Last activities and results of the WMO-CIMO Testbed for Aerosols and Water Vapor Remote Sensing Instruments (Izaña, Spain)

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1. Introduction

The Izaña Observatory (IZO) is a high mountain atmospheric baseline station in which high quality atmospheric observations and scientific research are conducted to monitor atmospheric chemical composition and its related natural and anthropogenic variations capable of forcing climate change. IZO belongs to the State Meteorological Agency (AEMET), within the Ministry for Ecologic Transition, and is managed by the Izaña Atmospheric Research Centre (IARC). IARC hosts a Global Atmospheric Watch (GAW) station since 1984 and has actively contributed to international networks and databases such as Network for the Detection of Atmospheric Composition Change (NDACC), Total Column Carbon Observation Network (TCCON), NASA AERONET (AErosol Robotic NETwork), MPLNet (Micropulse Lidar Network), and GAW PFR (Precision Filter Radiometer) network. Because of the prevalent pristine skies, high atmospheric stability, low and stable total column O_3, and very low atmospheric humidity at IZO, this site results in a suitable location for background monitoring, representative of free troposphere conditions. Taking into account these privileged atmospheric conditions, it has been possible to implement international quality control facilities for several atmospheric parameters at IZO, such as the Regional Brewer spectrophotometer Calibration Centre (RBCC-E), since 2003, one of the two absolute calibration sites of NASA AERONET and AERONET-Europe, and the GAW-PFR sunphotometer triad instrument-members (PMOD-WRC, Davos Switzerland) calibration site. IZO is also a reference station for Fourier Transform Spectrometry (FTS) community.

Figure 1: Spectroradiometers at the Izaña Observatory facility terrace (Tenerife, the Canary Islands, Spain).

The WMO-CIMO Testbed for Aerosols and Water Vapour Remote Sensing Instruments (Izaña, Spain) began activities on July, 2014, when this station was appointed as WMO-CIMO Testbed in the CIMO 16th session held at Saint Petersburg (Russian Federation). In this report, the most outstanding results about all the activities carried out at IZO in the last two years are presented and assessed. These research activities have been framed in the development of remote sensing methodologies and instruments for the continuous monitoring of atmospheric aerosols and column water vapour using photometers, radiometers, and simple lidars/ceilometers. These activities are geared entirely to the development or improvement of new techniques and methodologies for AOD determination, and greatly to mineral dust aerosol.

2. Results of the first multi-instrument lunar photometric campaign was held at Izaña Observatory between June 1th and 17th 2017, including a side workshop on nocturnal aerosols measurement

The Izaña Testbed has been the facility of the first multi-instrument nocturnal aerosol optical depth (AOD) intercomparison campaign held in June 2017, with a parallel workshop on lunar photometry taking place at the time of this campaign. This campaign implied the first opportunity to compare nocturnal measurements taken by the few instruments with capability of monitoring AOD at night: the Cimel CE318-T Sun-lunar-sky photometers, the LunarPFR photometer from World Radiation Center, and a stellar photometer (belonging to University of Granada). The main purposes of this multi-instrument campaign were the identification of standard procedures to monitor aerosols at night-time, and the detection and correction of the most important instrumental problems that currently affects to aerosol monitoring at night. Among these problems arise the need to increase the dynamic range and sensitivity of these sensors as a result of the low incoming signals of the Moon and the stars, to improve the electronics required to increase the signal-to-noise ratio (SNR) under these conditions, and to use a lunar extraterrestrial irradiance model for calibration because the variability of the reflected Sun irradiance with the Moon's cycle,. The latter problem remains a challenging subject of ongoing interest. The Robotic Lunar Observatory (ROLO) model developed by the U.S. Geological Survey (USGS) is considered the most reliable lunar radiometric reference available until now, with an estimated accuracy ranging from 5% to 10% (Kieffer and Stone, 2004, 2005). Its large uncertainty and the restriction in its access make it difficult to be implemented by research groups.

No evidence of significant differences with the Moon’s phase angle was found when comparing raw signals and AOD of the six Cimel photometers involved in this field campaign. The AOD comparison of the two lunar photometers (Cimel and LunarPFR) revealed AOD differences up to 0.015 for higher phase angles. Higher differences were found for 500 nm, being attributed to some technical problems in this spectral band (Figure 2). In the case of the comparison of Cimel and star photometer, differences of ±0.02 were observed, along with noticeable AOD fluctuations in star photometry (Figure 3). The overall conclusion of this study is that the three types of photometers have consistent results, being the small differences observed between them within the expected AOD uncertainty of these photometric techniques. These small differences can be only detectable under pristine sky conditions such as those found in this field campaign.

This campaign was also used to quantify the important technical difficulties that still exist when routinely monitoring aerosol optical properties at night-time as well as to offer a lunar irradiance model (ROLO Implementation for Moon's Observations, RIMO) freely available to the scientific community, which was compared to the reference ROLO model (see next section).

A paper about this field has been submitted to Atmospheric Environment (Barreto et al., 2018, submitted).

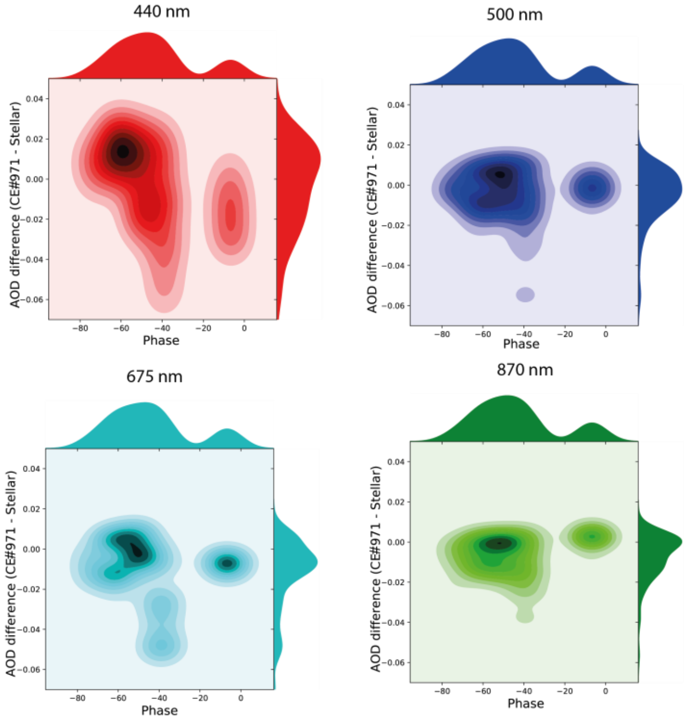

Figure 2: Bivariate kernel density estimate plots of AOD difference (between Cimel CE318-T and LunarPFR) and the Moon's phase angle, calculated with RIMO, for the three coincident spectral bands. Univariate density distribution of each variable is displayed on separate axes (from Barreto et al., 2018).

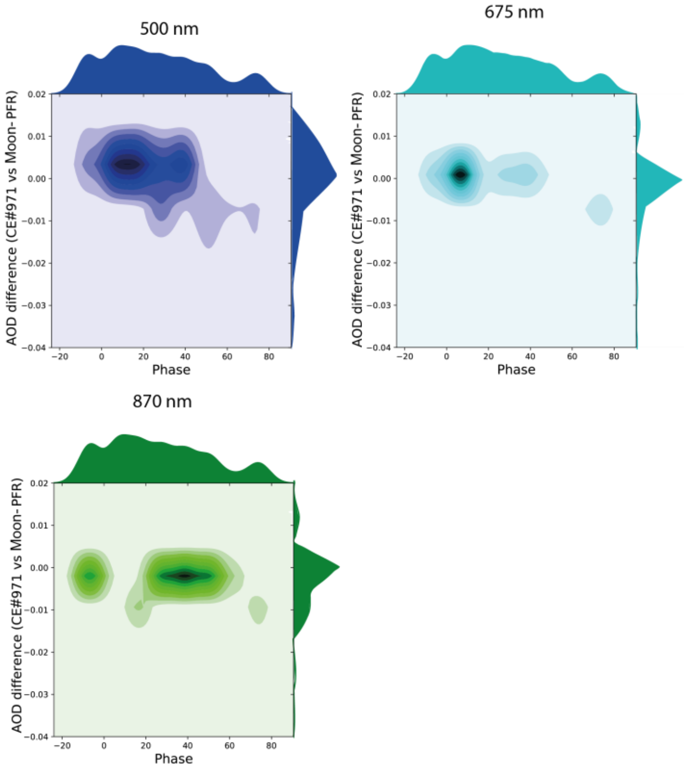

Figure 3: Bivariate kernel density estimate plots of AOD difference (between Cimel CE318-T and stellar photometer) and the Moon's phase angle, calculated with RIMO, for the four coincident spectral bands. Univariate density distribution of each variable is displayed on separate axes (from Barreto et al., 2018).

3. The new open-access "ROLO Implementation for Moon-photometry Observation" (RIMO) model development and comparison with USGS ROLO model

The Moon is considered photometrically stable long term with a similar reflectance level than the Earth and has not atmospheric interference. For these reasons the Moon is an important calibration target for on-orbit sensors, extremely useful to monitor the stability of satellite sensors (detection of possible long-term drifts), to calibrate satellites in orbit and to perform cross comparison of different on-orbit sensors. Therefore, the vicarious calibration and validation using the Moon as reference source is currently be viewed as a key technique to ensure an unprecedented accuracy for past, present and future Earth Observation (EO) missions. In this sense, the absolute uncertainty of the USGS/ROLO model as well as the lack of a unique and easily accessible model remains a challenging subject of ongoing interest for polar lunar photometry and satellite community. As a matter of fact, one of the challenges of the scientific community is the use of a unique reference model for lunar irradiance or to reconcile the existing ones.

We have developed at Izaña Testbed, in the frame of the first lunar photometry campaign and the associated workshop, the open-access ROLO Implementation for Moon-photometry Observation (RIMO) model (Barreto et al., 2018). This model pretends to constitute a unified lunar irradiance model freely available to the scientific community until a new and improved lunar irradiance model is developed and completely available.

Rather small differences were observed over a two-month period between the AOD calculated using the RIMO and USGS/ROLO lunar irradiance models (Figure 4). We concluded that the two models show similar performances during the Moon's cycle.

This model is available at http://testbed.aemet.es/rimoapp/.

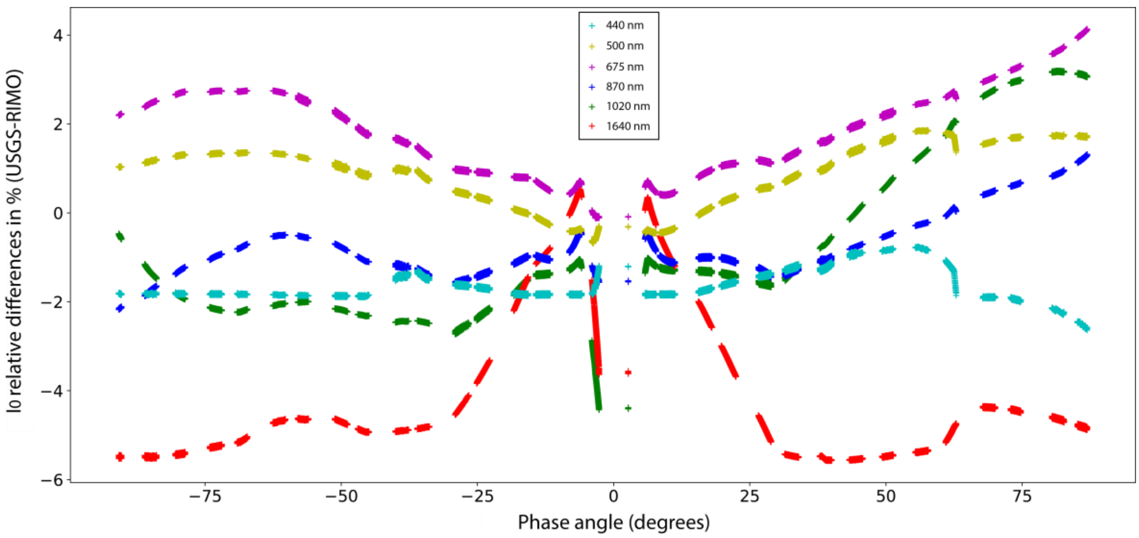

Figure 4: Relative differences between lunar extraterrestrial irradiances (I_0) from USGS/ROLO and RIMO in June-July 2017 at Izaña for the Cimel wavelengths (from Barreto et al., 2018).

4. Synergy photometer/lidar methodologies for retrieving vertical aerosol extinction including a two-layer approach using two sun-photometers located at two different levels

Lidars are the most efficient systems for continuous monitoring the vertical structure of atmospheric aerosols. Taking advantage of the situation of the IARC-AEMET research observatories on the island of Tenerife, and its strategical location within the Saharan Air Layer when it intrudes into the subtropical North Atlantic, one of the Izaña Testbed activities has been focused on a comprehensive assessment of the classical Fernald-Klett method. This method is generally used to retrieve information of vertical extinction profiles, assuming the ratio between the aerosol extinction and backscattering coefficients to be constant in the atmospheric column. This assumption implies the existence of an aerosol vertical distribution with range invariant physico-chemical properties and prevents the accurate derivation of extinction profiles where the atmospheric aerosols properties are range-dependent. It happens typically in the lower atmosphere, and more precisely within the planetary boundary layer (PBL) or in presence of atmospheric layering such the Sahara Air Layer (SAL).

A preliminary two-layer approach has been developed to obtain more reliable vertical atmospheric extinction (α) using Micropulse lidar (MPL-3 Lidar) and AOD measurement at two sites at different heights in Tenerife: Santa Cruz de Tenerife (SCO, 52 m a.s.l.) and IZO stations. With this information we are able to determine two lidar ratios corresponding to two different layers: the lower layer associated to the MBL and the upper layer which typically corresponds to free troposphere conditions.

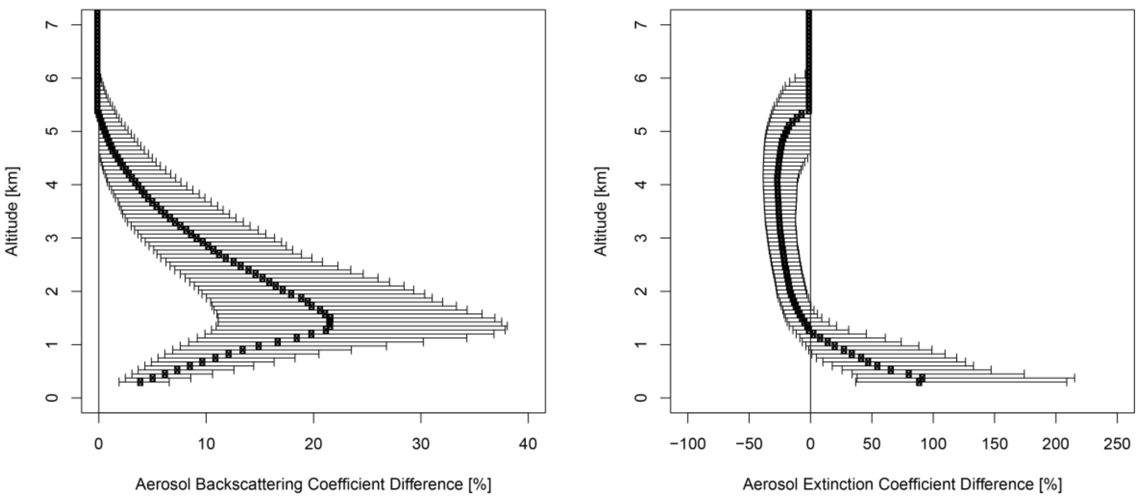

Figure 5: Statistics of the differences on extinction and backscattering coefficients obtained by using One- and Two-layer methods. For each height, median difference, first and third quartile are shown (from Berjón et al., in preparation).

With this new approach, we have obtained a median difference of about 92% at surface level, -25% above the thermal inversion, and the backscattering coefficient showed a median difference up to 21% when the One- and Two-layer methods were compared (Figure 5). The consistency of the lidar ratios retrieved in the upper layer by means of the Two-layer method and an independent method which involves photometric measurements at IZO over a decade is presented in Figure 6. Average discrepancies between these two methods is only about 1 sr, which lead us to conclude that uncertainties commonly associated with the estimation of lidar ratio by the standard One-layer method are notably reduced with the new Two-layer approach.

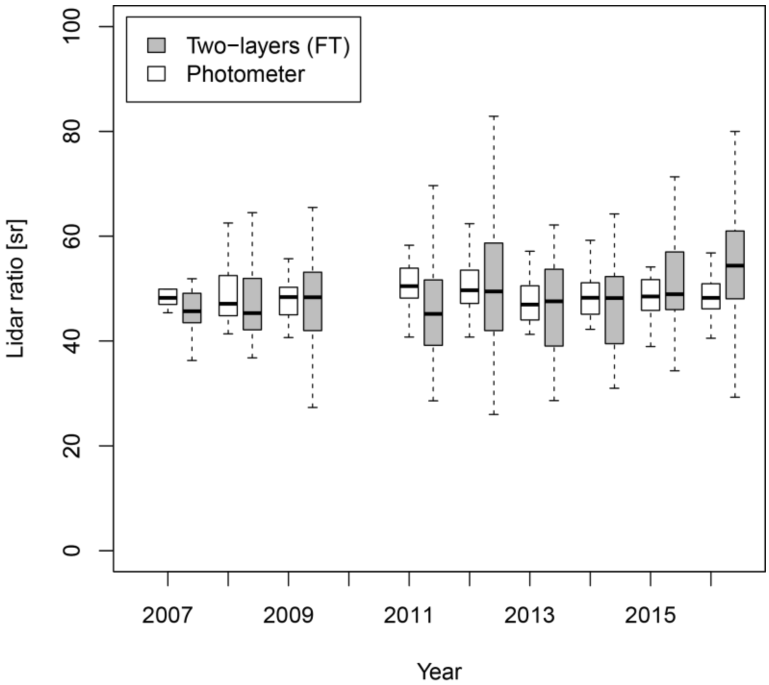

Figure 6: Upper layer lidar ratio from Two-layer method (grey boxes) and from AERONET inversion of the sun photometer data at IZO (white boxes) for each year between 2007 and 2016 (from Berjón et al., in preparation).

Finally, CL51 extinction vertical profiles are routinely computed and submitted to the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Regional Centre for Northern Africa, Middle East and Europe for comparisons with model extinction vertical profiles.

5. Validation of AOD in the UV range using Brewer spectrophotometers in a pre-operational basis

It is well known that the optical properties of aerosols in the UV are quite different from those in the visible. Furthermore, the effect of aerosols on solar UV radiation is important since it is linked with the impact of UV radiation on human health, atmospheric chemistry and biosphere (Carlund et al., 2017; and references therein). AERONET network provides an extensive database of AOD in the UVA spectral range. However, only a few instruments are capable of performing AOD measurements in the UVB. Brewer spectrophotometers, conceived for column ozone monitoring have already demonstrated their ability to measure AOD in this spectral range (see Rodríguez-Franco, 2016; Carlund et al., 2017, López-Solano et al., 2018, and references therein).

The UVB AOD product generated using a common data processing procedure has been developed and assessed within the European COST project EUBREWNET (European Brewer network, http://www.eubrewnet.org/cost1207) at the Regional Brewer Calibration Center for Europe (RBCCE, Izaña Atmospheric Research Center, AEMET), and as part of the activities carried out at the WMO-CIMO Testbed, (López-Solano et al., 2016a; 2016b; 2018). This new algorithm implemented in EUBREWNET produces AOD in an operational basis, allowing real-time aerosols monitoring to more than 50 Brewer instruments operating at 43 sites. These measurements in the UV wavelength range are of high scientific interest, in the particular case of mineral dust, which is responsible of a large contribution to AOD worldwide.

As part of the Izaña Testbed activities, the precision, stability, and uncertainty of the Brewer AOD in the ultraviolet range from 300 to 320 nm have also been carried out by means of an analysis of data from the Brewer intercomparison campaigns in the years 2013 and 2015 and the period in-between. This analysis includes comparisons with Cimel sun photometers and UV-PFR instruments. The results of this analysis showed a Brewer AOD precision better than 0.01 (Figure 7), an uncertainty of less than 0.05 as well as a stability similar to that of the ozone measurements in the case of well-maintained instruments. See López-Solano et al. (2018) for further details.

Future improvements to this algorithm with respect to the input data, data processing, and the characterization of the Brewer instruments for AOD measurement continues to be a specific challenge to solve within the Izaña Testbed activities.

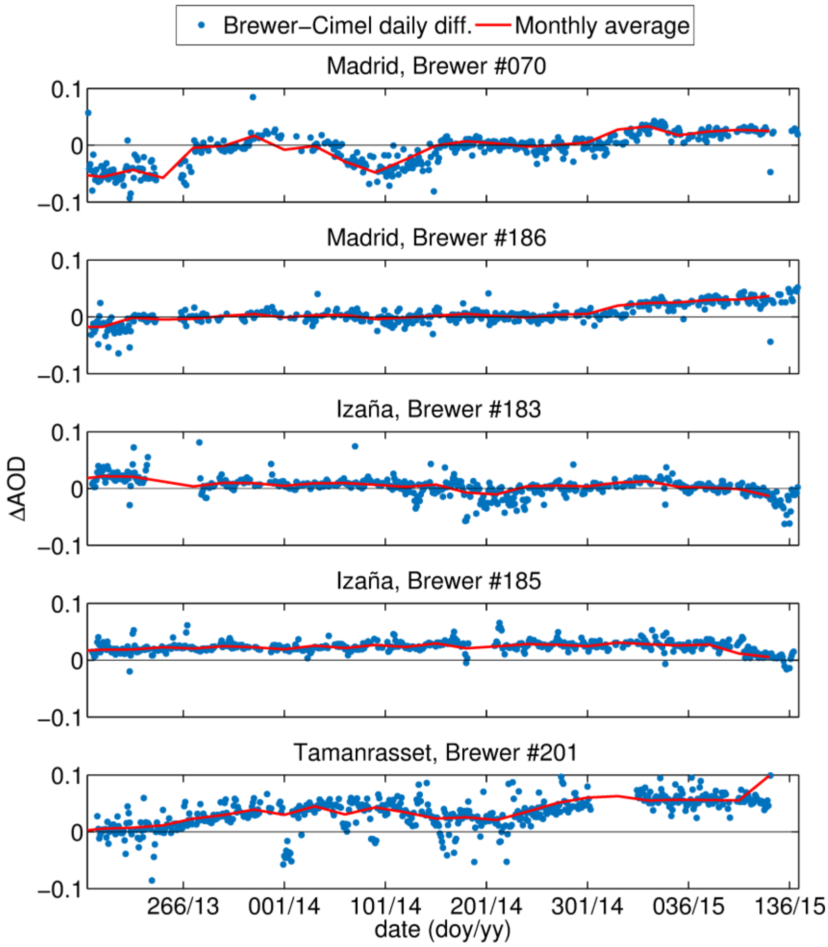

Figure 7: Brewer and Cimel AOD daily difference for the 2013–2015 period for different stations (from López-Solano et al., 2018).

6. Validation of the ZEN-52 zenith radiometer for aerosols and water vapor determination using both Look-up Table and GRASP inversion

One of the most important Izaña Testbed activities geared to the development of new techniques and methodologies for AOD determination and mineral dust characterization is the development in 2016 of the ZEN-R41 prototype (Almansa et al., 2017). This new system is a zenith looking narrow-band radiometer system conceived for dust AOD monitoring, especially in remote areas. Since the most important aerosol source areas are located in remote regions, sparsely populated and difficult to access, the reduced number of stations in these areas restrains the representativeness of the current aerosol networks for constraining global and relatively coarse-resolution models (Boucher et al., 2013) as well as for the validation of satellite products. Despite AERONET is currently the most wide-spread ground-based photometric network, with over 600 stations around the world, the geographic inhomogeneity of the observation sites (strongly biased toward populated regions) is one of the major shortcoming of this type of networks based on high-cost accurate and sophisticated photometers.

The ZEN-R41 prototype and its associated methodology for AOD retrieval were jointly developed by Sieltec Canarias S.L. Company, and the IARC. This system was conceived to expand dust aerosol monitoring from ground-based instrumentation in desert areas with a high degree of autonomy and robustness. It was successfully checked by Almansa et al. (2017), showing a fairly good agreement with AERONET data in Santa Cruz de Tenerife, Izaña, and Tamanrasset stations.

Figure 8: the new 5-channel zenith looking narrow-band radiometer (ZEN-R52), developed by SIELTEC Canarias Company, and the Izaña testbed. (From Almansa et al., in preparation.).

The new ZEN-R52 (Figure 8) is an improved and upgraded version of the ZEN-R41 prototype, with remarkable differences, such as a reduced field of view, an increased signal to noise ratio, better stray light rejection and an additional channel in 940 nm for precipitable water vapor (PWV) retrieval. The scatter plot between ZEN-R52 and AERONET AOD (Figure 9) for two spectral bands (440 nm and 870 nm) showed a good correlation between the two datasets, with a Pearson determination coefficient (R) ≈ 0.99 and low RMSEs (0.015–0.016). Around 97% of points are within the confidence region (defined as 0.04 for AOD below 0.4, or 0.1*AOD for larger AOD values). This analysis clearly shows an improved performance of the ZEN-R52 compared with the old ZEN-R41. In addition, the ZEN-R52 PWV comparison against AERONET data showed R ≈ 0.89 (Figure 10) and concluded that ZSR measurements are sensible to variations in the column water content, providing fair good estimations of PWV.

The new ZEN-R52 system could play a key role in dust models data assimilation nearby dust source regions and satellite validation. It therefore could play a role in dust early warning networks within the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS WAS).

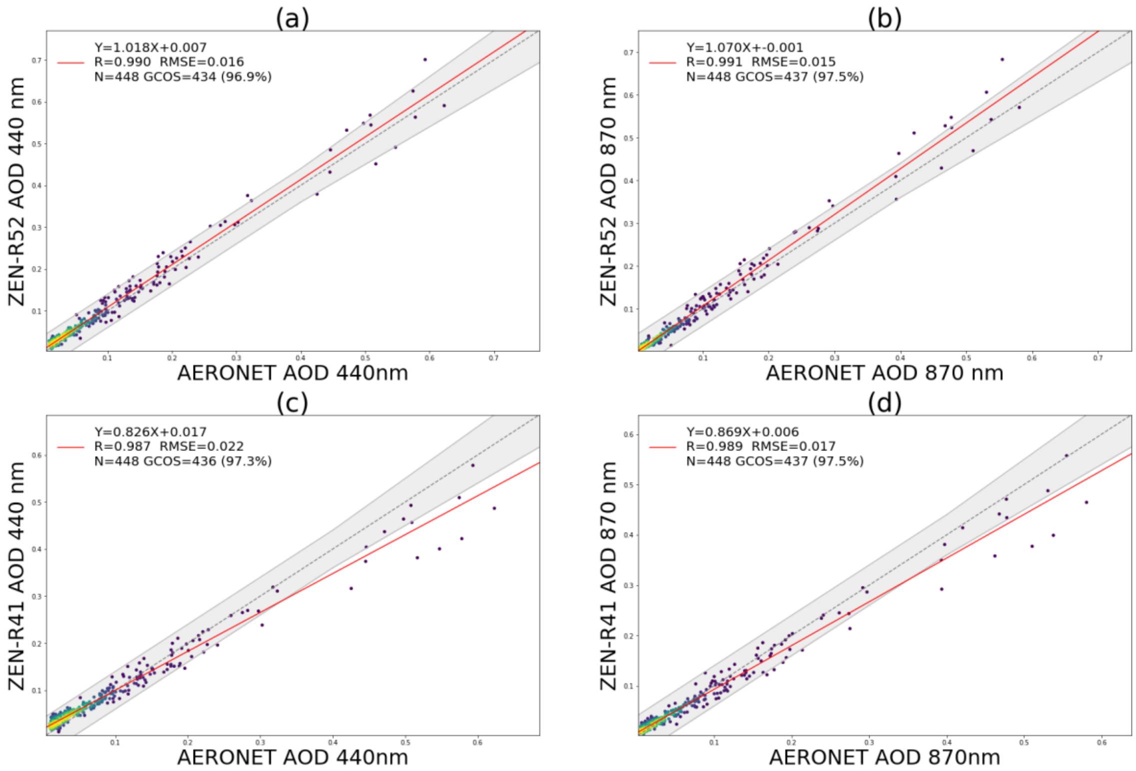

Figure 9: Scatterplot between AOD measured at 440 nm and 870 nm by the two ZEN systems and AERONET data: ZEN-R52 in (a) and (b) and ZEN-R41 in (c) and (d), respectively (from Almansa et al., in preparation).

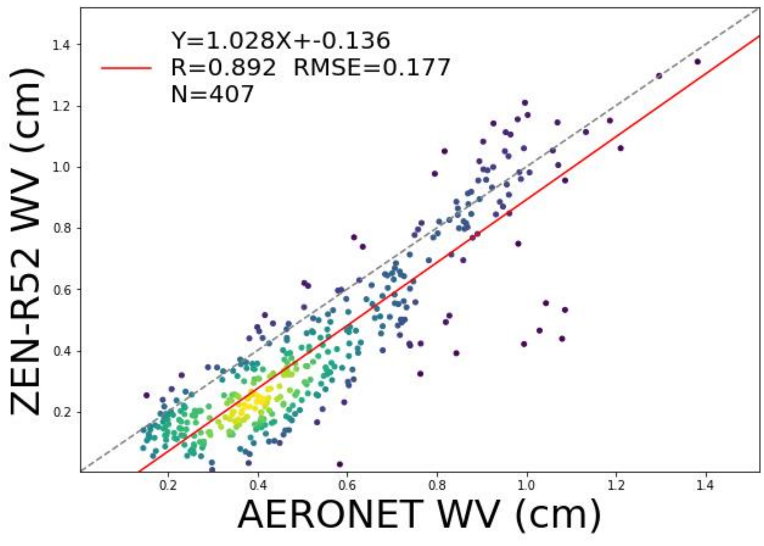

Figure 10: PWV comparison between AERONET and ZEN-R52 (from Almansa et al., in preparation).

7. Aerosols retrievals from spectral direct irradiance measurements with an EKO MS-711 spectroradiometer

EKO MS-711 spectroradiometer (Figure 11 (a)) has been acquired in 2016 by the Izaña Testbed to develop new capabilities in aerosols and PWV monitoring using commercial spectroradiometers. This instrument performs spectral direct solar radiation measurements (spectral direct normal irradiance) (Figure 11 (b)). EKO MS-711 covers a wavelength range from 300 to 1100 nm, exhibiting a full width at half maximum <7 nm. It is equipped with its own built-in entrance optics, and the housing makes the temperature to be stabilized at 25° ± 5° (Egli et al., 2016).

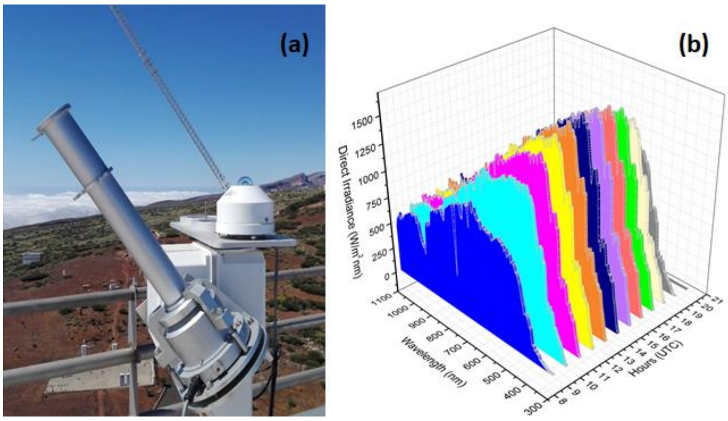

Figure 11: (a) EKO MS-711 spectroradiometer installed at IZO. (b) Example of a spectrum obtained with EKO MS-711 at IZO on June 2, 2017.

This spectroradiometer has been mounted on an Owel INTRA 3 sun-tracker, an intelligent tracker which combines the advantages of automatic-tracking operation (automatic alignment with the system of astronomical coordinates follows after a few days), and actively-controlled tracking (a 4-quadrant sun sensor).

From the measurements of spectral direct solar radiation we have obtained the AOD at several wavelengths coincident with AERONET and GAW-PFR (340, 380, 440, 500, 675 and 870 nm), and PWV using the Bouguer-Lambert law between March and December 2017. A total of 5,547 measurements were used. These results have been compared with AOD performed with CIMEL sun photometer (CE-318) at IZO during this period.

The straightforward comparison between AOD performed with both instruments for all wavelength shows an excellent agreement (Figure 12), more than 97% of the variance agree (R > 0.99) and RMSE (root mean square error) < 0.01 for the wavelengths within the visible range (440,500,675 and 870 nm), and 0.02 for 340 and 380 nm. These results are within the instrumental uncertainty of CIMEL sunphotometer (Holben et al., 2001).

The WMO traceability criteria (Baltensperger et al., 2005) can also be used to check the AOD quality from different instruments. For finite field-of-view (FOV) instruments, this criteria requires at least 95% of the differences between the measurements of two instruments to be within the limits:

$$U95 = \pm (0.005 + 0.010/ma)$$

The percentages of differences within the limits range from 60% at the shortest wavelength and greater than 90% at the longest.

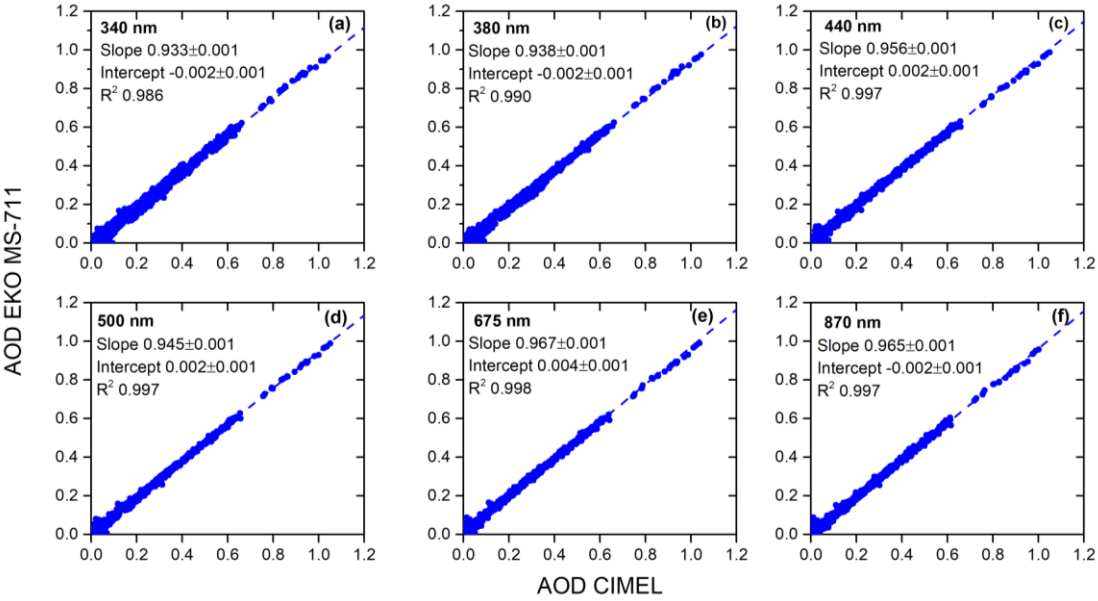

Figure 12: Scatterplot of AOD obtained from spectral direct irradiance performed with EKO MS-711 vs. AOD performed with CIMEL sun photometer between March and December 2017 at IZO at 340, 380, 440, 500, 675 and 870 nm. The fitting parameters of 5,547 simultaneous measurements are shown in the legend.

In order to validate the PWV obtained from EKO-MS711, we have compared with PWV values measured with CE-318 sunphotometer at 940 nm channel. The comparison presented in Figure 13 shows a high correlation (R≈0.990), with a mean absolute difference of 0.4 mm and RMSE of 0.6 mm. Note that 0.2 mm PWV represents the detection limit for most of the instruments.

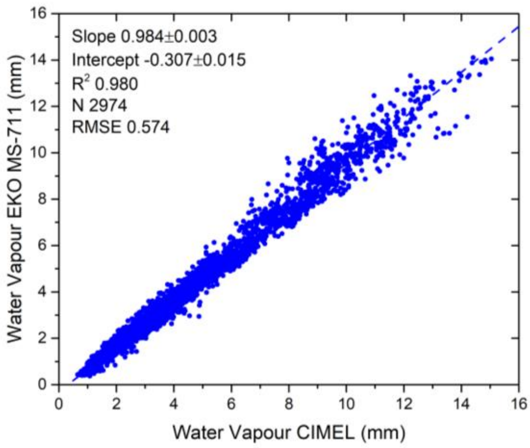

Figure 13: Scatterplot of the water vapour obtained from spectral direct irradiance performed with EKO MS-711 at 941 nm vs. water vapour performed with CIMEL sun photometer between March and December 2017 at IZO. The fitting parameters (2,974 pair data) are shown in the legend.

8. Educational and capacity building activities

From 26 June to 3 July 2017, one hundred Calitoo sun-photometers have been calibrated at Izaña Testbed. This low-cost educational sun-photometer has been manufactured by TENUM and developed under the scientific and technical supervision of the Laboratoire d'Optique Atmosphérique (LOA; CNRS-University of Lille). Calitoos are involved in the Global Learning and Observations to Benefit the Environment (GLOBE) program, which is a worldwide hands-on, primary and secondary school-based science and education program. Two calibrations and evaluations of hand-held sunphotometers involved in the Global Learning and Observations to Benefit the Environment (GLOBE) Programme have been carried out in 2014 and 2015.

The Ministry of Education and Universities of the Canary Islands Government and AEMET-IARC have initiated a joint project to raise awareness of the problem of airborne dust and its impacts on health and the environment throughout the educational community in April 2018. This project, called “Calima”, includes the pioneering use of remote sensing instruments, and specifically low cost sun photometers designed and produced for the GLOBE project. These photometers are Calitoo models, manufactured by Tenum. The Canary Islands Government has purchased 10 of these photometers which have been calibrated and checked at the Izaña Observatory (AEMET). A user-friendly interface based on mobile phones has been developed at IARC so that students can send AOD data to a centralized database of the CALIMA project with their own means.

9. New scientific equipment

New scientific equipment that contributes to increase the technical capabilities of Izaña Testbed has been obtained through the project “Equipment for the Monitoring and Research on the atmospheric components that cause and modulate climate change at the Izaña GAW (Global Atmospheric Watch) (Tenerife)” (contract nº AEDM15-BE-3319). The new Ulbricht integrating 20’’ sphere with four lamps inside is used for conducting radiance calibrations of the CE318-T in the SKY mode. The radiance calibrations (SKY) are important to determine, by conducting atmospheric inversion modelling, aerosols optical proprieties and size distribution. Three new CE318-T photometers have been purchased under this project, and they will be mainly used for quality assurance activities at Izana, and at the satellite station of Teide Peak Observatory, where moon irradiance measurements are performed in order to develop a new model of lunar irradiance for calibration satellite atmospheric sensors calibration.

This R+D infrastructure project has been financed by the State Research Agency of the Ministry of Economy, Industry and Competitiveness, in the Call for projects of scientific equipment, co-financed with ERDF funds.

10. Conclusions and final remarks

The Izaña testbed has ideal conditions adequate infrastructure and equipment necessary to perform tests and evaluation of new remote sensing methodologies and techniques for detecting aerosols and water vapor, as it has been well evidenced by the achievements and developments carried out since July 2014.

In particular Izaña testbed offers ideal conditions to test methodologies and techniques for measuring mineral dust, and hence for assessing the performance of remote sensing instruments designed for the detection and monitoring of volcanic ash clouds.

In the next three years Izaña testbed will incorporate new remote sensing techniques, as lidar Raman, cloud radar, and microwave radiometer, in order to improve its capacity as testbed for aerosol and water vapour.

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