This project is co-financed by the European Union

Grant Agreement No.: 824603
Call: H2020-SwafS-2018-1
Type of action: RIA
Starting date: 1/02/2019

Tutorial: to identify the spectra of common street lamps

Coordinator: [Jaime Zamorano]
Quality reviewer: [Kat Austen]

Deliverable nature	
Dissemination level	
Work package and Task	D2.1
Contractual delivery date	01/2020
Actual delivery date	

Authors

Author name	Organization	E-Mail
Jaime Zamorano	**UCM**	**jzamorano@fis.ucm.es**
Rafael González	**UCM**	**rafael08@ucm.es**
Carlos Tapia	**UCM**	**carloseugeniotapia@ucm.es**

Abstract	This document explains all the steps to obtain the spectra of street lights, how to determine their nature, and also how to contribute with this information to the StreetSpectra citizen science project. The first sections are devoted to introduce the StreetSpectra project, and also the light pollution (LP) problem. We have also included some of the science basics (LP and simple physics of spectra).
Keywords	Public lighting - Light Pollution - Spectrum - Smartphone - Citizen Science

Disclaimer

The information, documentation and figures available in this deliverable, is written by the ACTION project consortium under EC grant agreement 824603 and does not necessarily reflect

How to quote this document

J. Zamorano, R. González & C. Tapia (2019), ACTION Street Spectra Manual

TABLE OF CONTENTS

1. Introduction

This document explains all the steps to obtain the spectra of street lights and also how to contribute with this information to the StreetSpectra citizen science project.

The scope of the deliverable is defined by the title 'Tutorial: to identify the spectra of common street lamps'. To include some context we have added information about the light pollution problem and how the citizen science can help by providing information on the public street lighting. Since at the time of writing it we have already developed some tools, the document constitutes the complete Street Spectra Manual, including the design of the spectrograph and the initial the app.

Before the tutorial, the first sections are devoted to introduce the StreetSpectra project, and also the light pollution (LP) problem. We have also included some of the science basics (LP and simple physics of spectra). You can skip this part of the manual if you are acquainted with these topics and/or you are in a hurry.

We provide an atlas of comparison spectra, and some Annex with information on how to build a handheld visual spectroscope and how to classify lamps by their colors.

2. The StreetSpectra project

The light emitted by street lamps could be analysed using smartphone cameras, and other simple and inexpensive portable devices. We wish to turn the smartphones into scientific instruments to analyze lamps colors and their spectra[1]. We will define a process and tools so that any citizen will be able to determine the kind of lamp installed on lampposts and its main characteristics. We are developing a very simple method to obtain the spectra of the lamps (StreetSpectra). This is a citizen science pilot study of the H2020-SwafS-2018-1-824603 EU project. More info about the project at https://actionproject.eu/

Artificial light can cause pollution that is a significant contributor to biodiversity loss and health, and also has consequences for climate change. While the current transition to LEDs can sometimes lead to energy savings, the wavelength of light emitted is more

[1] Spectra is used as plural of spectrum.

likely to produce skyglow – the atmosphere reflects light back towards the Earth's surface - and can be much more damaging to plants and animals than old-style lights. The light that escapes to the atmosphere, due to an excess of illumination of a bad design of luminaires, is dispersed and some of this light is directed back to us. Thus one of the undesired effects of light pollution is the brightening of the night sky and the lost of the starry skies in our cities. The artificial illumination of our streets is one of the major contributors to light pollution.

We are experiencing a major change in the technology used for street lighting and most of the high-pressure sodium (HPS), metal halide (MH) and mercury vapor (MV) lamps are being replaced by light-emitting diode lamps (LEDs). Light pollution experts working across different fields have warned about the impact of blue artificial light at night both on human health, flora and fauna. Some of the LEDs used on the street are too white and contains a potential hazardous blue component. Read for example 'Long-Term Comparison of Attraction of Flying Insects to Streetlights after the Transition from Traditional Light Sources to Light-Emitting Diodes in Urban and Peri-Urban Settings' by Roy H. A. van Grunsven, Julia Becker, Stephanie Peter, Stefan Heller & Franz Hölker (https://www.mdpi.com/2071-1050/11/22/6198).

In several US cities, where the retrofit has been performed using too white LEDs, citizens are asking the authorities to re-introduce the old warm lights.

Figure 1. Image of Berlin at night taken by astronauts aboard the International Space Station (ISS) showing different illumination colors of the streets: white LEDs and orange HPS lamps. The North direction in on the right of the picture.

The replacement of street lights to LED technology is already taking place in Europe. The Figure 1 shows a picture that has been taken by astronauts aboard the International Space Station (ISS035-E-17210, taken at 2013.04.06), and shows clearly the differences in lightning between areas in Berlin where such changes have occurred. The west of the city (up in the picture) is experiencing the change from gas lights, fluorescent and mercury vapor lights to LEDs while the east of Berlin lighting is mainly composed of sodium lamps (although also is switching to LEDs) (you can browse more examples at http://citiesatnight.org/). There is a vast diversity of lamps used as they belong to different companies and models, ranging from very white LEDs with CCT 6000K to warm ones with 2700K and even amber lights with lower CCT.

There is scarce information on the fraction of lighting technologies employed in our cities and also of the schedule of the retrofit changes. Location, type, number of sources and light pollution brightness are needed to feed into scientific models that describe the scattering in the atmosphere and the impact of light pollution at medium and long distances from the sources.

How could the citizens participate? Participants, using their own smartphone camera and calibrating it, can determine and analyse the lamps' spectra. Usually all the lamps in a typical street are similar and it is not necessary to take a spectrum of every lamppost. To map the lamps getting information at both ends of the street will do.

They are contributing by sending the measurements to a public repository. This archive contains the pictures and the location of the lamps. The contributor, or any interested citizen or researcher, can browse the open data and also the maps.

The project is very well suited for educational purposes and to raise awareness of light pollution. We will provide primary and secondary school educators with resources for practical labs. The data will be used to map the lamps locations and their kind. The results also have scientific interest.

3. Lamps used for street illumination

Using a diffraction grating (read later) we can obtain the spectrum of the lamp. This is a decomposition of the light into its components, as occurs in nature when we see the colors of the solar spectrum (sun light) in a rainbow. The spectrum provides information of the components of the lamp. For example, the lamps with sodium vapor in its bulb shows a yellow sodium line at 589 nm (nanometers is unit for the wavelength of the light).

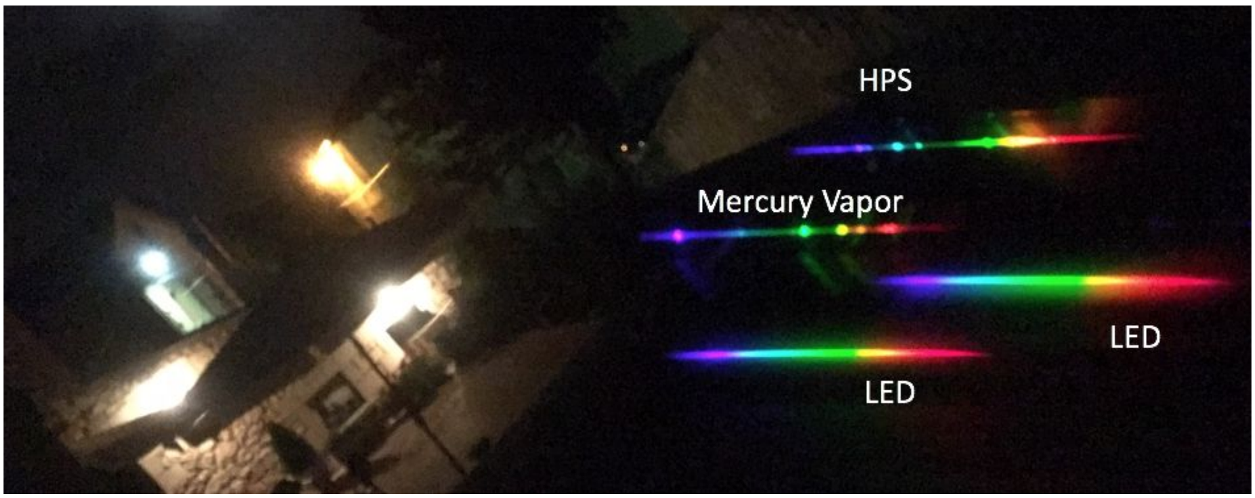


Figure 2. Picture of lamps and their spectra taken at night in a location with mixed illumination luminaries.

The Figure 2 shows a picture with sources of light at left and three kinds of lamps that are usual in our streets: High pressure sodium (HPS), Mercury Vapor (MV) and two LEDs lamps. The spectra (rainbows at right) are clearly different and we can determine the nature of the lamp by comparing its spectrum with a catalog of reference spectra. A library of reference spectra is available for this purpose, see Annex I.

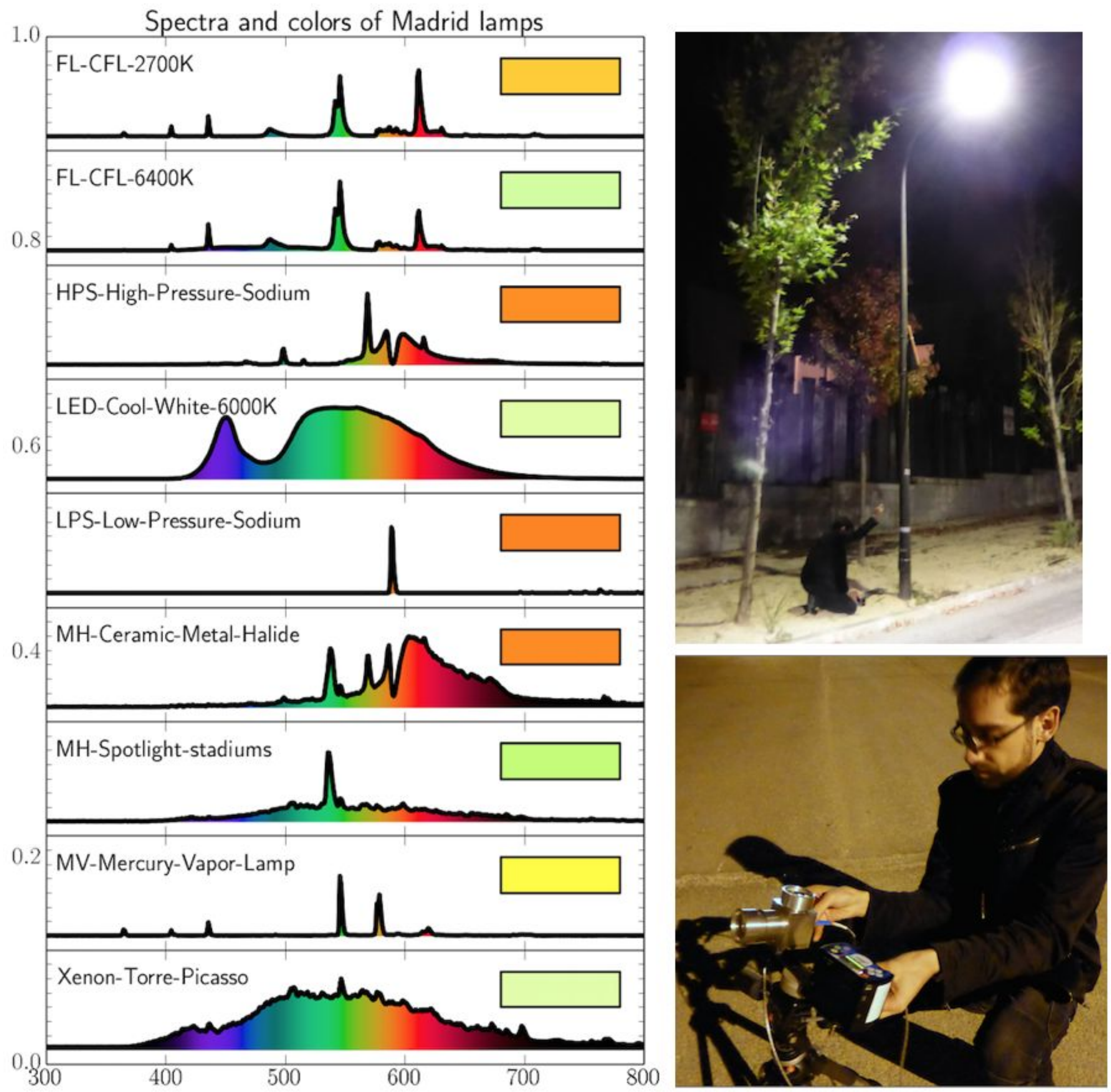


Figure 3. A collection of typical spectra of lamps collected in Madrid urban area and the researcher using a portable spectrograph to obtain the data in situ.

Comparing the spectra displayed in Figure 3 we can understand how the spectral features can help to distinguish among different types of lamps. The graphs indicate the amount of light emitted for each wavelength (x-axis) or color of the spectrum. Some of the lamps show emission lines, the isolated peaks of Low Pressure Sodium (LPS) or Mercury Vapor (MV) lights, for instance. Most of the spectra belong to Gas-discharge lamps and there is an example of Light-emitting diode (LED).

The integrated color of the lamp is also displayed in the Figure 3 graphs. Due to the high intensity of the lamp and the human eye spectral response, we see most of them as white, except the orange sodium lights. The color and spectrum of the sky at night in a light polluted location depends on the nature of the sources of light pollution. We can see yellowish skies (orange sky glow) near cities with sodium lights, for instance.

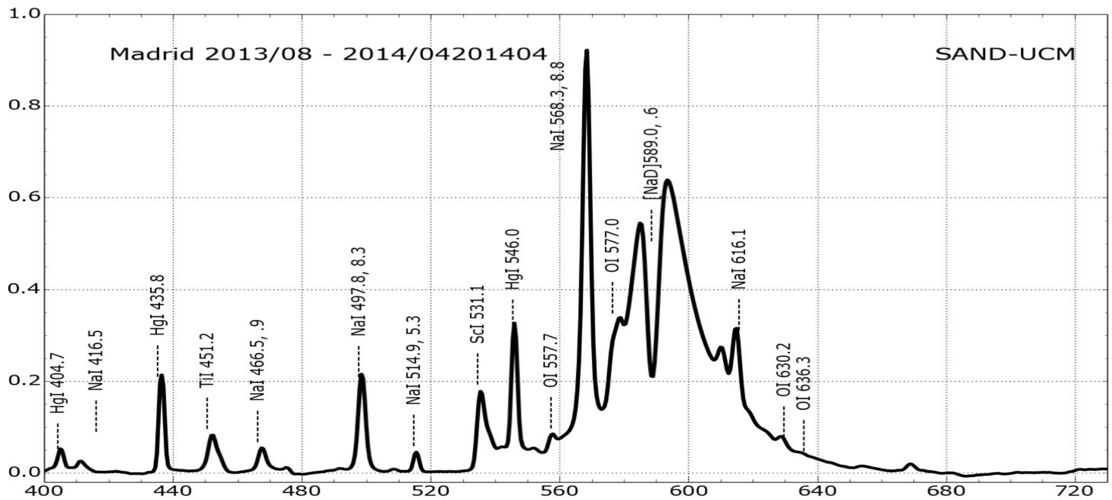


Figure 4. Spectrum of the sky of Madrid at night showing a mix of the spectra of lamps used in streets and those of the ornamental lights used to illuminate monuments. The Y-axis is relative intensity and the X-axis is wavelength in nanometers (nm).

The Figure 4 shows the typical averaged spectrum of the sky of Madrid at night. The main spectral features (emission lines) are labeled indicating the atomic element and the wavelength of the line. As an example HgI 435.8 is the line of mercury at 435.8 nm. Most of the lines belongs to artificial illumination. A comprehensive catalog of electric lamps can be found at the Museum of Electric Lamp Technology webpage: http://www.lamptech.co.uk/

4. A simple spectrograph design to take lamp spectra

4.1 Spectrographs and smartphones

The spectrographs are the scientific devices used to obtain the spectrum of a light source. The main part of the system is the dispersive element: diffraction grating or prism that decomposes the light into their color components. Other optical components of an optical spectrometer are the slit at the entrance, the collimator and the camera (lenses or mirror elements).

Spectrographs are expensive scientific instruments. This is why we need a portable low budget device that could fulfill our requirements: obtain a spectrum of the lamps used in street illumination that could be characterized. There are some low cost spectrograph developments that can be found after an internet search. Most of them are dedicated to obtain spectra at the laboratory for chemical analysis of samples (gases or liquids).

Some are simple designs that could be used for our purposes but are still complicated. The spectrographs are connected to the camera of the smartphone to register the spectra but they need a mounting that should be built with a 3D printer and that is different for each smartphone model. One example of these kind of designs is the Smartphone Spectrometer[2] of the Universidad Privada Boliviana. Another interesting design is that of the Public Lab DIY Spectrometers[3].

The Multiscale Observation Networks for Optical monitoring of Coastal waters, Lakes and Estuaries (MONOCLE) European project https://monocle-h2020.eu/ has designed iSpex http://ispex-eu.org/ citizen science project to measure air pollution with smartphones. iSPEX consists of an add-on that is attached in front of the smartphone camera. The add-on is essentially a slit spectrograph that uses a transmission grating foil and a plastic lens in addition to the smartphone camera. Unfortunately you need a different add-on that should be built tailored to each smartphone.

[2] http://www.upb.edu/en/contenido/smartphone-spectrometer
[3] https://publiclab.org/wiki/video-spectrometer-construction

4.2 The StreetSpectra design

Being the lamppost light source almost a point source at the distance where we will use the spectrograph, for instance from the sidewalk in front of the lamp, we do not need to use a slit to obtain the spectra. This is why we have designed the most simple spectrograph that can be used with a smartphone camera: a transmission grating on top of the camera lens (objective grating spectrograph). Figure 5a shows the simple setup and some transmission gratings.

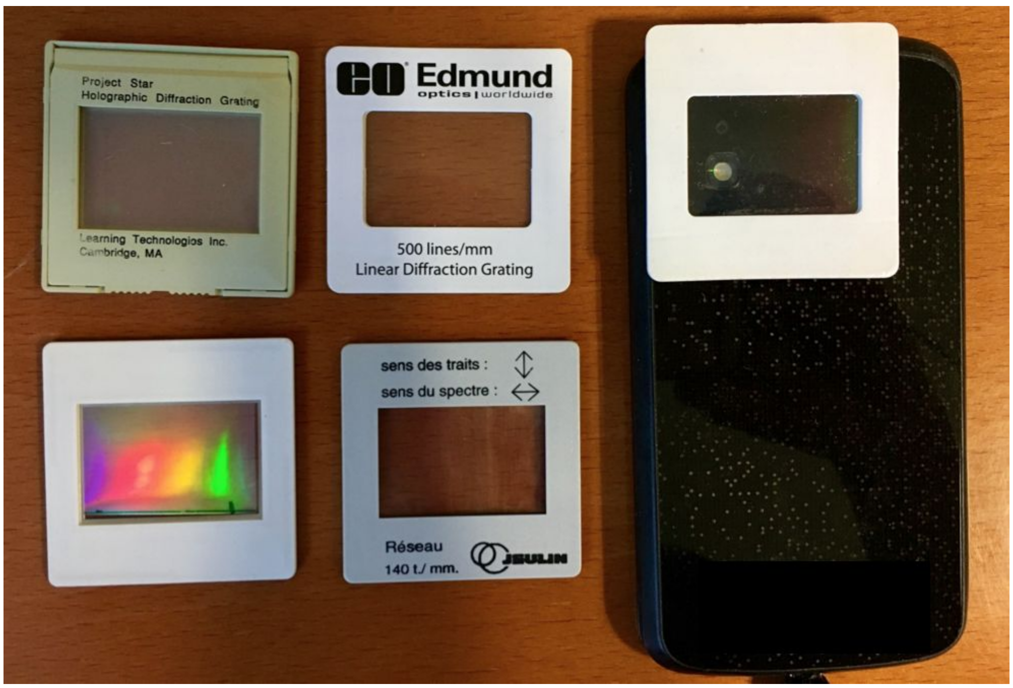


Figure 5a. Smartphone with a transmission grating covering the lens of the camera and some examples of transmission gratings.

Figure 5b. Citizens using the setup to obtain the spectra of street lamps.

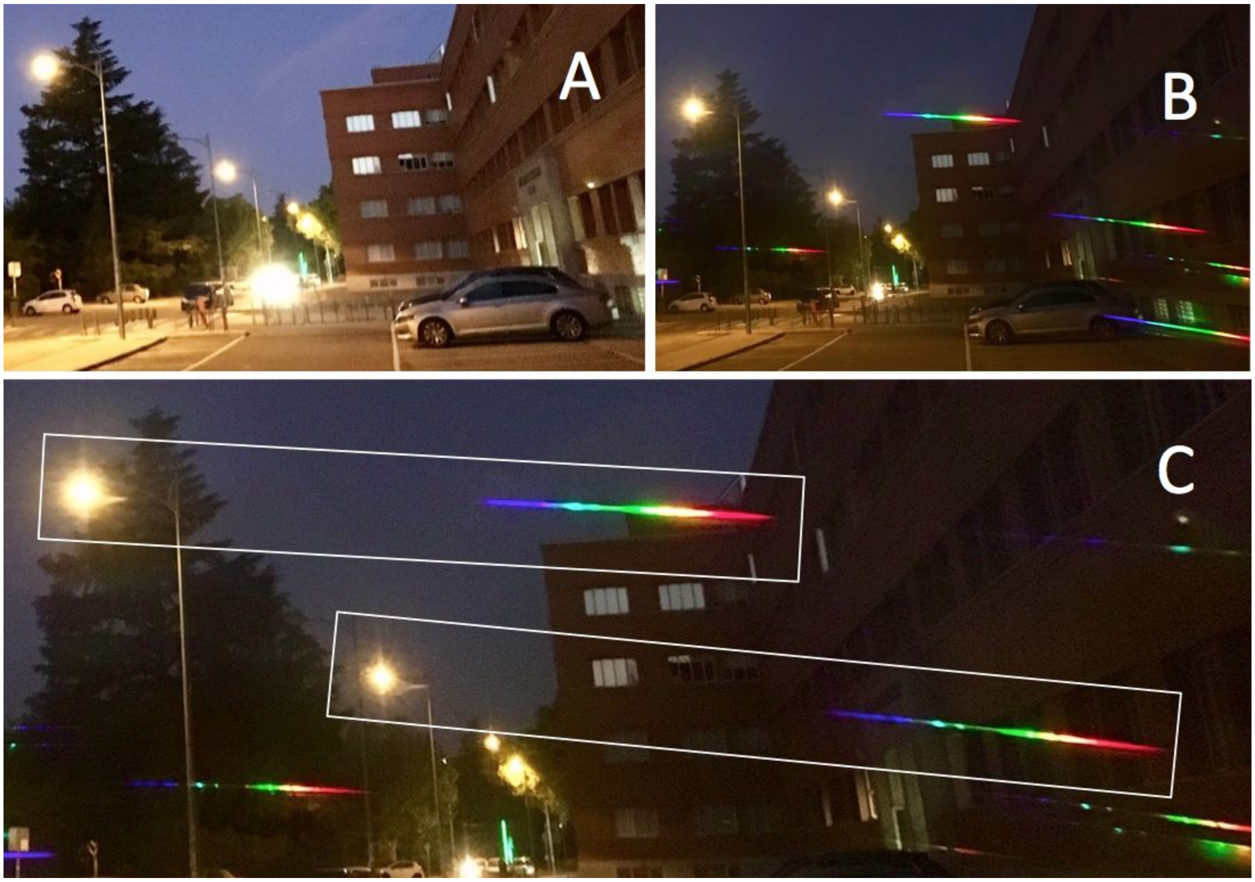


Figure 6. Spectra of HPS lamps obtained with a transmission grating and recorded with a smartphone. (A) Direct picture obtained with the phone. (B) Picture taken at the same place after placing a grating over the camera lens. (C) Detail of two of the lamps with their corresponding spectrum.

Using a transmission grating we can obtain the direct image (no dispersion) and the spectra of every light source on the scene as shown in Figure 6. The image obtained with the dispersion element (panel B) presents many spectra. On panel C we have draw a rectangle for two of the sources, assigning the direct image of the lamp to their spectrum.

The spectra annotated in Figure 6 correspond to the first order (m=1). The distance between the image of the lamp (direct image, order 0, m=0) and its spectrum depends on the camera lens, the distance of the observer to the lamp and the grating used. The main parameter of the grating is the number of lines per millimeter (lines/mm).

In fact the grating disperses the incoming light in multiple orders as shown in Figure 7. We can see on top a bright lamp, close to the observer that presents grating orders up to order three (m=3). The spectra of the different orders are similar (same source) but the width of the successive orders is increasing. Order m=2 has a double width while m=3 has a 3x width. Order m=1 is saturated in this case and order m=3 shows the auto-absorption of the sodium line. For the lower source we see that orders extend also on the other side of the source. In this case the orders are labelled with negative numbers: m=-1, m=-2, etc.

To summarize, all the rainbow lines aligned with the lamp image are showing the same information about the spectrum of each lamp. The different orders m=1, 2 , etc differs in the length of the spectrum, being the order m=2 more extended that the m=1 spectrum.

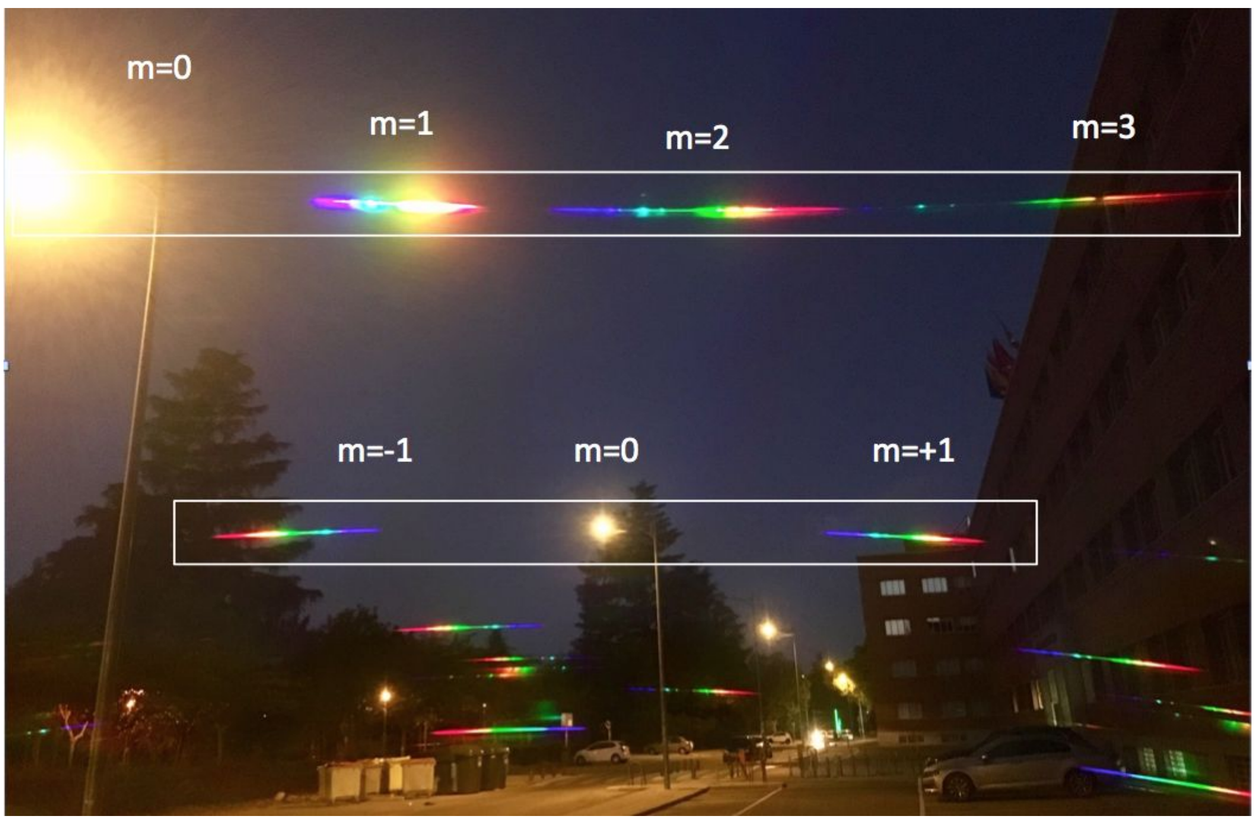
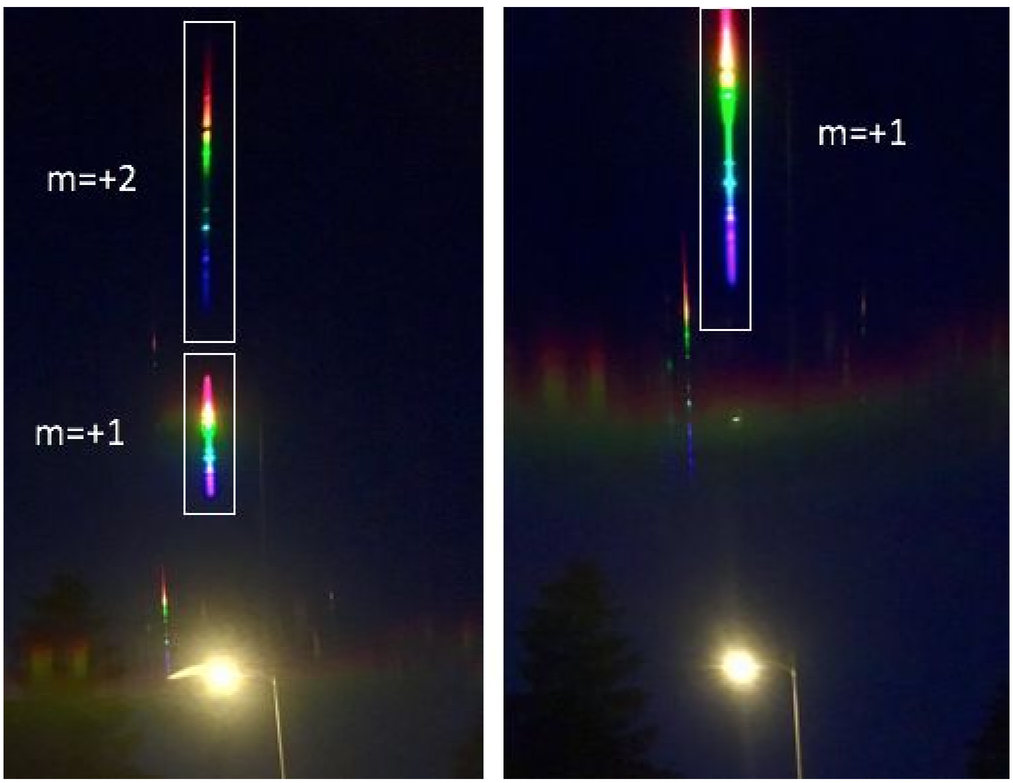


Figure 7. Annotated grating orders for two light sources. See text for explanation.

The main parameter of the grating is the number of lines per millimeter (lines/mm). The dispersion increases in linear proportion: the higher this value, the spectrum is more extended. Figure 8 shows two pictures of a lamp and its spectrum obtained from the same location but with different gratings. The order m=1 and m=2 are visible in the image at left (500 ln/mm) while only the m=1 order appears in the image taken with the 1000 ln/mm grating. The length of m=-1 order at left is equal to the m=1 order at right since the linear dispersion depends linearly of the value of the order and the number of lines per millimeter of the grating.



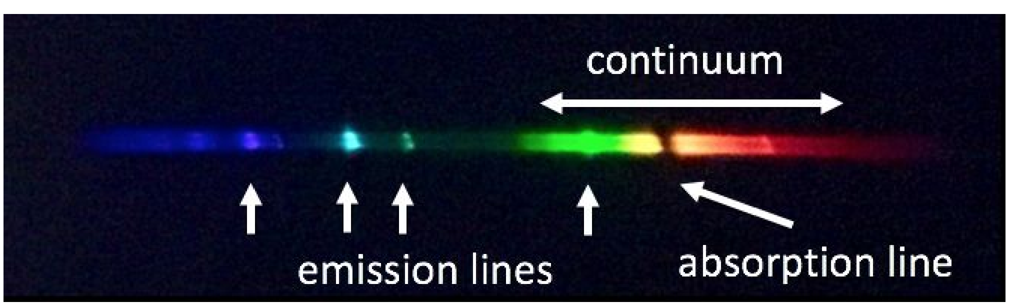


Figure 8. Same HPS lamp pictured with a 500 lines/mm grating (left) and 1000 lines/mm grating (right) showing the differences in linear dispersion. Principal features of a spectrum (bottom).

The spectra of HPS of Figure 8 allows us to describe the main spectral features. In this case we see a continuum of colors in the green to red part with an absorption line (dark line in the yellow) and some emission lines (bright color lines) in the blue and green.

5. Take your Spectrum using a Smartphone

You need your own smartphone as the main device for the spectrograph. The camera of the phone will be used to record the spectra. The location of the picture will be also obtained from the smartphone (you will need to give access to your GPS location data, although the information can also be added manually). You also need a transmission diffraction grating. Most of the examples shown above were made with a grating of 500 lines/mm using a smartphone. With this grating it is easy to get an image with the lamp and the first two orders (with different brightness and dispersion) which facilitates the identification.

The grating is placed over the camera as depicted in Figure 5a, in close contact with the camera lens. You can hold the grating using your fingers or attach it to the phone using masking tape or by any other means. Then you should aim the camera to the selected lamp or lamps, frame the scene and shot to obtain the spectra. After some tries you will gain expertise in where to stand to take the picture, how to grab the phone and the grating together, and how to frame the spectra with a dark background.

5.1 Some tips for taking good spectra

This is a short list of steps to take a good picture of a lamp with its spectrum.

- Select the approximate location from where to take the spectra.
  If there are too many light sources the spectra will be overlapped and will not be usable. It is better to find an isolated lamp or two lamps not very close.
- Stand in a safe place at 15-25 m from the lamp source.
  Step back from the lamp. The lamp should appear as a point source, i.e. as small

as possible. Sometimes the best place is at the other side of the street on a safe place as the sidewalk, be careful with the traffic. If you shoot too close to the lamp, the resulting picture will be probably saturated. This is not important for the source itself but the spectrum or spectra should be identifiable.

- Let the camera adjust the settings.
  Usually the automatic camera settings works OK for obtaining a well exposed picture. The final result could be improved after the shot with the camera edit options.

- Aim the camera and frame the lamp and the spectrum.
  Depending on the distance the direct image of the lamp and the spectra (order m=1 and order m=2). One well exposed m=1 spectrum is enough but obtaining two orders facilitate the identification. You can turn the smartphone and/or grating to obtain spectra aligned with the long side of the picture or even along the diagonal of the frame. Changing the orientation helps to prevent overlapping spectra.

- It is not necessary to take a spectrum of every lamppost in a typical street. They are likely to be identical, so both ends of the street will do. However, keep an eye on them. Every noticeable difference should be registered as well.

- Perceptive observers will probably notice things like “Bright lights in a small playground among neighboring houses”, “Many lamp posts together in a traffic roundabout” or “storefront lights still on at 03 am”. This is useful information and we have provided a comment field for it in the capture application.

5.2 How to improve your results

Good examples of pictures are shown in the preceding pages. The camera could oriented horizontal (landscape) or vertical (portrait). Sometimes it is difficult to decide which orientation of the camera and grating is the best. For instance, the two pictures shown in Figure 9 were taken from the same location and looking at the same lamppost. The picture at left was taken in landscape mode with the grating rotated to obtain the spectra in diagonal and in the dark part of the field of view (dark background). The picture at right was taken in portrait mode and also shows the spectral orders m=1 and m=2 on the bright part of the picture. These spectra are still identifiable and the picture shows the illuminated street and sidewalk.

Figure 9. Same lamppost pictured with the camera in landscape (left) and portrait mode (right).

While the spectra in Figure 9 is well exposed, we show in Figure 10 a common problem of overexposure. When the picture is taken too close to the lamp the resulting spectra could be too bright and saturated. The regions on the pictures with white spots are saturated. This saturation (the detector of the camera reach the maximum level) prevents us from a correct identification.

Figure 10. Spectra of sources taken too close to the lamps showing saturated spectra.

The first order spectrum (m=1) in Figure 10 at left is completely saturated while the second order (m=2) is still useful. The m=1 and m=-1 orders (at both sides of the lamp) in the picture at right of Figure 10 are saturated and is very difficult to identify which kind of lamp is portrayed.

6. Add your Spectrum to the Repository

The resulting picture should be shared with us to be useful. At this time we are using epicollect5 (https://five.epicollect.net/) which is a Mobile (iOS and Android) & Web Application for free and easy data collection developed by the Imperial College London (https://www.imperial.ac.uk/).

Our project is called ACTION Street Spectra and you can browse the data collected upto now at the webpage https://five.epicollect.net/project/action-street-spectra .

6.1 Download and register epicollect5

- Download the epicollect5 app
  Android users
  https://play.google.com/store/apps/details?id=uk.ac.imperial.epicollect.five

iOS users
https://itunes.apple.com/us/app/epicollect5/id1183858199?mt=8

- Register as user
  Quoting five.epicollect.net **“**Currently Epicollect5 requires public users to have a Google Account as the only option. We do not store any users credentials, only the name, email and profile picture (if available) after the user is successfully authenticated with Google. Imperial College enforces this for security purposes, as Google offers a very strong level of security. A Google account accepts any type of email, not only Gmail.”

- Find and Add the action-street-spectra project.
  To add a project, click on the '+ Add Project' button from the top right corner of the 'Projects' page. All the information on adding a project at https://epicollect5.gitbooks.io/epicollect5-user-guide/content/add-a-project.html

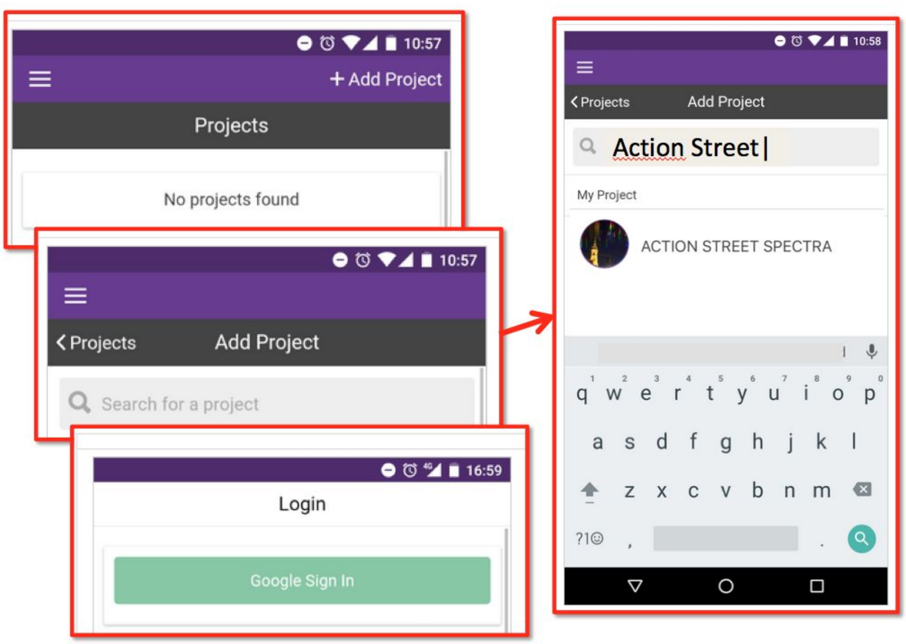


Figure 11. Adding StreetSpectra project to the epicollect5 projects and display of the login window.

6.2 Start using the app.

6.2.1 Creating an entry

Using epicollect5 is simple; the complete manual can be found at the epicollect5 pages. You should open the app and select our project (you can contribute to more epicollect5 projects) and add an entry. The procedure is straightforward and is displayed in successive images in Figure 13 to 15. The picture can be taken at the moment of creating the entry or can be one of the pictures stored in the photo gallery of your phone. Although not strictly necessary, adding your nickname helps greatly in the data analysis.

For the simplest case (picture taken at this moment) the location, date and time are obtained automatically from your phone. If you are introducing a picture taken in advance this relevant data could be edited if necessary to introduce the real parameters. Complete info at:
https://epicollect5.gitbooks.io/epicollect5-user-guide/content/add-an-entry.html

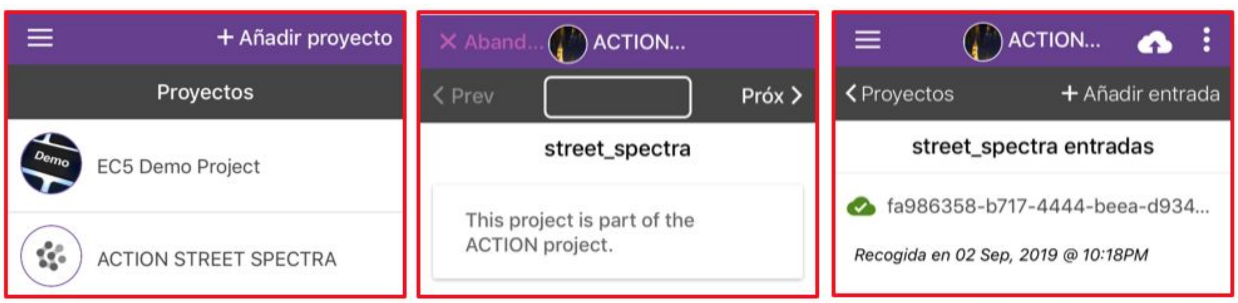


Figure 12. Selecting StreetSpectra project to create a new entry. The third screen shows a previous entry uploaded from the same user.

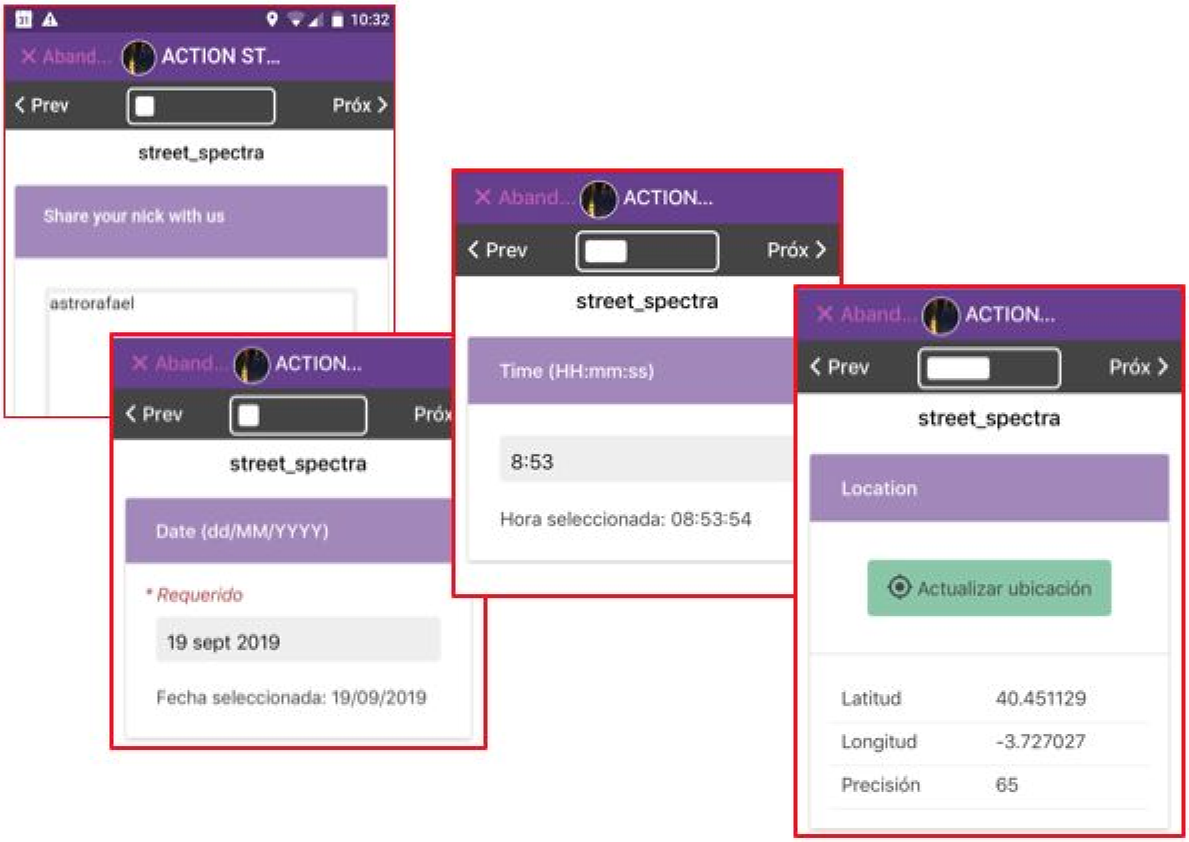


Figure 13. Sequential screens after add entry.

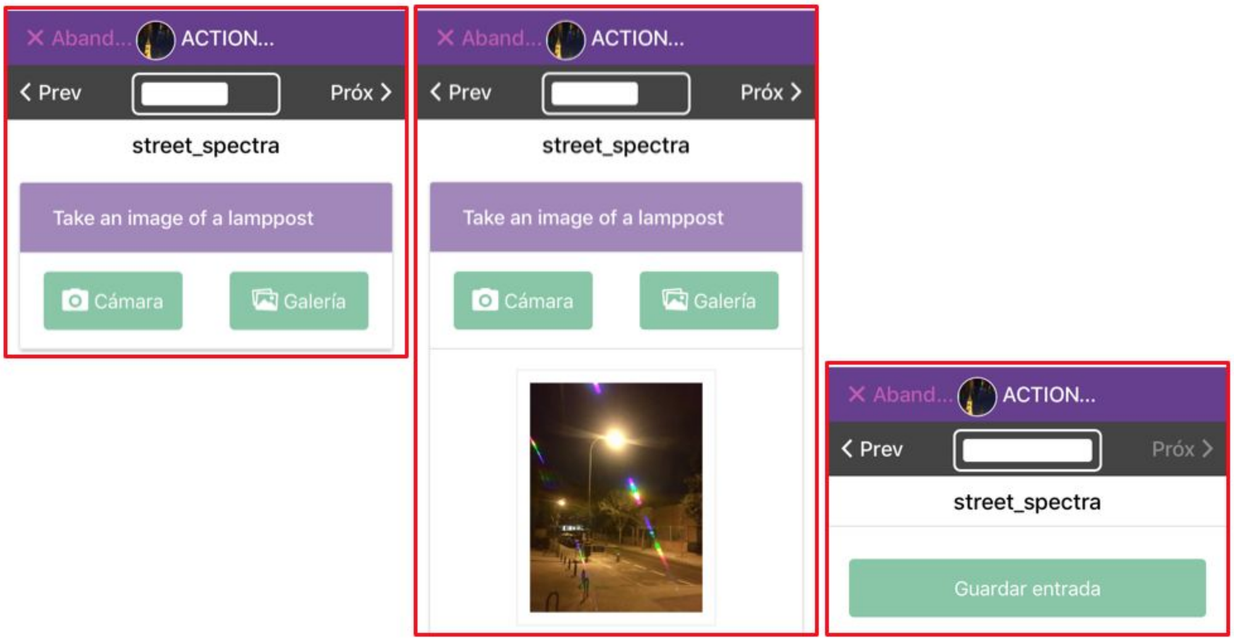


Figure 14. You can choose to take the picture in that moment or get one obtained previously and stored in the photo gallery of your phone. The second screen shows the picture selected or taken at this moment. After all these steps you should save the entry.

6.2.2 Uploading entries

Your entry should be uploaded to the epicollect5 repository to contribute. You can do that at the same time when you create the entry or later using the internet connection of your home, for instance.

In Figure 16 we show an entry which has not been previously uploaded. It is marked with an empty cloud. You should click the cloud icon in the top right corner (the one with the arrow) to start uploading entries. You can select the 'Upload data' button, if you have entries to upload. If you have media to upload (photos in our case), you will be able to do this once all your data has been uploaded. You will be shown a progress indicator when your data is being uploaded and once complete, you will be notified that all entries are uploaded.

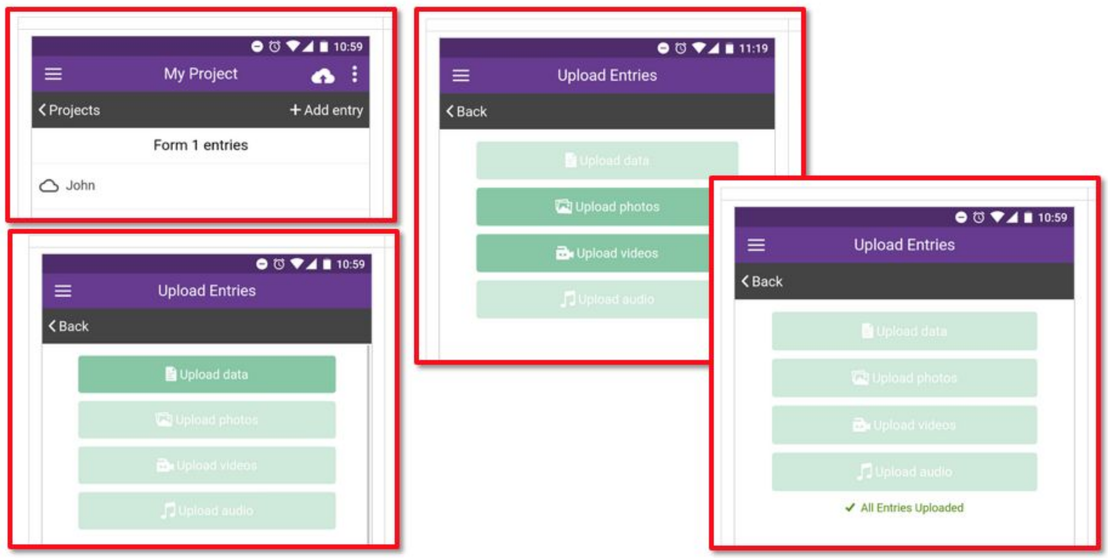


Figure 15. Selecting an entry to upload and successive steps.

Complete info at:
https://epicollect5.gitbooks.io/epicollect5-user-guide/content/upload-entries.html

6.2.3 Browsing the results

Your contributions and those of other citizens are archived in the repository. Some screenshots are shown in Figure 16. You can browse webpage to see all the information collected https://five.epicollect.net/project/action-street-spectra .

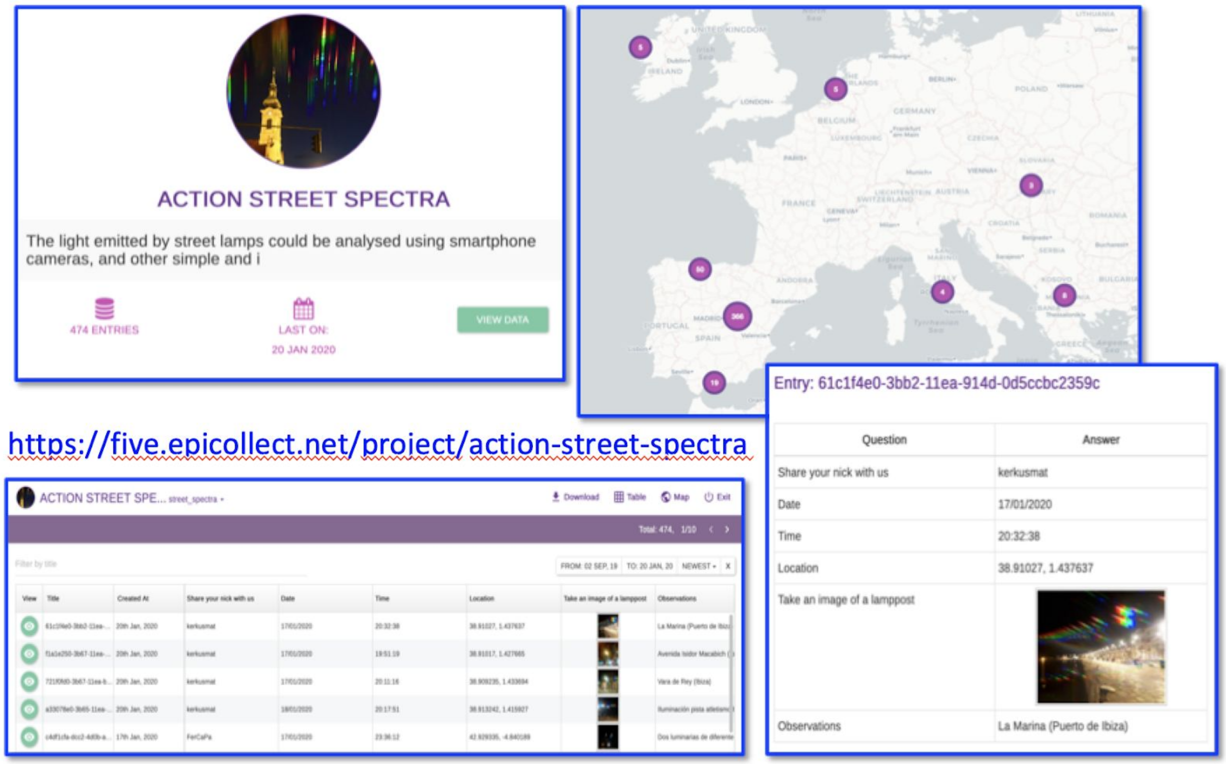


Figure 16. StreetSpectra webpage repository at Epicollect5 showing the project introduction, the map with the observations, last spectra submitted and the information of one of the entries.

7. Tutorial: Identify the spectra of common street lamps

The spectra are identified by comparing with those of similar lamps. All the lamps of the same type and manufacturer present the same spectrum. There are small differences among lamps of the same type and different brands. But the main characteristics (spectral features) are common for each type. You will find an atlas of typical spectra of lamps usually used in street illumination at the end of the manual (Annex I).

You can guess the kind of lamp by looking at its color (see Annex II). The orange lamps are probably High Pressure Sodium (HPS) or Low Pressure Sodium (LPS). It is difficult to find nowadays these LPS lamps that present only an orange emission line. If you are lucky, you could find Light-Emitting Diode lamps **(**LEDs) which a similar orange color that are more friendly to the environment since they lack most of the blue component. Some of the white lights found in streets are Mercury Vapor lamps (MV) and Metal

Halide (MH) gas discharge lamps. The massive introduction of LED lamps has filled our street with white lights. Most of the new white lamps are probably LEDs.

The spectra of gas discharge lamps show emission lines. This spectral features correspond to the elements that are present in the gas contained in the bulb. They are easy to find because appears always in the same wavelength or color.

Figure 17. Three different lamps in the same location allows us to compare their spectra obtained at the same time with a single picture. From top to bottom: HPS, MH, and MV lamps.

At the end of this section we provide a flowchart for identification of the main types of lamps that we can find in street lighting. Before that we show the main characteristics of the spectra of these lamps.

We are showing plots of the spectrum of typical lamps. These graphs represent the energy distribution of the light emitted. The vertical axis (Y-axis) represents the relative flux (maximum value 1) for each wavelength (X-axis) expressed in units of nanometers (1 nm = 10^{-9} meters), i.e. there are 1 thousand millions nm in 1 m. The graphs are obtained from the LICA-UCM lamps spectra database, see Annex I. With the StreetSpectra observations you do not get these plots but rather the rainbow spectrum images.

A) Sodium lamps HPS

The most prominent emission lines appear at 569, 594, 595, 598, and 616 nm. The 569 nm line is green while the rest are in the yellow-orange part of the spectrum. Other apparent lines are located at 467, 475, 515 nm and the more intense 498 nm doublet (two close lines).

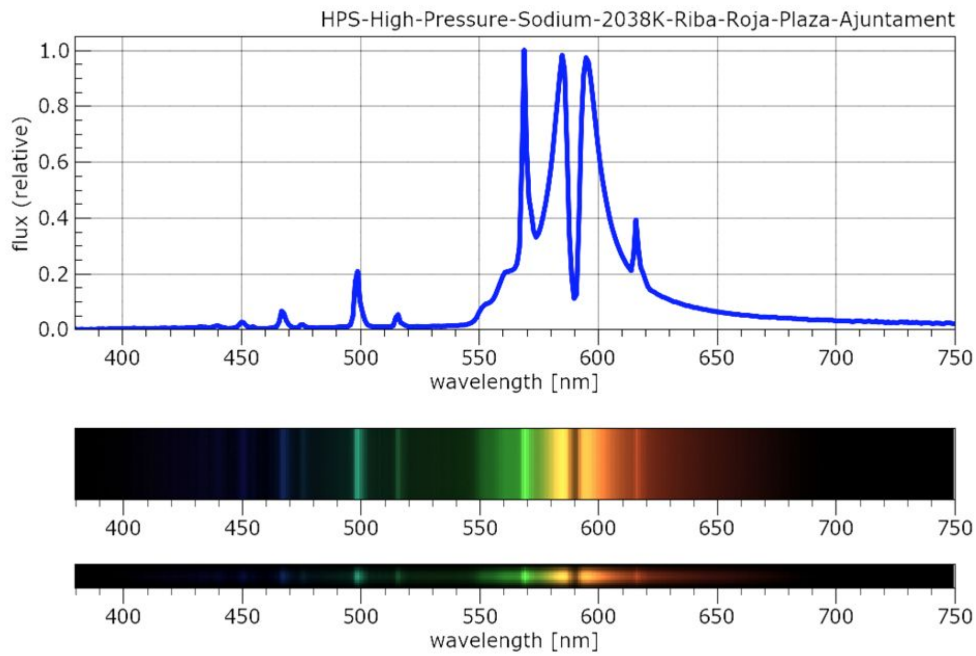


Figure 18. Example of Sodium HPS lamp from the LICA-UCM lamp spectra database.

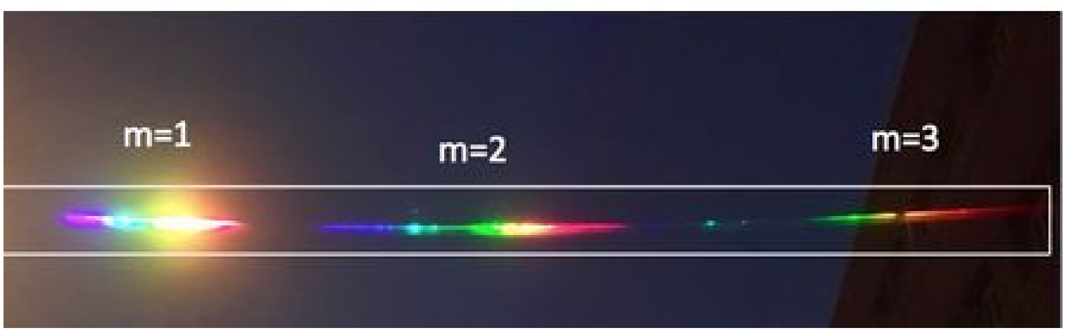


Figure 19. Spectrum of street HPS. Order m=1 is saturated but we can see in order m=2 that most of the light is in the yellow part and some emission lines are present in the blue-green. In order m=3 the absorption (dark lane) in the 589 nm splitting the yellow spectrum in two.

B) Mercury vapor MV

The spectrum has emission lines of mercury as 408, 436, 492 (very faint), 546, 577, 579, 620 nm

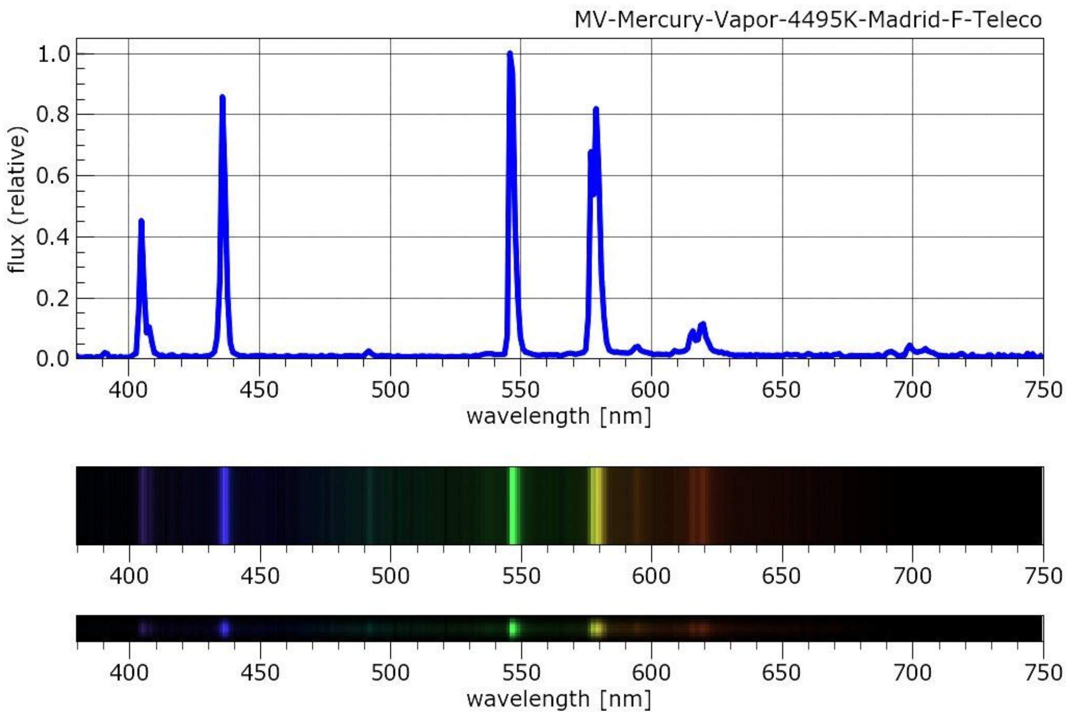


Figure 20. Example of MV lamp spectrum from the LICA-UCM lamp spectra database.

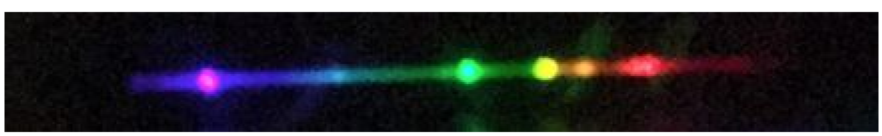


Figure 21. Spectrum of street MV lamp. Some isolated emission lines are clearly seen: 436 nm (magenta),   492 nm (blue, faint), 546 nm (green), the 577,579 nm doublet (yellow), 620 nm doublet (red). An additional line is also visible (orange).

C) Metal Halide MH

The most prominent emission lines belongs to mercury and appear at 405, 436, 546, and 579 nm. They are similar to those of the MV lamps. Other observable lines are 474, 509, 536, 571, 591, 631 nm.

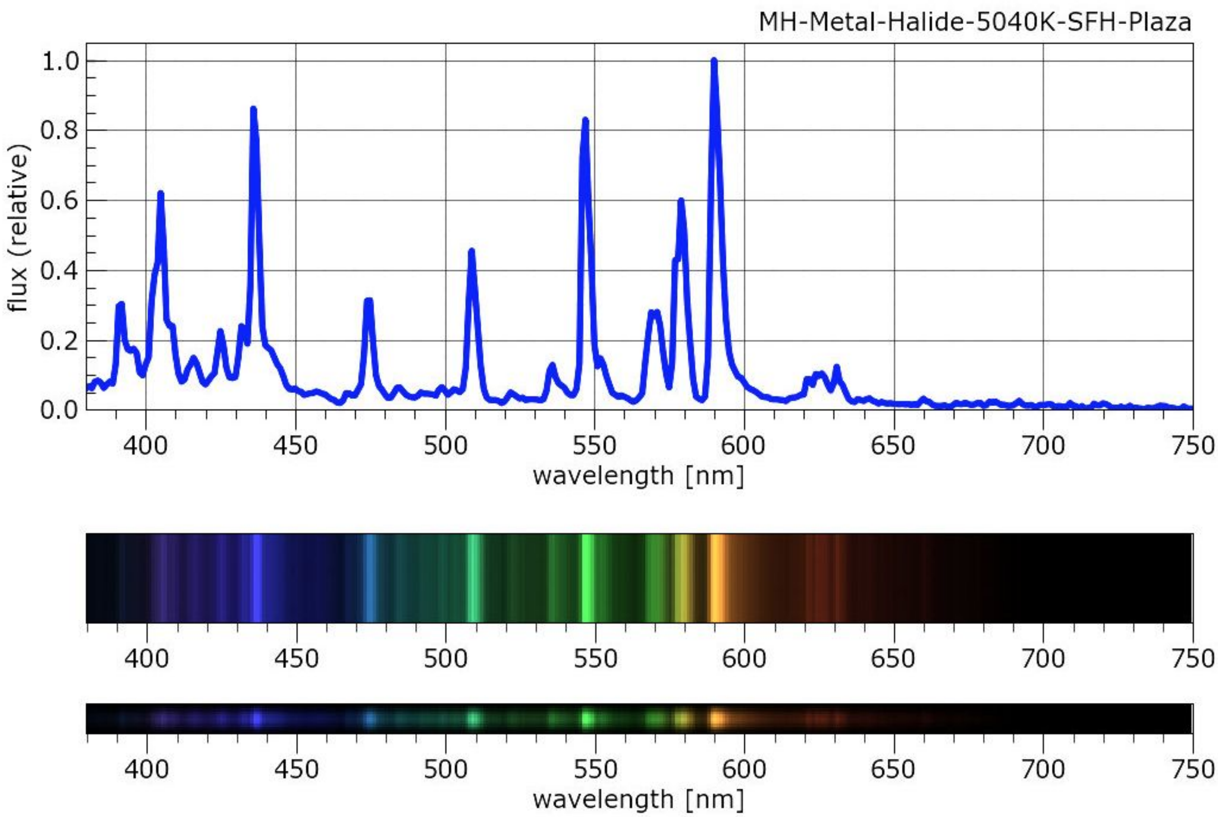


Figure 22. Example of MH lamp spectrum from the LICA-UCM lamp spectra database. Besides the emission lines of MV lamps they are some additional lines as the yellow 591 nm line.

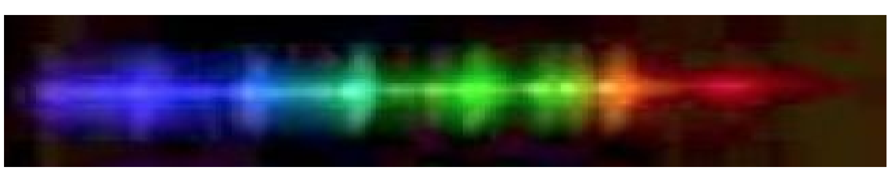


Figure 23. Spectrum of street MH lamp.

D) Light Emitting Diode LED

The spectra of this lamps is a continuous rainbow of light without any other spectral features as emission (bright) or absorption (dark) lines.

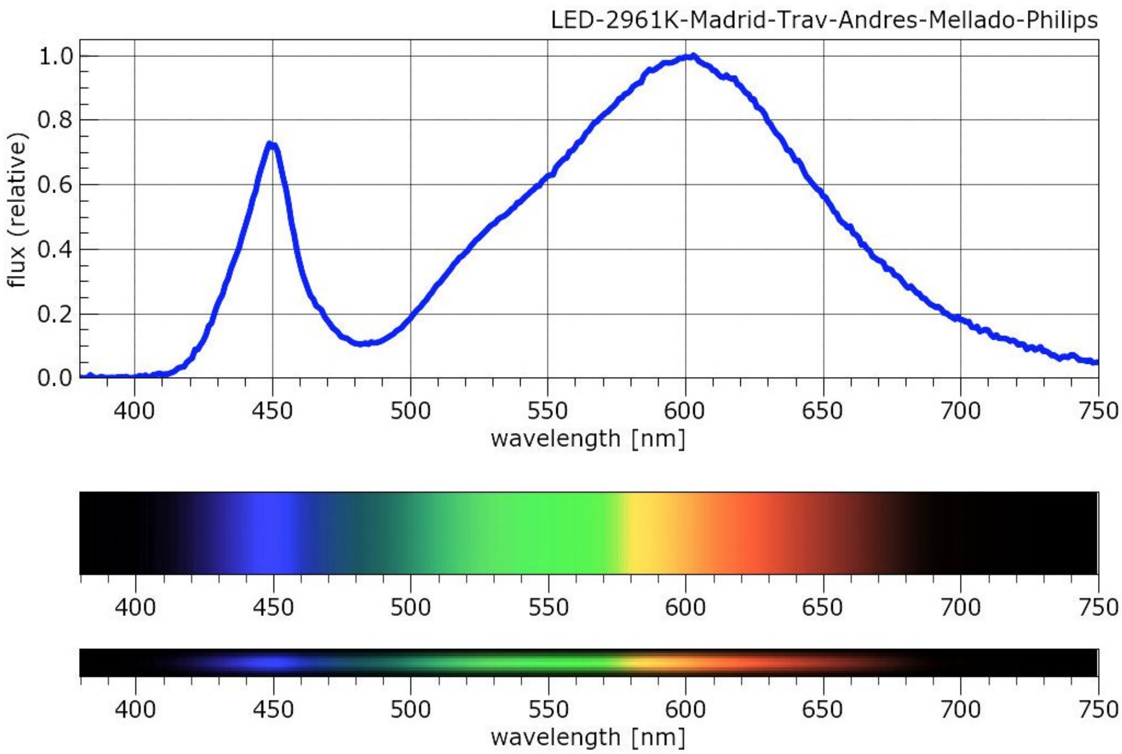


Figure 24. Example of LED lamp spectrum from the LICA-UCM lamp spectra database.

The LED lamps come with different colors (see ANNEX II). As you can see the spectrum presents two bumps: one centered in 450 nm and the other in the 600 nm region. The color of the lamp depends on the relative strength of the light emitted in the blue part of the spectrum (first bump, below 490 nm). Figure 24a shows an example with four spectra belonging to LED lamps with increasing blue content. The identification among LEDs using the spectrum taken with a smartphone is not an easy task as the resulting image is not calibrated and the colors depends on the camera and detector of each smartphone model.

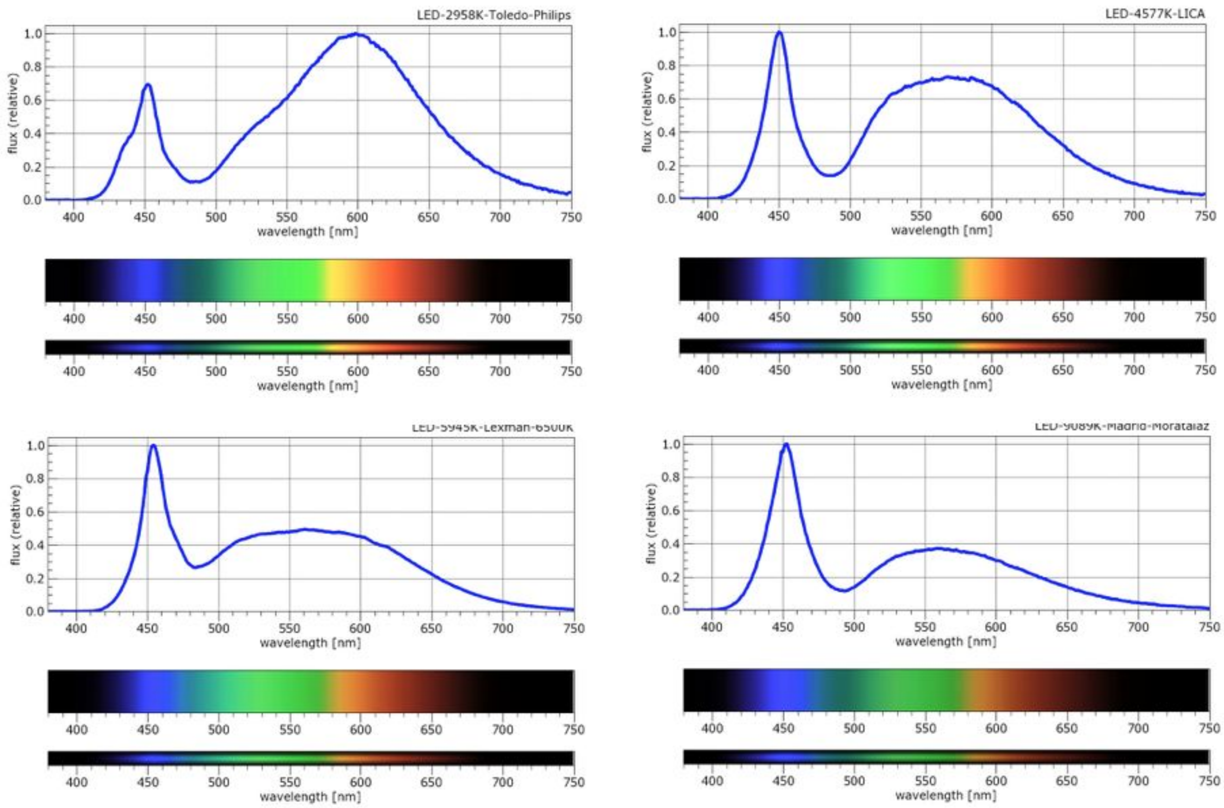


Figure 25a. Example of LED lamps of different colors.

The very white LED lamps will show a rainbow of colors with increasing brightness in the blue part of the spectrum. On the other side, the LED lamps with lower color temperature (see ANNEX II) have spectra with yellow-orange contribution.

There are LED lamps designed to have very low or none blue contribution at all. These ‘PC amber LEDs’ are very difficult to find in our streets but they are increasingly being installed in light pollution protected areas. The picture in Figure 25b was taken by Andreas Hänel at Rheda-Wiedenbrück (Germany). The spectrum plot of a similar lamp (Figure 25b, lower right) shows the absence of light of color below 500 nm.

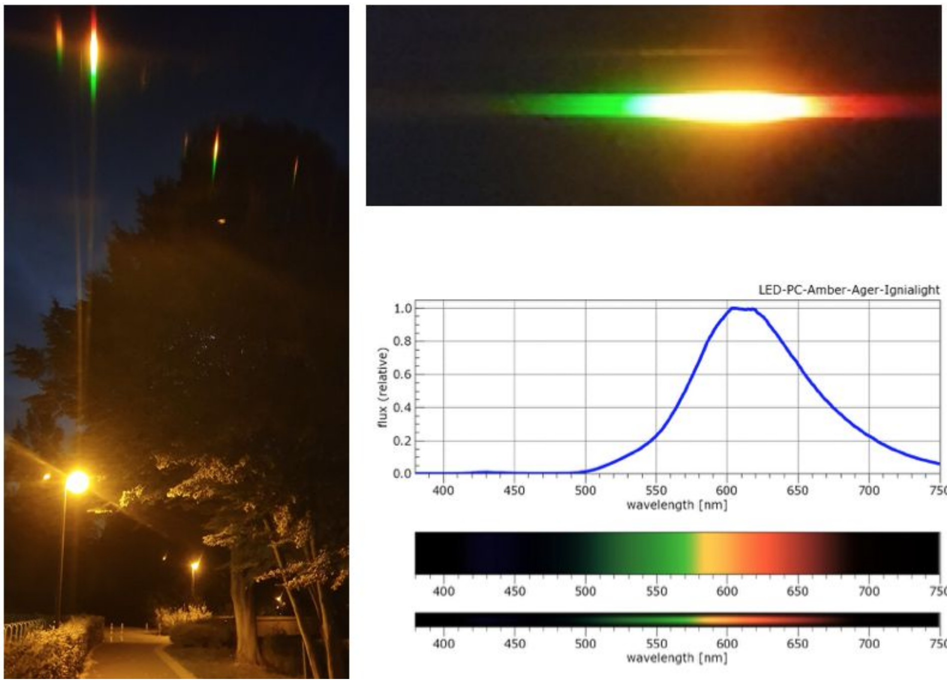


Figure 25b. PC amber LED lamp. Picture taken at Rheda-Wiedenbrück (Germany) by Andreas Hänel (left). The color of the lamp is orange and the spectrum does not show any blue light (upper right).

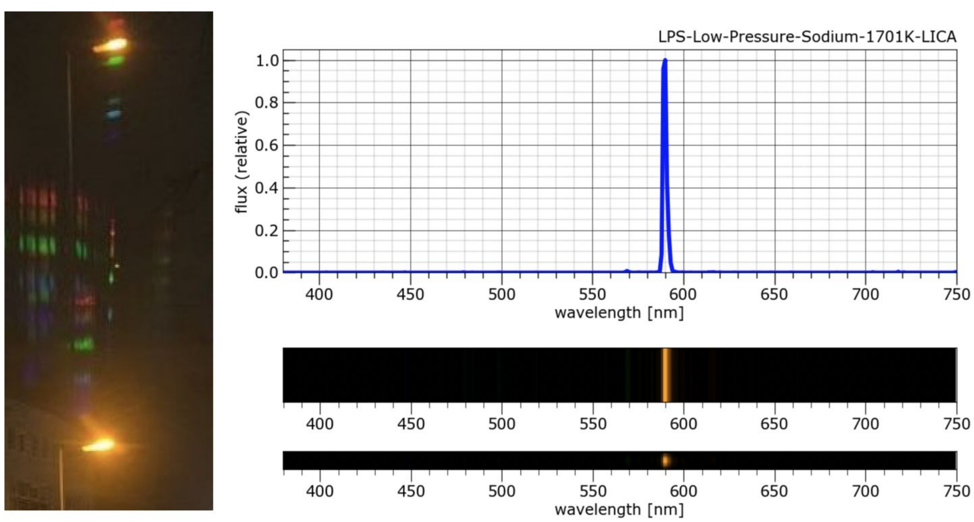


Figure 25c. LPS lamp and its spectrum (left). Picture taken at Erasmus University Rotterdam campus. Only the sodium orange line is prominent.

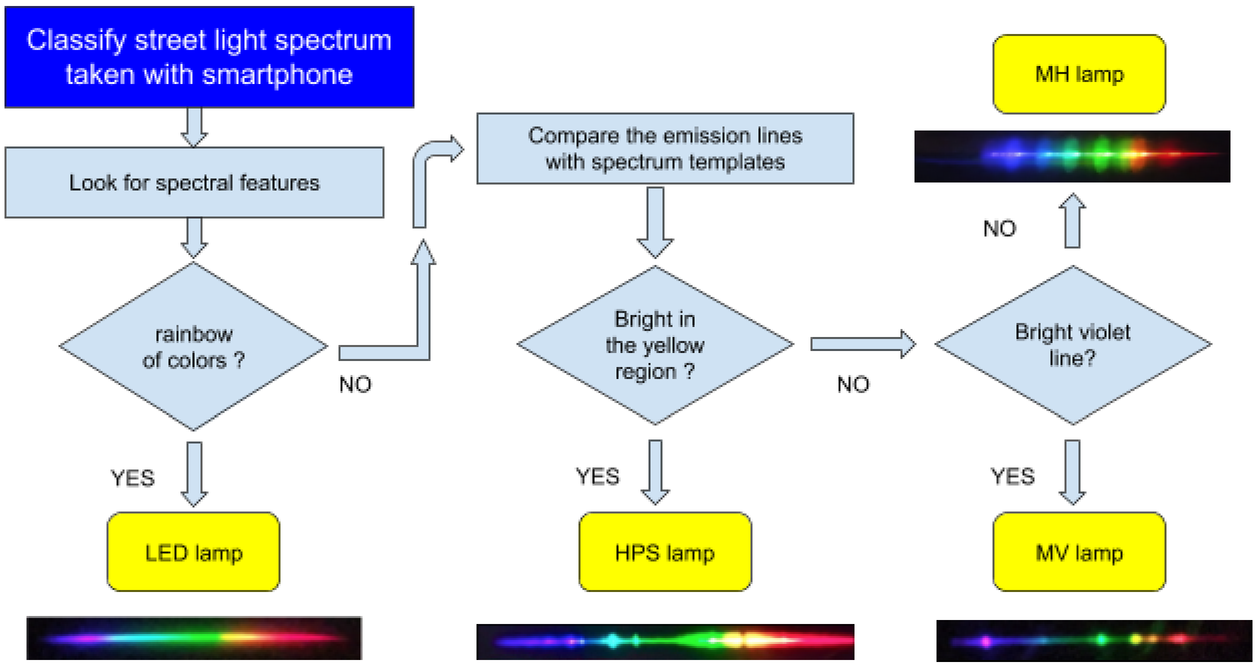


Figure 26. Flowchart to help on lamp classification according to the spectrum.

ANNEX I. Atlas of typical spectra of street lamps

AI.1 The UCM lamps spectra database

For this project we have improved the "LICA-UCM lamps spectral database" (C. Tapia, A. Sánchez de Miguel & J. Zamorano UCM-eprint 40930)

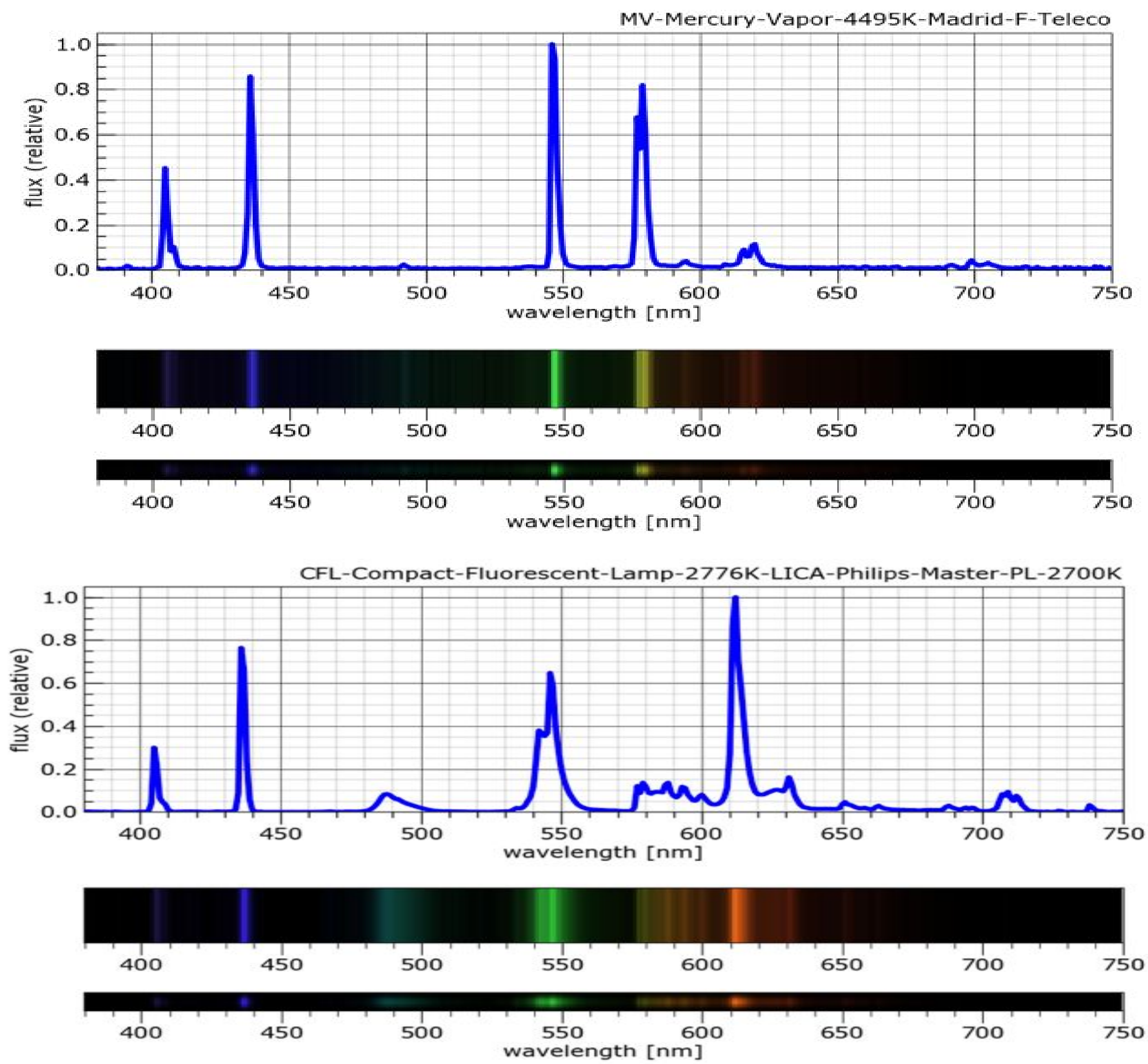


Figure 27. Two of the spectra of the LICA-UCM lamps spectral database showing the plots and a visual rendering of the color spectra.

The database (https://guaix.fis.ucm.es/lamps_spectra) contains a repository of spectra of lamps (most of them street lights) obtained by Carlos E. Tapia et al. using the LICA-UCM professional instrumentation (portable spectrographs and monochromators).

The database can be used as an atlas of spectral types. Besides the plots (mostly used by researchers to identify and measure the spectral features) we include a visualization of the color spectra as seen through a diffraction grating. The data and plots are free to use (open data) for researchers and interested citizens. For practical purposes we will add the main spectra found in the streets reproduced at the end of this manual.

The visualizations are the predicted or modelled spectra as they will show in the smartphone screens. The smartphone cameras have a detector with three channels (R, G, and B) and the final picture is a composition of these channels that the camera process.

The final color rendering depends on the characteristics of the detector (spectral response) for each smartphone model and the camera settings. Note that we are using the JPEG or PNG files provided by the smartphone because we are interested only in classification, not calibration. Some smartphones can provide pictures in RAW, unprocessed images. With these files one can calibrate and measure in the images since there is a proportional correspondence brightness-pixel value.

The database contains spectra of lamps used in our houses (indoor, not for public external illumination) in case you can obtain spectra of these lamps or for teachers who wish to use the setup to prepare some hands on experiments at the school.

AI.2 Examples of lamps spectra taken with smartphones

For comparison purposes it is more useful to compare the spectrum to be identified with real spectra taken with a similar setup: smartphone camera + grating.

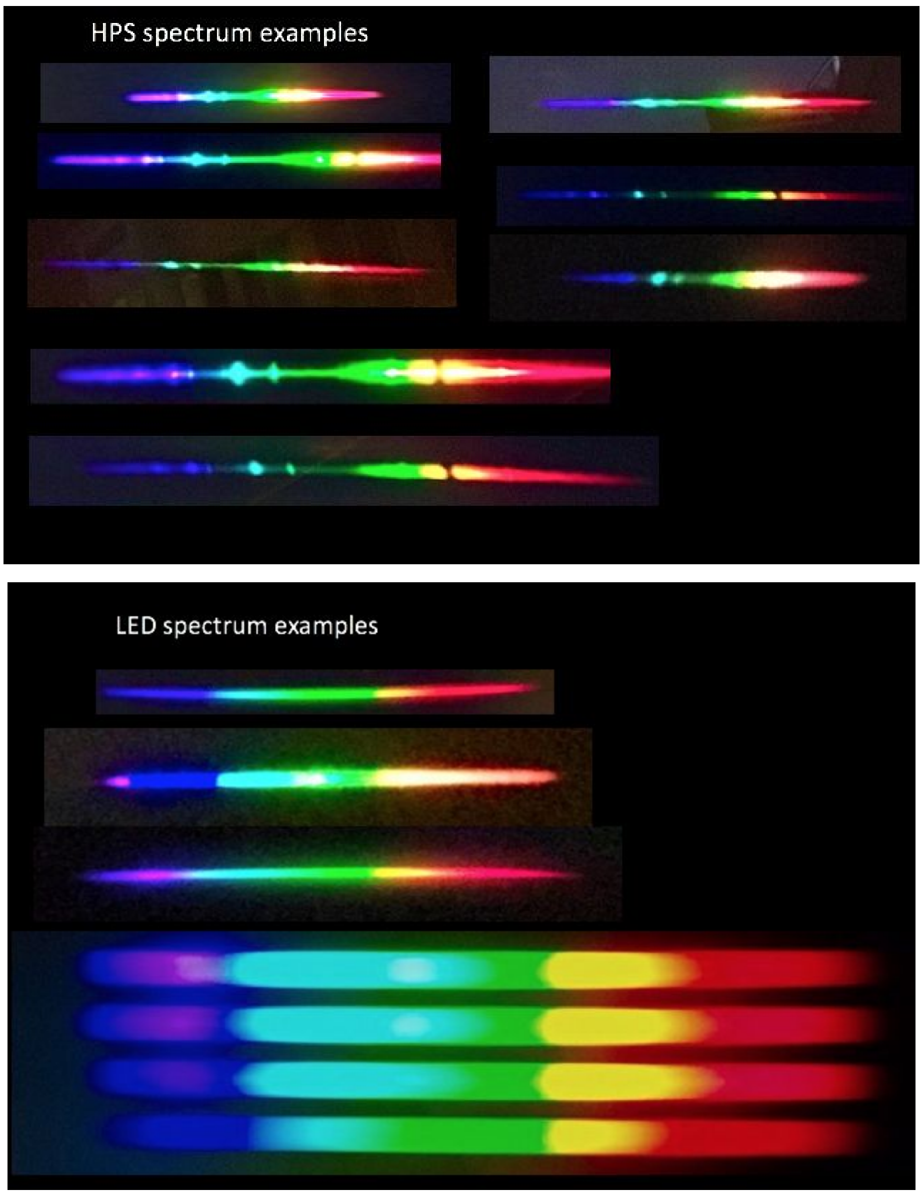


Figure 28. Examples of spectra taken with smartphone and grating for HPS and LED lamps.

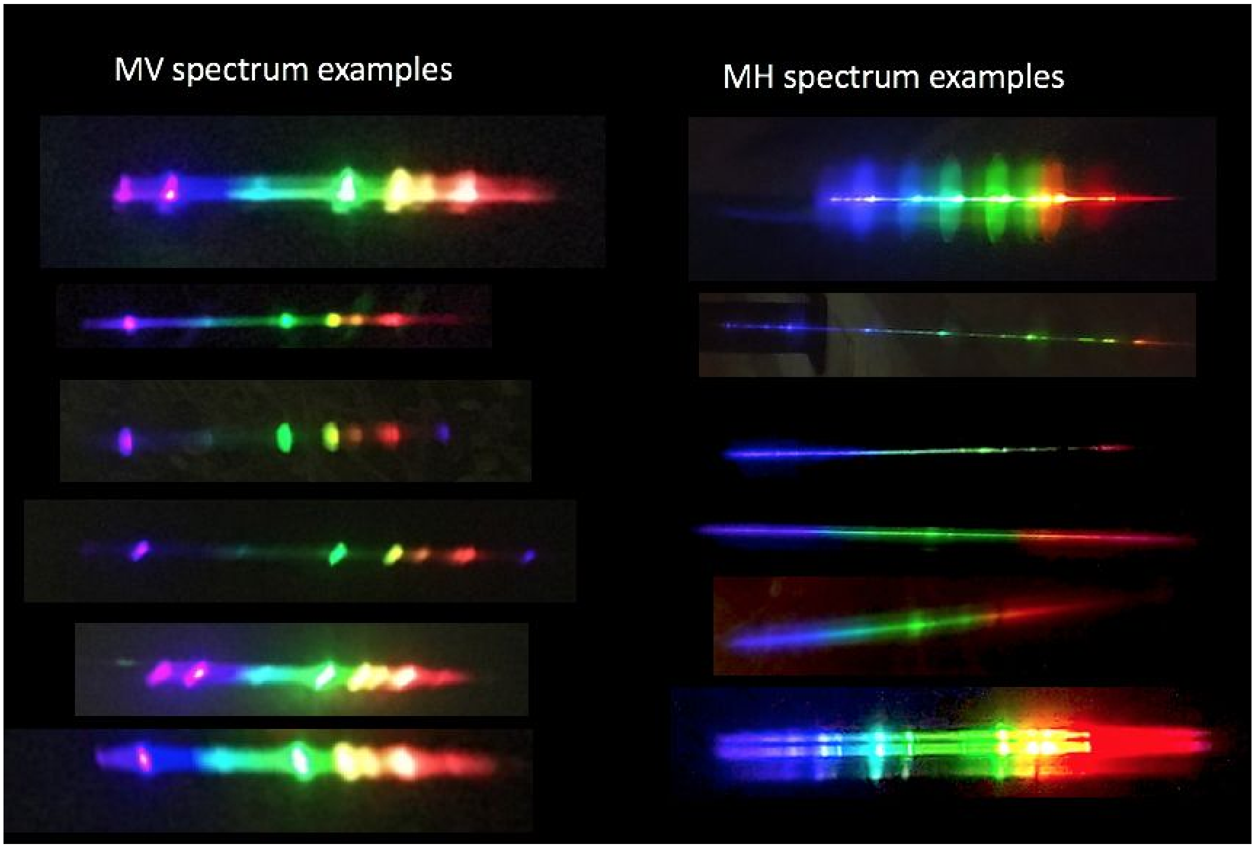


Figure 29. Examples of spectra taken with smartphone and grating for MV and MH lamps.

ANNEX II. The color of the lamps

Before the invention and popularization of electric lighting (beginning of the 20th century in developed areas), only fires, oil lamps, candles and gas lights were used. All these lamps emits orange light. The first commercial incandescent light bulbs were also very orange. Humanity has been using orange lights for a long time. Its spectrum is similar to a black body which is an ideal radiator and absorber of light.

A blackbody[4] emits a continuum spectrum (without spectral lines) whose color is related to the temperature of the blackbody. If we change its temperature the color changes accordingly. The temperature is expressed in units of Kelvins and for instance the temperature of a candle flame is around 1850K (One thousand and fifty kelvins). Incandescent lamps emit as a 2400K blackbody. The maximum of the emission falls in the near infrared (this is why these lamps are very hot at touch) and are not energy efficient. This is why the European Union banned the incandescent lamps by 2012[5].

For lamps whose spectrum is composed of emission lines is makes no sense to assign a temperature since they are not blackbody emitters. However even these lamps are labelled with a color temperature (CCT correlated color temperature) which refers to the temperature of a blackbody that produces a similar color. So we say that a lamp has a cool color (bluish) for CCT of around 5000K and warm color (yellowish) to those with CCT ~ 2500 K. Please note that cool color corresponds to higher temperature, to add more confusion to the CCT parameter.

Before going further we reproduce here a paragraph about the color of the lamps extracted from the basic information and the recommendations of the International Dark Sky Association (IDA) for outdoor lighting: “Lighting with lower color temperatures has less blue in its spectrum and is referred to as being ‘warm’. Higher color temperature sources of light are rich in blue light. IDA recommends that only warm light sources be used for outdoor lighting. This includes LPS, HPS and low-color-temperature LEDs”[6]. The European Union has released a report about road lighting (including roads inside

[4] https://en.wikipedia.org/wiki/Black_body
[5] https://europa.eu/rapid/press-release_IP-08-1909_en.htm
[6] https://www.darksky.org/our-work/lighting/lighting-for-citizens/lighting-basics/

the cities) “Revision of the EU Green Public Procurement Criteria for Road Lighting and traffic signals”[7] including light pollution criteria.

The orange lights in the street are mainly HPS (High Pressure Sodium) and in some cases LPS (Low Pressure Sodium) with CCTs around 1700K-2200K, a warm light with colors similar to those of the incandescent lamps and that of the candles. Some modern LEDs called PC amber are manufactured with this low CCT values to avoid splitting blue light at night.

White street illumination has been provided with Mercury Vapor (MV) and Metal Halide (MH) gas discharge lamps. The mercury inside the bulb is vaporized by an electric arch and that produces light. MV lamps has strong emission lines in the blue (435.8 nm) and green (546.1 nm) but also in the ultraviolet (UV). Those lamps are usually coated with phosphor to convert part of the UV light to the red part of the spectrum. For the MH lamps there is an addition of some metal halides to increase its efficiency. A variant is the Ceramic Metal Halide lamps (CMH) with ceramic in the arc instead of quartz of the metal halide lamps. The color temperature for MV and MH lamps ranges between 3000K - 6000K.

Compact Fluorescent Lamps (CFL) are mainly used indoors or around the houses. They also contains mercury inside the bulb and phosphor in the coating. They can be manufactured with different colors from daylight (very white, 5000-6500K CCT), Neutral White (3500K) and Soft or Warm white (2700K).

These lamps are being progressively replaced by Light Emitting Diode lamps (LEDs) that can be manufactured in a variety of colors. Unfortunately most of the LEDs in our street are too white with a blue component that is very harmful for the environment.

7 https://susproc.jrc.ec.europa.eu/Street_lighting_and_Traffic_signs/docs/JRC115406_eugpp_road_lighting_technical_report.pdf

Figure 30. Some LED lamps used in indoor illumination showing different colors.

ANNEX III. How to build a handheld visual spectroscope.

With a transmission grating and some materials that are very easy to find at home or school you can build a hand-held visual spectroscope. You can see the spectra of lamps in the street or the spectra of any light source using this simple spectroscope. The sketch of Figure 31 shows a simple design using a cardboard tube.

Do not aim the spectroscope to the Sun. NEVER

Spectroscope parts:

- *Cardboard tube or similar*. Suggestions for this tube are the one in the kitchen paper roll or those of cylinder tube chips packages. You can also use plastic tubes, PVC pipe or any long rectangular box. Use your imagination. This tube should be opaque.
- *Transmission grating*
- *Slit.* This narrow rectangular aperture is used to improve the spectral resolution, i.e. to better define the spectral lines. You can try with different widths, to begin we recommend around 1mm. You can open this aperture with a cutter (be careful) on a hard card paper or any material that you have at hand.

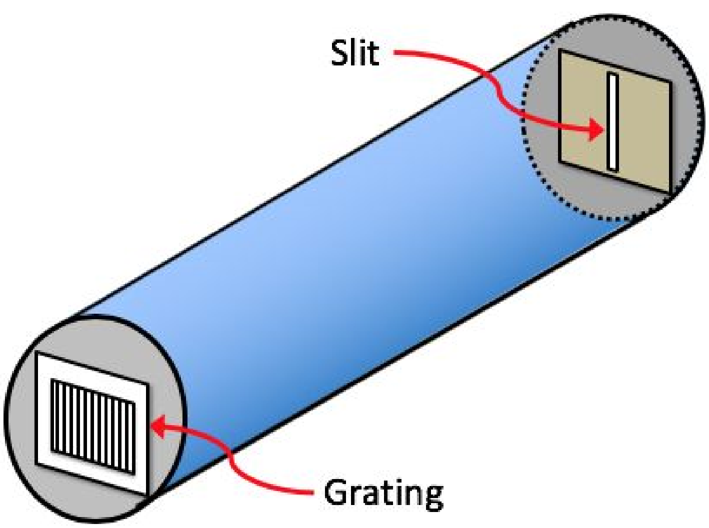


Figure 31. Visual spectroscope sketch.

Mounting the spectroscope:

The construction is straightforward: the slit and the grating should be placed at both opposite parts of the tube. Be sure that the lines of the grating are parallel to the slit as shown in the figure.

Using the spectroscope:

To see the spectrum of a lamp you should hold the spectroscope, put your eye near the grating and aim the tube to the light source.

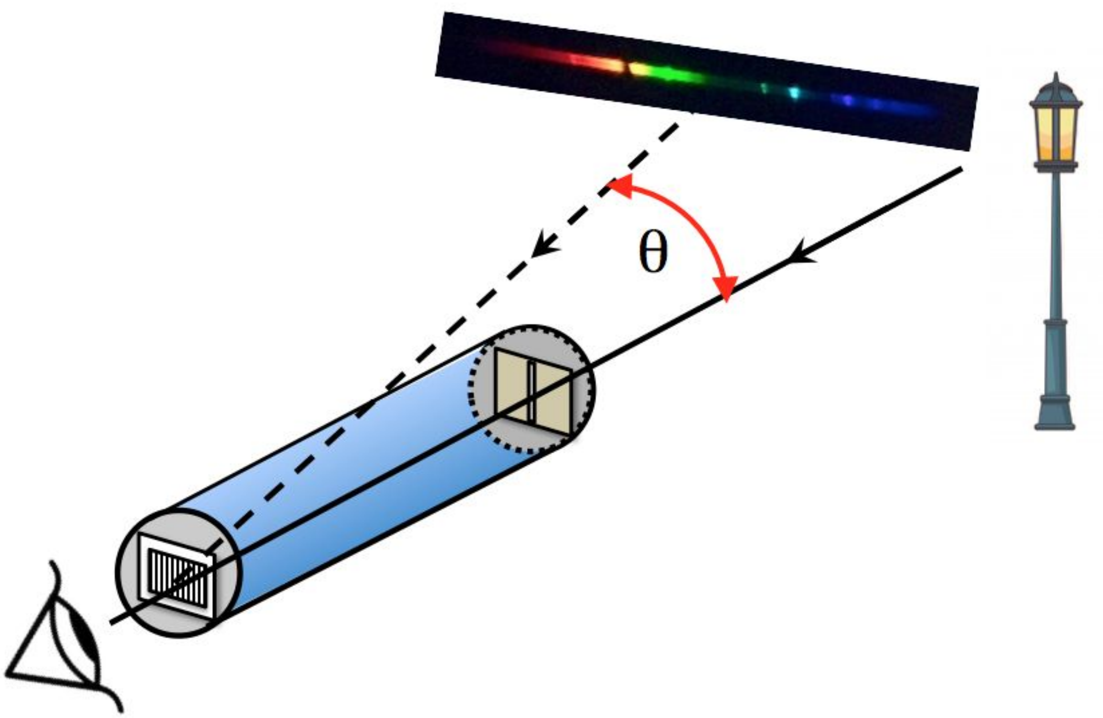


Figure 32. Using the visual spectroscope.

The spectrum is displaced from the direct image of the lamp in an angle that depends on the grating spacing (number of lines per millimeter) and the order. If you aim the spectroscope to the light source the deviation angle θ is determined with the grating equation,

$$m\,\lambda = \sigma\, sin\,\theta$$

where m is the order (m=1 in this case), λ is the wavelength of the light, and σ is the distance between the grating lines. For a 500 lines/mm grating (σ= 1/500 mm) and using the wavelength of the green part of the spectrum (λ=550 nm) we obtain a deviation of θ = 16º. For grating with more lines per millimeter this angle is proportionally greater (23 degrees for 750 lines/mm and 33º for 1000 lines/mm).