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IN SITU CALIBRATION USING SATELLITE DATA RESULTS

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RESUMEN

El principal objetivo de este trabajo es analizar nuevas aproximaciones en el estudio de la calidad astronómica de un determinado lugar. El objetivo es calibrar el coeficiente de extinción atmosférica con las medidas de teledetección que proporcionan los satélites. Hemos seleccionado los datos proporcionados por diferente espectrógrafos a bordo de satélites de NASA y ESA con mejor resolución espacial y temporal que el TOMS y centrados en canales de interés astronómico como una posible herramienta para la caracterización astronómica de un lugar. Además, de estas medidas proporcionadas por los satélites es posible extraer información relacionada con la cobertura de nubes, las tendencias climáticas o la turbulencia atmosférica a partir de los vientos troposféricos. El principal problema en el uso de estos valores es su interpretación y su calibración cuantitativa. El análisis de los datos necesita ser complementado con los proporcionados por instrumentos in situ (telescopios, contadores de partículas del aire, estaciones meteorológicas, etc.).

ABSTRACT

The main goal of this work is the analysis of new approaches in order to study the properties of astronomical sites. The objective is to calibrate the atmospheric extinction provided by in situ techniques through remote sensing data retrieved from satellite-platforms. We have selected data provided by different spectrographs on board NASA and ESA satelites with better spatial and temporal resolutions than TOMS and centered on channels of astronomical interest as a possible tool for site characterization. In addition, from these satelite measurements it is possible to derive data related to the cloud coverage and climatic trends, or about the atmospheric turbulence from troposphere winds. The main problem to use these values is their interpretation and their quantitative calibration. Data analysis need to be complemented with those provided by in situ instruments (telescopes, airborne particles counters, ground meteorological stations, etc.).

Key Words: **ATMOSPHERIC EFFECTS — SITE TESTING**

1. GENERAL

Site testing campaigns are performed under the classical scheme of optical seeing properties, meteorological parameters, transparency of the air, sky darkness, cloudiness, etc. New concepts related to geophysical properties (seismicity and microseismicity), local variability climate, atmospheric conditions related to the optical turbulence (tropospheric and ground wind regimes) and aerosol presence have been recently introduced in the era of the selecting the best sites for hosting a new generation of Extremely Large Telescopes and also for telescope and dome designs and for feasibility studies of adaptive optics (Muñoz-Tuñón 2000; Muñoz-Tuñón et al. 2003, 2004; Varela et al. 2000; Varela & Muñoz-Tuñón 2004).

The Canarian Observatories are among the top sites for astronomical observations and have been monitored and characterized over several decades (see Muñoz-Tuñón 2000, and references therein). The trade wind scenario and the cold oceanic stream, in combination with the local orography, play an important role in the retention of low cloud layers well below the summits to the windward (north) of the islands (Bustos 2004), above which the air is dry and stable. The cloud layers also trap a great deal of light pollution and aerosols from low troposphere.

The main type of aerosols arriving to the Canary Islands are marine, ClNa, cryogenic emissions, and of African origin (Sahara and Sahel). The latter (clays, quartzes, feldspars and calcites) are the ones that, because of their size, can reduce visibility in the optical wavelength range and can therefore affect astronomical observations.

Aerosols cause radiative forcing, oceanographic deposits by winds (together with Fe and Al), they provide nutrients and minerals for algae (coastal increase in chlorophyll −biomass of phytoplankton), sanitary effects, etc. The aerosols also play an important role for the astronomical site conditions:

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producing more stable condensation nuclei, delaying precipitation and causing the extinction, absorption, diffusion and reflection of extraterrestrial radiation.

Most of the airmass flux component arriving at the Canarian Archipelago comes from the North Atlantic Ocean and consists of sea aerosols, i.e. absorbing chloride in the UV which does not affect the extinction in the visible range.

African dust intrusions affect the western and eastern Canary Islands differently. Moreover, the presence of a stable inversion layer and the sharp orography of the western islands (La Palma and Tenerife) produce different mass flux patterns in the low (mixing) layers closer to the sea and in the median-upper (or free) troposphere layer, causing a seasonal dependent vertical drainage of airborne particles.

Our purpose is the analysis of new approaches in order to study the aerosol content of astronomical sites. The idea is to calibrate the extinction values in V through remote sensing data retrieved from satellite-platforms. The main problem in order to use these values is their interpretation and their quantitative calibration. More extended information in Varela et al. (2007).

The aerosol index provided by the TOMS (Total Ozone Mapping Spectrometer) is one of the most widely accepted products to detect the daily aerosol content. On the other hand, several techniques have been developed in situ to characterize the presence of dust locally at the Canarian Observatories. In particular, a parameter related to sky transparency, the atmospheric extinction coefficient in filters V of Johnson (551 nm) and r' (625 nm), has been measured at the Observatorio del Roque de los Muchachos (ORM) on La Palma –at 2400 m above the sea level– since 1984 by the Carslberg Automatic Meridian Circle Telescope (CAMC). The archive is of public access in the web at: `http://ast.cam.ac.uk` and it has a good temporal comparison with the value retrieved in remote sensing from TOMS on board of Nimbus7 and Earth Probe like on board of the other probes that we have examined (OMI-aura, TERRA-MODIS and AQUA-MODIS).

We require that the satellite data overlap with the geographical area of the ORM; for this reason we have used level 2 data that are not directly available on internet at the link `http://toms.gsfc.nasa.gov`, level 3 data is available and are gridded in squares of $1^\circ \times 1.25^\circ$.

2. ATMOSPHERIC EXTINCTION AND AEROSOL CONTENT CHARACTERIZATION: *IN SITU* AND SATELLITE TECHNIQUES

2.1. *Atmospheric extinction coefficient measured at La Palma Observatory*

Atmospheric extinction is the astronomical parameter that evaluates sky transparency. Extinction is associated with the absorption/scattering of Earth's atmosphere and is characterized by the extinction coefficient, k. Sources of sky transparency degradation are the clouds (water vapor) and the aerosols (dust particles included). This coefficient is wavelength-dependent and can be determined by making multiple observations of stars at different airmasses.

Long baseline extinction coefficient values for ORM have been measured at the Carlsberg Automatic Meridian Circle Telescope (CAMC) in the V-band (k_V), at 550 nm with a band with of 10 nm, and more recently in the Sloan r'-band (625nm) (converted by calibration at V wavelength; `http://www.ast.cam.ac.uk`). The methodology is explained by King (1985).

The extinction values and their stability throughout the night are essential for determining the accuracy of astronomical measurements. As nights with low and constant extinction are classified as photometric, this parameter is considered among those relevant for characterizing an observing site.

On photometric, dust-free nights the median extinction is 0.19 magnitudes at 480 nm, 0.09 magnitudes at 625 nm, and 0.05 magnitudes at 767nm. The extinction coefficients reveal that on clear days (denoted coronal-pure) the extinction values at 680 nm are never higher than about 0.07-0.09 mag airmass^{-1}, while on dusty days (diffuse-absorbing) they are always higher (Jiménez & González Jorge 1998). We underline that the threshold that point out an higher presence of dust (dusty days) respect at clear photometric nights (clear days) is about 0.153 mag airmass^{-1} (Guerrero et al. 1998). Extinction in V is less than 0.2 mag on over approximately 88% of the nights, and extinction in excess of 0.5 mag only occurs on less than 1% of nights.

Figure 1 shows the frequency of extinction over the ORM during the winter (October-May) and summer (June-September). In summer, 75% of the nights are free of dust, while at other times of the year over 90% of the nights are dust-free (Guerrero et al. 1998). These results are consistent with those provided by Torres et al. (2003).

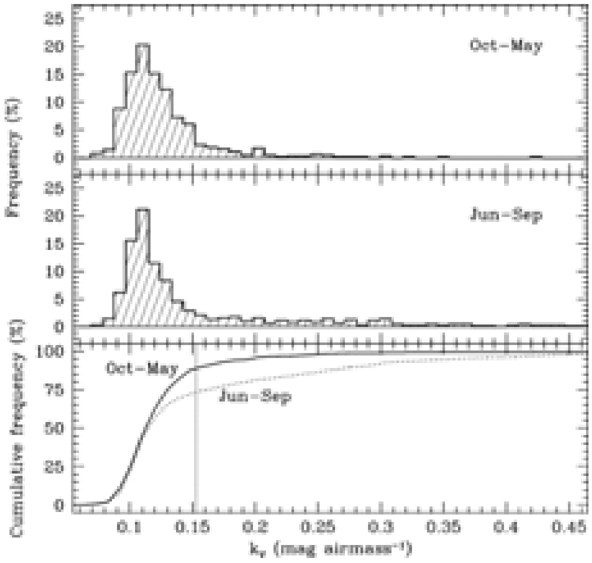

Fig. 1. Frequency of extinction over the ORM during winter (top) and summer (center). In both cases the modal value is 0.11 mag airmass^{-1}. Their corresponding cumulative frequencies are also shown (bottom). The vertical line indicates the extinction coefficient limit for dusty nights, $k_V \geq 0.153$ mag airmass^{-1} (Guerrero et al. 1998).

2.2. *Characterization of aerosols in the near-UV by satellites*

Data coming from Total Ozone Monitoring Spectrometer (TOMS) and from Ozone Monitoring Instrument (OMI) are analyzed to see absorbing and non-absorbing aerosol in ultraviolet (UV) wavelength; this is defined as the ratio between the 331 nm and 360 nm radiance and is named aerosol index (AI).

Absorbing aerosol include smoke deriving from biomass burning, industrial activity, mineral dust, volcanic aerosol and soot. Non-absorbing aerosol are mostly sulphates.

AI>0 indicates the presence of absorbing aerosols and the presence of clouds (AI±0.2) and negative AI values indicate no aerosols or non-absorbing aerosols (Herman et al. 1997; Torres et al. 1998).

3. COMPARISON OF THE ATMOSPHERIC EXTINCTION COEFFICIENT AGAINST THE AEROSOL INDEX PROVIDED BY TOMS

Atmospheric extinction is conceptually related to the aerosol optical thickness (or depth) and to the aerosol index. In this section we shall analyze the first results of comparing the atmospheric extinction coefficient with the aerosol index (AI) provided by TOMS (Total Ozone Mapping Spectrograph) on board the Earth Probe NOAA satellite.

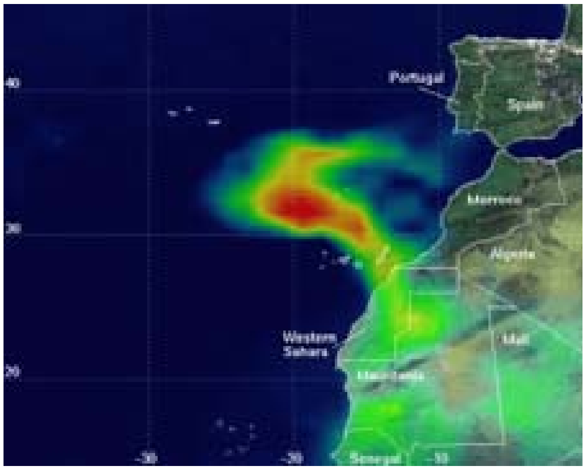

Fig. 2. Dust plume obtained from TOMS data over the western Sahara Desert and extending over the Atlantic Ocean and Canary islands. From `http://toms.gsfc.nasa.gov/aerosls/africa/canary.html`

Level 3 aerosol data are immediately available (and therefore more extended and easily to be used) at `ftp://toms.gsfc.nasa.gov/pub/eptoms/data/aerosol`

To demonstrate why there is not necessarily any correlation between the AI and the atmospheric extinction we have selected an intense invasion of African dust over the Canary Islands that occurred on February 26, 2000 (Figure 2). We have used AI values obtained for the Canarian Observatories and atmospheric extinction values provided by the CAMC at the ORM during the night before and after this episode. AI reaches its maximum (2.4 at the OT and 2.7 at the ORM) on February 27, precisely on the day when the plume reached Tenerife. Nevertheless, the CAMC measures an extinction value of less than 0.2 mag, with a high number of photometric hours. The reason for this is that when the plume arrived at La Palma it did not reach the level of the Observatory (Varela et al. 2004a).

In Figure 3 we represent the atmospheric extinction coefficient in the V band (k_V) provided by the Carlsberg Meridian Telescope at the Roque de los Muchachos Observatory against the aerosols index provided by the TOMS/Earth Probe, both from 1996 to 2004. We have classified 4 quadrants corresponding to different regimes: k_V=0.15 mag airmass^{-1} is the limit for dusty nights, whereas positive AI values indicate the presence of absorbing aerosols.

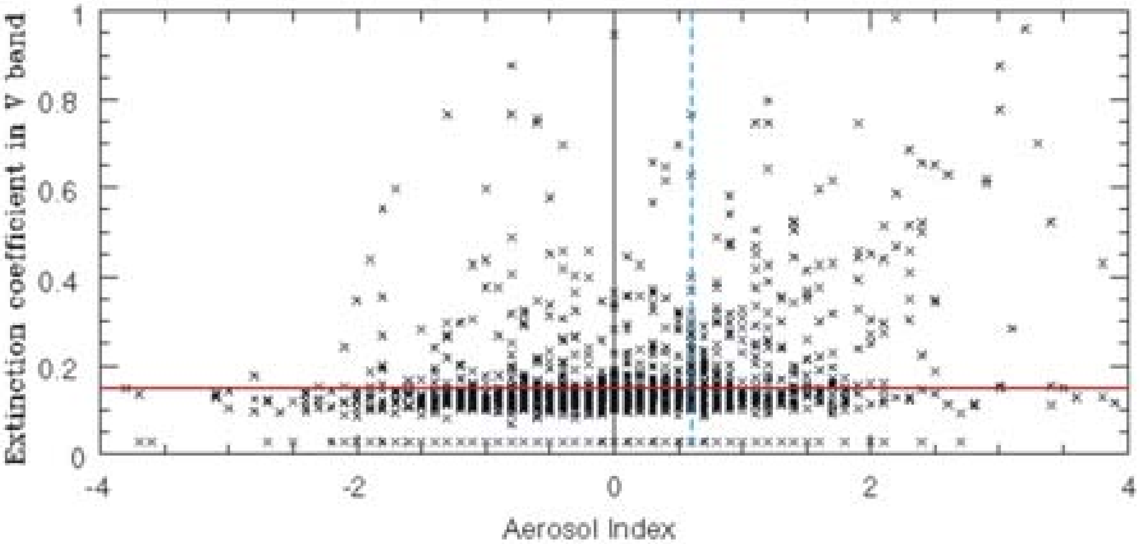

Fig. 3. Aerosol index provided by TOMS against the atmospheric extinction coefficient in V (integrated values) from the CAMC above the ORM. Red horizontal line is the threshold line indicating the presence of dust in the atmosphere (Guerrero et al. 1998). Blue vertical line is the threshold line indicating the presence of absorbing aerosols in the atmosphere. The top right quadrant in the figure corresponds to points seen as dusty (from CAMC –$k_V > 0.2$–) and of high absorbing aerosol presence (from TOMS – AI>0.7–). See Varela et al. 2004b.

In the four cases, the correlation coefficient and the square of the coefficient of the Pearson' moment correlation is smaller than 0.1, then, there is not linear correlation at all between both parameters (the maximum correlation is found in the second quadrant, i.e., AI positive and extinction coefficient larger than 0.15). When this interval is narrowed to AI larger than 0.7 and k_V larger than 0.2 mag airmass^{-1} (only a 4% of the cases), this correlation slightly increases up. Only when summer period is considered under these last conditions, the correlation can reach 0.55 (Varela et al. 2004b).

This last result is confirmed by Siher et al. (2004), correlating AI TOMS data recorded by Nimbus7 and the atmospheric extinction coefficient at the ORM during summertime dusty events (AI>0.7 and $k_V > 0.2$). The correlation found is 0.76, but we emphasize that this case corresponds only for a few percent of the cases (4% when TOMS-EP is used), and then it has not statistical significance. In fact, the yearly average extinction derived from TOMS/Nimbus7 AI over the ORM by Siher et al. (2004; see Figure 6 therein) is non consistent with the typical mean and median extinction coefficients observed (smaller than 0.2 mag airmass^{-1}).

The correlation absence is explained in terms of the low spatial resolution (see the pixel size in Figure 4) of the TOMS/EP which does not distinguish local effects since averages over a surface equivalent to a full island (139 km × 111 km) and cannot distinguish the vertical dust drainage. This drainage is associated to the seasonal dependence of the air masses flux over the Canaries and to the presence of a thermal inversion layer (just below the astronomical observatories). The stratocumulus layer of sea of clouds formed at this condensation level plays an important role trapping the dust and causing a relative descent of the inversion stratus. This effect is known as anticyclonic gloom and is illustrated in Figure 5. Thus, even under dust storms episodes, the airborne dust particles do not reach the level of the Observatories.

4. SELECTION OF SATELLITES

The proposal for our work is to obtain the best possible spatial and vertical resolution assuring that the retrieved data fields in remote sensing from different satellites (as aerosol values or geolocation parameters) are absolutely over the ORM site where we will compare them with the atmospheric extinction values come by CAMC Observatory. For this reason, the parameters which have conditioned our choice are:

- Large spatial resolution
- Good vertical resolution
- NearUV, Optical and NIR channels
- Long-term database

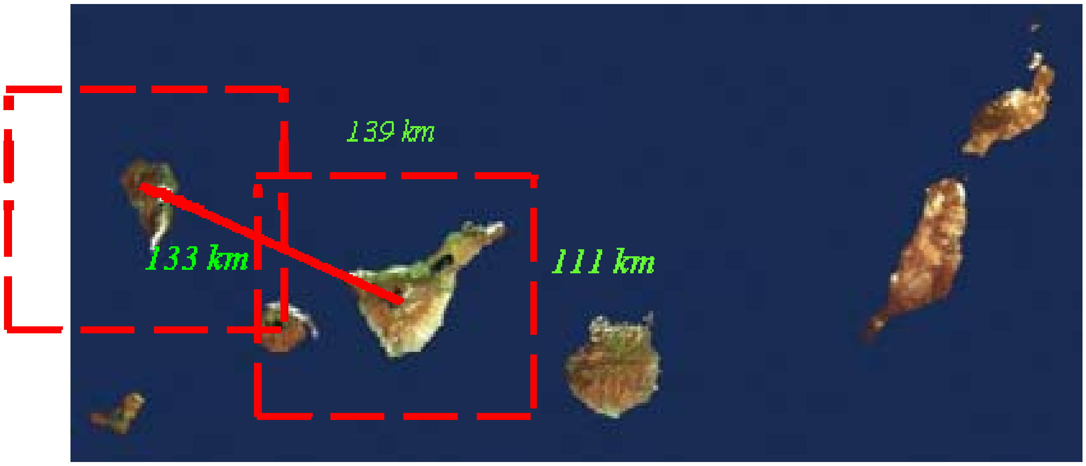

Fig. 4. TOMS pixel size over-imposed on an satellite image of Canary Island: 1.25 deg ×1 deg, i.e. 139 km × 111 km. Both Observatories (ORM at La Palma is in the left box and the Teide Observatory at Tenerife is in the right one) are 133 km separated. The pixel size comprises an entire island.

In order to respect these pressing ties, we have decided to work only with level data 2 which have the same resolution as the satellite IFOV (Instantaneous Field of View). The overview of the satellites useful for our work are summarized in Table 1.

5. PRELIMINARY RESULTS

We have explored the use of other detectors on board different satellites that operate in bands of astronomical interest (the visible and NIR) and with larger spatial resolution than TOMS.

The new generation of satellites provide better resolution images (MODIS-AQUA&TERRA, OMI-AURA, SEVIRI-MSG1, etc.).

On March 10, 2007, thick plumes of dust blew off the west coast of Africa and over the Canary Islands, similarly to the case above mentioned (on February 2000). The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite took for this day the picture shown in Figure 5 (with much better resolution than TOMS). We can see that the eastern islands are more affected by the dust plume than the western ones. And also, the abrupt orography and the inversion layer play an important role retaining the dust below the summits (where the Observatories are located) of the highest western islands (Tenerife and La Palma). This effect is named anticyclonic gloom.

This situation has been verified by data provided by the CAMC indicating no atmospheric extinction at all:

- Extinction Coefficient in r' $k_{r'} = 0.083$ mag airmass^{-1} (good quality free dust-night) i.e. $k_V = 0.12$ mag airmass^{-1}.
- Number of hours of photometric data taken = 10.22
- Number of hours of non-photometric data taken = 0.00

The selected parameters we have retrieved are the Aerosol Index provided by OMI-AURA –with visible and ultraviolet channels and with a spatial resolution from 13 km × 24 km to 24 km × 48 km– and the Aerosol Optical Depth (AOD) provided by MODIS on board TERRA (from 2000) and AQUA (from 2002) –with its 36 spectral bands, from 0.47 to 14.24 μm, including two new channels 0.405 and 0.550 μm, with a spatial resolution of 10 km x 10 km– . In order ot obtain the best spatial, spectral, radiometric and temporal resolutions, we have decided to work only with level data 2 which have the same resolution as the IFOV of the satellite.

The AI threshold for dusty nights is 0.6 and AOD>0.1 will be the threshold for dusty episods (Romero & Cuevas 2002; Varela et al. 2007).

The correlation analysis of satellite aerosol parameters and *in situ* k_V measurements is given in Varela et al. (2007). We conclude that despite the much better spatial and spectral resolution of the recent satellite aerosol measurements, AI and AOD provided by NASA satellites are not for the moment a useful tool for the aerosol content characterization of an astronomical observatory. *In situ* data are required, in particular in those astronomical sites with abrupt orography (ORM, Mauna Kea or San Pedro Mártir). Spatial resolution of the order of the observatory area will be required in these cases.

TABLE 1

OVERVIEW OF INSTRUMENTS ON BOARD SATELLITES THAT PROVIDE PARAMENTERS USEFUL FOR OUR WORK

Instrument-Satellite	Horizontal resolution	Parameter	Period
TERRA-MODIS	$10\times10\,\mathrm{km}^2$	Aerosol Optical Thickness (AOT)	from 2002
AQUA-MODIS	$10\times10\,\mathrm{km}^2$	Aerosol Optical Thickness (AOT)	from 2002
OMI-AURA	From $13\times24\,\mathrm{km}^2$ to $24\times48\,\mathrm{km}^2$	Aerosol Index (AI)	from 2004
SEVIRI-MSG1 (Met8)	$4.8\times4.8\,\mathrm{km}^2$	Aerosol Parameter	from 2004

Fig. 5. Plumes of dust blew off the west coast of Africa and over the Canary Islands observed by The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite on March 10, 2007 (full image in `http://earthobservatory.nasa.gov/Newsroom/NewImages/Images/canary_amo_2007069_lrg.jpg`). The peaks of La Palma and Tenerife islands remain clear of dust.

6. CONCLUSIONS AND FUTURE WORK

From the comparison of Aerosol Index (AI) and Aerosol Optical Depth (AOD) provided by NASA satellites against the atmospheric extinction values (provided by the CAMC), we conclude that satellite data lacks spatial resolution to provide reliable aerosol content over the ORM, and in general in those astronomical sites with abrupt orography.

The high peaks, the sharp orography and the small size of islands can make the discrepancy between in situ and satellite data even more severe than in flatter and more extended areas. Spatial resolution of the order of the Observatory area will be required in these cases.

With this aim we are now exploring the use of SEVIRI-MSG2 (1.4 km × 1.4 km) (Dec. 2005-2012) for Europe and Africa, and in the future, ATLID(LIDAR)-EARTHPROBE (with horizontal sampling interval smaller than 100 m; planned for 2012-2015) for global coverage.

Ground measurements will be complemented by LIDAR data (Instituto Nacional de Técnica Aeroespacial, INTA) of 30 m resolution (NASA MPL-NET-AERONET); by the IAC airborne particle counter (from Pacific Scientific Instruments) installed at the ORM in February 2007 (with 6 channels: 0.3, 0.5, 1, 3, 5, 10 μm), and by the Multi-Filter Rotating Shadowband Radiometer (MFRSR) belonging to the Instituto Nacional de Meteorología (INM) and planned to be installed at the ORM in summer 2007 (consisting on 6 narrow bands between 414 nm and 936 nm). These instruments will provide the size, density and vertical distribution of the aerosols.

We express our deepest thanks to TOMS, OMI and MODIS groups from NASA Goddard Space Flight center for Aerosol Index and Aerosol Optical

Depth measurements, and to the Carlsberg Meridian Telescope (CAMC) of the Isaac Newton Group on La Palma for the coefficient extinction data. This study is part of the site characterization work developed by the Sky Quality Group of the IAC and has been carried out under the framework of the European Project OPTICON and under the FP6 Proposal for Site Selection for the European ELT.

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