

## ***Corrigendum to*** **“Assessing the stability of surface lights for use in retrievals of nocturnal atmospheric parameters” published in Atmos. Meas. Tech., 13, 165–190, 2020**

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This document contains corrections to a previously published article. Please find the corrected text below. The changes are necessary to correct a sign error in our original paper, wherein “east” and “west” were flipped in handling the solar zenith angle. The required changes are fairly minimal but do require a small change in the interpretation of our results.

### **5.3 Directional satellite zenith angle dependency**

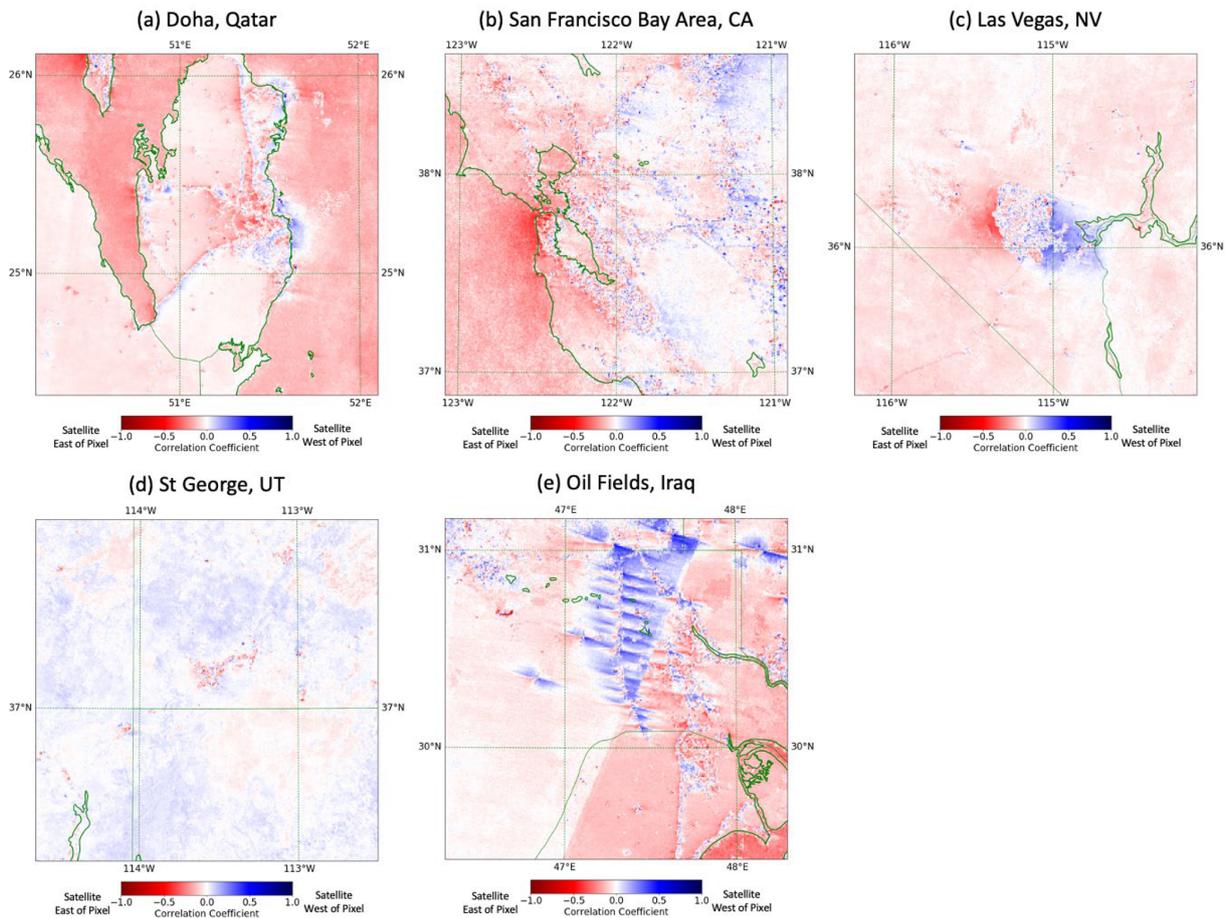
The relationship between day–night band (DNB) radiance and satellite zenith (SZ) angle gave information on whether a location is brighter when viewed from above or from an oblique angle but is unable to tell us anything about the across-track directionality of a light source. To examine whether there is a dependence between DNB radiance and the direction from which a location is viewed when viewed from an oblique angle, we adjust the satellite zenith angle to create the directional satellite zenith (DSZ) angle. While the satellite azimuth angle might be used to fill this role, its results are difficult to interpret and result in more nonlinear relationships. The DSZ ranges from  $-70$  to  $70^\circ$  and is defined such that when the satellite is to the west of the location it is viewing (i.e., the satellite is looking eastward across its track) the DSZ is positive, and when the satellite is to the east of the location it is viewing (i.e., the satellite is looking westward across its track) the DSZ is negative. Given this definition for DSZ, a positive correlation between DNB radiance and DSZ indicates that a location is brighter when the satellite is

positioned to the location’s west (looking east), and a negative correlation indicates that a location is brighter when the satellite is positioned to the location’s east (looking west).

Correlation between DNB radiance and DSZ is shown for each of the five domains in Fig. 11. It is immediately obvious from these figures that many locations are brighter when viewed from one direction than when viewed from the other. While, for this study, we are most interested in the response of populated locations to viewing conditions, it is difficult to draw specific conclusions from city locations due to their high spatial variability in this relationship. The directionality of emission and blocking of light due to buildings make cities difficult to directly interpret but are important if city lights are to be used as light sources for retrievals.

Unpopulated land and ocean surfaces are much easier to interpret. For example, the land surface on the eastern (western) side of a bright light source is brighter when the satellite is west (east) of the location it is viewing. This is most obvious in the unpopulated locations to the east and west of Las Vegas (Fig. 11c). Locations to the east of Las Vegas are brightest when viewed from the west (blue), and locations to the west of Las Vegas are brightest when viewed from the east (red). This indicates that the city’s light dome, which is created by atmospheric scattering of light emitted by the city, is contributing path radiance to the DNB signal. Another example of this can be seen in the unpopulated locations surrounding the highway that runs northwards from Doha, Qatar, to the northern tip of the peninsula (Fig. 11a). Locations immediately east of the highway are brighter when viewed from the west (blue), while locations immediately

## Correlation Coefficient: DNB Radiance vs. Directional Satellite Zenith Angle



**Figure 11.** Same as Fig. 8 but for DNB radiance vs. directional satellite zenith angle ( $-70$  to  $70^\circ$ ). Positive (negative) values of the directional satellite zenith angle indicate that the satellite is positioned to the west (east) of the location that it is viewing. Positive (blue) values of the correlation coefficient indicate that a location appears brighter when viewed by a satellite positioned to the west of that location (i.e., when the DNB is looking toward the east). Negative (red) values indicate that a location appears brighter when viewed by a satellite positioned to the east of that location (i.e., when the DNB is looking toward the west). Zero correlation (white) indicates that a location's brightness is independent of viewing direction.

west of the highway are brighter when viewed from the east (red), and the locations that contain the highway itself show no correlation with DSZ (white). Similar features can be seen around most population centers, with locations to the east (west) of the populated area brighter when viewed from the west (east) and the population centers themselves a mix of different relationships.

Another notable feature is a general negative (i.e., brightest when viewed from the east) correlation of both land and ocean features. With the exception of areas near populated locations (and the St. George, UT, domain, which is very rugged), unpopulated land and ocean tend to be brighter when viewed from the west. This can be explained by considering lunar geometry and the orbit of Suomi-NPP. Since Suomi-NPP views each location at approximately 01:30 LT a larger fraction of the lunar disk is illuminated when the moon

is on the western side of the swath than when it is on the eastern side of the swath. This geometry means that, on average, more lunar illumination reaches the sensor when viewing a flat, unpopulated location from an eastward vantage point. Figure 12 shows correlations between DNB radiance and DSZ for only moonless nights ( $SZ > 95^\circ$ ). In this figure, without lunar illumination, the general tendency for unpopulated locations to be brighter when viewed from the east disappears. The correlation between DNB radiance and DSZ for locations far from population centers (e.g., the southwest corner of the San Francisco domain) is weak. The weakness of the correlation in these locations can be attributed to their radiance values, which approach the noise floor for the sensor.

As noted previously, the unpopulated locations in the St. George, UT, domain (Fig. 11d) do not exhibit the same trend

as the unpopulated locations from other domains. This is likely due to a combination of rugged terrain and, possibly, different scattering properties of the surface. Another area that breaks from the general trend for unpopulated locations is the northern tip of the Southern Coast Ranges located to the east of San Jose, CA, in Fig. 11b. As seen in Fig. 12b, under moonless conditions this region is brighter when viewed from the west. This could be due to backscatter of light from the Bay Area cities off the mountainous land surface. The opposite phenomenon can be seen to the west of the San Jose area.

## 7 Summary and conclusions

To develop a baseline understanding of the characteristics of nighttime light sources and aid efforts towards nighttime atmospheric retrievals of cloud and aerosol properties, we have collected 18 months of data from the VIIRS day–night band, four coincident brightness temperature channels, and several variables that describe Earth–satellite and Earth–moon geometries. The data were cloud-cleared using the VIIRS cloud mask (Sect. 3.1) and manual examination of the imagery (Sect. 3.2). We then examined the stability of a variety of terrestrial light sources as observed by the DNB in several different Northern Hemisphere domains (Sect. 4). Additionally, we have explored the correlations that exist between DNB-observed visible radiance, infrared brightness temperature, and the geometric variables (Sect. 5).

Some general conclusions that can be drawn from this study include the following.

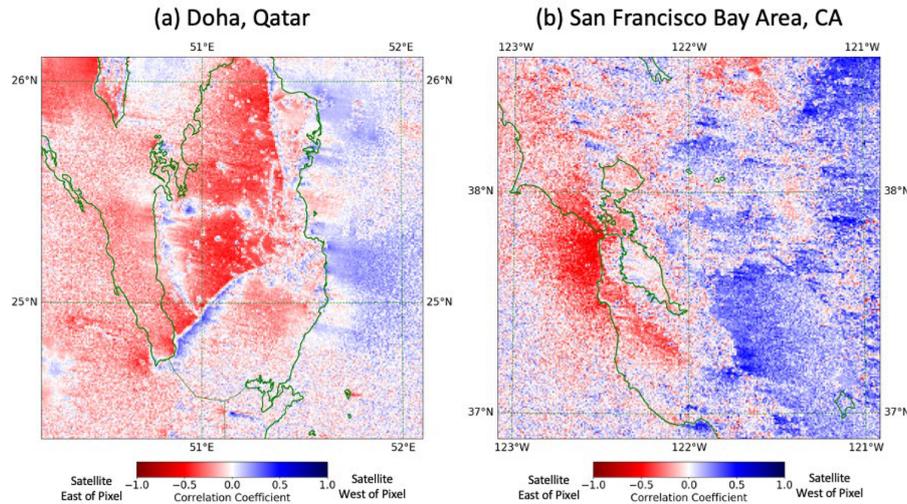
- Both populated and unpopulated locations exhibit a wide range of stabilities.
- Even the most stable locations in this study have some variability (on the order of 10 %–20 % relative standard deviation).
- Some light sources are stable enough that they might provide the stability required to make accurate aerosol optical depth (AOD) retrievals ( $RSD < 0.2$ ), but many others are not.
- Stable locations appear to be coincident with population centers such as the Financial District in San Francisco and the densely populated areas of Doha, Qatar.
- Suburban locations vary over a wide range of relative standard deviation (RSD) values but can be relatively stable as well.
- Significant vertical structure can cause light to be blocked when viewed from the sides. These locations appear brighter when viewed from above than when viewed from the sides.

- Areas with a lack of vertical structure can exhibit the opposite correlation (i.e., brighter when viewed from the side).
- Some locations (e.g., airports and the Las Vegas Strip) that might be expected to be useful as light sources for retrievals are unstable and would result in significant errors in retrievals that rely on those light sources.
- While the data in this study are limited for physically hot light sources, such as the flames emitted by oil wells, these light sources appear to be unstable and are likely unreliable as light sources for retrievals.
- DNB radiance observed from unpopulated locations is generally unstable in time.
- Unpopulated areas near bright light sources are more stable and are brightest when the satellite’s observation path goes above the light source, passing through its light dome.

Section 5 discusses potential sources for the variability observed in this study and examines the correlations between DNB radiance and other variables. We find that for unpopulated locations, the lunar zenith angle, which correlates well with the lunar phase for Suomi-NPP’s 01:30 LT overpass time, likely explains much of the variability. However, proximity to visible emission sources, rugged terrain, and surface scattering effects have impacts on the brightness of unpopulated locations.

More to the point of this study, the brightness of populated locations exhibits a variety of different relationships. Due to the brightness of populated locations, which can be orders of magnitude higher in DNB radiance than unpopulated locations even under full-moon conditions, populated locations have little dependence on lunar zenith angle and lunar phase (Sect. 5.1). The visible brightness of populated locations appears to correlate most strongly with satellite viewing geometry. As seen in Sect. 5.2, locations that contain a significant number of tall buildings appear brighter when viewed from above (low satellite zenith angle) than when viewed from oblique angles (high satellite zenith angle). Other locations that exhibit a similar negative correlation between satellite zenith angle and DNB radiance are locations with significant numbers of vertically pointing lights such as lighted highways and shopping complexes with large lighted parking lots. Conversely, less densely populated locations such as residential neighborhoods appear brighter when viewed from an oblique angle (high satellite zenith angle), likely due to the directionality of light emission and a lack of occluding structures such as tall buildings. For locations that appear brighter when viewed from an oblique angle it is also important to consider which direction they are viewed from (Sect. 5.3). For populated locations, this directional dependence is likely caused by the direction of light emission from the source and occlusions such as tall buildings.

## Correlation Coefficient: DNB Radiance vs. Directional Satellite Zenith Angle Moonless Nights



**Figure 12.** Correlation coefficient on moonless nights (lunar zenith angle  $> 95^\circ$ ) for DNB radiance with directional satellite zenith angle ( $-70$  to  $70^\circ$ ) for (a) Qatar and (b) the San Francisco Bay Area, CA. Negative (red) values indicate that a location appears brighter when viewed from the east (i.e., DNB looking toward the west). Positive (blue) values indicate that a location appears brighter when viewed from the west (i.e., DNB looking toward the east). Values of zero (white) indicate that there is no correlation between the brightness of the pixel and viewing direction.

While most of the observed brightness of most light sources shows little correlation with infrared brightness temperature (Sect. 4), temperature is an important factor for some physically hot light sources. For example, oil wells and refineries sometimes burn off excess gas, resulting in visibly bright, physically hot light sources. As stated previously, the data for physically hot light sources are limited in this study; however, it can be said that these light sources exhibit a strong relationship between DNB radiance and infrared brightness temperature. With additional data and study it might be possible to constrain the brightness of these physically hot emission sources using retrieved estimates of their physical temperatures, but that is a subject for further research.

The two major sources of error in this study are cloud contamination in our dataset and the use of nearest-neighbor interpolation to map our data to standard latitudes and longitudes. Despite our best efforts at cloud screening using both the automated VIIRS cloud mask and manual examination of the imagery, it is certain that some cloud contamination remains in the dataset. Improvement in this area would require the development of a more robust nocturnal cloud mask, especially with regards to low-altitude cloud layers. Interpolation to standard latitudes and longitudes is required for the development of time series; however, this process does not adequately account for the point-spread function of the sensor. More sophisticated methods that do not require interpolation of the data may yield better results.

Although this study has been limited in scope it indicates that different visible emission sources will have differing levels of usefulness for efforts to use terrestrial emissions as stable light sources due to their inherent temporal instability. The temporal stability of each light source should be examined prior to use in retrieval algorithms to avoid using unstable sources. Studies that endeavor to use terrestrial light sources in retrieval algorithms should also consider the impacts of viewing geometry on the observed brightness of light sources under cloud-clear conditions, even for the most temporally stable locations.

Further research will be required to develop datasets that can be used as the basis of retrieval algorithms. In the future we hope to expand this study to larger domains and over longer time periods using the data available from both Suomi-NPP and JPSS-1. Expanding the study to larger domains, however, will require improvements to cloud masking techniques to remove the need for expert screening. We are currently examining methods to improve upon IR-based cloud masks by including information from the DNB over light sources. Additionally, future work will examine the stability and spatial characteristics of spatially grouped city lights to determine if stability and spatial variability over a larger area may prove to be more useful for retrieval algorithms. We also hope to extend the work we have done with correlation coefficients to develop models that are able to describe the variability of city lights under cloud-cleared conditions to reduce the uncertainty in assumed brightness.