WMO-CIMO Testbed for Aerosols and Water Vapor Remote Sensing Instruments (Izaña, Spain)

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1. Introduction

The Izaña Observatory (IZO) is an atmospheric baseline site that conducts research related to atmospheric constituents which are capable of forcing climate change through modification of the atmospheric radiative environment (greenhouse gases and aerosols), and those that may cause depletion of the global ozone layer. IZO is managed by the Izaña Atmospheric Research Centre (IARC), from the Meteorological State Agency of Spain (AEMET), which is supervised by the Ministry of Agriculture, Food and Environment. IARC has been actively contributing to international networks and databases. It hosts a Global Atmospheric Watch (GAW) station since 1984, and the Regional Brewer spectrophotometer Calibration Centre (RBCC-E) since 2003. At present IZO is an absolute calibration site of NASA AERONET (AErosol Robotic NETwork) and AERONET-Europe. Instrument-members of the GAW-PFR sunphotometer triad (PMOD-WRC, Davos Switzerland) are permanently calibrated at Izaña. IZO is also a reference station for Fourier Transform Spectrometry (FTS) community.

Figure 1; The Izaña Atmospheric Observatory facility (Tenerife, the Canary Islands, Spain).

Izaña was appointed as the WMO-CIMO Testbed for Aerosols and Water Vapour Remote Sensing Instruments on July 2014 during the CIMO 16th session was held at Saint Petersburg (Russian Federation). In this report, the most outstanding results achieved since July 2014, as well as going activities and forthcoming projects are presented and assessed.

1. Achievements

The first activity in 2014 related to the development of new technologies and methods of observation was the retrieval of an aerosol optical depth (AOD) long term series (1976-2012) at Izaña (Tenerife, Spain) using the Mark-I potassium-based resonant scattering spectrometer. This instrument, from the Instituto de Astrofísica de Canarias (IAC) has been successfully running and providing unique information on the sensitivity of helioseismic parameters since 1976. The development of a new methodology to derive AOD from the Mark-I measurements has permitted the recovering of an AOD long term series (37 years), that can be considered as one of the longest existing high-accuracy AOD records in the world (Barreto et al., 2014).

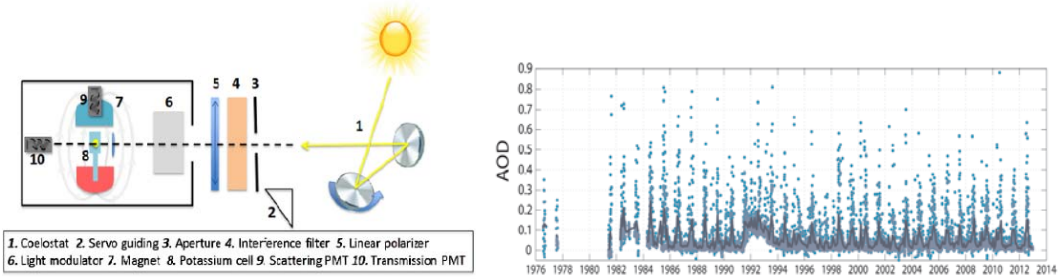

Figure 2; Scheme of the Mark-I spectrometer (left), and AOD long-term series obtained with Mark-I (from Barreto et al., 2014).

Simultaneously to the development of the previous project, we began to conduct studies to perform AOD observations during the night. Several lunar-photometer prototypes (i.e. modified CE318-N and CE318-U) capable of measuring aerosols and column water vapour during the night period have been developed and tested at IZO in collaboration with Cimel Electronique (http://www.cimel.fr). New methodologies for calibration and standard operation have been designed and implemented. The final version, the CE318-T, is able to perform day and night time photometric measurements using the sun and the moon as light sources, respectively (Barreto et al., 2016). This new photometer permits obtain a complete cycle of diurnal aerosol and water vapour measurements valuable to enhance atmospheric monitoring. Two new methodologies to transfer the calibration from a reference instrument using only daytime measurements (Sun Ratio and Sun-Moon gain factor techniques) have been developed and evaluated. These methods allow the reduction of the previous complexities inherent to nocturnal calibration. A quantitative estimation of CE318-T AOD uncertainty by means of error propagation theory during daytime and night period has been assessed. Subsequent comparisons with reference instruments have served to assess the CE318-T performance, day and night, as well as to confirm its estimated uncertainty. The CE318-T has been recently adopted by AERONET as the new standard instrument of the network. This new instrument will allow extending the period of aerosols surveillance (day and night), improving significantly the dust storms and volcanic ash monitoring and providing complementary data to lidar and ceilometer networks.

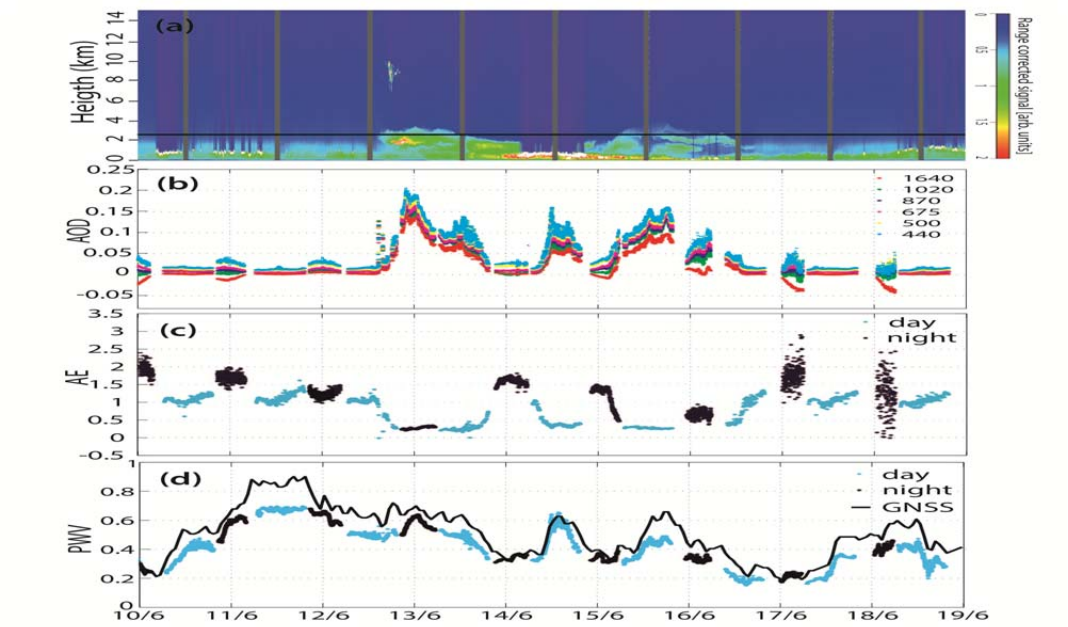

Figure 3; Day and night AOD, Ängstrom exponent (AE), and precipitable water vapour (PWV) at Izaña obtained with the new CE318-T photometer (from Barreto et al., 2016).

The reconstruction of long-term data series of aerosols has been one of our priorities because it's importance in studies of climate and its variability. The reconstruction of a 73-year time series of AOD at 500 nm at IZO has been achieved by using artificial neural networks (ANNs) from 1941 to 2001 and AOD measurements directly obtained with a Precision Filter Radiometer (PFR) between 2003 and 2013. The ANN AOD time series has been comprehensively validated against coincident AOD measurements performed with a solar spectrometer Mark-I (1984–2009) and AERONET CIMEL photometers (2004–2009) at IZO, obtaining a rather good agreement on a daily basis (Pearson r=0.97 between AERONET and ANN AOD, and 0.93 between Mark-I and ANN AOD estimates). The ANN method has proved to be a very useful tool to obtain daily AOD_500 values from meteorological input data, such as the horizontal visibility, fraction of clear sky, and relative humidity recorded at IZO. This methodology might be extrapolated to other sites, especially those affected by high dust loads. See García et al. (2016). This methodology might be extrapolated to stations with long-term meteorological records in desert regions for estimating long AOD records might be used in climate studies.

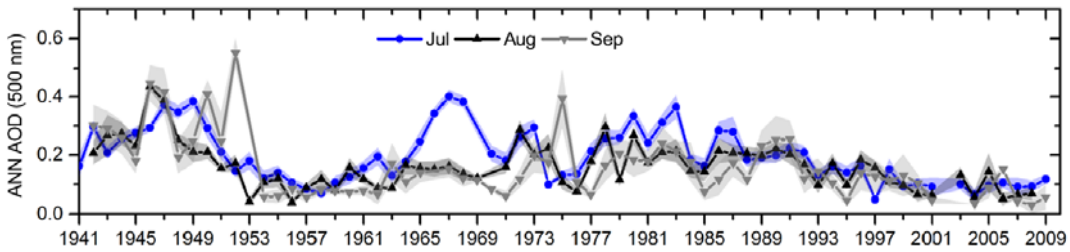

Figure 4; Reconstructed long-term AOD data series (1941-2013) for July, August and September at the Izaña Atmospheric Observatory (from García et al., 2016).

In another completely different field of research, the development of methodologies envisaged obtaining vertical profiling of HDO/H216O, and corresponding validation and comparison with in-situ airborne and ground-based observations during the MUSICA remote sensing validation campaign were performed during 2014 and 2105. The project MUSICA (MUlti-platform remote Sensing of Isotopologues for investigating the Cycle of Atmospheric water, http://www.imk-asf.kit.edu/music a), supported by the European Research Council within the Seventh Framework Programme (FP7/2007-2013/ERC Grant Agreement, nº 256961), has as main goal the generation of a high-quality database in a global scale of tropospheric water vapour isotopologues (H216O y HD16O) from ground-based remote measurements (Fourier Transform InfraRed spectrometers, FTIR) and space-based platforms (Infrared Atmospheric Sounding Interferometer, IASI, on board the satellites EUMETSAT/MetOp-A and MetOp-B). The Izaña Tesbed has played a very active role in MUSICA being the main station supporting different experiments. The results of this project will contribute to a better understanding of the different processes affecting the cycle of atmospheric water and its link to the energy balance at a global scale. Last results have been published by Dyroff et al. (2015), González et al. (2015), and Schneider et al. (2015; 2016).

2. On-going activities

The activities we are carrying out as a testbed are geared entirely to the development or improvement of new techniques and methodologies for AOD determination, and greatly to the mineral dust aerosol.

The USGS (United States Geological Service) Robotic Lunar Observatory (ROLO) provides radiometric calibration and sensor stability monitoring for space-based remote sensing instruments using the Moon as a reference source. We have developed at Izaña Testbed a modified version of ROLO in order to be used in calibration and observation of nocturnal AOD and water vapor with the Lunar Cimel photometers. We are studying the evolution of AOD at nighttime in a sufficiently high number of clean and stable nights at Izaña high mountain observatory. We have detected a significant bias with moon's phase and zenith angles, especially in longer wavelength channels. Working under the assumption of stable AOD conditions, we are doing the parameterization of this residual dependence in nocturnal AOD in terms of moon's phase and zenith angles through an empirical regression model. We expect AOD at nighttime will be significantly corrected with averaged errors < 0.01, below the CE318-T photometer precision. This improvement of Izaña's ROLO outputs permits to obtain more accurate calibrations and AOD observations during the night period. A scientific article explaining the main results will be submitted for publication soon.

AERONET is the largest and most important global aerosol network providing unique information on atmospheric column aerosols in more than 400 stations globally, allowing adequate spatiotemporal characterization of aerosols. It is also of great importance for assessing AOD obtained from models and satellite sensors. However AERONET is not yet contributing to the WMO GAW program because there are no studies on the comparability and compatibility of AERONET observations and calibration procedures with those of the GAW-PFR network managed by PMOD-WRC. This fact means losing outstanding information on atmospheric aerosols trends and characterization might be provided by AERONET. For this reason we are performing a comprehensive AERONET/WRC-PFR long-term AOD comparison assessment. The main objective of this study is to provide consistent, detailed and accurate information on the degree of agreement between AERONET-Cimel and GAW-PFR observations. For this, a long-term intercomparison Cimel/AERONET – PFR/GAW at Izaña in the period January 2005 – November 2014 (10 years) has been performed in collaboration with PMOD-WRC using 1' minute simultaneous Cimel-PFR AOD data at 500 and 870 nm channels. A total of 15 Cimel sunphotometers and 3 PFR were used during this period. Preliminary results indicate that more than 93% of 1-minute AOD differences at 500 and 870 nm (more than 81,000 data in each channel) fell within the AOD 95% uncertainty limits defined by WMO. A scientific paper with these results is in preparation.

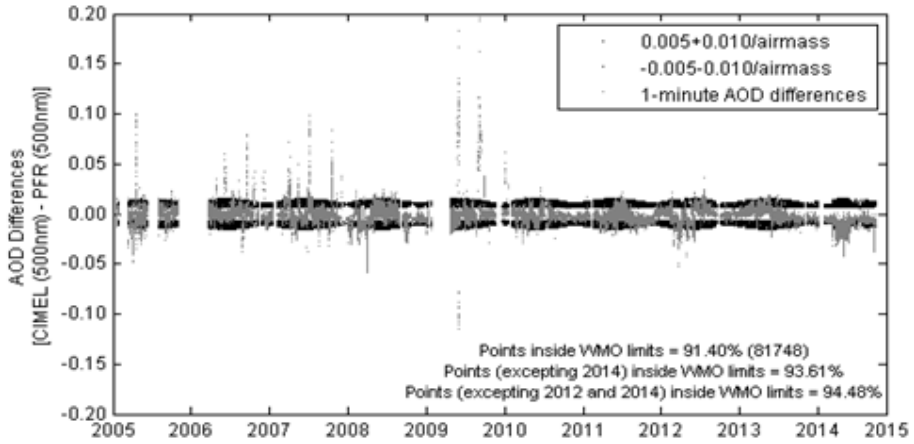

Figure 5; Long-term differences of AOD @500nm between AERONET-Cimel and GAW-PFR instruments. (10 years) at the Izaña Atmospheric Observatory (from Romero Campos et al., in preparation).

On the other hand we are working on the establishment of permanent traceability between Cimel masters at Izaña, used to transfer calibration to station Cimel instruments from AERONET-Europe, and GAW-PFR reference. To face this issue we are carrying several actions. The first activity was the participation with two masters (CE318-N and the new CE318-T) in the 4th WMO Comparison Filter Radiometer (FRC-IV) was held from September 28 - October 16 2015 in Davos, Switzerland. More than 99% of 1-miniute AOD differences at 500 between AERONET and PFR reference fell within the AOD 95% uncertainty limits defined by WMO. The good agreement between the Cimel Masters and the GAW-PFR triad will be shown in the Campaign Report (Kazadzis et al., 2016). At present we are working, in close collaboration with PMOD-

WRC, in designing procedures, and corresponding protocols, to ensure traceability of the AERONET-Cimel Masters calibrated at Izaña with GAW-PFR Masters which form part of the PMOD-WRC PFR triad and that are, in each moment, at Izaña. An AERONET CE318-T Master will be installed permanently at Izaña to be intercompared on a continuous-basis (in the common channels) with PFR-Masters, and transfer / validate these calibrations to Cimel travel Masters. Calibration and traceability procedures between PMOD-PFR and Cimel AERONET-Europe will be hopefully implemented within the next two years.

A new zenith looking narrow-band radiometer system (ZEN), conceived for dust AOD monitoring has been developed and implemented at the Izaña testbed (see presentation S1 in this Conference from Almansa et al.). The ZEN system comprises a new four channel radiometer (ZEN-R41), developed by SIELTEC Canarias company and the Izaña testbed. This prototype version consists of four separate channels with a ~3º field of view, equipped with four Silicon detectors (350-1100nm) and four optical filters of 10 nm FWHM with nominal wavelengths centered in 440, 500, 675 and 870 nm, respectively. This instrument has been designed to be stand-alone and without moving parts, making ZEN-R41 a low-cost and robust instrument with low maintenance, appropriated to be deployed in remote and unpopulated desert areas. Dust AOD is inferred from Zenith Sky Radiances (ZSR) using a lookup table (LUT) methodology based on a set of simulated ZSR and AOD values obtained with LibRadtran radiative transfer code. The validation of the LUT technique was performed using as reference AOD from AERONET located in three sites characterized by regular presence of desert mineral dust (Izaña and Santa Cruz de Tenerife, and Tamanrasset in Algeria). The results show a R^2 ranging from 0.99 at Santa Cruz to 0.95 at Tamanrasset, and a maximum root mean square error (RMSE) ranging from 0.010 at Izaña to 0.035 at Tamanrasset. The comparison of ZSR values from ZEN-R41 and the CE318 showed absolute relative mean bias (RMB) <10%. ZEN-R41 AOD values inferred from LUT methodology were compared with AOD provided by AERONET, showing a fairly good agreement in all wavelengths, with absolute AOD differences < 0.030, and R^2 higher than 0.97. A paper about this new development has been submitted to AMT (Almansa et al., submitted).

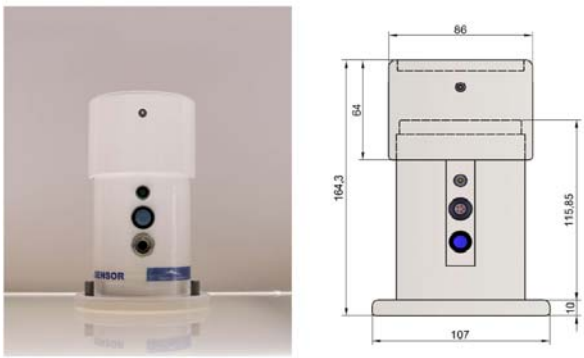

Figure 6; the new 4-channel zenith looking narrow-band radiometer (ZEN-R41), developed by SIELTEC Canarias company and the Izaña testbed. (from Almansa et al., Submitted to Atmos. Meas. Tech.).

A preliminary two-layer approach to obtain vertical atmospheric extinction (α) at Santa Cruz de Tenerife station (Canary Islands, Spain) using Micropulse lidar (MPL-3 Lidar) and CL-51 Vaisala ceilometer has been developed. Uncertainties commonly associated with the estimation of Lidar Ratio (LR) are notably reduced by using a two-layer inversion model, in which AOD is extracted from two different sun-photometers

located at two different layers: one in Santa Cruz de Tenerife coastal station (SCO, 52 m a.s.l.) and another one at high mountain IZO. Comparisons between MPL-3 and CL51 extinction vertical profiles are routinely performed 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.

Brewer spectrophotometers, conceived for column ozone monitoring have already demonstrated their ability to measure AOD in the UV range (see Rodríguez-Franco, 2016; Carlund, 2016, and references therein). Within the COST Action 1207 – European Brewer Network (EUBREWNET; http://rbcce.aemet.es/eubrewnet), at the Regional Brewer Calibration Center for Europe (RBCCE, Izaña Atmospheric Research Center, AEMET) a new AOD product in the UV range has been developed and assessed using the Izaña Testbed facilities and ancillary data (López-Solano et al., 2016a; 2016b). This new algorithm is being implemented in EUBREWNET to produce AOD in an operational basis. It will allow real-time aerosols monitoring at more than 20 Brewer stations, from Algeria to Finland.

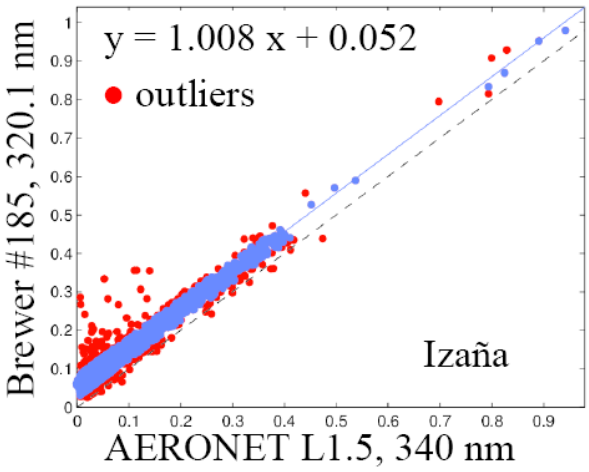

Figure 7; AOD@320 from Brewer#185 nm vs. AOD@340nm from AERONET at Izaña Testbed (from López-Solano et al., 2016b).

The Izaña Tesbed site has been used for different field campaigns of radiation/aerosols prototypes, such as the new Precision Solar Spectroradiometer (PSR), developed at PMOD/WRC, which will replace or complement current filter PFR sunphotometers for long-term AOD monitoring and absolute solar irradiance measurements. This instrument has been absolutely calibrated at Izaña with Langley technique and compared with other reference photometers. Preliminary stellar measurements have also been performed.

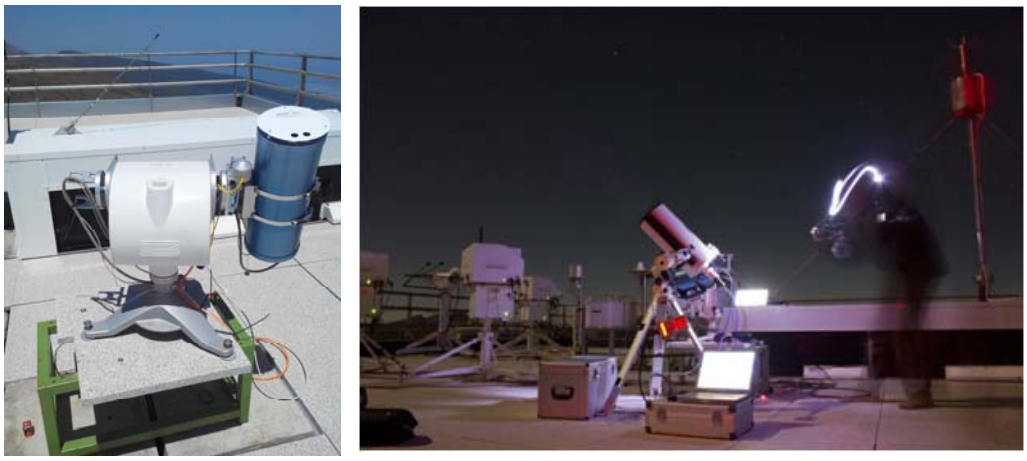

Figure 8; The new Precision Solar Spectroradiometer (PSR) developed at PMOD/WRC, at the Izaña Testbed during sun observations (left) and stellar observations (right).

The Izaña Testbed has been the facility of an intensive 2-month campaign for the determination of the NIR irradiance spectra will be used to retrieve the top-of-atmosphere (TOA) solar spectral irradiance through wavelength ranges free of O2, O3, CO2 and H2O absorption the Bouguer-Langley technique. The results obtained within this campaign are expected to solve some discrepancies observed in published TOA solar spectra in the infrared range. An accurate knowledge of the NIR TOA solar irradiance is important due to its role in Earth radiative budget, namely atmospheric and upper layer of the ocean absorption processes. NIR TOA is also needed to validate semi empiric models of solar atmosphere. Results have been reported by Bolsée et al. (2014).

Two campaigns of TENUM Calitoo hand-held photometers (http://www.calitoo.fr/index.php?page=calibration) in 2014 and 2015.

During September 2016, a 3-week large Dobson-Brewer campaign will be held at Izaña in collaboration with PMOD-/WRC. During this campaign we will have another opportunity to perform an accurate comparison of PFR masters (two), a UV-PFR, a PSR and two AERONET Cimel Masters, including the new CE318-T.

3. Forthcoming projects

The Generalized Retrieval of Atmosphere and Surface Properties (GRASP) algorithm, developed at LOA (CNR-Université de Lille; France), infers a high number of aerosol and surface parameters including particle size distribution, the spectral index of refraction, the degree of sphericity and absorption. The algorithm is designed to retrieve aerosol properties from spectral, multiangular polarimetric remote sensing observations. We have agreed with GRASP team to implement and test GRASP in nocturnal observations with the new CE318-T (see section 1.1.) at Izaña Testbed and

at the Santa Cruz satellite station at sea level. GRASP will be also implemented to obtain inversion products with the ZEN-R41 instrument (see previous section).

Getting AOD from PANDORA photometer as a contribution to the global PANDONIA network will be one of the next steps. The first PANDORA photometer was conceived to monitor atmospheric column trace gases. However, a new Pandora dual spectrometer system (Pandora-2S) is being developed by Luftblick company (Austria), as an evolution of the existing Pandora. Pandora-2S contains two spectrometers, capable of covering the full wavelength range up to 900 nm, and will capable to obtain spectral AOD over the entire range 300-900nm (SpecAOD) within ±0.05 what would extend its capability as ground based instrument for satellite observations evaluation. Development and evaluation of new algorithms for aerosol retrieval with the new PANDORA-2S spectrometer, in collaboration with Luftblick and PMOD-WRC, will be a future activity of the Izaña Testbed. This instrument will form the new PANDONIA global network whose Reference Triad will be maintained at Izaña.

4. Capacity building activities

Training courses about sunphotometry for operators and technicians of the AERONET stations at Ouarzazate (Morocco), Tamanrasset (Algeria), Cairo (Egypt) and Tunis (Tunisia) in 2014 and 2015. Two new missions for Algeria and Tunisia will be carried out in Autumn 2016. A new ZEN-41 will set up at the GAW Tamanrasset station, in collaboration with the “l’Office National de la Météorologie– Algerie” to be tested under strong desert dust conditions.

Two calibration and evaluation 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.

5. 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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