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Evaluation of light pollution sources over Tuscany with an autonomous payload for sounding balloons

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Abstract

The MINLU ("Misurazione dell' INquinamento LUminoso") payload was successfully launched on July 7th 2021 with a sounding balloon from Tuscany, achieving continuous observation of sky brightness and ground light sources from ground to maximum stratospheric altitude near to 34 km. The operation was the result of a joint effort by the Department of Industrial Engineering (DII) and the Center of Studies and Activities for Space "G. Colombo" of University of Padova which realized the scientific gondola in collaboration with the Space Systems Lab from University of Pisa, which provided its UniPiHAB04 flight platform to carry the system to stratospheric altitude and safely back to ground.

MINLU autonomous payload has been designed and tested to provide complete and detailed aerial observations of Light Pollution and Sky brightness, with the capability to be integrated either on stratospheric balloons or drones. The implemented architecture includes three cameras with dedicated filters (one monochromatic camera working as raw spectrometer, one as luminance meter and a colour camera for overall ground illumination reconstruction) and two commercial Sky Quality Meter (SQM-L) units, controlled a Raspberry based Central Data Management Unit performing sensor conditioning, data acquisition, compression and storage; inertial position and attitude information are acquired by on board GPS and IMU systems and automatically linked to scientific data.

The work will briefly present the calibration activity of the luminance camera and the raw spectrometer conducted in the laboratories of university of Padova and then describe the balloon flight trajectory and attitude reconstruction focusing on the elaboration of camera's inertial pointing used for the calculation of ground illuminating sources based on luminance data.

Light polluting sources in the Pistoia area will be analysed from 34km altitude highlighting the entity and reconstructed type of emission sources and comparing elaborated stratospheric measurements with the available radiance values from satellite imaging (based on VIIRS instrument data)

Keywords: light pollution monitoring; autonomous payload for sounding balloon; trajectory and pointing reconstruction

1. Introduction

Light pollution is becoming an increasingly important issue not only for astronomical observations but also for the living environment, since negative effects linked to excessive illumination during night have been demonstrated to affect human health [1] and behaviour of wildlife [2].

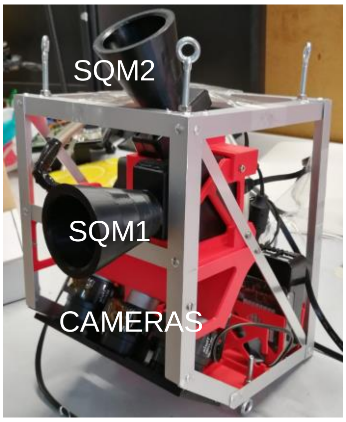
Global light emission is to date monitored mainly using images from Visible Infrared Imaging Radiometer Suite (VIIRS) on board sun-synchronous orbiting satellites, but satellite's coverage of interest areas is not continuous in time and shows limited horizontal spatial resolution (around 800 m/pixel) [3]. Furthermore, VIIRS operates using a day/night panchromatic band with wavelength range between 500 nm and 900 nm [3] so most radiation from blue LEDs (with energy peak around 450 nm) cannot be detected; these emissions are particularly harmful to star visibility and human health, as underlined by recent reports by International dark Sky Association [4] and American Medical Association [5]. Ground based sky brightness measurements are also locally available, mainly conducted using SQM commercial units [6], but they do not allow to reconstruct global maps or to monitor effects of light dimming (typically after midnight). The gap between terrestrial surveys and observations obtained by satellite images needs to filled using dedicated measurement systems able to correlate available radiance and sky brightness reconstructions; this can be covered using aerial observations at different altitudes and locations by flying dedicated payloads with drones or balloons. A low-cost autonomous system using commercial cameras with different pass-band filters can efficiently monitor main light emission sources on ground with a resolution of few meter and calibrated photodiodes can be used to investigate in parallel sky brightness evolution. Furthermore, by properly controlling the flight trajectory over a limited area with drones or using tethered balloons it may be possible to track the time evolution of the luminosity over many hours during the night, following the dimming of outdoor and street lights.

2. MINLU autonomous payload

MINLU (“Misurazione dell’ INquinamento LUminoso”) is a completely autonomous payload system designed to measure sky brightness and in parallel identify and quantify sources of light pollution on ground. It is based on commercial off the shelf (COTS) components for whole architecture including images acquisition, georeferentiation and storage and thanks to a modular design can be adapted to be used on drones, stratospheric balloons and tethered balloons.

The payload is controlled by a Raspberry PI 3 model B single-board computer, which performs data acquisition, compression and storage and is connected though a digital hub to the imaging subsystem, which in the baseline flight configuration includes three Basler ace AC A3800-10 digital cameras (two monochromatic and one color) and the sky brightness subsystem, composed by two commercial SQM-LE units. In the imaging subsystem the colour camera is used to acquire a global map of the area, one monochromatic camera is provided with a photopic filter and operates as a luminance meter and the last monochromatic camera implements a visible transmission diffracting grid with 300 groves/mm to act as a raw multi-spectrometer.

A commercial Pixhawk Pixcube unit, comprising two IMUs and a GPS module, provides data for trajectory and pointing reconstruction, and operates as transmitting station for the long-range telemetry. Balloon flight configuration includes a Power Unit managing stable power conversion to all subsystems and guaranteeing at least 5 hours of continuous operation reaching an overall mass less than 3 kg comprising thermal insulating cover and flight chain harness.



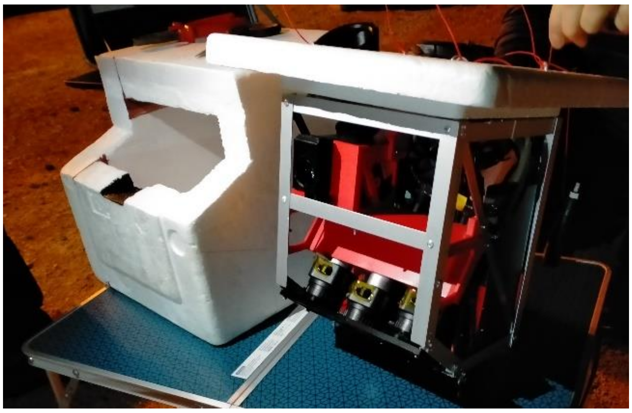


Figure 1 – MINLU autonomous payload architecture for sounding balloon flight.

3. Imaging unit laboratory test campaign

A dedicated test campaign of the image subsystem was conducted at Photometry and Lighting Engineering Laboratory of University of Padova for all cameras [7], focusing mainly on the characterisation of performance for luminance meter and raw multi-spectrometer.

3.1 Luminance meter calibration

The luminance meter (camera plus Omega Optical Photopic Filter) performance has been investigated considering different types of illumination sources and verifying the output from camera images with the reference measurement of a spot luminance meter Minolta LS-100. The detailed description of test set up and results of calibration tests are reported in [7], although the table presented in Figure 1 summarises the comparison of the luminance meter output in comparison with reference spot luminance meter Minolta LS-100

Lamp	Ref. (cd m^{-2})	Camera (cd m^{-2})	Diff. (%)	Std (%)
Fluorescent 2600K	13.1	12.5	-5.6	1.3
Fluorescent 3750K	12.9	12.8	0.5	0.7
Fluorescent 5800K	12.5	12.4	-0.8	1.0
Mercury vapor	54.5	57.0	4.4	0.12
HP Sodium	82.1	82.1	0.02	1.0
HP Sodium calibration	61.0	61.0	0.00	0.15

Figure 1: Image of test set up for luminance meter of imaging subsystem (left) alongside reference spot luminance meter Minolta LS-100 and results of standard deviation of measured level for different types of input light signal [7] (center); integrating sphere used for calculation of different CCD areas sensitivity (right)

In order to be able to accurately reconstruct luminance values from ground sources not only in the nominal nadir direction but present in the whole field of view, the luminance meter sensitivity has been evaluated considering the signals in different areas of the CCD pixel matrix using the output of integrating sphere with diameter of 38 mm.
The considered input luminance values and an example of reconstruction of average pixel values and standard deviation for central and side areas for an input luminance of 2.64 cd/m^2 are reported in Figure 2.

Luminance input (cd/m^2) Centre	Luminance input (cd/m^2) Side
0.001	0.001
0.006	0.036
0.156	0.191
0.388	0.314
	0.459
0.651	0.655
0.914	0.894
1.184	1.152
1.439	1.445
1.730	1.724
1.992	1.955
2.295	2.250
2.630	2.645

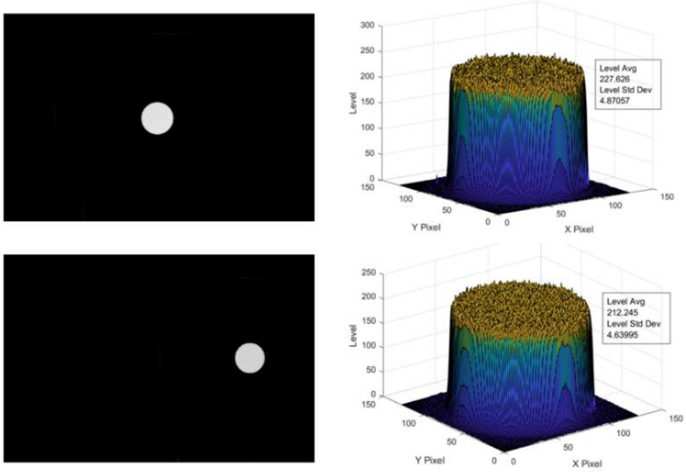


Figure 2: Input luminance values and elaboration of average pixel level at central and side CCD location for the highest input luminance (2.63 cd/m2)

The analysis of data for the central and side areas allowed to construct the calibrated least-square curve representing the average response of luminance camera pixel to input luminance coming by any direction in the field of view. The least square curve including uncertainty bands is reported in Figure 3 along with the specific curves for central and side areas.

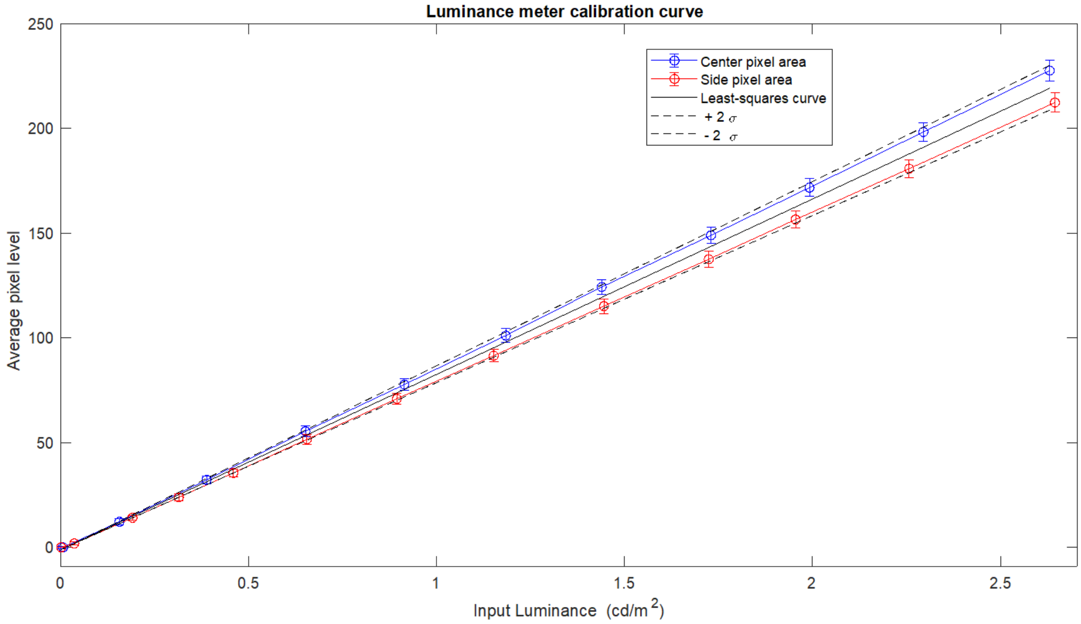


Figure 3: Least-squares luminance meter calibration curve

3.2 Raw multi spectrometer calibration

The wavelength calibration of the raw multi-spectrometer has been obtained in Photometry Laboratory using a mercury vapor lamp and comparing the output with a reference CS-1000 Konica Minolta portable spectroradiometer [7]. In order to investigate the possibility to discriminate among different LED types ("warm" or "cold" emission spectra), the response of the raw multi spectrometer camera has been acquired in presence of different illumination sources: Red and Green Laser, Fluorescent bulb , Halogen light, White Led with different Correlated Colour Temperature (CCT). Some of the elaborated spectra are reported in Figure 4.

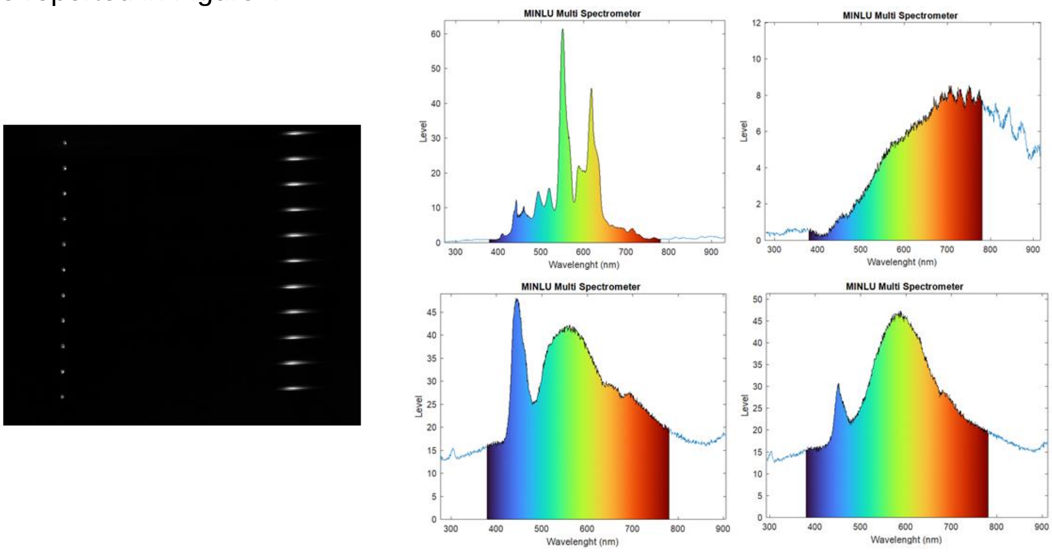


Figure 4: MINLU Multi Spectrometer image of a string of green LED (left) and results of MINLU analysis of common types of light sources: Fluorescent bulb (1), Halogen light (2), "Cold" White Led CCT=4000 K (3), "Warm" White Led CCT=3000 *K (4)*

It may be noted that the sensitivity of CMOS sensor used by raw multi-spectrometer camera (Sony IMX178) allows to reconstruct the spectral response of most common light with the possibility to identify LED sources with different color temperature and differentiate between "warm" and "cold" emissions.

4. Flight data elaboration

MINLU payload was successfully launched around 1.15 AM on July 8th 2021 during the astronomical night; the total flight time was 3 hour and 15 minutes with a maximum achieved altitude around 32 km. The imaging unit operation was started 30 min before launch and logging ended later than 5 hours after switching on after battery energy was consumed; color camera, luminance meter and raw multi spectrometer were acquired at a 12 second interval, resulting in a saved amount of raw data around 8 Giga bytes for the whole flight. The flight trajectory has been reconstructed from GPS data and transformed in a NED inertial reference centered at launch site (Lajatico) to calculate pointing direction of the imaging unit.

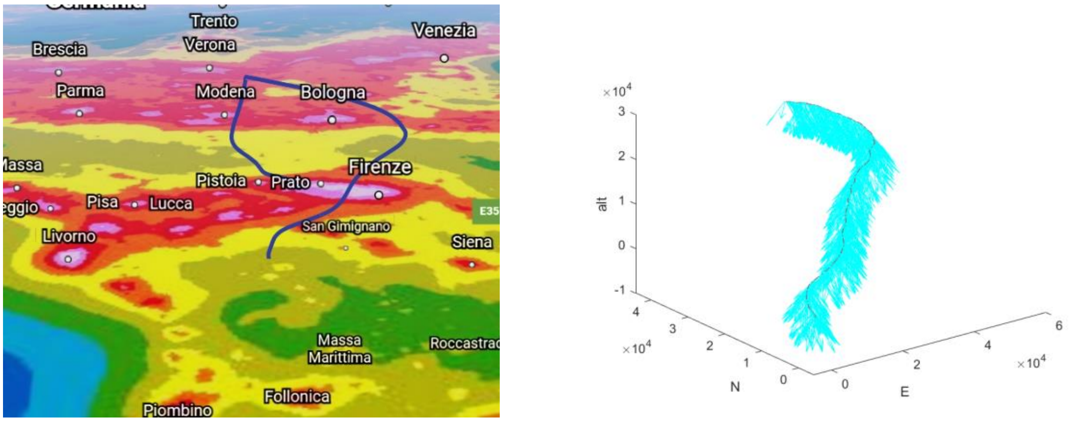


Figure 5: Flight trajectory reconstructed from GPS data trajectory over light pollution world atlas of Sky brightness based on VIIRS data (left) and image unit pointing reconstruction in NED reference centered at launch site

The payload attitude and consequently the inertial pointing direction of imaging system has been calculated elaborating measures of inertial sensors (IMU magnetometers, rate gyros and accelerometers) with a dedicated Kalman filter. Figure 9 presents an image of launch site taken few seconds after take-off from the colour camera and the elaboration of the relative multi spectrometer image showing the obtained spectra from lights associated with the car illuminating the pad, one garden lamp and a nearby house. It is evident that the spectrometer images allow to identify the technology used in the different sources.

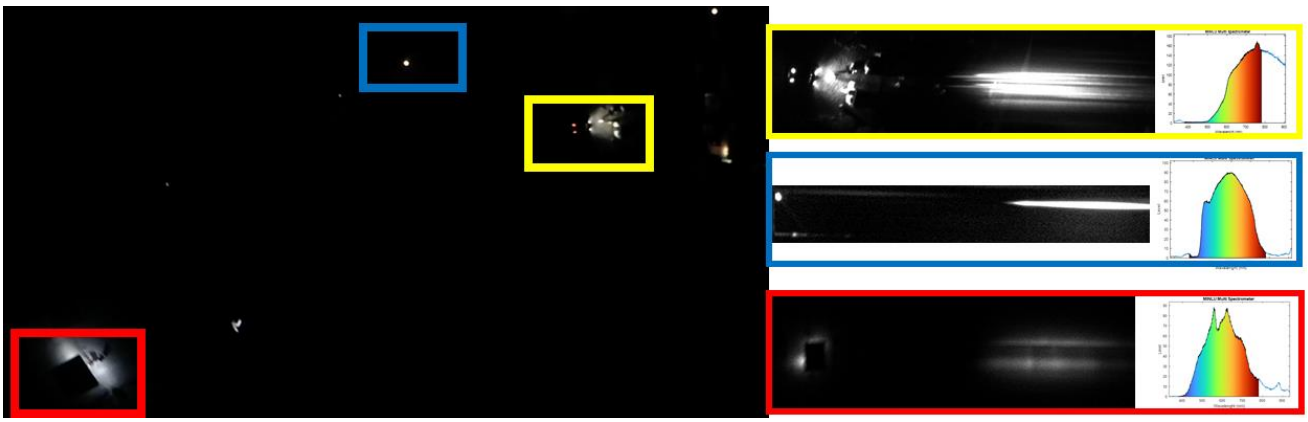


Figure 6: Image of launch site taken from color camera(left) showing car illuminating the pad, one garden lamp and nearby illuminated house and respective elaboration of emitted light spectrum from multi spectrometer (right)

The number of light sources present in the spectrometer field of view and consequently the number of spectral lines in the image increases with altitude and decreasing the capability to investigate single sources but producing an average spectrum of an interest area.

Figure 8 reports the images acquired by MINLU when floating over the area of Certaldo, a medium size town in Tuscany, at an altitude of 8494 m; reconstructed attitude of the payload shows a limited tilting (pitch 2.3 °, roll -1.2°, yaw -185.6°). As it is evident the number of diffraction lines is quite high, but it is in any case possible to reconstruct emission spectrum of main areas of interest.

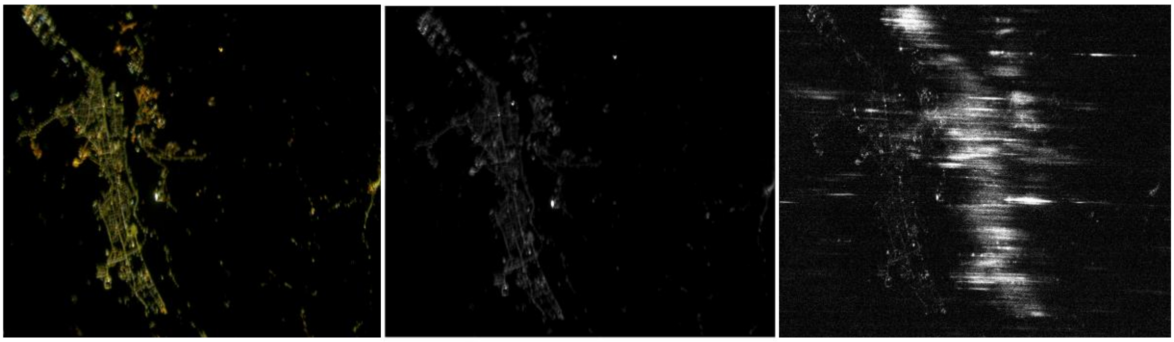


Figure 7: Image of Certaldo area from color camera (left), luminance meter camera (center) and raw multi spectrometer camera (right), this last adjusted in intensity for view

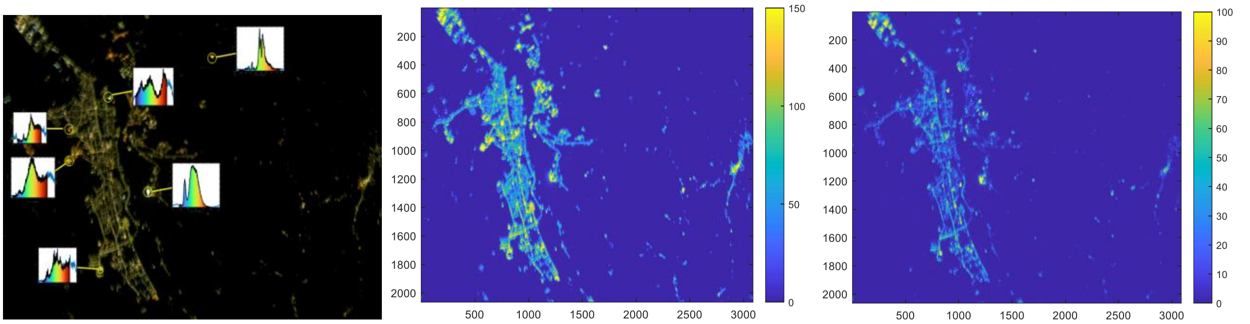
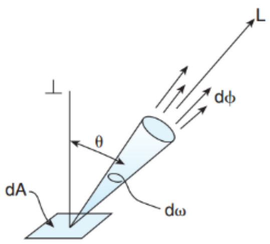


Figure 8: Reconstructed spectra of polluting sources in Certaldo area from raw spectrometer (left), Red level of RGB image from color camera (center), Blu level of RGB image from color camera (center)

Figure 8 presents the calculated spectra of main light polluting zones; it is still possible to calculate an average spectrum but the accurate guess of the illumination technology is possible only for areas with sites of uniform illumination (parking, industrial sites...). Information on the prominent emission in the blue or red area can also be extracted from the RGB levels of the colour camera image, achieving coherent information with the one elaborated using spectrometer data.

For the elaboration of luminance meter data, it must be recalled that the luminance L measured by the camera is the quotient of luminous intensity I in the given direction produced by an element of surface dA, by the area of the orthogonal projection of the element on a plane perpendicular to the given direction. The mathematical relation is presented below where dΦ is the luminous flux related with the spherical angle dω.



$$L = \frac{dI}{dA\ \cos\theta} \qquad where\ I = \frac{d\Phi}{d\omega} \qquad [1]$$

The correct estimation of the illumination from ground areas is therefore possible only after the elaboration of inertial attitude of the payload for the calculation of angle θ.

The value of area dA depends on altitude and total tilt of the probe, considering that the imaging system

is installed at a 35° angle in respect to nadir direction. With no tilt the system can achieve a ground sample distance of 3 centimetre when flying at 200 m altitude, going up to 8 m at altitudes above 30 km; this considerably improves the information provided by satellite images showing a ground resolution around 800 m.
A sketch of the area within the field of view of imaging subsystem is provided in Figure 9 , where the characteristic angles of FOV aperture depending on CCD geometry (3088 x 2064) are also presented. The plot in the right part of Figure 9 reports the calculated areas during the passage over Certaldo of 8494 m (pitch 2.3 °, roll -1.2°, yaw -185.6°).

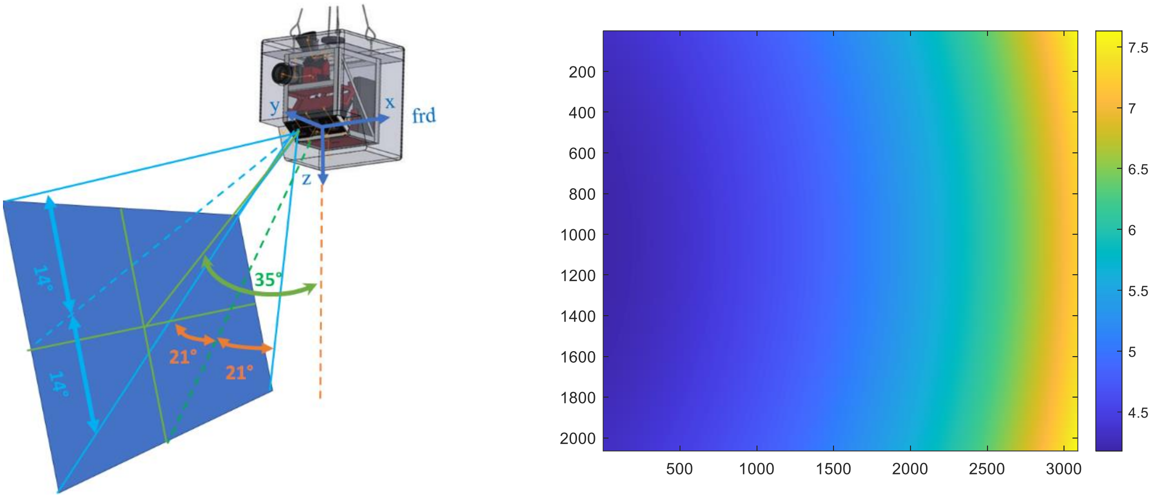


Figure 9: Sketch of area within the field of view of imaging subsystem (left) and projected surface area (in m2) related to pixel of CCD matrix (right)

The characterisation of light polluting areas is then achieved using calibration data and performing conversion of pixel values in upwards illumination levels in candles. The application for the Certaldo area is presented in following Figure 10.

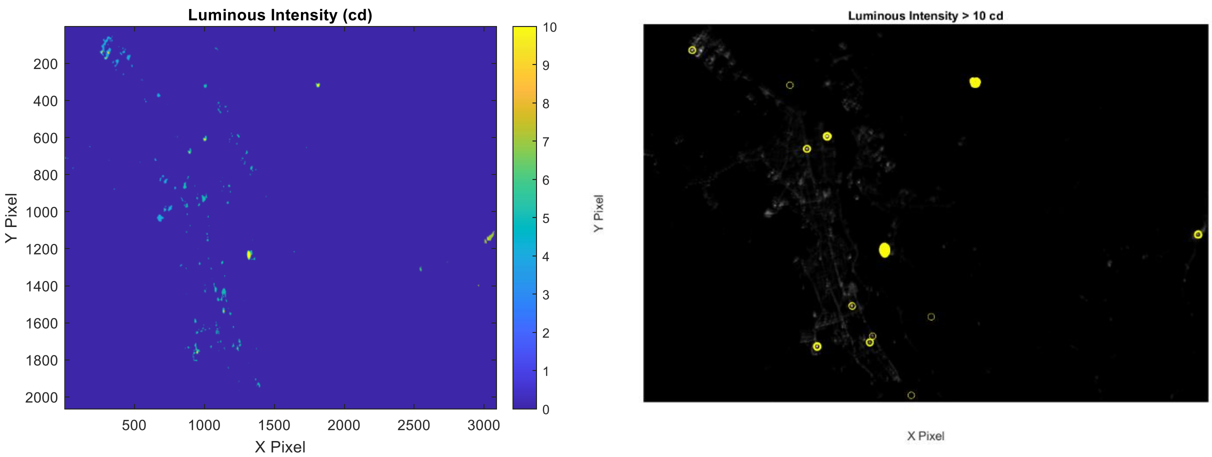


Figure 10: Reconstructed illumination sites of the Certaldo area (left) and identification of emission areas above 10 cd illumination (right)

The same procedure is utilised for the analysis of emitted light up to burst altitude of 32 km.

Figure 11 reports one image by colour camera of the Pistoia area at 31.9 km altitude and the calculated projected surface area related to pixel of CCD matrix in the considered flight condition.

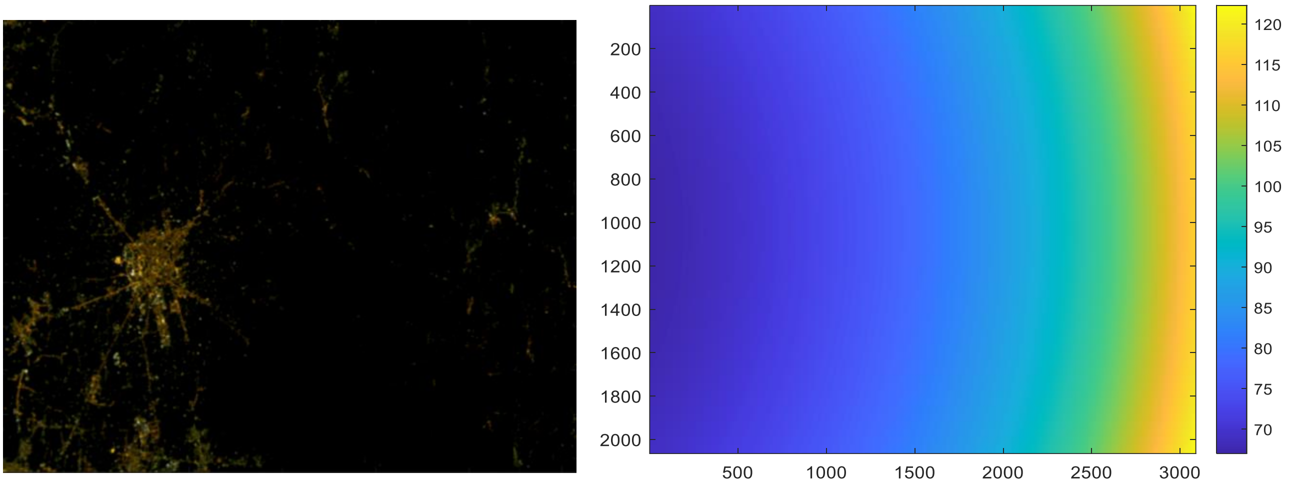


Figure 11: Colour image of Pistoia area near from 32 km altitude (left) and projected surface area (in m2) related to pixel of CCD matrix (right)

The image from luminance meter camera and its elaboration identifying ground areas with an illumination above the threshold of 150 cd are presented in Figure 12.

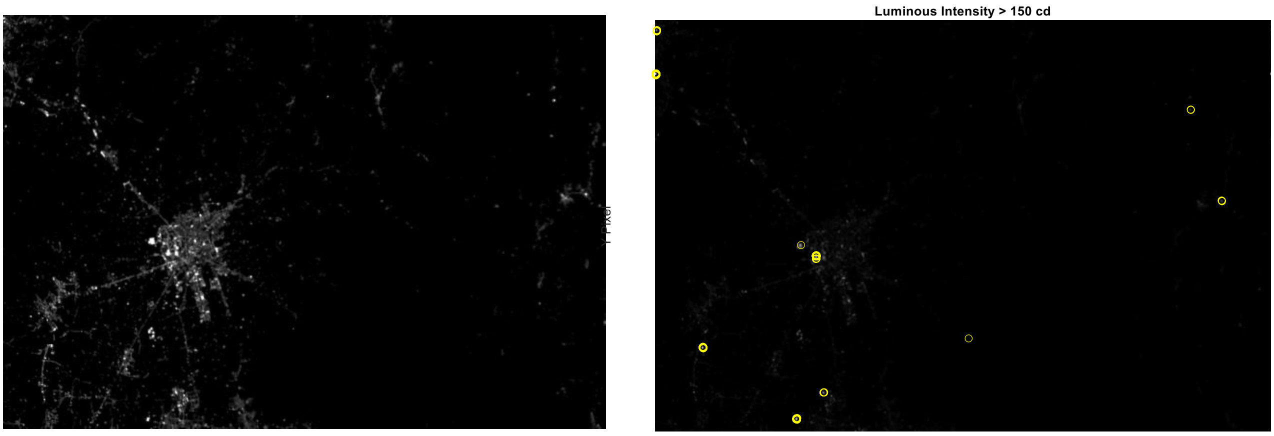


Figure 12: Luminance camera image of the Pistoia area from 32 km altitude (left), areas with reconstructed illumination intensity above 150 cd (right)

At considered altitude spectra from the multi spectrometer tend to overlap reducing the accuracy of light type reconstruction so qualitative analysis of type of illumination is on the consideration of emission in the red or blue colour region obtained by elaborating the output of pixel matrix of the colour camera in the RGB bands.

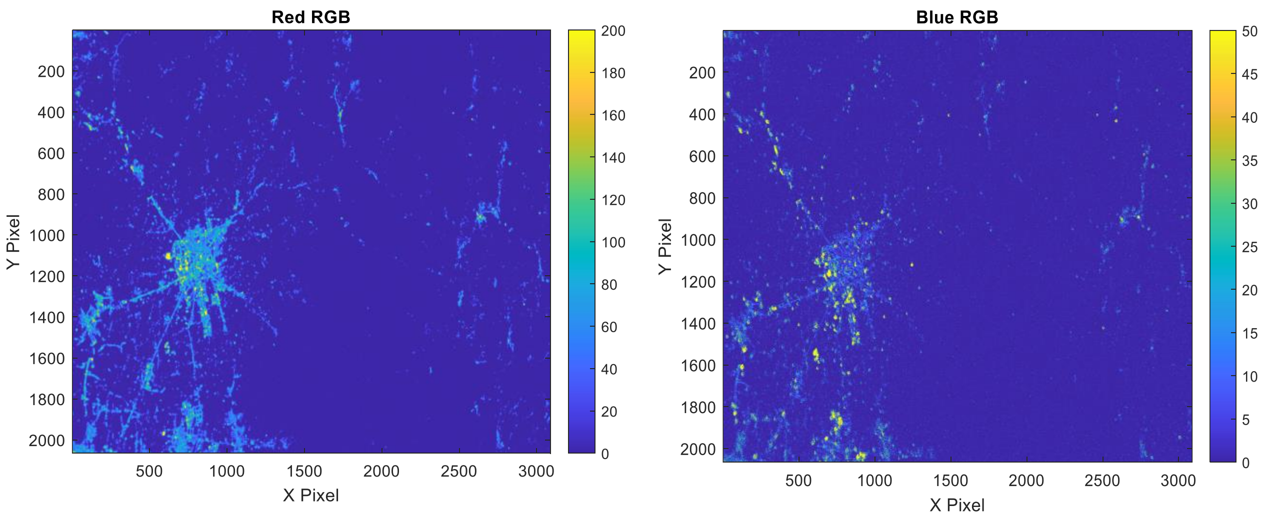


Figure 13: Map of illuminating areas emitting in red RGB band (left) and blue RGB band (right)

5. Conclusions

An autonomous scientific payload for monitoring light pollution and sky brightness has been developed at University of Padova and tested in a sounding balloon night flight on July 8th 2021. Based on commercial components and with extremely limited mass and dimensions the systems has been able to guarantee continuous operation for more than 5 hours providing in parallel data on sky brightness and information on ground emission sources up to 32 km altitude.

Flight data have been used to quantify ground emission in terms of luminous intensity and power density and allowed to identify sources causing the artificial luminance; data from raw multi spectrometer have been successfully used at low altitude to accurately identify ground source's illuminating technology; at higher attitudes mainly levels in RGB bands are used to have a qualitative insight of "warm" or "cold" emission sources.

Levels of illumination from areas of interest have been evaluated from images of luminance meter camera based on laboratory calibration and correct reconstruction of inertial attitude of the payload.

The limited dimensions and weight of the unit and the modularity of its architecture allow to use the developed system on drones and tethered balloons and significantly overcomes the performance achievable by satellites images in discriminating among the different light sources used for street and outdoor lighting.

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7. Copyright Statement

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