The benefit of multiple angle observations for visible band remote sensing using night lights

Christopher C. M. Kyba[1], Martin Aubé[2], Salvador Bará[3], Andrea Bertolo[4], Constantinos A. Bouroussis[5], Stefano Cavazzani[6], Brian R. Espey[7], Fabio Falchi[8], Geza Gyuk[9], Andreas Jechow[10], Miroslav Kocifaj[11], Zoltán Kolláth[12], Héctor Lamphar[13], Noam Levin[14], Shengjie Liu[15], Steven D. Miller[16], Sergio Ortolani[17], Chun Shing Jason Pun[15], Salvador José Ribas[18], Thomas Ruhtz[19], Alejandro Sánchez de Miguel[20], Matthias Schneider[21], Ranjay Man Shrestha[22], Alexandre Simoneau[23], Chu Wing So[15], Tobias Storch[21], Kai Pong Tong[11], Diane Turnshek[24], Ken Walczak[9], Jun Wang[25], Zhuosen Wang[26], and Jianglong Zhang[27]

[1]German Research Centre for Geosciences (GFZ)
[2]Cégep de Sherbrooke
[3]Universidade de Santiago de Compostela (USC)
[4]Regional Environmental Protection Agency of Veneto
[5]Lighting Laboratory, National Technical University of Athens
[6]University of Padova
[7]Trinity College Dublin
[8]ISTIL - Istituto di Scienza e Tecnologia dell'Inquinamento Luminoso
[9]The Adler Planetarium
[10]Leibniz Institute of Freshwater Ecology and Inland Fisheries
[11]ICA, Slovak Academy of Sciences
[12]Eszterházy Károly University
[13]The Centre for Research in Geography and Geosciences, Mexico city, Mexico.
[14]The Hebrew University
[15]The University of Hong Kong
[16]Colorado State University
[17]Universita di Padova
[18]Parc Astronòmic Montsec
[19]Freie Universitaet Berlin
[20]University of Exeter
[21]German Aerospace Center (DLR)
[22]Science Systems and Applications, Inc.
[23]Université de Sherbrooke
[24]Carnegie Mellon University
[25]the University of Iowa
[26]University of Maryland, College Park
[27]University of North Dakota

November 26, 2022

Abstract

The spatial and angular emission patterns of artificial and natural light emitted, scattered, and reflected from the Earth at night are far more complex than those for scattered and reflected solar radiation during daytime. Here we demonstrate (through examples) that there is additional information contained in the angular distribution of emitted light. We argue that this information could be used to improve existing remote sensing retrievals based on night lights, and in some cases could make entirely new remote sensing analyses possible. We encourage researchers and funding agencies to pursue further study of how multi-angle views can be analyzed or acquired.

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[1]German Research Centre for Geosciences GFZ, Telegrafenberg, 14467 Potsdam, Germany
[2]Cégep de Sherbrooke 475 rue du cégep, J1E 4K1, Sherbrooke, Canada
[3]Area de Optica, Universidade de Santiago de Compostela (USC), 15782 Compostela, Galicia (Spain)
[4]Regional Environmental Protection Agency of Veneto Via Ospedale Civile 24, 35131, Padova, Italy
[5]Lighting Laboratory, National Technical University of Athens, 9 Iroon Polytechniou Str, 15780, Zografou, Athens, Greece
[6]Department of Physics and Astronomy, University of Padova, Vicolo dell'Osservatorio 3, 35122, Padova, Italy
[7]INAF-Osservatorio Astronomico di Padova Vicolo dell'Osservatorio 5, 35122, Padova, Italy
[8]School of Physics, Trinity College DublinCollege Green, Dublin, 2 Ireland
[9]ISTIL - Istituto di Scienza e Tecnologia dell'Inquinamento Luminoso Via Roma 13, I-36016, Thiene, Italy
[10]The Adler Planetarium 1300 S. Lake Shore Dr., Chicago IL 60605, USA
[11]Leibniz Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587, Berlin, Germany
[12]ICA, Slovak Academy of Sciences, Dúbravská cesta 9, 845 03 Bratislava, Slovakia
[13]FMPI, Comenius University, Mlynská dolina, 842 48 Bratislava, Slovakia
[14]Department of Physics, Eszterházy Károly University Leányka út 6-7, 3300 Eger, Hungary
[15]The Centre for Research in Geography and Geosciences, Mexico city, Mexico
[16]The Department of Geography, The Hebrew University of Jerusalem Mt Scopus, Jerusalem 9190501, Israel
[17]The School of Earth and Environmental Sciences, The University of Queensland St. Lucia, QLD 4067, Australia
[18]Department of Physics, The University of Hong Kong Pokfulam Road, Hong Kong
[19]Cooperative Institute for Research in the Atmosphere, Colorado State University 375 Campus Delivery, Fort Collins, CO. 80523, USA
[20]Parc Astronòmic Montsec - Ferrocarrils de la Generalitat de Catalunya, Cami del coll d'Ares s/n, 25691 Àger, Lleida, Spain
[21]Freie Universität Berlin, Carl-Heinrich-Becker-Weg 6-10, 12165 Berlin, Germany
[22]Environment and Sustainability Institute, University of Exeter, Penryn, Cornwall TR10 9FE, U.K.
[23]German Aerospace Center (DLR), Earth Observation Center (EOC), Münchener Str. 20, 82234 Weßling, Germany
[24]Science Systems and Applications, Inc., Lanham, Maryland 20706, USA
[25]Terrestrial Information Systems Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD,USA
[26]Université de Sherbrooke, 2500 Boulevard de l'Université, J1K 2R1, Sherbrooke, Canada
[27]ICA, Slovak Academy of Sciences, Dúbravská cesta 9, 845 03 Bratislava, Slovakia
[28]Physics Department, Carnegie Mellon University, 5000 Forbes Ave, Pittsburgh, Pennsylvania, USA, 15213
[29]Department of Chemical and Biochemical Engineering, College of Engineering, University of Iowa, Iowa City, Iowa, USA, 52240
[30]Earth System Science Interdisciplinary Center, University of Maryland College Park, College Park,MD, USA
[31]Department of Atmospheric Sciences, University of North Dakota, Grand Forks, ND

Corresponding author: Christopher Kyba, `kyba@gfz-potsdam.de`

Key Points:

- Remote sensing using the visible band at night is more complex than during the daytime, especially due to the variety of artificial lights.
- Views of night lights intentionally taken from multiple angles provide several advantages over near-nadir or circumstantial view geometries.
- Night light remote sensing would benefit from greater consideration of the role viewing geometry plays in the observed radiance.

Abstract

The spatial and angular emission patterns of artificial and natural light emitted, scattered, and reflected from the Earth at night are far more complex than those for scattered and reflected solar radiation during daytime. Here we demonstrate (through examples) that there is additional information contained in the angular distribution of emitted light. We argue that this information could be used to improve existing remote sensing retrievals based on night lights, and in some cases could make entirely new remote sensing analyses possible. We encourage researchers and funding agencies to pursue further study of how multi-angle views can be analyzed or acquired.

Plain Language Summary

When satellites take images of Earth, they usually do so from directly above (or as close to it as is reasonably possible). In this paper, we show that for studies based on imagery of Earth at night, it would be beneficial to take several images of the same area at different angles within a short period of time. For example, different types of lights shine in different directions (street lights usually shine down, while video advertisements shine sideways), and tall buildings can block the view of a street from some viewing angles. Additionally, since different viewing directions pass through different amounts of air, imagery at multiple angles can be used to extract information about aerosols, as well as artificial and natural night sky brightness. The main point of the paper is to encourage researchers, funding agencies, and space agencies to think about what new possibilities could be achieved in the future with night lights views at different angles.

1 Introduction

Imagery of the Earth at night in the visible band provides unique data for remote sensing, especially because of the intrinsic connection between artificial light and human activity (Levin et al., 2020). The light field associated with Earth's night is, however, far more complex than that for the daytime. For example, the radiance of a night light scene often changes by up to 5 or 6 orders of magnitude over a distance of a few centimeters (Figure 1). In addition, while the physics of light propagation in the atmosphere is identical, the source distribution is not. Instead of the (comparatively) simple angular distribution of reflected sunlight, the hundreds of millions to billions (Zissis & Kitsinelis, 2009; Zissis et al., 2021) of artificial lights of Earth that emit some or all of their light outdoors have unique angular emission distribution functions, each of which vary over time (Dobler et al., 2015; Meier, 2018; X. Li et al., 2020). While this complication can be a challenge when working with night lights, it also provides an opportunity: night light imagery acquired at multiple angles contains information that could potentially be extracted via remote sensing. For the past year, our group has been discussing these possibilities in a series of online meetings. This article presents a summary of our discussions, and is intended to highlight the potential benefits of multi-angle night light imagery to the remote sensing community.

Existing night lights imagery (e.g. the Visible Infrared Imaging Radiometer Suite Day/Night Band, Elvidge, Baugh, Zhizhin, & Hsu, 2013) have often been acquired at multiple angles. However, this has in general been a feature related to the acquisition of a wide swath, not an intentional design decision. It also results in an unfortunate correlation between overpass time and imaging angle (Tong et al., 2020). In this article, we consider the possibilities that would arise if we had access to intentional multi-angle views acquired at similar overpass times. This could, for example, be a satellite instrument similar to the Multi-angle Imaging SpectroRadiometer, which views 9 different angles during its (daytime) overpass (Diner et al., 1998), or alternatively imagery from aerial platforms, including airplanes (C. Kyba et al., 2013), helicopters (Wuchterl & Reithofer, 2017), stratospheric balloons (Walczak et al., 2021), and drones, which are especially useful in

Figure 1. Aerial photo taken over Berlin on March 15, 2012. The dynamic range of night scenes is extremely large, ranging from diffuse reflection of starlight and skyglow from unlit surfaces (which appear black here due to underexposure), to direct views of the radiant elements of luminaires (e.g. the overexposed bright point). The variation over small spatial scales also extreme, as transitions related to individual light sources and shadows can have widths of centimeters or even smaller.

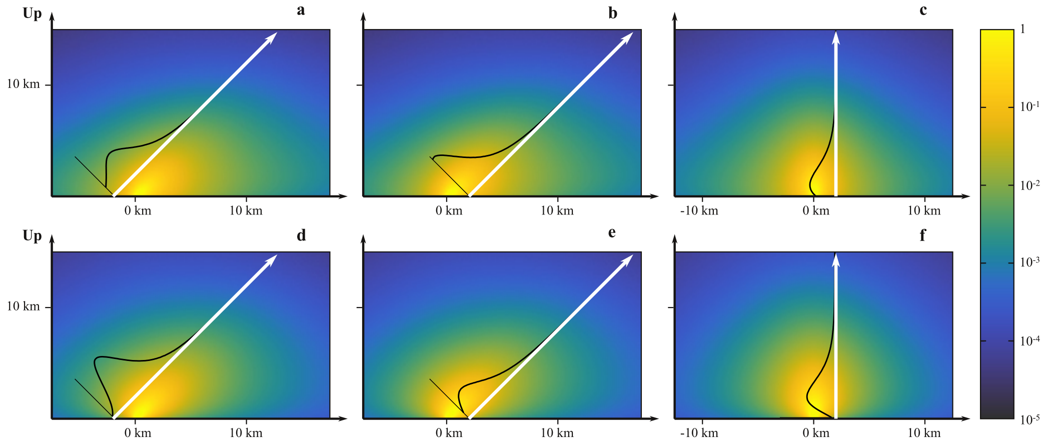

Figure 2. Three possible views of the identical unlit area located 2 km from a monochromatic (550 nm) light source. In each panel, the white arrow shows the direct light path from the emitter to the sensor. The top panels (a-c) are for a point source, the bottom panels (d-f) are for a vertical Lambertian emitter. The colors indicate the weighted scattering density into the line of sight within the vertical plane that includes the location of the source and observer. The black histograms show the contribution to the detected radiance as a function of the distance along the viewing path. Azimuthal symmetry is assumed, although this is often not be the case for real light sources. The atmospheric model includes Mie scattering according to the Henyey-Greenstein phase function with g=0.6, an aerosol optical depth of 0.3, and an aerosol scale height of 2.2 km.

the case of oblique and limb views (Bouroussis & Topalis, 2020; X. Li et al., 2020). We have identified three areas where multi-angle views will provide particular benefits: first, remote sensing of atmospheric and Earth surface properties, second, spatial analyses using night lights, and third, evaluations of the properties of artificial lights, and their environmental impacts. Our goal here is to present ideas for what could be accomplished with idealized multi-angle night light sensors – in the real world, further evaluation will be needed to test if the benefit of obtaining multi-angle views is worth the additional cost in time (for aerial platforms) or complexity (making satellites more expensive).

2 Remote sensing of atmospheric and Earth surface properties

As a first example of how multi-angle views contain additional information that can be extracted through remote sensing, consider the scattering of artificial light by atmospheric aerosols. Figure 2 depicts observations of an unlit location situated 2 km from a light source. As long as the light source is bright, the sensor will detect radiance above the natural background (de Miguel et al., 2020; Z. Wang et al., 2021), but this radiance is sometimes larger when the viewing path passes through the atmosphere above the source (Figures 2a and 2d). Multi-angle observations of both the light source itself and nearby unlit areas can provide information about extinction, bulk aerosol optical depth, the scattering phase function, aerosol particle size number distribution in the air column (Kocifaj & Bará, 2020). Multi-angle views would therefore enhance retrievals of aerosol properties at night in areas using artificial light. Sensitive night lights satellites could also remotely sense aerosol properties in unlit areas using scattered moonlight, which is especially advantageous in arctic areas during polar night. While some preliminary work has begun in this area (J. Wang et al., 2016; Zhang et al., 2019; Cavazzani et al., 2020; Zhou et al., in review), much more theoretical and experimental work is needed.

In the same way that scattered moonlight can provide information about aerosols, reflected lunar light can be used to estimate the bi-directional reflectance distribution function (BRDF) at high latitudes during polar night (J. Li et al., 2021). This data could help fill in gaps in daytime BRDF estimation in cloudy areas, but it is especially useful as a source of BRDF information at middle latitudes during winter, and in arctic areas during the polar night. Such data would improve both snow retrievals and the discrimination of snow and clouds. Presently, daytime observations of BRDF are used to correct night images that include moonlight (Román et al., 2018). This application would of course be improved with multi-angle observations of reflected moonlight, and the improved correction would have two knock-on advantages for remote sensing using artificial light. First, improved moonlight correction (Miller & Turner, 2009) would improve the stability (i.e. reduce the noise) of corrected imagery. Second, departures from the expected lunar signal often indicate artificial light, so the effective sensitivity for observing artificial light in snowy regions can be greatly increased over what is possible in temperate areas.

A major opportunity in multi-angle satellite views is that they can exhibit parallax displacement relative to the reference ellipsoid. The magnitude of this displacement depends on the viewing geometry and the object's height, which means that it is possible to remotely sense the height of a light emitting (or scattering) object. One of several possible uses of this phenomena is remotely sensing the altitude and motion (i.e. horizontal phase speed) of gravity waves, which play a major role in energy transfer in the atmosphere, and therefore impact weather and climate. The modulation of nightglow by gravity waves at elevations near the mesopause (about 87-90 km) is detectable on moon-free nights in night imagery (Miller et al., 2013, 2015). Near simultaneously acquired multi-angle observations of nightglow would therefore provide a great advance over the currently available single angle views in characterizing the phase speed and associated energy/momentum properties of these waves.

3 Spatial analyses using night lights

Information from parallax observations is also useful for light sources located closer to the Earth's surface. When objects are known to be located on or very close to Earth's surface (e.g. illuminated streets), the combination of multi-angle views and an elevation database would allow more precise geolocation, resulting in less movement of permanent features from one observation to the next, and therefore more stable time series (see e.g. Coesfeld et al., 2018). In areas with considerable vertical relief, multi-angle views would therefore provide improved position detection for bright natural sources like fires and lava flows. This may benefit monitoring and fighting of wildfires, which are generally less active at night (but nevertheless best detected using the visual band or the combination of visible and infrared, Elvidge, Zhizhin, Baugh, Hsu, & Ghosh, 2019; J. Wang et al., 2020).

Multi-angle night light views can also contribute information to land use and land cover analyses. For example, the angular distribution of artificial light reflected from the street surface is dramatically different compared to that for light emitted from vertical surfaces (e.g. commercial high rise buildings). Multi-angle views could therefore be useful in differentiating between commercial from residential buildings or areas in city centers (especially at high resolution). In addition, a more consistent picture of urban light emissions could be obtained with multiple views, because the strong variations in the angular distribution of light emissions can be directly accounted for (X. Li et al., 2019; Solbrig et al., 2020; Tong et al., 2020). In terms of land cover, it is helpful when BRDF information is obtained in a single overpass, rather than over several days of observations at different accidental angles. This avoids the issue of observing through different atmospheres, and under different conditions (e.g. moonlight, snow melting, or vegetation phenology). A day/night band instrument with multiple angle views might therefore be of considerable interest during the spring leaf out, when BRDF changes very rapidly.

Away from the land surface, another well-known remote sensing application of nighttime light imagery is the detection of boats (Elvidge et al., 2018; Duan et al., 2019). This application is more difficult on moonlit nights, especially in the area near the lunar specular reflection (Elvidge et al., 2015). Multi-angle views would therefore allow better detection of (especially smaller) boats on moonlit nights, as the target is only in the specular reflection region for some observing angles. In addition, in ocean areas with frequent broken cloud cover, multi-angle views increase the chance that at least one of the observation angles will have a clear view of the surface.

4 Evaluating impact and properties of artificial lights

In some cases, researchers are interested in obtaining information about the sources of artificial lights themselves, or using night lights data for studying environmental impact. For example, while we know that total global artificial light emissions are increasing (C. C. Kyba et al., 2017), it is unclear which lighting applications are responsible for the growth, as even the existing relative fraction of light emissions from different types of sources is not well known (Bará et al., 2018; C. Kyba et al., 2020). Multi-angle imagery contains some information about the light types, since different types have different upward angular radiance distributions (e.g. billboards vs reflected streetlight). This complements multi-spectral imagery, which is also important in this context (Elvidge et al., 2007; Sánchez de Miguel et al., 2019; De Meester & Storch, 2020). Furthermore, since lighting practice has strong geographical variations at both continental (Falchi et al., 2019) and local (C. Kyba et al., 2020) scale, better understanding of lighting character based on multi-angle views stands to benefit all of the remote sensing applications based on night lights (e.g. population or GDP, Gibson, Olivia, & Boe-Gibson, 2020). Given that temporal practices in lighting differ around the world, the interpretation of multi-angle views assembled in a short time span over a single overpass is much more straightforward than is currently the case (i.e. via different viewing angles obtained on different dates and times).

The 3D structure of artificially lit areas has a major factor on observations of artificial lights from high altitudes (Figure 3), as objects can partially or entirely block the view of a light source or surface reflection from above (Coesfeld et al., 2018; Levin et al., 2020; Z. Wang et al., 2021). Geographic variations in the urban structure (e.g. height of buildings and width of streets) mean that the blocking effect varies within cities and between countries and continents. Similarly, leaf area cover changes often result in seasonal effects in blocking (and therefore time series), and the presence and heights of trees (relative to light sources) differs on small geographic scales. In principle, (in areas without rapid construction) additional information such as 3D models could be used to estimate the impact of blocking, to account for it, and reduce the variability in night light imagery. Multi-angle observations would be critical for verifying that such corrections work properly.

Drones are likely of particular use in analyses directly related to artificial lights themselves. They can operate on cloudy nights, and provide multi-angle views with much higher resolution than is possible from space (including in the horizontal direction), which makes them ideal for quantification of the light field in 3D space (Bouroussis & Topalis, 2020). One example where this is likely the case is in the area of ecological light pollution (Longcore & Rich, 2004). Animals, for example, do not view the world in nadir view, but rather look forward and to the side (Van Doren et al., 2017; Vandersteen et al., 2020). Information about how lights appear in the forward view is therefore important for understanding animal attraction. Similarly, if there are epidemiological impacts of light shining into bedrooms (e.g. Gabinet & Portnov, 2021), then information about horizontal emissions is more relevant than that for light emitted towards zenith. This is an area where citizen science could perhaps benefit nighttime remote sensing, as citizens have views of light emission at many different azimuth and elevation angles from their homes.

Figure 3. Three views of the same area of downtown Chicago photographed from the International Space Station on January 28, 2016 taken between 2:44:43 and 2:45:38 local time. North is upward, and the images were taken from the northwest (a, 312°), north (b, 354°), and east (c, 105°). The image numbers are iss046e25703, iss046e25710, and iss046e25716, and are courtesy the Earth Science and Remote Sensing Unit, NASA Johnson Space Center.

Our final example of a field that would benefit from multi-angle views is the study of artificial night sky brightness (skyglow, Falchi et al., 2016). The angular distribution of light escaping above obstacles is one of the most critical parameters in skyglow simulation (Aubé, 2015), as the path length through the atmosphere (and therefore the scattering probability) vary extraordinarily with emission angle (Cinzano et al., 2000; Luginbuhl et al., 2009). Existing skyglow models have used estimated factors for blocking (Aubé & Simoneau, 2018), or inferred it indirectly from observations (Falchi et al., 2016; Kocifaj et al., 2019). However, these methods (at present) do not realistically account for the geographic variability in obstacle properties. Direct measurement of the upward light emission using multi-angle views is therefore critically important for the progress of this field. Due to the emissions decrease over the course of the night, multi-angle views on short time scales from satellites, balloons, and especially drones (e.g. X. Li et al., 2020) may be preferable to the longer timescales of airplane based surveys (C. Kyba et al., 2013). Finally, if a sensor has multi-angle capabilities combined with high resolution and high sensitivity, then the "light dome" of a city can be directly observed (de Miguel et al., 2020) by viewing unlit areas with low reflectance such as rivers and parks (as in the example of Figure 2).

5 Conclusion

The examples shown here demonstrate how intentional acquisition of multi-angle views of night lights on short time scales can provide new information compared to existing night lights datasets. This information will enable some entirely new remote sensing applications of night lights, and can improve the results of many others (e.g. by reducing the variability in night lights time series). In many cases, a combined package of multi-angle observation and analysis will offer additional advantages over the imagery alone. An example of this is remote sensing of nighttime aerosol properties, which can be fed back via an aerosol correction to sharpen night light imagery (Bu et al., 2019). We encourage researchers and funding agencies to consider how multi-angle views from existing platforms can be analyzed (or acquired), and we hope to see the development of future night light satellites that perform intentional multi-angle acquisitions over short time scales.

Acknowledgments

CK's contribution to this work was supported through the European Union's Horizon 2020 research and innovation programme ERA-PLANET, grant agreement no. 689443, via the GEOEssential project, and funding from the Helmholtz Association Initiative and Networking Fund under grants ERC-RA-0031 and CS-0003. MK's, KPT's and HL's contributions were supported by the Slovak Research and Development Agency under contract No: APVV-18-0014. SB's contribution was supported by Xunta de Galicia, grant ED431B 2020/29. ZW's contribution was supported by NASA's Terra/Aqua/Suomi-NPP program NNH17ZDA001N-TASNPP17-0007. SL's, CSJP's and CWS's contributions were supported by the University of Hong Kong's Knowledge Exchange Fund granted by the University Grants Committee of Hong Kong (Project No: KE-IP-2020/21-78) and the Environment and Conservation Fund (Project ID: 125-2018) of The Government of the HKSAR. MA's contribution to this work was supported through the Fonds de recherche du Québec - Nature et technologies grant #285926. ZK's and KPT's contributions were supported by the European Union and co-financed by the European Social Fund (Grant No. EFOP-3.6.2-16-201-00014: Development of international research environment for light pollution studies). ASM 's contribution was funded by the Cities at Night project and NERC grant NE/P01156X/1).

References

Aubé, M. (2015). Physical behaviour of anthropogenic light propagation into the nocturnal environment. *Philos T R Soc B*, *370*(1667), 20140117.

Aubé, M., & Simoneau, A. (2018). New features to the night sky radiance model illumina: Hyperspectral support, improved obstacles and cloud reflection. *J Quant Spectrosc Ra*, *211*, 25–34.

Bará, S., Rodríguez-Arós, Á., Pérez, M., Tosar, B., Lima, R. C., Sánchez de Miguel, A., & Zamorano, J. (2018). Estimating the relative contribution of streetlights, vehicles, and residential lighting to the urban night sky brightness. *Lighting Res Techno*, 1477153518808337.

Bouroussis, C. A., & Topalis, F. V. (2020). Assessment of outdoor lighting installations and their impact on light pollution using unmanned aircraft systems-the concept of the drone-gonio-photometer. *J Quant Spectrosc Ra*, *253*, 107155.

Bu, L., Xu, Z., Zhang, G., & Zhang, Z. (2019). Night-light image restoration method based on night scattering model for Luojia 1-01 satellite. *Sensors*, *19*(17), 3761.

Cavazzani, S., Ortolani, S., Bertolo, A., Binotto, R., Fiorentin, P., Carraro, G., & Zitelli, V. (2020). Satellite measurements of artificial light at night: aerosol effects. *Monthly Notices of the Royal Astronomical Society*, *499*(4), 5075–5089.

Cinzano, P., Falchi, F., Elvidge, C., & Baugh, K. (2000). The artificial night sky brightness mapped from DMSP satellite Operational Linescan System measurements. *Monthly Notices of the Royal Astronomical Society*, *318*(3), 641–657.

Coesfeld, J., Anderson, S., Baugh, K., Elvidge, C., Schernthanner, H., & Kyba, C. (2018). Variation of individual location radiance in VIIRS DNB monthly composite images. *Remote Sensing*, *10*(12), 1964.

De Meester, J., & Storch, T. (2020). Optimized performance parameters for nighttime multispectral satellite imagery to analyze lightings in urban areas. *Sensors*, *20*(11), 3313.

de Miguel, A. S., Kyba, C. C. M., Zamorano, J., Gallego, J., & Gaston, K. J. (2020). The nature of the diffuse light near cities detected in nighttime satellite imagery. *Sci Rep*, *10*, 7829.

Diner, D. J., Beckert, J. C., Reilly, T. H., Bruegge, C. J., Conel, J. E., Kahn, R. A., . . . Verstraete, M. M. (1998). Multi-angle Imaging SpectroRadiometer (MISR) instrument description and experiment overview. *IEEE Transactions on Geo-*

science and Remote Sensing, *36*(4), 1072–1087.
Dobler, G., Ghandehari, M., Koonin, S. E., Nazari, R., Patrinos, A., Sharma, M. S., … Wurtele, J. S. (2015). Dynamics of the urban lightscape. *Inform Syst*, *54*, 115–126.
Duan, H., Cao, Z., Shen, M., Liu, D., & Xiao, Q. (2019). Detection of illicit sand mining and the associated environmental effects in china's fourth largest freshwater lake using daytime and nighttime satellite images. *Sci Total Environ*, *647*, 606–618.
Elvidge, C. D., Baugh, K. E., Zhizhin, M., & Hsu, F.-C. (2013). Why VIIRS data are superior to DMSP for mapping nighttime lights. *Proceedings of the Asia-Pacific Advanced Network*, *35*(0), 62.
Elvidge, C. D., Cinzano, P., Pettit, D. R., Arvesen, J., Sutton, P., Small, C., … Ebener, S. (2007). The nightsat mission concept. *International Journal of Remote Sensing*, *28*(12), 2645-2670. doi: 10.1080/01431160600981525
Elvidge, C. D., Ghosh, T., Baugh, K., Zhizhin, M., Hsu, F.-C., Katada, N. S., … Hung, B. Q. (2018). Rating the effectiveness of fishery closures with visible infrared imaging radiometer suite boat detection data. *Front Mar Sci*, *5*, 132.
Elvidge, C. D., Zhizhin, M., Baugh, K., & Hsu, F.-C. (2015). Automatic boat identification system for VIIRS low light imaging data. *Remote sensing*, *7*(3), 3020–3036.
Elvidge, C. D., Zhizhin, M., Baugh, K., Hsu, F. C., & Ghosh, T. (2019). Extending nighttime combustion source detection limits with short wavelength VIIRS data. *Remote Sensing*, *11*(4), 395.
Falchi, F., Cinzano, P., Duriscoe, D., Kyba, C. C., Elvidge, C. D., Baugh, K., … Furgoni, R. (2016). The new world atlas of artificial night sky brightness. *Sci Adv*, *2*(6), e1600377.
Falchi, F., Furgoni, R., Gallaway, T., Rybnikova, N., Portnov, B., Baugh, K., … Elvidge, C. (2019). Light pollution in USA and Europe: The good, the bad and the ugly. *J Environ Manage*, *248*, 109227.
Gabinet, N. M., & Portnov, B. A. (2021). Assessing the impacts of ALAN and noise proxies on sleep duration and quality: evidence from a nation-wide survey in Israel. *Chronobiol Int*, 1–21.
Gibson, J., Olivia, S., & Boe-Gibson, G. (2020). Night lights in economics: sources and uses 1. *J Econ Surv*, *34*(5), 955–980.
Kocifaj, M., & Bará, S. (2020). Aerosol characterization using satellite remote sensing of light pollution sources at night. *Mon Not R Astron Soc*, *495*(1), L76–L80.
Kocifaj, M., Solano-Lamphar, H. A., & Videen, G. (2019). Night-sky radiometry can revolutionize the characterization of light-pollution sources globally. *P Natl Acad Sci USA*, *116*(16), 7712–7717.
Kyba, C., Ruby, A., Kuechly, H., Kinzey, B., Miller, N., Sanders, J., … Espey, B. (2020). Direct measurement of the contribution of street lighting to satellite observations of nighttime light emissions from urban areas. *Lighting Research & Technology*, 1477153520958463.
Kyba, C., Ruhtz, T., Lindemann, C., Fischer, J., & Hölker, F. (2013). Two camera system for measurement of urban uplight angular distribution. In *Radiation processes in the atmosphere and ocean (irs2012): Proceedings of the international radiation symposium (irc/iamas)* (Vol. 1531, p. 568-571).
Kyba, C. C., Kuester, T., de Miguel, A. S., Baugh, K., Jechow, A., Hölker, F., … Guanter, L. (2017). Artificially lit surface of Earth at night increasing in radiance and extent. *Sci Adv*, *3*(11), e1701528.
Levin, N., Kyba, C. C., Zhang, Q., Sánchez de Miguel, A., Román, M. O., Li, X., … Elvidge, C. D. (2020). Remote sensing of night lights: A review and an outlook for the future. *Remote Sens Environ*, *237*, 111443.
Li, J., Qiu, S., Zhang, Y., Yang, B., Gao, C., Qian, Y., … Zhao, Y. (2021). As-

sessment of BRDF impact on VIIRS DNB from observed top-of-atmosphere reflectance over Dome C in nighttime. *Remote Sensing*, *13*(2), 301.

Li, X., Levin, N., Xie, J., & Li, D. (2020). Monitoring hourly night-time light by an unmanned aerial vehicle and its implications to satellite remote sensing. *Remote Sens Environ*, *247*, 111942.

Li, X., Ma, R., Zhang, Q., Li, D., Liu, S., He, T., & Zhao, L. (2019). Anisotropic characteristic of artificial light at night–systematic investigation with VIIRS DNB multi-temporal observations. *Remote Sens Env*, *233*, 111357.

Longcore, T., & Rich, C. (2004). Ecological light pollution. *Front Ecol Environ*, *2*(4), 191-198. doi: 10.1890/1540-9295(2004)002[0191:ELP]2.0.CO;2

Luginbuhl, C. B., Duriscoe, D. M., Moore, C. W., Richman, A., Lockwood, G. W., & Davis, D. R. (2009). From the Ground Up II: Sky Glow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona. *Publ astron soc pac*, *121*, 204-212. doi: 10.1086/597626

Meier, J. M. (2018). Temporal profiles of urban lighting: Proposal for a research design and first results from three sites in berlin. *Int J Sust Lighting*, *20*, 11-28.

Miller, S. D., Straka, W., Mills, S. P., Elvidge, C. D., Lee, T. F., Solbrig, J., ... Weiss, S. C. (2013). Illuminating the capabilities of the Suomi National Polar-Orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band. *Remote Sens*, *5*(12), 6717–6766.

Miller, S. D., Straka, W. C., Yue, J., Smith, S. M., Alexander, M. J., Hoffmann, L., ... Partain, P. T. (2015). Upper atmospheric gravity wave details revealed in nightglow satellite imagery. *P Natl Acad Sci USA*, *112*(49), E6728–E6735.

Miller, S. D., & Turner, R. E. (2009). A dynamic lunar spectral irradiance data set for NPOESS/VIIRS day/night band nighttime environmental applications. *IEEE Transactions on Geoscience and Remote Sensing*, *47*(7), 2316–2329.

Román, M. O., Wang, Z., Sun, Q., Kalb, V., Miller, S. D., Molthan, A., ... others (2018). NASA's Black Marble nighttime lights product suite. *Remote Sens Environ*, *210*, 113–143.

Sánchez de Miguel, A. S., Kyba, C. C., Aubé, M., Zamorano, J., Cardiel, N., Tapia, C., ... Gaston, K. J. (2019). Colour remote sensing of the impact of artificial light at night (I): The potential of the International Space Station and other DSLR-based platforms. *Remote Sens Environ*, *224*, 92–103.

Solbrig, J. E., Miller, S. D., Zhang, J., Grasso, L., & Kliewer, A. (2020). Assessing the stability of surface lights for use in retrievals of nocturnal atmospheric parameters. *Atmos Meas Tech*, *13*(1), 165–190.

Tong, K. P., Kyba, C. C., Heygster, G., Kuechly, H. U., Notholt, J., & Kollth, Z. (2020). Angular distribution of upwelling artificial light in Europe as observed by Suomi–NPP satellite. *J Quant Spectrosc Ra*, *249*, 107009.

Vandersteen, J., Kark, S., Sorrell, K., & Levin, N. (2020). Quantifying the impact of light pollution on sea turtle nesting using ground-based imagery. *Remote Sens*, *12*(11), 1785.

Van Doren, B. M., Horton, K. G., Dokter, A. M., Klinck, H., Elbin, S. B., & Farnsworth, A. (2017). High-intensity urban light installation dramatically alters nocturnal bird migration. *P Natl Acad Sci USA*, *114*(42), 11175–11180.

Walczak, K., Gyuk, G., Garcia, J., & Tarr, C. (2021). Light pollution mapping from a stratospheric high-altitude balloon platform. *Int J Sustain Lighting*, *23*(1), 20–32.

Wang, J., Aegerter, C., Xu, X., & Szykman, J. J. (2016). Potential application of VIIRS Day/Night Band for monitoring nighttime surface PM2.5 air quality from space. *Atmospheric environment*, *124*, 55–63.

Wang, J., Roudini, S., Hyer, E. J., Xu, X., Zhou, M., Garcia, L. C., ... da Silva, A. M. (2020). Detecting nighttime fire combustion phase by hybrid application of visible and infrared radiation from Suomi NPP VIIRS. *Remote Sens Environ*, *237*, 111466.

Wang, Z., Román, M. O., Kalb, V. L., Miller, S. D., Zhang, J., & Shrestha, R. M. (2021, September). Quantifying uncertainties in nighttime light retrievals from suomi-NPP and NOAA-20 VIIRS day/night band data. *Remote Sens Environ*, *263*, 112557. Retrieved from `https://doi.org/10.1016/j.rse.2021.112557` doi: 10.1016/j.rse.2021.112557

Wuchterl, G., & Reithofer, M. (2017). *Licht über wien v* (Tech. Rep.). Kuffner Sternwarte.

Zhang, J., Jaker, S. L., Reid, J. S., Miller, S. D., Solbrig, J., & Toth, T. D. (2019). Characterization and application of artificial light sources for nighttime aerosol optical depth retrievals using the Visible Infrared Imager Radiometer Suite Day/Night Band. *Atmos Meas Tech*, *12*(6), 3209–3222.

Zhou, M., Wang, J., Chen, X., Xu, X., Colarco, P., Miller, S. D., ... Holben, B. (in review). Nighttime smoke aerosol optical depth over u.s. rural areas: a retrieval from VIIRS Day/Night Band moonlight observations. *Remote Sens Environ*.

Zissis, G., Bertoldi, P., & Serrenho, T. (2021). Update on the status of LED-lighting world market since 2018. *Publications Office of the European Union: Luxembourg*.

Zissis, G., & Kitsinelis, S. (2009). State of art on the science and technology of electrical light sources: from the past to the future. *Journal of Physics D: Applied Physics*, *42*(17), 173001.