Site Testing of the Sierra de Javalambre: First Results

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ABSTRACT. We present the main characteristics of the Pico del Buitre, at the Sierra de Javalambre, the proposed location for the Javalambre Astrophysical Observatory. The measurements have been obtained from spectro-photometric, photometric, and seeing data obtained with different monitors and instruments on the site. We have also used publicly-accessible meteorological satellite data to determine the total time useful for observations. The night-sky optical spectrum observed in a moonless night shows very little contamination by the typical pollution lines. Their contribution to the sky brightness is ~0.06 mag in B, ~0.09 mag in V, and ~0.06 mag in R. In particular, the comparison of the strengths of the sodium artificial and natural lines indicates that the site satisfies the IAU recommendations for a dark site. The zenith-corrected values of the moonless night-sky surface brightness are $B = 22.8\text{ mag arcsec}^{-2}$, $V = 22.1\text{ mag arcsec}^{-2}$, $R = 21.5\text{ mag arcsec}^{-2}$, $I = 20.4\text{ mag arcsec}^{-2}$, which indicates that the site is very dark. The extinction has been measured for the summer period, with a typical value of 0.22 mag in the V-band, with the best measured value of 0.18 mag in a totally photometric night. The median value of the seeing in the V-band for the last 2 yr (2008–2009) is 0.71″, with a mode of 0.58″. The seeing values present a seasonal pattern, being smaller in summer (~0.69″) than in winter (~0.77″). For 68% of the analyzed nights, the seeing was better than 0.8″ during the entire night. The seeing is found to be stable for rather long periods, in particular for the nights with good seeing values. The typical scale, for nights with the seeing below 0.8″, is about 5 hr for variations within 20% of the reference value. The fraction of totally clear nights is ~53%, while the fraction of nights with at least 30% of the night clear is ~74%.

Online material: color figures

1. INTRODUCTION

Any search for adequate sites for new observatories has to focus on the observing conditions such as the night-sky brightness, number of clear nights, seeing, transparency, and the photometric stability. Looking for a potential new site in continental Spain, we found in 1989 that the Sierra de Javalambre, in the province of Teruel, might be one such site. A limited number of studies and observations accumulated at that time indicated that it was a promising site. For a variety of reasons the assessment had to be interrupted until recently, when the idea of building a new observatory there regained interest and new studies were funded. Consequently we have started a program to determine the main observing conditions at the proposed site for the Javalambre Astrophysical Observatory (JAO, hereafter). The selected site is on the Pico del Buitre, Sierra de Javalambre (Teruel, Spain), 1957 m above sea level, at 40°02'28.67" north, 01°00'59.10" west.

The JAO will house two new telescopes to be built in the next 3 yr. It will be run by the Centro de Estudios de Física del Cosmos de Aragón, CEFCA, recently created in Teruel. The main telescope is intended to be a large Etendue instrument for large-scale surveys, with an aperture of 2.5 m and a field of view (FOV) of 7 deg², with good quality over the whole field. The first astronomical survey is being defined to match the requirements to accurately determine the baryonic acoustic oscillations along the line of sight using photometric redshifts for luminous red galaxies, as proposed by the Physics of the Accelerated Universe (PAU) project. The Javalambre-PAU Astrophysical Survey will be a large-scale (~8000 deg²) photometric survey with narrowband (~100 Å) filters covering the spectral range from ~4500–8500 Å. The details of the project, its aims, and implementation are given in Benítez et al. (2009a).

A smaller, auxiliary telescope of 80 cm of aperture will be also built. The main task of this telescope will be to perform the required photometric calibrations for the main survey. In addition, ~30% of the observing time will be accessible to the
astronomical community. The telescope will have a FOV of ~2 deg² square degrees.

In this work we study the main characteristics of the night sky at the Pico del Buitre, identified as the best location in the Sierra de Javalambre. The study is mostly focused on the last two years (2008–2009), which correspond to a period of rising solar activity from the last minimum. The derived main properties have been compared with similar properties at other observatories. In § 2 we describe the data set collected for the current study, including a description of the data reduction process; in § 3 we show the analysis performed on the different types of data and the results derived for each one. The main results are summarized in § 4.

2. DESCRIPTION AND ANALYSIS OF THE DATA

Data from several different sources were collected to characterize the different aspects of the night-sky emission at the proposed location for the JAO. These sources and the kind of data we used are described in the following subsections.

2.1. Spectroscopic Data

A 40 cm aperture telescope temporarily installed at the observatory, together with a commercial DSS-7 spectrograph and a ST-8XME camera from SBIG⁶ have been used to take night-sky spectra. The main characteristics of the spectrograph are listed in Table 1.

The observations were done the night of 2009 August 23, 3 days after the new moon, under clear conditions. A series of exposures of 600 s of integration time were taken over the course of the night, with the telescope pointing to the zenith and without tracking. With this setup, the traces of possible astronomical sources across the slit can be easily rejected. Moreover, only the spectra without contamination by the Milky Way were considered for the analysis. The final number of spectra amounts to 14, corresponding to a total integration time of 8400 s.

The data were reduced using the standard procedures included in IRAF and R3D (Sánchez 2006). First, the bias was determined for each frame, using the nonilluminated areas of the chip and dark exposures taken at the beginning of the night with the same exposure time. The bias frame was subtracted from the corresponding science frame, which was subsequently trimmed to consider only the illuminated region. A series of dark and twilight frames were used to identify bad pixels: hot, dead, and low-sensitivity ones. The values in those pixels were replaced by the median of the 5 adjacent pixels along the cross-dispersion axis, in the science frames. The twilight frames were used to derive a normalization response frame, obtained dividing them by the median spectrum (i.e., the median, for each column, of the values in the corresponding rows). This frame was used to normalize the response of the detector.

For each frame the median spectrum was extracted, corresponding to a total of 40 rows. It was wavelength calibrated using the most prominent night-sky emission lines. Then the 14 frames were combined, adopting a cosmic-ray rejection scheme, to produce a single combined frame, interpolated to a common wavelength step using a simple 4-order polynomial function (e.g., Sánchez 2006). The accuracy of the wavelength calibration was ~1.3 Å, acceptable given the wavelength resolution of the spectrum for the purposes of this study. The wavelength calibrated spectrum was relative flux calibrated by adopting the efficiency curve published by the manufacturer. Finally, it was scaled to a typical night-sky surface brightness for an astronomical dark site in the V band.

2.2. Sky-Brightness and Extinction Data

The night-sky surface brightness and extinction were monitored using an instrument built for this purpose by J. Aceituno: the Extinction Camera and Luminance Background Register (EXCALIBUR). It is a robotic extinction monitor able to do quasisimultaneous photometric observations in 8 bands covering the wavelength range between 3400 Å and 10200 Å. The sky-brightness and extinction curves are derived by comparing the instrumental and catalog photometry of precalibrated stars. About 16 extinction coefficients for each of the sampled bands are estimated every hour, together with up to ~50 extinction coefficients per band and per night. The same kind of instrument has been used to study the extinction curve at the Calar Alto Observatory (Sánchez et al. 2007).

The instrument was operative at the mountain for a total of 13 nights, between 2008 July 23 and October 5. For those nights, it was set up to obtain the sky brightness at B and R bands, and the extinction at ~500 nm, which basically corresponds to the V band. A total of 118 estimations of the night-sky surface brightness for the broadband filters, and 317 accurate estimations of the extinction for the narrowband filters, were derived.

2.3. Seeing Data

The night-sky seeing has been measured with a robotic differential image motion monitor (RoboDIMM, Aceituno 2004).

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See http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarradio.html.

See http://www.sbig.com/.

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### Table 1

| Parameter                        | Value |
|----------------------------------|-------|
| Slit width                       | ~2.7″ |
| Slit length                      | ~19″  |
| Spectral resolution (FWHM)       | 15 Å  |
| Spectral sampling                | 5.4 Å pixel⁻¹ |
| Spectral range                   | 4000–8100 Å |
| Peak efficiency                  | 0.4   |
| Wavelength of the peak efficiency| 6000 Å |
This instrument measures the seeing at the wavelength corresponding to the Johnson V-band. It was calibrated with a similar unit installed at the Calar Alto Observatory (Vernín & Muñoz-Tuñoz 1995; Sánchez et al. 2007) that was itself calibrated with a generalized seeing monitor in 2002 May (Ziad et al. 2005). The values measured by this instrument were also checked with simultaneous direct imaging obtained with the 3.5 m telescope at Calar Alto (Sánchez et al. 2008).

The instrument was first installed at the Pico del Buitre in 2008 March, and it has been systematically used since then, provided that the weather conditions and the still incomplete infrastructure permitted it. The data presented here include measurements up to the end of 2009 September. The coverage is not complete due to adverse meteorological conditions in addition to several accidents that affected the infrastructure.

RoboDIMM measures the transversal and horizontal components. Occasionally there is a large difference between these two values, most probably due to mechanical oscillations, that have to be eliminated from the statistics. Thanks to the inherent stability of the instrument, the frequency of such departures is rather low, less than ~5% in our case. The number of collected measurements was 81,651 in 132 nights. Despite the technical difficulties we encountered in working on the mountain, this coverage is similar to that of other well-established observatories (e.g., Sánchez et al. 2007).

2.4. Satellite Information

We used data from the satellites METEOSAT (148 images) and LANDSAT (2175 images) corresponding to the period 1983–1988 during the early site testing of the Sierra de Javalambre. They represent a faithful first approximation to the analysis of the cloud coverage in the area. Both sets of images were cross-checked and used to find the global properties of the Sierra and properties of the individual peaks.

More recently, publicly available high-resolution images corresponding to the period 2005–2006 were analyzed. The database consists of 3000 images from the NOAA satellite (sampling of 1.2 km pixel\(^{-1}\)) and 2000 images taken with the remote sensors MODIS Terra and MODIS Aqua (sampling of 250 m pixel\(^{-1}\)). The images correspond to selected time points of the day and night, UT = 0 h, 06 h, 12 h, and 18 h. MODIS Terra and MODIS Aqua are viewing the entire Earth’s surface every 1 to 2 days, acquiring data in 36 spectral bands covering the wavelength range between 0.4 \(\mu\)m to 14.4 \(\mu\)m. These images can be used to determine the presence of clouds at a given location, on the basis of the difference of temperature between the surface and the clouds, provided by the infrared measurements. The analysis was done on images of 20 \(\times\) 20 km centered on the Pico del Buitre.

3. RESULTS AND DISCUSSIONS

We describe here the analysis performed over each of the different sets of data.

3.1. Night-Sky Spectrum

Figure 1 shows the night-sky spectrum obtained as explained in § 2.1. This is the first time that a spectrum of the night sky over Javalambre is being published. The night-sky emission lines with wavelengths are labeled. For comparison purposes, published night-sky spectra corresponding to the Calar Alto and the Kitt Peak observatories have been included in the figure.

The main natural contribution to the night-sky light is airglow. It produces prominent lines like O I \(\lambda 5577\), 6300 Å, the OH bands in the red and NIR, and a pseudocontinuum in the blue (due to overlapping O\(_3\) bands, 2600–3800 Å), and in the green (NO\(_2\) bands, 5000–6000 Å). It also contributes to the ubiquitous Na D \(\lambda 5890/6\) doublet, a line that can be contaminated by light pollution from low and high-pressure street-lamps (see Fig. 1). A more detailed description of the effects of airglow on the night-sky emission can be found in Benn & Ellison (1998a). An atlas of the airglow from 3100 Å to 10000 Å was presented by Ingham (1962) and Broadfoot & Kendell (1968). Other contributions to the night-sky spectrum are also described in the atlas (Tuñoz 1995; Sánchez et al. 2007) and that of the Kitt Peak Observatory (Massey & Foltz 2000).

![Fig. 1. Night-sky spectrum at Pico del Buitre, Sierra de Javalambre, in the optical wavelength range (3700–7950 Å), obtained the night of 2009 Aug 23, with dark time and photometric conditions (black line). The intensity has been scaled to that of the typical moonless night-sky brightness in the V band. The most important night-sky emission lines have been labeled even if they are not present in the spectrum. The Na I broad emission centered at \(~5900\) Å, and the water vapor Meinel bands are clearly identified in the spectrum. For comparison purposes we have included the night-sky spectrum at the Calar Alto Observatory (Sánchez et al. 2007) and that of the Kitt Peak Observatory (Massey & Foltz 2000). The spectral resolution and the sky-brightness at 5000 Å, have been scaled to match our data. The low intensity of the pollution lines at Pico del Buitre is clearly appreciated in this image (e.g., the Na I 5893 Å and Hg 5770.91 Å lines). See the electronic edition of the PASP for a color version of this figure.](https://example.com/figure1.png)
are the zodiacal light, the starlight, and the extragalactic light, which increase the background continuum emission (see Benn & Ellison 1998a and references therein).

Apart from the natural contributions, the night-sky spectrum can be affected by light pollution, mostly from streetlights in populated areas near to observatories. Light-pollution arises principally from tropospheric scattering of light emitted by sodium (high and low pressure), mercury vapor, and incandescent street lamps (McNally 1994; Osterbrock et al. 1976; Holmes 1997). The low-pressure Na lamp has less impact on astronomical observations, as most of the light it produces is concentrated in the $\lambda$5890/6 and $\lambda$8183/95 lines. High-pressure Na lamps emit most of their light in a broad, FWHM $\sim$ 400 Å Na line centered at $\sim$5890 Å that shows a central reversal. They also show strong emission at $\lambda$8183/95 and fainter emission lines. Mercury lamps produce narrow lines at 3651/63 Å, 4047 Å, 4358 Å, 5461 Å, 5770 Å, and 5791 Å, together with broad features at 6200 Å and 7200 Å, FWHM $\sim$ 100 Å, from the phosphor used to convert UV to visible light. They also produce a weak continuum emission over the entire visible range.

The spectrum of incandescent lamps consists of continuum emission only, and it is difficult to identify in a night spectrum. Finally, the high-pressure metal halide lamps, nowadays frequently used in the illumination of sport stadiums and monuments, exhibit some scandium, titanium, and lithium emission lines, which are characterized by a blue edge due to molecular bands (General Electric 1975; Lane & Garrison 1978; Osterbrock et al. 1976).

The night-sky spectrum of the Pico del Buitre illustrated in Figure 1 shows little evidence of significant light pollution from streetlights. The mercury lines, which are present in the night-sky spectrum of the Calar Alto and Kitt Peak observatories, are not detected. Moreover, the broad emission at $\sim$5900 Å from high-pressure sodium lamps is significantly weaker than at those two observatories, whereas the potentially strong emission line at 5893 Å from low-pressure sodium lamps is barely detected if at all. The detected contamination, which includes the Sc line at 5351.1 Å, is dominated by the illumination of the city and metropolitan area of Valencia ($\sim$810,000 inhabitants), at $\sim$100 km toward the southeast. In this regard, the night-sky spectrum is more similar to that of the Observatory of the Roque de los Muchachos, at La Palma, published by Pedani (2005).

To quantify the contribution of light pollution to the night-sky spectrum of the Pico del Buitre we have determined the flux intensity corresponding to each detected emission feature using the procedure described in Sánchez et al. (2007). The values we have found are listed in Table 2, which also shows the flux from the sodium broadband emission, estimated by fitting the observed feature with a single broad Gaussian function. All the fluxes were converted to Rayleigh following the conversion formulae by Benn & Ellison (1998a).

Quantifying the artificial contribution to the sodium lines is difficult because of the natural contribution to them. From the analysis by Benn & Ellison (1998a) this natural contribution to the broad sodium emission band can be estimated to be $\sim$0.04 mag in the $V$ and $R$ bands. Adopting this value, the contribution from the artificial component can be easily estimated. The results are listed in Table 3 for the $B$, $V$, and $R$ bands, and for a set of medium band filters used by the ALHAMBRA survey (Moles et al., 2008; Benítez et al., 2009b). They are included to illustrate the effects of the pollution lines when medium/narrowband filters, as proposed for large-scale surveys (see Benítez et al., 2009b), are used. The results show that the contribution to the natural component at the Javalambre site in all bands is small. In fact, the site of Pico del Buitre satisfies the IAU criterium for a dark site since the artificial contribution to the sodium emission, estimated to be $\Delta$0.06 mag, does not exceed that of the natural airglow (Smith 1979).

A long-term monitoring of the night-sky spectrum at the observatory will be required to analyze the evolution of the light pollution along the time. Most major observatories nearby heavily populated areas have some kind of night-sky protection laws. Although the Sierra de Javalambre site does not benefit yet from any local sky-protection law to regulate the street illumination, it appears that its effect is low in the night-sky spectrum. In any case a proper protection law would be most convenient to preserve the quality of the site.

| Line | Wavelength (Å) | Flux$^a$ | Flux$^a$ R |
|------|----------------|----------|------------|
| Hg I | 4827.32        | 0.4 ± 0.1| 2.9        |
| Na I | 4978.83        | 1.2 ± 0.1| 8.6        |
| Na I | 5149.53        | 0.4 ± 0.1| 2.9        |
| Sc I | 5351.10        | 0.7 ± 0.1| 5.0        |
| Hg I | 5461.00        | 0.9 ± 0.1| 6.5        |
| O I  | 5577.00        | 6.8 ± 0.1| 48.8       |
| Na I | 5683.88        | 1.2 ± 0.1| 8.6        |
| Hg I | 5770.91        | 0.5 ± 0.1| 3.6        |
| Broad NaD | 5893.00 | 6.3 ± 0.2| 45.2 |
| Na I | 6154.61        | 0.8 ± 0.1| 5.7        |
| O I  | 6300.00        | 2.1 ± 0.1| 15.1       |
| O I  | 6364.00        | 0.9 ± 0.1| 6.5        |

$^a$ In units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$.

$^b$ In units of rayleighs.
3.2. Night-Sky Brightness and Atmospheric Extinction

The data from EXCALIBUR were used to determine the night-sky brightness in the $B$ and $R$ bands and the extinction in the $V$ band. The sky brightness measurements were not corrected for extinction, following the convention adopted in most of the recent studies of sky brightness (e.g., Walker 1988b; Krisciunas 1990; Lockwood et al. 1990; Leinert et al. 1995; Mattila et al. 1996; Benn & Ellison 1998a, 1998b, Sánchez et al. 2007). They are only corrected to the zenith using the expression by Patat (2003)

$$\Delta m = -2.5 \log_{10}[(1 - f) + fX] + \kappa(X - 1),$$

where $\Delta m$ is the increase in sky brightness at a given band for an airmass $X$; $f$ is the fraction of the total sky brightness generated by airglow, being $(1 - f)$ the fraction produced outside the atmosphere (hence including zodiacal light, faint stars, and galaxies); and $\kappa$ is the extinction coefficient at the corresponding wavelength. To apply that formula we have used the average extinction along each night and a typical value of $f = 0.6$ (Patat 2003; Sánchez et al. 2007). The collected data span two complete moon phases, with a good coverage of the different phases/illumination of the moon.

Table 4 lists the mean values of the sky brightness for dark nights, i.e., with Moon illumination less than 5%. It contains the measured $B$ and $R$ values and the estimated values for the $V$ and $I$ bands. The latter were obtained from the night-sky spectrum scaled to the $B$ and $R$ values measured for dark nights. Values for a selection of other observatories are also given. It appears that Javalambre is one of the darkest observatories even when it is taken into account that some of the data in the Table (e.g., for Paranal) were obtained during the maximum of solar activity.

The measurements of the extinction obtained for Javalambre correspond to the summer period when higher than year-average extinction values are expected. This is due to the presence of aerosols and, very occasionally at the Javalambre latitude, to dust from the Sahara desert. The overall effect is clearly seen in the seasonal evolution of the dust extinction at well-established observatories in Spain, like La Palma (Benn & Ellison 1998a) and Calar Alto (Sánchez et al. 2007).

Considering all of the 317 individual measurements of the extinction coefficient provided by EXCALIBUR, the median value amounts to 0.27 mag, with a high dispersion of 0.14 mag. Inspecting the data set, we verify that 4 nights have very high extinction coefficients, over 0.4 mag. These were highly non-photometric nights with a very unusual dust content in the atmosphere. Excluding them, the median value for $k_V$ is now 0.22, much closer to the expected values and very similar to that of the summer period in Calar Alto. Indeed, truly photometric nights are characterized by rather small extinction variations along the night. For the best night in our sampling, 2008 October 5, the variations of $k_V$ are within 15% and the night extinction coefficient is $\sim 0.17 \pm 0.03$ mag, a value consistent with that reported for the winter season in other major observatories, when the aerosol contribution is lower (Benn & Ellison 1998b; Sánchez et al. 2007). Despite that, the average extinction values reported so far seem to be rather high compared with the statistical values reported in other observatories. A visual inspection of the extinction curves derived by EXCALIBUR for different wavelengths for the different nights (e.g., Sánchez et al. 2007), points to an excess of ozone absorption, rather than a high aerosol content in the vicinity of the observatory. A more detailed analysis will require a larger data set than the limited amount of data collected so far. For similar reasons, no seasonal pattern in the extinction was analyzed due to the short time coverage of the collected data.

| Site & Date         | $B$       | $V$       | $R$       | $I$       | Reference          |
|---------------------|-----------|-----------|-----------|-----------|--------------------|
| Javalambre          | 22.8 $\pm$ 0.6 | 22.1 $\pm$ 0.5 | 21.5 $\pm$ 0.3 | 20.4 $\pm$ 0.5 | This work         |
| La Silla 1978       | 22.8      | 21.7      | 20.8      | 19.5      | Mattila et al. (1996) |
| Kitt Peak 1987      | 22.9      | 21.9      | 20.9      | 19.9      | Pilachowski et al. (1989) |
| Cerro Tololo 1987   | 22.7      | 21.8      | 20.6      | 18.7      | Walker (1987a, 1988a) |
| Calar Alto 1990     | 22.6      | 21.5      | 21.0      | 20.0      | Leinert et al. (1995) |
| La Palma 1990–1992  | 22.5      | 21.5      | 21.0      | 20.0      | Benn & Ellison (1998a, 1998b) |
| La Palma 1994–1996  | 22.7      | 21.9      | 20.8      | 19.7      | Patat et al. (2003) |
| Mauna Kea 1995–2006 | 22.8      | 21.9      | 21.9      | 20.3      | Taylor et al. (2004) |
| Paranal 2000–2001   | 22.6      | 21.6      | 21.9      | 20.3      | Walker & Schwarz (2007) |
| Mt. Graham 2000–2001| 22.86     | 21.72     | 21.19     | 20.3      | Sánchez et al. (2007) |
| Cerro Pachón 2005   | 22.43     | 21.63     | 21.36     | 19.25     | Pedani (2009)      |
| Calar Alto 2007     | 22.86     | 22.01     | 20.82     | 19.78     |                    |
| Mt. Graham 2008     | 22.81     | 21.81     | 21.81     | 19.78     |                    |

Note.—Based on spectrophotometric data obtained with PPAK.

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3.3. Atmospheric Seeing

The seeing data described in § 2.3 were used to determine an average seeing for each monitored night during the ~1.5 yr covered by the data discussed here. In Figure 2 the nightly measured data points are shown. The obvious lack of data for some periods is due to technical problems related to the still rather precarious situation at the mountain; we still need to get the monitors working reliably, and protect them from weather and other factors. In fact, the two longer periods without data correspond to two major events: damage by a strong wind, and a robbery. Looking at the nightly average values (Fig. 2), we see that ~68% of the nights have median seeing below 0.8″. Considering the entire data set of all the validated measurements, amounting to $N = 81,651$ data points, the median value we find is 0.71″. The distribution is shown in Figure 3. It can be seen that the mode is 0.58″ and more than 85% of the values are below 1″.

The trend of the average nightly values that can be appreciated in Figure 2 is suggestive of a seasonal pattern, as it is found in other places (Sánchez et al. 2007). To further investigate this possibility, we have built two subsets of data, one for May-September (summer period) and one for October-April (winter period). With some caution due to the lack of the data for January and February, it is clear from Figure 3 the seeing for the summer period (median value of 0.69″) is better than for the winter period (median 0.77″). Not only the median seeing is better in the summer season, but the chances of having better seeing in a summer night are much higher.

In Table 5 we have summarized the median seeing determined for Javalambre and published data for other observatories. It appears that the median seeing at Javalambre is comparable to that of the most highly reputed observatories in the world.

We have looked for the possible dependence of the seeing value on some meteorological parameter. We found strong indication of correlation only with the wind speed and direction. We selected all the seeing measurements that are coincident within 5 minutes with measurements of the wind direction, a total of 16,542 data points. We find that the seeing worsens for wind speeds over 18 m $\text{s}^{-1}$, a completely expected result. More interesting is the relation between seeing quality and wind direction. Figure 4 shows the median seeing for different wind directions. It is clear that the dominant winds are from western directions, and the best seeing values are found under these wind conditions (median = 0.60″). The worst seeing values are found when the wind comes from the north or northeast directions (~1″). Fortunately these are the less frequent wind directions.

We have also considered the stability of the seeing. Inspecting the data, we find that the seeing can be very stable. Indeed, it is frequent to find nights, particularly under good seeing conditions (<0.8″), presenting seeing variations of just a few percent. To characterize the stability of the seeing on an objective basis, we have worked out the typical time scales needed to have the same seeing within some percentage of the reference value by analyzing the entire data set and computing the point-to-point variations within a given percentage. Then the distribution of the resulting time scales for every percentage were computed. The result is plotted in Figure 5. We find that the time scale for the seeing stability is longer for better seeing values. It can be as long as 5 or more hours for variations up to 20% for reference seeing values below 0.8″.
so all the efforts were subsequently concentrated on the Pico del Buitre, the highest peak in that specific area.

The analysis of the high resolution images corresponding to the period 2005–2006 confirms the earlier values, indicating that no long-term evolution in the overall conditions has occurred. It is confirmed that the number of totally clear nights per year amounts to 193 or ~53%. Another important result is that the number of nights with less than 50% cloud cover amounts to 62.2% (227 nights per year). We notice that these figures compare very well with highly reputed Observatories around the world (see for example, Webster 2004; Sánchez et al. 2007).

The fraction of useful time has a clear seasonal pattern, being higher in Summer than in Winter. We show in Figure 6 the fraction of time with cloud coverage lower than a certain limit (10%, 50% and 70% of the time, for each night), for the different months along a year. The time period between June and August has the better weather statistics, with ~60% of totally clear nights. On the other hand, the worst months are March, May and November, with ~35% of clear nights. These months are traditionally the periods with the largest precipitation values in continental Spain.

With the current satellite data, we are able to determine the fraction of clear nights, understood as the nights when less than a 10% of the time is covered by clouds. This does not grant by itself that these nights are photometric. The standard definition of photometric conditions are such conditions in which it is possible to derive a photometric accuracy of 1%–2%, i.e., when the error in the derived magnitudes is of the order of ~0.01–0.02 mag. The accuracy of a photometric measurement depends on both the accuracy of the estimated zero-point for the considered band and the accuracy of the estimated extinction,

### Table 5

| Site                | Median seeing | Reference                        |
|---------------------|---------------|----------------------------------|
| Javalambre          | 0.71"         | This work                        |
| Javalambre (winter) | 0.77"         | This work                        |
| Javalambre (summer) | 0.69"         | This work                        |
| Mauna Kea (1987)    | 0.50"         | Racine (1989)                    |
| Paranal (1993)      | 0.64"         | Murtagh & Sarazin (1993)         |
| Paranal (2002–2007) | 0.65"         | Sarazin et al. (2008)            |
| La Palma (1997)     | 0.76"         | Muñoz-Tuion et al. (1997)        |
| La Silla (1999)     | 0.79"         | ESO webpage\(^b\)                |
| Paranal (2005)      | 0.80"         | ESO webpage\(^c\)                |
| La Silla (1993)     | 0.87"         | Murtagh & Sarazin (1993)         |
| Calar Alto (2006–2007) | 0.90"     | Sánchez et al. (2007)            |
| MtGraham (1999–2002) | ~0.97"    | Taylor et al. (2004)             |
| Paranal (2006)      | ~1.00"        | ESO webpage\(^d\)                |
| KPNO (1999)         | ~1.00"        | Massey et al. (2000)             |
| Lick (1990–1998)    | ~1.90"        | Mt. Hamilton webpage\(^d\)       |

\(^a\) See http://www.ls.eso.org/lasilla/seeing/.
\(^b\) See http://www.eso.org/gen-fac/pubs/astclim/paranal/seeing/adaptive-optics/statfwhm.html.
\(^c\) See http://www.eso.org/gen-fac/pubs/astclim/paranal/seeing/singstory.html.
\(^d\) See https://mthamilton.ucolick.org/techdocs/MH_weather/obstats/seeing.html.
by adopting the classical linear relation between the three parameters

$$\text{mag} = ZP - \kappa \chi - 2.5 \log_{10}(F),$$

where mag is the derived magnitude, $ZP$ is the zero-point, $\kappa$ is the extinction in the considered band, $\chi$ is the airmass, and $F$ is the measured flux in the instrument. Therefore, to obtain an accuracy of $\sim 0.01$–0.02 mag in the derived magnitude, it is required that the accuracy of both $ZP$ and $\kappa$ are better than this value (assuming that both $\chi$ and $F$ are perfectly known). Since $ZP$ is of the same order of magnitude than mag, this parameter should be estimated with a similar accuracy, i.e., $1$–$2\%$. This parameter presents a stronger dependency on the instrumental configuration than on the weather conditions, for clear nights, and therefore it is not a good parameter to characterize photometric conditions. On the other hand, the typical values for the extinction $\kappa$ are around $0.15$–$0.18$ mag, on clear nights and for the optical range. That is, they are at least an order of magnitude lower than the derived magnitude, for most of the astronomical objects. Therefore, to achieve the considered photometric quality it is required that this parameter is determined with an accuracy of a $5$–$15\%$. This parameter depends much stronger with the weather conditions, and therefore it is a preferable indicator for characterizing the photometric conditions.

In previous articles (e.g., Sánchez et al. 2007), we defined a photometric night as a night during which the extinction in the $V$ band does not change more than $20\%$, in the entire course of the night. This basically means that from a single calibration obtained at any given moment of such a night, it will be possible to obtain a photometric accuracy of $\sim 4\%$, i.e., $\sim 0.05$ mag. This definition is very restrictive, since it implies not only that there are photometric conditions at any moment during the night, but also that these conditions are stable within a few percent.

To date, we do not had enough time coverage of the values of the extinction in the proposed location for the Javalambre Observatory to estimate the fraction of photometric nights. However, it is clear that the night of 2008 October 5, mentioned in § 3.2, fulfills the requirement of a photometric night, since the extinction changes just $18\%$ during the entire course of the night.

4. CONCLUSIONS

We have characterized the main properties of the night sky at the Pico del Buitre, Sierra de Javalambre (Teruel, Spain), the site proposed for the Javalambre Astrophysical Observatory. Data taken with seeing, extinction, and night-sky brightness in situ monitors over a period of 1.5 yr, together with satellite high-spatial resolution meteorological data for the years 2005 and 2006, have been used to determine the relevant parameters for optical observations. The main conclusions that have been reached are:

1. A night-sky spectrum, covering the wavelength range form 3950 Å to 8150 Å, for the moonless dark time at the observatory has been presented for the first time. Airglow and light-pollution emission lines are detected in this spectrum. The strength of the light-pollution lines has been measured and their contribution to the emission in different bands has been estimated. The light pollution is weak or absent (e.g., for the Hg lines). The Pico del Buitre fulfills the IAU recommendations for a dark astronomical site (Smith 1979).
2. The moonless night-sky brightness at the zenith has been measured in the $B$ and $R$ bands, and deduced for the $V$ and $I$ bands. It is found that the site is particularly dark, with marginal contribution at most by artificial pollution.

3. The extinction, estimated for the summer season, shows a typical value of $k_V = 0.22$ mag, similar to that of other observatories for the same season. The extinction found for a photometric night was $k_V \sim 0.17$ mag, consistent with the expected value for a night without aerosols.

4. The median seeing during the 1.5 yr observation period was $0.71''$, with 68% of nights with $<0.8''$ median value. The seeing showed a seasonal dependence, being better in the summer period. These values put the Pico del Buitre among the first rank among known observatories.

The seeing shows a clear dependency with the wind direction. For N and NE directions, the seeing increased to near 1''. For all other wind directions, the typical value is $\sim 0.60''$. The frequency of N-NE wind directions is less than 10%.

The seeing at the observatory is remarkably stable. Our measurements indicate that in good seeing conditions ($<0.8''$), the seeing can be stable for over 5 hr within 20% of the reference value.

5. The fraction of completely clear (less than 10% cloud coverage) nights amounts to 53%. The fraction of useful nights (minimum 30% of the night is clear) amounts to 74%. So far, the fraction of photometric nights is still not known for the observatory, with the current data.

We conclude that Pico del Buitre, the proposed site for the Javalambre Astrophysical Observatory, is a particularly good astronomical site. The fact that Javalambre does not present special accessing difficulties and its location in continental Europe represent added advantages from the point of view of building and operation.

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