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COMMENTARY
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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 lights remote sensing would benefit from greater consideration of the role viewing geometry plays in the observed radiance

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

C. C. M. Kyba,
kyba@gfz-potsdam.de

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Author Contributions:

Conceptualization: Christopher C. M. Kyba, Martin Aubé, Salvador Bará, Andrea Bertolo, Constantinos A. Bouroussis, Stefano Cavazzani, Brian R. Espey, Fabio Falchi, Geza Gyuk, Andreas Jechow, Miroslav Kocifaj, Zoltán Kolláth, Héctor Lamphar, Noam Levin, Shengjie Liu, Steven D. Miller, Sergio Ortolani, Chun Shing Jason Pun, Salvador José Ribas, Thomas Ruhtz, Alejandro Sánchez de Miguel, Mathias Schneider, Ranjay Man Shrestha, Alexandre Simoneau, Chu Wing So, Tobias Storch, Kai Pong Tong,

Multiple Angle Observations Would Benefit 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[6,7], Brian R. Espey[8], Fabio Falchi[9], Geza Gyuk[10], Andreas Jechow[11], Miroslav Kocifaj[12,13], Zoltán Kolláth[14], Héctor Lamphar[12,15], Noam Levin[16,17], Shengjie Liu[18], Steven D. Miller[19], Sergio Ortolani[6,7], Chun Shing Jason Pun[20], Salvador José Ribas[21], Thomas Ruhtz[22], Alejandro Sánchez de Miguel[23,24], Mathias Schneider[25], Ranjay Man Shrestha[26,27], Alexandre Simoneau[28], Chu Wing So[20], Tobias Storch[25], Kai Pong Tong[12], Milagros Tuñón[1], Diane Turnshek[29], Ken Walczak[10], Jun Wang[30], Zhuosen Wang[27,31], and Jianglong Zhang[32]

[1]German Research Centre for Geosciences GFZ, Potsdam, Germany, [2]Cégep de Sherbrooke 475 rue du cégep, Sherbrooke, QC, Canada, [3]Area de Optica, Universidade de Santiago de Compostela (USC), Compostela, Spain, [4]Regional Environmental Protection Agency of Veneto Via Ospedale Civile 24, Padova, Italy, [5]Lighting Laboratory, National Technical University of Athens, Athens, Greece, [6]Department of Physics and Astronomy, University of Padova, Padova, Italy, [7]INAF-Osservatorio Astronomico di Padova Vicolo dell'Osservatorio 5, Padova, Italy, [8]School of Physics, Trinity College DublinCollege Green, Dublin, Ireland, [9]ISTIL - Istituto di Scienza e Tecnologia dell'Inquinamento Luminoso Via Roma 13, Thiene, Italy, [10]The Adler Planetarium 1300 S. Lake Shore Dr, Chicago, IL, USA, [11]Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany, [12]ICA, Slovak Academy of Sciences, Bratislava, Slovakia, [13]FMPI, Comenius University, Bratislava, Slovakia, [14]Department of Physics, Eszterházy Károly University Leányka út 6-7, Eger, Hungary, [15]The Centre for Research in Geography and Geosciences (CentroGeo), Mexico city, Mexico, [16]The Department of Geography, The Hebrew University of Jerusalem Mt Scopus, Jerusalem, Israel, [17]The School of Earth and Environmental Sciences, The University of Queensland St. Lucia, Brisbane, QLD, Australia, [18]Spatial Sciences Institute, University of Southern California, Los Angeles, CA, USA, [19]Department of Atmospheric Science and Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, USA, [20]Department of Physics, The University of Hong Kong, Pokfulam, Hong Kong, [21]Parc Astronòmic Montsec - Ferrocarrils de la Generalitat de Catalunya, Lleida, Spain, [22]Freie Universität Berlin, Berlin, Germany, [23]Depto. Física de la Tierra y Astrofísica, Instituto de Física de Partículas y del Cosmos (IPARCOS), Universidad Complutense, Madrid, Spain, [24]Environment and Sustainability Institute, University of Exeter, Penryn, UK, [25]German Aerospace Center (DLR), Earth Observation Center (EOC), Weßling, Germany, [26]Science Systems and Applications, Inc., Lanham, MD, USA, [27]Terrestrial Information Systems Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [28]Université de Sherbrooke, 2500 Boulevard de l'Université, Sherbrooke, QC, Canada, [29]Physics Department, Carnegie Mellon University, Pittsburgh, PA, USA, [30]Department of Chemical and Biochemical Engineering, College of Engineering, Iwoa City, IA, USA, [31]Earth System Science Interdisciplinary Center, University of Maryland College Park, College Park, MD, USA, [32]Department of Atmospheric Sciences, University of North Dakota, Grand Forks, ND, USA

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. In this commentary, we use examples to show 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. This work will be challenging, so we hope this article will 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 comment, we show that for studies that use imagery of Earth at night, it may 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 views from different directions pass through different amounts of air, imagery at multiple angles could be used to obtain information about Earth's atmosphere, and measure artificial and natural night sky brightness. The main point of the paper is to encourage researchers, funding agencies, and

Diane Turnshek, Ken Walczak, Jun Wang, Zhuosen Wang, Jianglong Zhang
Investigation: Martin Aubé
Methodology: Christopher C. M. Kyba, Martin Aubé, Constantinos A. Bouroussis, Brian R. Espey, Miroslav Kocifaj, Zoltán Kolláth, Steven D. Miller, Alexandre Simoneau
Resources: Christopher C. M. Kyba, Brian R. Espey, Geza Gyuk, Zoltán Kolláth, Ken Walczak
Software: Martin Aubé, Miroslav Kocifaj, Zoltán Kolláth, Alexandre Simoneau
Validation: Martin Aubé, Geza Gyuk, Miroslav Kocifaj, Steven D. Miller, Alexandre Simoneau, Kai Pong Tong, Diane Turnshek, Ken Walczak
Visualization: Christopher C. M. Kyba, Zoltán Kolláth, Milagros Tuñón, Ken Walczak
Writing – original draft: Christopher C. M. Kyba
Writing – review & editing: Christopher C. M. Kyba, Martin Aubé, Salvador Bará, Andrea Bertolo, Constantinos A. Bouroussis, Stefano Cavazzani, Brian R. Espey, Fabio Falchi, Geza Gyuk, Andreas Jechow, Miroslav Kocifaj, Zoltán Kolláth, Héctor Lamphar, Noam Levin, Shengjie Liu, Steven D. Miller, Sergio Ortolani, Chun Shing Jason Pun, Salvador José Ribas, Thomas Ruhtz, Alejandro Sánchez de Miguel, Mathias Schneider, Ranjay Man Shrestha, Alexandre Simoneau, Chu Wing So, Tobias Storch, Kai Pong Tong, Milagros Tuñón, Diane Turnshek, Ken Walczak, Jun Wang, Zhuosen Wang, Jianglong Zhang

space agencies to think about what new possibilities could be achieved in the future with views of night lights at different angles.

1. Introduction

Imagery of the Earth at night in the visible band provides unique data for remote sensing, 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 lights scene often changes by up to five or six orders of magnitude over a distance of the few centimeters separating an emitter from an unlit area (Figure 1). In addition, while the physics of light propagation in the atmosphere is identical during day and night, the light sources are not. Instead of the (comparatively) simple angular distribution of reflected sunlight, the hundreds of millions to billions (Zissis et al., 2021; Zissis & Kitsinelis, 2009) 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; Li et al., 2020). While this complication presents a challenge for working with night lights, it also provides an opportunity: night lights imagery acquired at multiple angles contains information that could potentially be extracted via remote sensing. Over the past 2 years, our author group has discussed these possibilities in a series of online meetings, and this commentary summarizes these discussions. We highlight the potential benefits of multi-angle night lights imagery to the remote sensing community, but do not propose a specific analysis or instrument, as further research will be necessary to make them possible.

Existing night lights imagery (e.g., the Visible Infrared Imaging Radiometer Suite Day/Night Band (DNB), Elvidge et al., 2013) have often been acquired at multiple angles. However, this has in general been a feature related to the acquisition, not an intentional design decision, and in the case of DNB this results in an unfortunate correlation between overpass time and imaging angle (Tong et al., 2020). In this commentary, we consider the possibilities that intentional multi-angle views acquired over a short time period might provide. This could be from a future satellite instrument similar to the Multi-angle Imaging SpectroRadiometer, which views nine different angles during its (daytime) overpass (Diner et al., 1998). But it could just as well come from existing aerial platforms, including airplanes (Kyba et al., 2013), helicopters (Wuchterl & Reithofer, 2017), stratospheric balloons (Walczak et al., 2021), or drones, which are especially useful in the case of oblique and limb views (Bouroussis & Topalis, 2020; 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. We present ideas of what might be accomplished with idealized multi-angle night lights sensors; turning these ideas into operational retrievals will certainly be challenging. We hope that our commentary will provide motivation and justification for acquiring new data and attempting new analyses.

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). The figure depicts observations of an unlit space located 2 km away from a single bright artificial light, viewed from different angles. Provided the source is bright enough, a sensor can detect light scattered by the atmosphere above the level of natural background (de Miguel et al., 2020; Wang et al., 2021). However, the radiance of scattered light depends on the viewing path, and here is larger when the path passes through the atmosphere above the source (Figures 2a and 2d).

Multi-angle observations of both a light source itself and nearby unlit areas can therefore provide information about extinction, bulk aerosol optical depth, the scattering phase function, aerosol particle size number distribution in the air column (see Supplement and Kocifaj & Bará, 2020; Kocifaj & Bará, 2022), complementing observations of aerosol properties during day. Future 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 (Cavazzani et al., 2020; Wang et al., 2016; Zhang et al., 2019; Zhou et al., 2021), much more theoretical and experimental work is needed.

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Figure 1. Aerial photo taken over Berlin on 15 March 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).

Reflected lunar light can also be used to estimate the bi-directional reflectance distribution function (BRDF) at high latitudes during polar night (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 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 be improved with multi-angle observations of reflected moonlight, and this would have two knock-on advantages for remote sensing using artificial light. First, improved moonlight

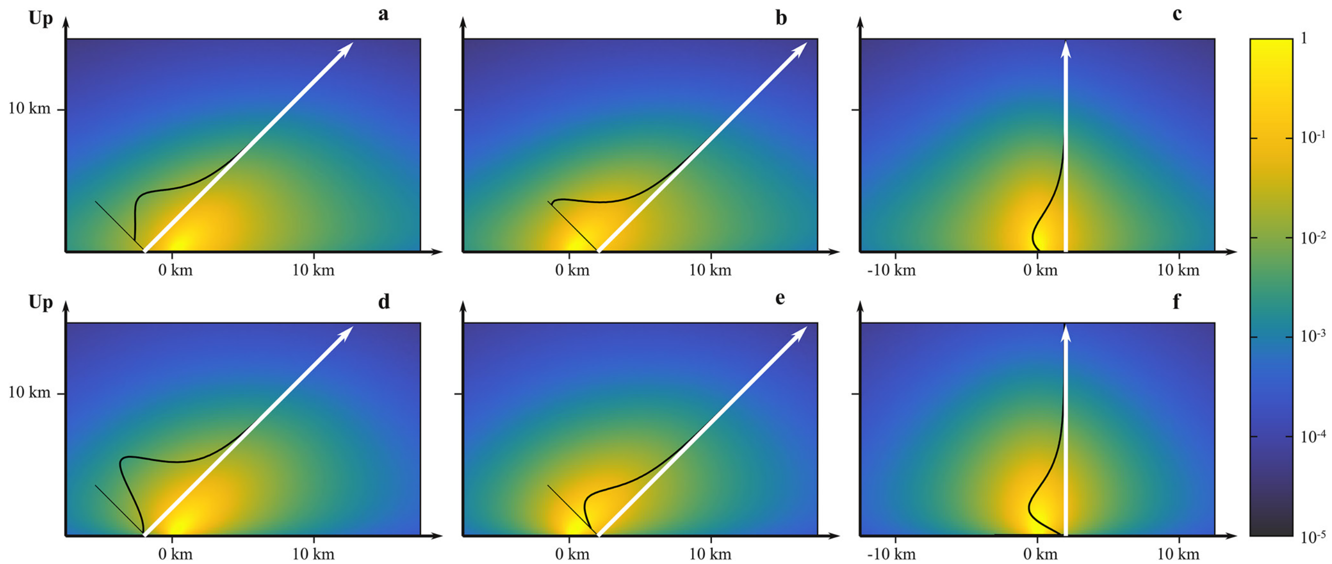

Figure 2. Schematic hypothetical views of an unlit area located 2 km from a light source. In each panel, the white arrow shows the direct light path from the emitter to the sensor. The top panels (a–c) are for a point source, the bottom panels (d–f) are for upward Lambertian emission. The colors indicate 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. Model details are provided in the supplement.

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 could be increased over what is currently possible.

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 an emitting (or scattering) object. One possible use of this phenomenon 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. For objects located on or 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 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 (and best detected by or together with the visual band Elvidge et al., 2019; Wang et al., 2020).

Multi-angle night lights 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 from that for light emitted from vertical surfaces (e.g., building and signs). Multi-angle views could therefore help differentiate commercial from residential buildings, especially at high resolution in city centers. 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 (Elvidge et al., 2020; Li et al., 2019; Solbrig et al., 2020; Tan et al., 2022; Tong et al., 2020). For land cover analyses, 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 rapidly.

Finally, consider detection of boats (Duan et al., 2019; Elvidge et al., 2018). This application is most 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 boats on moonlit nights, as the lunar reflection only affects some observing angles. In addition, in 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 (Gao et al., 2021).

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 (Kyba et al., 2017), it is unclear which lighting applications are responsible for the growth, as the relative fraction of light emissions from different types of sources is not well known (Bará et al., 2018; C. Kyba et al., 2021). Multi-angle imagery contains information about the light types, since different types have different upward angular radiance distributions (Figure S1 in Supporting Information S1). This complements multi-spectral imagery, which is also important in this context (De Meester & Storch, 2020; Elvidge et al., 2007; Sánchez de Miguel et al., 2019). Furthermore, since lighting practice varies at both continental (Falchi et al., 2019) and local (C. Kyba et al., 2021) scale, better understanding of lighting character based on multi-angle views stands to benefit all of the remote sensing applications based on night lights, such as estimating population or GDP (Gibson et al., 2020). Given the varied temporal practices in lighting, interpretation

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of multi-angle views assembled in a short time span over a single overpass is far 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 impact on observations of artificial lights (Figures S2–S3 in Supporting Information S1), 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; Tan et al., 2022; 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 (Elvidge et al., 2020). Similarly, leaf area cover changes often result in seasonal effects in blocking (and therefore affect time series), and the presence and heights of trees (relative to light sources) differs on small geographic scales. Additional information such as 3D models could in principle be used to account for this blocking, reducing the variability in night lights imagery. Multi-angle observations would be critical for verifying that such corrections work properly.

Drones are 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 helpful is in the study of ecological light pollution (Longcore & Rich, 2004). Animals generally do not view the world in nadir view, but rather look forward and to the side (Vandersteen et al., 2020; Van Doren et al., 2017). 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 emissions toward zenith. This is an area where citizen science could be of use, as people can observe light emission toward multiple azimuth and elevation angles directly from their homes.

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), which is a form of pollution with both cultural and ecological impacts (Gallaway, 2010; Torres et al., 2020). The angular distribution of light escaping above obstacles is one of the most critical parameters in skyglow simulation (Aubé, 2015), because 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 do not yet correctly account for the geographic variability in obstacle properties (see e.g., Espey, 2021). Direct measurement of the upward light emission using multi-angle views is therefore critically important for the progress of this field, and cannot wait for future satellites. Due to the decrease in emissions over the course of the night, multi-angle views on short time scales from satellites and especially drones (e.g., Li et al., 2020) may be preferable to the longer timescales of airplane-based surveys (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 by viewing unlit areas with low reflectance, such as rivers and parks (as in Figure 2 and de Miguel et al., 2020).

5. Conclusion

The study of night lights is a fascinating multidisciplinary topic, with major societal relevance. Artificial light emissions are both a form of pollution and source of information, and have deep intrinsic connections to human activity and energy consumption. Night lights are also continuously changing with the development of new technologies and environmental policy (such as the city of Pittsburgh's recent adoption of a Dark-Sky ordinance Carter, 2021). Our examples show that intentional acquisition of multi-angle views of night lights on short time scales could provide new information compared to existing night lights datasets, which would benefit numerous fields. Developing successful retrievals based on multi-angle views will require considerably more theoretical and experimental work. Ideally, multi-angle observations will not be undertaken on their own, but will rather contribute with other observations toward a deeper understanding of Earth's radiation field at night. For example, remotely sensed nighttime aerosol and surface properties could be re-used to sharpen night lights imagery by correcting for aerosols (Bu et al., 2019) and moonlight.

We hope that this commentary encourages researchers and funding agencies to consider how multi-angle views from existing platforms can be analyzed (or acquired). If the benefits are found to be sufficient, this could justify the development of future night lights satellites that perform intentional multi-angle acquisitions over short time scales.

Data Availability Statement

Figure 2 was produced using proprietary software described in Kolláth et al., 2021, which is not currently available but is planned to be openly released in the future. The image is meant as an example schematic, not a scientific result, and as such could be recreated by any radiative transfer algorithm.

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References

Aubé, M. (2015). Physical behaviour of anthropogenic light propagation into the nocturnal environment. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*(1667), 20140117. https://doi.org/10.1098/rstb.2014.0117

Aubé, M., & Simoneau, A. (2018). New features to the night sky radiance model illumina: Hyperspectral support, improved obstacles and cloud reflection. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *211*, 25–34. https://doi.org/10.1016/j.jqsrt.2018.02.033

Bará, S., Rodríguez-Arós, Á., Pérez, M., Tosar, B., Lima, R. C., Sánchez de Miguel, A., et al. (2018). Estimating the relative contribution of streetlights, vehicles, and residential lighting to the urban night sky brightness. *Lighting Research and Technology*, *51*(7), 1092–1107. https://doi.org/10.1177/1477153518808337

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. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *253*, 107155. https://doi.org/10.1016/j.jqsrt.2020.107155

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. https://doi.org/10.3390/s19173761

Carter, J. (2021). *Pittsburgh goes dark: Could this new dark-sky ordinance begin a trend?* Sky & Telescope.

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. https://doi.org/10.1093/mnras/staa3157

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. https://doi.org/10.1046/j.1365-8711.2000.03562.x

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. https://doi.org/10.3390/rs10121964

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. *Scientific Reports*, *10*(1), 7829. https://doi.org/10.1038/s41598-020-64673-2

De Meester, J., & Storch, T. (2020). Optimized performance parameters for nighttime multispectral satellite imagery to analyze lightings in urban areas. *Sensors*, *20*(11), 3313. https://doi.org/10.3390/s20113313

Diner, D. J., Beckert, J. C., Reilly, T. H., Bruegge, C. J., Conel, J. E., Kahn, R. A., et al. (1998). Multi-angle Imaging SpectroRadiometer (MISR) instrument description and experiment overview. *IEEE Transactions on Geoscience and Remote Sensing*, *36*(4), 1072–1087. https://doi.org/10.1109/36.700992

Dobler, G., Ghandehari, M., Koonin, S. E., Nazari, R., Patrinos, A., Sharma, M. S., et al. (2015). Dynamics of the urban lightscape. *Information Systems*, *54*, 115–126. https://doi.org/10.1016/j.is.2015.06.002

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. *Science of the Total Environment*, *647*, 606–618. https://doi.org/10.1016/j.scitotenv.2018.07.359

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. https://doi.org/10.7125/apan.35.7

Elvidge, C. D., Cinzano, P., Pettit, D. R., Arvesen, J., Sutton, P., Small, C., et al. (2007). The nightsat mission concept. *International Journal of Remote Sensing*, *28*(12), 2645–2670. https://doi.org/10.1080/01431160600981525

Elvidge, C. D., Ghosh, T., Baugh, K., Zhizhin, M., Hsu, F.-C., Katada, N. S., et al. (2018). Rating the effectiveness of fishery closures with visible infrared imaging radiometer suite boat detection data. *Frontiers in Marine Science*, *5*, 132. https://doi.org/10.3389/fmars.2018.00132

Elvidge, C. D., Hsu, F.-C., Zhizhin, M., Ghosh, T., Taneja, J., & Bazilian, M. (2020). Indicators of electric power instability from satellite observed nighttime lights. *Remote Sensing*, *12*(19), 3194. https://doi.org/10.3390/rs12193194

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. https://doi.org/10.3390/rs70303020

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. https://doi.org/10.3390/rs11040395

Espey, B. R. (2021). Empirical modelling of public lighting emission functions. *Remote Sensing*, *13*(19), 3827. https://doi.org/10.3390/rs13193827

Falchi, F., Cinzano, P., Duriscoe, D., Kyba, C. C., Elvidge, C. D., Baugh, K., et al. (2016). The new world atlas of artificial night sky brightness. *Science Advances*, *2*(6), e1600377. https://doi.org/10.1126/sciadv.1600377

Falchi, F., Furgoni, R., Gallaway, T., Rybnikova, N., Portnov, B., Baugh, K., et al. (2019). Light pollution in USA and Europe: The good, the bad and the ugly. *Journal of Environmental Management*, *248*, 109227. https://doi.org/10.1016/j.jenvman.2019.06.128

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. *Chronobiology International*, *1–21*.

Gallaway, T. (2010). On light pollution, passive pleasures, and the instrumental value of beauty. *Journal of Economic Issues*, *44*(1), 71–88. https://doi.org/10.2753/jei0021-3624440104

Gao, M., Knobelspiesse, K., Franz, B. A., Zhai, P.-W., Martins, V., Burton, S. P., et al. (2021). *Adaptive data screening for multi-angle polarimetric aerosol and ocean color remote sensing accelerated by deep learning*. UMBC GESTAR II.

Gibson, J., Olivia, S., & Boe-Gibson, G. (2020). Night lights in economics: Sources and uses 1. *Journal of Economic Surveys*, *34*(5), 955–980. https://doi.org/10.1111/joes.12387

Kocifaj, M., & Bará, S. (2020). Aerosol characterization using satellite remote sensing of light pollution sources at night. *Monthly Notices of the Royal Astronomical Society*, *495*(1), L76–L80. https://doi.org/10.1093/mnrasl/slaa060

Kocifaj, M., & Bará, S. (2022). Diffuse light around cities: New perspectives in satellite remote sensing of nighttime aerosols. *Atmospheric Research*, *266*, 105969. https://doi.org/10.1016/j.atmosres.2021.105969

Kocifaj, M., Solano-Lamphar, H. A., & Videen, G. (2019). Night-sky radiometry can revolutionize the characterization of light-pollution sources globally. *Proceedings of the National Academy of Sciences*, *116*(16), 7712–7717. https://doi.org/10.1073/pnas.1900153116

Kolláth, Z., Száz, D., & Kolláth, K. (2021). Measurements and modelling of aritificial sky brightness: Combining remote sensing from satellites and ground-based observations. *Remote Sensing*, *13*(18), 3653. https://doi.org/10.3390/rs13183653

Kyba, C., Ruby, A., Kuechly, H. U., Kinzey, B., Miller, N., Sanders, J., et al. (2021). Direct measurement of the contribution of street lighting to satellite observations of nighttime light emissions from urban areas. *Lighting Research and Technology*, *53*(3), 189–211. https://doi.org/10.1177/1477153520958463

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, pp. 568–571).

Kyba, C. C., Kuester, T., de Miguel, A. S., Baugh, K., Jechow, A., Hölker, F., et al. (2017). Artificially lit surface of Earth at night increasing in radiance and extent. *Science Advances*, *3*(11), e1701528. https://doi.org/10.1126/sciadv.1701528

Levin, N., Kyba, C. C., Zhang, Q., Sánchez de Miguel, A., Román, M. O., Li, X., et al. (2020). Remote sensing of night lights: A review and an outlook for the future. *Remote Sensing of Environment*, *237*, 111443. https://doi.org/10.1016/j.rse.2019.111443

Li, J., Qiu, S., Zhang, Y., Yang, B., Gao, C., Qian, Y., et al. (2021). Assessment of BRDF impact on VIIRS DNB from observed top-of-atmosphere reflectance over Dome C in nighttime. *Remote Sensing*, *13*(2), 301. https://doi.org/10.3390/rs13020301

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 Sensing of Environment*, *247*, 111942. https://doi.org/10.1016/j.rse.2020.111942

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 Sensing of Environment*, *233*, 111357. https://doi.org/10.1016/j.rse.2019.111357

Longcore, T., & Rich, C. (2004). Ecological light pollution. *Frontiers in Ecology and the Environment*, *2*(4), 191–198. https://doi.org/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* (Vol. 121, pp. 204–212). Publications of the Astronomical Society of the Pacific. https://doi.org/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. *International Journal of Sustainable Lighting*, *20*(1), 11–28. https://doi.org/10.26607/ijsl.v19i2.82

Miller, S. D., Straka, W., Mills, S. P., Elvidge, C. D., Lee, T. F., Solbrig, J., et al. (2013). Illuminating the capabilities of the Suomi National Polar-Orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band. *Remote Sensing*, *5*(12), 6717–6766. https://doi.org/10.3390/rs5126717

Miller, S. D., Straka, W. C., Yue, J., Smith, S. M., Alexander, M. J., Hoffmann, L., et al. (2015). Upper atmospheric gravity wave details revealed in nightglow satellite imagery. *Proceedings of the National Academy of Sciences*, *112*(49), E6728–E6735. https://doi.org/10.1073/pnas.1508084112

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. https://doi.org/10.1109/tgrs.2009.2012696

Román, M. O., Wang, Z., Sun, Q., Kalb, V., Miller, S. D., Molthan, A., et al. (2018). NASA's Black Marble nighttime lights product suite. *Remote Sensing of Environment*, *210*, 113–143. https://doi.org/10.1016/j.rse.2018.03.017

Sánchez de Miguel, A. S., Kyba, C. C., Aubé, M., Zamorano, J., Cardiel, N., Tapia, C., et al. (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 Sensing of Environment*, *224*, 92–103. https://doi.org/10.1016/j.rse.2019.01.035

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. *Atmospheric Measurement Techniques*, *13*(1), 165–190. https://doi.org/10.5194/amt-13-165-2020

Tan, X., Zhu, X., Chen, J., & Chen, R. (2022). Modeling the direction and magnitude of angular effects in nighttime light remote sensing. *Remote Sensing of Environment*, *269*, 112834. https://doi.org/10.1016/j.rse.2021.112834

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. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *249*, 107009. https://doi.org/10.1016/j.jqsrt.2020.107009

Torres, D., Tidau, S., Jenkins, S., & Davies, T. (2020). Artificial skyglow disrupts celestial migration at night. *Current Biology*, *30*(12), R696–R697. https://doi.org/10.1016/j.cub.2020.05.002

Vandersteen, J., Kark, S., Sorrell, K., & Levin, N. (2020). Quantifying the impact of light pollution on sea turtle nesting using ground-based imagery. *Remote Sensing*, *12*(11), 1785. https://doi.org/10.3390/rs12111785

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. *Proceedings of the National Academy of Sciences*, *114*(42), 11175–11180. https://doi.org/10.1073/pnas.1708574114

Walczak, K., Gyuk, G., Garcia, J., & Tarr, C. (2021). Light pollution mapping from a stratospheric high-altitude balloon platform. *International Journal of Sustainable Lighting*, *23*(1), 20–32. https://doi.org/10.26607/ijsl.v23i1.106

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. https://doi.org/10.1016/j.atmosenv.2015.11.013

Wang, J., Roudini, S., Hyer, E. J., Xu, X., Zhou, M., Garcia, L. C., et al. (2020). Detecting nighttime fire combustion phase by hybrid application of visible and infrared radiation from Suomi NPP VIIRS. *Remote Sensing of Environment*, *237*, 111466. https://doi.org/10.1016/j.rse.2019.111466

Wang, Z., Román, M. O., Kalb, V. L., Miller, S. D., Zhang, J., & Shrestha, R. M. (2021). Quantifying uncertainties in nighttime light retrievals from suomi-NPP and NOAA-20 VIIRS day/night band data. *Remote Sensing of Environment*, *263*, 112557. https://doi.org/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. *Atmospheric Measurement Techniques*, *12*(6), 3209–3222. https://doi.org/10.5194/amt-12-3209-2019

Zhou, M., Wang, J., Chen, X., Xu, X., Colarco, P., Miller, S. D., et al. (2021). Nighttime smoke aerosol optical depth over u.s. rural areas: A retrieval from VIIRS Day/Night Band moonlight observations. *Remote Sensing of Environment*, *257*. in press.

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

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. https://doi.org/10.1088/0022-3727/42/17/173001

References From the Supporting Information

Holben, B. N., Eck, T. F., Slutsker, I. a., Tanre, D., Buis, J., Setzer, A., et al. (1998). Aeronet—A federated instrument network and data archive for aerosol characterization. *Remote Sensing of Environment*, *66*(1), 1–16. https://doi.org/10.1016/s0034-4257(98)00031-5

Johnson, R. S., Zhang, J., Hyer, E. J., Miller, S. D., & Reid, J. S. (2013). Preliminary investigations toward nighttime aerosol optical depth retrievals from the VIIRS Day/Night Band. *Atmospheric Measurement Techniques*, *6*(5), 1245–1255. https://doi.org/10.5194/amt-6-1245-2013

McHardy, T., Zhang, J., Reid, J., Miller, S., Hyer, E., & Kuehn, R. (2015). An improved method for retrieving nighttime aerosol optical thickness from the VIIRS Day/Night Band. *Atmospheric Measurement Techniques*, *8*(11), 4773–4783. https://doi.org/10.5194/amt-8-4773-2015

Miguel, A. S. (2022). Current multispectral night data sources from the orbit: The international Space Station and other sources. *Zenodo*. https://doi.org/10.5281/zenodo.6409120

Sánchez de Miguel, A. (2015). Variación espacial, temporal y espectral de la contaminación lumınica y sus fuentes: Metodologıa y resultados. (Doctoral dissertation). https://doi.org/10.5281/zenodo.1289932

Zhang, J., Spurr, R. J., Reid, J. S., Xian, P., Colarco, P. R., Campbell, J. R., et al. (2020). Development of an OMI AI data assimilation scheme for aerosol modeling over bright surfaces–a step toward direct radiance assimilation in the UV spectrum. *Geoscientific Model Development*, 1–47.