Quantification of the artificial airglow over Stockholm

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January 15, 2016

Up to now, astronomers have mainly been measuring the brightness of the night sky (in magnitudes/arcsec^2) at dark sites, especially at modern mountain observatories, or at potential observatory sites as a part of "site-testing" and "site-monitoring". Within the past few years, it has become evident that increasing night sky brightness and light pollution have far-reaching consequences for many branches of human life as well as wildlife. Therefore, it is desirable to measure and monitor the night sky brightness not only at remote mountaintop observatory locations, but also close to the centers of modern civilization, and to do so every night, in a reproducible way, with the aim of performing long-term studies (such as in climate research). Only in this way can the impact of night sky brightness on biological rhythms on animal behaviour, and human health be assessed. This is the aim of ongoing night sky brightness measurements in Stockholm at the Albanova University Center. In this article, I first recap a few aspects of how light pollution acts onto our ecosystem as well as the human body and then show the variability of the night sky brightness in Stockholm and how it compares to Vienna, the capital of Austria.

Impact of Light Pollution on the Ecosystem

Many aspects of how light pollution affects our ecological system have been addressed in a previous article by Henrik Sandgren (see PopAst issue 02/2014), who e.g. explains the deathly impact of street lighting for insects caused by the attraction of the illuminant: insects start circling around the light source and finally die due to exhaustion. Eisenbeis et al. (2006) have used insect traps to count moths around lights and compared their results to previous ones. The authors find that the current number has decreased to a 10-percent level compared to measurements performed in 1949. Having in mind that 2/3 of all protein consumed on our planet come from insects, it seems likely that this already led and will lead to drastic consequences for the whole ecosystem.

It is known that light cones produced by "skybeamers", visible up to tens of kilometers, cause disorientation of migratory birds. The birds start circling around the light cones and subsequently die of exhaustion. Luckily, the use of skybeamers is increasingly restricted in many parts all over Europe, for example Upper Austria – one of the leading states in Austria in terms of industry, exports and technology – has recently published a guideline[1] that clearly disapproves the use of skybeamers and also the city of Berlin has agreed to resign the use of skybeamers and laser shows during periods of bird migration when the annual event "Berlin leuchtet" takes place [2]. However, no or little regulations seem to be made in Sweden, where skybeamers can still be found at various locations.

Impact of Light Pollution on the Circadian Rhythm

The multi-disciplinary field of research in light pollution is rapidly growing [3] and although yet only little is known about the impact of light pollution on the huge variety of existing species, it is becoming evident that light at night has also negative influence on humans. In particular, blue light stimulates the so called *intrinsically photosensitive retinal ganglion cells* (ipRGCs) which play a major role in synchronizing circadian rhythms to the 24-hour light/dark cycle, providing primarily length-of-day and length-of-night information. As a result, exposure to blue light late at night can cause circadian sleep disorders or may even enhance the risk of breast cancer, which is suggested by a recent Swedish study published by Akerstedt et al. (2015), who find that working at night for more than ~20 years is associated with an increased risk of breast cancer in women. An attached diagram shows the sensitivity curves of three different receptors found in the human eye: the cones (responsible for day-vision), the rods (night vision)

[1] `http://www.land-oberoesterreich.gv.at/files/publikationen/us_besseresLicht2013_leitfaden.pdf`
[2] `www.stiftung-naturschutz.de/fileadmin/img/pdf/Kleine_Anfragen/S17-17317.pdf`
[3] visit "Artificial Light at Night Research Literature Database" at `http://ida.darksky.org/refbase/` to find out more

Figure 1: Skybeamer near Kungsbacka

and the ipRGCs (responsible for the regulation of the circadian rhythm). The latter ones are mostly sensitive to light with a high fraction of blue light, or equivalent light of cool colors with a high color temperature. Thereby, the color temperature is stated in the absolute temperature unit given in “Kelvin” (K). Consequently, the use of blueish white light with color temperatures above approximately 3000 K should be avoided at late hours.

Measurement Campaigns

My involvement in light pollution research started end of 2011 as a student at the University observatory in Vienna, where I met PD DDr. Thomas Posch, a leading expert in the field and author of the textbook “Das Ende der Nacht”. He soon became my mentor and with his initiative we started to perform night sky brightness measurements in and around Vienna using “Sky Quality Meters” (SQMs). In 2013, after one year of continuous operation we decided to analyze our data to study the influence of the moon, clouds and other environmental effects on the night sky brightness[4]. One year later, I was thankfully provided with measurements obtained by researchers at the Leibniz Institute for Astrophysics in Potsdam. That enabled me for the first time to compare night sky brightness variations in two major European cities[5]. By end of 2013 I moved to Stockholm, where I am currently doing my PhD in extragalactic Astrophysics. Luckily, with Magnus Näslund and others, I found support to continue the work on light pollution in Stockholm. Funded by the “Alva and Lennart Dahlmark research grant”, a SQM was acquired in 2014 and since December of the same year we are continuously monitoring the night sky brightness from the roof of the Albanova University Center at a sampling rate of 8 measurements per minute.

SQMs yield data in a unit which is very widespread in astronomy, namely magnitudes per square arcsecond (mag/arcsec^2). This unit corresponds to a luminance, but is a logarithmic measure derived from stellar photometry, where larger values correspond to fainter objects. In the same way, larger NSB values in mag/arcsec^2 indicate darker skies (with less light pollution). Equation (1) gives the conversion from mag arcsec^{-2} to cd m^{-2} and Table 1 lists selected pairs of corresponding values.

$$\text{Luminance}\ [\mathrm{cd/m^2}] = 10.8 \times 10^4 \times 10^{(-0.4\,\times\,[\mathrm{mag arcsec^{-2}}])} \tag{1}$$

[4]Puschnig et al. (2014a)
[5]Puschnig et al. (2014b)

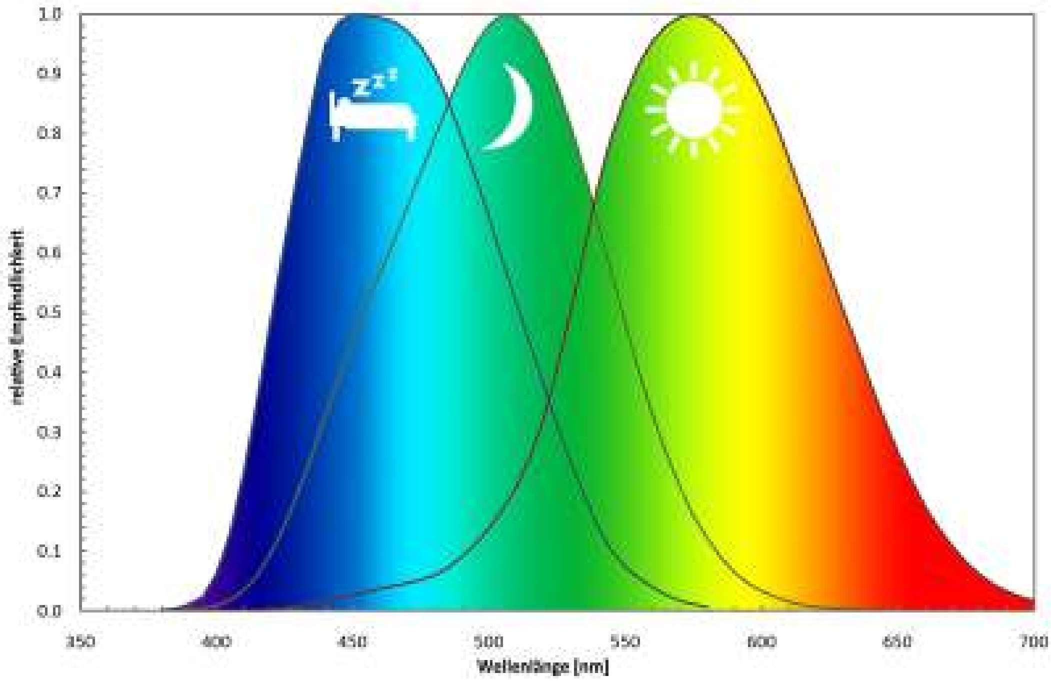

Figure 2: Normalized sensitivity curves of the *cones* responsible for day-vision (right), the *rods* (middle) used for night vision and the *intrinsically photosensitive retinal ganglion cells* that regulate the circadian rhythm (left). The latter ones are mostly sensitive to light with a high fraction of blue light, as fond in cold-white and neutral-white bulbs with a typical color temperatures above 3000 K.

Figure 3: Sky Quality Meter mounted at the roof of Albanova University Center in Stockholm

Table 1: Conversions between mag arcsec^{-2} and millicd m^{-2}.

mag/arcsec^2	millicd m^{-2}		mag/arcsec^2	millicd m^{-2}
14	271		19	2.71
15	108		20	1.08
16	43.0		21	0.430
17	17.1		21.75[6]	0.215
18	6.81		22.0[7]	0.172

It should be noted that all our measurements refer to “scattered light”. We measure only brightness values of the “sky background”, while we explictily avoid to measure any direct radiation from streetlamps. This is what we call “night sky brightness” (NSB). In other words: the brightness values presented here refer to the total backscattered light of the night sky. Its origin is the whole ensemble of streetlamps, facade illuminations, illuminated billboards etc. at the respective observing site and in its near and far surroundings. The natural nocturnal radiation from the Earth’s atmosphere, which is produced by different processes such as recombinations of atoms that have been ionized by the sun’s radiation during daytime, contributes very little to the light that we measure at our observing sites, since the latter is dominated by the influence of artificial light.

Natural Circalunar Rhythm

Our measurements meanwhile cover a period of one year. We were therefore interested in the behavior of the *mean* night sky brightness over Stockholm during this period. At a site without light pollution, a strong influence of the lunar phase on the NSB is expected: full moon nights should be recognizable by much brighter night skies, especially for clear sky conditions. In contrast, nights around new moon should be much darker. The NSB data from Stockholm show a completely different picture. Instead of the moon, the degree of cloudiness has the strongest influence on the NSB in Stockholm. The more clouds over a big city, the stronger the backscattering of urban light. Of course, the degree of cloudiness does not follow any strict periodicity. Therefore, the mean NSB measured in Stockholm seems to vary in a stochastic way. The circalunar rhythm is barely recognizable.

Range of NSB Values

The NSB we measure varies within a large range. The darkest clear nights are characterized by a NSB slightly above (= darker than) 18.6 mag$_{SQM}$ arcsec^{-2}(see top panel of Figure 5), corresponding to a zenithal luminance of 3.9 millicd m^{-2}, whereas under overcast conditions the NSB can be even lower than (= brighter than) 14.5 mag$_{SQM}$ arcsec^{-2}, corresponding to a zenithal luminance of more than 170 millicd m^{-2}(a value that can easily be measured even with a simple luminance meter). Not all NSB values occur equally often. Based on more than one million individual measurements, we find two brightness levels that occur much more often than others: one is 18.1–18.7 mag$_{SQM}$ arcsec^{-2} which is characteristic for clear skies (no clouds, little aerosol content of the air, relatively little amount of backscattering). The other range of frequently occurring NSBs is about 15.2–15.4 mag$_{SQM}$ arcsec^{-2}and is related to completely overcast conditions. The mid values of the two ranges differ by about a factor 17. Intermediate values ranging between ~15.5 and 18 mag$_{SQM}$ arcsec^{-2} are typically measured when the sky is partly cloudy, or cloudless but hazy, or clear but not moonless.

Seasonal Variations and Auroral Activity

During winter, when snow covers roofs and streets of the city, the increased albedo (reflection coefficient) leads to a typically brighter NSB, especially in the presence of the moon. Yet, due to lack of sufficient data, we cannot disentangle both contributors, but we find a maximum “amplification” of the NSB up to ~1.2 mag$_{SQM}$ arcsec^{-2} with both full moon and snow cover. Between 20th of April and 10th of August, the NSB is regulated by the solar elevation and from September to November the darkest mean NSB values were measured with values down to 18.7 mag$_{SQM}$ arcsec^{-2}.

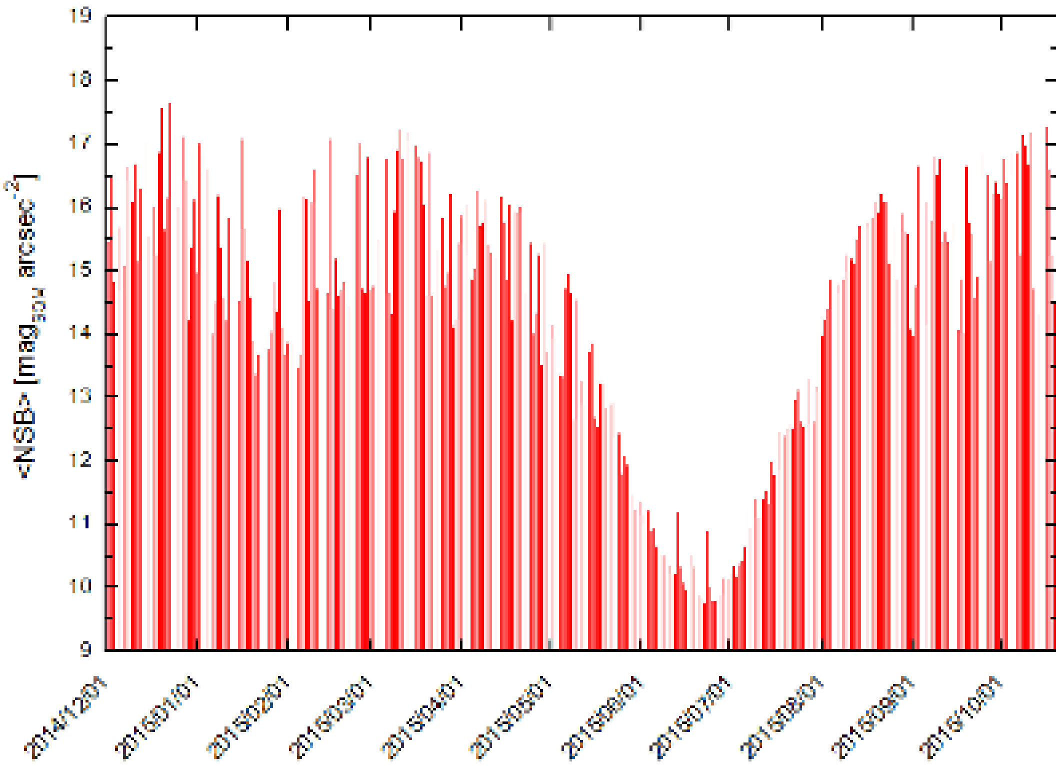

Figure 4: Mean NSB in Stockholm calculated from data taken after the end and before the beginning of civil twilight (range when the sun is more than 6 degrees below the horizon). The circalunar rhythm is barely recognizable.

On March 17th, 2015 a particularly strong auroral activity was visible from all over Sweden. Our photometric measurements during clear and moonless hours reveal an increase of the NSB of up to 1.1 $\mathrm{mag_{SQM}}$ arcsec^{-2} caused by the aurora.

Milkyway, Andromeda visibility and Limiting Magnitude

The zenithal NSB values in Stockholm reach approximately 18.7 $\mathrm{mag_{SQM}}$ arcsec^{-2}, at best. This corresponds to a "naked eye limiting magnitude" (the magnitude of the faintest star visible to the naked eye) of 4.5 mag. As a result, the number of stars seen under best conditions in Stockholm has already decreased to a 10–20 percent level compared to skies without light pollution. The situation worsens for extended objects such as our Milky Way or the Andromeda galaxy (M31). The latter one is clearly out of reach for the naked eye. As a consequence, the volume one can overlook from Stockholm is limited by the faintest stars with distances up to a few thousand light years, whereas without light pollution one could see as far as 2.5 million light years when gazing at M31, our neighboring galaxy. What about the Milky Way? With a zenithal NSB of 18.7 $\mathrm{mag_{SQM}}$ arcsec^{-2}under best conditions in Stockholm, the surface brightness for Milky Way visibility is exceed by ~0.2 $\mathrm{mag_{SQM}}$ arcsec^{-2}and the Milky Way cannot be recognized from Stockholm without any further equipment.

Comparison to Measurements performed at the Vienna University Observatory, Austria

Measurements of the zenithal night sky brightness are performed in both cities, Vienna and Stockholm, using SQMs. The devices are located at a similar distance of ~3km to the city centers. According to the 2012 statistics published by the OECD, the population of the metropolitan areas are 2.7 and 2.0 million inhabitants in Vienna and Stockholm respectively with a much higher population density in Vienna or equivalent a larger area of Stockholm.

For our comparison, we count the relative (normalized) number of measurements found within brightness intervals of 0.05 $\mathrm{mag_{SQM}}$ arcsec^{-2}and time ranges of 10 minutes and visualize the number density encoded with color. We create such "density plots" for Stockholm and Vienna to quantify the current levels of light pollution and find noticeable features or peculiarities. The results are quite surprising: moonless, clear nights in Stockholm are found to

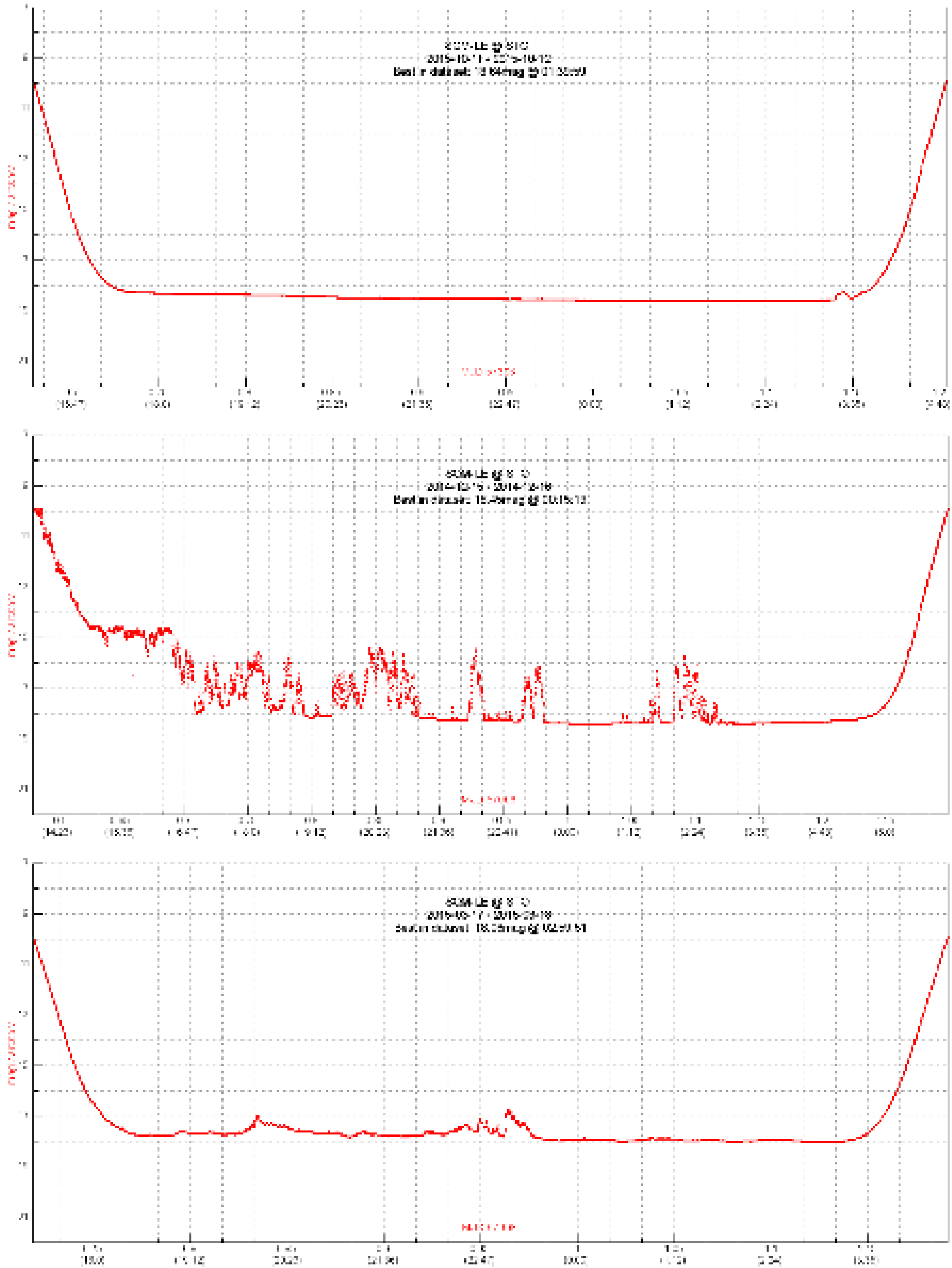

Figure 5: *Top panel:* Darkest skies are found during clear nights (no clouds, little aerosol content of the air, relatively little amount of backscattering). *Mid panel:* Scatter of NSB values during a single night caused by changing cloud coverage. *Bottom panel:* A clear night with NSB variations up to 1.1 $\mathrm{mag_{SQM}}$ arcsec^{-2} caused by auroral activity.

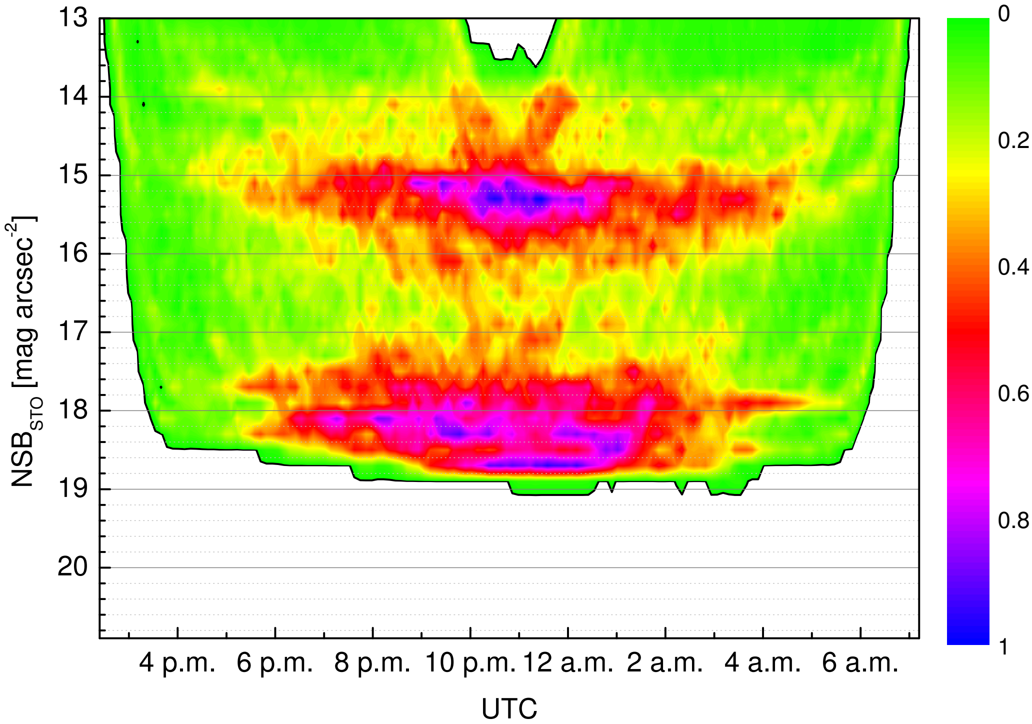

Figure 6: Normalized density plot of all measurements performed in Stockholm between Dec 1st, 2014 and Nov 30, 2015.

be ~60 percent brighter than the ones in Vienna. The difference gets even larger with clouds. In case of overcast sky, Stockholm is twice as bright as Vienna.

We further recognize that the brightness level in Stockholm does not decrease throughout the night as much as in Vienna, where on average a gradient of almost 0.1 $\mathrm{mag_{SQM}}$ arcsec^{-2}per hour can be observed. This gradient is partly induced by two effects: the city of Vienna reduces a substantial fraction of its street lighting at 11 p.m. (curfew) and at 12 p.m., most of the decorative facade lighting is switched off. The sky brightness in Vienna, therefore, shows two discontinuous steps towards lower values at 11 and 12 p.m., of which the first one is larger. Such a behavior is not observed in Stockholm.

Conclusion and Outlook

The night sky brightness above Stockholm is continuously monitored. That enables us to observe the influence that new technologies such as LEDs might have on the airglow in the future. However, more monitoring stations throughout (greater) Stockholm and other parts of Sweden would be advantageous, since variations between individual regions can be very large due to lightning policies and regulations. Light pollution in Stockholm is relatively strong. This is not only supported by the presented comparison to Vienna, but also by a recent study of Kyba et al. (2015), who studied worldwide variations in artificial skyglow based upon measurements from more than 50 sites (including rural, suburban and urban locations). I hope for an increasing awareness of light pollution and that dark skies and nightscapes are recognized as something deserving protection in the future.

Further Reading

Kyba, C. C. M., Tong, K. P., Bennie, J., et al. 2015, Scientific Reports, 5, 8409

Puschnig, J., Posch, T., & Uttenthaler, S. 2014a, Journal of Quantitative Spectroscopy and Radiative Transfer, 139, 64

Puschnig, J., Schwope, A., Posch, T., & Schwarz, R. 2014b, Journal of Quantitative Spectroscopy and Radiative Transfer, 139, 76

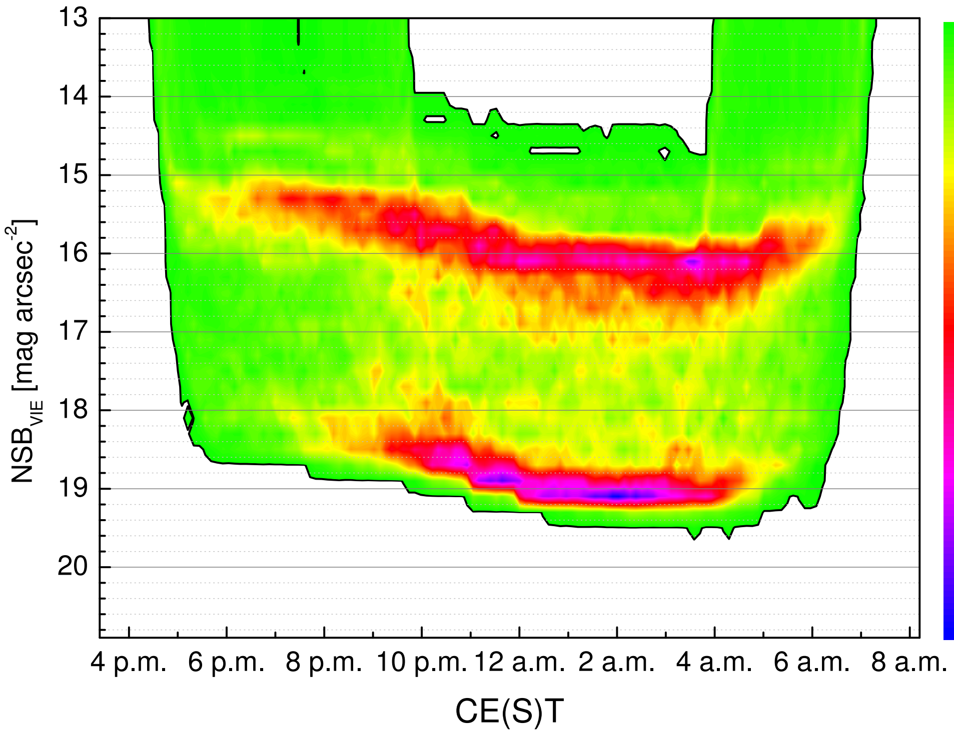

Figure 7: Normalized density plot of measurements performed in Vienna between April 2013 and April 2015.

Figure 8: Stockholm at Night

Figure 9: Stockholm at Night

Figure 10: Stockholm at Night