Evaluation of the sky brightness at two Argentinian Astronomical Sites

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ABSTRACT

Light pollution is a growing concern at many levels especially for the astronomical community. Indeed, not only does the artificial lighting veil celestial objects but it disturbs the measurement of many atmospheric phenomena. The sky brightness is one of the most relevant parameters for astronomical site selection. Our goal brightness of two Argentinian astronomical sites: Leo++ and El Leoncito. Both sites were candidate to host the Cherenkov Telescope Array. This project consist in an arrangement of many telescopes that can measure the high-energy gamma-ray emission via their Cherenkov radiation produced when entering the earth atmosphere. In this paper, we describe measurement methods used to determine whether those sites are valuable or not. We compared our results with the sky radiance of different renowned astronomical sites (Kitt Peak, Arizona, USA and Mont-Mégantic, Québec, CANADA). Amongst our results, we found that Leo++ is a good site, however the presence of a low layer of local aerosols can introduce uncertainties in the measurement. Consequently, El Leoncito would be a better option for such an installation. This later site shows very low sky brightness levels, which are optimal for low light detection.

Subject headings: Sky brightness, Cherenkov Telescope Array, Argentina, Spectrometry, Site evaluation, Light pollution

1. Introduction

The Cherenkov Telescope Array (CTA) is the outcome of an international interest for the high-energy gamma rays. In order to study this phenomenon, a certain variety of Cherenkov telescopes must be installed to assure accurate and complete data. CTA is an arrangement of more then 100 telescopes of 23-m, 12-m, and 6-m in both Hemispheres. Needless to say, such an infrastructure requires a quite vast territory. Furthermore, as determined by the CTA consortium, the candidate sites must optimize the annual number of hours with suitable observing conditions, and emphasise the expected sensitivity of the telescope arrays, which varies with the elevation, the local geomagnetic field, the darkness of the night sky, and the atmospheric aerosol content (CTA 2010; Actis 2014; CTA 2014).

These characteristics assure data of greater quality, thus maximising scientific benefits of the investment. The project's preparatory phase has brought up a number of candidate locations based on extensive analysis of these key features. Amongst these possibilities, Leo++ and El Leoncito, are sites that are both located in Argentina. LEO++ (S31°24'22"; W69°29'33") is found in the Valley of Calingasta, a flat area with an altitude of roughly 1600 meters above see level. El Leoncito (S31°47'58"; W69°17'36") on the other hand, is positioned in a plateau near the site of the Complejo Astronómico El Leoncito (CASLEO) where the altitude reaches 2600 meters. Figure 1 shows both sites, the nearest cities and towns as well as the capitals of the provinces of San Juan and Mendoza. Several weather studies were preformed at both sites using similar equipment along the period 2012-2014. The sites are very dry, with temperature between -10 and 35 Celsius degree, and wind speed below 50 km/h (De la Vega et al. (De la Vega 2013)). One of the requirement for the selection of astronomical sites is the quality of the night sky and one measure of this is the Sky Background Brightness (SBB). The objective of this study is to provide independent evaluations of the sky brightness at the preselected sites in San Juan province from traditional technique, such the measurements made using Sky Quality Meters (SQM) and from the Spectrometer for Night Aerosol Detection (SAND), developed by Cégep de Sherbrooke's group.

To achieve this goal, we have data taken with SQM-LR (Sky Quality Meter-Lens RS232) at El Leoncito for one year(March 2012 to March 2013) and with similar equipment at LEO++ for 10 month (October 2013 to May 2014). On the other hand, we gathered the night sky's spectral measurements with the SAND-4 portable spectrometer (Aubé 2014a, 2007). This procedure is preferable to the classic Sky Quality Meter (SQM) because, with this method, we can determine precisely the composition of the light sources but also where it comes from (by the addition of a modelling experiment with ILLUMINA model (Aubé 2007, 2005). The SQM measure the magnitude of the night sky without providing any information in regards to whether or not the radiation comes from natural sources such as OI sky lines or from nearby cities lights.

Beyond the CTA, the characterization of different sites with astronomical purpose, using complementary techniques, is part of a long term project of our groups.

In the following sections we present the experiment and the scientific context (Section 2) with a description of the techniques used as part of the presents study: SQM-LR measurements (Subsections 2.1 and 2.2) and SAND-4 spectrometer (Subsection 2.3); the Discussion is in Sec. 3, were the results are organized by technical approach and studied site (Subsections 3.1 to 3.3). Finally, the Conclusions are in Section 4.

2. Experimental context

In order to install a telescope, general requirements for the sky quality of a site involved certain limits for the sky brightness background. In the case of CTA the value is 21.5

mag/arcsec^2 or better in the V-filter (according the Matrix of Requirements proposed by CTA Consortium), but it can be also valid for any other astronomical facility. However, the main contribution to this measurement comes from the street lights, which in the most part of the cities are produced by lamps with Hg, Na or a mix of both. In the case of an optical observatory all these elements are problematic, but for CTA, the Hg contribution must be especially considered, because the wavelength range in which Cherenkov radiation can be detected. This study can also proves that the quality of the sky should be studied not only through the standard devices which provide a "global" result for the SBB, but also in a more detailed way, to discriminate the different chemical content of the outdoor illumination.

To achieve this, we used two different techniques to sample the sky brightness. The first one make use of the well known Unihedron's Sky Quality Meter, which is basically measuring the V magnitude inside a large field of view of about 20^o. The second technique use the SAND-4 spectrometer, a low resolution long slit spectrometer (spectral resolution of 1 nm) having a much more restricted field of view.

2.1. SQM-LR instruments and calibration

We have inter-calibrated the two SQMs, comparing simultaneous measurements in order to know the zero point differences, which allows to correct the data for systematic errors. This is equivalent to having all the measurements coming from the same instrument. We collected a large number of data and calculated the average of the measurements. The average should indicate if there are some systematic differences between the two SQM-LR while the standard deviation is a result of the small temporal changes in the experiment conditions. The systematic differences are lower than the instrument resolution, at least, for the two SQM-LR tested.

The SQM uses a solid state detector showing a linear response, which compensates the measurements according to the temperature of the detector. Their behavior and characteristics has been studied by Cinzano (Cinzano 2005). The SQM is designed to measure sky background brightness in a band encompassing photometric bands B and V of the Johnson photometric system. The units used by SQM to measures the surface brightness of extended objects are mag/arcsec^2. This astronomical unit is equivalent to the apparent magnitude of the flux emitted by a square arcsecond of the sky. In the case of a sky background brightness measurements, a value of 21 mag/arcsec^2 means you have a glow similar to a 21 magnitude star spreaded over an area of one square arc-second.

In order to protect the instrument from the environment it is placed inside an IP55 plastic box. An opening was carved on top of the box and a glass was attached and sealed (see Fig 2). The glass results in some attenuation of the incoming light, which was measured by pointing the SQM to a black surface under stable light conditions. The glass was alternatively removed and replaced to measure its effect. It result out of the measurements that the difference with or without the glass is 0.19 mag/arcsec^2.

2.2. SQM-LR Installation

To accurately characterize the night sky conditions at the sites, SQM-LR photometers which comes with an RS232 interface, were used. Its dedicated microprocessor can measure the output frequency of the sensor with high precision, and as the sensor is powered on all the time, the measurements are also more stable. During the laboratory evaluation, we tested the SQM performance according to the temperature changes, taking into account a recent study by Schnitt et al. (Schnitt 2013). The variation in the measurements are lower than the systematic errors of the device reported by the manufacturer. As at El Leoncito and LEO ++, the air temperature ranges from -10°C and +35°C . Under this weather conditions, we considered that a correction to the measurements was not needed. Fig 3 shows the waterproof box, containing the SQM-LR, mounted on the meteorological tower at the extreme of an arm which function is to avoid the eventual influence of the tower on the measurements. The installations at both potential sites are identical.

2.3. SAND-4 spectrometer measurements

Spectral measurements where made with an instrument that has proven its capacities over the years in various contexts. This instrument, the SAND-4 spectrometer (unit B), is the forth generation of its kind. The SAND platform was introduced in 2005 to evaluate the sky brightness levels for the Mont-Mégantic International Dark Sky Reserve (IDSR). The device itself is basically composed of a Charged Coupled Device (CCD) camera and a SBIG's DSS-7 longslit spectrograph. The spectral resolution of SAND-4 is 1 nm. The slit cover a field of view of $\sim 2\,^{o}\,22\,''$ x $5\,''$. As the DSS-7 is now discontinued, we are looking to replace it with the Alpy 600 spectrograph manufactured by Shelyak Instruments. If successful, this transition will lead us to the version 5 of SAND.

Five specific wavelengths have been identified for being ideal for measurement amongst the visible spectrum emitted by street lights. These correspond to the following sodium and mercury lines: 436 (Hg), 498 (Na), 546 (Hg), 569 (Na) and 615 (Na) nm. They are preferably analysed because they are not in competition with the Fraunhofer lines or with the atmospheric OI lines, and they are not absorbed by the atmosphere constituents. As a matter of fact except for the 546 nm wavelength, no Fraunhofer line influences the radiance outcome. The 546 nm line overlaps with a secondary Fraunhofer line, the e line. This results in a sum of their radiances, which influences the actual value. However, the impact is restrained to a single condition, the presence of light from the sun. Indeed, the mercury absorption line comes from the lights interaction with the suns atmosphere. For this reason, the e line will interfere with sky brightness only at dawn or in the presence of the moon. In brief, our radiance will be slightly under evaluated when the measurements are taken in presence of the moon or at dawn. Secondly, the atmosphere does not absorb these particular wavelengths. This is vital to an accurate measurement of the sky brightness. Indeed, the atmospheric absorption features would reduce the perceived radiance thus falsifying the results.

For our analysis, we chose to focus on the radiance of two specific wavelengths, 546 nm and 569 nm. In that order, they correspond with the sodium and mercury lines emitted by the regions artificial lighting. These particular wavelengths were chosen for three reasons. Firstly, artificial lighting is substantially composed of sodium and mercury based lamps. Thus we can assume that our measurements represent the actual light pollution. In addition to this, the spectral proximity of these two wavelengths is such that we can assume that the atmosphere almost identically affects them. Lastly, these wavelengths correspond well with the eye's most sensitive region of the spectrum. Therefore, we may validate in a qualitative way the measurements by comparing our results with the visual observation logs we produced while on sites.

Our data was collected in very specific conditions and time periods in order to have the most representative information of the artificial sky brightness over time according to the orientation in elevation and azimuth. The spectrometer was positioned in order to measure the sky radiance above the surrounding sources of light pollution. The elevation of our instrument varied between 15, 30 and 90 degrees above the sources to determine with the greatest precision their impact. These elevations were chosen because they furnish a global vu of the sky's light pollution. The integration time was of 3600 seconds except for a few captions where the brightness was insufficient to gather a clean spectrum, in the following case the exposure time was doubled. This procedure concerns mostly the measurements taken at the zenith in absence of the moon. As for the direction, we collected the radiance directly over the surrounding cities but also on each one of their sides in order to determine the impact of the luminous halos produced by the city's light on our measurements. We attached the spectrometer unit to a robotic mount (Fig 4) and automated the process of measurement at different elevation and azimuth angles. Before each measurement, individuals validated the orientation with angular level each time there was a change in direction. Also, the lens was verified frequently to assure that there was no dew or dust. The resulting images are automatically reduced by the program inspectre.bash available on google code repository (Aubé 2014c). All the control and analysis software can be found on the same site. Subsequently, the spectral sky radiance was approximated using a 6^{th} order polynomial and six Gaussian functions over the spectral range from 530 to 580 nm. The polynomial was used to remove the continuum radiation (stars, moon) while gaussian functions were used to estimate spectral lines fluxes. Indeed, the area of Gaussian approximations of the target lines corresponding to 546 and 569 nm wavelengths determines the radiance. These manipulations were made with fityk, a powerful open source curve fitting program. We constrained the Full Width Half Maximum (FWHM) of the gaussian functions to be fixed at a constant value since with SAND, the FWHM is determined by the spectral resolution of the instrument. Take note that these final manipulations using fityk were repeated several times in order to validate the radiance and establish a part of the uncertainty of each measurement. Two examples of fit are given in Figs 5 and 6 respectively for the cases of an observation made 30 deg above Tamberías (9 km distant to Leo++, population 860) with the moon up, and 30 deg above San Juan (80 km away El Leoncito, population 471389) without moon, when it was possible, because the observing run period at the Observatory.

3. Results and discussion

3.1. Sky Background Brightness at El Leoncito

The observations were taken each 15 minutes and selected taking into account the period of time between the beginning and the end of the astronomical twilight, during clear (without clouds, according images from a Full Sky camera installed at CASLEO) and moonless nights. In the histograms, the extreme values correspond to few observations in the limit of the night which were taken into account only to determine the limit of the twilight by visual inspection, and small fluctuations produced eventually by stars, were accepted. The data obtained with SQM after one year of measurements in El Leoncito is presented in the histograms of Figures 7 (the average over a year) and 8 (seasonal study, where average values and standard deviation are indicated in the figures.All the measurements at El Leoncito were made with the SQM pointed to zenith. The effect of a single star of low magnitude is negligible in the measurements of SBB, but for example 15 stars of magnitude 4 would increment the background by 0.23 mag/arcsec^2. This situation is evident during the transit of the Milky Way across the FOV of the instrument: the bulge of the Galaxy contributes with nearly a magnitude. By definition the SBB is a measurement of the general conditions of the night sky, with the lower natural light (stars, moon) contribution; for this reason, the Milky Way effect on this quantity must be removed. The seasonal study (see Figure 8) put in evidence the effect of the Milky Way on the SBB measurements, for example in Autumn the contribution by stars change in almost 0.5 magnitude the average value of the SBB.

Finally, if we apply all the corrections listed above, the average of the sky background brightness results is 21.6$\pm$0.4 mag/arcsec^2 for El Leoncito. This measurement is in agreement with the data obtained at CASLEO, using a similar equipment installed at Burek hill (Pereyra 2014), distant 9 km from the preselected site.

3.2. Sky Background Brightness at LEO ++

In order to study the altitude dependence and the influence of the near cities of Barreal (30 km away, population 3202) and Calingasta (12 km away, population 2039) to LEO ++ SBB, we performed observations with a SQM-LU (similar to teh SQM-LR but with a USB port). We used the V filter (standard SQM filter) and a B narrow band filter (with central = 420nm; FWHM $\sim$ 10 nm)), for one night (Oct 27, 2013). The results are presented in table 1.

3.3. Spectral measurement of the sky brightness

Typical spectrum taken with SAND at MMO (toward Notre-Dame-des-Bois), El Leoncito (toward San Juan) and Leo++ (toward Tamberías) are shown on Fig 9. Our measurements revealed to be consistent for each site; the relative radiance was in majority of the same order of magnitude (10^{-9} $Wm^{-2}sr^{-1}$). As anticipated the highest values were collected at an elevation of 15° both for El Leoncito and Leo++. For this elevation, as we can see on table 2, El Leoncito 15° elevation average a radiance of $5.0x10^{-9}$ $Wm^{-2}sr^{-1}$ for the 546 nm line and $7.8x10^{-9}$ $Wm^{-2}sr^{-1}$ for the 569 nm line. As for Leo++, the 546 nm line averaged a 15° elevation radiance of $7.6x10^{-9}$ W $m^{-2}sr^{-1}$ and the 569 nm line $2.2x10^{-8}$ W $m^{-2}sr^{-1}$. From this finding, we can deduct that there is a significant difference between the usage of sodium lighting and mercury lighting. Indeed, the radiance is greater in the sodium 569 nm line, no matter the elevation angle. However, this difference is less noticeable with increasing elevation angle. Radiances are higher for both wavelengths at Leo++, but the most important difference is for the 569 nm line. In that case Leo++ show a radiance almost 3 times higher than El Leoncito.

3.3.1. El Leoncito

San Juan is the most important source of light for El Leoncito. The ground being rocky, the wind did not produce as much aerosols as it did at Leo++. As a matter of fact, the presence of aerosols was negligible during our experiment. The presence of mountains surrounding the location partly hid the luminous halos from nearby cities. The last two nights of our experiment were partly cloudy; this affected our measurements by slightly decreasing the actual value of radiance. The line fluxes acquired at this site are shown in table 3.

3.3.2. Leo++

The small town of Calingasta was the most influent for this particular site. Two factors where particularly detrimental to the sky's quality. Firstly, there was a considerable amount of aerosols due to the presence of dusty soil entrained by winds. This layer of aerosol was principally influential for the measurements of low elevation angles. Secondly, we noticed an excessive amount of artificial lighting on the streets at certain points. Without a doubt this unnecessary illumination is the primary source of the luminous halo observed. This being said, there is a positive outcome to having the majority of the light coming from one source. Indeed, it is particularly easy to control. There are many ways to reduce the effect of this lighting such as abolition of the source, reduction of the power, redirection of the emission towards the ground and the installation of yellow filters. The line fluxes acquired at this site are shown in table 4.

3.3.3. Comparison with other astronomical sites

These values are compared with some other taken over the last few years at two well documented observation sites to establish whether or not the site is proper to welcome the Cherenkov Telescope Array. These sites are Kitt Peak National Observatory (KPNO) and Mont-Mégantic Observatory (MMO). KPNO is situated in Arizona USA. Its altitude is 2098 meters and the nearest city is Tucson (Population 980263, 70 km away). Tucson is under strict regulation as for the usage of mercury lighting, for this reason the radiance at this wavelength (546 nm) is significantly inferior to the other comparative sites. MMO, the first International Dark Sky Reserve (IDSR), is found in Québec, Canada. The city of Sherbrooke is the most important source of light pollution (Population 201980, 60 km away). MMO is at an altitude of 1111 meters.

As we can see on the table 6, the sky radiance at KPNO in direction of Tucson is $5.0\text{x}10^{-9}$ $\text{Wm}^{-2}\text{sr}^{-1}$ for the 546 nm line and $1.66\text{x}10^{-8}$ $\text{Wm}^{-2}\text{sr}^{-1}$ for 569 nm. The radiance due to the sodium artificial lighting is greater than the radiance due to the mercury line, as expected. In comparison, with the MMO, where the radiance of the 546 nm line is $1.26\text{x}10^{-8}$ $\text{Wm}^{-2}\text{sr}^{-1}$ and $1.29\text{x}10^{-8}$ $\text{Wm}^{-2}\text{sr}^{-1}$ for the 569 nm line, in direction of Sherbrooke. The night sky sodium radiance is similar for MMO and KPNO, but we must underline that MMO measurements were made during the lamp replacement program, before the region was officially declared the first IDSR. The comparison will consider the values of our measurements at an elevation angle of 30 deg with an azimuth corresponding to a certain city. This elevation is also more or less the limit of the observable sky for many astronomical measurements. As demonstrated in the figure 17 of J-D Giguère's M.Sc. Thesis (Giguère (2010)) and in Garstang (1986), the relative sky brightness decreases logarithmically according to the elevation angle. For this reason, measurements at an elevation angle of 30$^{\text{o}}$ are slightly sensitive to specific position of light domes along the horizon and then, they don't vary considerably with a change in azimuth. In brief, aiming the spectrometer on top or besides a luminous halo has a small influence on the measured radiance.

Table 5 confirms the resemblance as for the radiance of the 569 nm line measured at KPNO and MMO while directed towards the city of greatest influence. Consequently, we can affirm that MMO is as legitimate to compare with the candidate sites. Due to the lack of measurements at an elevation angle of 30° for a comparable city at El Leoncito and Leo++, we took notice of the radiance at this elevation angle for Notre-Dame-des-Bois (Canada), which showed similar characteristics to Tamberías. We established a link between those two sites. In fact, as we can see on table 6, the 546 nm radiance of Tamberías, $3.8\text{x}10^{-9}$ $Wm^{-2}sr^{-1}$, is approximately the third of Notre-Dame-des-Bois, $9.2\text{x}10^{-9}$ $Wm^{-2}sr^{-1}$. However, for the 569 nm line, the radiance was higher over Tamberias, $8.9\text{x}10^{-9}Wm^{-2}sr^{-1}$, in comparison with $5.9\text{x}10^{-9}$ $Wm^{-2}sr^{-1}$, over Notre-Dame-des-Bois. As said, it is interesting to know that the light conversion on the Mont-Mégantic IDSR was not completed at the time of measurements, which means that actually, the night sky radiance would probably be significantly lower, especially for the 546 nm line because mercury based lamps are now forbidden inside a radius of 25 km centered on MMO. As for the El Leoncito observation site, in the direction of San Juan the radiance for the 569 nm line is of $4.8\text{x}10^{-9}$ $Wm^{-2}sr^{-1}$. For a comparable direction, MMO's radiance for the 569 nm line is $5.9\text{x}10^{-9}$ $Wm^{-2}sr^{-1}$. For those same directions, the 546 nm line has a radiance of $3.8\text{x}10^{-9}$ $Wm^{-2}sr^{-1}$ for San Juan and $9.2\text{x}10^{-9}$ $Wm^{-2}sr^{-1}$ for Notre-Dame-des-Bois. The two candidate sites have very similar 546 nm radiances at an elevation angle of 30° above the city of greater influence. In fact, the difference between El Leoncito and Leo++ is lower that uncertainties for the 546 nm line. For the 569 nm line, the difference is $4.1\text{x}10^{-9}$ $Wm^{-2}sr^{-1}$ (Leo++ being the brightest). The 569 nm radiance at Leo++ is therefore almost the double of El Leoncito. This being said, it is important to precise that the measurements are of the same order of magnitude for the sites taken in comparison. Nonetheless, aerosols impact the measured radiance at Leo++.

4. Conclusion

In this paper, we briefly presented the two locations we were assigned. After which we explained our method of characterization for CTA's candidate sites in Argentina in addition to the physic fundamentals supporting it. The instruments used for the measurements (SAND-4, SQM-LR and SQM-LU) were also introduced.

Through our analysis, we demonstrated the legitimacy of the Mont-Mégantic Observatory as a comparative figure for Leo++ and El Leoncito. This analysis revealed that the three sites where similarly light polluted (in order of magnitude). In general Argentinian sites both have an appreciable potential for astronomical installations. However, El Leoncito was distinguished for its lower average radiance (especially for the 569 nm line), for characteristics such as the very low presence of aerosols (lower extinction), and for the presence of the mountains to reduce the impact of the surrounding luminous halos.

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Facilities: CASLEO

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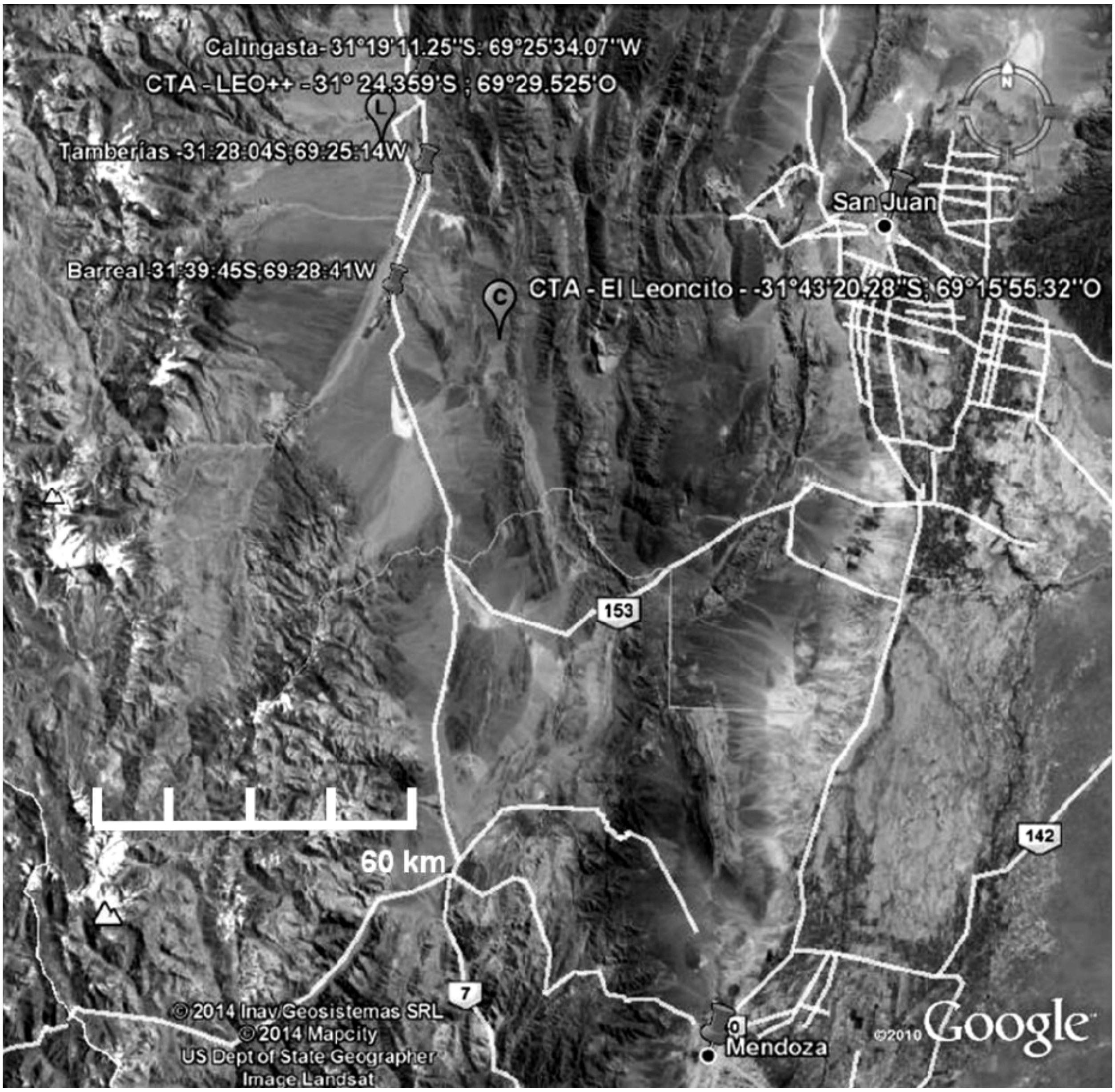

Fig. 1.— Map of LEO ++ and El Leoncito locations. Near cities, capitals and main roads are indicated.

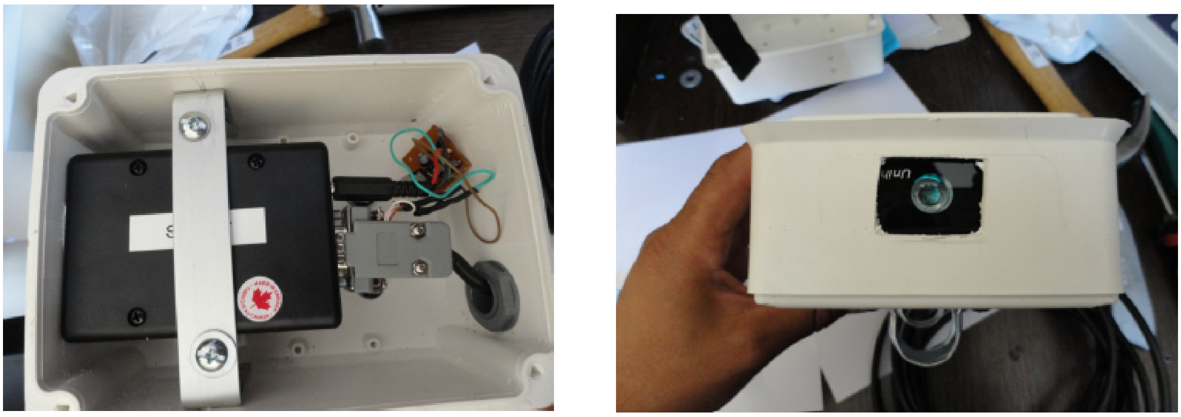

Fig. 2.— SQM-LR inside a waterproof plastic box (left); window with sealed glass (right).

Fig. 3.— SQM box mounted at the Tower at El Leoncito.

Fig. 4.— SAND-4 spectrometer and it's robotized mount.

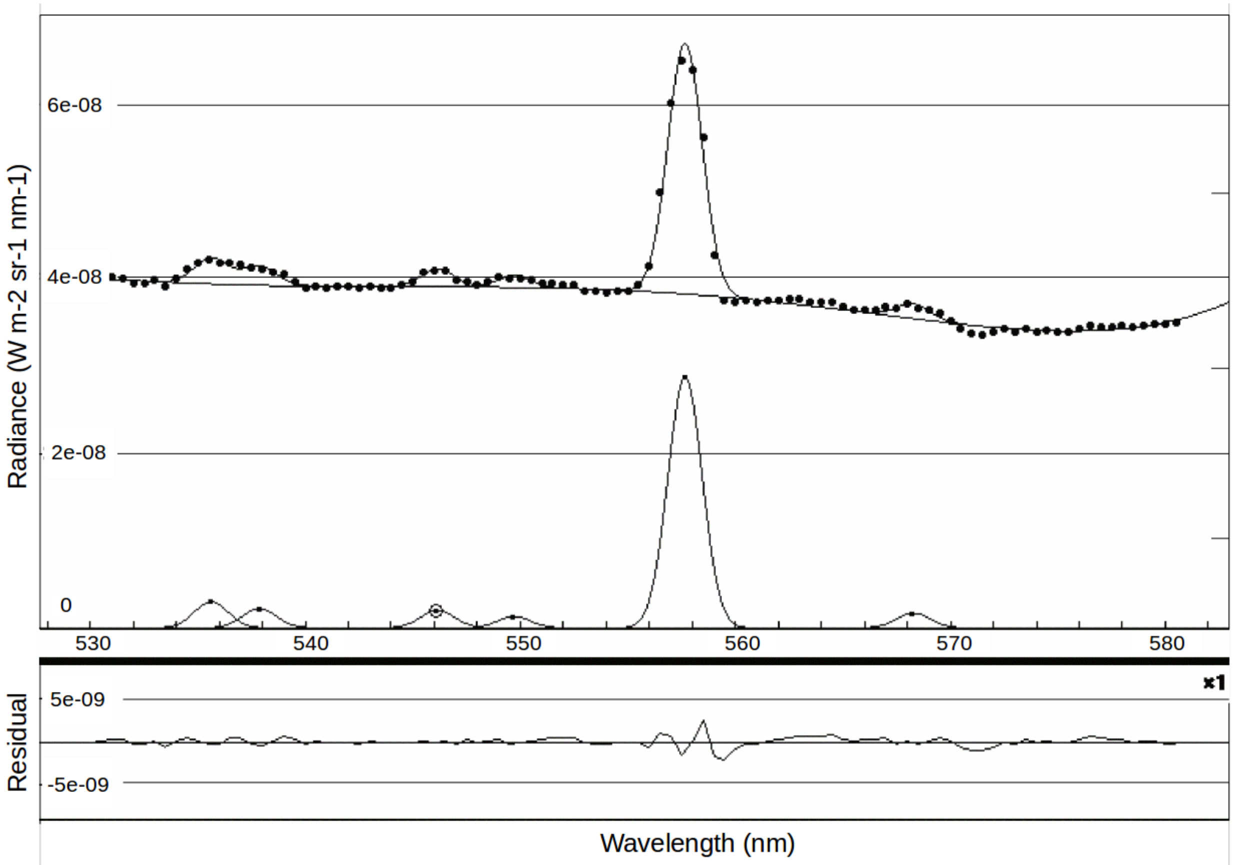

Fig. 5.— Multigaussian and polynomial fit of the 530-580 nm region at Leo++ toward Tamberias 30 deg above horizon, azimuth 134 deg. Dots are for the spectral data and black lines show the resultant fit and individual components. The black line in the lower pane is the residual of the fit.

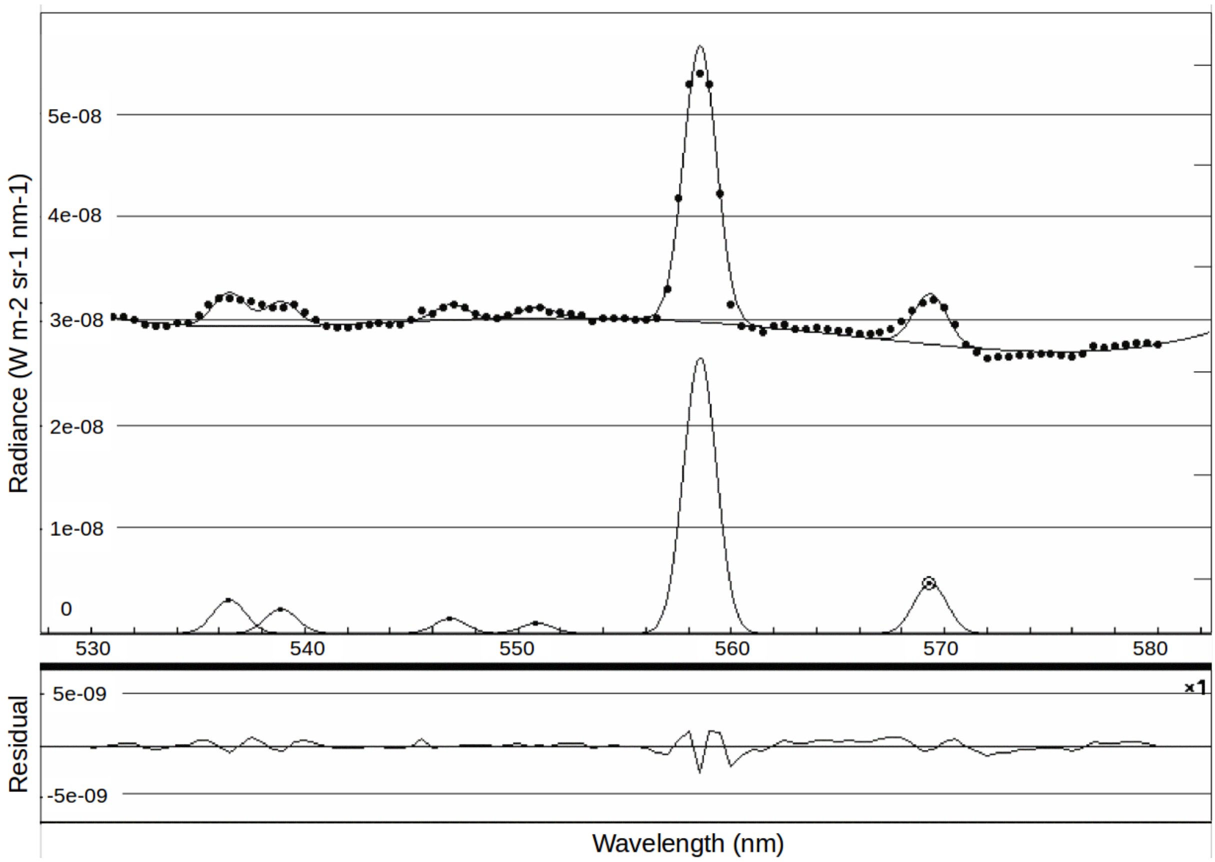

Fig. 6.— Same as Fig 5 but for El Leoncito toward San Juan 30 deg above horizon, azimith 67.

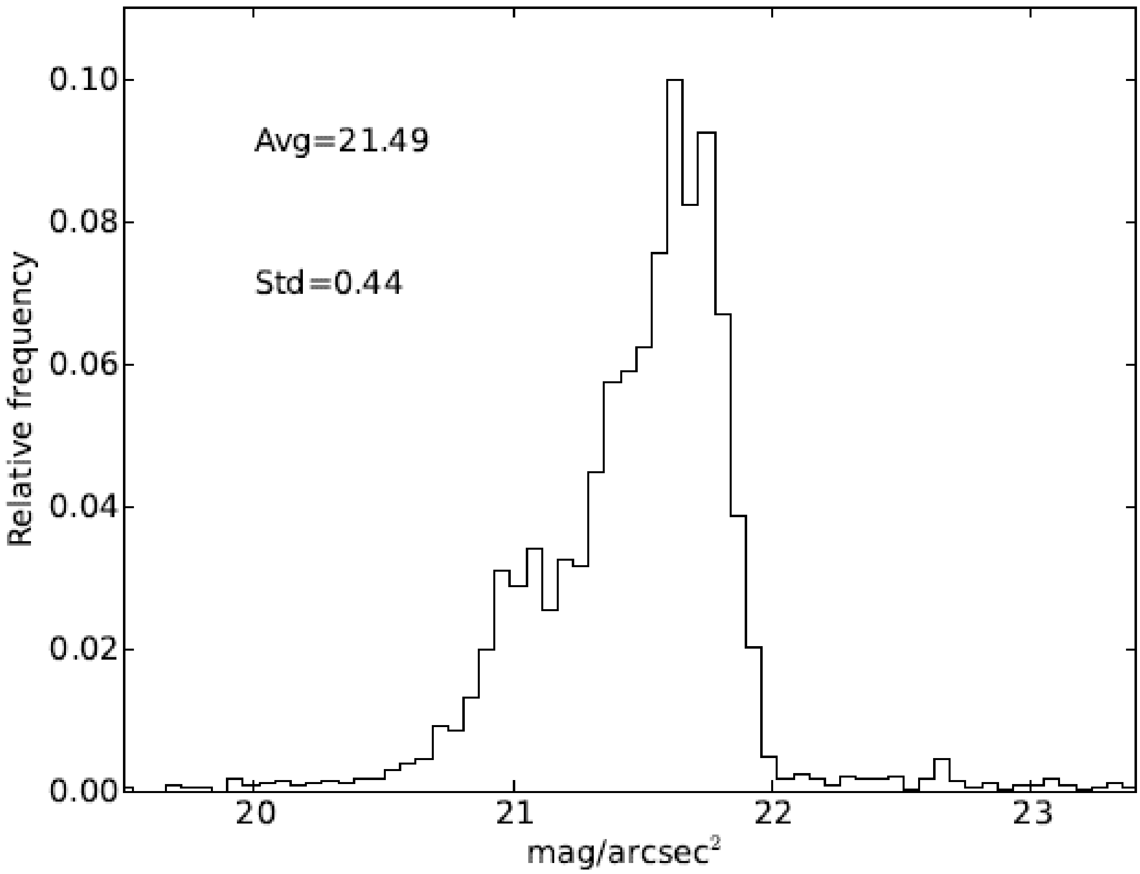

Fig. 7.— Histogram for Sky Background Brigthness data at El Leoncito.

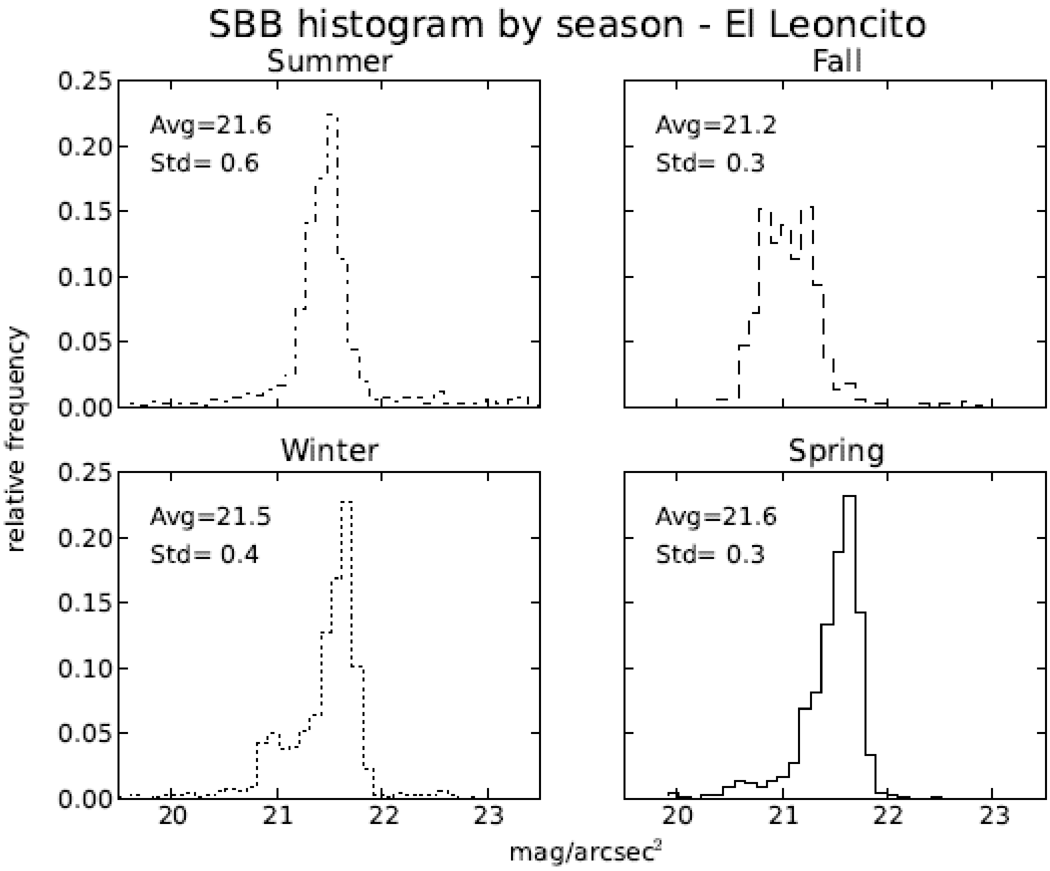

Fig. 8.— Seasonal behaviour of SBB at El Leoncito.

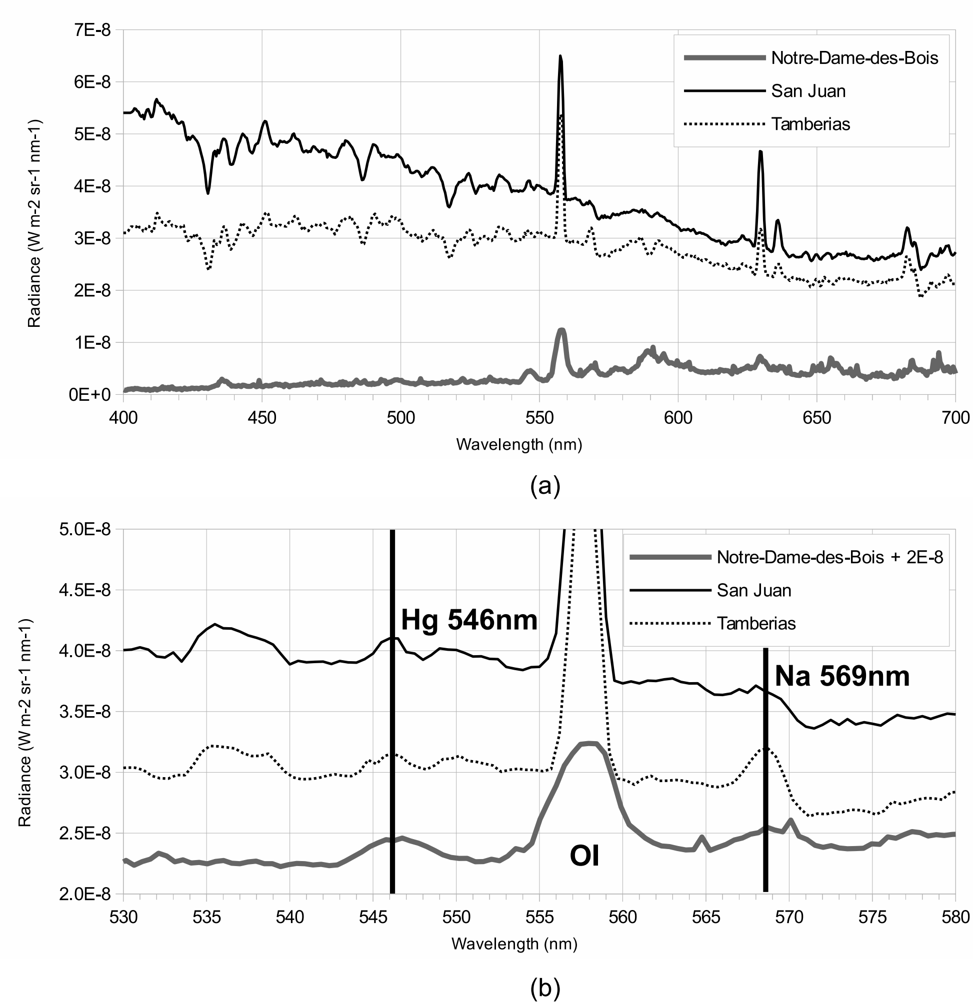

Fig. 9.— Comparison of spectrum for MMO, El Leoncito and Leo++ for 3 equivalent orientations 30 deg above horizon. Differents slopes for each curve of upper pane is coming from different levels of moon light scattering in the sky. The case of Notre-Dame-des-Bois correspond to a moon free sky. Pane b show a zoom on the 530-580 nm region. Note that on lower pane, we can see that the spectral resolution has changed from 2006 (Notre-Dame-des-Bois) to 2014 (Tamberias & San Juan). In 2006 we used the version 2 of SAND that had a spectral resolution of 2 nm while SAND-4 has a resolution of 1 nm.

Table 1. LEO++ - SBB (Oct. 27, 2013 22:00-22:55 hs)

Direction	Altitude	V-filter	B-filter
	(deg)	(mag)	(mag)
North	0	21.43	
	10	21.15	
	20	21.23	22.30
	30	21.28	22.15
	40	21.37	22.84
	50	21.39	22.94
	90	21.5	23.00
Calingasta	0	21.4	22.37
	10	21.17	22.60
	20	21.23	22.47
	30	21.45	22.49
	40		22.00
	50	21.76	
	90	21.73	22.55
Barreal	0	21.59	22.13
	10	21.59	22.35
	30	22.55	22.63
	40	21.80	22.7
	60	21.70	22.4
	90	21.70	22.98

Table 2. SBB seasonal dependence at El Leoncito

Site-Period	Average	std. dev.
	(mag.)	(mag.)
El Leoncito-All year	21.5	0.4
El Leoncito-Summer	21.6	0.6
El Leoncito-Autumn	21.2	0.3
El Leoncito-Winter	21.5	0.4

Table 3. Average of the sky radiance at El Leoncito and Leo++ sites according to the elevation angles.

Observation site	Wavelength	Elevation	Radiance
	(nm)	(^{o}) ±1	($Wm^{-2}sr^{-1}$)
El Leoncito	546	15	5.0E-09
		30	3.6E-09
	569	15	7.8E-09
		30	4.0E-09
Leo ++	546	15	7.6E-09
		30	3.0E-09
	569	15	2.2E-08
		30	8.9E-09

Table 4. Sky radiance on El Leoncito observation site according to the elevation and azimuth angles.

Wavelenght	Elevation	Azimuth	Radiance	Exposure	Date	Time	Moon
(nm)	(^{o})	(^{o})	($Wm^{-2}sr^{-1}$)	(s)	AAAA-MM-JJ	HH:MM:SS	y/n
	±1	±1			GMT	GMT	
	30	67	3.8E-09±3E-10	3600	2014-01-15	07:22:27	y
	30	159	3.3E-09±3E-10	3600	2014-01-15	05:11:55	y
	15	47	3E-09±3E-10	3600	2014-01-10	03:26:58	y
546	15	55	5.9E-09±9E-10	3600	2014-01-10	04:32:13	y
	15	67	1.11E-08±9E-10	3600	2014-01-15	06:17:11	y
	15	113	2.62E-09±4E-11	7200	2014-01-10	05:37:29	n
	15	159	4.8E-09±3E-10	3600	2014-01-14	01:50:48	y
	15	215	2.1E-09±5E-10	3600	2014-01-14	04:01:20	y
	30	67	4.8E-09±3E-10	3600	2014-01-15	07:22:27	y
	30	159	3.2E-09±2E-10	3600	2014-01-15	05:11:55	y
	15	47	4.7E-09±8E-10	3600	2014-01-10	03:26:58	y
569	15	55	8.8E-09±2E-10	3600	2014-01-10	04:32:13	y
	15	67	1.4E-08±1E-09	3600	2014-01-15	06:17:11	y
	15	113	4.32E-09±1E-11	7200	2014-01-10	05:37:29	n
	15	159	8.5E-09±3E-10	3600	2014-01-14	01:50:48	y
	15	215	6.4E-09±2E-10	3600	2014-01-14	04:01:20	y

Table 5. Sky radiance on Leo++ observation site according to the elevation and azimuth angles.

Wavelenght	Elevation	Azimuth	Radiance	Exposure	Date	Time	Moon
(nm)	(^{o})	(^{o})	($Wm^{-2}sr^{-1}$)	(s)	AAAA-MM-JJ	HH:MM:SS	y/n
	±1	±1			GMT	GMT	
546	90	90	1.3E-09±2E-10	7200	2014-01-11	05:33:17	n
	30	67	2.2E-09±4E-10	3600	2014-01-13	06:43:40	y
	30	134	3.8E-09±9E-10	3600	2014-01-13	05:38:26	y
	15	40	1.6E-08±1E-09	3600	2014-01-11	03:22:46	y
	15	60	4.8E-09±6E-10	3600	2014-01-11	02:17:29	y
	15	67	6.4E-09±4E-10	3600	2014-01-13	04:33:10	y
	15	100	6.0E-09±9E-10	3600	2014-01-11	04:28:01	y
	15	134	4.9E-09±1E-10	3600	2014-01-13	03:27:54	y
569	90	90	3.41E-09±2E-11	7200	2014-01-11	05:33:17	n
	30	67	8.81E-09±5E-11	3600	2014-01-13	06:43:40	y
	30	134	8.9E-09±7E-10	3600	2014-01-13	05:38:26	y
	15	40	4.4E-08±9E-09	3600	2014-01-11	03:22:46	y
	15	60	2.0E-08±4E-09	3600	2014-01-11	02:17:29	y
	15	67	1.65E-08±8E-10	3600	2014-01-13	04:33:10	y
	15	100	1.3E-08±6E-09	3600	2014-01-11	04:28:01	y
	15	134	1.73E-08±1E-10	3600	2014-01-13	03:27:54	y

Table 6. Comparison between El Leoncito and Leo++ with different well known observation sites.

Observation site	Orientation	Elevation	Azimuth	Radiance @ 546 nm	Radiance @ 569 nm	Date
		(^{o})	(^{o})	($Wm^{-2}sr^{-1}$)	($Wm^{-2}sr^{-1}$)	MM/YYYY
		±1	±1			
KPNO	Tuscon	30	66	5,0E-09	1,7E-08	05/2006
MMO	Sherbrooke	30	266	1,3E-08	1,3E-08	09/2006
	Notre-Dame-des-Bois	30	142	9,2E-09	5,9E-09	08/2007
El Leoncito	San Juan	30	67	3,8E-09	4,8E-09	01/2014
Leo++	Tamberias	30	134	3,8E-09	8,9E-09	01/2014