Reply to Referee #1

We would like to thank Referee #1 for all the constructive suggestions proposed. They have been certainly useful suggestions have been used to improve the revised version of this paper.

General Comments:

GC#1: This paper presents a new long-term data set of AOD at a high altitude observatory (Izana in the Canary Islands), based on astronomical spectrometer measurements. Accurate long-term data sets of AOD are relatively rare and very valuable to the scientific community. The authors suggest that the AOD data set (at one wavelength = 769.9 nm) they have created from these measurements do indeed have high accuracy. However, there are some important aspects of the calibration and data presented that suggest to me that there are significant issues with the data accuracy. First, the calibration of this instrument exhibits very large and rapid changes, on the order of >50% in one year at times (see 2010-2011 in Fig. 3) that are of concern and also large changes in a few months (2008: see green points in the first few months). These large and rapid changes imply larger uncertainty than suggested in the paper, and more detail needs to be provided to make a convincing argument for accuracy (scatter plot validation graphs of Mark-I AOD versus sunphotometers would be useful).

>> First of all, the authors want to clarify the reason for the rapid changes in V0 presented in fig. 3 of the manuscript. Indeed the explanation of these variations in V0 was not sufficiently described.

- Between 1983 and 1984 V0 changed ≈400%. We know perfectly the reason for this rapid variation of the instrument calibration. Firstly, from 1976 to 1983 we used information from scattered component and, in 1984, only photometric information from the transmitted beam was available. Therefore a change in the V0 is expected. However, the most important reason for this strong change, as it is explained in the text (see page 4103, lines 14 to 18), is attributed to changes in the gains of the photomultiplier (PMT).
- Between 2003 and 2004: We changed again from the scattered to the transmitted component.
- In 2008: A high dispersion in V0 is retrieved during the first part of the year. We attribute the low V0 values to lower transmission of the new two mirrors of the coelostat, which replaced the old ones on April 8th, 2008.
- In 2011: A new PMT for scattered component was introduced.
- Minor changes (≈50%) through the whole period as a result of the maintenance operations in the coelostat (basically mirrors replacement or mirrors cleaning).

We really would like to highlight that, in spite of these evident rapid changes in the instrument calibration, the Mark-I precision is well recognized and supported by outstanding scientific results obtained in the past using data from this instrument (see García et al., 2007, published in Science Journal). Therefore it is a reference instrument in helioseismology, being able to provide very accurate information of quite small velocity fluctuations in the solar radial velocity produced by normal modes solar oscillations. Furthermore, because of its high sensitivity and long term instrumental stability, Mark-I also provides a daily accurate determination (less than 1 ms^{-1}) of the daily radial velocity offset, the so-called "solar gravitational red-shift". We are referring to instrument stability because instrument operation is based on atomic transitions (is a magneto-optics filter) rather than interference filters, subjected to temporal degradation. In our case, we have ensured the Mark-I calibration for our purposes using a efficient methodology as the Langley technique applied **every "suitable" day** (in terms of AOD "loads" and stability). Since we cannot apply this technique every day, we have performed a smoothing analysis to account for the V0 evolution every day of the whole period (almost 37 years) in order to detect and correct the possible changes in the instrument. Later, it was corrected applying the methodology proposed by Cachorro et al. (2004, 2008). As a result of this meticulous procedure, we have obtained a long-term AOD series which agrees reasonably well with AOD from other reference instruments, as AERONET Cimel and World radiation Center PFR.

The authors also want to point out that the variations observed in Mark-I V0s are frequent in instruments involved in sun-photometry. We present in Fig. 1 the evolution of the V0 at Izaña extracted from AERONET masters, from 2004 to 2014. In this period of 10 years of AOD records we can see variations in V0 up to ≈80%. The reason for this variability is the frequent replacement of AERONET "master" instruments at the Observatory. Because of the instrument's change (optics, gains and even software) significant changes in V0 are expected and accepted. This is a common practice in stations belonging to certain networks, as AERONET, in which every year the instruments are replaced by calibrated ones, resulting in a long-term series of V0 with great variability. However it does not prevent us to have very stable and homogeneous AOD series available at each station which show excellent agreements with AOD obtained with permanent single instruments for long periods (such as GAW-PFR). For example, Kazadzis et al. (2014) reported that statistics, based on coincident AOD data, showed that the mean AOD difference between PFR and AERONET Cimel at 500nm and 865nm was −0.012 and 0.004 respectively. From the comparison of hourly AOD averages between PFR and CIMEL at 500nm at Izaña Observatory for the period 2004 – 2012 Romero-Campos et al. (2014, in preparation for AMT) reported that 97.3% of the simultaneous AOD-500nm observations show differences that fall within ± 0.02. The PFR AOD series has been obtained with a single instrument, and in contrast, the AERONET AOD series, consists of observations performed with more than a dozen different instruments with a V0 values highly variable.

.

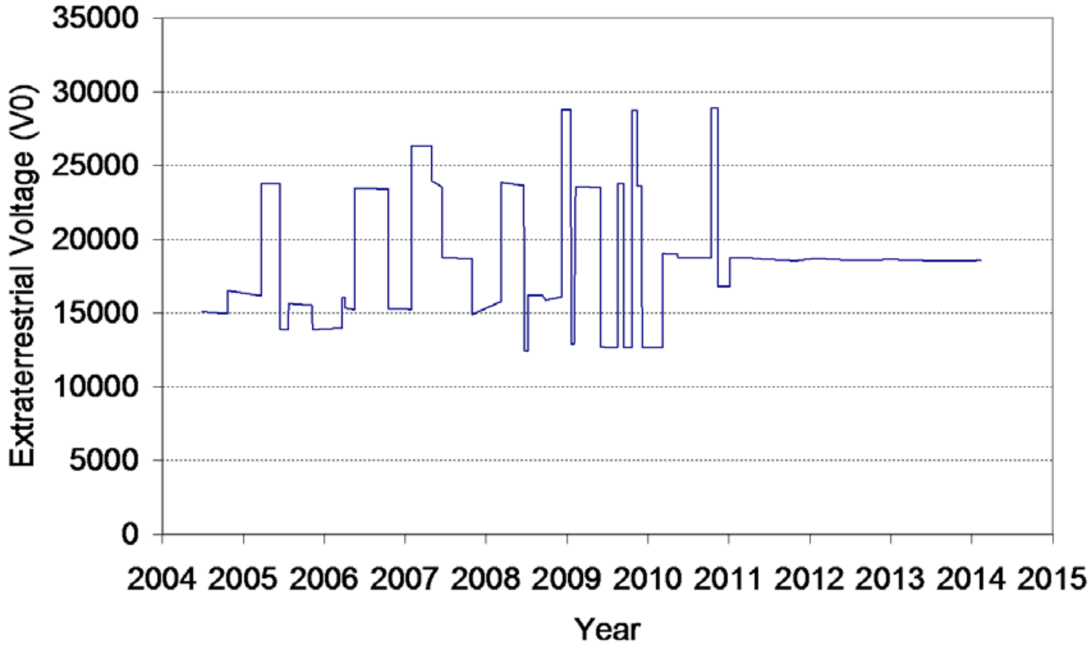


Fig. 1: Extraterrestrial constants (V0) variation of Cimel AERONET masters at Izaña Observatory in the period 2004-2014. Notice that these are "master" AERONET instruments and not field instruments.

At this point, it is easy to understand that the changes experienced in Mark-I V0, as a result of mirrors replacing, gains changes in PMT, and mirrors cleaning, have a similar impact than the replacement of the whole instrument, as it is performed in a global network like AERONET, but it does not prevent us at all to retrieve a good data set valid for climatic studies. The corrections we get with the Langley technique are really significant and provide excellent results.

We have introduced in the text a detailed description and explanation of changes in V0.

>> Scatter-plots of Mark-I AOD versus PFR and AERONET AOD have been included for every year included in the intercomparison (see figure 8 placed at the end of the document).

GC#2: Second, the authors have analyzed the data for temporal trends and have found that for 1984 through 1993 the trend was -0.047 per decade (page 4109 lines 18-20; also repeated in the Conclusions). However this decadal trend is the same magnitude as the average AOD (0.05) and it seems highly unlikely for an actual trend in AOD to be equal to the magnitude of the average AOD for the site. Further explanation is warranted regarding this trend.

>> The authors agree with the Reviewer. We consider that the reference period for the trend analysis assessment at Izaña must be reconsider, taking into account the special features of the station. Izaña is strongly affected by Saharan dust intrusions during

spring and summertime, being these events driven by atmospheric processes with strong interannual variability. Thus, we consider more appropriate to use only those months virtually unaffected by dust conditions (from December to February) to quantify and detect possible trends from Mark-I data. Doing this, no significant trends were observed. Anyway, further analysis will be performed to study in detail trend analysis at Izaña from Mark-I data, and to clarify the existence of a possible trend of -0.047 in AOD in the 1984-1993 decade. So, we have removed this part from the paper.

We also consider more convenient to use the median value rather than the mean value in those results involved in Section 6 (Table 4).

GC#3: Third, your analysis of the reported AOD data record at Izana suggested only a 0.02 enhancement in AOD due to the Mt. Pinatubo injection of sulfur dioxide into the stratosphere and subsequent sulfate aerosol production. This is a much smaller increase in AOD due to Mt. Pinatubo generated aerosols than has been measured by all other methods as reported in the refereed literature. This apparent lack of sensitivity to the increase in AOD associated with the Pinatubo eruption needs to be explained.

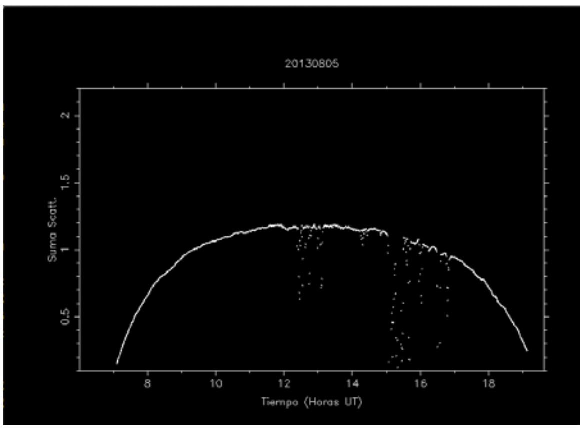
>> As it was explained in the GC#2, we remade the trend analysis as well as the reference AOD values of each decade using the AOD median restricted to wintertime (December, January and February). Doing this, we have obtained a departure from the decadal (1984-1993) median during 1992 (peak impact of Mt. Pinatubo) of 0.049. The reported values in the literature are usually referred to 500 nm, as it is the case of MLO measurements performed by Dutton and Christy (1992) or Dutton et al. (1994). These authors showed an increase in AOD at Mauna-Loa (MLO) up to 0.19 (August, 1991), with typical values of AOD at 500 nm ranging from 0.013 (August) to 0.033 (March-April) (Holben et al. 2001). It means an AOD departure from background conditions (in August) of 0.18. We have found at Izaña a peak impact of Pinatubo in July 1992 (0.14), with a deviation over the median decadal value of 0.049. If we transfer the values corresponding to 769.9 nm to 500 nm wavelength, considering the Angström Exponent for Pinatubo event aprox. 1, as it is expected for volcanic ash and reference in the literature (Tomasi et al., 2012), these values change to 0.20 and 0.075, respectively, quite similar to those found at MLO. Note that a departure of 0.075 from the median decadal value supposes an increment of 120% in the AOD from background conditions.

This new analysis has been incorporated into the text.

GC#4: Additionally there is a need for discussion of the cloud screening methodology applied to this AOD data set. If the Langley plot analysis method is the de facto means of cloud screening then this should be mentioned in the paper. If that is the case then all temporally variable aerosols events will be screened from the data record and may lead to sampling biases and differences with other methods.

>> The authors totally agree with this request. Basically, the cloud screening on Mark-I data is a careful process of cloud detection and data removal performed day by day by

the astronomer in service who looks at the photometric signal (R+L), which is strongly sensitive to clouds (see fig.2). However, since the presence of high clouds is not easily detected through variation in the photometric signal, it is also used a second cloud filter based on variations detection in the solar radial velocity curve (R-L)/(R+L) (see fig.3). In summary, the cloud screening applied on Mark-I data consists in the detection of anomalies in solar intensity and velocity, which is manually performed to ensure data quality (see fig. 4). As we have mentioned before, Mark-I is a reference instrument in helioseismology. This instrument is able to provide very accurate information of quite small velocity fluctuations in the solar radial velocity providing also an accurate determination (less than 1 ms^{-1}) of the so-called “solar gravitational red-shift”. These results were published in the prestigious journal “Science” in 2007 (see García et al., 2007) and thus Mark-I dataset quality is nowadays accepted.



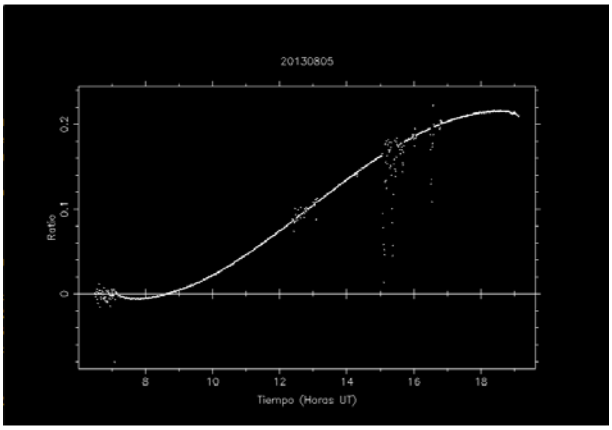


Fig. 2: Photometric signal for a day

Fig. 3: Solar radial velocity for the same day

.

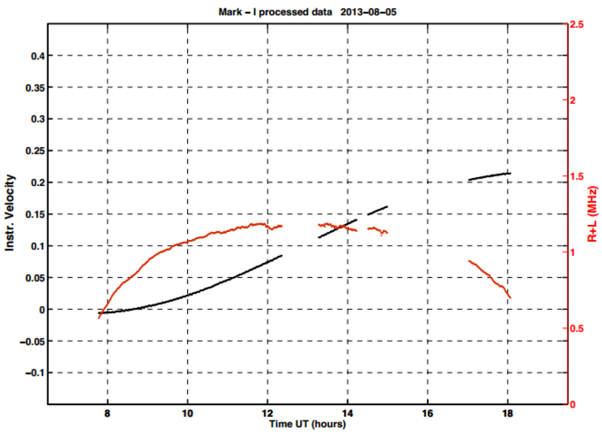


Fig. 4: Cloud screened signals for the same day

This information about cloud-screening with Mark-I data has been included in the text.

GC#5: It would also be valuable to plot monthly mean AOD as measured by sunphotometer versus the Mark-I monthly mean AOD, using all cloud-screened

observations from each data set separately, not just the data that are coincidently cloud screened in both.

>> We do not understand this request, since a comparison of instruments should be performed with quasi-simultaneous measurements under the same atmospheric conditions. Otherwise there could be a bias if different days are used for each instrument. This is especially true at Izaña in some seasons (spring and summer) highly influenced by Saharan dust which might raise the AOD an order of magnitude compared to background conditions.

Specific Comments:

SC#1: Page 4094, line 17: The assumption of constant AOD for the Langley technique is most likely met under low AOD conditions and much less probable as the AOD level increases. This needs to be mentioned in the paper.

>> Done. Included in Sect. 5.2, page 4105.

SC#2: Page 4097, line 19: The Holben et al. (1998) paper is not an appropriate reference to cite for the GAW network, as this sentence currently reads. Please replace with a GAW network paper.

>> Reference included.

SC#3: Page 4097, line 23: Suggest that ": : :the most adequate: : :" should be replaced with something like ": : :important: : :" Page 4098, line 10: Suggest that ": : :ad-hoc: : :" should be replaced with something like ": : :various: : :"

>> Done

SC#4: Page 4101, line 6: You say the ratio r is filtered for clouds. Please provide details on the cloud screening methodology and the physical basis for the cloud filtering technique.

>> Explained and described in GC#4.

SC#5: Page 4102, line 3: The Holben et al. (1998) paper is not an appropriate reference for the Langley technique. A much better choice would be Shaw (1983; Bull. Am. Met. Soc.).

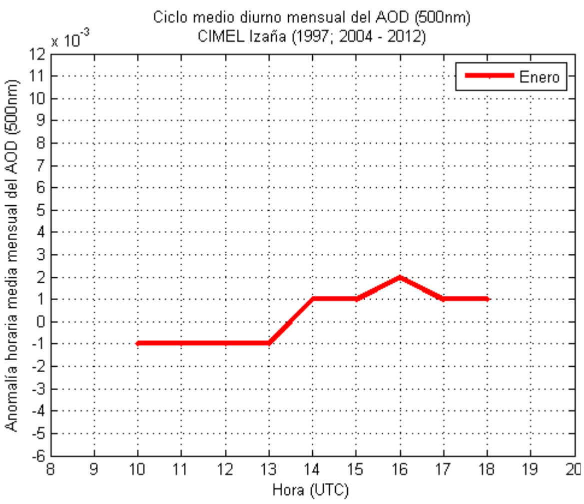
>> Reference included.

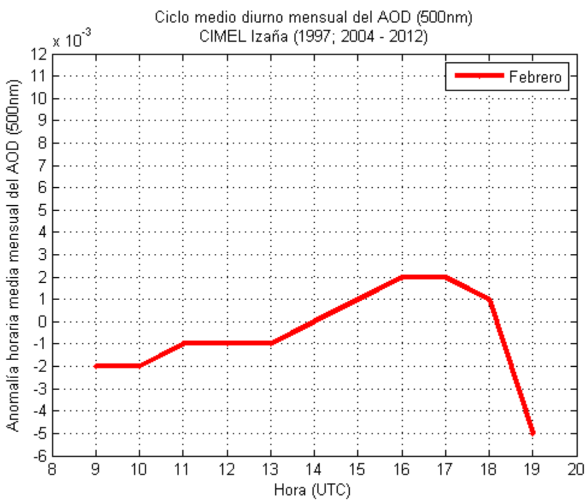
SC#6: Page 4102, line 16-18: It is confusing as to why you mention the same AOD threshold (0.3) for both scattering and extinction. More discussion is desired for clarification.

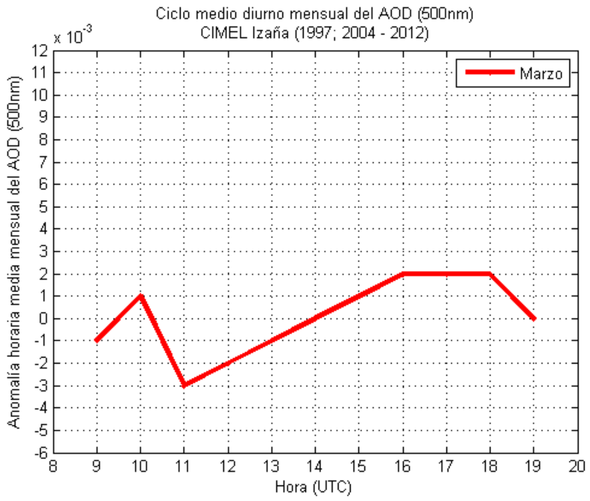
>> As we mentioned in page 4102, lines 12 to 18, we selected for Langley calibration those days with AOD conditions <0.04 and r>=0.99 in case of transmitted component, with the unique exception of 1991 and 1992, when we had to increase the AOD threshold to 0.3 (see also Referee 2, GC#3 for further explanation) due to the impact of Pinatubo. In case of scattered component, we calibrated under different conditions than in case of the transmitted component, due to the high dispersion of V0 when using this component (see page 4102, line 20, in which this large dispersion is attributed to the effect that solar velocity has on this quantity). If the same threshold than the transmitted component was selected (0.04), then less than 900 Langleys in the 1976-1983 + 2003-2012 period were available and therefore short periods of V0 variation won't be detected. We consider appropriate to extend this threshold to 0.3 in order to have 1,010 V0 values to discern the variability in instrument calibration. Anyway, we have changed this paragraph in order to avoid misunderstandings and to clarify the calibration process.

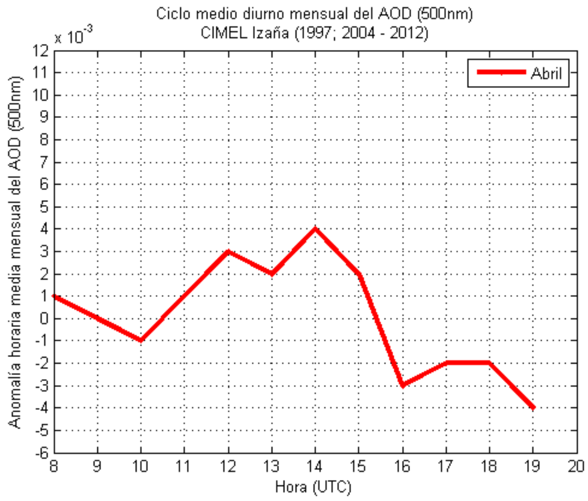
SC#7: Page 4103, line 1: Please add some discussion on how you separate the fictitious diurnal cycle of AOD from real diurnal cycles that may occur.

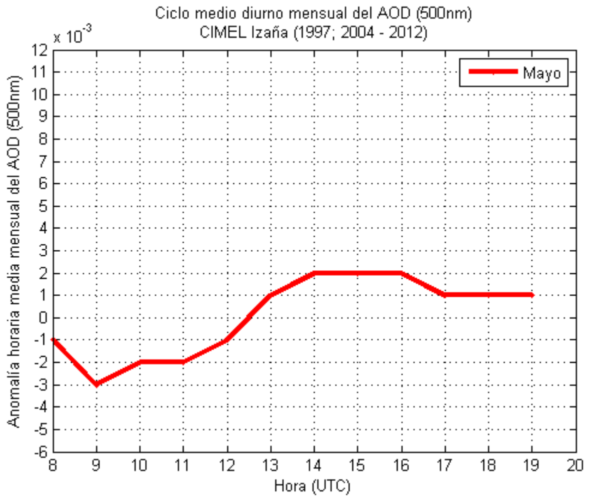
>> Real AOD diurnal cycle is not present at Izaña Observatory at 2,400 m a.s.l. above a quasi-permanent temperature inversion layer, representative most of the time of free troposphere conditions. Anyway, we have performed the analysis of hourly mean AOD anomaly (at 500nm) at Izaña Observatory using AERONET level 2 data for each month from 1997 and 2004 to 2012 (see figure 5). We can clearly see that it doesn't exist diurnal cycle on AOD. Please note that that the AOD anomaly in Y-axis is expressed in 10^{-3}.

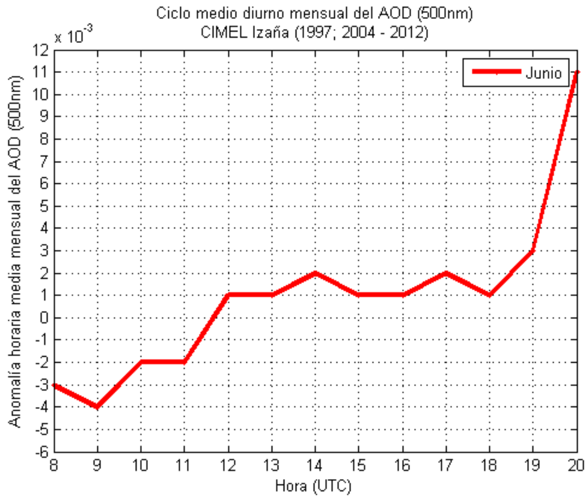


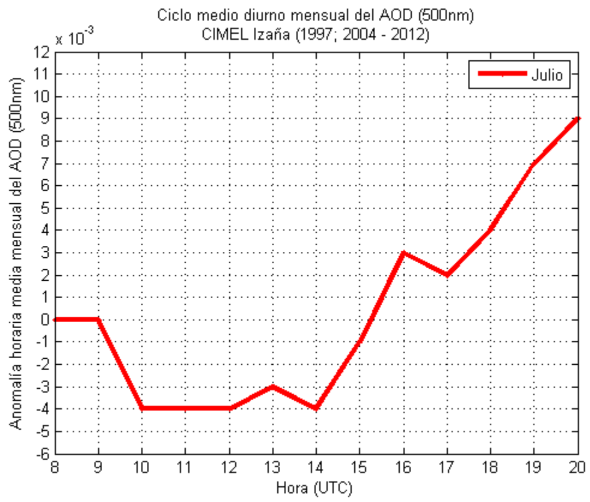


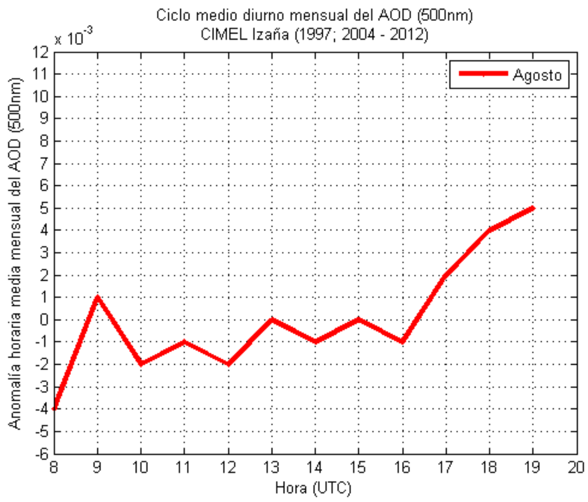

Ciclo medio diurno mensual del AOD (500nm)
CIMEL Izaña (1997; 2004 - 2012)
x 10^{-3}
Anomalía horaria media mensual del AOD (500nm)
Hora (UTC)
Marzo


Ciclo medio diurno mensual del AOD (500nm)
CIMEL Izaña (1997; 2004 - 2012)
x 10^{-3}
Anomalía horaria media mensual del AOD (500nm)
Hora (UTC)
Abril


Ciclo medio diurno mensual del AOD (500nm)
CIMEL Izaña (1997; 2004 - 2012)
x 10^{-3}
Anomalía horaria media mensual del AOD (500nm)
Hora (UTC)
Mayo


Ciclo medio diurno mensual del AOD (500nm)
CIMEL Izaña (1997; 2004 - 2012)
x 10^{-3}
Anomalía horaria media mensual del AOD (500nm)
Hora (UTC)
Junio


Ciclo medio diurno mensual del AOD (500nm)
CIMEL Izaña (1997; 2004 - 2012)
x 10^{-3}
Anomalía horaria media mensual del AOD (500nm)
Hora (UTC)
Julio


Ciclo medio diurno mensual del AOD (500nm)
CIMEL Izaña (1997; 2004 - 2012)
x 10^{-3}
Anomalía horaria media mensual del AOD (500nm)
Hora (UTC)
Agosto

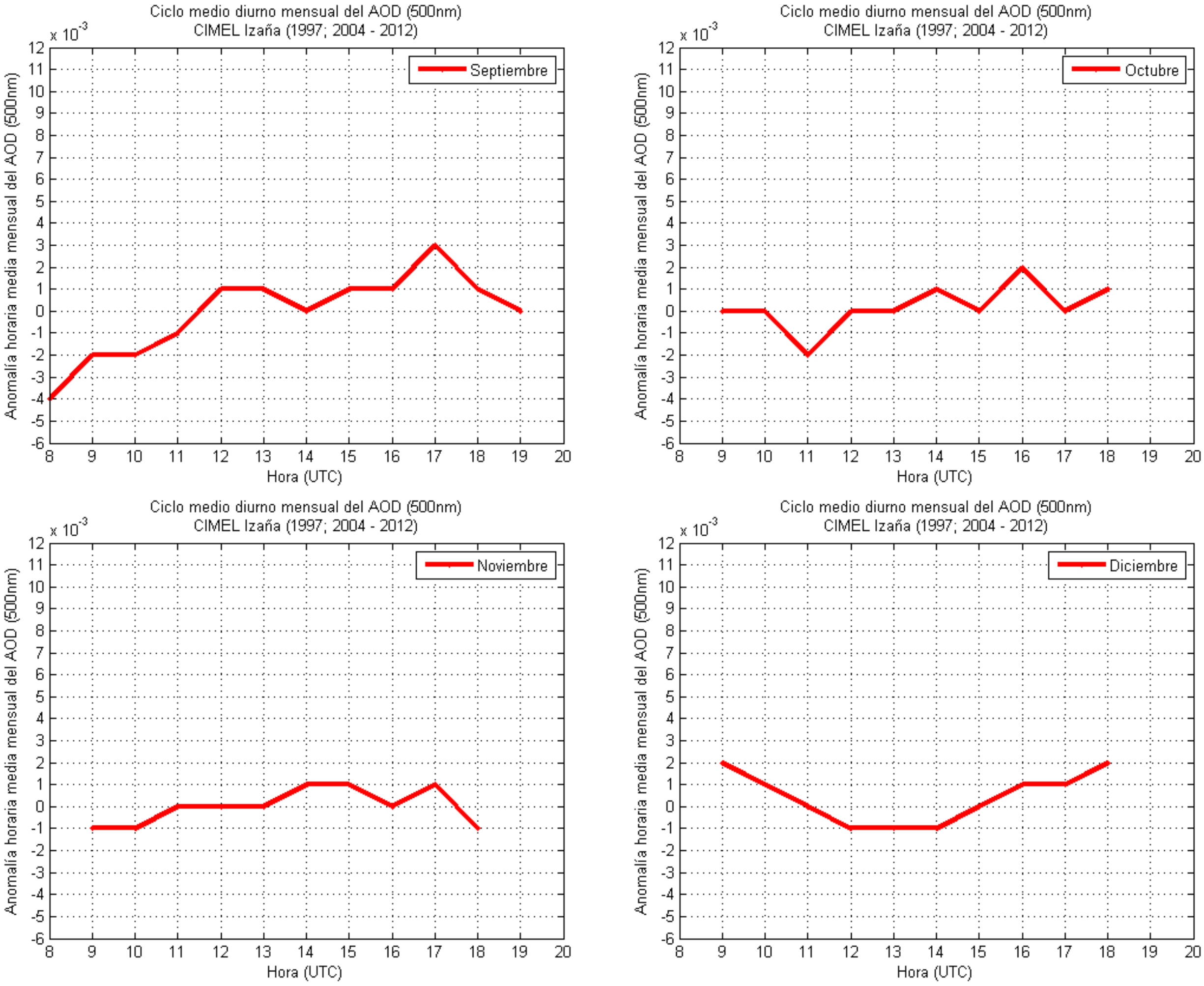


Figure 5: Hourly AOD anomalies at Izaña each month for the period 1997, 2004 to 2012.

SC#8: Page 4103, line 4-6: Note that an AOD diurnal amplitude of >0.3 is extremely large and if it is due to Vo uncertainty then the uncertainty in Vo is _30%, which is enormous. Please explain how you can have such large errors as 30% error in your calibration analysis.

>> Yes, it is large amplitude in AOD indeed. However, these type of errors are expected basically due to : 1) Very low AOD conditions at Izaña Observatory (it is well known that calibration errors have a strong impact in case of very low AOD) and 2) The important variability in V0's as a result of the instrument features. However after using efficient techniques published in the literature to overcome these problems, the result is an AOD series with good agreement with independent AOD measurements, with enough accuracy to be used in climatic studies. We present in fig. 6 an example of correction performed in case of amplitude in the AOD retrieved before K-ciclo correction >0.3.

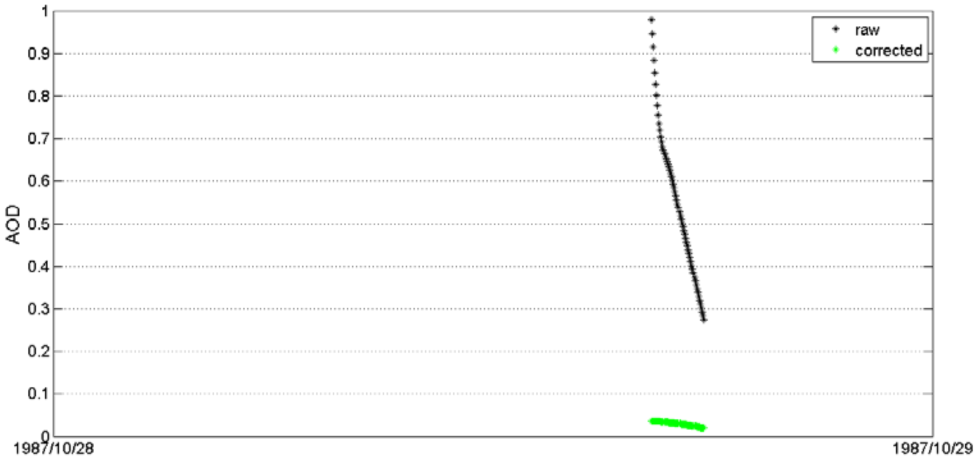


Figure 6: Case example of AOD correction after kCICLO procedure for October 29th, 1987. In black, raw data, in green corercted data

The AOD anomalies (AOD minus monthly mean AOD) comparison between Mark-I and Cimel are shown in Fig. 7, showing that, in spite of the large variations in V0, Mark-I dataset can be considered stable, with anomalies lower than those shown by the AERONET Cimel.

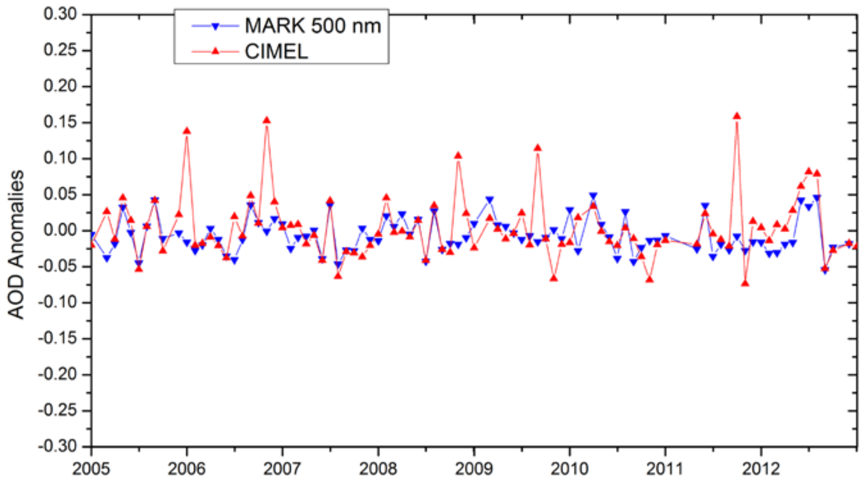


Fig 7: AOD anomalies at Izaña Observatory extracted from Mark-I and Cimel AERONET at 500 nm.

SC#9: Page 4103, line 13: When referring to the range in Vo you say: "It ranges from 3332 to 2.54 x 10ˆ5." This is somewhat unclear, and more discussion is desirable.

Also discuss the fact that there is very large scatter in Vo (blue and green points) about the cubic spline fit in Figure 3, and the reasons for this large scatter.

>> We detailed in GC#1 the reasons for the large variability found in V0. It is also evident the differences in some cases between V0 values and cubic spline, and we will emphasize it in the text. Anyway, as it is mentioned in the manuscript, the cubic spline does not provide the final value for the daily calibration because a subsequent correction based on the fictitious AOD cycle is also performed. The result is an AOD series with good agreement with both PFR and Cimel AERONET.

SC#10: Page 4103, line 21-24: Should use a 2nd order fit of ln AOD versus ln WL using multiple wavelengths from sun-photometer data to interpolate to the Mark-1 wavelength of 770 nm. This is a more accurate way to interpolate AOD data in wavelength (Eck et al., 1999). Also using multiple wavelengths, say from the interval of 400 to 870 nm is better than using only 2 wavelengths as implied in equation (1) since it minimizes an error in any single wavelength.

In principal we agree the Reviewer. However, in practice the differences using only 2 wavelengths or more wavelengths are quite small. We have analyzed the AOD differences found when using two wavelengths (straight line in logarithmic ln(AOD) vs ln(λ)) or more wavelengths (a 2nd order fit) for PFR 2001 to 2003 data and a mean difference in AOD of -0.001 was obtained. So, we consider it is appropriate the Angström exponent calculation and no significant errors are expected if the linear approximation is used.

SC#11: Page 4104, line 19: An RMSE of 0.3 is extremely large, suggesting very poor data quality. Is this a typo (0.03)?

>> Yes. It is a typo error. We have corrected this mistake.

SC#12: Page 4104, line 23-28: It would be useful to add scatter plots here of the Mark-I AOD versus sunphotometer values.

>> Done (see figure 8).

SC#13: Page 4105, line 7-9: Please note that Nyeki et al. (2012) showed much smaller differences between PFR and AERONET measurements of AOD. From Nyeki et al. (2012): “A comparison of the instantaneous AOD difference between AERONET and GAWPFR (WL = 500 nm) in 2007– 2010 at DAV resulted in a mean AOD difference of-0.0024 and a root-mean square error of 0.0071.”

>> Nyeki et al. (2012) found differences in AOD between Cimel AERONET and PFR below 0.01 while the precision of the PFR is established in ±0.01 (see Wehrli,

“calibration of filter radiometers for determination of atmospheric optical depth” Metrología, 2000) and the precision of Cimel masters is assumed to lie between 0.005-0.009 (Eck et al. 1999). However, a recent study performed by Romero et al. (to be published in AMT) for the period 2004-2012 showed hourly difference in AOD between PFR and Cimel (at 500nm) ranging from -0.000 to -0.002 for dust events (AOD>0.1) and between -0.035 to -0.016 for clean conditions (AOD <0.1). So, the discrepancies between both instruments at Izaña are dependent on aerosol conditions. For all the above we consider realistic the values reported in the paper although we will mention in the text the existence of comparisons reporting lower differences between PFR and Cimel.

SC#14: Page 4106, line 3-5: Please state here whether each point in Figure 4 is a monthly mean.

>> No. Each point in Fig. 4 are ≈1-minute AOD data, and solid blue line represents monthly mean of the homogenized AOD series. However, we admit this information can lead to confusion. So, we will change in this figure “instantaneous” data by daily AOD means.

SC#15: Page 4107, line 16-18: The peak impact of the Mt. Pinatubo eruption on your measured AOD from Mark-I data is only a 0.020 anomaly. Please compare this with other published results on Pinatubo AOD and explain the large discrepancy, as your AOD data from Mark-I suggests much less stratospheric AOD from the eruption than all other data that has published in the literature (see Russell et al., 1996 and Bauman et al., 2003 (Part 2) for example, plus numerous other published papers).

>> Look at the response to the question GC#3. We consider that there analyzed values, “reduced” to 500nm wavelength, are now quite consistent with AOD anomalies introduce by Pinatubo have been reported in the literature.

SC#16: Page 4109, line 5-8: The sunphotometer precision of AOD measurement is much better than 0.02. You seem to be confusing precision with accuracy (see below). Even then the accuracy of sunphotometer measured AOD is 0.01 or better, so this sentence is quite misleading.

>> We agree with the referee comment. We are referring to instrument accuracy. As we mentioned in SC#13, precision of Cimel master is assumed to be 0.005-0.009 (ground-based instruments precision: ±0.01-0.02) and PFR precision is established in ±0.01. We will include this information in the text to avoid any misunderstanding.

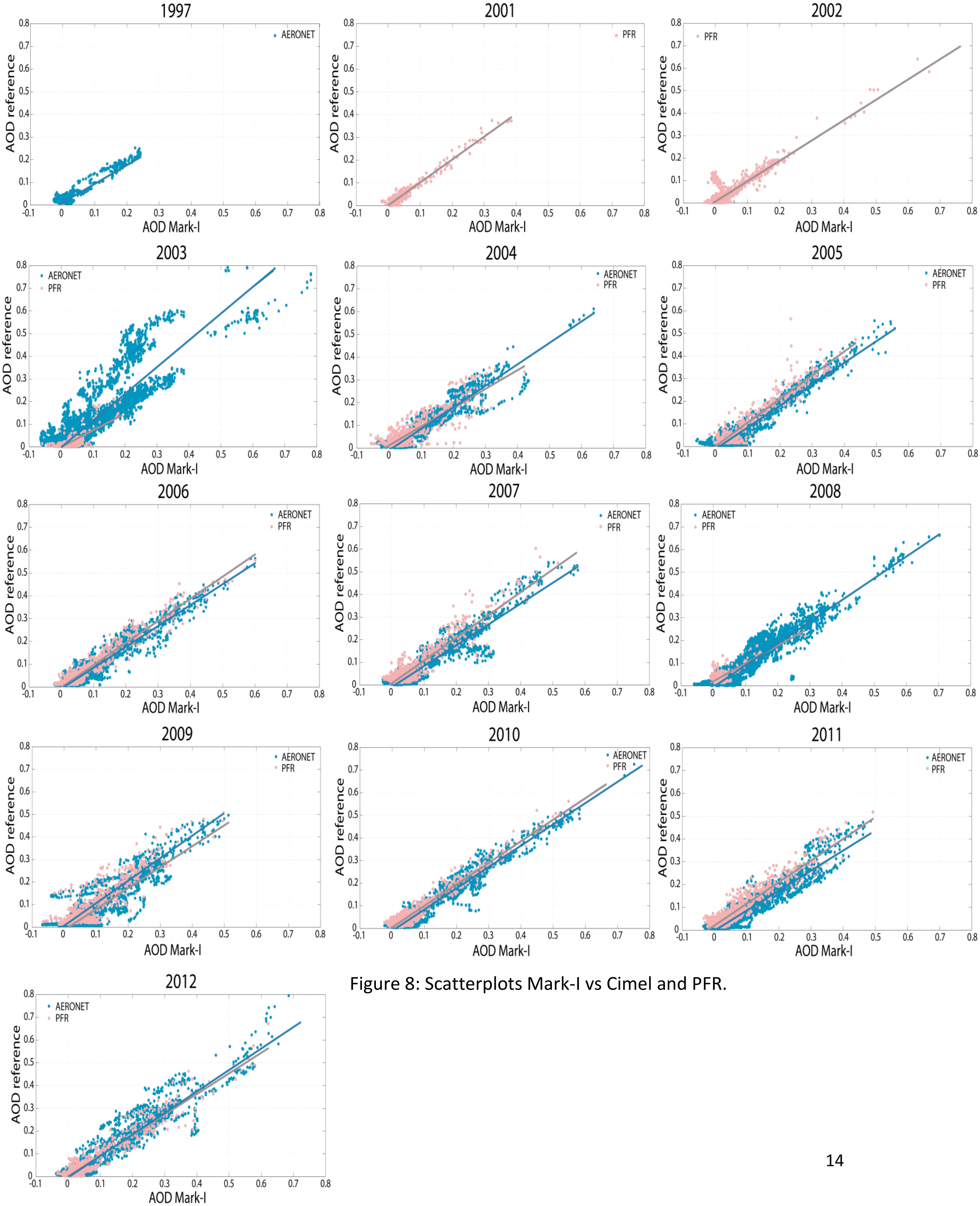


Figure 8: Scatterplots Mark-I vs Cimel and PFR.