A NEW LUNAR PHOTOMETER TO CHARACTERIZE AEROSOL PROPERTIES AND ATMOSPHERIC WATER VAPOR AT NIGHTTIME

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Abstract

A global ground-based long-term aerosol climatology is needed to characterize the aerosols and infer their impact on climate. Data from AERONET (AErosol RObotic NETwork) are widely used by the international research community to study aerosol properties and atmospheric water vapor. One of the major obstacles impeding successful derivation of a continuous sequence of τ_a is the lack of observations at nighttime. However the highly changeable moon's illumination inherent to the lunar cycle introduces an important limitation in lunar photometry, which must solve the problem of the instrument's calibration.

In this study we present the new lunar photometer CE-318U, designed to perform nocturnal measurements with a signal-to-noise ratio similar to classical sunphotometers. We use the new methodology to calibrate lunar photometers in high mountain conditions developed by Barreto et al. (2012a): the Lunar Langley Method. Using this new device and the described methodology we obtain τ_a in a two days period in July, 2011, with an accuracy of $\pm$0.01-0.02, similar to the sunphotometry precision in the AERONET network. It makes possible to compare daytime and nighttime measurements, giving us the possibility to include nocturnal aerosol information in the existing databases. In addition, the comparison between nocturnal PWV from GPS and the two channels of the new CE-318U within the water vapor absorption band shows differences below 0.03 cm for Filter#1, being notably higher for Filter#2 (0.15 cm).

1 INTRODUCTION

Atmospheric aerosol particles are suspension of solid and/or liquid particles in air derived from both natural and human processes. These particles influence the atmospheric radiative forcing on global scale in three ways. Firstly, they act directly into the energy transference process by scattering or absorbing the solar radiation (IPCC, 2007). Secondly, they impact indirectly by an important modification of clouds properties or lifetime, acting as cloud condensation nuclei. Finally, there is a "semidirect" forcing of aerosols due to the evaporation of clouds particles caused by the absorption of solar radiation. All these interactions are quite complex and any small perturbation of this energy balance can produce an important change in climate (Ohmura et al., 1998, García et al., 2008). In this sense, according to the report of

IPCC (2007), the aerosol radiative forcing is crucially important, varying between -0.6 to 0.1 Wm^2, even though is still highly uncertain (± 0.4 Wm^2). Its effect is currently estimated using numerical models able to simulate the emission of aerosols, precursors and clouds processes in the atmosphere. In this context, ground-based measurements for detecting and characterize aerosols constitute a key factor to provide independent and trustable validation to regional and global aerosol/dust models and to improve their quality.

Data from AERONET (AErosol RObotic NETwork) are widely used by the international research community to study aerosol properties. This program consists in continuous and globally distributed observations at daytime of Aerosol Optical Depth (τ_a), Angström exponent (α) and other aerosol properties, as well as Precipitable Water Vapor (PWV) using the Cimel CE-318 sun photometer as the standard instrument. The main constrain in sun photometry is that the information inferred is limited to the light period, resulting in important gaps in the actual ground-based networks during nighttime periods. Thus, nocturnal aerosol observations are certainly of capital importance for monitoring the aerosol transport, as well as to solve the lack of information problem in high latitude locations, given the extended periods of darkness in wintertime. They could also be of considerable importance to study the effect of aerosols on nocturnal cloud lifetime and coverage as well as to detect aerosol outbreaks at night. PWV nocturnal measurements are also important to expand the actual databases based on sunphotometry, taking into account the radiative impact of this trace gas as well as the highly spatial and temporal variability of this atmospheric constituent.

In this work, we present the technical specifications, the measurement techniques and the validation of a new instrument developed by *Cimel Electronique*. It was specifically design to perform automatic lunar irradiance measurements with a stability similar to the usual sunphotometers and hence to infer aerosol properties and PWV at night. This lunar photometer, trade name CE-318U, was installed at the high mountain Izaña Observatory (2400 m a.s.l.) in order to obtain absolute calibration and to develop a reliable and trustable validation against reference instruments. One of the major problems in lunar photometry was tackled by Barreto et al. (2012a), that is referred to the important complexities and limitations in determining the instrument calibration. The highly changeable moon's illumination inherent to the lunar cycle makes impossible the use of the usual Langley-plot methodology to perform the calibration. We used the new methodology to calibrate photometers under these conditions developed by Barreto et al. (2012a). This methodology is a modification of the usual Langley Method, requiring the implementation of a lunar empirical model to predict the extraterrestrial lunar irradiance.

We have expanded the preliminary results of the aerosol characterization developed by Barreto et al. (2012a) with a new study performed on $11^{th} - 12^{th}$ and $14^{th} - 15^{th}$ July, 2011. We examined τ_a retrievals under these two different nocturnal atmospheric conditions in July and compared them with daytime observations. In addition, we retrieved PWV from nocturnal CE-318U measurements and compared them with values obtained using a GPS receiver.

2 SITE INFORMATION

Izaña Observatory, managed by the Izaña Atmospheric Research Centre (IARC), from the State Meteorological Agency of Spain (AEMET), is a high mountain Global Atmospheric Watch (GAW) station located in Tenerife (Canary Islands, Spain; 28°18N, 16°29W, 2363 m a.s.l.). This observatory provides excellent conditions for in-situ accurate measurements of trace gases under free troposphere conditions, due to its location in a subsidence region, below the descending branch of the Hadley cell and above a quasi-permanent thermal inversion layer. Consequently, the Izaña Observatory is characterized by a high frequency of pristine days, a low and stable total column ozone and a very dry atmosphere. Furthermore, during the nighttime period a downward catabatic regime is well established, providing excellent conditions for accurate atmospheric measurements.

Izaña Observatory is a direct-sun calibration site of AERONET (`http://aeronet.gsfc.nasa.gov`) and for its associated networks PHOTONS (*PHOtometrie pour le Traitement Operationnel de Normalisation Satellitaire*; `http://loaphotons.univ-lille1.fr/photons/`) and RIMA (*Red*

Ibérica de Medida fotométrica de Aerosoles; www.rima.uva.es). In fact, PHOTONS, RIMA and IARC forms the present AERONET-Europe calibration infrastructure within the European project ACTRIS (Aerosols, Clouds, and Trace gases Research InfraStructure Network; www.actris.net), and Izaña Observatory is the site where master sunphotometers of AERONET-Europe are sun-calibrated.

Nocturnal PWV information was included from ground-based receivers placed at Izaña Observatory as a part of the EUMETNET (the Network of European Meteorological Services) GPS water vapor programme (E-GVAP).

3 INSTRUMENTATION

3.1 The new Lunar Cimel CE-318U

The Lunar Cimel (LC) CE-318U photometer is similar to the classical sunphotometer Cimel CE-318, extensively described in Holben et al. (1998), but with new improvements to perform nocturnal measurements. This instrument has incorporated a new moon tracker in the system. It is based in a four-quadrant detector with new electronics to amplify the signal, allowing the retrieval of the reduced incoming energy from the moon. This new tracker is also able to track the sun with a special device containing an attenuation filter to reduce the high incoming energy. It also incorporates a new software to process data while tracking.

LC performs nocturnal measurements with high gain and an approximate field of view of 1.29° at eight nominal wavelengths of 1640, 1020, 938, 937, 870, 675, 500 and 440 nm. The presence of two bands filters centered within the water vapor absorption band constitutes an interesting opportunity to evaluate the filter transmissivity effect on the precipitable water vapor calculation. The filter centered at 938 nm is one of the band filters used by AERONET network. In this new prototype, a new high transmissivity filter centered at 937 nm is included. In Fig. 1 are presented the filter transmission responses of Filter#1 (centered at 937 nm) and Filter#2 (at 938 nm). Filter#2 presents a transmissivity up to 0.7 as well as an important wavelength contribution outside the Full Width at Half Maximum (FWHM). This contributions is commonly known as "wings of the filter", which can lead to an inaccurate determination of aerosols and water vapor retrievals (Ortiz de Galisteo et al., 2009). Oppositely, Filter#1 is characterized by transmissivity close to unity and negligible contribution of the wings.

As in sun photometry, the LC takes a sequence of three measurements (triplets) every 30 seconds at each wavelength. Each triplet is defined as the maximum minus minimum divided by the mean value of these three consecutive measurements. The triplet information is usually used to detect and screen clouds as well as to check the instrument's stability. We have used them to calculated the instrument's stability in case of diurnal and nocturnal measurements, at different moon's illumination. Results are presented in Table 1. It shows that the triplet's variability is wavelength dependent, being higher in 500 and 440 nm channels during both daytime and nighttime observations. In case of daytime measurements, the variability ranges from 22% at 440 nm to 9% at 1020 nm. Nocturnal stability is dependent on moon's phase. It is slightly reduced in case of observations taken under near full moon illumination conditions, with variability values from 30% at 440 nm to 13% at 1640 nm, and more importantly reduced as lunar irradiance decreases. We have obtained variability in triplets up to 61% at 440 nm for a nocturnal measurement taken under a 87% of moon's fraction of illumination.

All these new features of the LC photometer might be used not only to implement aerosol databases covering both day and night periods, but also to improve the accuracy of a particularly important atmospheric gas as the water vapor retrieval.

3.2 Ancillary information for data validation

To perform day and nighttime comparison of τ_a we have used data from the Izaña AERONET instrument (http://aeronet.gsfc.nasa.gov) near sunset and sunrise.

We have used information from FLEXible backward TRAjectories (FLEXTRA) plots from the EMPA facility for Global GAW stations to confirm the pathways of air masses arriving to Izaña at several

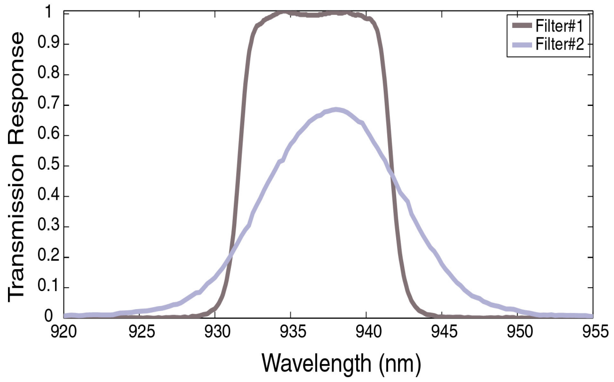

Figure 1: Filter transmission responses for the two CE-318U channels centered within water vapor absorption bands, Filter#1 centered at 937 nm and Filter#2 at 938 nm.

Table 1: CE-318U triplets in % obtained for two nights with different moon's fraction of illumination (FI) and for daytime measurements.

		Channels (nm)					
	Type of measurements	1020	1640	870	675	440	500
13/12/2011	Nocturnal (FI=87%)	0.36	0.18	0.23	0.26	0.61	0.52
9/02/2012	Nocturnal (FI=93%)	0.28	0.13	0.18	0.19	0.30	0.25
22/12/2011	Daytime	0.09	0.11	0.09	0.13	0.15	0.22

levels. The calculations are based on the FLEXTRA model and driven by ECMWF wind fields with a global resolution of 1° x 1°, being accessible via web at `http://lagrange.empa.ch/`.

Information from the Micropulse Lidar (MPL) running at Santa Cruz de Tenerife station (28.5°N, 16.2°W; 52 m a.s.l.) since January 2005 have been included to provide an independent qualitative information about the aerosol vertical distribution as well as their variability. This program (Spinhirne et al., 1995) has been implemented for monitoring and characterization of Saharan Air Layer (SAL) North Atlantic outflow, and it is currently in operation within NASA/MPLNET (`http://mplnet.gsfc.nasa.gov`), and is co-managed by National Institute for Aerospace Technology (INTA; Spain) and the Izaña Atmospheric Research Centre (IARC; AEMET).

We have included nocturnal PWV information extracted from ground-based GPS receivers placed at Izaña IARC station. The radio signals of GPS and GLONASS (the Russian GPS) perform quasi-simultaneous diurnal observations of PWV. Their radio signals are delayed due to refraction in the atmosphere, mainly caused by water vapor, providing the Zenith Total Delay (ZTD) and therefore the PWV with a 15-min temporal resolution (see Romero et al., 2009 for further details). We have used a Leica GRX 1200GG pro GPS/GLONASS receiver which has been operated at IZO within the European Reference Frame network (EUREF, Bruyninx, 2004) since June 2008 and a GPS/GLONASS receiver, part of the EUMETNET programme.

Information from Vaisala meteorological radiosondes was used to infer nocturnal humidity conditions. These vertical soundings were launched at 0:00 UTC from the AEMET station located in Güímar (Tenerife). It is the radiosonde WMO station #60018, part of the Global Climate Observing System (GCOS)-Upper Air Network (GUAN).

Table 2: Coefficients a and b obtained for each of the two CE-318U channels located within WV absorption band: Filter#1 centered at 937 nm and Filter#2 at 938 nm.

	Filter#1	Filter#2
a	0.5145	0.5607
b	0.5929	0.5777

4 METHODOLOGY

4.1 The Lunar Langley Method

The new Lunar Langley Method, developed by Barreto et al. (2012a), is based on the Beer-Lambert-Bouguer Law, including two contributions on the extraterrestrial voltage (V_0) term:

$$V_{0,j} = I_{0,j} \cdot \kappa_j \quad (1)$$

where $I_{0,j}$ is the extraterrestrial irradiance in a certain channel with a central wavelength at j, and κ_j is the instrument calibration constant which depends on the instrument features. $I_{0,j}$ is calculated using the implementation of the empirical model presented in Kieffer and Stone (2005). This model, know as ROLO (RObotic Lunar observatory) model, provides the exo-atmospheric lunar irradiance with relatively high precision ($\sim 1\%$). It needs several astronomical parameters, obtained using the astronomical calculator Alcyone 4.3, as lunar phase, sun-moon distance, as well as the selenographic latitude and longitude of the observer and the sun.

κ_j constant strictly accounts for the instrument's photometric responsivity and any residual systematic offset difference between ROLO predicted $I_{0,j}$ and the actual exoatmospheric irradiance.

As Barreto et al. (2012a) described, the instrument calibration was performed using the lunar data obtained on February 8^{th}-9^{th}, 2012. This night was selected due to the relatively low and constant τ_a conditions, especially during moonset, where τ_a at 440 nm remained stable and near 0.02.

4.2 PWV determination

In those spectral regions affected by strong spectral variation of molecular absorption, as occurred in near-infrared water vapor absorption band, the Beer-Lambert-Bouguer Law must be modified taking into account the water vapor transmittance: $T_{w,\lambda}$ (Schmid, 1996). As Bruegge et al. (1992) and Halthore et al. (1997) showed, $T_{w,\lambda}$ present a exponential dependence with PWV:

$$T_{w,\lambda} = exp(-a(m_w(\theta) \cdot PWV)^b) \quad (2)$$

As shown by Barreto et al. (2012b), the "a" and "b" constants can be determined by fitting the simulated $T_{w,\lambda}$ by a radiative transfer model for an specific filter function versus the PWV. Combining Eqs. 1 and 2 PWV is obtained using the following expression:

$$PWV = \frac{1}{m_w} \cdot \{\frac{1}{a} \cdot [ln(\frac{I_{0,\lambda}}{V_\lambda}) + ln(\kappa_\lambda) - m_R \cdot \tau_{R,\lambda} - m_a \cdot \tau_{a,\lambda}]\}^{\frac{1}{b}} \quad (3)$$

In this equation m_w is the water vapor optical mass, m_R is the Rayleigh optical mass and $\tau_{R,\lambda}$ is the Rayleigh optical depth in the central wavelength within water vapor absorption band ($\lambda = 937, 938$ nm for our two LC filters). $I_{0,\lambda}$ is obtained from the ROLO lunar irradiance model using the astronomical ephemeris, τ_a in this spectral region is obtained by extrapolation of τ_a at 870 and 440 nm, and "a" and "b" constants are obtained by simulation of water vapor transmittances using the radiative code MODTRAN 4.0 (Table 2). In order to account for nocturnal humidity conditions, 153 vertical soundings launched a relatively close AEMET station at 0:00 UTC have been introduced.

5 RESULTS

5.1 Aerosol Optical Depth

The calibration constants κ_j's were calculated by means of the Lunar Langley calibration using nocturnal measurements on the moonset of February 9^{th}, 2012 (Barreto et al., 2012a). The coefficients are shown in Table 3. Using the calibration coefficients from this table, nocturnal τ_a for LC have been calculated for July 11^{th}-12^{th} and July 14^{th}-15^{th}, 2011. In Figs. 2 and 3 the daytime and nocturnal τ_a is presented for this two nights period. The first event represents the transition between a stable and clean event on 11^{th} July, with τ_a values $\sim$ 0.04 until aproximately 16:00 UTC, to a saharan intrusion that started slightly on 11^{th} July afternoon, and more pronouncedly at midnight. It led to τ_a values up to 0.3 in 440 nm channel during 12^{th} July at daytime. On July 14^{th} event, high τ_a values up to 0.3 at 440 nm were found in the early morning. Then τ_a decreased slightly during the evening and the night, rising to 0.2 at 440 nm in the last part of July 15^{th} daytime.

We used the information from FLEXTRA backward trajectories in order to infer dust source regions in these two events. Figure 4 shows air mass pathways over the Sahara and the Sahel at altitudes $\sim$ 3000 m a.s.l. above Izaña Observatory during 12^{th} July, while Figure 5 shows the saharan influence in several height levels up to 5500 m a.s.l. in 14^{th} July.

For a quantitative analysis of daytime and nocturnal τ_a differences we compared nocturnal and daytime data corresponding to the consecutive 1-hour time period during sunset-moonrise (SS-MR) and moonset-sunrise (MS-SR): the first hour of the moonrise against the last hour of previous daytime data during sunset, as well as the last hour of the moonset against the first hour of subsequent daytime τ_a during sunrise. These results are shown in Table 4. From this table we can see that MS-SR τ_a differences in the two events are $\leq$ 0.01 for all channels, within the accuracy limit of $\pm$ 0.01 for longer wavelengths and $\pm$ 0.02 for 500 and 440 nm established in AERONET (Holben et al., 1998). They raised to values up to 0.06 in $11^{th} - 12^{th}$ July and 0.03 in $14^{th} - 15^{th}$ July for SS-MR period. This is precisely the period of higher variability in aerosol concentration in both events and hence higher differences are expected.

5.2 Precipitable Water Vapor

The comparison LC-GPS at nighttime was performed using 70 simultaneous LC-GPS pairs of PWV values, and correlation coefficient (R) obtained for both LC Filter#1-GPS and LC Filter#2-GPS was 0.96.

In Table 5 are presented the statistics of the LC-GPS comparison. It includes the mean value of PWV obtained by LC ($\overline{PWV_{LC}}$) and GPS ($\overline{PWV_{GPS}}$), as well as the mean difference between LC and GPS PWV values ($\bar{d}$), the standard deviation (σ) and the root-mean-square-error (RMSE). We found a significant low bias ($<$ 0.03 cm) for LC Filter#1, within the precision $\sim$ 10-20 % established by Schneider et al. (2010). These differences increase up to 0.15 cm by comparing GPS and LC Filter#2, above the expected precision for these two techniques.

These differences were confirmed by the mean PWV values using the two techniques. For Filter#1, nocturnal PWV matches reasonably well with GPS data, showing mean values of 0.68 cm and 0.71 cm for LC and GPS, respectively. A notable overestimation of PWV retrieval using LC Filter#2 is clearly shown in Table 5, with mean values of 0.86 cm and 0.71 cm, respectively.

Regarding σ and RMSE, similar values were obtained in the comparison GPS and both PWV LC channels.

Table 3: κ_j calibration constants extracted for each channel (in nm) obtained during the moonrise of 9^{th} February, 2012.

Channel (nm)	1020	1640	870	675	500	440
κ_j ($W^{-1}m^2nmDC$)	$2.15 \cdot 10^9$	$1.28 \cdot 10^{10}$	$3.02 \cdot 10^9$	$2.29 \cdot 10^9$	$1.74 \cdot 10^9$	$1.41 \cdot 10^9$

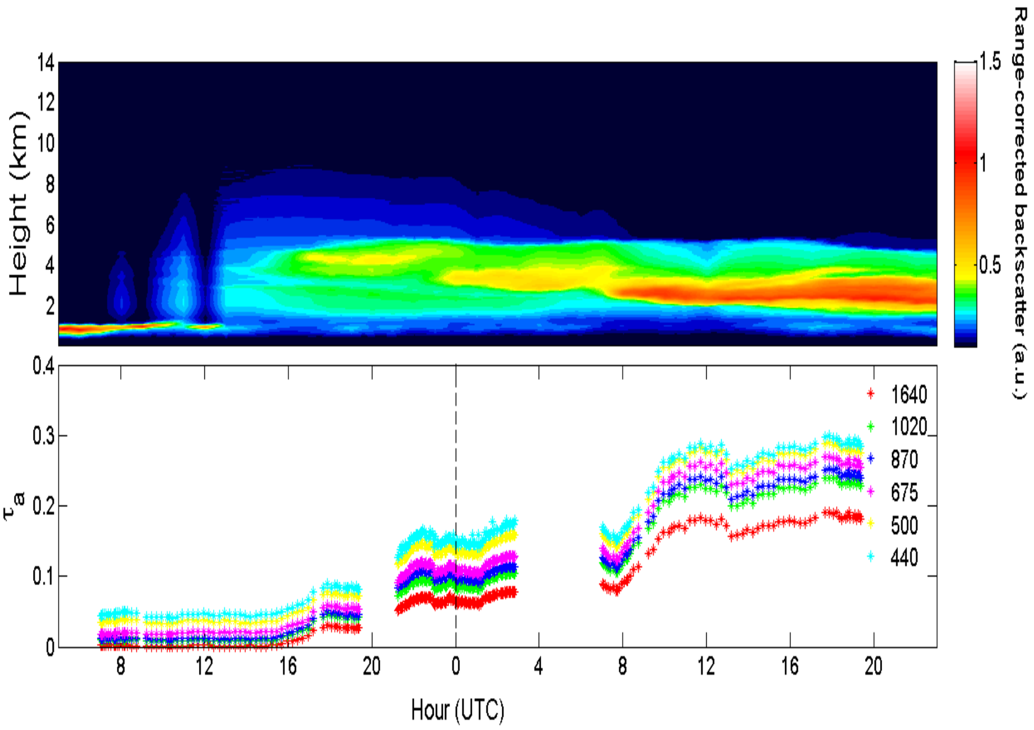

Figure 2: τ_a calculated on $11^{th} - 12^{th}$ July, 2011, using AERONET data for daytime and CE-318U data for nocturnal period. MPL corrected backscatter cross-sections obtained at Santa Cruz station in upper panel.

6 SUMMARY AND CONCLUSIONS

In this paper we have described the new lunar photometer (CE-318U) specifically designed to perform nocturnal photometric measurements, as well as the methodology to infer atmospheric properties and the validation of these results. We derived τ_a and PWV in a two-nights period in July, 2011, and we compared them with daytime observations extracted from AERONET and GPS databases. The new Lunar Langley Method has been used in order to perform the CE-318U calibration. The τ_a comparative study reported discrepancies similar to the sunphotometry precision in the AERONET network ($\pm$0.01-0.02) for those periods not affected by significant aerosol concentration variability. It constitutes a valuable assessment of CE-318U performance. The comparable daytime and nighttime measurements permits to include nocturnal aerosol information in the existing databases. It is of crucial importance for monitoring aerosol transport, specially for high latitude locations, given the extended periods of darkness during winter, to study the effect of aerosol particles on cloud lifetime or nocturnal coverage, and for detecting the sharp changes that aerosol concentration may experience in term of hours during dust events.

Regarding PWV, the comparison showed a good agreement between PWV obtained from GPS and LC Filter#1, with a bias < 0.03 cm. However, higher discrepancies were found between GPS and LC Filter#2 (0.15 cm). It is precisely the filter affected by a notable radiation outside the FWHM, caused by the "filter wings". It demonstrates that the use of the new PWV filter mounted in CE-318U improves notably the precision which is retrieved the atmospheric water vapor.

To conclude, the capabilities of the CE-318U lunar photometer to obtain aerosol properties and PWV at night could be applied to enhance the operational capability of global aerosol and PWV networks.

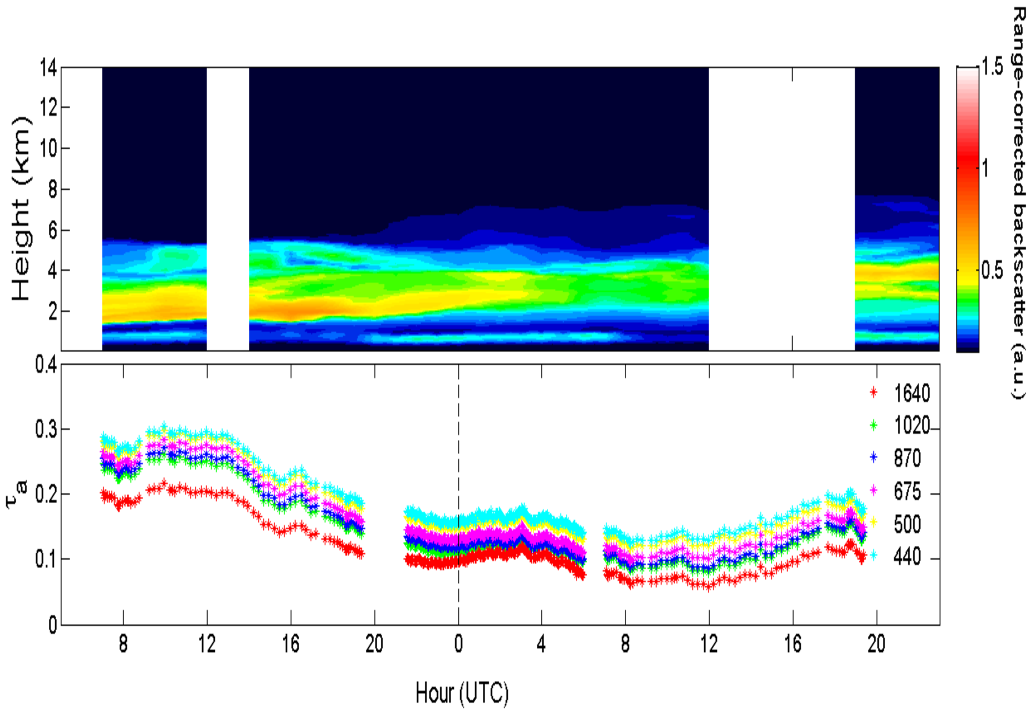

Figure 3: τ_a calculated on $14^{th} - 15^{th}$ July, 2011, using AERONET data for daytime and CE-318U data for nocturnal period. MPL corrected backscatter cross-sections obtained at Santa Cruz station in upper panel.

7 acknowledgements

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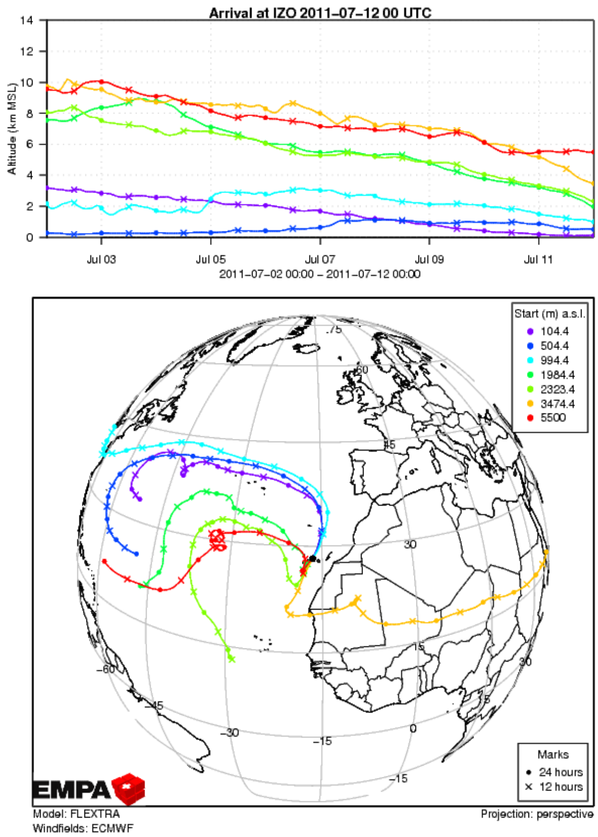

Figure 4: Flextra 10-days backward trajectories plot from Izaña for July 12^{th}, 2011.

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Table 4: τ_a averaged differences between daytime AERONET and LC data during sunset-moonrise (SS-MR, as the last 1 hour of daytime AERONET data versus the first 1 hour of nocturnal CE-1 data) and moonset-sunrise (MS-SR, as the first 1 hour of daytime AERONET data versus the last 1 hour of nocturnal CE-1 data).

	Channel (nm)	1020	1640	870	675	500	440
Jul. $11^{th}-12^{th}$, 2011	SS-MR	-0.03	-0.04	-0.05	-0.05	-0.06	-0.06
	MS-SR	0.01	0.01	0.01	0.00	-0.00	-0.01
Jul. $14^{th}-15^{th}$, 2011	SS-MR	0.02	0.03	0.02	0.02	0.02	0.02
	MS-SR	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01

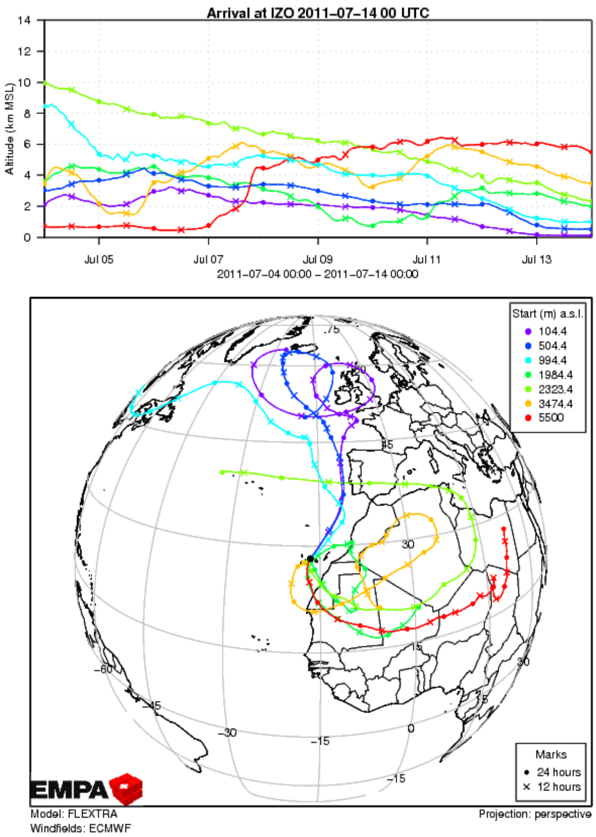

Figure 5: Flextra 10-days backward trajectories plot from Izaña for July 14^{th}, 2011.

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Table 5: Mean PWV values for LC ($\overline{PWV_{LC}}$) and GPS ($\overline{PWV_{GPS}}$) and mean difference ($\bar{d}$), standard deviation (σ) and RMSE, all in cm, obtained from the comparison study between nocturnal LC and GPS techniques.

LC Filter#1/GPS (cm/cm)	$\overline{PVW_{LC}}$	0.683
	$\overline{PWV_{GPS}}$	0.709
	$\bar{d}$	-0.026
	σ	0.181
	RMSE	0.183
LC Filter#2/GPS (cm/cm)	$\overline{PVW_{LC}}$	0.855
	$\overline{PWV_{GPS}}$	0.709
	$\bar{d}$	0.146
	σ	0.153
	RMSE	0.211