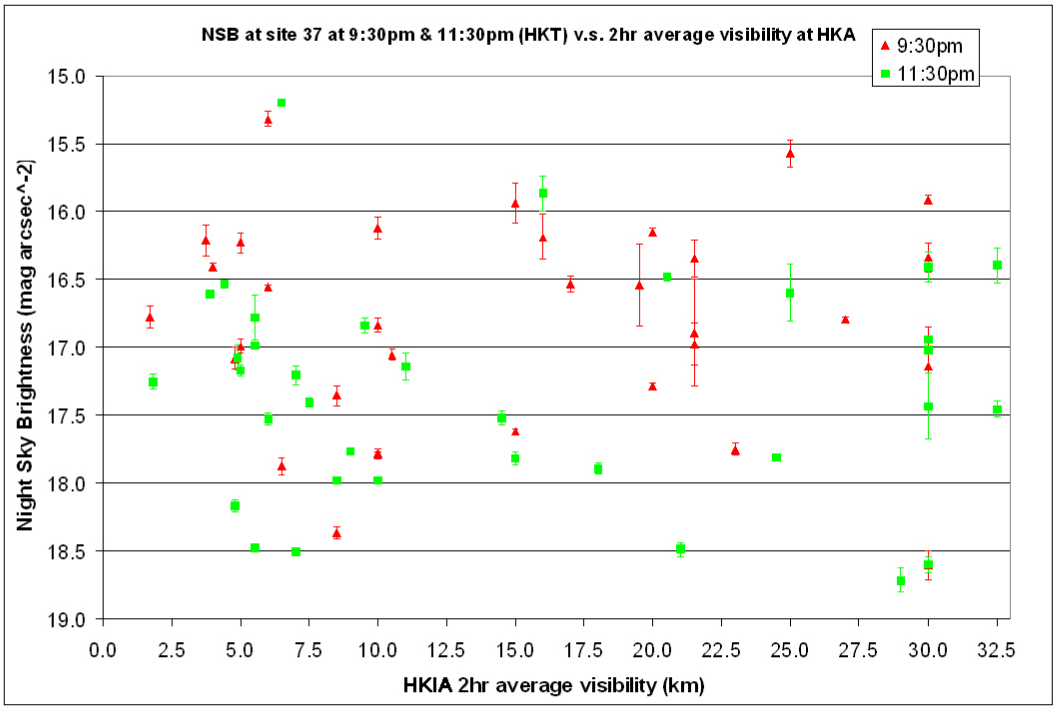

Fig. 17.— NSB at Silvermine Bay Camp (site 37) plotted against visibility measured at the HKO observation station at the airport (HKIA) between 2008 March 15 to 2008 September 30.

4.4.3. Air quality

The presence of air pollutants in the atmosphere, such as soot, aerosol molecules, and other particulates could have effects on the brightness of the night sky by the strong scattering properties of these atmospheric contaminants. Stray light from the ground directed upwards could have been scattered to all directions by these ingredients, thus spreading its effects to a wider region. It was not clear whether the scattering effects of these air pollutants had any effects on the NSB observed. To test this idea, we extracted the air quality data from two stations of the air quality monitoring network of the EPD, namely Yuen Long and Tung Chung, for comparison with the NSB data from site 35 (Tai Tong Camp, Yuen Long) and site 37 (Silvermine Bay Camp, Mui Woo) respectively. The data extracted included the API values, and concentrations of SO_2, RSP, nitrogen oxides (NO_x), NO_2, and CO. The measured values of NSB in sites 35 and 37 were plotted against the parameters from the EPD air monitoring stations at Yuen Long and Tung Chung in Figures 18 and 19 respectively. Similar to the cloud coverage data, the air quality data were taken every hour at the hour and the two values before and after the 9:30pm and 11:30pm observing time were averaged for comparison with the NSB measurements.

No concrete relation between the observed NSB and any of the 6 air quality parameters could be established for either of the sites. A limit of this survey was that the NSB brightness observing stations and the EPD air quality monitoring stations were a few kilometers apart. Moreover, the EPD air quality measurement stations were usually located not high above the ground level (usually fewer than 10m from the ground) and thus the parameters measured might not reflect the quality of the atmosphere directly above the zenith. Finally, the air quality data from the Tung Chung station could be abnormally affected by the nearby dense residential area and airport in Chek Lap Kok and thus could be quite different from the atmosphere at Mui Woo.

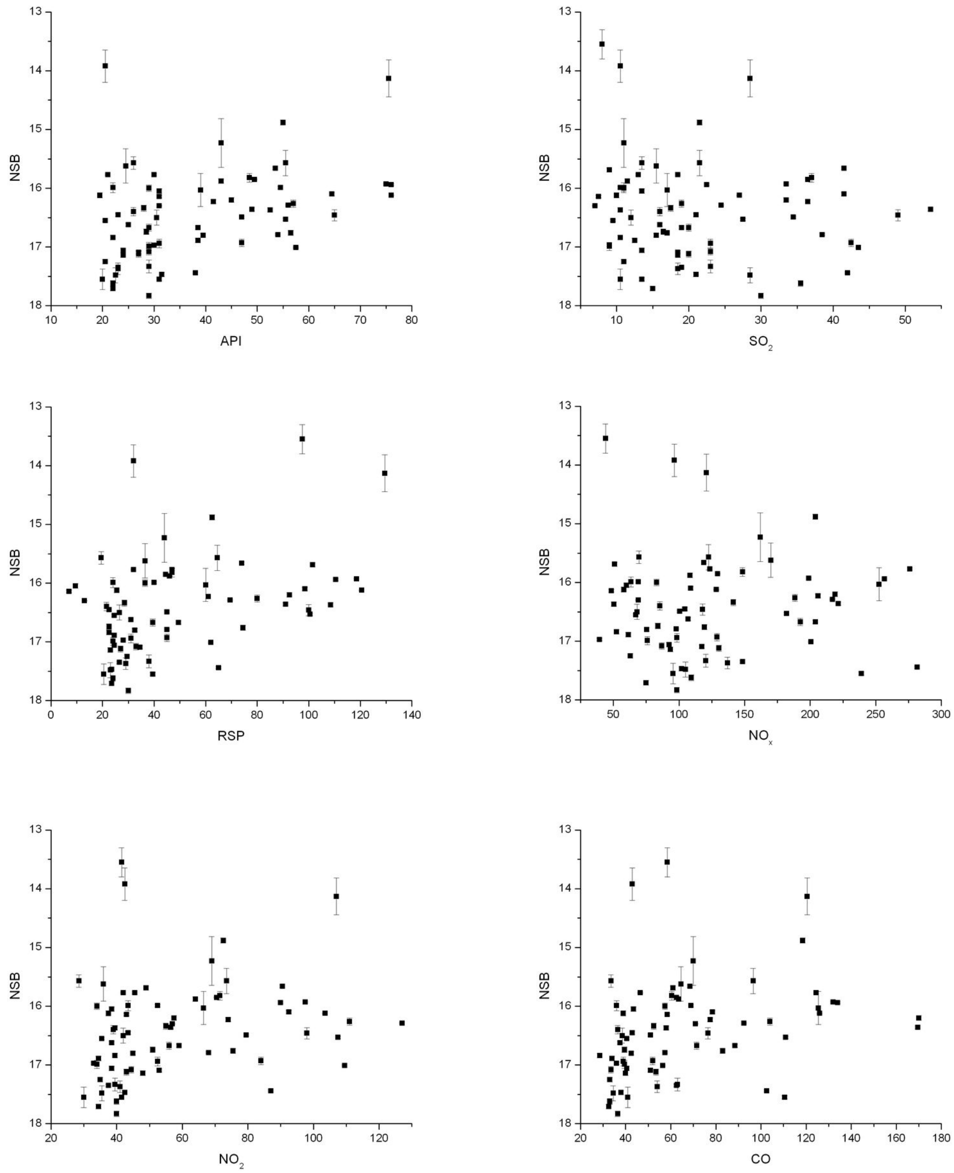

Fig. 18.— Night Sky Brightness (NSB) at site 35 (Tai Tong Camp, Yuen Long) in units of mag arcsec^{-2} plotted against the Air Pollution Index (API), and concentrations of sulphur dioxide (SO_2), respirable suspended particulate (RSP), nitrogen oxides (NO_x), nitrogen dioxide (NO_2), and carbon monoxide (CO) measured from the EPD air pollution observing station in Yuen Long. The concentrations are in units of μg m^{-3}, except for CO, which is in 10μg m^{-3}. The sampling period is 2008 March 15 to 2008 September 30.

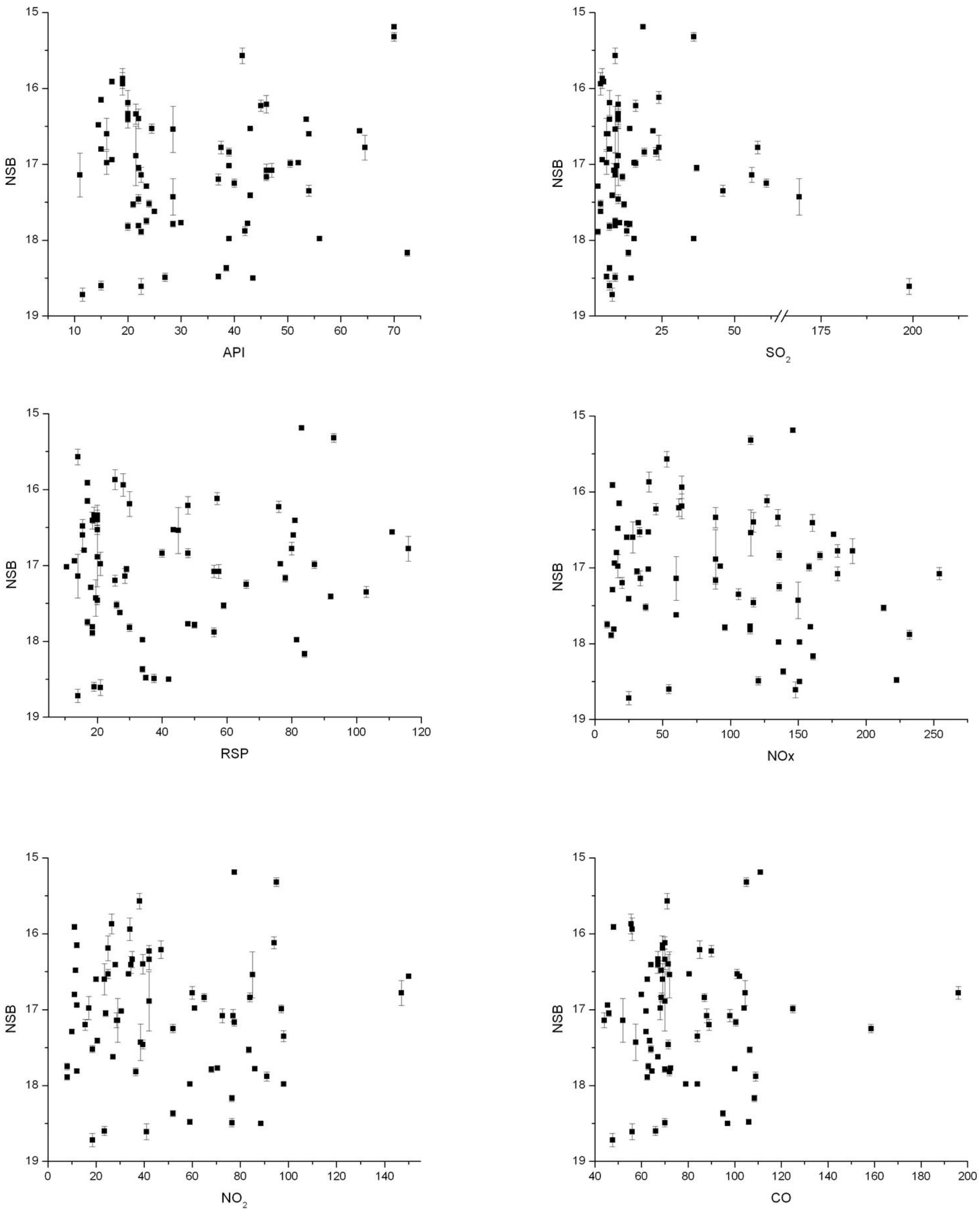

Fig. 19.— Similar as Figure 18 for NSB at site 37 (Silvermine Bay Camp, Mui Woo) plotted against air quality data measured from the EPD air pollution observing station in Tung Chung.

5. Conclusion

Light pollution poses negative impacts on our natural and our living environment, robs us of our night sky, and represents a waste of electric energy and hence contributes to the environmental degradations of the Earth. We conducted the first survey of the light pollution condition in Hong Kong by studying the night sky brightness (NSB) at different locations with a device called the Sky Quality Meter (SQM). Non-specialist volunteers who participated in the survey used these small and easy-to-use devices to take instantaneous readings of the NSB and reported the data online through the survey webpage. We included these volunteers not only to expand the geographical and time coverage of the survey, but also to educate the public on issues related to light pollution. During the 15 months of the survey, 171 participants contributed almost 2,000 data sets from over 199 distinct locations, allowing us to take first look at the overall situation of light pollution in Hong Kong and its variations with location, time, weather, and air quality. With the results, we put together a Hong Kong Light Pollution Map showing the distribution of the light pollution conditions in Hong Kong. The findings from the project would contribute to the overall environment of Hong Kong by promoting light pollution reduction and energy saving.

The survey shows that the light pollution in Hong Kong is severe — urban night skies were on average 100 times brighter than the darkest rural sites, indicating that high population and thus high lighting densities in dense urban areas could cause severe light pollution. In the worst polluted urban areas such as Wan Chai and Mong Kok, the night sky could be over 500 times brighter than the darkest sites in Hong Kong such as eastern Sai Kung and southern Lantau. The huge difference in the brightness of the night sky in urban and rural locations provides strong evidence to support for the development of regulations on the usage of external lightings in Hong Kong.

This survey also indicates that time is also an important determining factor of the night sky darkness. We found that the sky after 11pm to be on average darker than the sky before 11pm. The difference could be attributed to the turning off of the majority of public and private outdoor lighting throughout the city in late evenings. On the other hand, we could not identify any strong correlation between the measured NSB and meteorological factors (obtained from the Hong Kong Observatory, HKO) such as cloud coverage, air transparency, and air quality factors (obtained from the Environmental Protection Department, EPD) such as the Air Pollution Index and the concentrations of air pollutants. However, this conclusion should be taken with caution as the observations were taken at different sites and thus could affect the results.

While this survey provides a rough overall view of the situation, it is insufficient for a complete picture of the condition of the light pollution in Hong Kong. It is because while we advised our volunteering observers to make measurements every 5 days at 9:30pm and 11:30pm, only a handful actually followed the guideline closely to take data in all the prescribed time. Moreover, the goal of engaging more participants in the survey also meant that most only participated in part of the survey period and we only obtained a few sites with enough data for long-term studies. Moreover, as we advised our observers to take measurements near their home (for convenience and safety reasons), we received much less information at remote rural sites compared with the population centers. These factors prohibited us from making detailed studies of the geographical distribution of the night sky brightness at a particular time, the long-term temporal variations of the night sky brightness at a particular rural or urban location, and their relations with meteorological and other environmental factors. Furthermore, although we have arranged training sessions for all participants of the survey, human errors including improper use of the SQM, such as the SQM not pointing towards the zenith, and errors in reporting the data online, could affect the accuracy of the survey.

One possible method to comprehensively monitor the light pollution condition in Hong Kong is to deploy human-free automatic devices which can continually take data at high frequency in multiple locations all over Hong Kong. One such device is the updated version of the SQM, the Sky Quality Meter - Lens Ethernet, which can automatically measure and report the night sky brightness readings over the Internet. Data can be taken simultaneously at a much higher frequency at multiple locations. The readings can be reported to a central data center to generate a real-time map depicting the night sky condition in Hong Kong. This provides a platform to study the geographical variations and temporal characteristic of NSB against both natural and artificial factors in detail. It is only with this high data collection rate can we expect to perform a meaningful analysis with other environmental indicators such as meteorological and air pollution data. Furthermore, direct comparisons between the NSB data and other environmental parameters could be achieved if the NSB measuring stations were set up near existing weather stations of the HKO or the air pollution monitoring stations of the EPD. It is only with these data can we expect for a detailed comparison of our observations with the theoretical model of night time cloud brightness over a city (Garstang 2006), and the model predicting the relation between NSB observed and the concentration of dust and aerosols in the atmosphere (Garstang 1991).

The huge difference in the brightness of the night sky in urban and rural locations as seen in our current survey provides strong support for the development of regulations on the usage of external lightings in Hong Kong. Dark sky friendly outdoor light housings with *full-cut-off* designs which reflect light totally downward should be required for use by government and promoted for the general public. Better design of light shielding not only reduces light pollution by avoiding direct uplight effectively, but also means reduction of electrical energy consumption since we can apply light bulbs with lower power while achieving the same light intensity. Moreover, regulations for turn-off time, pointing direction, and timing-pattern (no rapidly flashing lights) of external lightings can also contribute to relieve the problem. Results from a more comprehensive survey can serve as an important database for consideration by the authorities in drafting the detailed rules and regulations. A full understanding of the existing condition is essential for the society in devising effective mechanisms to control the problem of light pollution in Hong Kong. In particular, special focus should be placed on the preservation of the night sky in rural areas. Ideas such as the establishment of *Night Sky Preservation Regions* should be considered.

6. Acknowledgements

We would like to thank all the 171 volunteering participants who have contributed data to our project. Each participant has been issued a *Certificate of Appreciation*. In particular, we would like to thank the following organizations who have contributed the highest number of reports (in alphabetical order):

- Chinese YMCA Wu Kwai Sha Youth Village
- Hong Kong Playground Association Silvermine Bay Outdoor Recreation Camp
- Po Leung Kuk Jockey Club Tai Tong Holiday Camp
- Po Leung Kuk Pak Tam Chung Holiday Camp
- The Salvation Army Bradbury Camp
- The Salvation Army Ma Wan Youth Camp

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- Chan Chi Man (Ling Liang Church E Wun Secondary School)
- Chan Kam Yuen (Po Leung Kuk Tong Nai Kan College)

- Cheng Wai Luen (Lui Cheung Kwong Lutheran College)
- Leung Chi Kong (Christian Alliance S W Chan Memorial College)

These participants have been issued the *Best Participation Award* which comes with a award statue and a letter of appreciation. Without great efforts of all the participants, we would not have been able to complete this first survey of the night sky of Hong Kong.

A. Procedures for data taking and reporting for observers

香港光害調查
A Survey of Light Pollution in Hong Kong

夜空光度測量指引

09 年 1 月

謝謝您參與本調查！為了使收集得來的數據可以互相比較，請細閱以下指引：

一) 擇吉時

在每月的 5、10、15、20、25 及 30 日，晚上 9:30 及 11:30(其他日子及時間亦可)，如配合下列條件，便可進行測量：

- ✓ 觀測地點安全(深夜出外要特別留意)。
- ✓ 沒有下雨、颱風訊號或雷暴警告等沒有生效。
- ✓ 在多雲或有月光的晚上都可以進行夜空光度測量。
- ✓ 測量時間應避免接近日落後、或日出前的短時間內，當時天空仍被陽光照亮(建議在黃昏曙暮光(twilight)完結後至少兩小時，或黎明曙暮光出現前至少兩小時進行測量。香港的日出日落時間，及各月份曙暮光的持續時間可參考香港天文台的網頁：http://www.hko.gov.hk/gts/astron2009/sunrise_main_c.htm, http://www.hko.gov.hk/gts/astron2009/twilight_c.htm)

二) 擇吉地

- ✓ 在您附近盡可能選擇一個黑暗及視野廣闊的觀測地點(如建築物天台、公園、球場等)。
- ✓ 避免觀測地點附近有街燈、大廈室外照明、停車場照明、球場照明、光管廣告招牌等人為光源。 **(例如請勿在街燈下收集夜空光度讀數)**
- ✓ 如附近有街燈等照明，觀測地點應遠離個別光源約十米，**以免這些人為光源影響夜空光度測量錶(SQM)的觀測結果**。

三) 使用夜空光度測量錶(SQM)

- 如發覺 SQM 紅色一面的膠片有污漬，請先用乾淨的紙巾輕輕抹走污漬。

1. 選擇了合適的時間和觀測地點後，手持 SQM 在頭頂附近位置，將紅色的一面向正天頂，SQM 需保持垂直(如圖示)。
2. 留意用作書寫照明的電筒光線不要照到 SQM 紅色的一面，及避免自己身體、附近樹木、建築物等的影子投影在 SQM 紅色的一面。
3. 保持姿態，按下 SQM 側面的紅色按鈕一次，直到「嘟」聲完結(約一至三秒)。
4. 記錄紅色一面顯示的讀數(兩個小數位)。
5. 在讀數消失之前，再按一下紅色按鈕，記錄顯示的溫度。
6. 重覆以上各點，每次收集五組夜空光度讀數及一組溫度讀數。
7. 請在數據收集後一星期內上傳(參考下文)。

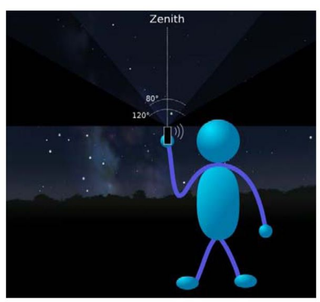
四) 上傳讀數

1. 利用您登記了的電郵地址及密碼，登入http://nightsky.physics.hku.hk。
2. 如觀測地點並未事先登記，請登記您的觀測地點，方法如下：

   i. 在左面的目錄，選擇**設定**下的**觀測地點**，再選擇右面版面的**新增觀測地點**。
   ii. 填上相關資料，包括上傳觀測地點的日間及晚間相片，資料請盡量詳細說明(**地點名稱**一項可輸入方便自己辨認的觀測地點名稱，**分區**一項參考十八區區議會選區分界：http://www.elections.gov.hk/dc2007/chi/ebmaps.html)。
   iii. 完成後按**新增觀測地點**。
   - 觀測地點資料將會總結在**顯示所有觀測地點**內，您可隨時增加或更新這些資料。
   - 每個不同的觀測地點只需登記一次。

3. 在左面的目錄，選擇**SQM 報告**下的**遞交SQM報告**，輸入相關資料，包括**觀測日期**、**觀測開始時間**、**觀測地點**、憑您判斷測量時的**雲量**及天空的**煙霞情況**，和**SQM機身編號**(編號貼在機背上)。
4. 輸入五組 SQM 顯示的夜空光度讀數、及一組 SQM 顯示的溫度。
5. 如資料正確無誤，按**確定及遞交**遞交數據。網頁將會顯示**你的SQM報告已上傳了**確認。

- 如您有更多數據上傳，可重覆以上步驟。
- 您亦可選擇**SQM報告**下的**查閱SQM報告**，查閱或修改你上傳了的報告。



圖片來源：http://unihedron.com/projects/darksky/holding.php

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Environment and Conservation Fund
The Government of the Hong Kong Special Administrative Region
香 港 大 學
THE UNIVERSITY OF HONG KONG

B. Data report sheet for observers

Environment and Conservation Fund
The Government of the Hong Kong Special Administrative Region

香港光害調查 (SQM 數據紀錄紙)

香 港 大 學
THE UNIVERSITY OF HONG KONG

日期	時間	地點	雲量(佔百分比)	煙霞情況(能見度)	SQM 編號	讀數 1	讀數 2	讀數 3	讀數 4	讀數 5	溫度	備註	已上傳?
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									

日期	時間	地點	雲量(佔百分比)	煙霞情況(能見度)	SQM 編號	讀數 1	讀數 2	讀數 3	讀數 4	讀數 5	溫度	備註	已上傳?
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									
			100 / 75 / 50 / 25 / 0	煙霞重 / 有煙霞 / 沒有煙霞									

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