Effects of light pollution revealed during a nocturnal aerial survey by two hyperspectral imagers

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A remote-sensing campaign was performed in September 2001 at nighttime under clear-sky conditions before moonrise to assess the level of light pollution of urban and industrial origin. Two hyperspectral sensors, namely, the Multispectral Infrared and Visible Imaging Spectrometer and the Visible Infrared Scanner-200, which provide spectral coverage from the visible to the thermal infrared, were flown over the Tuscany coast (Italy) on board a Casa 212 airplane. The acquired images were processed to produce radiometrically calibrated data, which were then analyzed and compared with ground-based spectral measurements. Calibrated data acquired at high spectral resolution (~2.5 nm) showed a maximum scene brightness almost of the same order of magnitude as that observed during similar daytime measurements, whereas their average luminosity was 3 orders of magnitude lower. The measurement analysis confirmed that artificial illumination hinders astronomical observations and produces noticeable effects even at great distances from the sources of the illumination. © 2003 Optical Society of America

1. Introduction
Light pollution is an emerging issue in the evaluation of environmental modifications that are caused by human settlement and activity. The level and the extent of artificial illumination at nighttime in a given region are practical as well effective measures of the overall activity of the local community and take into account both light from industrial and residential sources. The total power emitted by artificial light sources is, on average, directly related to the overall energy consumption of the community.1–3

The level of light pollution is therefore a general measure of how human activity modifies its environment, and hence is, although indirectly, an important parameter for monitoring and modeling all kinds of artificial pollution. This parameter is also relevant for economic investigations, because the amount of power (nocturnal light emission) that any country demands is strictly related to its gross domestic product.

Light pollution that affects the biosphere is important for many scientific purposes, such as improvement of ground-based astronomical observations.4–9 Because of the remarkable importance of the issues mentioned above, great effort is being devoted to assessing the intensity of scattered radiation that illuminates the night sky. Two kinds of light-pollution measurements are already being carried out:

**Ground-based measurements** of the scattered radiation level during nighttime is a reliable option for characterization of a single geographic site of a moderate spatial size. This technology permits accurate measurements to be made and is widely employed for choosing optimal sites for the installation of astrophysical instruments.

**Satellite observations** instead are often hindered by the low level of the available signal. The light sources' emission, in fact, is spatially localized, and only a fraction of the radiated power is reflected from the ground to the sensor. Therefore specialized instruments specifically designed for this type of measurement have to be used. Nowadays, only one highly sensitive satellite instrument [the Defense Meteorological Satellite Program's Operational Lines can System # (DMSP-OLS)] meets this requirement, and it is often used for remote assessment of light pollution.10–12

Ground-based observations have high accuracy but cannot encompass sufficiently large terrain to provide light-pollution maps over large areas; satellite-based measurements suffer from coarse spatial resolution and lower accuracy. Moreover, available
Surface-light emission $e(x, y)$ is the basic quantity used as input information for any theoretical model intended to compute the stray-light level in a given viewing direction. The essential structure of this type of calculation is:

$$ L(x, y) = \int e(\xi, \eta) f(x, y; \xi, \eta) d\xi d\eta, \quad (1) $$

where $f(x, y; \xi, \eta)$ is an empirical propagation function that describes the way in which artificial radiation emitted at location $\xi, \eta$ is conveyed by scattering at location $x, y$ in a given propagation direction. Under some selective hypotheses (e.g., when only small geographical areas with no height variation are investigated), this integral equation may be reduced to a simple convolution product, and integral kernel $f$ will become shift invariant. As has been pointed out by other authors, the use of population density data for estimating surface-light emission $e(x, y)$ suffers from some errors and uncertainties:

1. The average population density data of several countries are collected by use of different methods and timetables, which may be out of date,
2. The relation between population density and surface-light emission is only partially known and can vary noticeably with geographical location and with time as a result of economic development and type of industrial production; and
3. Function $f(x, y; \xi, \eta)$ is not known with the required accuracy.

Conversely, maps of urban light gathered at night from remote-sensing instruments represent, in a first instance, a good approximation of quantity $e(x, y)$ as long as the atmosphere is optically thin and diffuse radiance is, on average, far below the radiance of the related sources. The discussion above has shown how data on light pollution are important for many purposes and in scientific domains and that assessment of light pollution is still far from reaching satisfactory accuracy. In this connection the development of new sensors specifically designed for nocturnal Earth observations in the visible spectral range or the application of existing sensors to this problem will be important. Anyway, the selected sensors are required to provide higher spatial resolution than the DMSP-OLS does and acceptable spectral discrimimability. The availability of surface emission measurements with high spatial and spectral accuracy will lead to the calculation of more-detailed light-pollution maps for various visible subbands.

In this paper we report the results of research devoted to investigating the monitoring of light pollution by standard hyperspectral imagers that are routinely employed for daytime remote sensing of the Earth. In particular, we describe the results of a nocturnal remote-sensing campaign performed in September 2001 to assess levels of light pollution of urban and industrial origin. For the first time to our knowledge, nocturnal light pollution was measured at high spatial and spectral resolution by use of two airborne hyperspectral sensors, namely, the Multispectral Infrared and Visible Imaging Spectrometer (MIVIS) and the Visible Infrared Scanner (VIRS-200). These sensors, which provide spectral coverage from the visible to the thermal infrared, were flown in Italy, over the Tuscany coast, on board a Casa 212 airplane. The acquired images showed a maximum scene brightness that was comparable to that observed during similar daytime measurements, whereas their average luminosity was 3 orders of magnitude lower. The measurements, performed under clear-sky conditions before moonrise and involving only small-sized towns, confirm that artificial illumination hinders astronomical observations and produces noticeable effects even at great distances from its source.

We found that only a small number of the instruments usually employed for remote-sensing campaigns can be successfully converted for monitoring of nocturnal light pollution, which requires fine spectral resolution and good radiometric sensitivity. We show that if the Earth is remotely imaged with a sensor that has a small-bandwidth (e.g., 2 nm) spectral channel that is resonant with an emission spectral line of common city lights, the related light sources are easily recognized and that the reliability of source detection is higher than that allowed by panchromatic or low-resolution sensors.

In Section 2 we give details about the technical characteristics and imaging capabilities of the two digital imagers described here, together with information regarding the experiment. Section 3 is devoted to showing the raw data that were obtained and the processing method adopted to validate the observations and to compute higher-level remote sensing products. Finally, in Section 4 we draw some conclusions and point out some unresolved questions.

2. Remote-Sensing Experiment

To investigate the use of standard hyperspectral sensors to monitor levels of nocturnal stray light produced by artificial sources, we performed an aerial survey of the Tuscany coast in September 2001. Two hyperspectral sensors, the MIVIS and the VIRS-200, were selected to provide fine spatial and spectral resolution and extended spectral coverage. The remote-sensing campaign was preceded by some preliminary activity that is documented here.
A. Preliminary Activity

The remote-sensing campaign was preceded by in-field activity for observation of the signals emitted from light sources, information that allowed us to optimize the sensor configuration.

Several urban lights were observed at night from the ground by a portable spectrophotometer operating in the range 300–950 nm. The instrument is based on an optical-fiber-fed Rowland reflection grating whose output is sampled by a silicon photodiode array manufactured by Hamamatsu. Spectra comprise 256 10-bit independent samples acquired with a spectral resolution of 7 nm and pixel dispersion of 2.96 nm/pixel. A thorough discussion of the main technical characteristics and performance of this spectrometer can be found in Ref. 14.

Ground-based observations of the spectral radiance emitted by urban lights was aimed at recognizing the main emission lines from more-diffuse lamps. This knowledge was in its turn utilized for wavelength selection of the 20 spectral channels acquired by the VIRS-200 imager. The basic assumption was that because artificial sources emit most of their energy in narrow spectral features they can easily be detected by those standard remote sensing sensors (planned for daytime activity) that have fine spectral resolution. In this context the VIRS-200 appeared to be an ideal sensor because it collects radiance data at a spectral resolution of 2.5 nm and therefore has a bandwidth that is comparable with the widths of the lines emitted by the observed sources.

Figures 1–3 show the more interesting spectral features obtained from ground-based observations after ten independent measurements were averaged for each plot. Because of the uncalibrated radiometric response of the instrument, the relative intensities of the various spectral lines shown in these figures may be unrealistic. Let us note that often-utilized illumination sources that also include many residential lights are based on mercury or sodium lamps, as shown in Figs. 1–3.

We note that the spectrum plotted in Fig. 3 contains spectral lines from various elements, among which we have identified mercury and probably neon and krypton–helium. Another kind of source that is easily found comprises filament lamps, which emit continuous spectra in the visible and the infrared. These sources do not need specific preflight calibration.

B. Flat-Field Measurement

We examined the application of new and simple equipment that is able to produce a spatially and angularly flat radiation source. We used this system to assess the response of the VIRS-200 pushbroom sensor.

In its simplest form this system is made from two planar diffusers placed on parallel planes at a given distance. Ideally, the first diffuser produces homogeneous illumination of the second diffuser, upon which, however, a nonisotropic E.M. field is placed. The second diffuser then homogenizes the impinging radiation between the different propagation direc-
The agreement of the two measurements was only image information, without any laboratory data. The flat-field calibration was compared with that obtained with a two-dimensional array detector equipped with a two-dimensional array detector (CCD) and operating in the visible and the near-infrared spectral ranges. The sensor acquires 20 of 240 available spectral channels that are uniformly spaced from 400 to 1000 nm in 2.5-nm increments. The wavelengths of the 20 channels, which are digitized with 10-bit accuracy, are chosen by the operator of the spectrometer before the overflight. The main characteristics of the sensor are detailed in Table 1, and additional information concerning this sensor is given in other publications.\textsuperscript{16,17}

Let us note that the images gathered by this kind of sensor are affected by systematic patterns of disturbance that originate from fluctuations in the sensitivity of the two-dimensional array detector. To prevent occurrence of this artifact we performed some flat-field calibration measurements in the laboratory before and after the overflight.

Following the preliminary ground-based measurements described in Subsection 2.B, we selected a spectral configuration that was able to map the principal emission lines observed so far. In particular, four spectral channels were chosen for observation of the wide spectral emissions from the high-pressure sodium sources shown in Fig. 1 (broad features located roughly at 570 and 600 nm). Six channels were devoted to the measurement of three mercury emission lines (at 435.85 at 546.07 nm and an unresolved doublet 576.96–579.07 nm; Fig. 2). Six other spectral channels were selected for monitoring of three emission lines from mixed vapor sources, that had wavelengths near 450, 533, and 586 nm (Fig. 3). The remaining four spectral channels were used as references and tuned to the following wavelength positions: 506.25, 701.25, 801.25, and 936.25 nm. These channels could also observe continuum emission from filament, fluorescent, and high-pressure lamps. The channel at 936.25 nm falls within a strong atmospheric absorption band caused by \text{H}_2\text{O} vapor. The final spectral configuration of the VIRS 200 is shown in Table 2.

The MIVIS is a scanning (whisk-broom) imaging spectrometer, which collects image data from 102 independent spectral channels that cover the visible, the near and medium infrared to 2500 nm, and the thermal infrared spectral ranges with ten channels. Extended spectral coverage together with fine radiometric accuracy (12 bits) makes the MIVIS a useful sensor for many remote-sensing applications. In our case the MIVIS also represents an important reference for VIRS 200 data because of the availability of ten thermal infrared channels that can be useful for fire recognition (rejection) and geolocation.

Because of its operating mode the MIVIS does not need flat-field calibration, whereas standard radiometric and spectral calibrations are routinely per-
D. Remote-Sensing Campaign

On 13 September 2001, a CASA 212 airplane equipped with the two imaging spectrometers described above was flown at heights that ranged from 1500 to 3000 m. The flight was begun at approximately 1:00 A.M. (GMT), roughly 2 h before moonrise, from north-northwest toward south-southeast, over the Tuscany coast. Two small towns (Livorno and Viareggio) and some isolated buildings were imaged under clear-sky conditions. Figure 4 sketches the path of the overflight.

The duration of the overflight was \( \approx 1 \) h, during which some in-field measurements were performed to validate the remotely sensed spectra. These measurements were made with the portable spectrophotometer described in Subsection 2.A.

The VIRS-200 dark signal was collected twice during the flight, immediately after noticeable environmental temperature changes originated from variation in altitude of the plane. These ancillary data were subsequently used to improve the radiometric calibration of the sensor.

3. Results and Data Processing

Remotely sensed data preprocessing to produce radiance-calibrated images comprised the following steps:

1. Dark-signal subtraction,
2. Flat-field correction (only for the VIRS-200),
3. Conversion to radiance units \( [\text{nW cm}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}] \),
4. Geometric correction and image geolocation.

This preprocessing produces a first level of calibrated remote-sensing data that is useful for our re-

<table>
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<td>801.25</td>
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<tr>
<td>20</td>
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Fig. 4. Map of the aerial survey performed over the northern Tuscany coast. Two small towns, Livorno and Viareggio, were imaged.
search: the at-sensor radiance. Let us note that the radiance observed by the sensor is not that emitted by the corresponding source. Generally, the presence of a shield prevents the emitted light from reaching the sensor; hence the urban lamp radiation is initially reflected from the ground and then reaches the sensor after having been dimmed by the atmosphere. The main effects of the atmosphere on visible and near-infrared radiation are absorption and scattering; in the thermal infrared range appreciable atmospheric emission is observed, and scattering becomes negligible.

Therefore the radiance obtained from the four steps outlined above is generally underestimated, and one should compute the at-source radiance by removing the main atmospheric effects. This goal requires reliable theoretical modeling of the radiative transfer inside the atmosphere.

The basic relationship that drives the first two steps is

\[ g(x, y, \lambda) = \left[ i(x, y, \lambda) * H(\lambda) \right] S(x, \lambda) + g_0(x, y, \lambda), \]

where \( x \) and \( y \) are the horizontal and vertical image coordinates, respectively, \( g \) is the observed image, \( i \) is the imaged source, \( g_0 \) is the average dark signal, \( S \) is the detector sensitivity, \( H \) is the spectral point-spread function for the monochromator that is used, and \( i * H \) is the ideal image to be observed.

Dark-signal removal is important because it removes the average effects of noise and bias (\( g_0 \)) that are superimposed upon faint as well as upon rare light sources. To eliminate false signal (noise) that may have survived this Processing, we also filtered the raw image at a 3\( \sigma_g \) threshold, where \( \sigma_g \) is the dark signal's standard deviation, which is assumed to be equal to the noise. The point sources validated so far represent with more than 98% confidence, real sources of radiation. The two parameters \( g_0 \) and \( \sigma_g \) needed for processing were deduced by dark-signal measurements performed during the flight. Note that for the VIRS-200 both \( \sigma_g \) and average dark signal \( g_0 \) depend on the image column index (i.e., the across-track \( x \) coordinate).

We performed a conversion to radiance units by using calibration data measured during a remote-sensing campaign carried out in 2000. We corrected the MIVIS image geometry taking by into account only the perspective effect introduced by the scanning unit, because the survey was conducted over a flat coastal terrain where orography was negligible. We note that the VIRS-200, because of its push-broom operating mode, directly produces instrumental-distortion-free images.

A. Data Analysis

Figure 5 shows a MIVIS composite image of Livorno obtained by use of thermal (100th channel as blue) and visible (22th channel as green and 24th channel as red) radiometrically calibrated data. Compared this image with the corresponding VIRS-200 image, which is shown in Fig. 6 and maps the 15th channel (586.25 nm) as red, the 13th channel (578.75 nm) as green, and the 9th channel (546.25 nm) as blue. The VIRS-200 image portrayed in Fig. 6 corresponds to partially processed data that remained after subtraction of the dark signal, calibration of the flat field, and conversion to radiance units. Additional filtering aimed at removing fainter sources and residual noise was also applied. The wavelength positions of the spectral channels used for generating these false color images were selected such that we could map the more important emission lines recognized during the preflight activity and shown in Figs. 1–3. It is impressive to note how well the VIRS-200 imager detects even faint city lights.

Comparison of Figs. 5 and 6 clearly shows that, as expected, the VIRS-200 provides higher sensitivity to urban lights than does the MIVIS. This important behavior is ascribed to the circumstance that a narrow spectral channel tuned at a wavelength resonant with a source’s emission line senses a higher signal than a broadband channel does. In other words, it can be said that urban lights emit, on average, significantly lower power than solar radiation reflected by soil. However, the difference in emitted radiance between the two sources becomes small in the narrow spectral bands in which city light emission is concentrated.

Figure 7 shows a VIRS-200 image of a peripheral zone of Livorno together with the spectrum of extended and powerful urban light. This source probably is a low-pressure lamp that still has not been identified. This type of source has rarely been observed during in-field measurements performed to validate the remote-sensing products. Figure 8 shows the next image, which portrays the downtown area and the spectrum of a typical light source. This urban light has been identified as that of a low-
pressure mercury lamp. Note the high power output by the two sources in Figs. 7 and 8, which is roughly 1 order of magnitude less than diurnal soil brightness in the same spectral range.

Spectra of various types of city light retrieved from the VIRS-200 data at several locations are shown in Figs. 9 and 10. Any curve represents the spectral radiance of a single source, which often appears to be extended in the image. Thus the various spectra contained in a given figure are related to various image pixels that seem to belong to the same urban light. These spectra from adjacent pixels may originate from the ground halo of a single powerful central source as well as from unresolved secondary sources. We point out that imaged spectra show a large variety of city lights, a circumstance that is usually found in urban areas. The relatively high power emitted by most of these sources suggests the presence of a certain number of unshielded (or partially shielded) lights, the radiation of which perhaps is directly seen by the sensor. These city lights should, however, be recognized even in the MIVIS images, which instead reveal only a small number of sources (Fig. 5).

In particular, Fig. 9(a) shows the spectrum of a powerful source recognized as a high-pressure sodium lamp, and Fig. 9(b) illustrates the spectral emission from a high-pressure sodium source that is probably mixed with a smaller mercury component. We were not able to assess whether this spectrum results from mixing of two independent sources located close to each other or whether the source is a single lamp with a nonstandard gas fill. Figures 9(c) and 9(d) detail the spectral emissions of two low-intensity city lights from sodium [Fig. 9(c)] and mercury [Fig. 9(d)] lamps.

Figure 10(a) shows strong spectral emission from a continuous source, probably a halogen lamp. Figures 10(b) and 10(c) indeed show the spectra of two city lights that have not been identified but both of which contain mercury spectral lines. In particular, the bright source of Fig. 10(c) is of the same type as that shown in Fig. 3, whose spectrum was observed during the in situ campaign. We point out that the radiance...
signal revealed by the VIRS 200 sensor after the \(3\sigma_g\) filtering described in Section 2 is still affected by the low-level diffuse signal observed almost everywhere in the calibrated images. This signal does not show any meaningful spatial structure; nonetheless its amplitude and average power are too high to be interpreted as noise that was not removed by the \(3\sigma_g\) filtering. Figure 11, which portrays a rural scene essentially free from lights and inhabited areas, is an example of this phenomenon. Figure 12 shows the average stray-light spectrum retrieved from a \(30 \times 30\) window in the center of the image in Fig. 11. It can be seen that the amplitude of this diffuse signal is far below the city-light intensity shown in Figs. 9 and 10 and that it grows with decreasing wavelengths. Let us note that the first spectral channel of the VIRS-200 is less accurate because of degraded sensor performance at the beginning of its free spectral range (worst signal-to-noise ratio).

**B. Simulations**

We also simulated stray light affecting the night sky as perceived by an observer looking at zenith from the ground. To this purpose we utilized the mathematical framework depicted by Eq. (1) with the following point-spread function:

\[
f(x, y, \xi, \eta) = a(\lambda) \frac{U}{(x - \xi)^2 + (y - \eta)^2 + h^2} \times \exp\left\{-k(\lambda)\left[(x - \xi)^2 + (y - \eta)^2 + h^2\right]^{1/2}\right\},
\]

Here \(x, y\) indicate the observer’s location, \(\xi, \eta\) are the source coordinates, and surface light emission \(e(x, y)\) has been estimated from the radiometrically calibrated VIRS-200 images. The average atmospheric extinction coefficient \(k(\lambda)\) was estimated from a MODTRAN run in the spectral range covered by the VIRS 200 sensor. We used a MODTRAN estimation of atmospheric spectral transparency to compute the optical thickness of the whole atmosphere, a result that we compared with theoretical predictions of the vertical profile of the extinction coefficient modeled as an exponential decay law. Height \(h\) of the scattering layer was fixed at 2.4 km; the values of \(U\) and \(V\) together
Fig. 9. Spectra of various urban lights extracted from the VIRS 200 image after processing for dark-signal subtraction, flat-field calibration, and transformation to radiance units. (a) Emission from a powerful source, recognized as a high-pressure sodium lamp. (b) Spectral emission from a high-pressure sodium source probably mixed with a smaller mercury component. It is not clear whether this spectrum results from mixing of two independent sources located close to each other or whether it is from a single lamp with a nonstandard gas fill. (c) Low-intensity city light whose source is probably a sodium lamp. (d) Emission from low-intensity city light whose source was probably a mercury lamp.

Fig. 10. Spectra of various city lights extracted from the VIRS 200 image after processing for dark-signal subtraction, flat-field calibration, and transformation to radiance units. (a) Strong spectral emission from a continuous source, probably a halogen lamp. (b) Spectrum of a faint city light that has not been identified, which contains contributions of mercury spectral lines. (c) Spectrum of an unidentified bright source, which contains mercury spectral lines. This spectrum seems to be of the same type as that shown in Fig. 3 that was observed during the in situ campaign.
with the relative spectrum of amplitude factor $a [\lambda]$ were taken from the literature.\textsuperscript{18,19} We note that previously reported studies were generally aimed to estimate the nocturnal stray-light level by use of population data only. Hence the empirical value found for amplitude factor $a (\lambda)$ converts population density into radiance. However, we possess an accurate map describing the radiance coming from ground distribution of urban light; as a consequence we rescaled amplitude $a (\lambda)$ by a factor of $10^5$ to obtain a rough estimate of the radiance produced by a given ground location. Nonetheless, we remark that a good estimation of the true radiance observed at a given point would require more-accurate modeling of ground radiance $e(\xi,\eta)$, which could be affected by local ground reflectance\textsuperscript{20–25} and other unpredictable factors.

A final point regarding the integration in Eq. (1) that was made with the VIRS 200 radiance-calibrated signal used as the ground distribution of light $e(\xi,\eta)$ is related to the narrow swath imaged by this sensor, i.e., $\sim 1.2$ km. The result obtained from our simulations is always underestimated because our calculation excludes city lights outside the VIRS-200 image (1.2 km wide), whereas the point-spread function that we used [Eq. (4)] has a full width of not less than $h$ (2.4 km).

Results from numerical simulations are shown in Figs. 14 and 15. Figure 13 shows the input image used as a sources map: it is a scene that comprises the center of the town of Livorno and therefore the more polluted region observed during our overflight. The nocturnal radiance distribution that would be observed in the same geographic area by seeing at zenith is displayed in Fig. 14, which also shows an unrealistic side effect (darkening) caused by the small spatial extent of the available image data. The spectrum of this scattered radiance as averaged on a $30 \times 30$ pixel window located in the center of the image (which corresponds to the center of the town) is plotted versus wavelength in Fig. 15. As can be seen, this spectrum is very similar to the spectrum of diffuse light perceived by the VIRS 200 far from any ground source (Fig. 12).

4. Conclusions

The problem of light pollution that affects night sky near urban areas has been reexamined. The option of measuring diffuse light at nighttime by use of standard remote-sensing instruments has been investigated. A remote-sensing campaign was performed in September 2001 to assess the stray-light level near the Tuscany coast (Italy) and to investigate the optimal experimental methodology for this detection. Two hyperspectral sensors, the MIVIS and the VIRS-200, were flown on board a Casa 220 airplane at 1.5–3.0-km heights. The acquired images showed a maximum scene brightness (at-sensor radiance) that was three to five times less than that that observed during similar daytime measurements. The measurements have confirmed that observation of nocturnal stray light is possible by use of narrowband hyperspectral imagers that have bandpass channels centered about the emission features of common artificial light sources.

A spectrum of nocturnal diffuse light was retrieved from the processed (calibrated) data and has shown some interesting properties: As a general rule, increasing diffuse light toward the blue was found. This property was to a degree expected, because Rayleigh scattering efficiency increases strongly at shorter wavelengths. The spectrum of stray light also showed the spectral signatures of commonly
used line emission lamps. The amplitude of this at-sensor radiance, which originated from scattering of light emitted by ground sources outside the imaged scene, is 3–4 orders of magnitude less than the corresponding amplitude at sensor radiance measured during daytime observations. This experimental result confirms that light pollution is a relevant handicap to astronomical observation and even to the integrity of environment.

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that has been widely utilized in this research. This research has been partially supported by the Italian Space Agency.

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