SPECTRAL SIGNATURES OF NIGHTTIME LIGHTS

Christopher D. Elvidge
NOAA National Geophysical Data Center, Boulder, Colorado USA

David M. Keith
Marshall Design Inc., Boulder, Colorado USA

Abstract

A spectral library is being built for a wide range of lighting types. The purpose of the library it to provide a basis for recommending bandpasses for future sensor designed to map lighting type and efficiency. Such an instrument could produce lighting maps which could be used to accelerate the implementation of energy efficient lighting types and fixtures.

Introduction

Society faces a huge challenge to reduce carbon emissions and build sustainable energy supplies. Lighting accounts for approximately 20% of electric power consumption (IEA, 2006). Ongoing developments in light emitting diodes (LEDs) suggest that these sources could eventually replace most other sources based on their efficient use of electricity, durability, long service life and compatibility with solar and wind energy sources. Today 79% of all light bulb sales are incandescent lights, which produce only 8% of the usable electric lighting. In fact, 80% of the light emitted by incandescent bulbs falls in the infrared and the bulbs burn out after about 1000 hours of use. In contrast, LED design makes it possible for all the emitted light to fall in the visible and they commonly have service lives 50 times longer than the standard incandescent bulb. While incandescent bulbs continue to dominate for residential lighting, most commercial and street lighting is accomplished with more efficient and longer-lived gas discharge lamps, including fluorescent, high pressure sodium and metal halide lamps. However, there is little scope for improving the efficiency or service life for the gas discharge lamps. In contrast, LEDs are still undergoing technological improvements year-by-year.

The detection of lights from space has been possible with data from the Defense Meteorological Satellite Program (DMSP) since the early 1970's (Croft, 1978; Elvidge et al., 1997). While global in extent, the DMSP collects low light imaging data in a single spectral band only covering part of the visible spectrum, making it impossible to discriminate types of lighting or the spectral quality of lights. More recently a Nightsat concept (Elvidge et al., 2007 a,b) has been defined, which outlines the spatial resolution, spectral band options, overpass time and repeat cycle for future satellite sensors capable of collecting global nighttime lights for use in a variety of social, energy and environmental applications.

In this study we investigate the emission characteristics of primary lighting types at high spectral resolution using a combination of lab and airborne data collections. Our objective is to build a spectral library for use analyzing band settings for a future Nightsat sensor capable of producing spatially explicit survey maps of lighting type, lighting quantity and lighting character worldwide. We believe that such maps would be useful in accelerating the conversion to more efficient lighting types and tracking the progress of lighting type conversions in a cost effective manner.

Methods

Laboratory emission spectra of a variety of lighting sources were acquired using an ASD, Inc. FieldSpec 3 spectroradiometer equipped with an 8 degree field of view foreoptic. The instrument had been radiometrically calibrated and spectra were acquired in radiance (Watts/m^2/sr/um) mode over the 350 to 2500 nm range at one nm resolution. Lamps measured included incandescent, quart halogen, fluorescent, high pressure sodium, metal halide, and LED. Each of the lamps were warmed up prior to measurement and the spectra were acquired from one lamp at a time in an otherwise-dark room.

Airborne emission spectra were acquired over the Las Vegas strip in Nevada using a SpecTIR imaging spectrometer flown at 1000 feet above the earth surface at night on July 28, 2009. The SpecTIR instrument collected data in 360 narrow bands spanning 400 to 2500 nm.

Results From Laboratory Spectra

Incandescent Lamps: These lamps have tungsten filaments inside a vacuum enclosed by a glass bulb. The emission follows a blackbody shape (Figure 1), with an emission peak at near 1000 nm.

Quartz Halogen Lamps: These are incandescent lamps in which a tungsten filament is sealed in a quartz glass envelope filled with an inert gas, plus a small amount of halogen gas such as iodine or bromine. The presence of the halogen increases the lifetime of the filament and the quartz glass envelope allows the tungsten to be heated to a higher temperature. The emission spectra of the measured quartz halogen lamps (Figure 2) are very similar to the standard incandescent lamps, with emission peaks in the 980 to 1080 range.

Fluorescent Lamps: These are low-intensity gas-discharge lamps that generate light by exciting mercury gas with an electric arc. The glass tube is filled with a gas containing low pressure mercury vapor and inert gases such as argon, xenon, neon, or krypton. The primary mercury emissions are in the ultraviolet, which can damage eyes and are outside of the visual range. To redistribute the emitted light into the visible, the inner surface of the tube is coated with a fluorescent coating made of metallic and rare-earth phosphor salts. The fluorescent lamp spectra consist of a set of sharp emission lines (Figure 3) with two primary emission lines at 544 and 611 nm. The line at 611 nm is usually the stronger of the two. If the 611 nm line were always the strongest it would show up with a normalized peak height of 1.0 on Figure 8. Secondary emission lines occur at 546, 436, 545, 437, and 574 nm. The infrared emissions are quite low.

Metal Halide Lamps: These are high intensity gas discharge (HID) lamps that produce light by passing an electric arc through a high-pressure mixture of argon, mercury and a variety of metal halides. The composition of halides determines the location and intensity of the emission lines, making it possible for metal halide lamps to range from “cool white” to “warm white”. An example of a metal halide lamp spectrum is shown in Figure 4. All the metal halide lamps measured had a prominent emission lines at 819 nm and 671 nm. Other visible band emission lines found were at 474, 509, 536, 569, and 578 nm. In addition to the major emission line at 819 nm, infrared emissions are present at 915, 937, 1013, 1139, 1365, 1634, 1846 and 2207 nm.

High Pressure Sodium Lamps: These are HID lamps the emit light by passing an electric arc through a chamber containing sodium and small amounts of neon and argon. The strongest emission line is at 819 nm (Figure 5). There are secondary lines at 569, 564,595,598, 582, 585, 584 and 616 nm. In addition to the 819 nm line, there are infrared emission lines at 767, 1139, 1269, 1846, 2207, and 2339 nm.

Light Emitting Diodes (LED): These are solid-state light sources that generate light by electroluminescence, moving electrons from a high energy state to a lower energy state on a semi-conductor substrate. We measured a variety of LEDs with appearance ranging from white to blue, green, orange and red. Figure 6 shows a spectrum from an LED streetlight featuring two Gaussian shaped emissions that overlap slightly. The primary emission at 450-460 nm. The second emission, which enable the lamp to produce white light, is a phosphor induced emission in the green and into the red. Note that only a small amount of emission occurs in the infrared and the relatively broad emission, as compared to the line emissions from the gas discharge lamps.

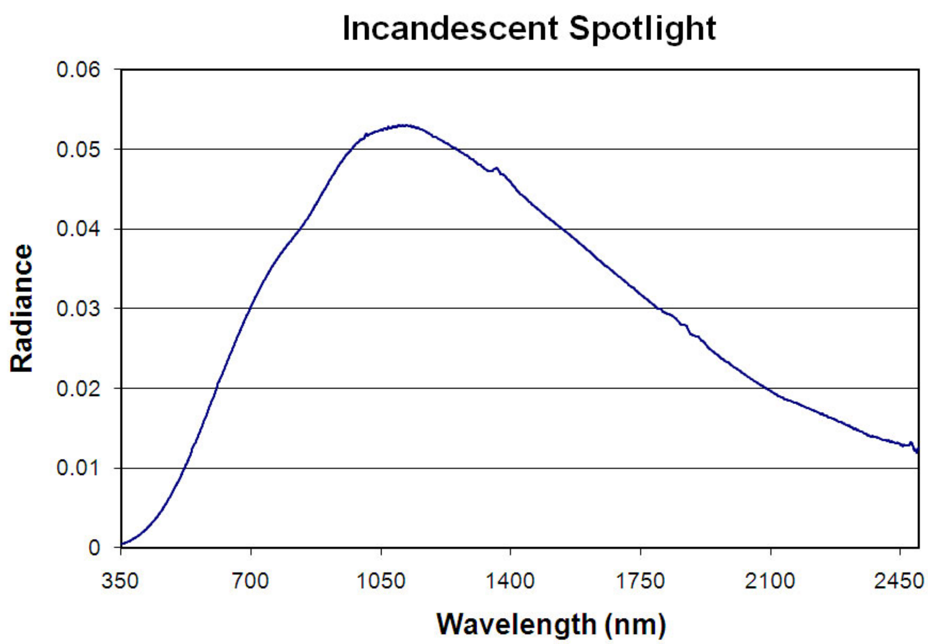


Figure 1. Emission spectra of an incandescent lamp.

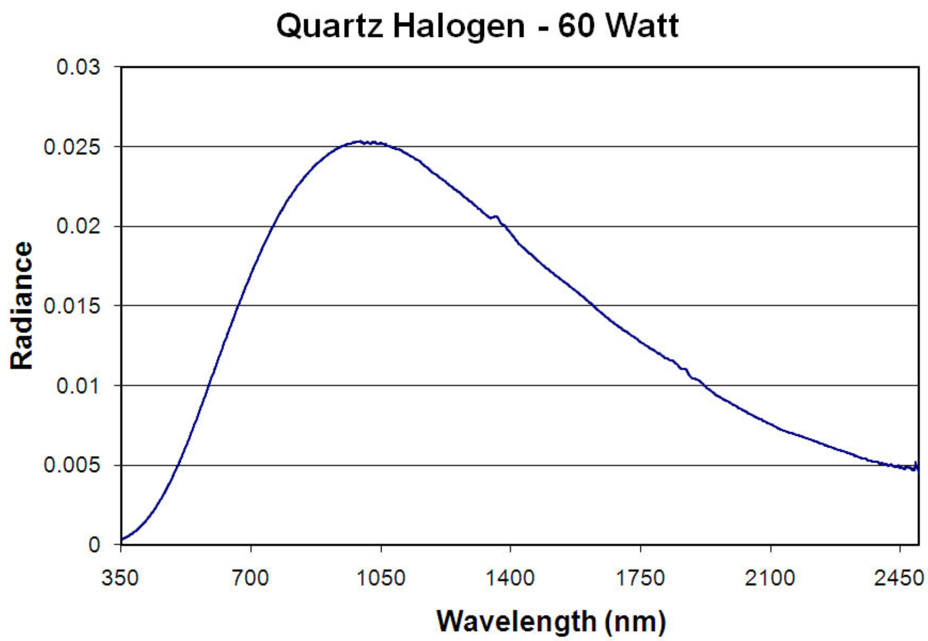


Figure 2. Emission spectrum of a quart halogen lamp.

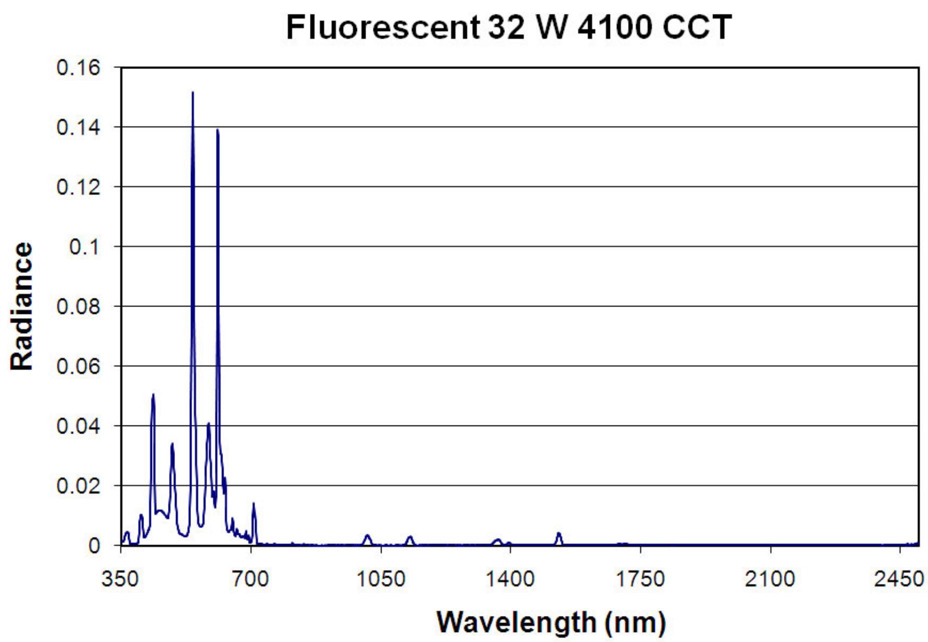


Figure 3. Emission spectra of a standard fluorescent tube.

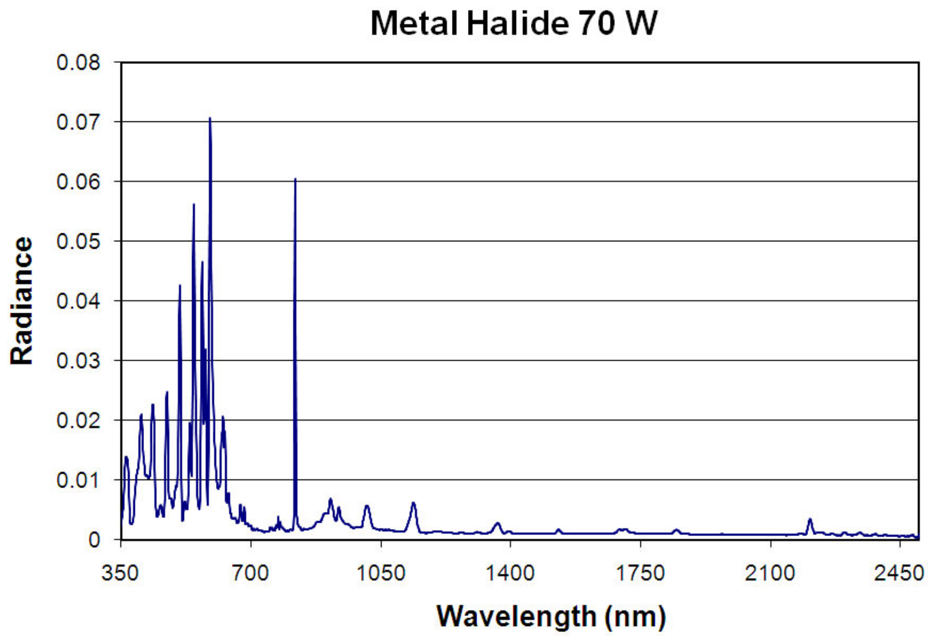


Figure 4. Emission spectrum from a metal halide lamp.

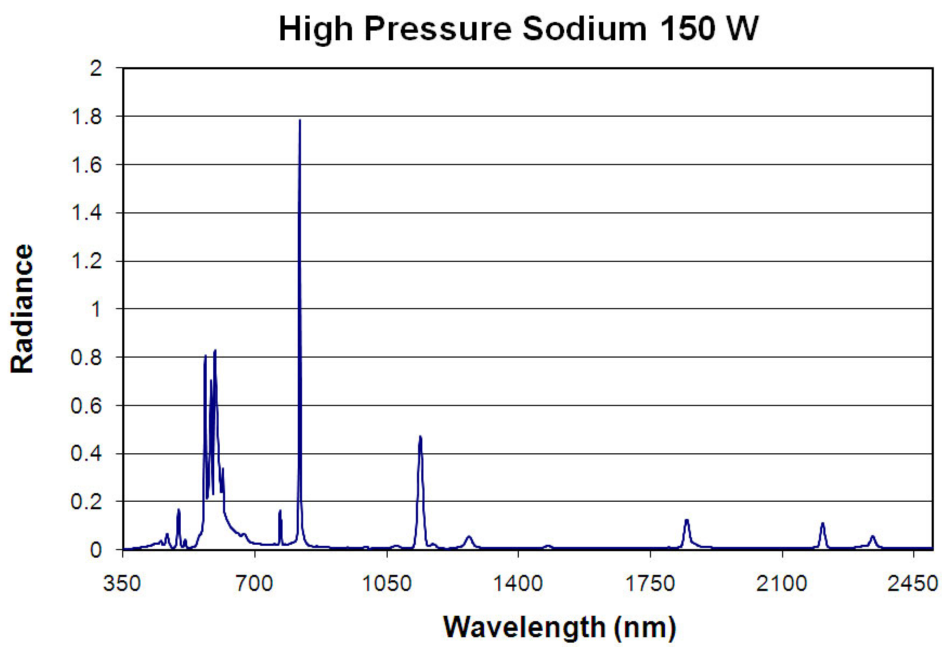


Figure 5. Emission spectrum from a high pressure sodium lamp.

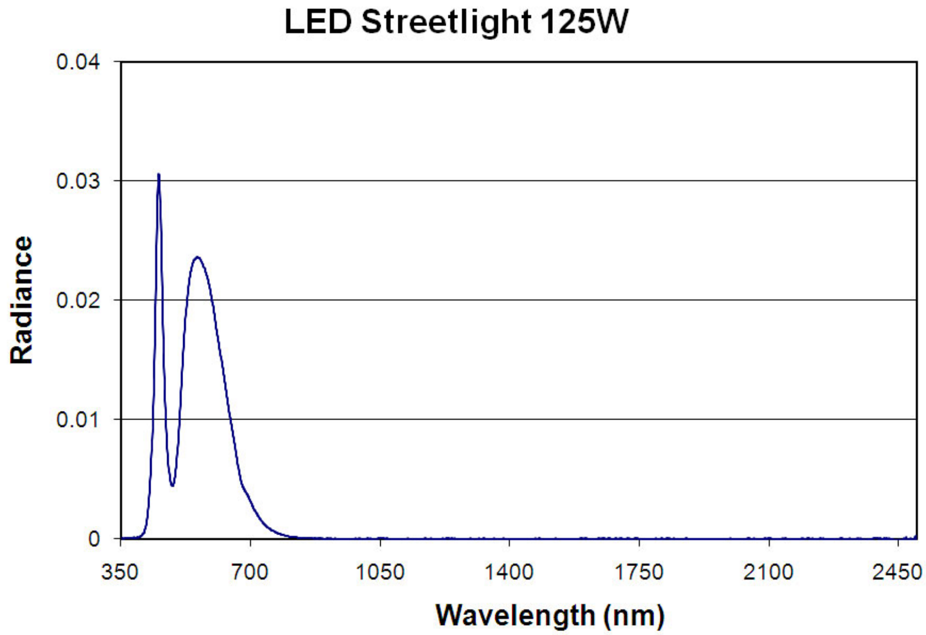


Figure 6. Emission spectrum from a white LED streetlight.

Results From the Airborne Data

The airborne data were geolocated and displayed with bands from 821, 581 and 490 nm as red, green and blue. After adjusting the contrast it was possible to see many lights and many colors of lights. Spectra were examined for individual pixels for features that appeared interesting. Latitudes and longitudes of interesting features were entered into Google Earth to discover the names of the sites or identity of the features.

Palace Station Hotel and Casino: A pale blue diagonal line of lights was identified that yielded a spectrum that has a set of sharp emission lines in visible and a few emission lines in the infrared, plus a broad emission centered in the blue/green (Figure 7). The emission line bear some resemblance to those found in the fluorescent lamps. Review of Google Earth revealed that the feature is a giant lit neon sign in front of the Palace Station Hotel and Casino.

Eiffel Tower, Paris Hotel and Casino: This is one of the modern landmarks of the Las Vegas Strip and shows up on the image as a four sided symmetrical feature (Figure 8). The spectrum indicates that the lights being used are high pressure sodium lamps.

Venice Tower, Venetian Hotel and Casino: A white four sided feature yielded a spectrum that we cannot yet identify. It has a sharp emission line at 819 nm, found in metal halides and high pressure sodium lamp spectra. Another emission line is present at 1150 nm. These emission lines are standing out from a continuous blackbody emission spectrum with some perturbations in the visible range. The feature is the Venice Tower at the Venetian Hotel and Casino.

Bill's Gamblin' Hall and Saloon: A narrow rectangle made of white lights yielded a spectrum that matched that of a metal halide lamp (Figure 9). This turned out to be the lights shining up to illuminate the side of Bill's Gamblin' Hall and Saloon (formerly the Barbary Coast Hotel Casino).

Conclusion

We found substantial variation in the emission spectra of lighting types. Lamps that produce light through heat (incandescent, quartz halogens, and fuel lamps) emit primarily like blackbodies, with peak emission in the near infrared and emissions higher in the red than green and blue. Fluorescent, metal halide, high pressure and low pressure sodium lamps are gas discharge lamps, which emit different series of narrow emission lines. The identity of the gas discharge lamps can be discerned based on the wavelength positions of the emission lines. Fluorescent lamps have a pair of very strong mercury emissions at 544 and 611 nm. Outside of these two strong emissions lines there is substantial variability in the secondary emission lines from fluorescent lamps in the visible range and virtual no emission in the infrared. Metal halide lamps have a highly variable set of emission lines in the visible, but always have strong emission at 819 nm and a set of tightly packed emissions lines centered at 569 nm. High and low pressure sodium vapor lamps have very little variability. Both have strong emission lines at 819 nm. The low pressure sodium lamp has only one additional emission line of any consequence, at 589 nm. The high pressure sodium lamp has a series of emission lines from 569 to 616 nm and a set of minor emission lines in the blue region. The emission spectra of LED's are highly variable – but characteristically have Gaussian shaped emission peaks and extremely low emission in the NIR.

Over the coming decades humans have a huge opportunity to reduce energy consumption, reduce greenhouse gas emissions, and improve living standards by installing energy efficient light bulbs and improving lighting fixtures. In addition to these factors, the health and environmental consequences of nocturnal lighting are increasingly playing a role in decisions on lighting. It is common knowledge that prolonged exposure to bright lights at night can cause insomnia. More recently a growing body of evidence has linked exposure to bright lighting at night to increased risk of life threatening conditions such as breast and prostate cancer. The primary mechanism for these human health impacts is the disruption of melatonin production associated with exposure to blue light. For many years the astronomy community has advocated for reductions in artificial sky brightness that reduces the visibility of astronomical features such as the Milky Way. A wide range of nocturnal lighting impacts have been identified for animal species.

While there is much to be gained through the conversion of lighting types and fixtures, to date there is no systematic mechanism to inventory lighting type, lighting character or the quantity of lighting. Such information could be used to accelerate lighting conversions. Nighttime satellite remote sensing could be used to make detailed maps of outdoor lighting and light escaping from buildings through windows, doors and skylights. But this would require a specialized low light imaging sensor capable of distinguishing lighting types, lighting character and measuring the quantity of light escaping to space. The spectral library we are building using laboratory and airborne hyperspectral data will be analyzed to provide recommendations of specific bandpass options for consideration on future Nightsat missions.

Acknowledgements

We had assistance in the collection of the spectra from Nate Bloomingdale and Gary Fager of ASD and Drs. Sharolyn Anderson and Rebecca Powell of the Geography Department of University of Denver. The airborne imaging spectrometer data was kindly provided to us by Timothy Pachter and Mark Landers of SpecTIR LLC.

References

Croft, T.A. (1978). Night-time images of the earth from space, *Scientific American*, *239*, 68-79.

Elvidge, C.D., Baugh, K.E., Kihn, E.A., Kroehl, H.W, Davis, E.R. (1997). Mapping of city lights using DMSP Operational Linescan System data. *Photogrammetric Engineering and Remote Sensing*, *63*, 727-734.

Elvidge, C.D.; Cinzano, P.; Pettit, D.R.; Arvesen, J.; Sutton, P.; Small, C.; Nemani, R.; Longcore, T.; Rich, C.; Safran, J.; Weeks, J.; Ebener, S. (2007) The Nightsat mission concept. *International Journal of Remote Sensing*, *28(12)*, 2645 – 2670.

Elvidge, C.D.; Safran, J.; Tuttle, B.; Sutton, P.; Cinzano, P.; Pettit, D.; Arvesen, J.; Small, C. (2007) Potential for global mapping of development via a Nightsat mission. *GeoJournal*, *69*, 45 – 53.

International Energy Agency *Light's Labour Lost*, Paris, France, 2006.

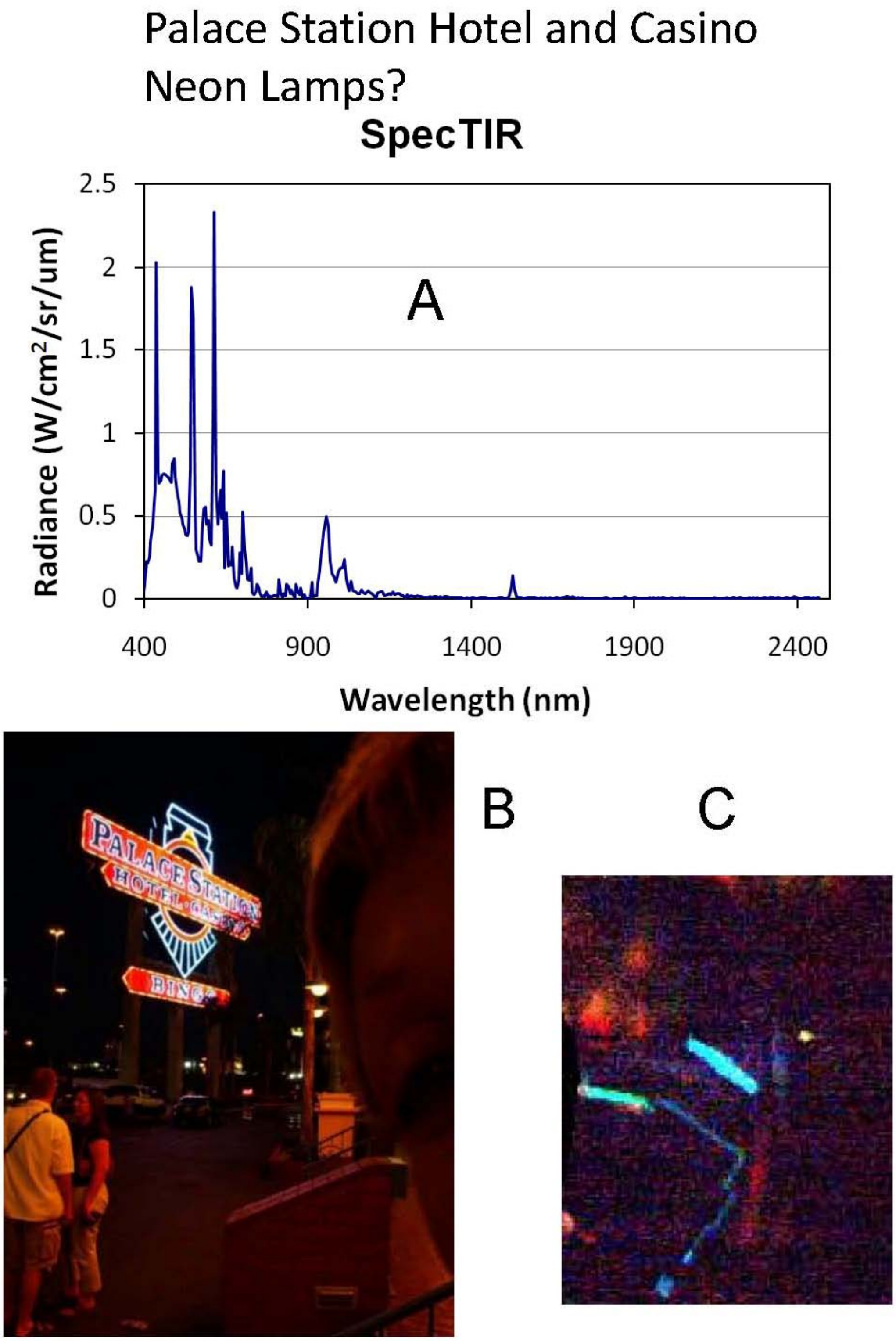


Figure 7. The large neon sign in front of the Palace Station yielded a spectrum that did not match our current spectral library. A. Spectrum from the SpecTIR imaging spectrometer. B. Street view of the sign. C. SpecTIR image of the feature with bands at 821, 581 and 490 nm as red, green and blue.

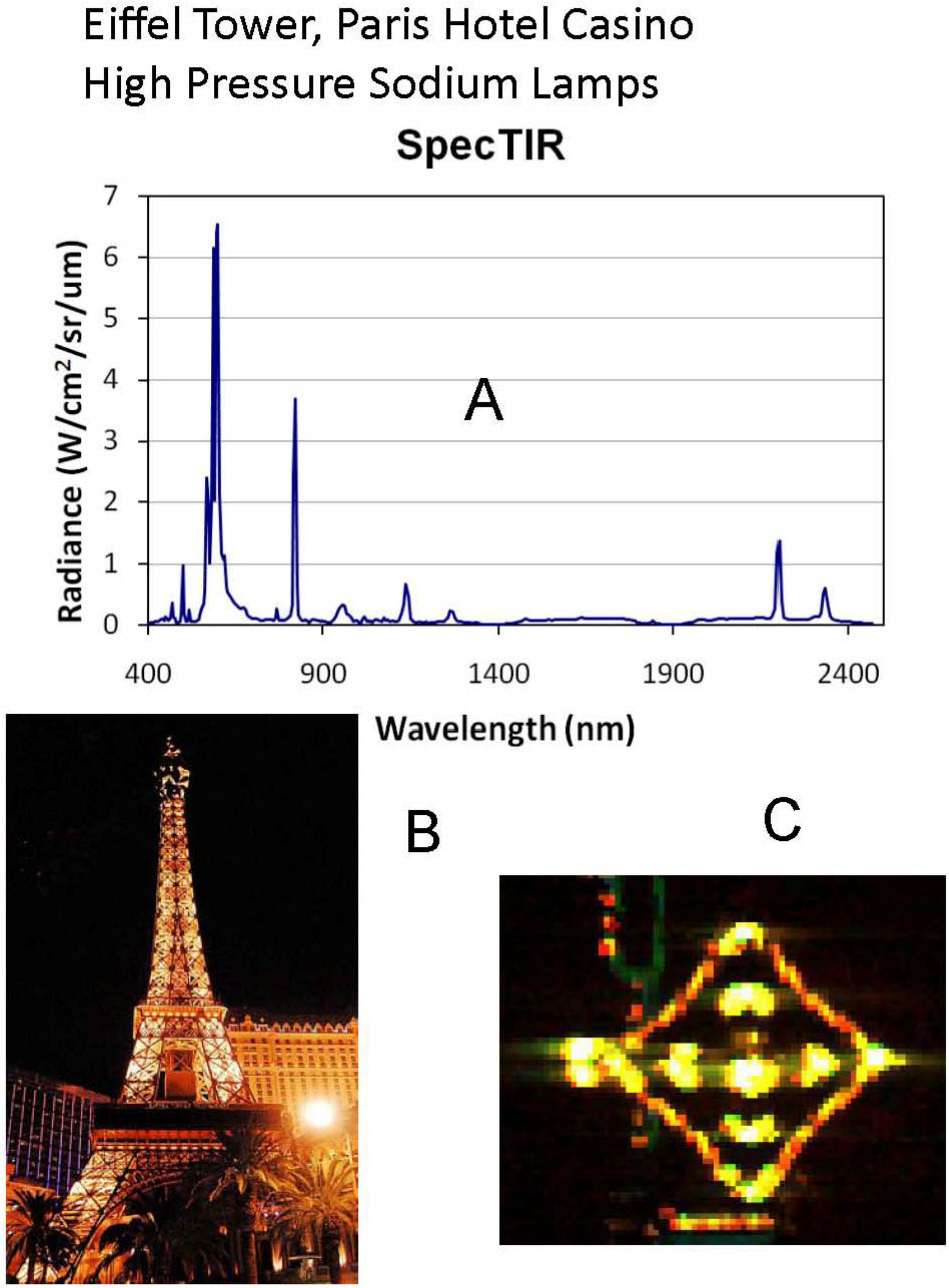


Figure 8. The replica of the Eiffel Tower in front of the Paris Hotel and Casino yielded a high pressure sodium lamp spectrum. A. Spectrum from the SpecTIR imaging spectrometer. B. Street view of the tower. C. SpecTIR image of the feature with bands at 821, 581 and 490 nm as red, green and blue.

Venice Tower, Venetian Hotel Casino
Unknown Lamp Type

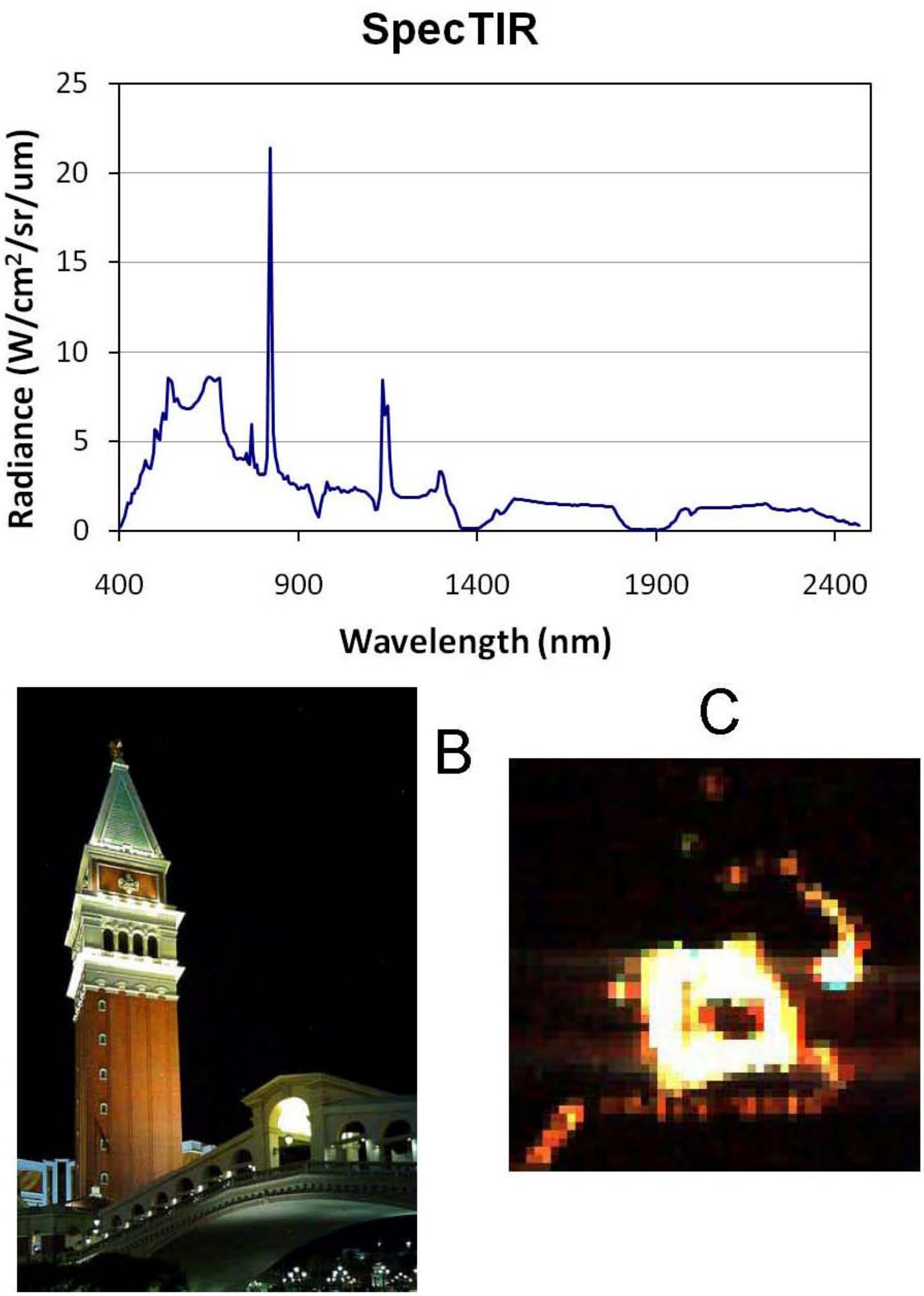


Figure 9. The replica of the Venice Tower in front of the Venetian Hotel and Casino yielded a spectrum that did no match our spectral library. A. Spectrum from the SpecTIR imaging spectrometer. B. Street view of the tower. C. SpecTIR image of the feature with bands at 821, 581 and 490 nm as red, green and blue.

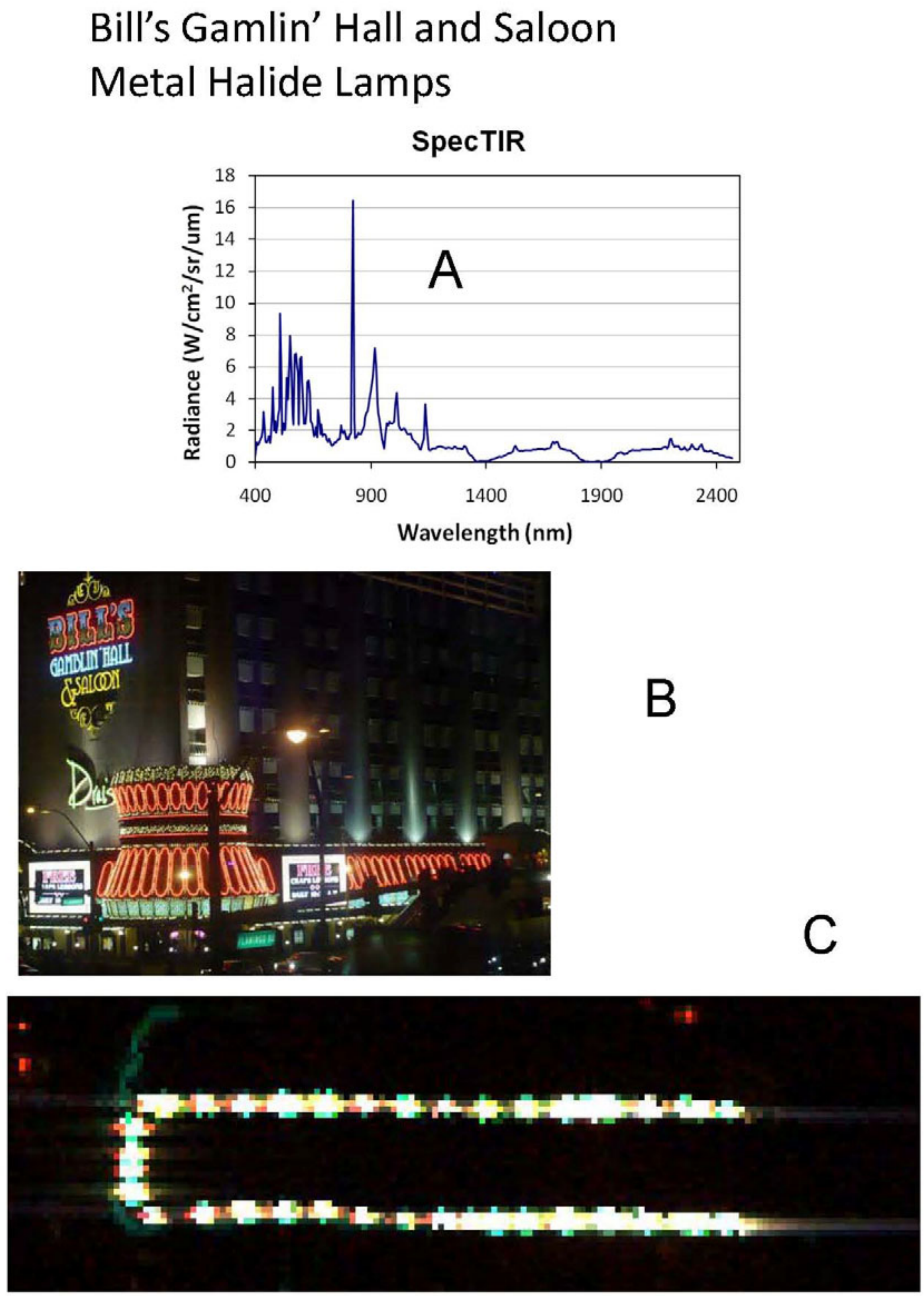
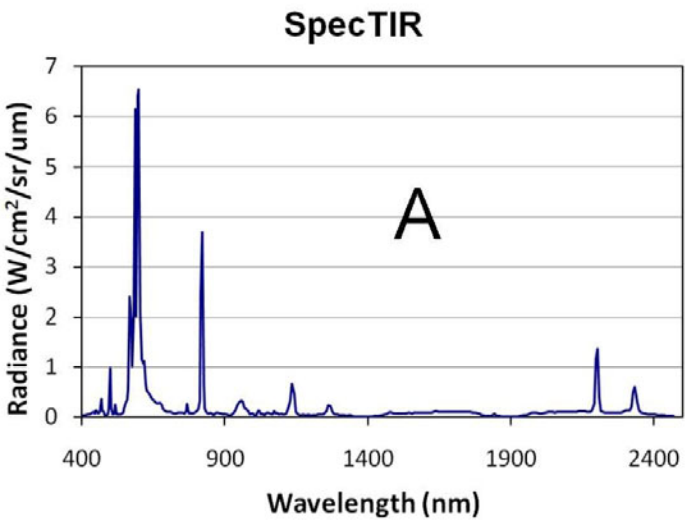


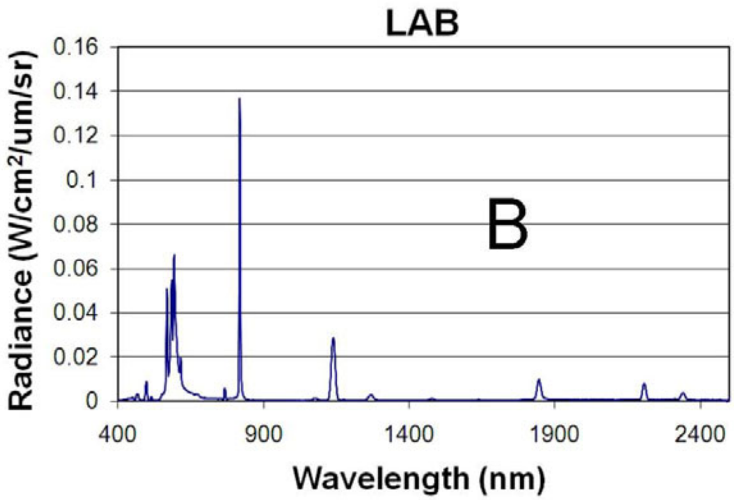
Figure 10. White lights are shining up on the sides of Bill's Gamblin' Hall and Saloon, creating a narrow rectangle of lights in the SpecTIR image. The spectrum indicate that these are metal halide lamps. A. Spectrum from the SpecTIR imaging spectrometer. B. Street view of the tower. C. SpecTIR image of the feature with bands at 821, 581 and 490 nm as red, green and blue.

References

The typing format for references should be with hanging indent and is: author's last name, initials, year in (parenthesis). Title. Journal name in *italics,* followed by volume number in *italics*, and page number(s).



Eiffel Tower
Paris Casino
High Pressure
Sodium Lamps



C

D