

1 **Remote sensing of lunar aureole with a sky camera: Adding**
2 **information in the nocturnal retrieval of aerosol properties**
3 **with GRASP code**

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30 **Abstract**

31 The use of sky cameras for nocturnal aerosol characterization is discussed in this study.
32 Two sky cameras are configured to take High Dynamic Range (HDR) images at
33 Granada and Valladolid (Spain). Some properties of the cameras, like effective
34 wavelengths, sky coordinates of each pixel and pixel sensitivity, are characterized. After
35 that, normalized camera radiances at lunar almucantar points (up to 20° in azimuth from
36 the Moon) are obtained at three effective wavelengths from the HDR images. These
37 normalized radiances are compared in different case studies to simulations fed with
38 AERONET aerosol information, giving satisfactory results. The obtained uncertainty of
39 normalized camera radiances is around 10% at 533 nm and 608 nm and 14% for 469
40 nm. Normalized camera radiances and six spectral aerosol optical depth values
41 (obtained from lunar photometry) are used as input in GRASP code (Generalized
42 Retrieval of Aerosol and Surface Properties) to retrieve aerosol properties for a dust
43 episode over Valladolid. The retrieved aerosol properties (refractive indices, fraction of
44 spherical particles and size distribution parameters) are in agreement with the nearest
45 diurnal AERONET products. The calculated GRASP retrieval at night time shows an
46 increase in coarse mode concentration along the night, while fine mode properties
47 remained constant.

48

49 **Keywords**

50 Sky camera, Moon, GRASP, Aerosol, High Dynamic Range.

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53

54 **1.-Introduction**

55 Aerosols have an important impact on the weather and climatic system and their
56 contribution to the total radiative forcing estimation remains as the most uncertain
57 [IPCC, 2014]. Depending on their properties, aerosols can increase the cooling or
58 warming of the Earth surface by two mechanisms [Haywood and Boucher, 2000;
59 Lohmann and Feichter, 2005]: the direct extinction (scattering and absorption) of solar
60 and thermal radiation (direct effect), and acting as cloud droplet nuclei that leads to
61 changes in the cloud properties and lifetime (indirect effect).

62 At night there is no solar radiation, but aerosol radiative forcing in the longwave
63 range can be significant for large particles like desert dust and sea salt [Stier et al., 2007;
64 Sicard et al., 2014]. In addition, at night the aerosol indirect effect still works and could
65 provide changes on nocturnal cloud properties [Ramanathan et al., 2001; Kaufman et al.
66 2005; Rosenfeld et al. 2006]. These changes could contribute to global warming since
67 clouds at night absorb part of the longwave radiation emitted by Earth, and then, they
68 re-emit radiation back to the Earth surface [Ramanathan et al., 1989; NASA Facts,
69 1999; Wild, 2012]. Moreover, the knowledge of aerosol properties at night is important
70 for the aerosol characterization in polar areas and in winter seasons, which present low
71 sunshine duration values [Stone et al., 2010; Tomasi et al., 2015].

72 Some instruments and techniques are used for the characterization of aerosol
73 properties at night: lidar systems provide backscatter and extinction profiles using Klett-
74 Fernald-Sasano retrievals [Klett, 1981, 1985; Fernald, 1984; Sasano, 1984] and Raman
75 measurements [Ansmann et al., 1990]; in-situ equipment can provide an accurate
76 aerosol characterization but only for the local point where it is installed and not for the
77 whole atmospheric column [McMurry et al., 2000; Rodríguez et al., 2012]; star and

78 lunar photometry provides aerosol optical depth (AOD) at different wavelengths
79 [Ansmann et al., 2001; Pérez-Ramírez et al., 2008, 2011; Berkoff et al., 2011; Barreto et
80 al., 2013, 2016, 2017]. The AOD measurements at night provide information to
81 discriminate between the extinction of fine and coarse mode [O'Neill et al., 2003]. They
82 are also useful for obtaining a reliable characterization of the fine mode properties,
83 though the characterization of the coarse mode is less accurate [Torres et al., 2016].

84 Spectral AOD together with sky radiance provides adequate information to
85 retrieve aerosol microphysical/optical properties (absorption and scattering) during
86 daytime [Dubovik and King, 2000]. That is the case of the AERONET network
87 (AErosol RObotic NETwork; <http://aeronet.gsfc.nasa.gov>), which provides these
88 diurnal properties from sun/sky photometers distributed around the world [Holben et al.,
89 1998]. At night, the sky radiances near the Moon (lunar aureole) could be used as a
90 source of aerosol scattering information, at least between quarters when the Moon is
91 brighter. This information could be combined with the spectral AOD, also obtained
92 from the Moon (lunar photometry) to retrieve aerosol characteristics.

93 A sky camera can be used to obtain relative sky radiance near the Moon since it
94 records the full hemispherical sky radiance measuring different wavelength intervals
95 and it can operate at night with an appropriate exposure time (ET). It should be noted
96 also that sky cameras usually present a low signal to noise ratio. Cloud detection is the
97 most spread use of sky cameras [Long et al., 2006; Calbó and Sabburg, 2008; Cazorla et
98 al., 2008a; Ghonima et al., 2012; Kazantzidis et al., 2012; Mandat et al., 2014, Alonso
99 et al., 2014] though they have been used with other purposes [Horváth et al., 2002;
100 Cazorla et al., 2008b; Kreuter et al., 2009; Sigernes et al., 2014], including the
101 retrieval of sky radiances in daytime [Voss and Zibordi, 1989; López-Alvarez et al.,
102 2008; Román et al., 2012; Toshing et al., 2013; Chauvin et al., 2015].

103 The main goal of this work is to propose and validate the use of sky cameras to
104 obtain normalized radiances in the lunar aureole region. The secondary goal consists of
105 using those normalized radiances as inputs in an inversion algorithm together with
106 spectral AOD measurements (gained by lunar photometry) to retrieve aerosol properties
107 during night time.

108 This paper is structured as follows: Section 2 presents the sites and
109 instrumentation used in this work. The characterization of the sky camera and the
110 methodology used to obtain normalized radiances are explained in Section 3. Section 4
111 introduces the GRASP code. A thorough comparison between normalized camera
112 radiances and simulations is developed in Section 5. The GRASP inversion of camera
113 radiances and AOD for a particular case is also shown in Section 5. Finally, Section 6
114 summarizes the main conclusions.

115

116 **2 -Location and ancillary instrumentation**

117 The present work utilizes data from Granada and Valladolid (both located in
118 Spain). Valladolid is an urban area, surrounded by rural areas, sited in North-Central
119 Iberian Peninsula (150 km North from Madrid) with a population of ~300.000
120 inhabitants. Román et al. [2014b] characterized the predominant aerosol at Valladolid as
121 “continental clean” obtaining monthly mean values of the AOD at 443 nm ranging from
122 0.10 to 0.24, and Angström Exponent (AE) from 0.9 to 1.5, showing higher/lower
123 AOD/AE values in summer due to episodic Saharan dust events [Cachorro et al., 2016].
124 Granada, located in the South-East of the Iberian Peninsula, is a medium-sized and non-
125 industrialized city situated in a natural basin surrounded by mountains and with a
126 population similar to Valladolid; the local aerosol sources are mainly the heavy traffic

127 (particularly diesel vehicles) together with the re-suspension of material available on the
128 ground, especially during the warm season. In winter, domestic heating (based on fuel
129 oil combustion) also represents an important anthropogenic aerosol source [Lyamani et
130 al., 2010; 2011; Titos et al., 2012; 2014]. AERONET provides a climatology table
131 (Level 2.0) for Granada with monthly mean values of the AOD at 500 nm between 0.10
132 and 0.20 and AE values between 0.8 to 1.4, being AOD/AE values higher/lower in
133 summer, also because of frequent Saharan dust outbreaks.

134 Both places are equipped with a “CHM-15k Nimbus” ceilometer (*Lufft*
135 manufacturer), a “CE318-T” photometer (*Cimel Electronique*) and a “SONA” sky
136 camera (*Sieltec Canarias S.L.*). One “CE318-N” photometer (*Cimel Electronique*) is
137 also installed at Valladolid. These instruments are on the rooftop of the Science faculty
138 of the University of Valladolid (41.66°N; -4.71°W; 705 m a.s.l.) and on the rooftop of
139 the Andalusian Institute for Earth System Research (IISTA-CEAMA; 37.16°N; -
140 3.61°W; 680 m a.s.l.). The mentioned ceilometers belong to the Iberian Ceilometer
141 Network, ICENET, which processes raw data and provides information about the
142 vertical attenuated backscatter at 1064 nm [Cazorla et al., 2017]. This information helps
143 to detect possible changes in the aerosol properties at night.

144 The CE318-N photometer takes measurements of Sun irradiance and sky
145 radiance, and CE318-T photometer also measures lunar direct irradiance, performing
146 daytime and night time photometric measurements [Barreto et al., 2016]. The
147 photometer #914 (CE318-T) was available for a short campaign at Valladolid and used
148 in this work. For the rest of the period, the photometer #788 or the photometer #383
149 (both CE318-N), located at the same station, were used. Both photometers belong to the
150 RIMA network (Iberian network for aerosol measurements), which is federated to
151 AERONET. The #918 (CE318-T), used for this work at Granada, belongs to I-AMICA

152 (Infrastruttura di Alta Tecnologia per il Monitoraggio Integrato Climatico-Ambientale
153 of Italy) and operates within AERONET. These instruments are periodically calibrated,
154 following the AERONET protocol, ensuring high quality data. In addition, AERONET
155 processes the photometer data providing a wide set of products such as daytime AOD at
156 8 wavelengths, aerosol size distribution, fraction of spherical particles (sphere fraction)
157 and refractive indices [Holben et al., 1998; Dubovik et al., 2000, 2006]. Regarding night
158 time measurements, AOD is obtained at 6 wavelengths (440, 500, 675, 870, 1020 and
159 1640 nm) following the method described in Barreto et al. [2016] which uses the ROLO
160 (RObotic Lunar Observatory) model [Kieffer and Stone, 2005] for the lunar
161 extraterrestrial irradiance calculation. ROLO is an empirically-based model that
162 provides, for a given place and time, the spectral extraterrestrial lunar irradiance using
163 the following geometrical variables: lunar phase angle; selenographic latitude and
164 longitude of the observer; and selenographic longitude of the Sun. The calibration of the
165 instrument for lunar measurements was done by the “Lunar Langley Method” explained
166 by Barreto et al. [2013].

167

168 **3- Sky camera**

169 SONA (“Sistema de Observación de Nubosidad Automático”: Automatic Cloud
170 Observation System) sky camera is a device which provides full sky images at day and
171 night. The system was mainly designed for cloud cover detection, but it can be used
172 with other purposes. It is composed of a surveillance CCD camera with a fisheye lens
173 inside a waterproof case and a dome with a shadow band blocking the Sun [González et
174 al., 2012]. The CCD sensor provides RGB images with 8 bit-digitalization yielding 256
175 counts per channel [Cazorla et al., 2015]. The CCD resolution is 640x480 pixels, but the

176 system at Granada site was configured to record images of 480x480 pixels. An infrared
177 (IR) cut-off filter is installed between the CCD and the fisheye lens in a mobile platform
178 in order to block or to allow IR light into the sensor. Both cameras used in this paper
179 were configured to take all images with the IR cut-off filter. The temperature (T) of the
180 CCD is also logged with a resolution of 0.5°C.

181 **3.1- Camera characterization**

182 **3.1.1- Effective wavelengths**

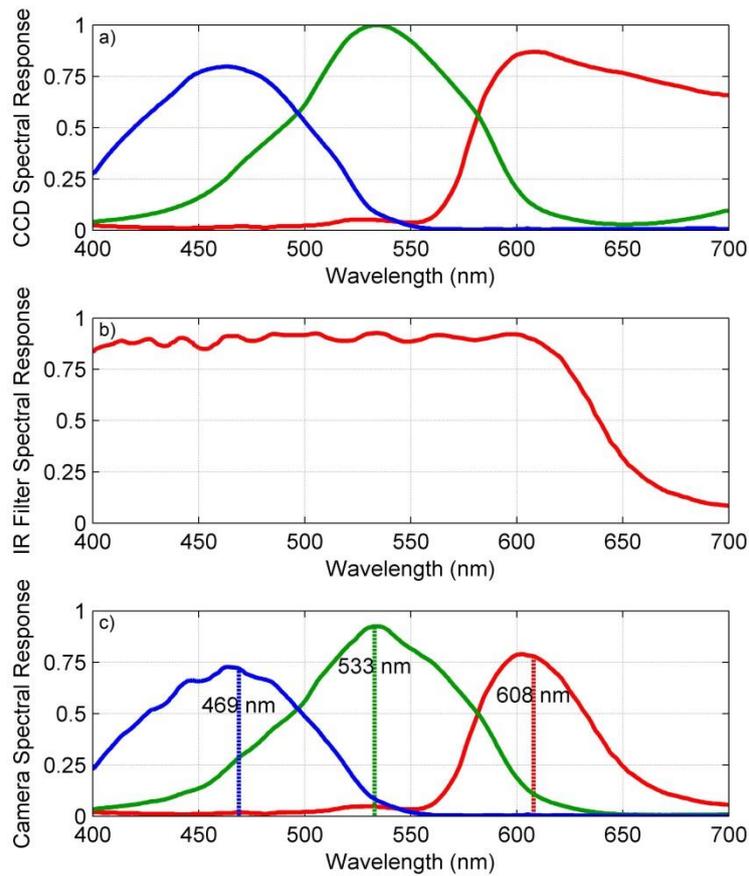
183 The CCD spectral response, given by the manufacturer, is shown in Fig. 1a. This
184 response is only available up to 700 nm, but red channel seems to have certain
185 sensitivity to longer wavelengths. As mentioned above, the camera also contains an IR
186 cut-off filter to block the longest wavelengths. The spectral response of this filter, given
187 by the manufacturer, is also shown in Fig. 1b. The filter transmittance can be considered
188 constant and with a value about 90% from 400 nm up to 600 nm. At longer
189 wavelengths, the transmittance starts to decrease, being ~50% at 640 nm and below
190 10% at 700 nm. The total spectral response of the sky camera is the CCD response
191 weighted by the IR cut-off filter transmittance, shown at Fig. 1c. This total spectral
192 response shows that the camera is not sensitive to infrared light above 700 nm, due to
193 the effect of the IR cut-off filter, and presents its highest response in the green channel.

194 Sky radiance is measured in three broadband channels (Fig. 1c) but, as a first
195 approximation, the radiance at these broadband channels can be considered proportional
196 to the radiance at an effective wavelength. This is due to the following fact: the ratio of
197 two broadband measurements, which are taken under different conditions but with the
198 same instrument (the same spectral response), is equal to the ratio of the same

199 measurements taken with an instrument which is only sensitive at the effective
200 wavelength, λ_e , calculated as [Kholopov, 1975; Román et al., 2012]:

$$201 \quad \lambda_e = \frac{\int_{\lambda} \lambda I(\lambda) S(\lambda) d\lambda}{\int_{\lambda} I(\lambda) S(\lambda) d\lambda} \quad (1)$$

202 where I is the incoming irradiance to the instrument at the wavelength λ , and S the
203 spectral response of the instrument channel. In order to obtain the effective wavelength
204 of the SONA sky camera channels in this work, the effective wavelength of each
205 channel has been calculated for a half Moon cycle at every midnight from first to third
206 lunar quarter with I calculated using the ROLO model. The average (\pm standard
207 deviation) of the calculated effective wavelengths is 468.8 ± 0.3 nm, 533.3 ± 0.3 nm and
208 607.7 ± 0.2 nm for blue, green and red channels, respectively. Finally, these effective
209 wavelengths have been rounded to 469 nm, 533 nm and 608 nm, which approximately
210 is within the standard deviation interval. Román et al. [2012] calculated the effective
211 wavelengths for another sky camera under various aerosol conditions, finding standard
212 deviations around 2 nm, which indicated that effective wavelengths of this kind of sky
213 cameras do not vary largely with the real changes on the incoming radiation.



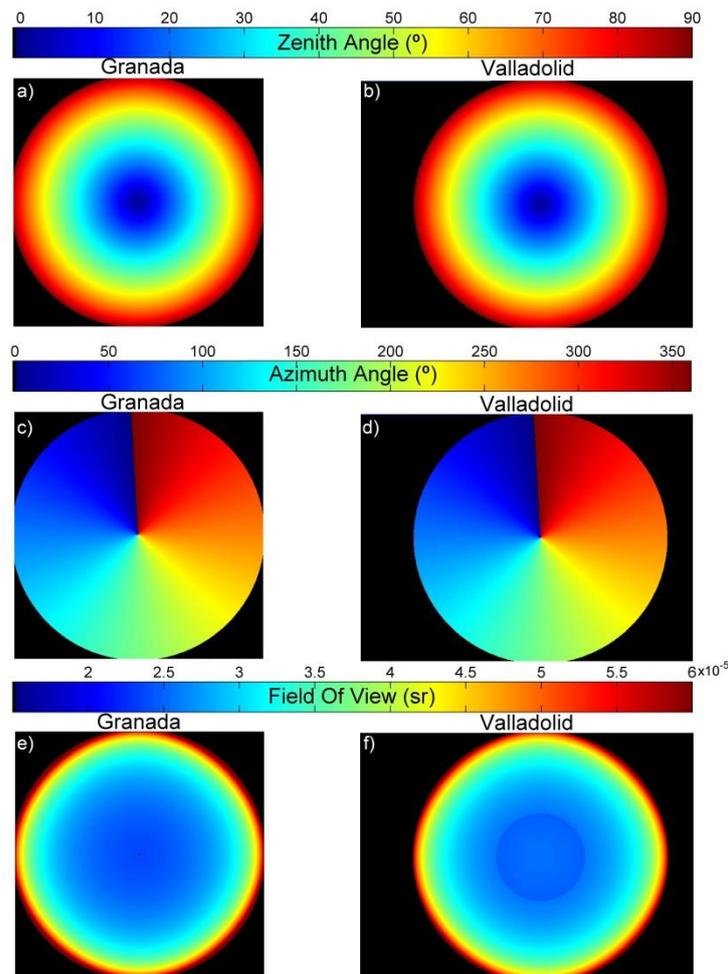
214

215 Figure 1: Spectral responses of the three channels (blue, green and red) of the CCD (panel a), of the
 216 infrared (IR) cut-off filter (panel b), and of the three channels of the camera (CCD plus infrared cut-off
 217 filter; panel c). The effective wavelengths of the camera for lunar applications are marked in panel c.

218 3.1.2- Sky coordinates of each pixel

219 SONA sky camera position is fixed, thus every pixel measures the same region
 220 of the celestial vault. Hence, the zenith and azimuth angles corresponding to all the
 221 pixels can be calculated to locate any celestial body in every image (in this work we
 222 focus on the position of the Moon and its aureole). The zenith and azimuth matrices
 223 have been calculated using a dataset of sky images under cloud-free conditions and
 224 visible stars and planets whose celestial coordinates are well-known in these images.
 225 The stellar bodies used at Granada have been Arcturus, Jupiter and Vega; while for
 226 Valladolid they have been Altair, Arcturus, Jupiter, Saturn, Vega and Venus. The pixel
 227 positions of these stellar bodies have been correlated with their sky coordinates, finding
 228 a relationship between the zenith and azimuth with pixel position. As a result, Fig. 2

229 presents zenith and azimuth calculated for the cameras at Granada (panels a, c and e)
 230 and Valladolid (panels b, d and f). The representation of zenith and azimuth angles is
 231 similar for both cameras. In both cases, a slight shift in the azimuth can be observed in
 232 the north direction. Moreover, the field of view (FOV) of each pixel has been calculated
 233 as the solid angle obtained from zenith and azimuth. FOV increases with zenith as can
 234 be observed in Fig. 2e and 2f. Figure 2 also shows that Valladolid images have a
 235 resolution of 640x480 pixels whereas resolution is 480x480 pixels for Granada. Zenith
 236 angles above 80° have been masked in this work since city skylines usually occupy that
 237 region.

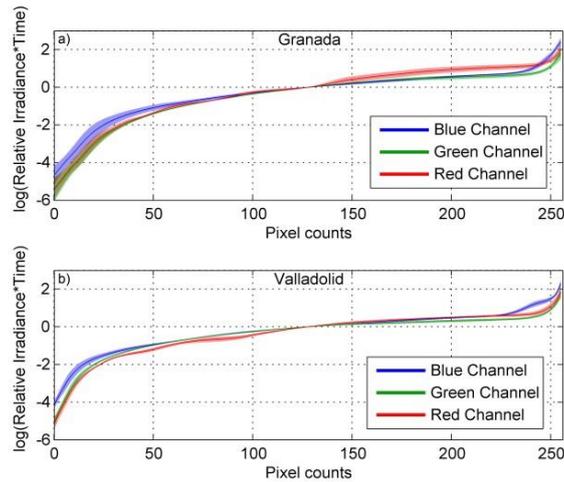


238

239 Figure 2: Zenith (panels a and b), Azimuth (panels c and d) and FOV (panels e and f) viewed by each
 240 camera pixel at Granada (panels a, c and e) and Valladolid (panels b, d and f). Azimuth is defined from 0°
 241 (North) to 360° being East 90° and West 270°.

242 **3.1.3- Pixel sensitivity**

243 Pixel sensitivity is usually not linear with exposure time in commercial cameras.
244 This is the case for the SONA sky camera. In order to obtain the pixel sensitivity of
245 both cameras, consecutive cloud-free images were taken at different exposure times.
246 Looking at some points of the cloud-free sky, and assuming that the irradiation reaching
247 each pixel must be proportional to the exposure time, the pixel sensitivity function can
248 be obtained by the method explained by Debevec and Malik [1997]. This method uses
249 differently exposed images of the same scene to recover the response function of the
250 imaging process, up to factor of scale, using the assumption of reciprocity. Following
251 this method, the pixel sensitivity of each camera has been calculated under daytime and
252 cloudless conditions for 70 cases distributed in 7 days. These sensitivity values have
253 been averaged for each location, and these averages and their standard deviations are
254 shown in Fig. 3 for both sites and for the three broadband channels. The pixel sensitivity
255 is similar but not equal in the two analyzed cameras. The sensitivity function present
256 similar graphs to those obtained by Debevec and Malik [1997] (see Figs. 2, 4 and 7 of
257 the mentioned paper). The blue channel has the highest sensitivity for low pixel counts,
258 and the saturation effect can be seen at higher pixel counts, where the pixel sensitivity
259 strongly increases. Standard deviation is higher for low pixel counts, which could be
260 associated to fluctuations in the very short exposure times used to reach these pixel
261 counts.



262

263 Figure 3: Sensitivity of the camera pixels for each channel as a function of pixel counts for both Granada
 264 (panel a) and Valladolid (panel b) cameras. The shadow band around the lines represents the standard
 265 deviation.

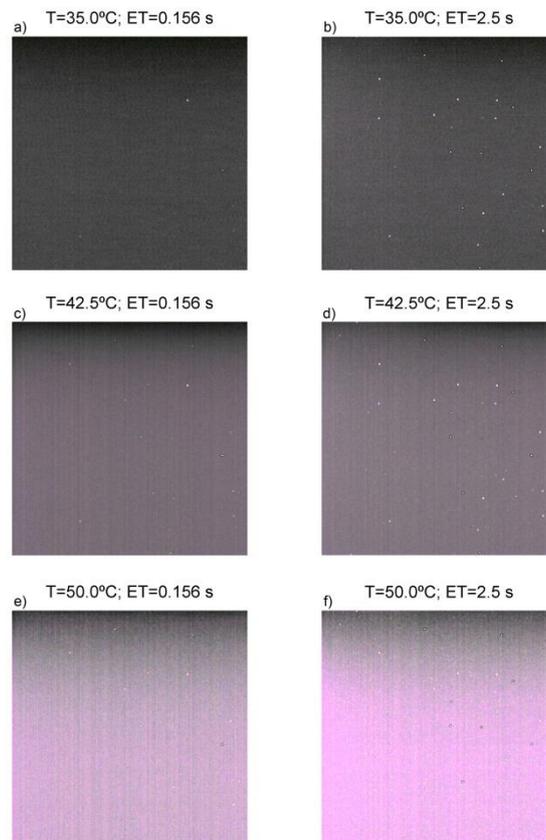
266 3.1.4- Dark signal

267 The signal of CCD is not only produced by incoming radiation (photons), but
 268 also by thermal energy [Mullikin et al., 1994]; it means that an image taken under dark
 269 conditions will show a response different to null, which is called dark image. The
 270 response of a dark image usually increases with temperature and with exposure time
 271 [Pérez-Ramírez et al., 2008]. These dark images, or dark frames, must be subtracted
 272 from an original sky image to remove the thermal noise. Dark signal has been obtained
 273 in a different way for both analyzed cameras as detailed below.

274 The Granada camera was temporally installed in a dark place and covered by an
 275 opaque cloth in order to take images in complete dark conditions. Under these dark
 276 conditions, the camera recorded dark images at different exposure times and
 277 temperature values. The chosen exposure times were the same as the ones that will be
 278 shown in Section 3.2.1. The obtained dark images with the same exposure time and
 279 temperature have been averaged to reduce the random noise present in single
 280 measurements [Urquhart et al., 2015]. These averages have been considered as dark
 281 frames (DF). Figure 4 shows the obtained DF (Granada camera) for two different

282 exposure times and three different temperatures. The signal of the frames is shown
283 upscaled by a factor 4 for better visualization. The dark signal is not equal for all pixels
284 under the same conditions of exposure time and temperature. Temperature has a direct
285 effect on DF with a larger dark signal for higher temperatures. An increase in exposure
286 time also produces higher dark signal values.

287

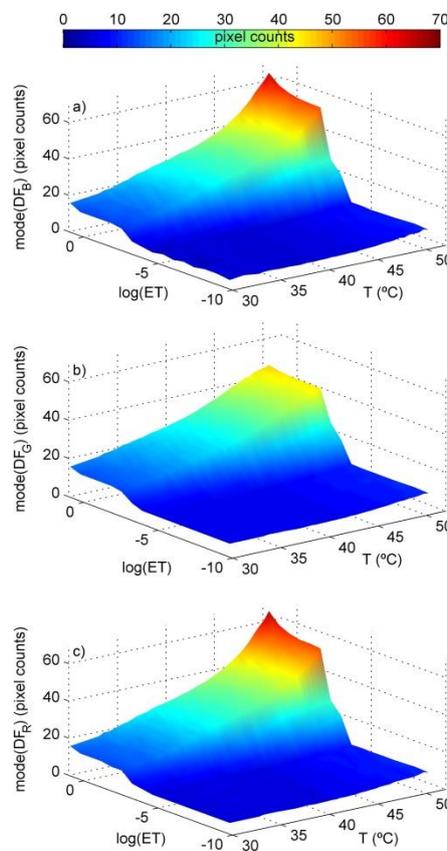


288

289 Figure 4: Dark frames obtained with the Granada camera for different temperatures (T) and exposure
290 times (ET). The signal shown is multiplied by 4 in order to be better appreciated.

291 Figure 5 points out to the same conclusion showing the mode (most frequent
292 value) of all pixels of every dark frame for the channels blue (DF_B), green (DF_G) and
293 red (DF_R) as a function of exposure time and temperature. For low exposure times the
294 dependence of the dark signal on temperature is low but this dark signal presents values
295 higher than zero, indicating the presence of a bias. Dark signal is low while exposure
296 time is below 7 ms, but for higher exposure times it increases especially for high

297 temperatures. For a given exposure time, the dependence of dark signal on temperature
 298 presents an exponential behavior. The logarithm of the dark signal (not shown) presents
 299 a negative linear relationship with the inverse of the temperature following the
 300 Arrhenius law as previously was observed in a different camera by Widenhorn et al.
 301 [2002]. The green channel presents the lower dark signals for high temperatures, while
 302 red and blue channels can reach dark signal above 60 digital counts for temperatures
 303 near 50°C and high exposure times.



304

305 Figure 5: Most frequent value in a dark frame as a function of temperature (T) and logarithm of the
 306 exposure time (ET), for the three Granada camera channels.

307 The dark frame has been corrected for an original sky image and a given
 308 exposure time and temperature subtracting the DF (obtained for the same exposure time
 309 and temperature) from the non-saturated pixels of the original image. This method has
 310 been applied in this work to the Granada camera, but not to the images recorded by the

311 Valladolid camera since obtaining the dark frames in a dark place was not feasible. In
312 order to obtain a dark frame for the Valladolid images, as a first approach, the dark
313 signal of each channel has been considered the same for all pixels and equal to the
314 average of the signal of various pixels located in a non-illuminated zone, as in Román et
315 al. [2012]. For Valladolid camera the non-illuminated zone has been considered the
316 33x24 pixel rectangle (proportional to the image size) located at the down-right corner
317 of each image. For each channel (R, G and B) the average of the pixel signals in this
318 zone provides a dark signal, and the dark frame (DF_R , DF_G and DF_B) is an image in
319 which all pixels have this same dark signal. Then, for each image taken at Valladolid
320 the calculated DF has been subtracted for the non-saturated pixels.

321 **3.1.5- Hot pixels**

322 Pixels with a very high dark signal are referred as dark current spikes or
323 hot pixels [Widenhorn et al. 2002]. They are generally randomly distributed in a CCD
324 and show up as white, but evenly colored, dots in a dark frame. Hot pixels of the
325 Granada camera can be perfectly appreciated in Fig. 4. The hot pixels of each camera
326 have been determined taking a high exposure image under dark conditions (and low
327 temperature) and considering as hot pixels all the pixels with a signal above 30 digital
328 counts for at least one channel. The obtained hot pixels (not shown) fit well with the hot
329 pixels that can be visually detected in all dark images. Once hot pixels have been
330 identified, they and their neighbors have been masked from all the images.

331 **3.2- Retrieval of relative sky radiance**

332 **3.2.1- High Dynamic Range imagery**

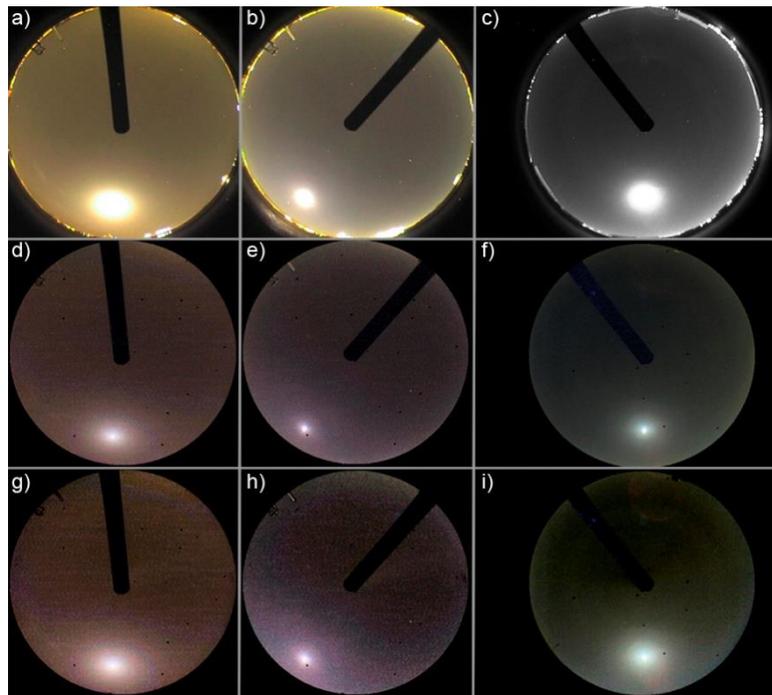
333 The CCD provides 256 digital counts per channel, which presents two main
334 problems: some pixels are saturated (in the lunar region in this work), and some pixels

335 are fully dark; pixels in both situations do not provide useful information about the real
336 radiance. The multi-exposure technique has been used to solve both issues [Debevec
337 and Malik, 1997]. It consists of recording the same image at different exposure times, in
338 order to increase the dynamic range, having images where the brightest parts are not
339 saturated (for the lowest exposure times) and images where the darkest parts are bright
340 enough. Once the images at different exposure times are recorded, a linear High
341 Dynamic Range (HDR) image can be obtained using the pixel sensitivity of the camera
342 (to linearize the output) and applying the method of Debevec and Malik [1997]. As a
343 result, a linear HDR image gives, for each channel and pixel, a signal proportional to the
344 incoming irradiance to the CCD [Stumpf et al., 2014].

345 In this work, the sky cameras have been configured to record 16 consecutive sky
346 images with exposure times following a doubling sequence. The first image (im_1) is
347 taken with an exposure time, $ET(im_1)$, then the second image (im_2) is taken with an
348 exposure time, $ET(im_2)$, equal to $2 * ET(im_1)$, then the third (im_3) with an exposure time
349 equal to $2 * ET(im_2) = 2^2 * ET(im_1) \dots$, and finally the last image (im_{16}) is taken with a
350 exposure time, $ET(im_{16}) = 2^{15} * ET(im_1)$, around 2.5 seconds. The elapsed time obtaining
351 the 16-image dataset is about 30 seconds. The gain (ISO) used for these images has
352 been set to constant at night time, and equal to the one used for obtaining the dark
353 frames (Section 3.1.4). These sequences of 16 images have been taken every five
354 minutes at Granada and Valladolid. As a result, every 5 minutes a linear HDR image
355 has been composed from these 16 images (dark frame corrected) combined with the
356 pixel sensitivity of Fig. 3.

357 For visualization purposes, a linear tone mapped HDR image would show little
358 detail. To improve visualization, the linear HDR images have been tone mapped
359 following the method described by Reinhard et al. [2002]. This method computes the

360 key of the HDR image, a measure of the average logarithmic luminance, and then the
 361 image is scaled to the desired brightness level. Figure 6 shows three non-HDR images
 362 (panels a, b and c) and the corresponding tone mapped images (panels d, e and f). In the
 363 non-HDR images the pixels around the Moon are saturated, especially at Granada, while
 364 the signal around the Moon can be discerned in the tone mapped images. Also, the
 365 masks covering hot pixels can be appreciated in the HDR images.



366

367 Figure 6: Non-HDR (upper; panels a, b and c) tone mapped sky images before removing background
 368 signal (middle; panels d, e and f) and tone mapped sky images with background corrected (bottom; panels
 369 g, h and i). Images corresponds to Granada 21st July 2016, 00:40UTC (left; panels a, d and g); Granada
 370 20th May 2015, 21:25UTC (middle; panels b, e and h); Valladolid 3rd August 2015, 02:40UTC (right;
 371 panels c, f and i). The non-HDR image at Valladolid was taken under colorless conditions. Pixels with
 372 zenith angle above 80° are masked except for non-HDR images.

373 3.2.2- Point spread function

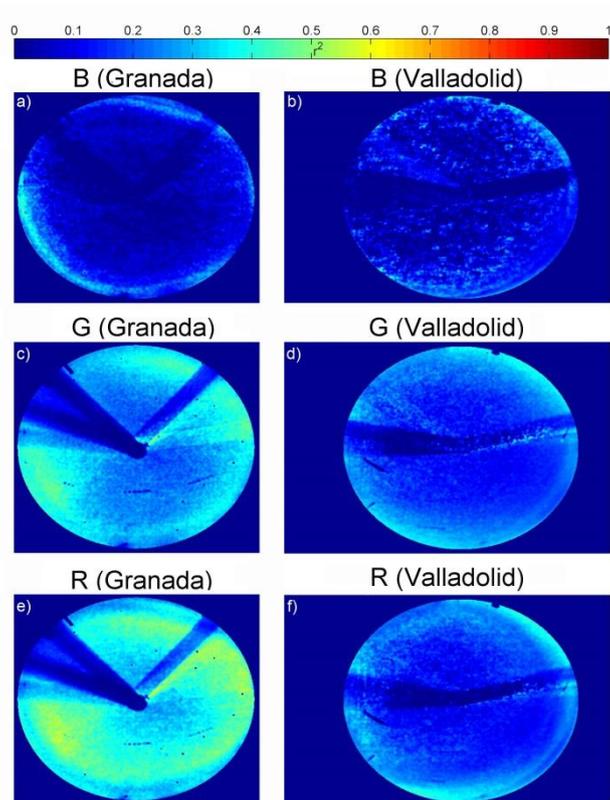
374 The point spread function (PSF) is the bidimensional signal viewed by a pixel
 375 and its neighbors when this pixel is illuminated by a point source. PSF could cause
 376 changes on the variation of the signal between pixels near to an illuminated point source
 377 (like the Moon). In this work, PSF has been calculated for both cameras using the
 378 method explained by Pinilla et al. (1999) which is based on McGillen et al. (1983) and

379 on Forster and Best (1994). This method basically consists of studying the changes in
380 pixel signal with respect to pixel distance from dark to bright pixels. The first derivative
381 (slope) of the curve of the transition from dark pixels to bright pixels is assumed
382 proportional to the PSF in the selected direction. To this end, diurnal HDR images have
383 been used considering as dark region the pixels containing the camera shadow band, and
384 the bright pixels those containing the blue sky near to the shadow band. For each
385 camera, PSF has been obtained for 6 different images and then averaged. This PSF has
386 been used to correct the HDR images by a deconvolution of PSF on the image using
387 Lucy-Richardson algorithm (Richardson, 1972; Lucy 1974). This correction helps
388 deblurring some parts of the HDR image. However, the night time images show a larger
389 noise, especially near the Moon, which could be associated to a non-perfect PSF
390 characterization. These results suggest that PSF correction could add noise to the HDR
391 images and, therefore, PSF has not been corrected in this work.

392 **3.2.3- Background correction**

393 The nocturnal sky images also recorded part of the city background light (city
394 lamps, buildings and others). As a consequence, the sky is not fully dark even without
395 Moon. The lunar aureole viewed by the camera can be contaminated by these lights,
396 hence, in order to detect the Moon aureole, the city lights need to be characterized and
397 removed for the original HDR image. With this aim, a data base of background images
398 (BG) has been constructed from images taken under cloud-free conditions and with both
399 Moon Zenith Angle (MZA) and Solar Zenith Angle (SZA) above 100°. In these
400 conditions, we guarantee that the images are not contaminated by the Moon nor the Sun
401 light and neither the clouds. Note that these BG images have been taken at low
402 illumination and they usually are quite noisy. To partially correct for this effect, all the
403 BG images have been smoothed by an averaging filter of 5x5 pixels.

404 As a first guess, we could assume that the signal of background images depends
405 on the aerosol load, since aerosols can scatter part of the city lights back to the camera.
406 The data base of BG images has been analyzed and correlated to the closest AOD value
407 measurement (note that there are no simultaneous measurements of AOD since BG
408 images are taken under skies without the Sun and Moon). The maximum gap allowed
409 between BG images and AOD measurements has been 3 hours for Granada and 4 hours
410 for Valladolid due to the lower number of images available in the latter. AODs at 440,
411 500 and 675 nm have been assigned to the blue, green and red channels of the camera,
412 respectively. The determination coefficient (r^2) between the pixel signal of each channel
413 and its AOD value has been calculated using the chosen BG images for both cameras
414 (151 images for Granada and 61 for Valladolid). Figure 7 shows the obtained
415 determination coefficient for every pixel, channel and camera, pointing out that red
416 channel presents the best correlation between the background signal and the AOD.
417 However, the correlation is not high, since the r^2 values at Granada are usually below
418 than 0.5, 0.4 and 0.2 for the red, green and blue channels, respectively. The correlation
419 at Valladolid is lower, being r^2 below 0.4 in most of pixels for all channels, but this
420 behavior could be explained by the short AOD range used for the calculation of r^2 :
421 AOD at 440 nm ranges from 0.03 to 0.13 and AOD at 675 nm from 0.01 to 0.06.
422 However, for Granada camera the AOD intervals have been larger, ranging from 0.03 to
423 0.35 (AOD at 440 nm) and from 0.01 to 0.33 (AOD at 675 nm). These results indicate
424 that background light does not present a clear dependence on AOD and, therefore, BG
425 images have been considered as independent on aerosol load.



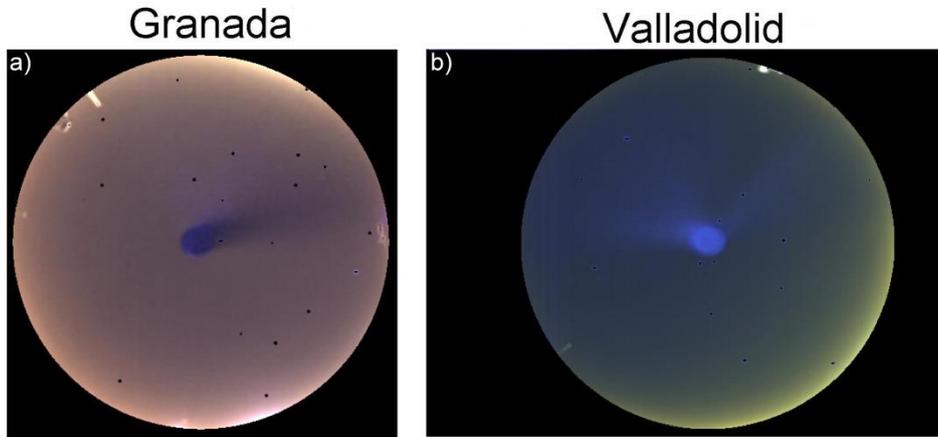
426

427 Figure 7: Determination coefficient (r^2) between the background pixel signal and the AOD assumed at
 428 each channel. These values are shown for each channel at Granada (left; a-c-e) and Valladolid (right; b-d-
 429 f). Pixels with zenith angle above 80° are masked.

430

431 Assuming that the background light from the city is constant, an averaged BG
 432 image (ABG) has been calculated for each location in order to remove the noise and
 433 fluctuations of single BG images. To this end, a set of BG images under clean (low
 434 aerosol load) conditions have been chosen, trying to obtain similar conditions for all
 435 images despite of the observed low correlation between BG and AOD. The selected
 436 night BG images also satisfy that previous and next diurnal AOD at 440 nm
 437 measurements were below 0.1. A total of 182 and 156 BG images for Granada and
 438 Valladolid, respectively, have been chosen by these criteria, and then they have been
 439 averaged. As a result, the ABG has been obtained and is shown in Fig. 8 for Granada
 440 and Valladolid, being representative of the background light of each location. ABG
 441 images of Fig. 8 include a spot in the sky zenith which is not representative of the

442 background light but it is caused by the shadow band, which always block this position.
443 This artefact does not affect results in this work since the Moon never reaches that
444 position.



445
446 Figure 8: Averaged background HDR images obtained at Granada (panel a) and Valladolid (panel b).
447 Images are not tone mapped and pixels with zenith angle above 80° are masked.

448 Finally, all obtained HDR images have been corrected subtracting the
449 corresponding ABG of Fig. 8. Figures 6g, 6h and 6i present the tone maps of three HDR
450 images after the background correction, showing significant differences against the non-
451 corrected images.

452 **3.2.4- Normalized Lunar Almucantar extraction**

453 Once the background light is removed from the HDR image, the relative
454 radiance at the lunar aureole can be obtained. First, every pixel signal has been divided
455 by its FOV, in order to transform the recorded relative irradiance in the CCD to relative
456 sky radiance (RSR). Several points of the lunar almucantar (points with same zenith
457 angle of the Moon but different azimuths) have been selected and located in the image,
458 and the signal in the pixels within $\pm 0.5^\circ$ azimuth and $\pm 0.5^\circ$ zenith have been averaged
459 for each channel. The points selected range from azimuth 3° to 20° azimuth (1° steps)
460 away from the Moon. The first azimuth angle has been chosen at 3° in agreement with

461 the first angle of the almucantar measurements sequence used in the AERONET
 462 photometers [Holben et al., 2006]; the last azimuth of 20° has been manually selected
 463 since it was observed that beyond 20° the camera signal does not significantly change.
 464 In addition, pixel signals which are below the double of the corresponding ABG signal
 465 have been discarded even if the azimuth is below 20°. This criterion has excluded
 466 several RSR values for very low AOD or low Moon irradiance (at least between the
 467 third and first Moon quarters); in both cases the scattered light in the lunar aureole
 468 region is low.

469 Once the points of almucantar are selected (3° to 20° and -3° to -20° with at least
 470 the double of background signal), both branches of the almucantar have been averaged
 471 assuming the sky radiance is symmetric. The number of averaged pixels for each
 472 almucantar point (considering its azimuth and its symmetric azimuth) depends on zenith
 473 angle because of the lens distortion (see Fig. 2); this number is around 8 pixels for
 474 zenith equal to 20°, increasing up to 16 pixels for zenith values of 60° and going down
 475 to about 12 pixels for zenith equal to 80°. Finally, for each channel, the obtained signals
 476 have been normalized by the sum of all of them, giving as result the normalized camera
 477 radiance (NCR); the sum of the normalized camera radiances must be 1 for each
 478 channel. Then, the normalized camera radiance at a given λ -wavelength and a φ_i -angle
 479 has been calculated as:

$$480 \quad NCR_{\lambda, \varphi_i} = \frac{RSR_{\lambda, \varphi_i}}{\sum_{j=1}^N RSR_{\lambda, \varphi_j}} \quad (2)$$

481 where N is the number of points used to extract the almucantar.

482 Figure 9a shows the normalized lunar almucantar radiance obtained using this
483 method for the HDR image on Fig. 6g; the straight lines are the averaged values from
484 both branches, and the azimuth value of the Moon is considered to be 180°.

485

486 **4- GRASP code**

487 GRASP (Generalized Retrieval of Aerosol and Surface Properties) is a highly
488 accurate algorithm for the retrieval of optical and microphysical aerosol properties and
489 optical surface properties [Dubovik et al., 2014]. GRASP stands out by its versatility (it
490 can be run with a large variety of input variables) and its flexibility (it has the capacity
491 to incorporate and exchange different methods, modules and libraries). This code has
492 been used by other authors with lidar systems, photometers and satellites [Lopatin et al.,
493 2013; Kokhanovsky et al., 2015; Bovchaliuk et al., 2016; Fedarenka et al., 2016;
494 Benavent-Oltra et al., 2017], but not with sky cameras until now. Another important
495 advantage of GRASP is that it is open-source and free (available at [www.grasp-](http://www.grasp-open.com)
496 [open.com](http://www.grasp-open.com)).

497 **4.1- Forward model**

498 GRASP has two main independent modules. One of them is the forward model,
499 which allows the simulation of various atmospheric observations [Dubovik et al., 2014].
500 In this work, this module has been used to simulate the lunar normalized radiance at the
501 same points that were obtained with the camera. Aerosol properties obtained from
502 AERONET have been used as inputs to make these simulations of normalized radiance
503 on the lunar almucantar for the three camera effective wavelengths. For a given night,
504 the nearest AERONET aerosol inversion of the previous afternoon or the next morning

505 has been chosen. The AERONET aerosol properties used from this inversion have been:
506 22-bin volume size distribution (logarithmically spaced), real and imaginary refractive
507 indices at four wavelengths, and sphere fraction. In order to obtain the radiance at the
508 camera wavelengths the refractive indices at these wavelengths is needed; therefore the
509 refractive indices at 469, 533 and 608 nm have been calculated using a linear
510 interpolation of the AERONET available values. All these aerosol properties and, in
511 addition, the MZA have been introduced into GRASP forward model. The output of the
512 model has given the normalized radiance in the lunar almucantar at 469 nm, 533 nm and
513 608 nm.

514 **4.2- Aerosol retrieval**

515 The main module of GRASP is the numerical inversion, which includes general
516 mathematical operations not related to the particular physical nature of the inverted data
517 [Dubovik et al., 2014]. This module, in combination with the forward module, can
518 retrieve aerosol properties from a data set of atmospheric measurements. GRASP is
519 configured to process absolute radiances but also normalized radiances. The inverted
520 data set in this work, used as input in GRASP, have been six values of AOD (440, 500,
521 675, 870, 1020, and 1640 nm) from CE318-T photometer and the normalized radiance
522 from the camera at 469 nm, 533 nm and 608 nm at 36 points per wavelength (lunar
523 almucantar points from 183° to 200° every 1°). A bilognormal size distribution has been
524 selected in order to represent the retrieved size distribution (instead of the 22-bin
525 representation used in AERONET), and different smoothness and “a priori” constraints
526 on the aerosol size distribution have been applied [Dubovik et al., 2014]. Aerosol
527 refractive indices, both real (RRI) and imaginary (IRI), have been assumed as constant
528 (non spectral variation); this assumption has been done due to the lack of information

529 regarding the diurnal retrievals which consider that refractive indices can vary with
530 wavelength.

531 As a result, for each HDR image and 6-AOD dataset, the following parameters have
532 been obtained: bilognormal size distribution, real and imaginary refractive indices,
533 single scattering albedo (SSA) at the same wavelengths than input values, and sphere
534 fraction. The retrieved bilognormal size distribution is described by six independent
535 parameters [Torres et al., 2016]: volume concentration of the fine (C_f) and coarse mode
536 (C_c); volume median radius of the fine (r_f) and coarse mode (r_c), and geometric standard
537 deviation for both modes: σ_f (fine) and σ_c (coarse). This geometric standard deviation is
538 related to the width of the size distribution centered in the median radius.

539

540 **5- Results**

541 **5.1- Camera radiances versus simulations**

542 As described in the introduction, the first step will be the validation of the
543 normalized radiances obtained with the sky camera. For this purpose, the lunar
544 almucentars obtained from the camera and their equivalent simulated with the GRASP
545 forward model have been compared on different nights.

546 **5.1.1- Individual case**

547 A desert dust plume was detected at Granada during the evening of 20th July
548 2016. The ceilometer signal (not shown) indicated that it arrived in Granada at around
549 15:00 UTC. The AERONET values of Table 1 point out the presence of desert dust
550 after 15:00 UTC: Angström Exponent at 17:55 UTC was 0.2, indicating coarse particle
551 predominance with a strong AOD at 440 nm of 0.98. The AOD along the night (not

552 shown) did not present significant changes and the AERONET retrieval at the next
553 morning (not shown) is similar to the one shown in Table 1. Therefore, the aerosol
554 characteristics did not present relevant variations along the night from 20th to 21st July
555 2016. That night the Moon Phase Angle (MPA) was 13° at midnight (one day after full
556 Moon), therefore with a large Moon irradiance associated. The normalized radiance at
557 lunar almucantar geometry has been obtained from the sky camera at various night
558 times. The radiance has also been simulated at the same times using as input the
559 AERONET aerosol optical properties obtained the afternoon of 20th July at 17:55 UTC
560 (Table 1) and the size distribution (not shown in Table 1).

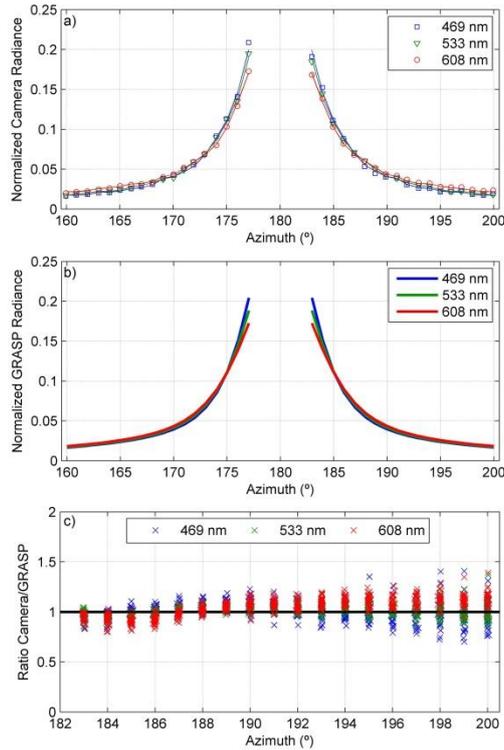
561 Table 1: Retrieved aerosol optical properties from AERONET sunphotometer (level 1.5) near to the
562 previous sunset or the following sunrise for eight nights.

Properties	Wavelength (nm)	29 May 2015 07:45 UTC	3 Aug 2015 06:43 UTC	21 Feb 2016 15:35 UTC	19 May 2016 06:27 UTC	20 May 2016 18:03 UTC	24 May 2016 09:24 UTC	20 July 2016 17:55 UTC	24 July 2016 06:37 UTC
Place	-	Valladolid	Valladolid	Valladolid	Granada	Granada	Granada	Granada	Granada
Photometer ID		#788	#788	#383	#918	#918	#918	#918	#918
Real RI	440	1.39	1.44	1.50	1.35	1.45	1.45	1.42	1.33
	675	1.41	1.44	1.48	1.36	1.44	1.45	1.44	1.34
	870	1.42	1.44	1.47	1.37	1.45	1.45	1.44	1.37
	1020	1.42	1.43	1.46	1.38	1.43	1.44	1.41	1.37
Imaginary RI	440	0.0035	0.0073	0.0035	0.0106	0.0093	0.0053	0.0038	0.0055
	675	0.0030	0.0031	0.0008	0.0082	0.0073	0.0017	0.0010	0.0049
	870	0.0029	0.0029	0.0005	0.0085	0.0073	0.0014	0.0008	0.0053
	1020	0.0029	0.0031	0.0005	0.0083	0.0071	0.0013	0.0007	0.0054
AOD	440	0.20	0.27	1.84	0.21	0.23	0.36	0.98	0.22
	675	0.09	0.20	1.82	0.10	0.11	0.31	0.93	0.11
	870	0.07	0.18	1.75	0.07	0.08	0.30	0.89	0.09
	1020	0.05	0.17	1.70	0.05	0.06	0.29	0.85	0.07
Angström Exponent	440-870	1.6	0.6	0.1	1.7	1.5	0.3	0.2	1.4
Sphere fraction (%)	-	97	3	0	97	98	1	0	94

563

564 Figure 9a shows the obtained camera almucantar for the image of Fig. 6g for
565 Granada on 20th July 2016 at 00:40 UTC. This almucantar is similar to the simulated
566 one (Fig. 9b), both showing the highest radiances near the Moon at 469 nm, followed by
567 533 nm. Finally for this case, the ratio between the camera and the simulated

568 normalized radiances has been represented in Fig. 9c as a function of azimuth for
 569 different HDR images taken that night. This ratio presents values near to 1 for all
 570 wavelengths, except for the highest azimuth values where the ratio fluctuates especially
 571 for 469 nm. These results indicate a good agreement between measurements and
 572 simulations for this case.



573

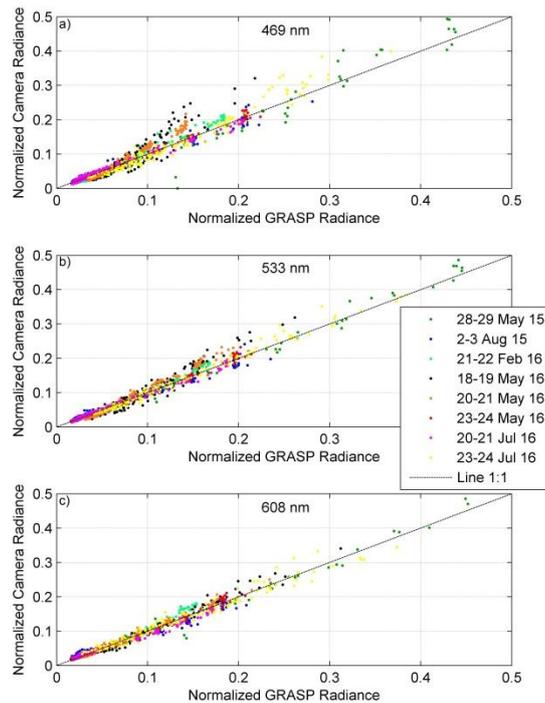
574 Figure 9: Normalized lunar almucantar radiances from camera (panel a) and simulated ones by GRASP
 575 (panel b) for Granada 21st July 2016, 00:40UTC. Panel c shows the ratio of normalized camera radiance
 576 to normalized GRASP radiance along the night 20th-21st May 2016 as a function of azimuth.

577 5.1.2- Statistical analysis

578 In addition to the analyzed case, seven other nights have been added to the
 579 dataset for comparison, with a total of 8 nights (4 cases with fine aerosol predominance
 580 and 4 coarse aerosol cases), 5 at Granada and 3 at Valladolid. The normalized radiances
 581 have been simulated for the eight nights as in the previous case using the parameters of
 582 the AERONET retrievals (corresponding to the afternoon before or to the morning after)
 583 shown in Table 1. Clean cases (low aerosol load) have not been considered due to the

584 uncertainties in the aerosol parameters under low aerosol load. In fact, the aerosol
585 parameters retrieved by AERONET present quality assurance only when the AOD at
586 440 nm is higher than 0.4 [Holben et al., 2006]; however, due to the lack of coincident
587 cases with high AOD values and camera measurements under stable and constant
588 aerosol conditions along a full night, AERONET data used were retrieved with AOD at
589 440 nm higher than 0.2, with only two cases of AOD at 440 nm above 0.4 (related to
590 coarse particle events).

591 Figure 10 shows the scatter plots (one per wavelength) of normalized camera
592 radiance against simulated radiances for the eight nights. The aerosol type of each night
593 is also available at Table 2. The normalized camera radiances show a high correlation
594 with the simulated one for all nights, but normalized radiance at 469 nm presents the
595 largest deviation. Some of the cases present high normalized radiances due to a lack in
596 the number of data in the lunar almucantar caused by the criteria explained in Section
597 3.2.4: Moon intensity likely too low (near quarters). If the number of points of lunar
598 almucantar decreases, the normalized radiance values increase.



599

600 Figure 10: Normalized radiance from camera as a function of simulated by GRASP for 8 different nights
 601 at 469 nm (panel a), 533 nm (panel b) and 608 nm (panel c).

602 Table 2 shows the slope, y-intercept and determination coefficient of the least
 603 squares fit between camera and simulated radiances. A large correlation is observed,
 604 with r^2 values above 0.90 for all cases, the fine aerosol cases presenting the lowest
 605 correlation. From all the cases, the values at 469 nm have the lowest correlation but the
 606 overall r^2 is still high at 0.96. The slope of the fit frequently indicates that the values
 607 from the camera overestimate the simulations for shorter wavelengths. The y-intercept
 608 values usually decrease in absolute value with wavelength, being farther from zero for
 609 the fine aerosol cases, especially at 469 and 533 nm. When all the analyzed nights are
 610 considered together, the fit slope shows that camera radiance overestimates around 6%
 611 and 3% the simulations at 469 and 533 nm, respectively, being the slope equal to 1.00
 612 for 608 nm. These results point out that normalized camera radiance is in good
 613 agreement with the simulated radiance, especially at 608 nm.

614

615 Table 2: Statistical parameters of the scatter plots of normalized camera radiance against simulated one
616 for three wavelengths and different cases. N is the number of available data pairs for each wavelength.

Case (Type)	Wavelength (nm)											
	469				533				608			
	N	Slope	y-intercept	r ²	N	Slope	y-intercept	r ²	N	Slope	y-intercept	r ²
Valladolid 28-29 May 2015 (Fine)	43	1.16	-0.0490	0.93	36	1.03	-0.0100	0.99	42	1.03	-0.0082	0.99
Valladolid 2-3 August 2015 (Coarse)	275	0.94	0.0034	0.98	281	0.90	0.0054	0.98	285	0.88	0.0070	0.98
Valladolid 21-22 Feb 2016 (Coarse)	522	1.12	-0.0064	0.99	522	1.05	-0.0028	0.99	522	1.09	-0.0049	0.98
Granada 18-19 May 2016 (Fine)	275	1.51	-0.0349	0.90	232	1.29	-0.0236	0.96	228	1.10	-0.0086	0.98
Granada 20-21 May 2016 (Fine)	502	1.48	-0.0268	0.99	464	1.29	-0.0176	0.99	462	1.06	-0.0035	0.99
Granada 23-24 May 2016 (Coarse)	299	1.03	-0.0016	1.00	294	1.02	-0.0009	0.99	297	0.99	-0.0005	0.99
Granada 20-21 July 2016 (Coarse)	504	0.95	0.0025	0.99	504	0.97	0.0019	1.00	504	0.90	0.0057	0.99
Granada 23-24 July 2016 (Fine)	154	1.18	-0.0232	0.97	141	1.05	-0.0075	0.99	158	0.96	0.0046	0.97
All	2574	1.06	-0.0042	0.96	2474	1.03	-0.0020	0.99	2498	1.00	-0.0001	0.99

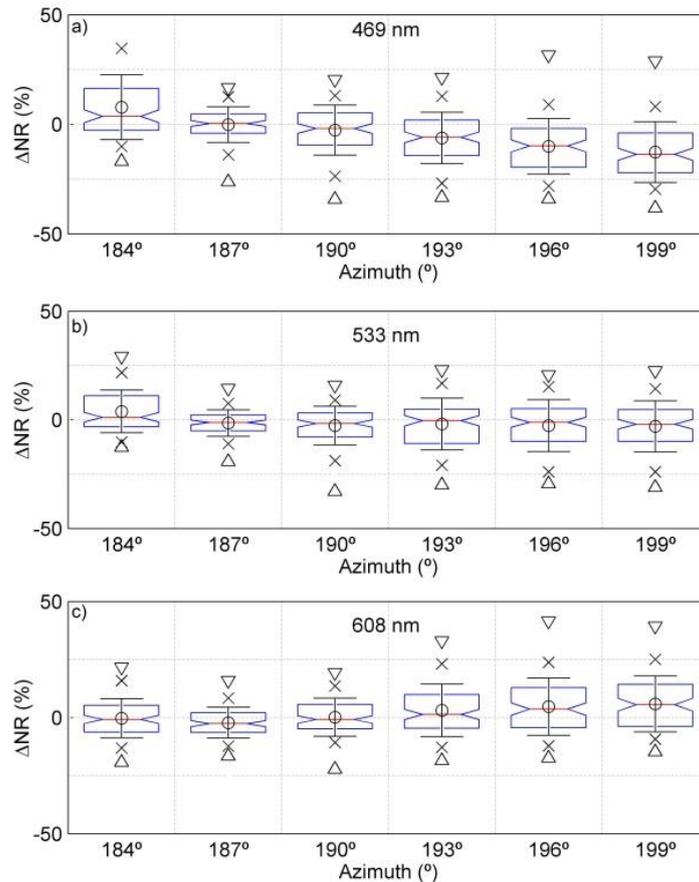
617

618 For an in-depth analysis, the relative differences (ΔNR) between the camera and
619 simulations have been calculated for each night, image and channel as:

$$620 \quad \Delta NR(\%) = 100\% \frac{NCR - NGR}{NGR} \quad (3)$$

621 where NCR is the normalized radiance of the camera and NGR (normalized GRASP
622 radiance) the simulated one. ΔNR has been calculated using all available data and its
623 distribution is shown for different azimuth angle intervals in Fig. 11. The green channel
624 presents the lowest changes on bias (mean of ΔNR) being near zero for all azimuth
625 values, while for high azimuth values the camera measurements over/under-estimates
626 the simulations near the Moon at blue/red channel. These bias values are also shown in
627 Table 3, ranging from -3.2% (469 nm) to 1.5% (608 nm) when all azimuth values are

628 considered. The standard deviation (σ) increases with azimuth and the highest values
 629 are found for 469 nm. The standard deviation can be assumed as the uncertainty if the
 630 Δ NR distribution is Gaussian, which implies that the percentage of Δ NR data (absolute
 631 value) lower than standard deviation ($P < \sigma$) must be about 68%, and the percentage of
 632 Δ NR data (absolute value) lower than two standard deviations ($P < 2\sigma$) must be around
 633 95% [Román et al., 2014a].



634
 635 Figure 11: Box plots for the relative distribution of Δ NR at 469 nm (panel a), 533 nm (panel b) and 608
 636 nm (panel c) for different azimuth intervals. The box limits are the 25 and 75 percentiles, the error bar is
 637 the standard deviation, the circle is the mean, the red line inside the box is the median, the crosses are the
 638 5 and 95 percentiles, and the triangles are the 1 and 99 percentiles.

639 Table 3 presents the values of $P < \sigma$ and $P < 2\sigma$, which are close to 68% and 95% for all
 640 cases, especially for 533 and 608 nm, hence the standard deviation can be considered as
 641 the uncertainty of the normalized camera radiance. Then, uncertainty for azimuth
 642 intervals from 182.5° to 191.5° falls within 8%-15%, 6%-10% and 7%-8% for 469 nm,

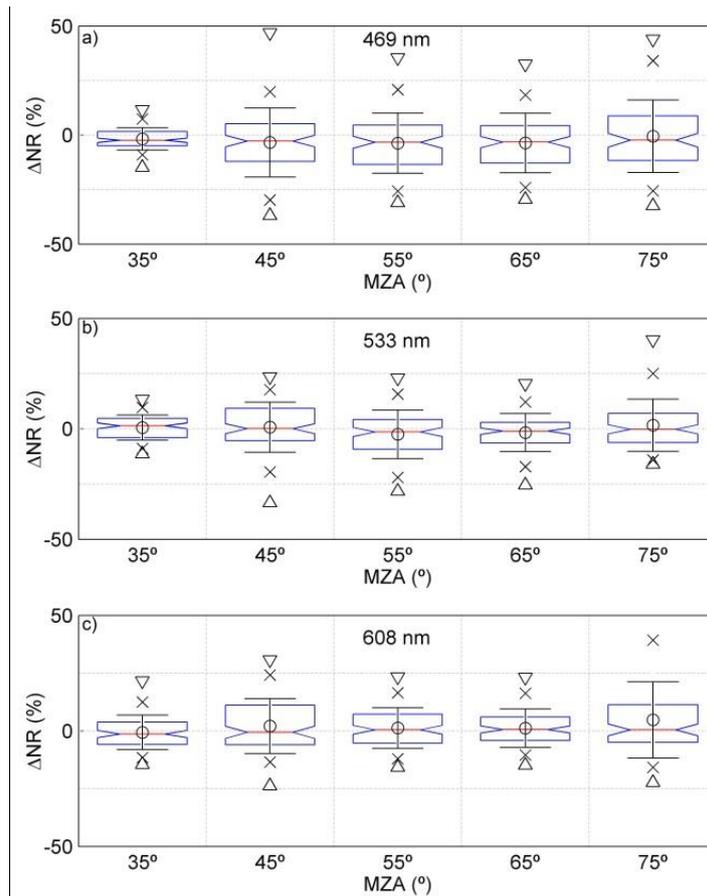
643 573 nm and 608 nm, respectively. The obtained uncertainty considering all data at each
644 channel (~2500 data) is 14%, 10% and 10% for 469 nm, 533 nm and 608 nm,
645 respectively. In general the fit between measurements and simulations is similar for the
646 green and red channels and slightly worse for the blue channel.

647 Table 3: Statistical estimators of ΔNR for different azimuth intervals and three wavelengths. N is the
648 number of data used; σ is the standard deviation, RMSE is the root mean square difference between
649 camera and simulated radiances; $P < \sigma$ is the percentage of ΔNR values inside the interval $(-\sigma, \sigma)$; and
650 $P < 2\sigma$ is the percentage of ΔNR values inside the interval $(-\sigma, 2\sigma)$.

		Azimuth interval (°)						
Wavelength (nm)		182.5-185.5	185.5-188.5	188.5-191.5	191.5-194.5	194.5-197.5	197.5-200.5	182.5-200.5
N	469	505	475	438	399	389	368	2574
	533	501	468	429	392	358	326	2474
	608	499	475	437	390	366	331	2498
Mean (%)	469	7.85	-0.08	-2.61	-6.23	-10.02	-12.67	-3.21
	533	3.87	-1.47	-2.63	-1.92	-2.64	-2.94	-1.02
	608	-0.29	-2.19	0.19	3.15	4.73	5.92	1.53
Median (%)	469	3.73	0.42	-1.83	-5.85	-9.78	-13.64	-3.06
	533	1.26	-1.20	-1.66	-0.35	-1.08	-2.00	-0.60
	608	-0.73	-2.54	-0.81	1.39	3.70	5.60	0.17
σ (%)	469	14.84	8.15	11.40	11.73	12.71	13.91	14.06
	533	9.83	6.07	8.87	11.92	11.98	11.72	10.38
	608	8.42	6.61	8.23	11.32	12.39	12.00	10.19
$P < \sigma$ (%)	469	70.30	74.95	73.74	59.90	52.19	47.83	71.10
	533	66.47	71.58	73.89	67.60	66.48	69.94	72.39
	608	69.14	69.05	72.54	71.28	68.85	66.77	73.66
$P < 2\sigma$ (%)	469	90.69	94.53	93.84	91.23	89.20	91.58	94.76
	533	93.01	94.44	93.47	96.43	94.69	94.17	93.98
	608	95.79	94.97	94.97	94.10	96.17	93.05	95.56

651
652 The obtained results have been calculated using the eight nights simulated with
653 the properties of Table 1. However, only two retrievals of Table 1 satisfy the criteria of
654 quality assurance of AERONET at 440 nm; then if the same analysis is done for all
655 azimuth values with only these two cases, the uncertainty of the normalized camera
656 radiance decreases to 11%, 6% and 9% for 469 nm, 533 nm and 608 nm, respectively.
657 These uncertainty values range between 5%-14% (469 nm), 4%-7% (533 nm) and 6%-
658 9% (608 nm) for the different azimuth intervals.

659 The ΔNR distribution has been represented for different MZA intervals in Fig.
 660 12. The best agreement between camera and simulations appears at MZA values from
 661 30° to 40° , as percentile 5 and 95 indicate for all wavelengths, but this behavior is not
 662 significant since only one of the eight nights analyzed reached these low MZA values.
 663 The mean, median and standard deviation values do not show a clear dependence on
 664 MZA. The values of $P < \sigma$ and $P < 2\sigma$ (Table 4) show that the standard deviation can be
 665 considered the uncertainty of the normalized camera radiances, and the lowest values of
 666 this uncertainty are for 30° - 40° interval (5%-7%), followed by 60 - 70° interval (8%-
 667 14%). The worse agreement appears for the largest MZA values, which could be due to
 668 the stronger background light at these angles.



669
 670 Figure 12: Box plots for the relative distribution of ΔNR at 469 nm (panel a), 533 nm (panel b) and 608
 671 nm (panel c) for different MZA intervals. The box limits are the 25 and 75 percentiles, the error bar is the
 672 standard deviation, the circle is the mean, the red line inside the box is the median, the crosses are the 5
 673 and 95 percentiles, and the triangles are the 1 and 99 percentiles.

674 Table 4: Statistical estimators of ΔNR for different MZA intervals and three wavelengths. N is the
675 number of data used; σ is the standard deviation, RMSE is the root mean square difference between
676 camera and simulated radiances; $P < \sigma$ is the percentage of ΔNR values inside the interval $(-\sigma, \sigma)$; and
677 $P < 2\sigma$ is the percentage of ΔNR values inside the interval $(-2\sigma, 2\sigma)$.

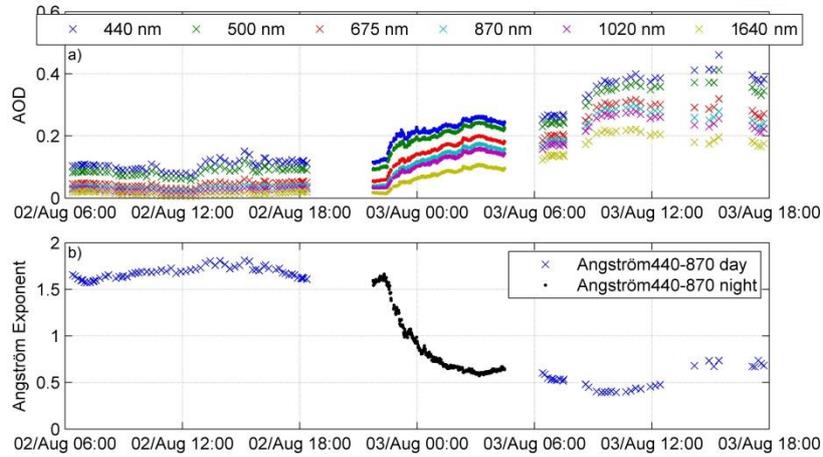
		MZA interval (°)				
Wavelength (nm)		30-40	40-50	50-60	60-70	70-80
N	469	216	590	970	596	202
	533	216	562	944	561	191
	608	216	578	962	554	188
Mean (%)	469	-1.75	-3.42	-3.70	-3.64	-0.53
	533	0.51	0.71	-2.51	-1.74	1.60
	608	-0.64	2.08	1.26	1.18	4.72
Median (%)	469	-2.37	-2.75	-3.30	-3.21	-2.30
	533	1.36	0.07	-1.42	-1.06	-0.21
	608	-1.37	-0.61	0.50	0.62	0.46
σ (%)	469	5.09	15.85	13.84	13.70	16.64
	533	5.70	11.32	10.97	8.62	11.78
	608	7.46	11.88	8.76	8.28	16.48
$P < \sigma$ (%)	469	67.59	72.03	67.32	68.79	69.80
	533	63.43	70.28	69.70	73.44	75.39
	608	73.15	68.86	67.88	72.74	81.91
$P < 2\sigma$ (%)	469	94.91	93.90	94.95	96.48	93.07
	533	97.69	94.66	93.64	93.23	94.76
	608	95.37	93.60	96.26	94.77	93.09

678

679 5.2- Retrieval of aerosol properties

680 A desert dust event arrived at Valladolid the night from 2nd to 3rd August 2015.
681 Figure 13 shows the AOD and Angström Exponent on both days during the day-night
682 period. The aerosol load during 2nd August was low, with an AOD at 440 nm close to
683 0.1 during all day and Angström Exponent about 1.5, indicating fine mode
684 predominance. However, at the beginning of the next day, the AOD at 440 nm was
685 about three times higher and the Angström Exponent was 0.5 (indicating coarse particle
686 predominance). The night time measurements of the CE318-T photometer show that
687 about 22:30 UTC the AOD started to increase while Angström Exponent began to

688 decrease; indicating the dust plume outbreak. Ceilometer profiles and back-trajectories
 689 (not shown) confirm the Saharan dust outbreak that night.

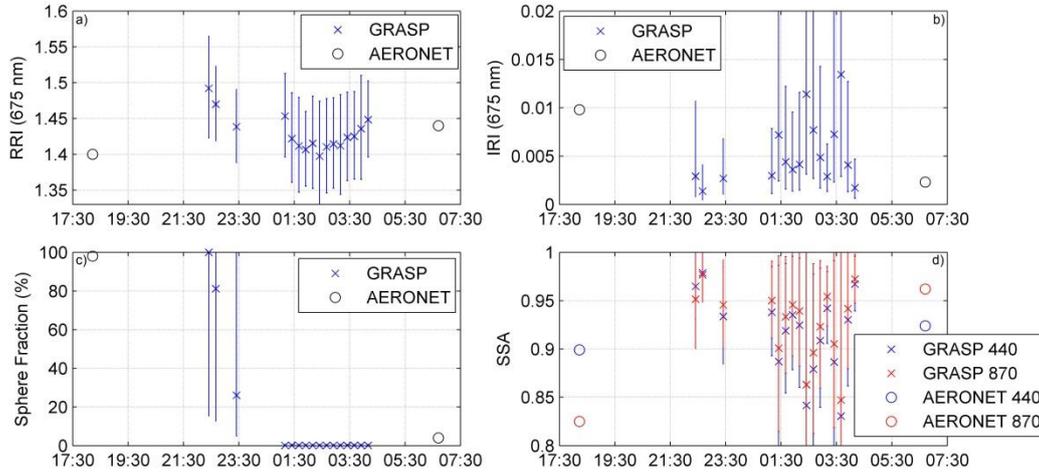


690

691 Figure 13: Spectral AOD (panel a) and Angström Exponent (panel b) at day and night from 2nd to 3rd
 692 August 2015 at Valladolid. Crosses and points represent nocturnal and diurnal data, respectively.

693 The normalized radiance obtained from the SONA camera has been calculated
 694 for that night and it has been used as input in GRASP together with the 6 spectral AOD
 695 measurements derived from direct lunar observations, as commented in Section 4.2. The
 696 GRASP retrievals for that night have been run every 15 minutes, but there is a lack of
 697 data around midnight when the camera was not operative. One of the HDR images used
 698 in this analysis is the one shown in Fig. 6i. Figure 14 shows the retrieved real (panel a)
 699 and imaginary refractive (panel b) indices, sphere fraction (panel c) and SSA values
 700 (panel d). The previous and next daytime AERONET values are also included in the
 701 graphs. Real part of refractive index presented values around 1.40 and 1.49 and with an
 702 error bar that fits with the diurnal AERONET retrievals. The imaginary part of the
 703 refractive index shows more fluctuations along the night and with a large error bar; the
 704 most IRI values are low once the dust aerosol appeared, as the AERONET value of the
 705 next morning. Sphere fraction also shows the dust intrusion in the night since at the
 706 beginning of the night the aerosols were mainly spherical but they progressively
 707 changed to predominance of non-spherical particles, i.e. desert dust. These changes can

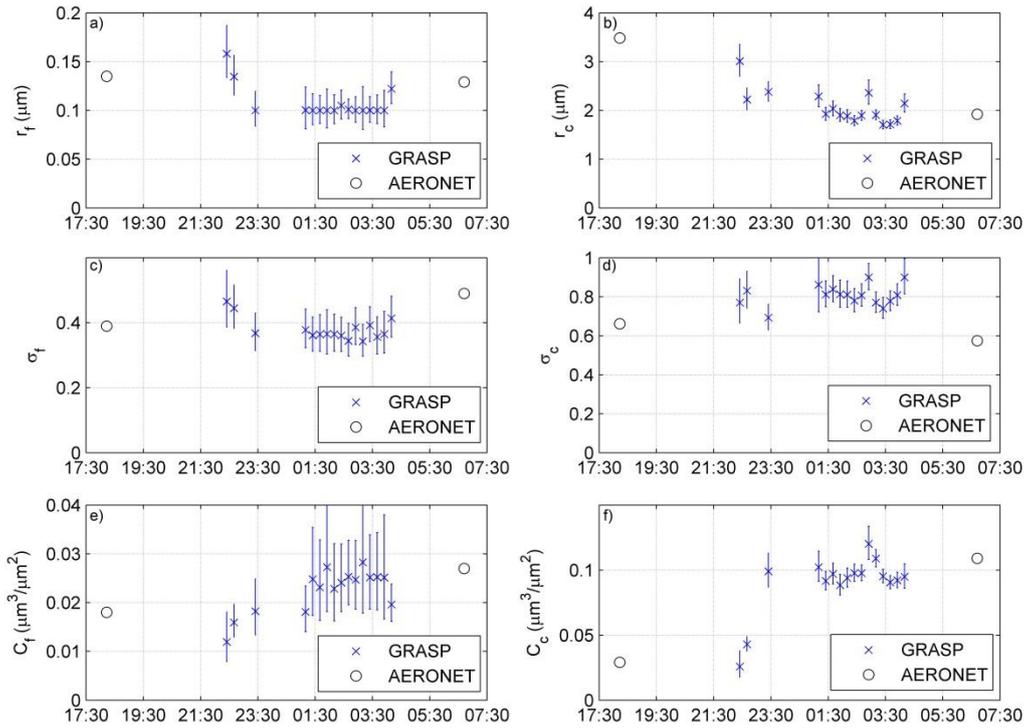
708 be also appreciated in the wavelength dependence of SSA, since at the beginning of the
 709 night the SSA was higher for shorter wavelengths but this fact changed with the dust
 710 intrusion, which typically presents lower SSA values for shorter wavelengths.



711

712 Figure 14: Evolution of the real (panel a) and imaginary (panel b) refractive indices, sphere fraction
 713 (panel c) and SSA (panel d) at Valladolid from 2nd to 3rd August 2015. Diurnal values retrieved by
 714 AERONET are represented as circles, while nocturnal values retrieved by GRASP, using normalized
 715 camera radiances and nocturnal AOD, are represented by crosses with their error bars.

716 Regarding the volume size distribution, Figure 15 shows the volume median
 717 radius (panels a and b), the geometric standard deviation (panels c and d) and the
 718 volume concentration (panels e and f) for both fine and coarse modes. Diurnal retrieved
 719 values from AERONET are also included. Regarding the fine mode, the properties do
 720 not present strong changes along the night, being similar the retrieved (night time)
 721 properties and the AERONET ones. The r_c values decreased along the night being
 722 centered around 2 μm after midnight; this variation is in agreement with the AERONET
 723 data. Volume concentration of the coarse mode, V_c , is also in agreement with the
 724 AERONET values since it presented values around $0.03 \mu\text{m}^3/\mu\text{m}^2$ at the beginning of
 725 the night and this concentration raised up to around $0.1 \mu\text{m}^3/\mu\text{m}^2$ at the end of the night.
 726 The geometric standard deviation values of coarse mode σ_c obtained by GRASP are
 727 higher than the nearest AERONET product, which indicates that the coarse mode of the
 728 size distribution was wider at night.



729

730 Figure 15: Parameters of the fine (panels a, c and e) and coarse (panels b, d and f) aerosol size
 731 distributions from AERONET (black circles) and from GRASP retrieval using normalized
 732 camera radiances and nocturnal AOD (blue crosses with error bars) at Valladolid from 2nd to 3rd
 733 August 2015.

734

735 **6- Conclusions**

736 Normalized radiances around lunar aureole can be measured with a sky camera
 737 if it is configured to capture HDR images. Lunar almicantars from the camera have
 738 been compared with simulated radiances, obtaining a better fit between camera and
 739 model when the aerosol load is high and the Moon light is bright enough. The
 740 uncertainty of normalized camera radiance gets higher as the azimuth value goes farther
 741 from the Moon. This uncertainty is lower for MZA values from 30° to 40°, but it does
 742 not present a clear dependence on MZA. The camera normalized radiance uncertainty is
 743 10% with an absolute bias around 1.0% and 1.5% for green and red channels, while the
 744 uncertainty of blue channel is 14% with an absolute bias of -3.2%. In general, the

745 normalized camera radiances fits the simulations better for the green (533 nm) and red
746 (608 nm) channels.

747 GRASP code has the capability to include normalized radiances in the aerosol
748 retrievals. The inversion of nocturnal AOD and normalized camera radiances together
749 with GRASP could be used to study the aerosol properties evolution along the night, as
750 it has been observed for a dust outbreak episode at Valladolid. In general, the obtained
751 aerosol properties by GRASP at night fit well with the nearest diurnal properties
752 provided by AERONET.

753 This work has demonstrated that normalized radiance near the lunar aureole can
754 be detected by a sky camera, but, as a future work, the use of these normalized
755 radiances in GRASP will need an exhaustive sensitivity study in order to ascertain
756 which lunar aureole points provide more information, what aerosol properties can be
757 retrieved with enough accuracy using this kind of measurements, and what are the best
758 retrieval constraints.

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1067 **List of Figure Captions**

1068 Figure 1: Spectral responses of the three channels (blue, green and red) of the CCD (panel a), of
1069 the infrared (IR) cut-off filter (panel b), and of the three channels of the camera (CCD plus
1070 infrared cut-off filter; panel c). The effective wavelengths of the camera for lunar applications
1071 are marked in panel c.

1072 Figure 2: Zenith (panels a and b), Azimuth (panels c and d) and FOV (panels e and f) viewed by
1073 each camera pixel at Granada (panels a, c and e) and Valladolid (panels b, d and f). Azimuth is
1074 defined from 0° (North) to 360° being East 90° and West 270°.

1075 Figure 3: Sensitivity of the camera pixels for each channel as a function of pixel counts for both
1076 Granada (panel a) and Valladolid (panel b) cameras. The shadow band around the lines
1077 represents the standard deviation.

1078 Figure 4: Dark frames obtained with the Granada camera for different temperatures (T) and
1079 exposure times (ET). The signal shown is multiplied by 4 in order to be better appreciated.

1080 Figure 5: Most frequent value in a dark frame as a function of temperature (T) and logarithm of
1081 the exposure time (ET), for the three Granada camera channels.

1082 Figure 6: Non-HDR (upper; panels a, b and c) tone mapped sky images before removing
1083 background signal (middle; panels d, e and f) and tone mapped sky images with background
1084 corrected (bottom; panels g, h and i). Images corresponds to Granada 21st July 2016, 00:40UTC
1085 (left; panels a, d and g); Granada 20th May 2015, 21:25UTC (middle; panels b, e and h);
1086 Valladolid 3rd August 2015, 02:40UTC (right; panels c, f and i). The non-HDR image at
1087 Valladolid was taken under colorless conditions. Pixels with zenith angle above 80° are masked
1088 except for non-HDR images.

1089 Figure 7: Determination coefficient (r^2) between the background pixel signal and the AOD
1090 assumed at each channel. These values are shown for each channel at Granada (left) and
1091 Valladolid (right). Pixels with zenith angle above 80° are masked.

1092 Figure 8: Averaged background HDR images obtained at Granada (panel a) and Valladolid
1093 (panel b). Images are not tone mapped and pixels with zenith angle above 80° are masked.

1094 Figure 9: Normalized lunar almucantar radiances from camera (panel a) and simulated ones by
1095 GRASP (panel b) for Granada 21st July 2016, 00:40UTC. Panel c shows the ratio of normalized
1096 camera radiance to normalized GRASP radiance along the night 20th-21st May 2016 as a
1097 function of azimuth.

1098 Figure 10: Normalized radiance from camera as a function of simulated by GRASP for 8
1099 different nights at 469 nm (panel a), 533 nm (panel b) and 608 nm (panel c).

1100 Figure 11: Box plots for the relative distribution of ΔNR at 469 nm (panel a), 533 nm (panel b)
1101 and 608 nm (panel c) for different azimuth intervals. The box limits are the 25 and 75
1102 percentiles, the error bar is the standard deviation, the circle is the mean, the red line inside the
1103 box is the median, the crosses are the 5 and 95 percentiles, and the triangles are the 1 and 99
1104 percentiles.

1105 Figure 12: Box plots for the relative distribution of ΔNR at 469 nm (panel a), 533 nm (panel b)
1106 and 608 nm (panel c) for different MZA intervals. The box limits are the 25 and 75 percentiles,
1107 the error bar is the standard deviation, the circle is the mean, the red line inside the box is the
1108 median, the crosses are the 5 and 95 percentiles, and the triangles are the 1 and 99 percentiles.

1109 Figure 13: Spectral AOD (panel a) and Angström Exponent (panel b) at day and night from 2nd
1110 to 3rd August 2015 at Valladolid. Crosses and points represent nocturnal and diurnal data,
1111 respectively.

1112 Figure 14: Evolution of the real (panel a) and imaginary (panel b) refractive indices, sphere
1113 fraction (panel c) and SSA (panel d) at Valladolid from 2nd to 3rd August 2015. Diurnal values
1114 retrieved by AERONET are represented as circles, while nocturnal values retrieved by GRASP,
1115 using normalized camera radiances and nocturnal AOD, are represented by crosses with their
1116 error bars.

1117 Figure 15: Parameters of the fine (panels a, c and e) and coarse (panels b, d and f) aerosol size
1118 distributions from AERONET (black circles) and from GRASP retrieval using normalized
1119 camera radiances and nocturnal AOD (blue crosses with error bars) at Valladolid from 2nd to 3rd
1120 August 2015.