ANALYZING ARTIFICIAL NIGHTTIME LIGHTING USING HYPERSPECTRAL DATA FROM ENMAP

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ABSTRACT

Over the years, space-based remote sensing of nighttime light has mostly utilized panchromatic or multispectral sensors. The hyperspectral mission EnMAP, primarily intended for daytime observations, can also produce hyperspectral data of nighttime lighting. EnMAP data from the Las Vegas Strip was analyzed by detecting locations of certain lighting types using matched filtering and detection of sharp emission spikes at known wavelengths. Additionally, images from different nights were compared to determine how changes in observation geometry affect the observed spectra. The results indicate that corrections for geometric effects would be necessary to produce robust time-series data. The EnMAP data were also used to approximate two indices related to the efficiency and spectral quality of the light, the luminous efficiency of radiation (LER) and the spectral G index. Future developments will include analyzing scenes from other cities using similar approaches. Program code used in this work is available at `https://github.com/silmae/EnMAP_nightlights`.

***Index Terms*—** Remote sensing, hyperspectral, nighttime observation, artificial light, EnMAP

1. INTRODUCTION

Remote sensing of artificial nighttime light can be used for example to monitor the progress of urbanization and the level of nocturnal human activity. Up to now space-based nighttime data has been produced mainly with panchromatic or in a few cases multispectral sensors [1]. In order to characterize and classify the lighting itself, the measurement of a full spectrum with a high number of contiguous spectral channels is desirable [2]. The EnMAP mission [3] includes a hyperspectral push-broom sensor that is primarily intended for daytime use, but is also suitable for nighttime observation of artificial lighting [4]. EnMAP data cover the spectral range between 420 nm and 2450 nm in a total of 224 wavelength channels and each tile covers approximately 30 km by 30 km with a spatial resolution of 30 m.

In this work we build on the previous publication of [4], where the authors used EnMAP data to examine the nighttime lighting of Las Vegas. We focus on the same area but analyze images from different nights and apply other methods to locate areas with emissions from certain lighting types. We also compare images from different nights and finally produce maps of indices designed to characterize the efficiency and spectral quality of the lighting.

2. MATERIALS AND METHODS

We analyzed four EnMAP images from the Las Vegas area, taken on four different nights between 8.7.2023 and 8.8.2023. Each image was captured at approximately 21:40 local time during the spacecraft's ascending orbit. The images were retrieved as georeferenced L1C data products (top-of-atmosphere radiances) from the EnMAP portal where they are freely available. All four images were subset to the show the same area with the Las Vegas Strip in the center of the images. An RGB reconstruction created from one of the images can be seen in Fig. 1.

Spectral matched filtering was used to detect the locations of certain types of illuminants. The target signals for the matched filter were spectral radiances of different lamps measured in a laboratory setting in [2]. To implement the matched filtering of the images we used the Python package `spectral` (version 0.21) [5].

Locations of gas discharge lamps such as metal halide and mercury vapor lamps were also examined by looking for sharp atomic emission spikes at 1140 nm and 2208 nm . The spikes were located by considering the spectral channels closest to these wavelengths and comparing the values to the mean value of the adjacent channels. Results of the comparison were turned into a binary map of spike locations by choosing

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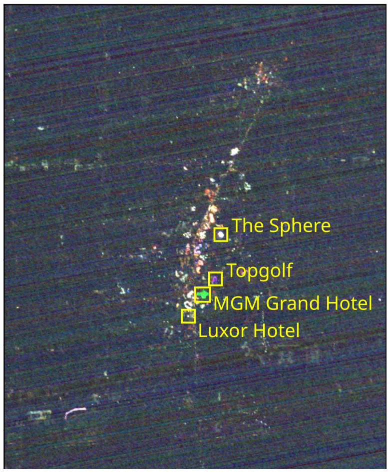


Fig. 1: RGB reconstruction created from an EnMAP image captured on 16.7.2023, with the locations and names of some interesting targets marked on the image. The RGB image was created by averaging 10 spectral channels around the wavelengths 640 nm, 540 nm, and 460 nm, and assigning the averaged images to red, green, and blue channels of the image.

threshold values for the spike heights.

The four images taken on different nights were compared by examining changes in the spectra of two light sources: the Luxor Hotel Sky Beam and the green exterior lighting of the MGM Grand Hotel. The Luxor light source is smaller than EnMAP's spatial resolution limit at approximately five meters, while the MGM grand is a cross-shaped structure more than 300 meters across. The comparison was done by locating the light source separately in each image, calculating the mean spectrum of the approximate area encompassed by the light source, and plotting these mean spectra from different nights in a single figure.

Finally, we calculated maps of two indices related to the efficiency and spectral quality of lighting: the luminous efficiency of radiation (LER) and the spectral G index. LER is defined as the fraction of light useful for the human visual system: the amount of light seen by human eyes divided by the total amount of electromagnetic radiation. Light sources that emit infrared radiation in addition to visible light thus exhibit low LER values. The spectral G index is a measure of how blue the detected light is, with its calculation motivated by blue light's greater contribution to light pollution and possible health risks related to it [6]. The spectral G index is calculated by dividing the amount of light below 500 nm by the amount of light seen by the human eye, taking the decimal logarithm of this value, and finally multiplying it by -2.5 [6]. Lower values of the G index indicate large amounts of blue light.

It is to be noted that calculating these indices from EnMAP data requires an approximation due to the limited wavelength range of the instrument. The lower limit of EnMAP is 420 nm, yet the definitions of both indices include wavelengths shorter than this. This discrepancy will affect especially the values of the G index, which focuses on these short wavelengths.

3. RESULTS

3.1. Matched filtering

Figure 2(a) shows a combination of three matched filter outputs as an RGB image. This map was created by assigning the filter outputs for red, green, and blue OSRAM LED testers as the three channels of an RGB image, and using a 3×3 median filter on the resulting image to reduce noise.

An area of special interest in this figure is that of the Sphere, shown enlarged in a smaller window. This location has a 150 m diameter spherical concert hall that has its outer surface covered by an LED display. The display is typically used to show constantly shifting animations. As expected, the matched filters of RGB LEDs show activation in this area. Figure 2(b) shows spectra of some pixels from the area of the sphere, where the separate emission peaks of the colored LEDs are clearly visible.

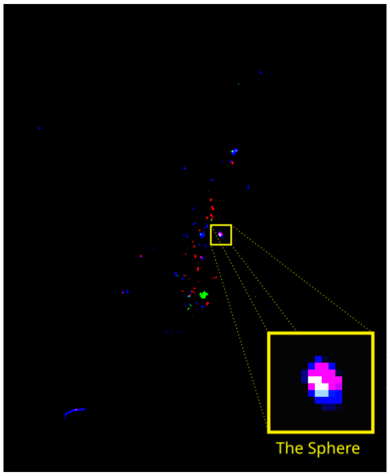
The matched filter for the blue LED spectrum also activated on some areas illuminated by white LEDs. These light-sources are typically constructed by encasing a blue LED in a fluorescent material, resulting in a spectral profile that includes the peak of blue LED emission together with emission from the fluorescence.

3.2. Atomic emission spikes

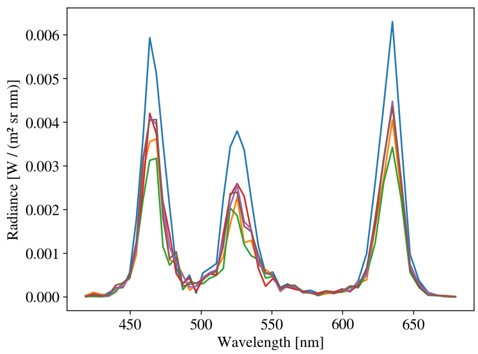
Detected locations of atomic emission spikes at two wavelengths, 1140 nm and 2208 nm, are presented in Fig. 3(a), while Fig. 3(b) shows an example spectrum from a pixel where both spikes were detected. Narrow emissions at these wavelengths are commonly seen in gas discharge lamps, and the locations of these spikes could approximate the locations of such illuminants. The spectrum in Fig. 3(b) highlights the capability of EnMAP in detecting narrow emission peaks in both the VNIR and SWIR wavelengths.

3.3. Comparing observations from different nights

To examine differences between the four EnMAP images from the same area, spectra from the same location from all images were plotted next to each other. This was done for the Luxor Hotel Sky Beam, and the green exterior lighting of the MGM Grand Hotel, and the results are presented in Fig. 4. The differences between the four observations of the Luxor Sky Beam are drastic, with the highest intensity approximately a hundred times stronger than the lowest one. The images with the smallest and largest across-track off-nadir angles exhibit the highest and lowest radiances, respectively. For the MGM Grand the differences between the images are

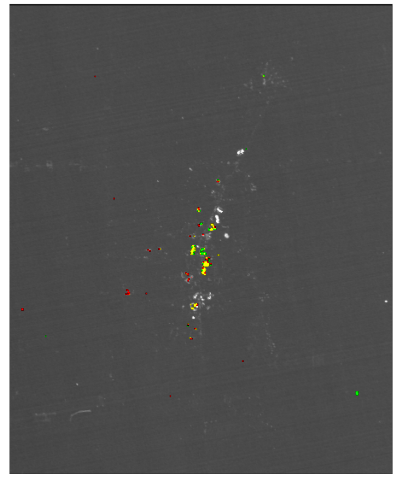


(a) Matched filter output

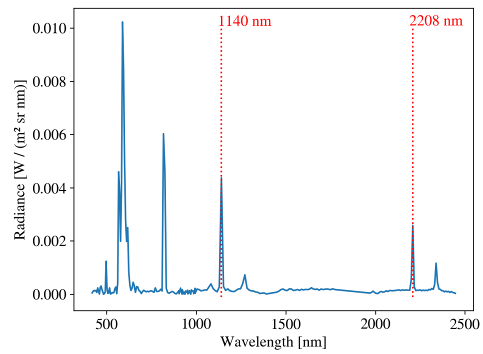


(b) Sphere spectra

Fig. 2: RGB image from matched filter outputs for red, green and blue LEDs (a), and some spectra from the area of the Sphere (b). The analyzed image was captured on 16.7.2023.



(a) Atomic emission spike map



(b) Spectrum

Fig. 3: Subfigure (a) shows a map of detected narrow emission spikes at 1140 nm (green) and 2208 nm (red) wavelengths. Yellow pixels indicate detection of both spikes, and the white areas show the radiance integrated over wavelengths for context. Subfigure (b) shows an example spectrum from a pixel with both spikes detected. The analyzed image was captured on 16.7.2023.

much smaller. Additionally, the observed radiance does not decrease as the off-nadir angle increases.

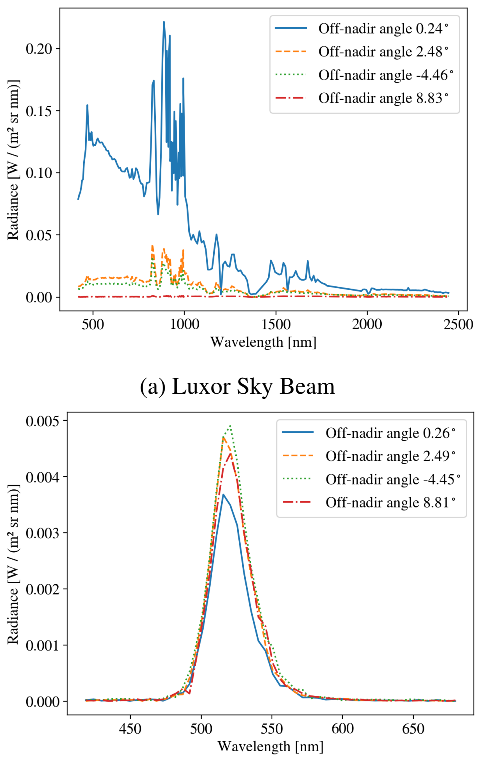
We suspect the differences in the trends observed for the two light sources are mainly caused by differences in the geometry of the lighting. The Luxor Sky Beam is a directional high-power xenon lightsource aimed straight up, while for the MGM Grand the lighting is used to illuminate the walls of the building. Other than the lighting geometry, differences in atmospheric conditions and the observation geometry may also cause different degree of absorption in the atmosphere.

3.4. LER and G index

Approximative maps of LER and G index calculated from one of the EnMAP images are presented in Fig. 5. In both maps the location of the brightest lightsource, the Luxor Sky Beam, is fairly dark. As seen in the spectra of the Sky Beam in Fig. 4(a), the emission has large amounts of infrared not useful for the human visual system, lowering the LER value for this location. The spectrum also has a significant amount of blue light in it, leading to a low value for the G index as well. For the G index, another interesting target is the dark region of the Topgolf golf range. This area is illuminated with adjustable colored lights, which can be seen in Fig. 1 to have a blueish tint.

4. DISCUSSION AND CONCLUSIONS

High-resolution hyperspectral images from EnMAP were used to analyze artificial nighttime lighting of the Las Vegas Strip. Spectral matched filtering and searching for sharp emission spikes at known wavelengths were used to locate certain types of light sources. While these are not the most sophisticated or accurate methods to detect the lighting type from the spectral profiles, they are simple to implement, are reasonably cheap in terms of computational resources, and



(a) Luxor Sky Beam

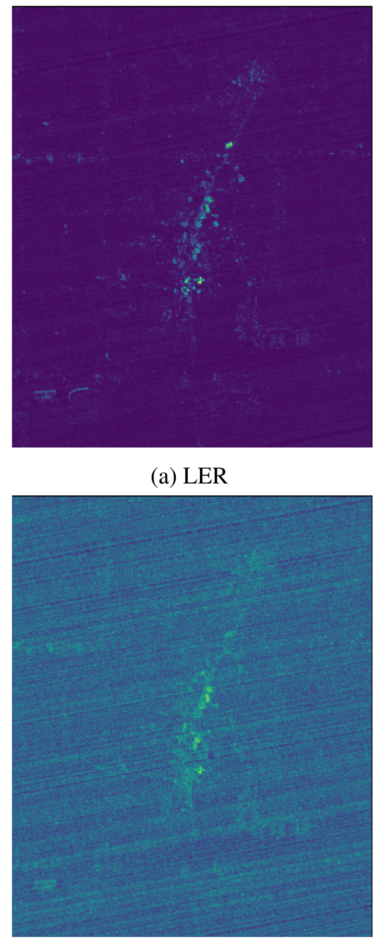
(b) MGM Grand

Fig. 4: Differences in observed spectral radiance on different nights for the Luxor Sky Beam and the MGM Grand Hotel. The legend in both subfigures lists the across-track off-nadir angles of the targets.

appear to produce decent results.

Differences between images captured on separate nights were analyzed by examining four spectra of the Luxor Hotel Sky Beam and four spectra of the exterior lighting of the MGM Grand Hotel. Spectra from different nights from the same light source show large differences. We suspect the changes are caused by differences in observation geometry and atmospheric conditions. The upward-pointing directional lamp of Luxor is not a common case, but analyzing spectra from it and comparing the changes to MGM show how the directionality of the observed lights can affect the results. Implementing correction for the geometric effects could enable time series analysis of the images.

To analyze the efficiency and spectral quality of nighttime lighting, luminous efficiency of radiation (LER) and the spectral G index can be approximated using data from EnMAP. As EnMAP's wavelength range does not extend below 420 nm, these approximative indices are not directly comparable to results from other data. Scattering and absorption in the atmosphere may also have affected the shape of the spectra, and thus the values of the indices. However, we still see value in calculating the approximative indices, as they could successfully locate inefficient lighting and blue lighting. Such maps could be invaluable to decision-makers responsible for regulating outdoor lighting.



(a) LER

(b) G index

Fig. 5: Approximative maps of luminous efficiency of radiation (LER) and spectral G index calculated from an EnMAP image captured on 16.7.2023.

Our study illustrates that EnMAP data is of sufficient quality to derive a wealth of useful information in the challenging case of nighttime observations despite this not being the main aim of the mission. Las Vegas has many well-known lightsources and is famous for its bright nightlights, but EnMAP can also be used to analyze the lighting of other cities. We have started looking into images from Riad and Tokyo, and the lighting is clearly visible in there as well, enabling the use of similar analysis techniques.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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