Desert dust remote sensing with the new zenith looking narrow-band radiometer based system (ZEN)

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ABSTRACT

The main features and performance of the new zenith looking narrow-band radiometer based system (ZEN) are presented in this study. The instrument has been jointly developed by SIELTEC Canarias S.L. company and the Izaña Atmospheric Research Center (IARC) from the State Meteorological Agency of Spain (AEMET). The ZEN system has been conceived to retrieve dust Aerosol Optical Depth (AOD) by means of a simple operational technique, which involves zenithal measurements of downwelling sky radiance in four narrowband channels using the ZEN-R41 radiometer and a look up table (LUT) based methodology, especially designed to infer AOD for desert aerosols. The new ZEN-R41 instrument has been designed to operate without moving elements, such as tracking system or filter wheel. These features make the ZEN-R41 a low-cost instrument more robust and less prone to suffer operational failures than those photometers equipped with sun tracking system. Such characteristics are especially desirable in remote places like deserts where appropriated maintenance by qualified staff is not always available.

The performance of two ZEN-R41 instruments and the LUT methodology have been assessed at Tamanrasset (Algeria) and Izaña (Tenerife, Spain) Global Atmosphere Watch (GAW) stations by comparing with collocated standard AERONET (AErosol RObotic NETwork) Cimel instruments. This validation analysis was performed specifically for mineral dust aerosol conditions. The results are very promising, indicating that this inexpensive instrument might be suitable to monitor atmospheric dust with little maintenance in remote desert locations, allowing us to fill important observational gaps in such areas.

1. INTRODUCTION

The growing scientific interest in atmospheric aerosols relies on the important role these atmospheric constituents play in climate and atmospheric chemistry, with significant local, regional and global impacts. The aerosols concentration, composition and size distribution are spatially and temporally highly variable, and the high complex interactions with other atmospheric constituents hinder an accurate determination of their climate effect. In fact, according to the latest report of the Intergovernmental Panel on Climate Change (IPCC) (Klein et al., 2010; Hoose and Möhler, 2012; Stocker et al., 2013), atmospheric aerosols are one of the main drivers of climate change and the most uncertain of them.

At present, there exist extensive networks of ground-based sun-photometers devoted to the atmospheric aerosol monitoring. These networks, such as the Aerosol Robotic Network (AERONET), have an extensive global coverage in order to adequately monitor the aerosol spatial distribution and their regional effects. As a matter of fact, AERONET is composed of hundreds of stations distributed all over the world using the CE318-N (CE318-AERONET hereinafter) as standard instrument (Holben et al., 1998). However, there is currently a lack of stations in the desert regions of the Northern Hemisphere, preventing the aerosol monitoring near the most important mineral dust sources and the adequate description of dust cycles. This lack of information is mainly due to the operational problems that are prone to occur with instruments operating with moving elements such as sun trackers or filter wheels, which increases considerably the power consumption and the cost of the instrument and its maintenance, in addition to the absence of appropriated maintenance by qualified staff, which is not always available in remote areas.

Almansa et al. (2016) presented a new zenith looking narrow-band radiometer based system (ZEN) conceived to estimate the dust Aerosol Optical Depth (AOD) by means of downwelling Zenith Sky Radiance (ZSR) measurements. This ZEN system comprises the radiometer ZEN-R41, designed to be stand-alone and without moving parts, making it a low-cost instrument more robust and automated than the standard sun photometers, and a look up table (LUT) based methodology, especially designed to infer AOD for desert aerosols. All these features make ZEN a suitable system to fill the current observational gaps in the AOD series in remote desert areas. However, as Almansa et al. (2016) stated, the use of ZSR to estimate the AOD is not as straightforward as the classic methodology of direct sun observations. AOD estimation in this case requires the development of a LUT methodology using LibRadTran radiative transfer code

(Mayer and Kylling, 2005; Emde et al., 2016) to simulate ZSR and the associated AOD values. Then, AOD is inferred by minimizing the difference between simulated and measured ZSR values at a corresponding solar zenith angle (SZA) and wavelength.

Almansa et al. (2016) also performed a preliminary evaluation of the LUT methodology by means of an AOD comparison analysis between AERONET and LUT CE318-AERONET data for Izaña, Santa Cruz and Tamanrasset stations in 2013 showing high correlations (0.95 to 0.99) and maximum root mean square error (RMSE) ranging from 0.010-0.035. Then, both the LUT and the ZEN-R41 performance was evaluated at Izaña in 2015 with a good agreement in all wavelengths (correlations > 0.97), and absolute AOD differences < 0.030.

We present in this work an assessment analysis of two ZEN instruments installed at Tamanrasset (Algeria) and Izaña (Tenerife, Spain) Global Atmosphere Watch (GAW) stations by means of an intercomparison with collocated CE318-AERONET instruments during 2015-2016. These two analyses have been restricted to mineral dust aerosol conditions.

2. MEASUREMENT SITES

We have carried out the ZEN evaluation at Izaña (28.3°N; 16.5°W; 2373 m a.s.l.) and Tamanrasset (22.8°N; 5.5°E; 1377 m a.s.l.) GAW stations. Izaña (Canary Islands, Spain) is a high mountain station representative most of the time of atmospheric background conditions. It is normally located above a strong temperature inversion formed as a consequence of subsidence processes. Furthermore, there exists an important influence of mineral dust due to the proximity with the Saharan desert, mainly in summertime. Further information about Izaña's aerosol climatology can be found in Basart et al. (2009) and Cuevas et al. (2015).

Tamanrasset (Algeria) is a station located in southern Algeria near the most important dust sources (Mali, Algeria, Lybia and Chad). This station shows little impact of industrial activities being mineral dust the predominant aerosol, especially during the wet-hot season (Guirado et al., 2014).

3. ANCILLARY INFORMATION

In this study we have used Tamanrasset and Izaña AOD level 1.5 information extracted from AERONET network (Holben et al. 1998) to validate the results obtained with the ZEN system and with the LUT methodology applied to CE318-AERONET data. AERONET network uses the CE318-AERONET sun photometer as standard instrument, which performs direct sun measurements at 1640, 1020, 870, 675, 500, 440, 380 and 340nm. CE318-AERONET is a reference instrument with typical AOD uncertainties ranging between ±0.01 and ±0.02 (Eck et al., 1999).

We have also used diffuse sky measurements in the principal plane (PPL) routine from AERONET in order to infer ZSRs and to extract the CE318-AERONET AOD with the LUT methodology.

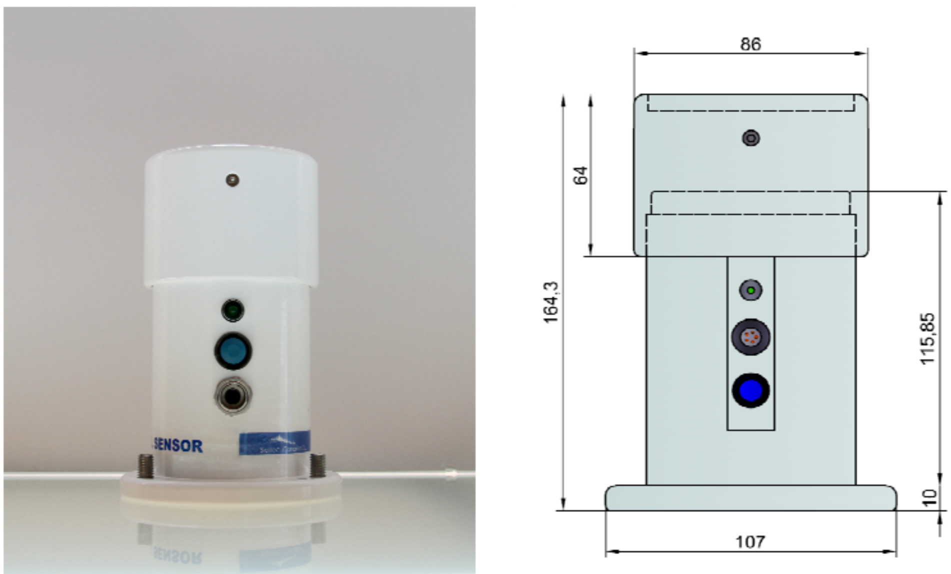

Figure 1: Main features of the ZEN-R41 radiometer.

4. THE ZEN SYSTEM

4.1. The ZEN-R41 radiometer

The ZEN-R41 radiometer (Fig. 1) is an instrument jointly developed by SIELTEC Canarias S. L. company and the Izaña Atmospheric Research Center (IARC), belonging the State Meteorological Agency of Spain (AEMET). This instrument is a radiometer with 3° field of view and four silicon detectors in order to perform simultaneous radiance measurements in four channels (440, 500, 675 and 870 nm), each one associated to one optical filter with a FWHM of 10 nm. The most outstanding features of the ZEN-R41 are the following:

- It is equipped with an aluminum weatherproof case with a thick borosilicate window to prevent damages.
- No moving parts.
- Operation in temperature range between -40°C and 85°C.
- Internal sensors for humidity and temperature monitoring, allowing us to correct the temperature dependence of the silicon detectors.
- Optional external blower to facilitate the removal of dust on the window.
- Communications through fixed IP or in DHCP mode. As a result, data can be downloaded manually or automatically and the internal variables can be checked regularly online.

All these features make the ZEN-R41 an autonomous and robust instrument, suitable to be deployed in desert places. It is also easy to establish a ZEN network for aerosol monitoring and use the ZEN-R41 as a dependent sensor part of a weather station or another instrument which requires AOD as input.

ZEN-R41 instruments were calibrated using an integrated sphere in order to convert the output signal ratio into radiance units, as it was explained in Almansa et al. (2016).

4.2. LUT methodology for AOD retrieval

Almansa et al. (2016) developed a LUT method to estimate AOD from downwelling ZSR measurements. This method involves a comparison of the measured ZSRs with a set of simulated ZSRs at 440, 500, 675 and 870 nm. The simulation process was carried out by means of the LibRadtran radiative code, assuming as initial inputs the extraterrestrial spectrum provided by Kurucz (1992), the mid-latitude summer standard model for the atmospheric profile, and the molecular absorption parameterized with the LOWTRAN band model (Pierluissi and Peng, 1985). It is worth to highlight that the AOD estimation by means of this methodology strongly depends on our ability to prescribe an accurate description of aerosols in the atmosphere. For this reason, Almansa et al. (2016) followed the indications given by the report global aerosol data set (Koepke et al., 1997), who proposed a mix of four different components in the boundary layer in desert areas (mineral nucleus mode or MINM, mineral accumulation mode, or MIAM, mineral coarse mode, or MICM, and water soluble aerosols, or WASO) as well as their expected concentrations through empirical relationships depending on the total mineral dust particle density ($N_{mineral}$). In the rest of layers above the boundary layer, Almansa et al. (2016) adopted the LibRadtran Optical Properties of Aerosols and Clouds (OPAC) library profiles. Further information about this methodology can be found in Almansa et al. (2016).

5. RESULTS

The main results obtained for the evaluation analyses of the ZEN-R41 radiometer and the LUT methodology are shown hereinafter. We have information from two ZEN-R41 instruments. The first ZEN-R41 was installed at Izaña in January, 2015, while the second ZEN-R41 was deployed at Tamanrasset station in November, 2015.

Clouds contaminated data have been removed using the Modified Thompson Tau outliner method presented in Cimbala (2011).

5.1. LUT performance evaluation at Tamanrasset (2014 to 2016)

AOD scatterplots between CE318-AERONET and CE318-LUT for three years (2014, 2015 and 2016) are presented in Fig. 2, in which is confirmed the good agreement between the two AOD values (coefficient of regression or R^2 ranging from 0.94 in 2015 to 0.91 in 2014 and RMSEs of 0.064 in 2014 and 0.075 in 2015). The analysis restricted to the 2014-2015 period confirms the results obtained by Almansa et al. (2016), showing a LUT method able to retrieve AOD from ZSR measurements with AOD differences < 0.1 considering CE318-AERONET as reference.

Despite the relatively high correlation found in 2016 (R^2 of 0.83), the existence of a bias in CE318-LUT AOD data in this year is evident as an increased AOD RMSE (0.12) and an increase AOD difference with CE318-AERONET AOD (Figs. 2, d, e, f) in 2016. Similar high AOD differences were found in 2016 with SZA (Figs. 2, g, h, i), showing a significant SZA dependence.

The discrepancies found in 2016 were caused by some instrumental errors affecting the CE318 instrument installed in Tamanrasset. These instrumental problems were confirmed by the operator's logbook: presence of dust in the lenses, collimators and connections affecting measurements during long periods in 2016. Such kind of troubles have been previously reported in other periods (Guirado et al., 2014). Therefore the good performance of the CE318-LUT allowed us to identify a malfunction of CE318-AERONET at Tamanrasset in 2016.

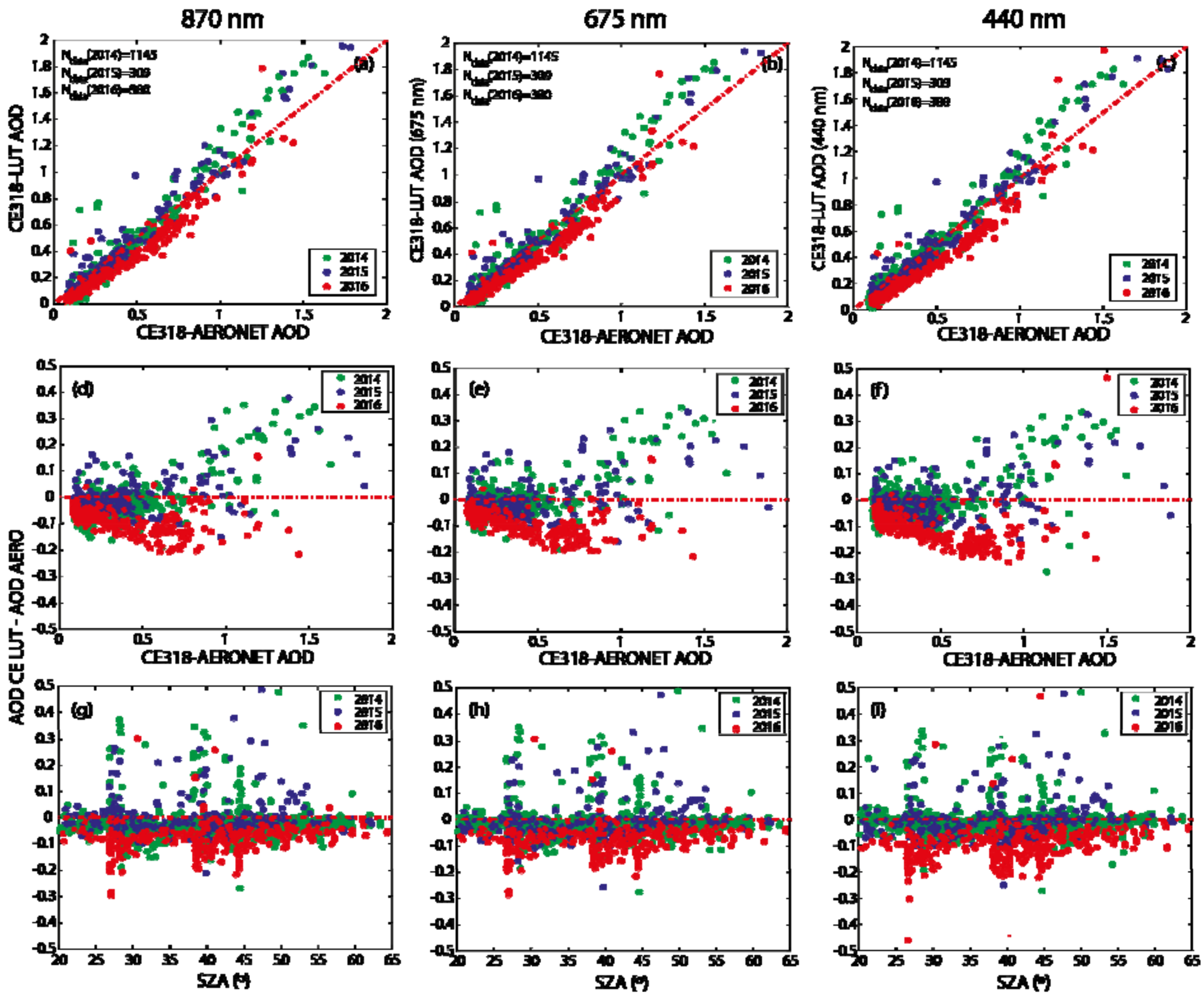

Figure 2: AOD scatterplot at Tamarasset between CE318-AERONET and CE318-LUT in 2014, 2015 and 2016 (a, b, c), for 870, 675 and 440 nm. The dashed lines are the diagonals (y = x). Number of data (N) for each year is shown in the legend. AOD difference between CE318-AERONET and CE318-LUT respect to CE318-AERONET (d, e, f) and SZA (°) (g, h, i), respectively.

5.2. ZEN performance evaluation at Tamanrasset

Once we have tested the LUT methodology at Tamanrasset, we have evaluated the ZEN performance at this station using ZEN-R41 measurements and the LUT methodology over a time period when the CE318-AERONET data quality is not questionable. For this reason we have limited the analysis to two months (November-December 2015) period after the ZEN-R41 installation.

AOD scatterplots between CE318-AERONET and ZEN-R41 LUT for each channel and for the period November-December 2015 are presented in Fig. 3 (black points). We have also included the CE318-AERONET and CE318-AERONET LUT (CE318-LUT) AOD scatterplot (red points). We observed a good correlation between ZEN-R41 LUT and CE318-AERONET AODs (R^2 of 0.81 for the four channels). In case of CE318 LUT and CE318-AERONET AOD comparison we obtained slightly lower correlations (up to 0.71) and RMSEs of 0.018. We did not observe any SZA dependence on AOD.

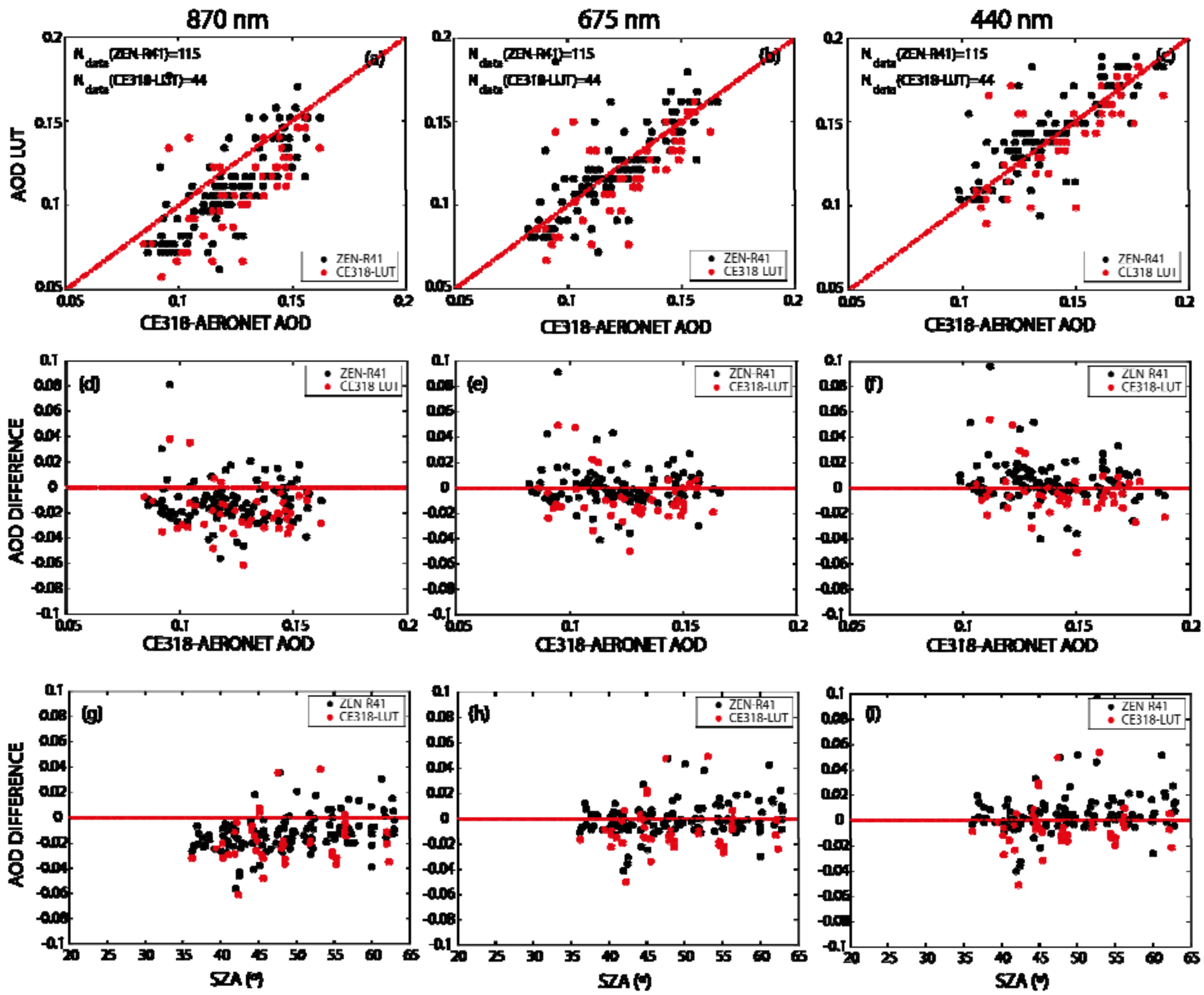

Figure 3: AOD scatterplot at Tamanrasset between CE318-AERONET and ZEN-R41 LUT (black points) and CE318-LUT (red points) in November and December, 2015 (a, b, c), for 870, 675 and 440 nm. The dashed lines are the diagonals (y = x). Number of data (N) for each year is shown in the legend. AOD difference between CE318-AERONET and ZEN-R41 (black points) and CE318-LUT (red points) respect to CE318-AERONET (d, e, f) and SZA (°) (g, h, i), respectively.

5.3.ZEN performance evaluation at Izaña (2015-2016)

We have performed a similar CE318-AERONET and ZEN-R41 intercomparison analysis for Izaña, where the CE318-AERONET data quality is assured in the whole period. This study has been carried out in 2015 and 2016 (from January to June). We present the main results in Fig. 4. A good agreement between CE318-AERONET and ZEN-R41 LUT AOD values is obtained. We have found R^2 of 0.97 for the four channels and RMSE values up to 0.023, confirming the good performance of the ZEN system to infer AOD in dust conditions.

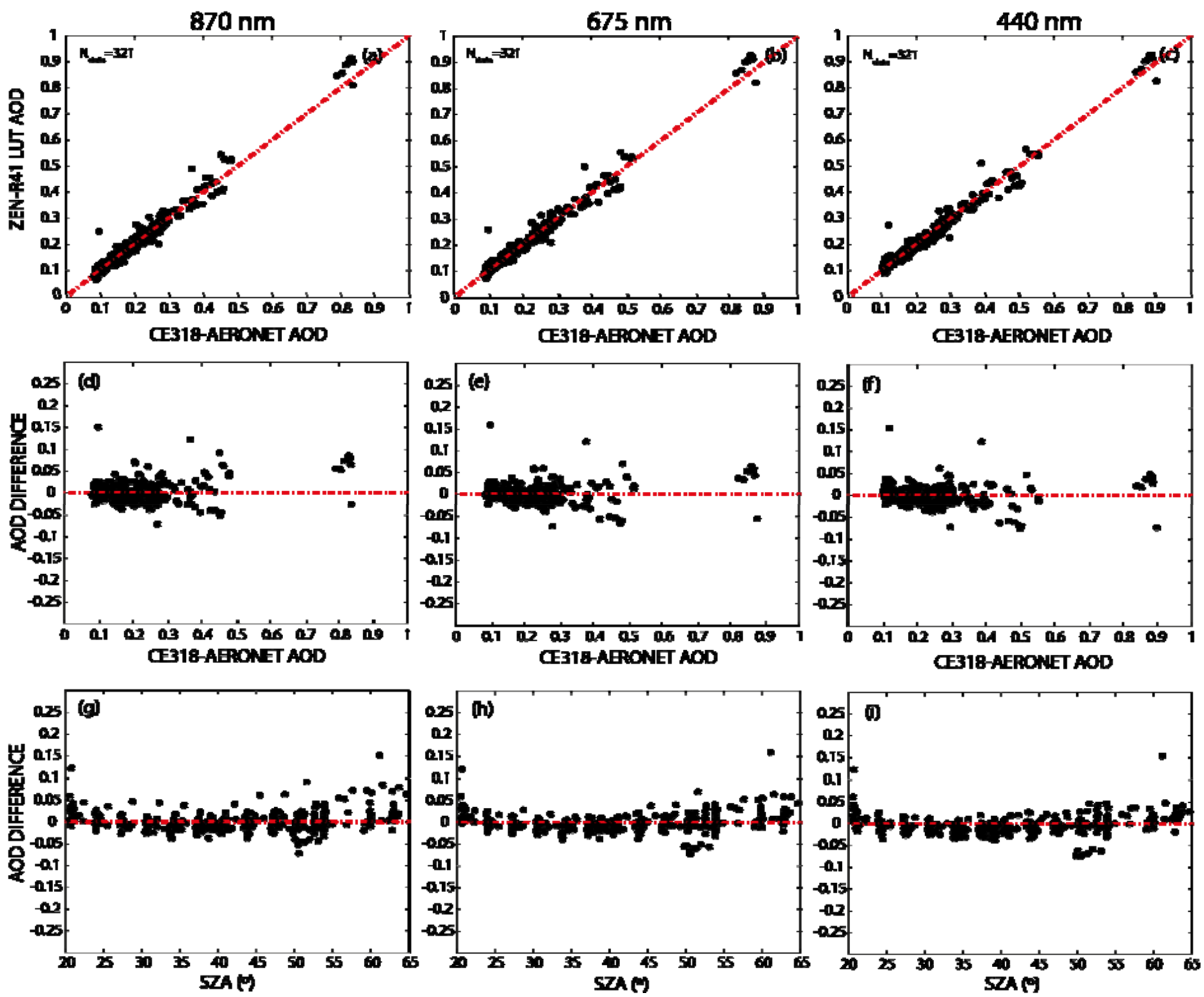

Figure 4: AOD scatterplot at Izaña between CE318-AERONET and ZEN-R41 in 2016 (a, b, c), for 870, 675 and 440 nm. The dashed lines are the diagonals (y = x). Number of data (N) for each year is shown in the legend. AOD difference between CE318-AERONET and ZEN-R41 (d, e, f) and SZA (°) (g, h, i), respectively.

6. CONCLUSIONS

In this work we have extended the results presented in Almansa et al. (2016) by using a second ZEN-R41 instrument installed at Tamanrasset (Algeria), and an extended measurement period (2015-2016) at Izaña. The AOD comparison between CE318-AERONET and LUT AERONET performed at Tamarasset for 2014-2016 time period showed ability the LUT methodology to infer AOD with sufficient accuracy. The LUT method even allowed us to detect a malfunction of AERONET over a period of time in 2016 when lower regressions (R^2 of 0.83) and higher RMSEs values (0.12) were found in this comparison. Therefore LUT method could be used in AERONET stations located in remote regions (such as Tamanrasset), where it is not always possible to ensure a good calibration, as quality control system.

The subsequent analysis performed at Tamanrasset was carried out in the two-months period when CE318-AERONET data quality is not questionable. High correlations ($R^2 \approx 0.81$) and low RMSE values (0.015) were found in the CE318-AERONET and ZEN-R41 AOD comparison. Finally, the ZEN-R41 analysis at Izaña showed a good performance of the ZEN-R41 radiometer with CE318-AERONET as reference, with $R^2 \approx 0.97$ and RMSEs up to 0.023.

These results indicate that ZEN-R41 instrument and the LUT methodology are appropriate to monitor atmospheric dust with little maintenance in remote desert locations, allowing us to fill important observational gaps in such areas. The ZEN-R41 is an inexpensive and robust instrument suitable to be deployed in remote desert regions, and the LUT methodology has been specifically conceived to retrieve dust AOD. In addition, despite the low complexity of the ZEN-R41 instrument in comparison with CE318-AERONET, we have proved it might be used to detect and check instrumental problems in this type of reference instruments, which require more maintenance and important calibration efforts. As a result, the ZEN system might be used to complement AOD measurements performed by the current sun photometer networks, such as AERONET, in order to improve our knowledge of dust cycles and properties in key regions near dust sources. This system could also play an important role in dust model assimilation near these dust source regions, satellite validation and early warning within the World Meteorological Organization (WMO) Sand and Dust Storm Warning Advisory and Assessment System (SDS WAS).

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