Answer to the referee

We want to thank to the referee for the comments, to ask the main question: the problem of extrapolating the stray light correction. We have perform an statistical analysis of the prediction bounds of the fit that will be further included in the error budget analysis of the TOC of the Brewer. To probe the reliability of the extrapolation we have used observations from the Nordic campaign with the Brewer #037 that was also used by Karppinen 2005 work, this allows us to have a more complete range of OSC and the comparison with the Karppinen model . Unfortunately the Brewer #037 do not participate in the campaign and we do not consider appropriate to include the plots on this paper.

p. 1 l. 6: can you explain better what areas still require attention? Reformulate the sentence to be grammatically consistent

Every RBCC-E campaign advances our understanding of the Brewer calibrations in general and specifically what areas still require attention. In this 2015 campaign we have introduced a formal approach to characterization of the internal instrumental stray-light, the filter non-linearity and the algorithm for correcting for its effects on the TOC calculations.

Rephrase, the sentences have been moved to the introduction:

Before the establishment of the RBCC-E, the Brewer spectrophotometer calibrations were referenced to the Brewer World Calibration Centre hosted by Environment Canada (EC). However, most of the Brewer instruments were, and still are, calibrated by private companies, in the main by International Ozone Services (IOS) and to a lesser extent by Kipp and Zonen bv (Staehelin, 2010). The RBCC-E calibration adapts the methodologies and tools developed by EC and IOS, but also investigates and improves particular issues. The foci of the first campaigns were related to the instrument characterization and the ozone absorption calculation (Redondas and Rodriguez-Franco, 2012) whereas in this campaign the focus was on the stray light correction and the investigation of the error due to non-linear filter attenuation.

Staehelin, J.: TOTAL OZONE MONITORING BY GROUNDBASED INSTRUMENTS AS PART OF GAW, in TECO-2010 - WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, p. 12, WMO-GAW, Helsinki. [online] Available from: https://www.wmo.int/pages/prog/www/IMOP/publications/IOM-104_TECO-2010/1_3_Stahelin_Switzerland.pdf, 2010.

p. 1 l. 7: could you add a chart of the filter non-linearity effect in the paper? It is mentioned in the abstract as an important point, however only a text description is provided in the paper;

Figure 6 were added:

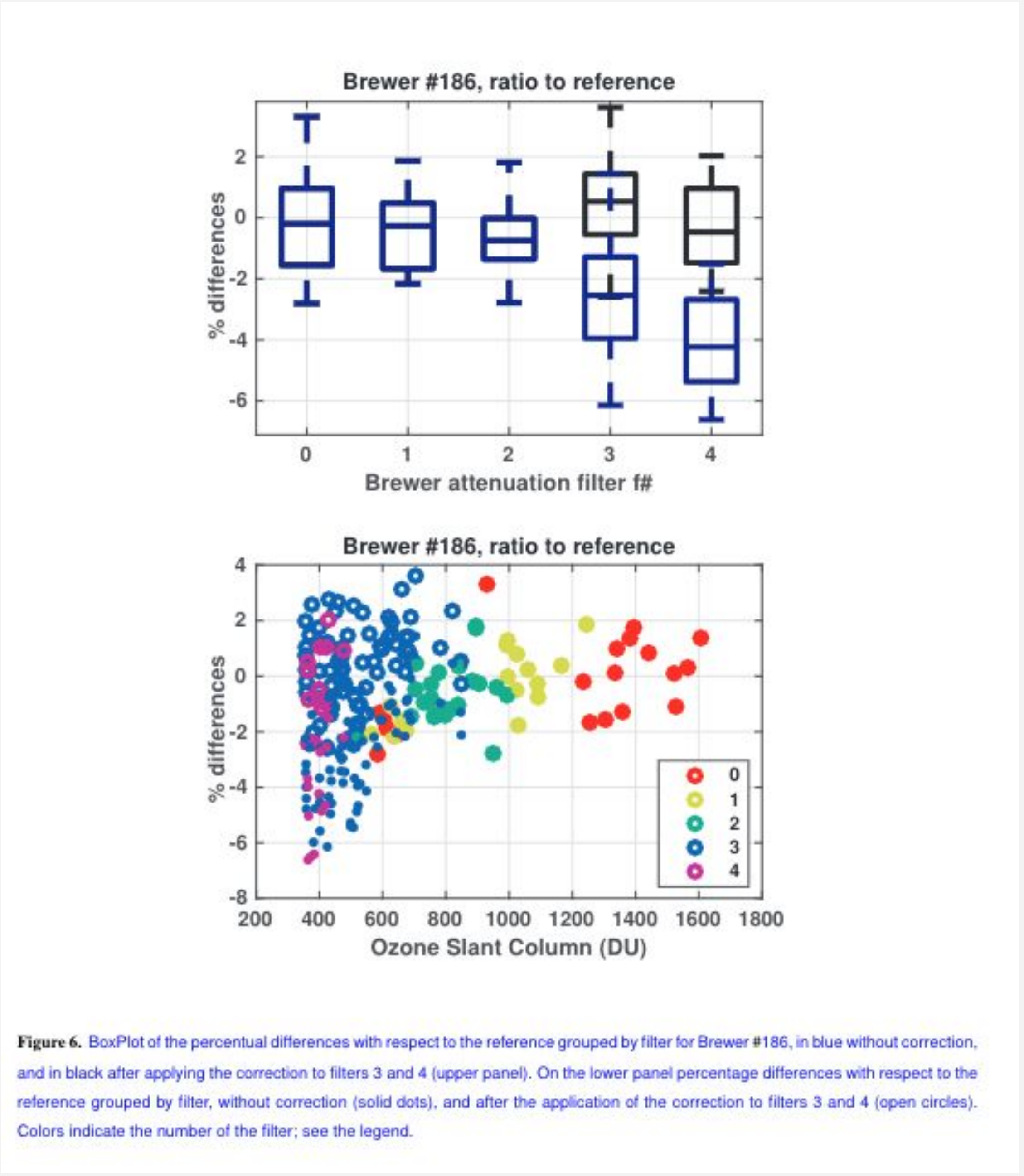


Figure 6. BoxPlot of the percentual differences with respect to the reference grouped by filter for Brewer #186, in blue without correction, and in black after applying the correction to filters 3 and 4 (upper panel). On the lower panel percentage differences with respect to the reference grouped by filter, without correction (solid dots), and after the application of the correction to filters 3 and 4 (open circles). Colors indicate the number of the filter; see the legend.

p. 1 l. 8: "its effects" refers to stray-light or non-linearity? "its" or "their"?

It refers to both the stray-light and non-linearity.

p. 3 l. 11: "also"..."also" - remove one recurrence;

Corrected

p. 3 l. 15: "the" results;

Corrected

p. 4 l. 8: "measurements" -> "measurement";

Corrected

p. 4 l. 14: add comma ("filter, a");

Corrected

p. 4 l. 18: "because of using a unique grating". I would say "monochromator", not grating, which is only one component of the monochromator;

Corrected:

However, both instruments are affected by stray light, mainly because both use a single monochromator. In contrast, the MKIII model is a double monochromator which provides enough stray light rejection to work in the first diffraction order for UV and ozone measurements.

p. 5 l. 2: Eq. 1 was not corrected. It should read (ETC-F)/alpha*mu;

Corrected:

```
\begin{equation}
      \label{eq:ozone}
      X = \frac{{ ETC -F }}{\alpha \mu }\
\end{equation}
```

p. 5 l. 4: "ozone differential absorption coefficient";

```
where $F$ is a linear combination of the algorithm of the measured spectral
direct irradiances (also called double ratios) corrected for Rayleigh molecular
scattering, $\alpha$ is the ozone differential absorption coefficient, $\mu$ is
the ozone air mass factor, and $ETC$ is the extra-terrestrial constant. The $F$,
$\alpha$ and $ETC$ parameters are weighted functions at the operational
wavelengths:
```

p. 5 l. 9-18: those lines are confusing. The authors talk about weights (SO2 and aerosol), then about the wavelength choice (and the dispersion test is only described at p. 6 l. 4-6 - by the way, F0 at line 12 is not defined), then again about the weights

(wavelength-independent factors and aerosol). Please re-order this paragraph;

We agree with referee the paragraph has been changed:

The four longer wavelengths (310.1, 313.5, 316.8 and 320.1 \unit{nm}) are used for the ozone calculation with weightings$w=[1,-0.5,-2.2, 1.7]$, respectively. These wavelengths have been selected near stationary points in the ozone absorption spectrum and are thus optimized to minimize the influence of small wavelength shifts (i.e. $\delta F // \delta \lambda =0$). The weightings were determined to suppress the influence of SO_2 and aerosol. Moreover, as λ_i and w_i satisfy the conditions defined by Eqs. (\ref{eq:sum_w}) and (\ref{eq:sum_wl}), the measurement independent of wavelength-independent parameters such as the absolute calibration. Also, it largely eliminates absorption processes which depend, to first approximation, linearly on the wavelength,such as the contribution from aerosols \citep{kerr_Brewer_2010}.

p. 6 l. 6: "... Langley method (Redondas et al., 2014b; Leon-Luis et al., 2018), in case of reference Brewers, or by comparison with a reference instrument in the case of the other Brewers of the network". Moreover, I would eliminate l. 14-18, since the Langley technique is not a topic of this paper;

We agree; the paragraph has been changed.

p. 6 l. 26: the ozone coefficient is not derived from the dispersion test itself, but from calculations based on spectroscopic datasets and the wavelengths chosen from the dispersion test;

We agree, the text has been rewritten as

The network Brewers were calibrated using the one parameter ETC transfer method, i.e., the ozone differential absorption coefficient was derived from the calculations of the wavelength calibration (the so-called “dispersion test”, see Redondas et al., 2018-01-31) applied to the spectroscopic set of ozone cross sections, and only the ozone ETC constant was transferred from the reference instrument. The so-called “two parameters calibration method” (Staehelin et al., 2003), where both the ozone absorption coefficient and the ETC are calculated from the reference, is also obtained and used as a quality indicator

p. 6 l. 29: "iterative process, i.e. changes..." and reformulate the sentence, which is too long. Also, could you explain what are "some instrumental characteristics revealed during the ETC transfer" that require full reprocessing?

The calibration is an iterative process because changes during the instrumental and/or wavelength calibration will affect the final ETC. Some instrumental characteristics which have been improperly accounted for, such as the non-linearity of the filters and the dead-time mismatch (Rodriguez-Franco et al., 2014), are revealed by the comparison with the reference during the ETC transfer. A change in the instrumental constants then requires a full reprocessing of the calibration. For this reason the calibration campaigns are scheduled in three different periods:

p. 7 l. 5: "The calibrations are maintained between transfer" -> do you mean that changes in the spectral sensitivity are monitored and tracked using the internal quartz halogen lamp? Please, reformulate;

We agree with the referee, the text has been rewritten as:

The changes in the spectral sensitivity of the instruments are tracked between calibration transfers using the measurements of the internal quartz halogen lamp, the so-called Standard Lamp (SL) test. A value, corresponding to a fictitious column density and often called R6, R5 or F-ratio (depending on whether the ozone, sulphur dioxide or nitrogen dioxide processing algorithm is applied), is obtained after processing.

p. 7 l. 19-22: I wouldn't go into details about the FOV straylight, since this is not addressed in the present paper. Just remove the lines after the bibliographic reference to Josefsson;

Removed

p. 7 l. 24: "such as" -> "so that"?

Corrected

p. 8 Fig. 3: the label of the y-axis is not understandable by the inexperienced reader. Caption: "0.6 cm". "Compared with the 1 point calibration": where are the results?

Corrected:

The reference to two point calibration is removed.

p. 8 l. 6: the mathematical notation is inconsistent throughout the paper. In the previous text, F was the linear combination of the measured counts, now it represent the true counts and Fm the combination of the measured counts. Please, choose a notation and keep it throughout the paper. Also, F are NOT the true counts, but the linear combination

of the true counts. Finally, mention that k<0;

agree

where F are the true weighted ratios (Eq \ref{eq:double_ratios}), F_m, the measured ones, and the k parameter are negative. This is equivalent to correcting the extraterrestrial constant.

p. 8 l. 8: "This is equivalent to correcting the extraterrestrial constant, i.e.";

Corrected

p. 8 l. 11: "... ozone calibration, as explained in the text below.";

where F are the true weighted ratios (Eq \ref{eq:double_ratios}) and F_m, the measured ones. This is equivalent to correcting the extraterrestrial constant.

\begin{equation}

ETC_i= ETC_0 + k {(X \mu)}^s

\end{equation}

where ETC_0 is the ETC for the OSC region which is free of stray light, and k and s are retrieved from the reference comparison (Figure~\ref{fig:stray_det}). These parameters, determined in several campaigns, have been found to be stable and independent of the ozone calibration.

p. 9 l. 14: "OSC free region" -> "straylight-free region". Additionally, what does "starts" mean here?

Corrected to “end”

p. 9 l. 15: can you quantify "enough"?-

-we need observations to derive the k and s parameters, observations up to 1600 seem enough to properly determine the parameters- (See detailed explanation on p10.10 section)

p. 10 l. 8: if you mention the "model from Karppinen", please first define it;

We have added a reference to the model

p. 10 l. 8: can you quantify "significant"? ,

During the campaign there were 97 simultaneous observations with OSC>1600, but they are not equally distributed between all instruments, so we have decided to remove the comment as it is not relevant.

p. 10 l. 10: how can the authors use the empirical correction as the reference term for the comparison at those OSCs? This is a point that I raised previously: first the authors say that "getting observations to 1600 DU is enough", but then they extrapolate the correction for comparison up to 2000 DU. Taking as an example the k and s values from Fig. 4, the straylight correction doubles from 1600 to 2000 DU (-232 to -466), so extrapolating above 1600 DU is very dangerous. Please, clarify this fundamental point;

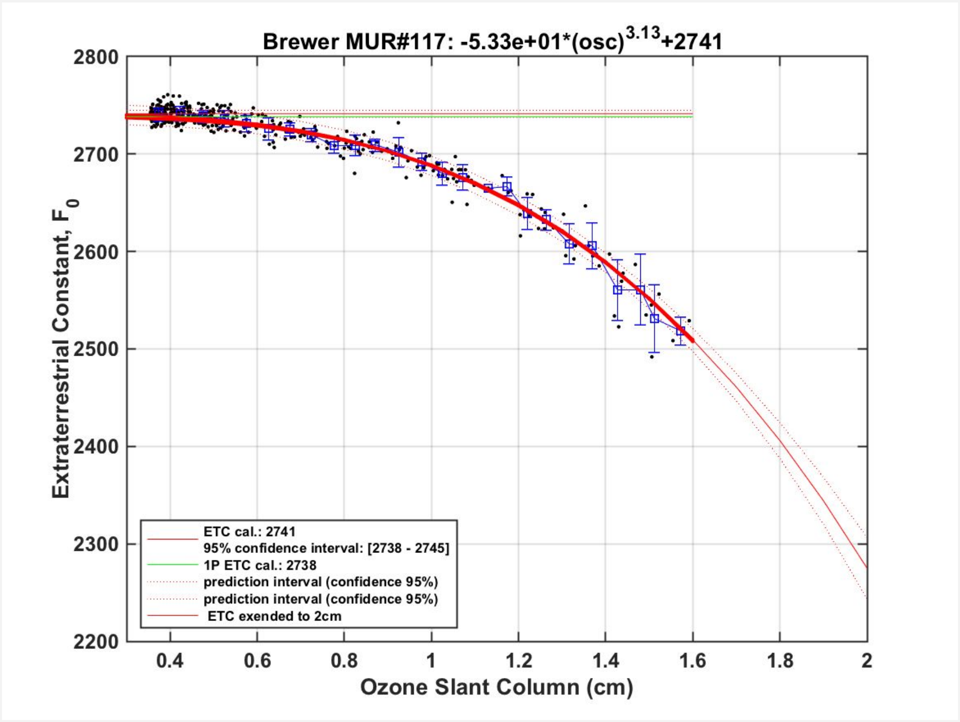


Figure 1: Figure 4 of the paper extended to osc 2 cm and prediction interval added

Using data up to 1600 DU we can provide a good determination (r-square of the fit better than 0.99) of the non-linear parameters k and s. Once these parameters are determined, the correction can then be applied to any range. We have extended figure 4 with the prediction interval up to 2000 DU, as provided by Matlab's fit function. The correction follows a power law but is well reproduced by the model and the maximum values of the 95% confidence limits are small compared to the correction.

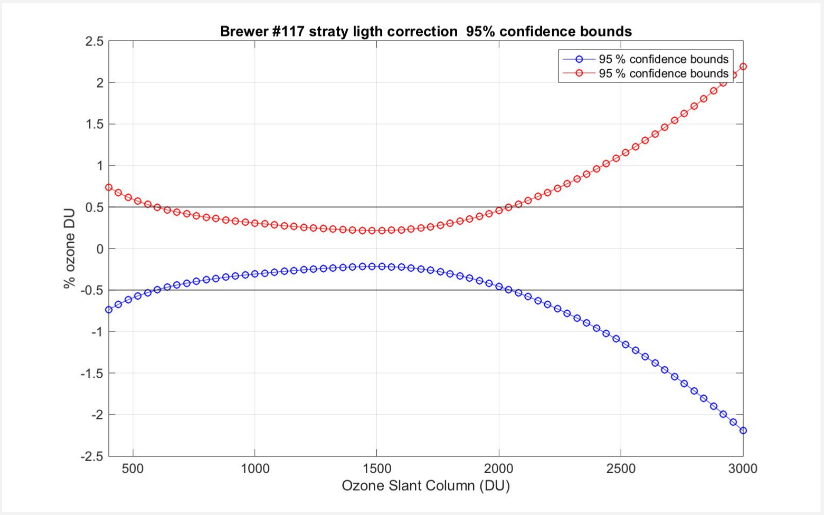


Figure 2: Stray light correction bounds

In the case of #117 the 95% confidence limits reach the +/-1% at 2500 DU, and its value is approx. 0.5% at 2000 DU.

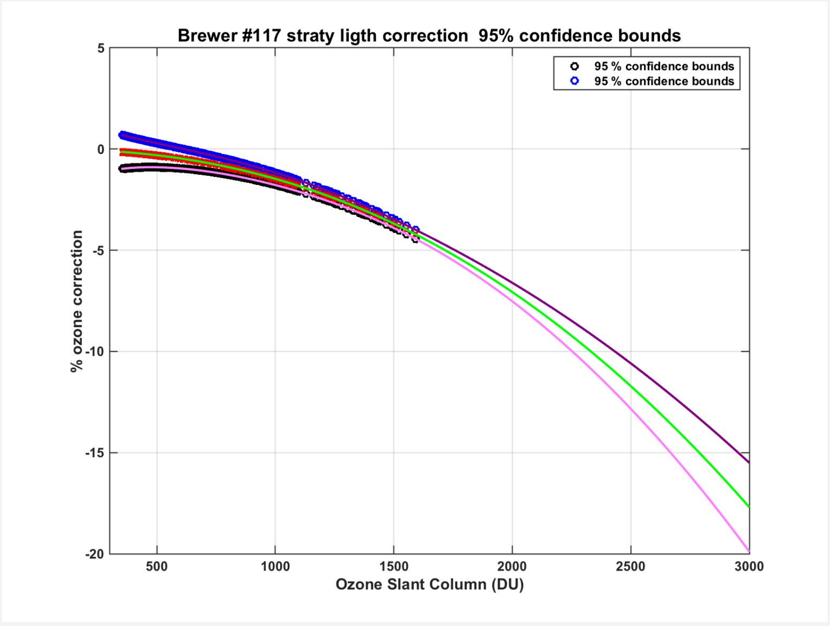


Figure 3: Figure: The same observations as Figure 4 of the paper, but converted to ozone correction, plotted together with the 95% confidence limits. Points are real observations during the campaign and the lines extend up to 3000 DU.

As the referee pointed out, the error bounds increase exponentially with the extrapolation. Using the data of the Brewer #037 at Izaña Nordic campaign, the error at 2000 DU increases from +/-1% if we use observation up to 1600 to 5% if we use only observations up to 1400. The error on the extrapolation will also depend on the particular instrument, on the campaign with observations up to 1600DU the error bounds at 2000 DU for all the instruments are lower than +/- 2 %.

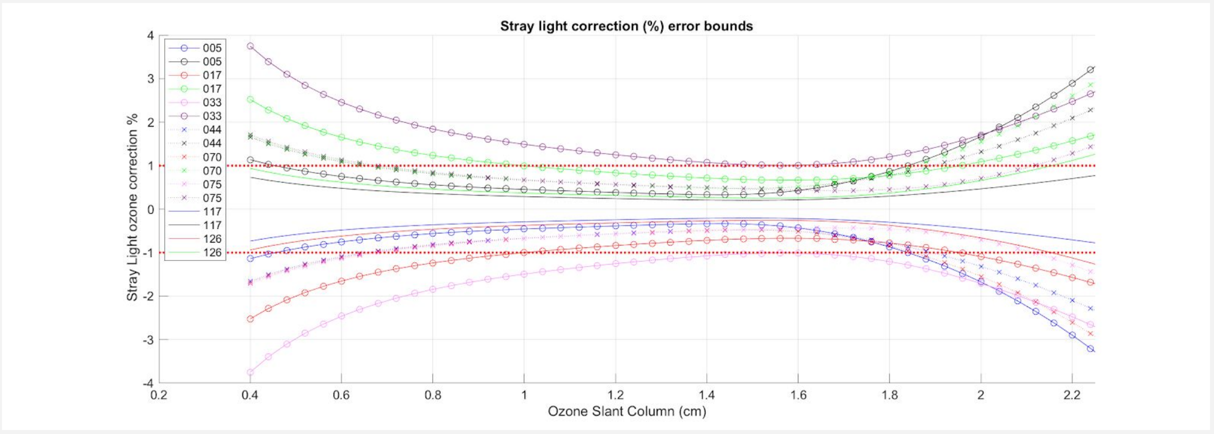


Figure 4: Stray light correction error bounds for the single brewer at the campaign

We have also compared for Brewer #037 at Izaña the stray light correction error bounds predicted by the model with the correction finally obtained with fits with different extrapolations from 1400 to 1700 DU . The mean of the correction applied are very similar in all cases with less than 0.4% at the highest measured OSC (~1800 DU)

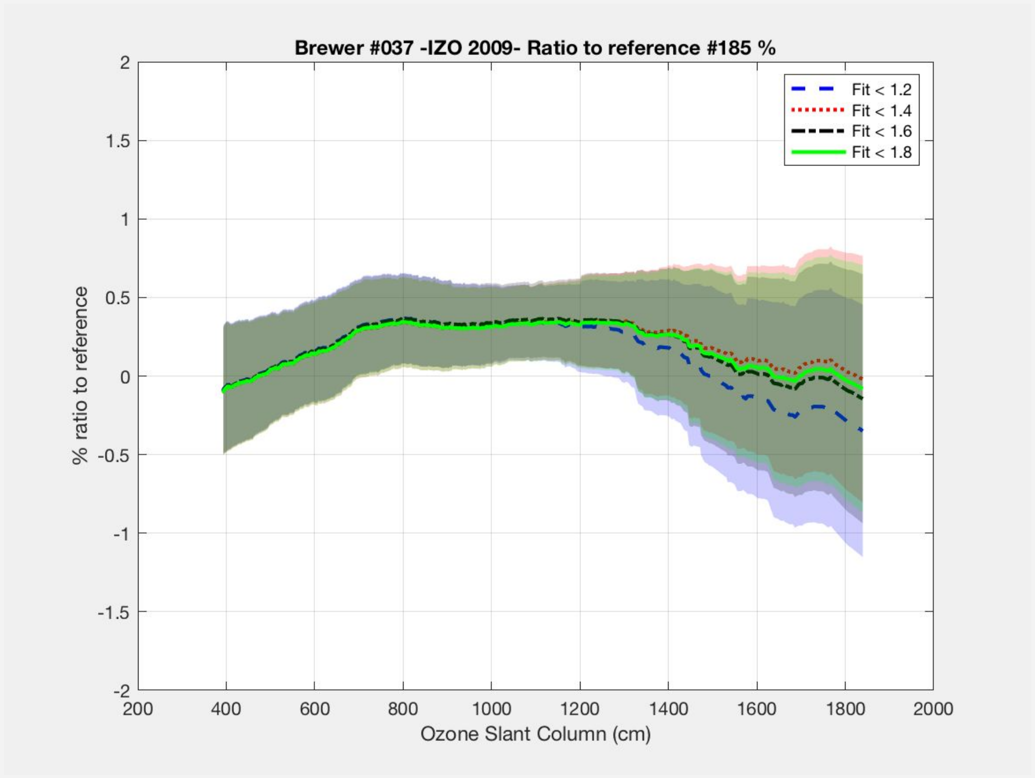


Figure 5: Ration to the reference of the corrected stray light data using for the fit observations up to osc 1.2,1.4,1.6 and 1.8 cm

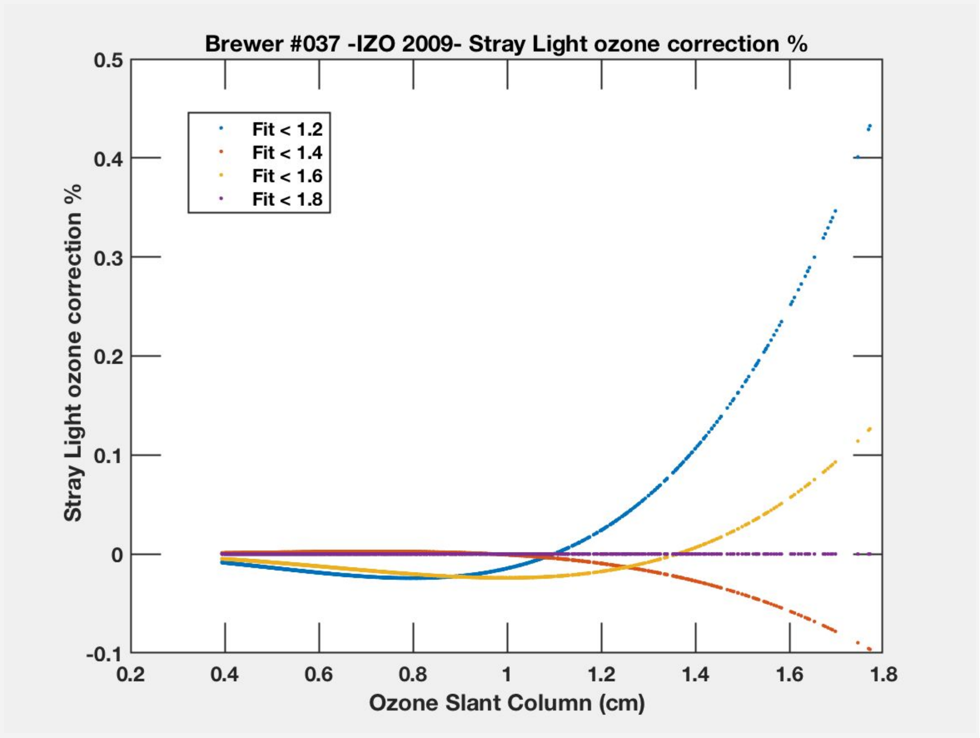


Figure 6: % Differences of the correction of the different models to the fit that use all the observations

Rephrased

Figure \ref{fig:stray_osc} shows the ratio of the TOC calculated by single Brewer participating in the campaign with respect to the reference instrument, where we can see that the stray-light free region which we use for calibration ends for some instruments at 600 \unit{DU} and is almost evident at 1000\unit{DU}.

The error due to the extrapolation can be estimated from the fit, these error bounds will depend on every instrument and strongly on the extrapolation (figure stray det). During the Nordic campaign the error bounds for Brewer #037 at 2000 DU increases from +/- 0.25%, if we use observations up to 1600 DU, to 1.7% if we use only observations up to 1200 DU. During this campaign with observations up to 1600 DU, the error bounds at 2000 DU are lower than 2% for all the instruments. This results are consistent with the results obtained from the model of Karpinen that shows an error of 1.29 % on 1900-2000 DU interval (Table 2 of karpinen). To help the determination of these parameters the measurement schedule is carefully defined to maximize the observations at high OSC, where around 30\% of the simultaneous observations are performed with OSC> 600 and 15\% are obtained with OSC >900 DU.

p. 11 l. 2: who is the subject of "has"? Please correct;

`Differences up to 20 ETC units (around 4% in ozone) have been observed during the campaign.`

p. 11 l. 6: F0 was never defined before;

Changed by Fm measured in consistence with the stray light correction:

```
where $F$ are the true weighted ratios (Eq \ref{eq:double_ratios})  and
$F_m$, the measured ones.
```

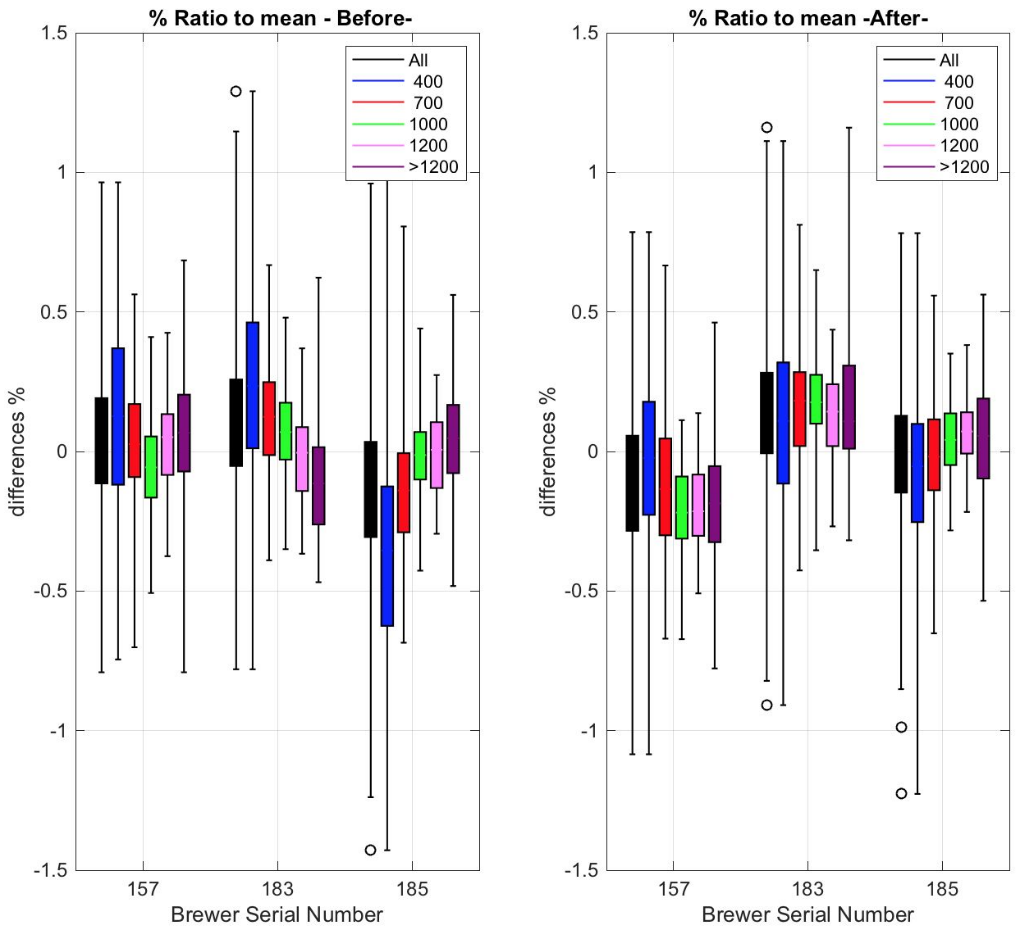
p. 11 l. 10: "test" -> "tests";

Changed

p. 13 Fig. 7: I can't understand to what the x-axis refers. Brewers #157 and #183 are not listed in Table 1;

Correct

We have added an explanation in the figure caption. Furthermore, both figures have been merged into a single one



```
      \caption{Box plot of the ozone percentage deviation from the mean of
the RBCC-E triad reference Brewer#157,Brewer#183 and Brewer#185 before
(left panel)  and after (right panel) the X RBCC-E campaign at El
Arenosillo in 2015, grouped by ozone slant columns ranges. The color
indicates the intervals used for the averaging of the observations- blue,
lower than  400 DU; red, between 400 and 700 DU; green, between 700 and
1000 DU; pink, between 1000 and 1200 DU; and purple for OSC > 1200 DU.
```

p. 15 both figure caption and l. 7: the text was not updated to clarify my previous question why Brewer #151 cannot be considered an "operative instrument";

We consider that an operative instrument is one that is capable of sending reliable data routinely to eubrewnet or the woudc. This is not the case of Brewer #151, because of the huge change in the SL record (note that more than 300 R6 units are outside the limits of the axes). This indicates that Brewer #151 cannot be considered operative.

Calibration report: https://docs.google.com/document/d/1tD-acUKRj-25Tyuv0DAW1QwSqEyqt2-fuXqAY8EeVAI/edit?usp=sharing

We have include this paragraph in the article:

In the following analysis we do not consider non-operative instruments, an operative instrument is one which is capable of providing reliable data during the campaign suitable for submission to databases like EUBREWNET or WOUDC (Word Ozone and UV Data Center). This is not the case for \#151, because the instrument shows a huge change on the SL record from the last calibration (300 R6 units while the instrument range is +/- 60 DU), indicating serious instrumental issues.

p. 15 l. 21: "Sec" -> "Sect";

Changed

p. 16 l. 12-27: why is a new topic (two parameters vs 1 parameter method) introduced in the conclusions?? I would suggest the authors to simply summarise the main topic of the paper, mentioning some quantitative results, instead of introducing new concepts. (Anyway, l. 21: "base" -> "based")

We moved the topic to the previous section. The conclusion for the calibration is that all the Brewer instruments can be calibrated with one point calibration.

p. 22 Fig. 11: the x-axis label of the upper panel is missing and the axis is not the same as the one below;

corrected

p. 22 caption of Fig. 11: "campaing" -> "campaign";

corrected

p. 25 table 2: Brewer #145 is missing in Table 1, therefore you must explain which Brewer is.

Corrected the caption of Table 2.

Reference Comparison during RBCC-E campaigns, Brewer #017 is the travelling reference from International Ozone Service (IOS), Brewer #158 is the travelling reference from Kipp Zonen, and Brewer #145 from Environmental Canada is a double Brewer directly calibrated using as reference the World Reference Triad which participated in the previous RBCC-E campaigns.

EUBREWNET RBCC-E Huelva 2015 Ozone Brewer Intercomparison

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[11]Danish Meteorological Institute, Copenhagen, Denmark
[12]Kipp & Zonen, Delft, The Netherlands
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Abstract.

From May 25th to June 5th 2015, the [..[1]]10th Regional intercomparison campaign of the [..[2]]Regional Brewer Calibration Center- Europe (RBCC-E) was held at El Arenosillo atmospheric sounding station of the Instituto Nacional de [..[3]]Técnica Aeroespacial (INTA). This campaign was jointly [..[4]]conducted by COST Action ES1207 EUBREWNET and the Area of Instrumentation and Atmospheric Research of INTA. Twenty one Brewers, 11 [..[5]]single and 10 double monochromator instruments from eleven countries participated and were calibrated for total column ozone (TOC) and solar UV irradiance. [..[6]]In this 2015 campaign we have introduced a formal approach to the characterization of the internal instrumental [..[7]]stray light, the filter non-linearity and the algorithm for correcting for its effects on the TOC calculations. This work shows a general overview of the ozone comparison [..[8]]and the evaluation of the correction of the spectral stray light effect for

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[1] removed: 10th

[2] removed: Brewer Calibration Center -

[3] removed: Técnica

[4] removed: conduced

[5] removed: singles

[6] removed: Every RBCC-E campaign advances our understanding of the Brewer calibrations in general and specifically what areas still require attention.

[7] removed: stray-light

[8] removed: ,

the single-monochromator Brewer spectrophotometer, derived from the comparison with a reference double-monochromator Brewer instrument. At the beginning of the campaign, 16 out of the 21 participating Brewer instruments agreed within better than ± 1%, and 10 instruments agreed within better than ± 0.5% considering data with Ozone Slant Column between 100 and 900 DU, which [..[9]]doesnt require instrumental stray light correction.

1 Introduction

The fully automated Brewer Spectrophotometer (Brewer, 1973; Kerr et al., 1985; Kerr, 2010) is together with the Dobson ozone spectrophotometer, the backbone of the World Meteorological Organization (WMO) ozone observation network providing high quality Total Ozone Column (TOC) data for more than 30 years and is now deployed at 200 ground based TOC monitoring stations worldwide. It is also capable of measurements of ozone vertical profiles (Umkehr method), spectral UV radiation and aerosol optical depth in the UV (AOD-UV), as well as columns of other trace constituents such as sulphur dioxide and nitrogen dioxide.

In November 2003 the WMO/GAW Regional Brewer Calibration Center for Europe (RBCC-E) was established at the Izaña Atmospheric Observatory (IZO) of the Agencia Estatal de Meteorología (AEMET) in Tenerife (Canary Islands, Spain). The RBCC-E consists of calibration laboratory facilities and reference-maintenance equipment mainly composed of three Brewer spectrophotometers, the denoted IZO Triad. This includes a Regional Primary Reference (Brewer #157), a Regional Secondary Reference (Brewer #183), and a Regional Traveling Reference (Brewer #185) which can be transported for calibration campaigns outside IZO. Initially, the RBCC-E transferred the calibration from the World Reference Triad in Toronto. However, due to uncertainties on the future maintenance of the World Triad, in 2011, the WMO scientific advisory group (WMO-SAG) authorized the RBCC-E to transfer its own calibration obtained by the Langley method.

RBCC-E regular intercomparisons are held annually, alternating between Arosa in Switzerland, and the El Arenosillo sounding station of the Instituto Nacional de Técnica Aeroespacial (INTA) at Huelva in the south of Spain. Since 2005, a total of 130 Brewer ozone spectrophotometer calibrations have been performed in these campaigns (see the campaign reports at the RBCC-E website, http://rbcce.aemet.es, and the GAW reports of the VII (Redondas et al., 2015), VIII (Redondas and Rodriguez-Franco, 2016), and IX (Redondas and Rodriguez-Franco, 2015b) intercomparison campaigns). In addition to the regular intercomparisons, the RBCC-E performs two types of campaigns supported by the ESA (European Space Agency) Validation projects: the NORDIC campaigns, with the objective to study the ozone measurements at high latitudes, and the Absolute calibration campaigns performed at IZO with the participation of Brewer and Dobson reference instruments. Figure 1 shows the number of Brewer instruments calibrated at these campaigns since 2003.

The aim of COST Action 1207 “EUBREWNET” is to establish a coherent network of European stations equipped with Brewer spectrophotometers for the monitoring of total ozone column (TOC), spectral UV radiation, and aerosol optical depth in the UV spectral range (AOD-UV), ensuring sustainable operation in the long-term (Rimmer et al., 2018). Among the primary aims of EUBREWNET is to harmonise operations and develop approaches, practices and protocols to achieve consistency in

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[9] removed: doesn’

quality control, quality assurance and coordinated operations, as well as to eliminate duplication of efforts at individual stations. It also aims at establishing knowledge exchange and training, and at opening up a route to link with international agencies and other networks globally.

It was proposed by Fioletov et al. (2008) that the main problem of the Brewer network was the lack of QA/QC, the non-uniformity of the data processing, and the lack of reprocessing of the observations after the calibration. This problem is also aggravated because there are more than 100 agencies providing Brewer data with different calibration practices, operational procedures and data processing, including many of these stations within Europe. The intercomparisons are a basic tool to achieve EUBREWNET objectives, in particular during RBCC-E calibration campaigns the instruments perform a common measurement schedule, the observations are uniformly processed and can be used to organise operator training on applying uniform operational procedures. During these campaigns we are able to address some important issues which affect the Brewer performance, these include instrumental parameters and the calibration methodology (Redondas and Rodriguez-Franco, 2012)

Before the establishment of the RBCC-E, the Brewer spectrophotometer calibrations were referenced to the Brewer World Calibration Center hosted by Environmental Canada (EC). However, most of the Brewer instrument were, and still are, calibrates by private companies, in the main by International Ozone Servicies (IOS) and to a lesser extent by Kipp and Zonen (Staehelin, 2010). The RBCC-E calibration adapts the methodologies and tools developed by EC and IOS, but also investigate and improves particular issues. The focus in the first campaigns were related to the instrument characterisation and the ozone absorption calculation (Redondas and Rodriguez-Franco, 2012) whereas in this campaign the focus was on the stray light correction and the investigation of the error due to non-linear filter attenuation.

The EUBREWNET RBCC-E Huelva 2015 Ozone Brewer Intercomparison campaign had two main objectives: to establish the current status of the network with the participation of about the half of the participating Brewers in the network and to test the improvements introduced during the COST action on the total ozone processing (the stray light correction on single Brewer and the attenuation filter corrections). As well as ozone calibration, solar UV irradiance calibration was also performed by the travelling reference standard QASUME instrument of the World Calibration Center for UV (WCC-UV) and is described by the companion paper by (Lakkala et al., 2017), also it is remarkable that this campaign [..[10]]provided the AOD-UV (López-Solano et al., 2017).

The present work is organised as follows. The Brewer algorithm for TOC and the calibration methodology implemented during the RBCC-E campaigns is described in Sect 2, with focus on the improvements introduced by the stray light and the filter corrections. In Sect. 3 we describe and present results of [..[11]]intercomparisons. In the blind days section we check the stability of the TOC for the approximately 2-year period between calibrations and the final days subsection shows the agreement of the instrument at the end of the campaign. In Sect. 4 we discuss the results and the implications of the correction introduced by the EUBREWNET processing and provide some closing remarks.

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[10] removed: also

[11] removed: the

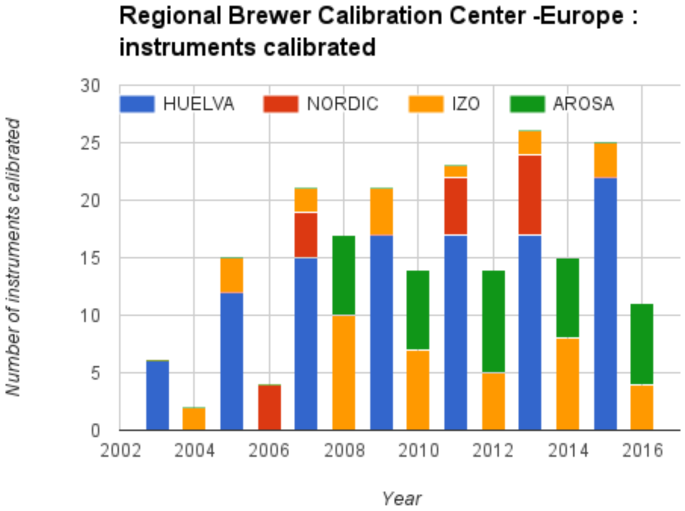

Figure 1. Brewer instruments calibrated since 2003 by the RBCC-E in regular campaigns (at Huelva and Arosa), Nordic intercomparisons, and the Absolute calibrations performed at the Izaña Observatory.

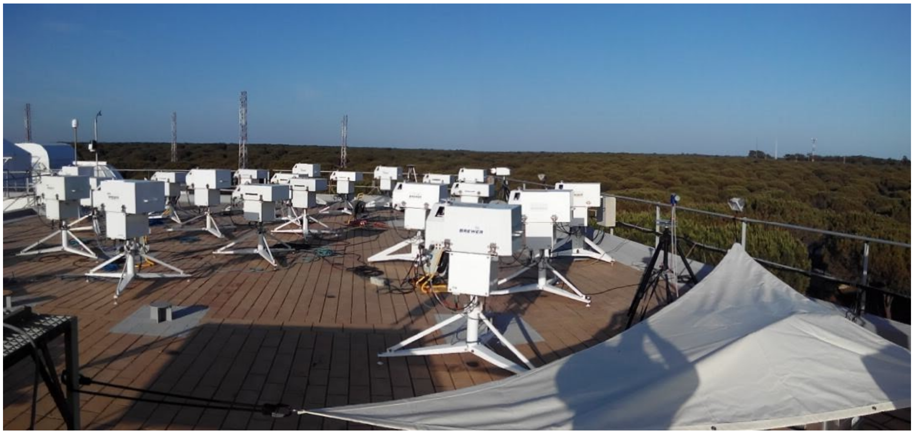

Figure 2. Panoramic view of the 21 Brewer spectrophotometers on the terrace of the El Arenosillo sounding station, Huelva, coming from Canada (1), Netherlands (2), United Kingdom (3), Switzerland (1), Finland (1), Greece (1), Denmark (2), Russia (1), Algeria (1) and Spain(7).

2 The calibration of the Brewer spectrophotometer

A brief description of the instrument and its operating principles in relation to the calibration is described in this section. A more detail description can be found in (Kerr, 2010; Savastiouk, 2006) .

The Brewer instrument measures the intensity of direct sunlight at six wavelengths (λ) in the UV (303.2, 306.3, 310.1, 313.5, 316.8, and 320.1 nm) each covering a bandwidth of 0.5 nm (resolution power $\lambda/\delta\lambda$ of approximately 600). The spectral measurement is achieved by a holographic grating in combination with a slit mask which selects the channel to be analysed by a photomultiplier. The longest four wavelengths are used for the ozone calculation. The basic ozone measurement is the direct sun [..[12]]measurement. The sunlight enters the instrument through an inclined quartz window after which a right-angle prism directs the incoming light to the optical axis of the instrument. The light subsequently passes through the fore-optics, which consist of a set of lenses to adequately focus the beam, an iris diaphragm, and two filter wheels. A ground quartz diffuser is located on the first filter wheel. The second filter wheel consists of a set of five neutral density filter attenuators which guarantee that the detector is working in its linear regime. After passing through the filter wheels, radiation is then focused onto the entrance slit of the monochromator. Presently, there are three commercially available installed Brewer models. The oldest model MKII is a single monochromator with a solar-blind filter, a $NiSO_4$ element sandwiched between two UG-11 glass filters, located between the exit slit and the PMT to block radiation at wavelengths longer than about 325 nm. The model MKIV is capable of measuring NO_2, this instrument works with its grating in the third diffraction order for the ozone retrievals and the second diffraction order in NO_2 retrievals. However, both instruments are affected by stray light, mainly, because of using a [..[13]]single monochromator. In contrast, the the model MKIII is a double monochromator which provides enough stray light rejection to work in the first diffraction order for UV and ozone measurements.

Based on the Lambert-Beer law, the total ozone column in the Brewer algorithm can be expressed as (Kerr, 2010)

$$X = [..^{14}]\frac{\mathrm{ETC}-\mathrm{F}}{\alpha\mu} \tag{1}$$

where F is a linear combination of the logarithm of the measured spectral direct irradiances (also called double ratios) corrected for Rayleigh molecular scattering, α is the ozone differential absorption coefficient, μ is the ozone air mass factor, and ETC is the extra-terrestrial constant. The F, α and ETC parameters are weighted functions at the operational wavelengths:

$$F = \sum_i^4 w_i F_i - \frac{p}{p_0}\beta_i\mu \tag{2}$$

$$\alpha = \sum_i^4 w_i \alpha_i \tag{3}$$

$$ETC = \sum_i^4 w_i F_{0i} \tag{4}$$

where β_i are the Rayleigh coefficients, p is the climatological pressure at the measurement site, p_0 is the pressure at sea level, and F_i and F_{0i} are the individual measured and extra-terrestrial irradiances at each wavelength respectively. The [..[15]

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[12] removed: measurements

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]four longer wavelengths (310.1, 313.5, 316.8 and 320.1 nm are used on the ozone calculation with the respective weights of $w = [1, -0.5, -2.2, 1.7]$[..[16]]. These wavelengths have been selected near stationary points in the ozone absorption spectrum and are thus optimized to minimise the influence of [..[17]]small wavelengths shift (i.e. [..[18]]$\delta F // \delta \lambda = 0$). The weightings were determined to suppress the influence of SO_2 and aerosol. Moreover as λ_i and w_i satisfy the conditions defined by Eqs. (5) and (6), the measurement not no depend on wavelength-independent parameters such as the [..[19]]

[..[20]][..[21]][..[22]]

[..[23]][..[24]][..[25]][..[26]][..[27]]

[..[28]]absolute calibration[..[29]][..[30]]. Also, it largely eliminates absorption processes which depend, to first approximation, linearly on the wavelength [..[31]]such as the contribution from aerosols [..[32]](Kerr, 2010).

$$\sum_{i}^{4} w_i = 0 \tag{5}$$

$$\sum_{i}^{4} w_i \lambda_i \approx 0 \tag{6}$$

The Brewer retrieval of the TOC requires the knowledge of some instrument characteristics which are determined by calibration experiments during intercomparison campaigns (Redondas et al., 2015; Redondas and Rodriguez-Franco, 2015a, b, see e.g. the GAW reports of the Seventh, Eighth, and Ninth Intercomparison Campaigns of the RBCC-E). The instrumental calibration includes all the parameters that affect the counts measured by the spectrometer (F_i), in particular the dead time correction (Fountoulakis et al., 2016), temperature coefficients (Berjón et al., 2017), and filter attenuations. The wavelength calibration determines the ozone absorption and Rayleigh scattering coefficients. The exact wavelengths measured by each Brewer spectrophotometer are slightly different from instrument to instrument. The so-called “dispersion test” is thus used to determine the exact wavelengths of each instrument and its slit, or instrumental, function (Gröbner et al., 1998; Redondas et al., 2014a). An extra-terrestrial (calibration) constant is determined by the Langley method (Redondas et al., 2014b; León-Luis

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[16] removed: have been chosen

[17] removed: SO_2 and aerosol. To minimise effects of small shifts in wavelength

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[29] removed: see Eq. (5)

[30] removed: , and widely eliminates absorption features

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[32] removed: see Eq.(6)

et al., 2018) , in the case of reference brewers , or by comparison with a reference instrument in the case of the other Brewer of the Network.

It is important to note that TOC It is then finally determined using ratios of measurements so there is no transfer of the radiometric scale. During the campaigns the transfer of the calibration to a network instrument is achieved by operating side by side with the reference Brewer. Once we have collected enough near-simultaneous direct sun ozone measurements, we calculate the new extra-terrestrial constant after imposing the condition that the measured ozone will be the same for simultaneous measurements for both instruments. In terms of Eq. 1, this leads to the following condition:

$$ETC_j = F_j + X_j^{reference}\alpha\mu_j \tag{7}$$

[..[33]][..[34]][..[35]]

For a correctly characterised network instrument, the determined ETC values show a Gaussian distribution and the mean value is used as the instrument's extra-terrestrial constant. One exception to this rule is the single monochromator Brewer models (MK-II and MK-IV) which are affected by stray light (Karppinen et al., 2015). In this case, the ETC distribution shows a tail at the lower ETC values for high Ozone Slant Column (OSC, the product of the total ozone content by the airmass). As we discuss in detail on the next section for this type of Brewer, only the stray-light-free region is used to determine the ETC, which generally ranges from 300 to 800 DU in the OSC, depending on the instrument.

The network Brewers were calibrated using the one parameter ETC transfer method[..[36]]: i.e., the ozone differential absorption coefficient was derived from the [..[37]]calculations of wavelength calibration, the so-called "dispersion test" (Redondas et al., 2018-01-31), applied to the spectroscopic set of the ozone cross section and, only the ozone ETC constant was transferred from the reference instrument. The so-called “two parameters calibration method” (Staehelin et al., 2003), where both the ozone absorption coefficient [..[38]]and the ETC are calculated from the reference, is also [..[39]]obtained and used as a quality indicator.

The calibration is an iterative process [..[40]]because changes during the instrumental and/or wavelength calibration will affect the final ETC[..[41]]. Some instrumental characteristics which have been improperly accounted such as the non-linearity of the filters and the dead-time mismatch (Rodriguez-Franco et al., 2014), are revealed by the comparison with

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[33] removed: In the Langley determination of the ETC we assume that the ozone, as well other interfering absorbents, is constant through half of a day

[34] removed: see Eq. (7)

[35] removed: thus the regression of the double ratios F_j against the airmass will be a line with slope αX and intercept ETC (Komhyr et al., 1989) . These assumptions are only achievable in clear environments and high altitude subtropical stations like Izaña and Mauna Loa. The Langley calibration of the RBCC-E instruments are described in detail in (Redondas et al., 2014b; León-Luis et al., 2018) and are outside the focus of this work.

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the reference [..[42]]during the ETC transfer. A change in the instrumental constants then requires a full reprocessing of the calibration. For this reason the calibration campaigns are scheduled in three different [..[43]]period:

1. **Blind days:** the first days of the campaign are dedicated to determine the current status of the instrument by comparison with the reference instrument. During this period modifications of the instrument are not allowed.
2. **Characterisation:** after the determination of how the instrument is measuring, the next days are dedicated to characterise the instrument and perform the necessary adjustments and maintenance. The instrumental and wavelength calibration must be finished at the end of this period.
3. **Final days:** the period where the ETC transfer is performed, when the instrument is fully characterised and stable.

The [..[44]]changes in the spectral sensitivity of the instruments are tracked between calibration transfers using the measurements of the internal quartz halogen lamp, the [..[45]]so-called Standard Lamp (SL) test. A value, corresponding to a fictitious column density and often called R6, R5 or F-ratio (depending on whether the ozone, sulphur dioxide or nitrogen dioxide processing algorithm is applied), is obtained after processing. Slow variations of the SL test results with time may be representative of a change in the relative spectral (but not absolute, because of the way the retrieval algorithm works) sensitivity of the Brewer and may be even used to correct the final value of the solar measurements.This test is performed routinely to track the spectral response of the instrument and, therefore, the ozone calibration. A reference value for the SL, the so-called R6 ratio, is provided as part of the calibration of the instrument. The ozone is routinely corrected assuming that deviations of the R6 value from the reference value are the same as the changes in the ETC Extraterrestrial constant. This is then described by the Standard Lamp correction:

$$ETC_{new} = ETC_{old} - (SL_{ref} - SL_{measured}) \tag{8}$$

2.1 Stray light

There are two major sources of stray light on the Brewer: the “sky scattered” and the “out of band stray light, both of them produce an underestimation on the ozone calculation. The "sky scattered" stray light is due to the instrument having a field of view (FOV) larger than the apparent angle subtended by the sun in the sky, approximately 0.5º whereas the instrument FOV is about 1.5º, the measurement will thus include a “sky scattered” component (Josefsson, 2003, 2012). [..[48]]

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[42] removed: which requires

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[44] removed: calibrations are maintained between

[45] removed: so called

[48] removed: The measured radiation is a mixture of direct and sky scattered light with different spectral components resulting in relatively more radiation from shorter wavelengths resulting in an ozone underestimation. The contribution with high sun is negligible but for low sun or hazy conditions is highly significant.

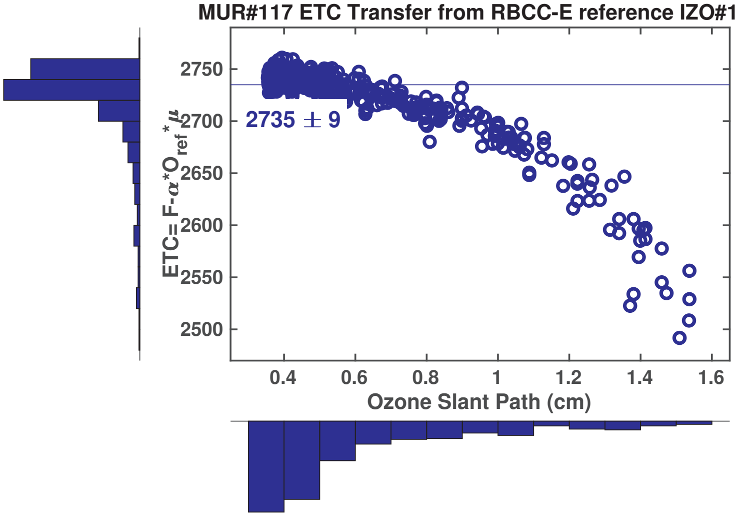

Figure 3. Distribution of individual ETC values determined by simultaneous measurements. In the horizontal axis, the ozone slant column (OSC). For this particular Brewer , the effect of the stray light is strong and clearly shown at values above 0.6 [..[46]]cm.[..[47]]

The second source of stray light is due to the finite dimensions of the exit slits and imperfections on the gratings or other optical components [..[49]]so that the intensity measured contains radiation from other unwanted wavelengths. The higher level of stray light in single monochromators increase the error of the measured UV radiation compared with the double-monochromators. This effect is largest at short UV wavelengths where the spectral irradiance level is low compared with the level of potential stray light. It is known to affect the Brewer spectral UV measurement (Kerr and McElroy, 1993; Bais et al., 1996) but only relatively recently has the effect on the ozone calculation been studied (Bojkov et al., 2008; Kiedron et al., 2008; Evans et al., 2009; Petropavlovskikh et al., 2011). The effect on the ozone calculation is enhanced when the short wavelength proportion is decreased due to a high slant path or high ozone content. The air mass in combination with the total ozone amount gives a measure of the absorption of the UV photons and is the key parameter for the stray light. There have been several attempts to model the stray light (e.g. Karppinen et al. (2015), Pulli et al. (2018) and the references within) but this requires the use of models or characterisation of the instruments that is not always available. Here we propose an empirical method based on the comparison of a double Brewer.

The stray light effect can be corrected if the calibration is performed against a double monochromator instrument, assuming that it can be characterised following a power law of the ozone slant column:

$$F = F_m + k(X\mu)^s \tag{9}$$

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[49] removed: such as

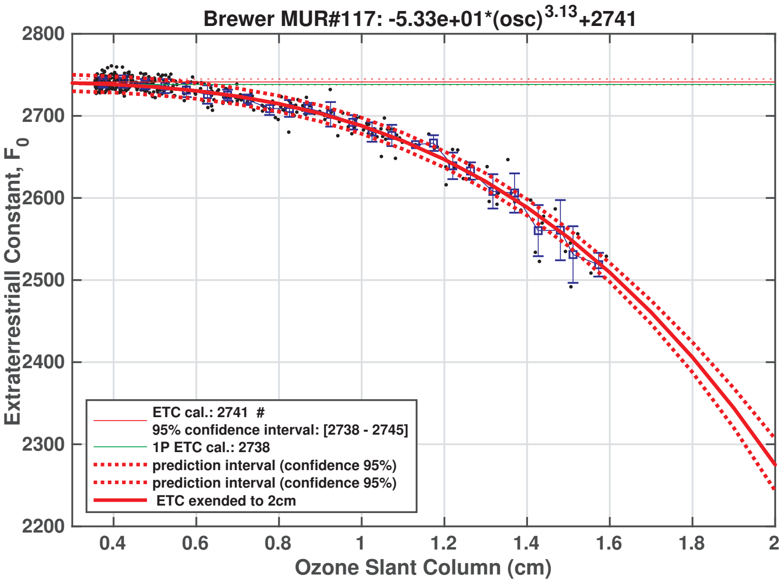

Figure 4. The stray light parameters k and s are determined by a nonlinear fit using the ETC determined from the [..[50]]stray-light-free region as first guess parameters. The red horizontal line indicate the ETC constant retrieved from the fit, and the green one, the initial guess. The upper and lower 95% prediction bounds are also displayed in red dot lines.

where F are the true [..[51]]weighted ratios (Eq 2) , F_m, the measured ones, and the k parameter are negative. This is equivalent to correcting the extraterrestrial constant.

[..[52]]

$$ETC_i = ETC_0 + k(X\mu)^s \tag{10}$$

where ETC_0 is the ETC for the [..[53]]OSC region free of stray light, and k and s are retrieved from the reference comparison (Figure 4). These parameters, determined in several campaigns, have been found to be stable and independent of the ozone calibration.

As the counts (F) from the single Brewer instrument are affected by stray light, the ozone is calculated using an iterative process:

$$X_{i+1} = X_i + \frac{k(X_i\mu)^s}{\alpha\mu} \tag{11}$$

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[53] removed: stray-light-free OSC region

This empirical method was tested during the NORDIC campaigns and the counterpart campaigns at Izaña with the MKII Brewer #037 operated by the Finish Meteorological Institute at Sodankyla (Finland) since 1988 (Karppinen et al., 2016). This instrument was calibrated four times at Izana in 2009, 2011, and 2015 and at Sodankyla in 2011 (Roozendael et al., 2013b, 2014). From these measurement campaigns we found the stray light correction obtained during the first campaign can be applied to the subsequent campaigns, obtaining a good agreement better than 0.5% on the 300-1800 OSC range. This is confirmed with the agreement of the determination of the stray light parameters k and s obtained during different campaigns (Table 3 of (Roozendael et al., 2014)) at different locations with quite different sky conditions and even with changes on spectral response of the instrument. A similar experiment was done at Huelva with a good agreement using the previous campaign determination of the stray light parameters.

Figure 5 shows the ratio of the TOC calculated by single Brewer participating in the campaign respect to reference instrument, where we can see that the [..[54]]stray light-free region which we use for calibration [..[55]]ends for some instruments at 600 DU and is almost evident at 1000DU[..[56]]. The error due to the extrapolation can be estimated from the fit, these error bounds will depend on every instrument and strongly on the extrapolation (Fig 4). During the Nordic campaign the error bounds for Brewer #037 at 2000 DU increases from +/- 0.25%, if we use observations up to 1600 DU[..[57]], to 1.7% if we use only observations up to 1200 DU. During this campaign with observations up to 1600 DU, the error bounds at 2000 DU are lower than 2% for all the instruments. This results are consistent with the results obtained from the model of Karpinen that shows an error of 1.29 % on 1900-2000 DU interval (Table 2 of Karppinen et al. (2015)). To help the determination of these parameters the measurement schedule is carefully defined to [..[58]]maximize the observations at high [..[59]]OSC, where around 30% of the simultaneous observations are performed with OSC> 600 and 15% [..[60]]are obtained with OSC >900 [..[61]]DU.

Usually just one iteration is needed for the atmospheric conditions at the intercomparisons carried out at El Arenosillo, with OSC values up to 1500 DU. For OSC measurements in the 1500–2000 DU range, two iterations are enough to correct the ozone (Figure 7). These stray light corrections are now implemented in the standard procedure of EUBREWNET.

The effect of the [..[62]]stray light has been studied in the Sodankyla total ozone series, one of the longest record in the Artic (Roozendael et al., 2014). In this location even at noon the ozone slant column can be quite large. When the model from Karppinen et al. (2015) is applied to the series the effect on the monthly means is significant in spring but with a marginal effect on the trends. The comparison between the empirical correction and the model shows a good agreement (0.1 %) in most of the operative range but the model underestimate above 1600 DU reaching 1% at 2000 DU.

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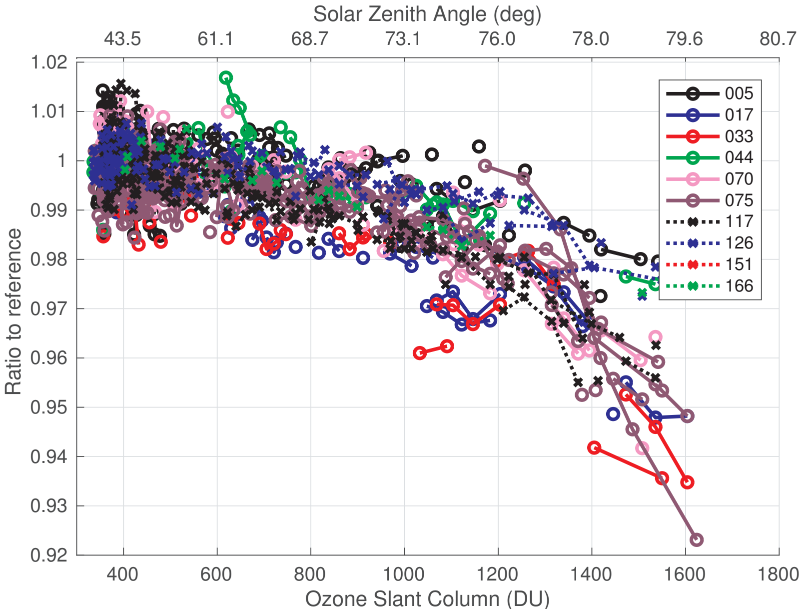

Figure 5. Percentage ozone differences with respect to the reference of the participating Single Brewers. On the upper x-axis the approximate solar zenith angle is indicated assuming TOC of 300 DU

2.2 Correction of filter non-linearity

The Brewer spectrophotometer uses neutral density filters in order to optimise the intensity of the light which reaches the photomultiplier. The ozone is calculated using ratios so if the filters are neutral they have no effect on the ozone calculation (Eq. 5). In addition the weighing coefficients also verify (Eq. 6) so a linear attenuation with wavelength also does not affect the ozone calculation. In a real instrument however, some of the filters are not neutral, the ozone wavelengths vary from instrument to instrument, and the second condition is only an approximation. The effect on the calculated ozone will depends on the filter used (Savastiouk, 2006; Redondas et al., 2011). This dependence is clear when the instrument is compared with a reference and the comparison is seen to depend on the filter [..[63]](Fig 6). Differences up to 20 ETC units ([..[64]]up to 4% in ozone) [..[65]]have been observed during the campaign.

This error can be corrected if we know the spectral dependence of the filter AF_i and introduce a correction dependent of the filter used (f#)

$$F(f\#) = [..^{66}]\mathrm{F_m} + \sum_{i=1}^{4} w_i AF(f\#)_i$$

where F are the true weighted ratios (Eq 2) and F_m, the measured ones.

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The effect on ozone is only important at low air masses, where the ozone calculation is more dependent of the ETC, which implies high solar signal and in consequence high attenuation filters used.

Several methods have been developed to determine the wavelength dependence of the filter, using the internal lamp, the sun as source. However, as it affects high attenuation filters, there is not enough signal with the lamp and the non-linearity is difficult to determine with precision. Frequently the results are not significant with the number of [..[67]]tests that can be performed during a campaign, and the comparison with a well characterised instrument is the preferred method during the intercomparsions. Also we can determine the correction directly by examining the record of the instrument and looking for the simultaneous measurements performed with consecutive filters or determine the ETC constant for every filter.

3 Intercomparison Results

3.1 The X RBCC-E campaign

From May 25th to June 5th 2015, 21 Brewer spectrophotometers from 11 countries (see Table 1) took part in the X RBCC-E campaign held at the El Arenosillo atmospheric sounding station (Huelva, Spain). Besides the ozone calibration, a solar UV irradiance calibration was performed by the traveling reference standard QASUME (Hülsen et al., 2016) instrument of the World Calibration Center for UV (WCC-UV). The X RBCC-E campaign was the result of the collaboration between COST Action 1207 “EUBREWNET” (http://www.eubrewenet.org/cost1207), and the Area of Instrumentation and Atmospheric Research of INTA. (Redondas et al., 2016).

El Arenosillo Atmospheric Sounding Station, which belongs to the National Institute for Aerospace Technology (INTA), is located on the Atlantic Coast, in the province of Huelva of the region of Andalusia, in south-west Spain. Its surroundings correspond to the "Doñana" National Park, which guarantees its natural environment. Moreover, the climate at "El Arenosillo" is characterised by very frequent sunny conditions, around 280 clear sky days per year, being a really suitable site for intercomparison campaigns. The observatory has a big terrace with completely open horizon Fig(2). The surroundings of the station consist of pine trees which provide a uniform albedo spatially and temporally throughout the whole year. This constant behaviour of the albedo allows the comparability of results obtained in different seasons and years.

We collected during the campaign ≈ 650 direct sun ozone measurements with the reference instrument, most of them ($\approx 65\%$) within the 300-600 DU and 18% on the 600-900 DU and 17% 900-1700 DU ozone slant path range, in larger airmass. The mean number of near-simultaneous ozone measurements between the Brewers and the reference instrument was 350. Total ozone content values at El Arenosillo station during the intercomparison ranged between 320 to 380 DU. This campaign was characterised by high internal temperatures, with an average of 32°C and a standard deviation of 5°C, which is 10°C above the spectrometer normal operating temperatures (Berjón et al., 2017).

Briefly the Brewer network is calibrated with two main parameters: the ETC and the effective ozone absorption coefficient. The comparison with a reference instrument is used to establish the ETC but the effective ozone absorption

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[67] removed: test

coefficient can be derived also from the reference (two parameters method) as was done in the past (Staehelin et al., 2003) or directly from wavelength calibration as is performed at present (one parameter method) (Fioletov et al., 2005). Historically the two parameter method was used until around year 2000 after that the one parameter method has been adopted in the Brewer network. Although both methods give the same results in the 300-800 DU range (stray light free range), the two parameters calibration gives uniform results, smoothing the instrumental differences and reduces the stray light error on single Brewer (Bojkov et al., 2008). On the other hand, the one parameter calibration is more robust, it does not depend on reference wavelength calibration, and it highlights instrumental differences. An error in the ETC value yields an error that depends on the solar zenith angle, while an error in effective ozone absorption coefficient introduces a relative bias. The transition in the calibration methodology around the year 2000 can explain the change of the seasonal difference between ground base Brewer and satellites observed by Fioletov et al. (2008). During the RBCC-E campaigns we can show that the two point calibration can mask instrumental issues which are air-mass dependent. Moreover, both calibration methods give the same results on well characterised instruments and the difference between the calibration constants can be used as an indicator of the quality of the instrument calibration (Redondas and Rodriguez-Franco, 2012; Roozendael et al., 2014).

3.2 Reference Calibration

The RBCC-E triad is regularly calibrated, performing the instrumental characterisation and wavelength calibration monthly. The three instruments are independently calibrated by the Langley plot method following the procedure described in Redondas et al. (2014b) and León-Luis et al. (2018). Before and after the intercomparison campaigns, the travelling instrument is compared with the two static instruments to verify that the calibration has not changed during transport (Figures **??**red [..[68]]$_t riadfig : box_plot$[..[69]]$_t$riad)$, (Redondaset\ al., 2015; RedondasandRodriguez-Franco, 2015a, b; Len-Luiset\ al., 2018).$ [..[71]]

The campaign is a good opportunity to compare travelling reference instruments, that is instruments that are used to transfer calibrations. Brewers #017, managed by International Ozone Services (IOS) and directly calibrated to the Environment and Climate Change Canada, Toronto Triad (Fioletov et al., 2005; Fioletov and Netcheva, 2014; Netcheva, 2014), and #158, managed by Kipp & Zonen, manufacturer of the Brewer spectrophotometer, took part in the X RBCC-E campaign. Since 2007 the Brewer #158 is calibrated annually during the RBCC-E intercomparisons so it is already referenced to the RBCC-E triad. The calibration of IOS and RBCC-E Triads primary reference for the travelling instruments are discussed by León-Luis et al. (2018).

The agreement between the travelling reference instrument during this campaign was found to be quite good, with differences lower than 0.5% for OSC lower than 900 DU (see Table 2). Note that Brewer #017 is a single-monochromator instrument and is affected by stray light, thus underestimating the ozone at high OSC values above 600 DU.

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[68] removed: $_b efore$

[71] removed: Box plot of the ozone percentage deviation from the mean after the X RBCC-E campaign at El Arenosillo in 2015.

Table 2 shows the comparison of the reference instruments during the RBCC-E campaigns and the corresponding calibration report. The agreement is generally around +/- 0.5% but with exceptions. In contrast to the RBCC-E travelling instrument which is transported by boat/car to Huelva and as hand luggage using two extra-sites of the plane, to Arosa campaigns. The travelling instrument are usually transported by cargo and can have issues during transportation that are reflected in table 2 or require instrumental changes for example #158 had a new PMT and new electronics during Arosa 2014 and the SL tests do not reflect this change.

3.3 Blind Days

A blind comparison with the reference Brewer instrument is performed at the beginning of the campaign, thus providing information on the initial status of the instrument, i.e. how well the instrument performs using the original calibration constants (those operational at the instrument's station). Possible changes of the instrument response due to the travel can be detected through the analysis of internal tests performed before and after the travel.

The analysis of the SL historical record is one of the principal tools to establish the stability of the instrument calibration. Moreover the comparison with a reference during calibration campaigns is the most suitable tool to determine if the observed R6 changes are related or not with changes in the ETC constant. During the El Arenosillo 2015 intercomparison campaign, most instruments agreed on average with the corresponding R6 reference value within ± 10 units, which is about 1% in ozone. The stray light record tracks well small and slow changes on instrument responsivity but has issues when these changes are abrupt or huge. Generally, from our experience, the SL correction tracks the changes in the relative spectral sensitivity of the Brewers well unless the instruments characteristics change (whether intentionally or not) in ways that affect the ozone observations differently from the SL measurements, e.g. changes in the iris diaphragm, neutral density filters or zenith prism pointing towards the lamp or the sun. During the analysis we focus on the instruments that showed deviations of R6 values to the reference larger than 20 units (Fig. 11). Even in these cases for some instruments, for example Brewer#228, the SL correction improves the comparison, whereas for others like #163, where the change was produced by the modification of the fore optics the opposite happens. The comparison with a standard reference instrument is the only way to assess whether the SL correction properly tracks changes on the calibration or the changes observed are just due to changes of the lamp's spectral emission (Fig. 10). This analysis will determine if a re-evaluation of the ozone observations between calibrations are required after an analysis of the history of the instrument.

On the following analysis we do not consider non-operative instruments, an operative instrument is one which is capable of providing reliable data during the campaign suitable for submission to databases like EUBREWNET or WOUDC (Word Ozone and UV Data Center). This is not the case of #151 because the instrument shows a huge change on the SL record from the last calibration (300 R6 units while the instrument range is +/- 60 UD), indicating serious instrumental issues.

Table 3 shows the mean relative difference for the simultaneous direct sun measurements with the reference for all the participating instruments, with and without the standard lamp correction, in the [..[73]]stray light-free OSC region. With the exception of Brewer #151, that can not be considered an operational instrument, the maximum difference found is

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[73] removed: stray-light-free

1.5%. This is a really good result considering that most of the instruments were calibrated two years previously. The third column of the table shows the average of the best result for all the observation OSC range. This result is an estimation of the calibration agreement of the EUBREWNET network, with half of the instruments showing a perfect agreement within ±0.5%, and 75% within the ±1% level.

3.4 Final comparison

We define the final days as those available after the maintenance work has been finished for each participating instrument. These days are used to calculate the final calibration constants, so we endeavour not to manipulate the instruments during this period. Furthermore, the SL R6 value recorded during the final days is normally adopted as the new reference value. It is also expected that this parameter will not vary more than 5 units during this period. We show in Fig. 12 the differences between the daily standard lamp R6 ratio and the proposed R6 reference value during the final days. As expected, the recorded SL values did not vary more than 5 units during this period.

Deviations of ozone values for all the participating instruments with respect to the RBCC-E travelling standard Brewer #185 are shown in Fig. 13 and summarized in Table 3. We have recalculated the ozone measurements using the final calibration constants and, in the case of single Brewer instruments, with and without the stray light correction as described in [..[75]]Sect. 2.

The effect of the stray light correction is not large on the statistics, only 30% (sza> 60º) of the observations are affected on the single Brewer, and only for %15 (sza>70º) is the effect bigger than 1% but taking into account the stray light allows for the instruments to be calibrated using the one parameter method. Not taking into account this correction using the two parameters method as in Bojkov et al. (2008) can cause a misleading calibration constant. For all the instruments, both the one parameter and the two parameters ETC transfer methods agreed to each other within the limit of ±5 units for ETC constants and ±0.3% for ozone absorption coefficients, which is an indication of the quality of the calibration provided.

We achieved a good agreement with the reference instrument Brewer #185 using the final calibration constants, see Fig. 13 and Table 3. With the application of the stray light correction to the single Brewer spectrophotometers, all instruments are within the ±0.5% agreement range.

4 Conclusions

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[..[76]][..[77]]

To summarise the calibration results of the 10th RBCC-E campaign, we found that during the blind days, using the two-year-old calibration issued in the previous campaign,

- 16 Brewer spectrophotometers (∼75% of the participating instruments) were within the 1% agreement range.
- 10 Brewer spectrophotometers (∼50%) were within the ±0.5% range, i.e., show a perfect agreement.
- The max average error was 1.5% for operational Brewer instruments within [..[78]]stray-light-free conditions (OSC $<$ 700 DU).

This results are in agreement with the RBCC-E campaigns celebrated in Huelva and Arosa from 2009 to 2015 (Figure 14), in this period 85 spectrometers have been calibrated: 59 (69%) show an agreement better than 1%, 32 (38%) within 0.5% and 7 (8%) show a discrepancy greater than 2%.

For all participating instruments are calibrated with one parameter calibration. One parameter and the two parameters ETC transfer methods agreed to each other within the limit of ±5 units for ETC constants and ±0.3% for ozone absorption coefficients, indicating a high quality calibration.

After the new calibration was issued at the end of the X RBCC-E campaign,

- All participating Brewer spectrophotometers were within the ±0.5% agreement range.
- Without the stray light correction implemented large errors of up to 4% can be expected for single-monochromator Brewer instruments operating at OSC larger than 1000 DU.
- The implementation of the stray light correction in the calibration of single Brewer instruments improved their performance. Therefore, this correction has been introduced in Eubrewnet for the automatic processing of data sent by single monochromators Brewers.

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[76] removed: Briefly the Brewer network is calibrated with two main parameters: the ETC and the effective ozone absorption coefficient. The comparison with a reference instrument is used to establish the ETC but the effective ozone absorption coefficient can be derived also from the reference (two parameters method) as was done in the past (Staehelin et al., 2003) or directly from wavelength calibration as is performed at present (one parameter method) (Fioletov et al., 2005). Historically the two parameter method was used until around year 2000 after that the one parameter method has been adopted in the Brewer network. Although both methods give the same results in the 300-800

[77] removed: range (stray light free range), the two parameters calibration gives uniform results, smoothing the instrumental differences and reduces the stray light error on single Brewer (Bojkov et al., 2008). On the other hand, the one parameter calibration is more robust, it does not depend on reference wavelength calibration, and it highlights instrumental differences. An error in the ETC value yields an error that depends on the solar zenith angle, while an error in effective ozone absorption coefficient introduces a relative bias. The transition in the calibration methodology around the year 2000 can explain the change of the seasonal difference between ground base Brewer and satellites observed by Fioletov et al. (2008). During the RBCC-E campaigns we can show that the two point calibration can mask instrumental issues which are air-mass dependent. Moreover, both calibration methods give the same results on well characterised instruments and the difference between the calibration constants can be used as an indicator of the quality of the instrument calibration (Redondas and Rodriguez-Franco, 2012; Roozendael et al., 2014). For all participating instruments both the one parameter and the two parameters ETC transfer methods agreed to each other within the limit of ±5 units for ETC constants and ±0.3% for ozone absorption coefficients, indicating a high quality calibration.

[78] removed: stray-light free

Acknowledgements. All this work would have not been possible without the participation, work and dedication of all the Brewer operators in the RBCCE intercomparison campaigns.

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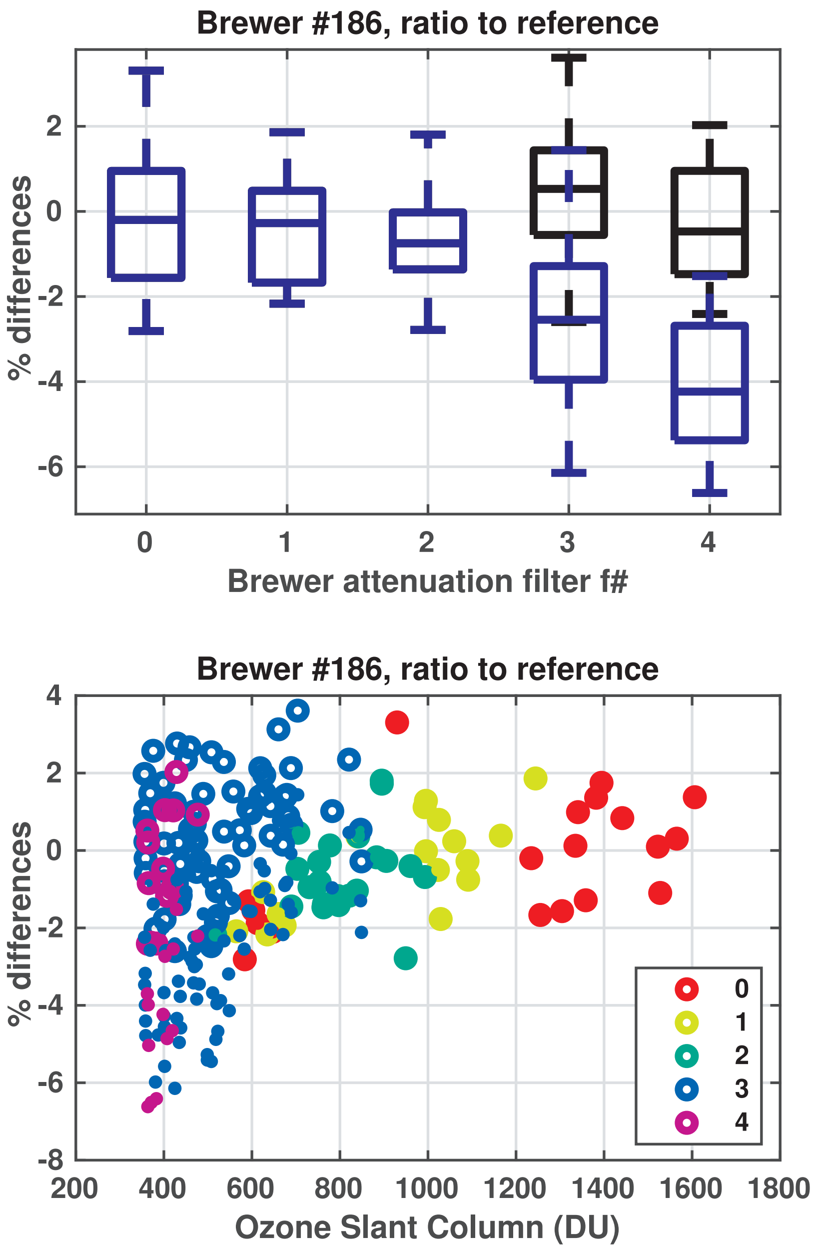

Figure 6. BoxPlot of the percentual differences with respect to the reference grouped by filter for Brewer #186, in blue without correction, and in black after applying the correction to filters 3 and 4 (upper panel). On the lower panel percentage differences with respect to the reference grouped by filter, without correction (solid dots), and after the application of the correction to filters 3 and 4 (open circles). Colors indicate the number of the filter; see the legend.

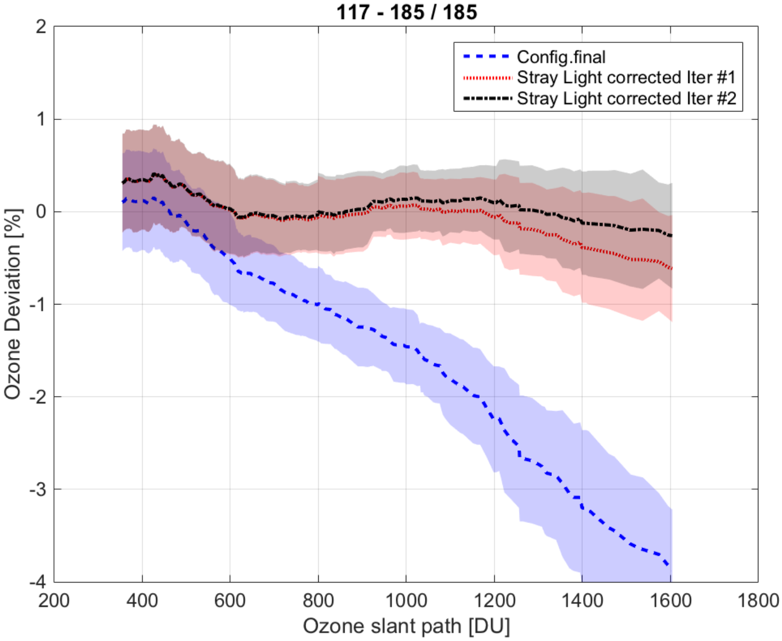

Figure 7. Percentage ozone differences with respect to the reference *vs.* Ozone Slant Path. In blue, using the final configuration constants, and in black and red, after the stray light correction has been applied, with one and two iterations, respectively. Data are averaged in ±50DU intervals, the shadow area represents one standard deviation.

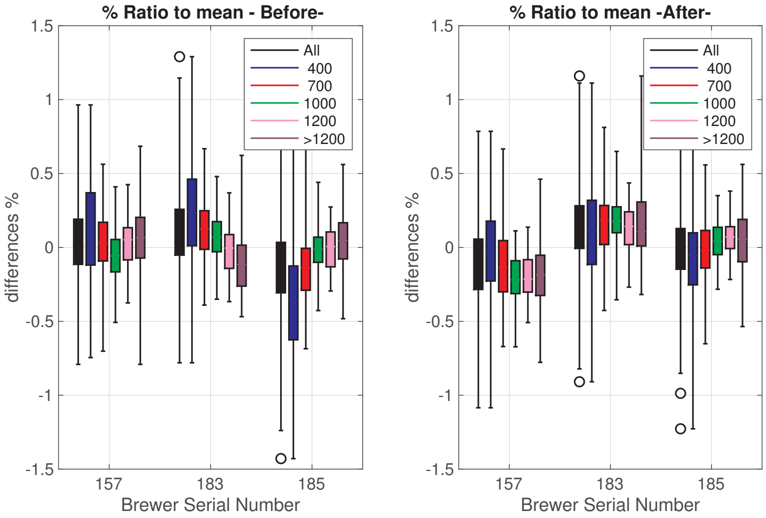

Figure 8. Box plot of the ozone percentage deviation from the mean of the RBCC-E triad reference Brewer#157, Brewer#183 and Brewer#185 before (left panel) and after (right panel) the X RBCC-E campaign at El Arenosillo in [..^{70}]2015, grouped by ozone slant columns ranges. The color indicates the intervals used for the averaging of the observations- blue, lower than 400 DU; red, between 400 and 700DU; green, between 700 and 1000DU; pink, between 1000 and 1200DU; and purple for OSC >1200 DU. In black the average of all observations.

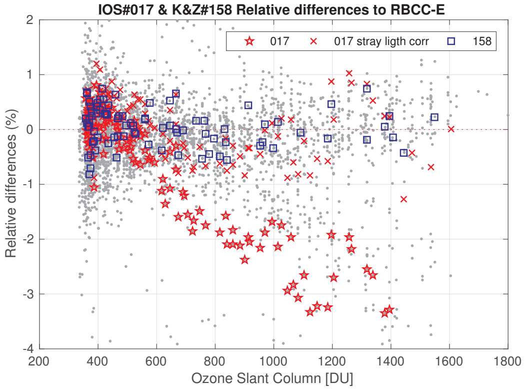

Figure 9. Comparison of reference instruments during the X RBCC-E campaign: relative differences with respect to the IZO reference using the initial configuration during the campaign, in red for the IOS Brewer #017 (stars are used for the original observations and crosses for the stray light corrected ones), and in blue for the K&Z Brewer #158. The gray points are the relative differences to the IZO reference for all participating instruments

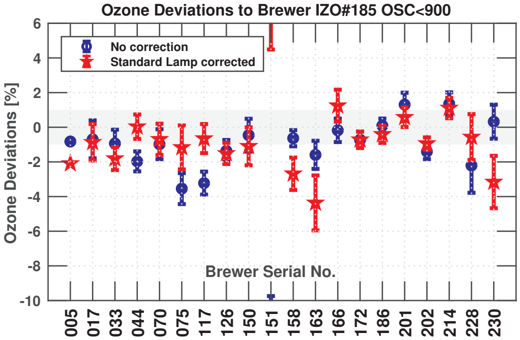

Figure 10. Percentage mean difference for the simultaneous direct sun measurements with the reference for all the participating instruments, with and without the standard lamp correction, in the [..[72]]stray light-free OSC region (OSC<900). (The Brewer #151 is an not operative brewer , is not providing reliable data , and is outside the limits.)

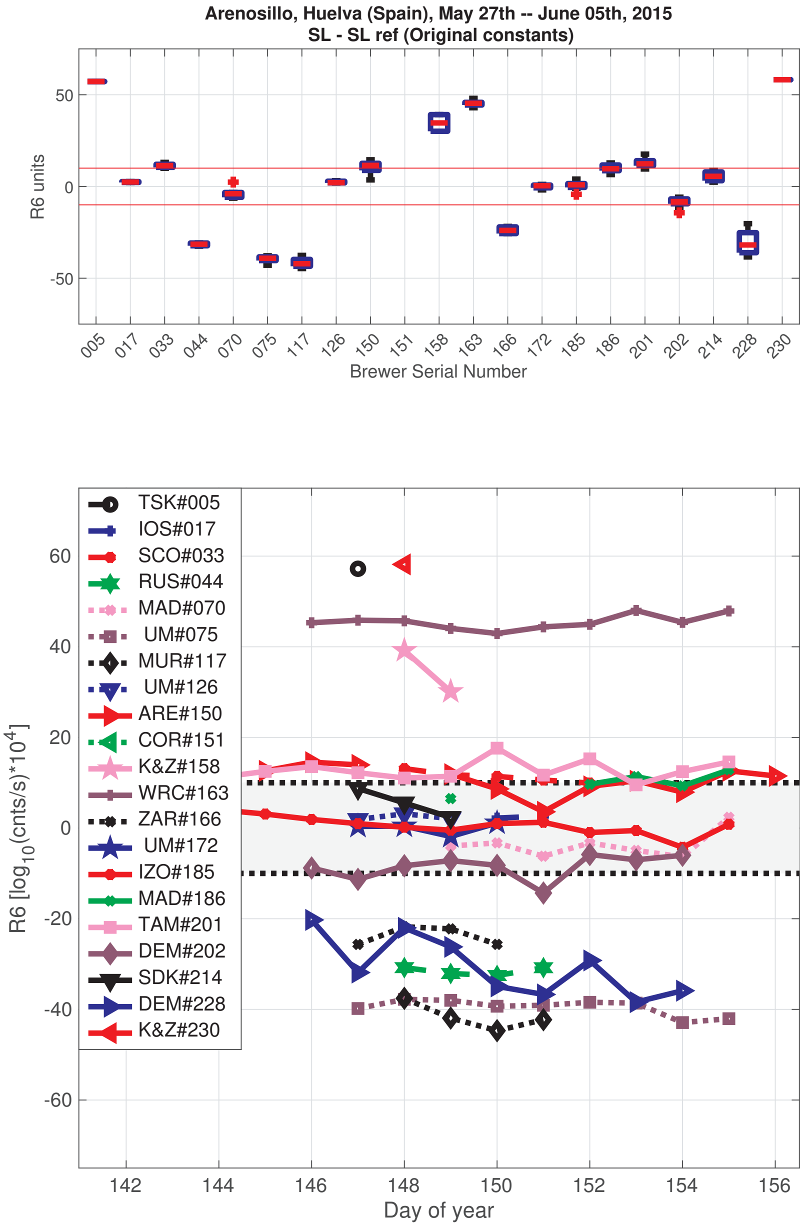

Figure 11. Standard lamp R6 difference with respect to the R6 reference value from the last calibration during the blind days, before the maintenance, the upper panel shows the mean value for each instrument and the lower panel the daily mean during the campaing. Variations within the ±10 units range (∼1% in ozone) from the reference value are considered normal, whereas larger changes would require further analysis of the instrument performance.

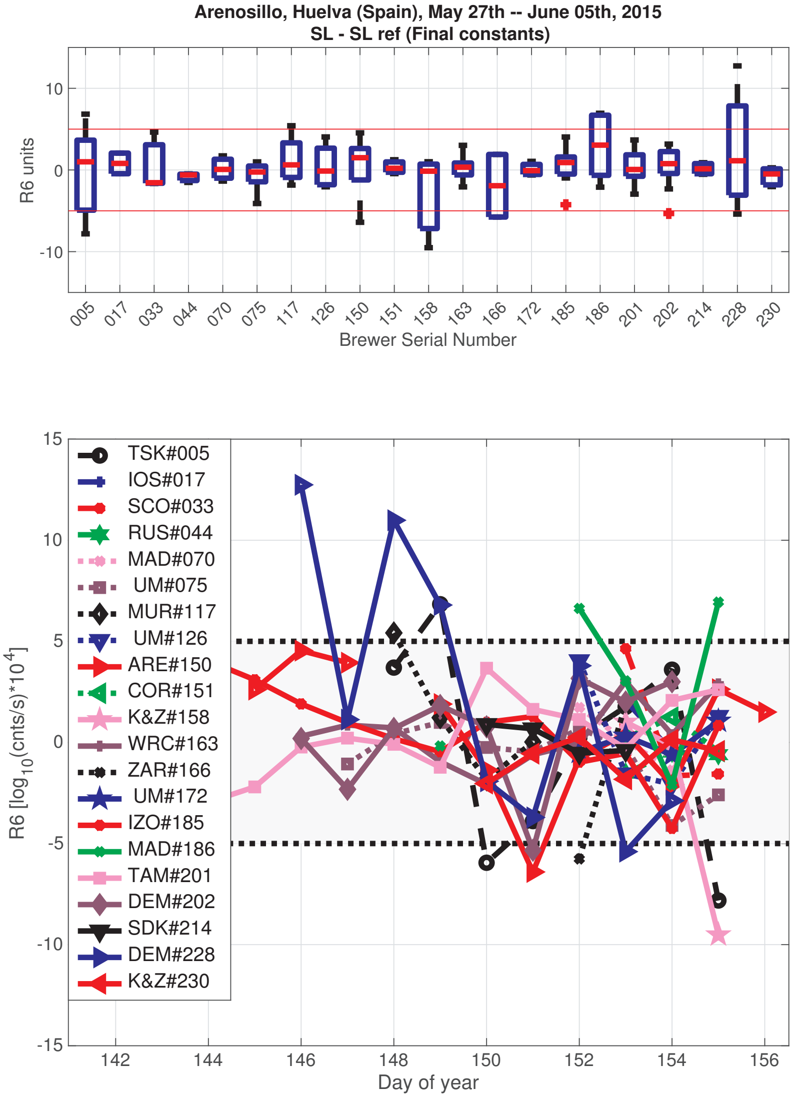

Figure 12. Differences between the daily standard lamp R6 ratio and the proposed R6 reference value during the final days, the upper panel shows the mean value for each instrument, and the lower panel the daily mean during the [..^{74}]campaign, is important to get an stable R6 value during the final days , within the ±5 units range (∼.5% in ozone), to stabilise the reference value of the calibration.

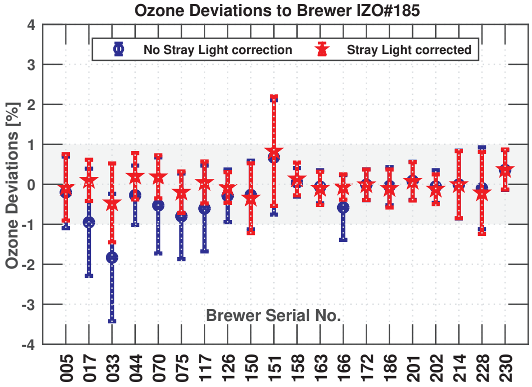

Figure 13. Final days mean percentage difference with respect to the reference Brewer for the simultaneous direct sun measurements for all the participating instruments, blue circles shows results without the stray light correction and red starts show results with the correction applied to single Brewer spectrophotometers.

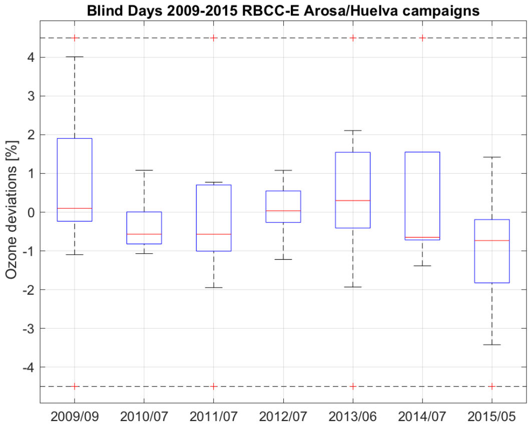

Figure 14. Ozone deviations for the Blind Days with respect to the reference Brewer for the simultaneous direct sun measurements for all the participating instruments during the RBCC-E regular campaigns 2009-2015, the campaigns performed in odd years correspond to Arosa (Switzerland) and in even years in Huelva (Spain). This results correspond to the [..79]stray-light-free region OSC$<$ 700 DU, the outliers (red cross at +/- 4.5% levels) generally correspond to non-operating instruments.

Table 1. Principal Investigators and Instruments participating on the X RBCC-E campaign

Nr.	Country	Brewer	Participants	
1	Greece	005	Alkis Bais	Thessaloniki University
2	Canada	017	Volodia Savastiouk	International Ozone Services
3	Spain	033	Juan R. Moreta	AEMET,State Meteorological Agency from Spain
4	Russia Federation	044	Vadim Shirotov	Scientific and Production Association “Typhoon”
5	Spain	070	Juan R. Moreta	AEMET,State Meteorological Agency from Spain
6	United Kingdom	075	John Rimmer	Manchester University
7	Spain	117	Juan R. Moreta	State Meteorological Agency from Spain
8	United Kingdom	126	John Rimmer	Manchester University
9	Spain	150	J. M. Vilaplana	National Institute for Aerospace Technolog
10	Spain	151	Juan R. Moreta	State Meteorological Agency from Spain
11	Netherlands	158	Oleksii Marianenko	Kipp & Zonen
12	Switzerland	163	Julian Gröebner	Physikalisch-Meteorologisches Observatorium Davos
13	Spain	166	Juan R. Moreta	AEMET, State Meteorological Agency from Spain
14	United Kingdom	172	John Rimmer	Manchester University
15	Spain	185	Alberto Redondas	Izaña Atmospheric Research Center,AEMET
16	Spain	186	Juan R. Moreta	AEMET,State Meteorological Agency from Spain
17	Algeria	201	Bukelia Lamine	National Meteorological Office
18	Denmark	202	Paul Eriksen	Danish Meteorological Institute,
19	Finland	214	Tomi Karpprinen	Finnish Meteorological Institute
20	Denmark	228	Niss Jepsen	Danish Meteorological Institute,
21	Netherlands	230	Keith M. Wilson	Kipp & Zonen

Table 2. Reference Comparison during RBCC-E campaigns, the Brewer #017 is the travelling reference from International Ozone Service (IOS), the Brewer #158 is the travelling reference from Kipp & Zonen and finally Brewer #145 from Environmental Canada is a double Brewer and direct calibrated to the World Reference Triad who participates on the previous RBCC-E campaigns

Location	year	#017	#158	#145	Report
Arosa	2008	-0.6			(Redondas and Rodriguez-Franco, 2008)
Huelva	2009	-0.6	0.8	-0.1	(Roozendael et al., 2012)
Arosa	2010	-0.6			(Roozendael et al., 2013b)
Huelva	2011	-0.1	-0.2	-0.6	(Roozendael et al., 2013a)
Arosa	2012		-0.1		(Redondas et al., 2015)
Huelva	2013	-1.0	0.7		(Redondas and Rodriguez-Franco, 2015a)
Izaña	2014			-2.2	(Redondas et al., 2014b)
Arosa	2014	-1.2	1.5		(Redondas and Rodriguez-Franco, 2015b)
Huelva	2015	-0.5	-0.5		this work

Table 3. Summary of mean percentage difference before calibration, without and with Standard Lamp Correction, and after the calibration, on the last column with the stray light correction applied.

Brewer ID	No corr.	SL corr.	Blind	Final	Stray
005	-	-	-1.93	-0.2	-0.08
017	-0.31	-0.49	-0.98	-0.95	0.11
033	-0.8	-1.77	-1.09	-1.83	-0.48
044	-2.04	0.13	-0.21	-0.27	0.2
070	-0.73	-0.42	-0.71	-0.53	0.18
075	-3.42	-0.71	-1.2	-0.8	-0.2
117	-3.38	-0.45	-0.68	-0.6	0.04
126	-1.25	-1.41	-1.36	-0.29	-0.08
150	-0.45	-1.07	-0.45	-0.27	-
151	-17.36	9.94	7.95	0.67	0.83
158	-0.54	-2.45	-0.54	0.05	-
163	-1.5	-4.16	-1.5	-0.06	-
166	-0.15	1.45	-0.24	-0.58	-
172	-0.67	-0.67	-0.67	-0.01	-
186	0.13	-0.34	0.13	-0.05	-
201	1.21	0.52	0.52	0.09	-
202	-1.39	-0.95	-0.95	-0.06	-
214	1.42	1.19	1.19	-0.01	-
228	-1.93	-0.4	-0.4	-0.1	-
230	-0.15	-3.48	-0.15	0.36	-