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Discussions

EUBREWNET RBCC-E Huelva 2015 Ozone Brewer Intercomparison

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Abstract. From May 25th to June 5th 2015, the X Regional intercomparison campaign of the Brewer Calibration Center - Europe (RBCC-E) was held at El Arenosillo atmospheric sounding station of the Instituto Nacional de Técnica Aeroespacial (INTA). This campaign was a joint effort of COST Action ES1207 EUBREWNET and the Area of Instrumentation and Atmospheric Research of INTA. Twenty one Brewer instruments from eleven countries participated and their ozone and solar UV irradiance calibrations were performed, in the latter case using the traveling reference standard QASUME instrument of the World Radiation Center for UV (WRC-UV).

This work shows a general overview of the ozone comparison focused on the correction of the stray light effect for 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 (76%) agreed within better than ±1%, and 10 instruments (50%) agreed within better than ±0.5%. After applying the final calibration that included the stray light correction, all working instruments agreed at the ±0.5% level.

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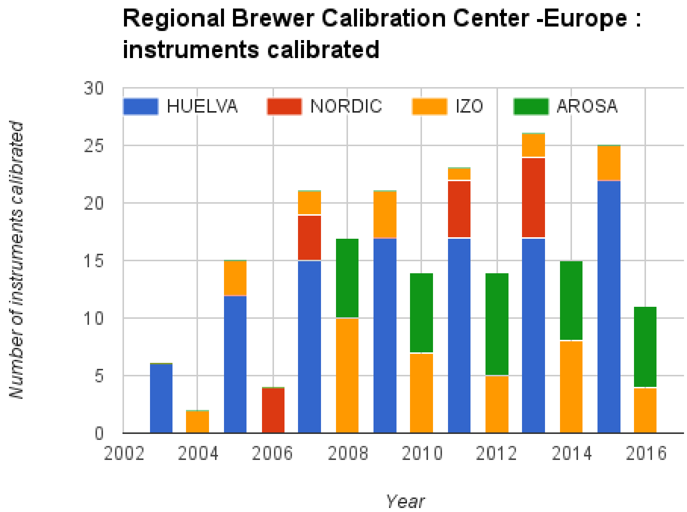

Figure 1. Brewer instruments calibrated since 2003 by the RBCC-E in regular campaigns (at Huelva and Arosa), Nordic intercomparisons, and the Absolute calibrations performed at the Izaña Observatory.

1 Introduction

In November 2003 the WMO/GAW Regional 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 owns calibration and reference-maintenance equipment mainly composed by 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 Rodríguez-Franco, 2015a), and IX (Redondas and Rodríguez-Franco, 2015b) intercomparison campaigns). In addition to the regular intercomparisons, the RBCC-E performs two types of campaigns supported by the ESA CalVal project: 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. Fig. 1 shows the number of Brewer instruments calibrated at these campaigns since 2003.

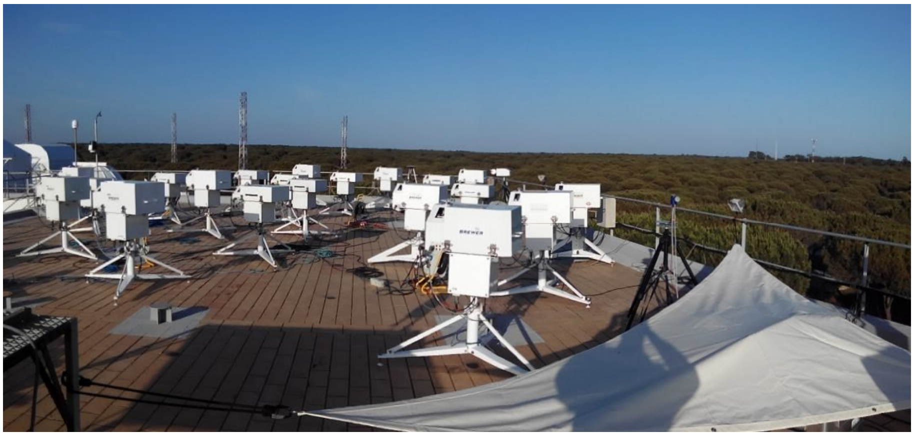

Figure 2. Panoramic view of the 21 Brewer spectrophotometers on the terrace of the El Arenosillo sounding station, Huelva, coming from Canada (1), Netherlands (2), United Kingdom (3), Switzerland (1), Finland (1), Greece (1), Denmark (2), Russia (1), Algeria (1) and Spain(7).

1.1 The X RBCC-E campaign

From May 25th to June 5th, 21 Brewer spectrophotometers from 11 countries (see Table 2) 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 instrument of the World Radiation Center for UV (WRC-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).

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, spectral UV radiation, and aerosol optical depth in the UV spectral range, ensuring sustainable operation in the long-term (Rimmer et al., 2016). One of the primary aims of EUBREWNET is to harmonize operations and develop approaches, practices and protocols to achieve consistency in quality control, quality assurance and coordinated operations, as well as to eliminate duplication of efforts at individual stations to achieve separately best practice and accuracy. It also aims at establishing knowledge exchange and training, and at opening up a route to link with international agencies and other networks globally. Close to 50 Brewer spectrophotometers are deployed in Europe, independently funded by national institutions.

In parallel to the campaign, COST Action 1207 organized several experiments to improve the quality of the Brewer data. These included, studies on the Dead Time determination using the direct-sun measurements (Fountoulakis et al., 2016), characterization of the temperature dependence of the Brewer diffuser (Fountoulakis et al., 2017), cosine response measurements (León-Luis et al., 2016), investigation of the effects of polarization of the input window (Carreño et al., 2016), aerosol optical depth calibration (López-Solano et al., 2017), stray light characterization, comparison of total ozone between Phaethon and Brewer instruments, and an intercomparison of UV reference lamps.

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2 The calibration of the Brewer spectrophotometer

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 analyzed by a photomultiplier. The longest four wavelengths are used for the ozone calculation.

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

$$X = \frac{F - ETC}{\alpha\mu} \tag{1}$$

where F are the measured double ratios corrected for Rayleigh effects, α is the ozone 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 weights $w = [1, -0.5, -2.2, 1.7]$ have been chosen so as to minimize the influence of SO_2 and verify:

$$\sum_i^4 w_i = 0 \tag{5}$$

$$\sum_i^4 w_i \lambda_i = 0 \tag{6}$$

This widely eliminates absorption features which depend, in local approximation, linearly on the wavelength, like for example the contribution from aerosols.

We can divide the calibration in instrumental, wavelength, and ETC transfer steps:

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1. The instrumental calibration includes all the parameters that affect the measured counts (F_i), in particular dead time correction ((Fountoulakis et al., 2016)), temperature coefficients (Berjón et al., 2017) and filter attenuation .

2. The wavelength calibration allows to determine the ozone absorption coefficient. The so-called "dispersion test" are used to obtain the particular wavelength for the instrument and the slit, or instrumental function, of each spectrophotometer, which differs slightly from instrument to instrument (Redondas et al., 2014).

3. Finally, the ETC transfer is performed by comparison with the reference or, in the case of the reference instruments, by the Langley method.

The calibration is an iterative process – changes during the instrumental and/or wavelength calibration will affect the final ETC and changes in the wavelength calibration will affect also to the final ETC. For this reason the calibration campaigns are scheduled in three different periods:

1. **Blind days:** the first days of the campaign are dedicated to determine the current status of the instrument. During this period modifications of the instrument are not allowed.

2. **Characterization:** after the determination of how the instrument is measuring, the next days are dedicated to characterize 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 characterized and stable.

2.1 ETC transfer and stray light

The transfer of the calibration scale (namely, the ETC) to an instrument is done operating side by side with the reference Brewer. Once we have collected enough near-simultaneous direct sun ozone measurements, we calculate the new extraterrestrial constant after imposing the condition that the measured ozone will be the same for simultaneous measurements. In terms of Eq. 1, this leads to the following condition:

$$ETC_i = F_i - X_i^{reference} \alpha \mu \tag{7}$$

For a correctly characterized instrument, the determined ETC values show a Gaussian distribution and the mean value is used as the instrument's extraterrestrial 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 (see Fig. 3) a tail at the lower ETC values for high Ozone Slant Column (OSC, the product of the total ozone content by the airmass). For this type of Brewer, only the stray-light-free region is used to determine the ETC, which generally ranges from 300 to 900 DU in the OSC, depending on the instrument.

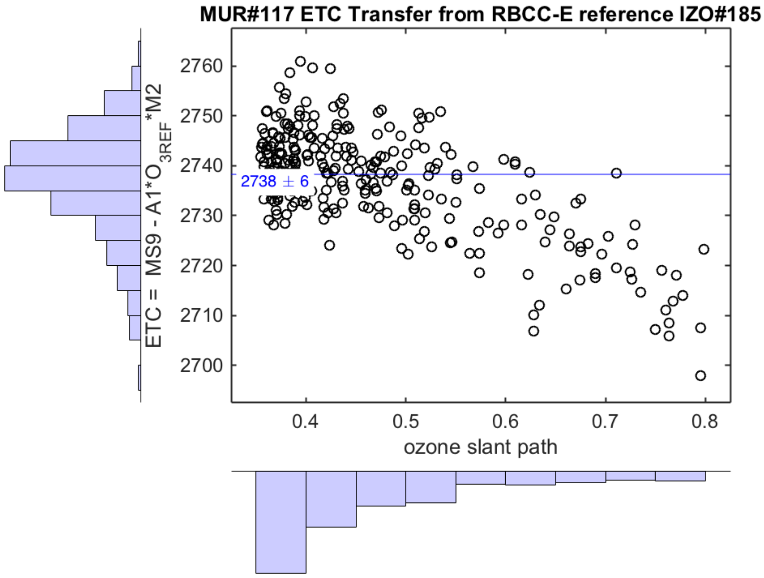

Figure 3. Distribution of individual ETC values determined by simultaneous measurements. In the horizontal axis, the ozone slant column (OSC) is written in cm divided by 1000. For this particular Brewer instrument, the effect of the stray light is clearly shown at values above 0.6 for the scaled OSC.

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

$$F = F_o + k(X\mu)^s \tag{8}$$

where F are the true counts and F_o, the measured ones.

The extraterrestrial constant is

$$ETC_i = ETC_o + k(X\mu)^s \tag{9}$$

where ETC_o is the ETC for the stray-light-free OSC region 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.

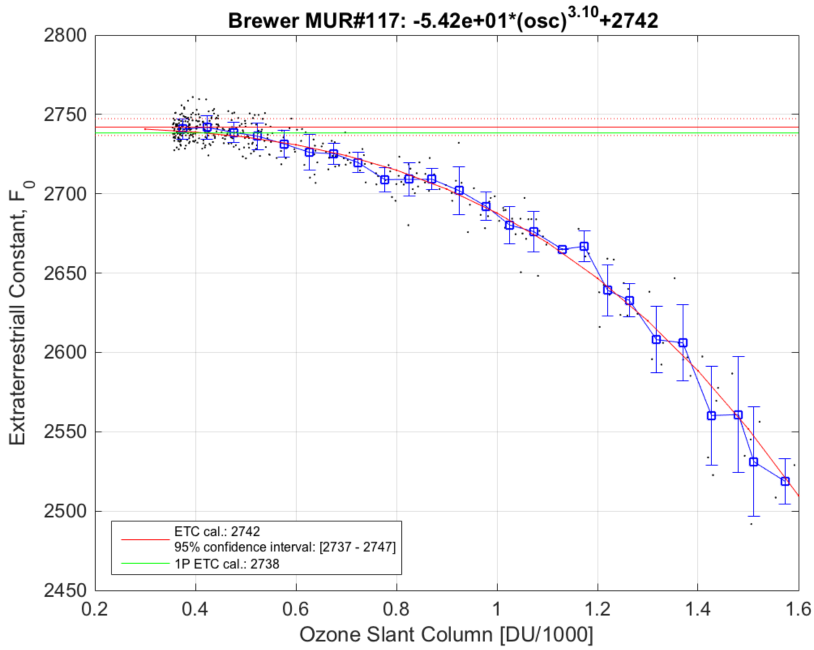

Figure 4. The stray light parameters k and s are determined by a nonlinear fit using the ETC determined from the stray-light free region as first guess parameters. The red horizontal line indicate the ETC constant retrieved from the fit, and the green one, the initial guess.

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

$$X_{i+1} = X_i + \frac{k(X_i\mu)^s}{\alpha\mu} \tag{10}$$

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 5). These stray light corrections are now implemented in the standard processing of EUBREWNET.

3 Intercomparison Results

3.1 Reference Calibration

The RBCC-E triad is regularly calibrated, performing the instrumental characterization and wavelength calibration monthly. The three instruments are independently calibrated by the Langley plot method following the procedure described in Ref. Redondas (2007). Before and after the intercomparison campaigns, the traveling instrument is compared with the two static instruments to verify that the calibration has not changed during transport (Figures 6 and 7).

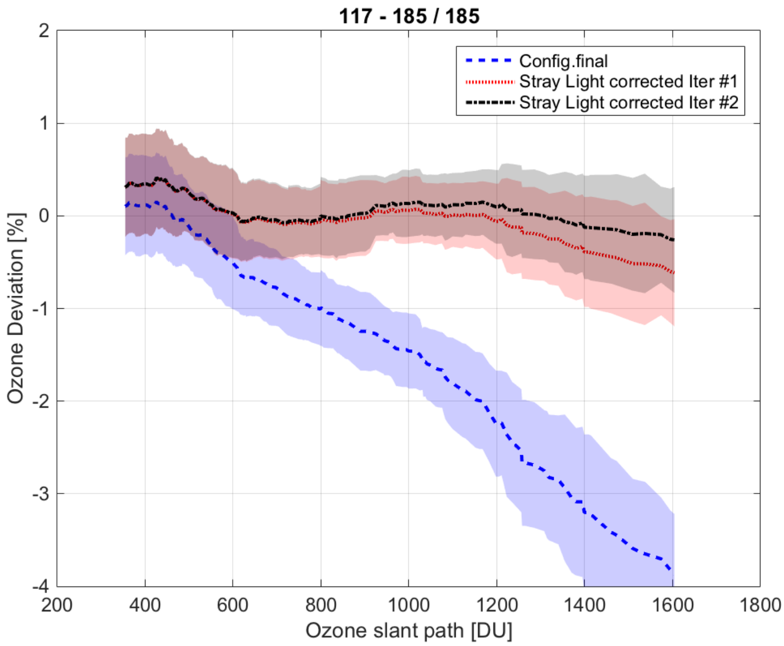

Figure 5. Percentage ozone differences with respect to the reference *vs.* Ozone Slant Path. In blue, using the final configuration constants, and in black and red, after the stray light correction has been applied, with one and two iterations, respectively. Data are averaged in $\pm 50 DU$ intervals, the shadow area represents one standard deviation.

The campaign is a good opportunity to compare 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, and #158, managed by Kipp & Zonen, manufacturer of the Brewer spectrophotometer, took part in the X RBCC-E campaign. The agreement between the reference instrument was found to be quite good, with differences lower than 0.5% for OSC lower than 900 DU (see Table 1). 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.

3.2 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 instruments are working during this period with their home calibration and the ozone is calculated using these calibration constants. The Standard Lamp (SL) test is an ozone measurement using the internal halogen lamp as a source. This test is performed routinely to track the spectral response of the instrument and, therefore, the ozone calibration. A reference value for

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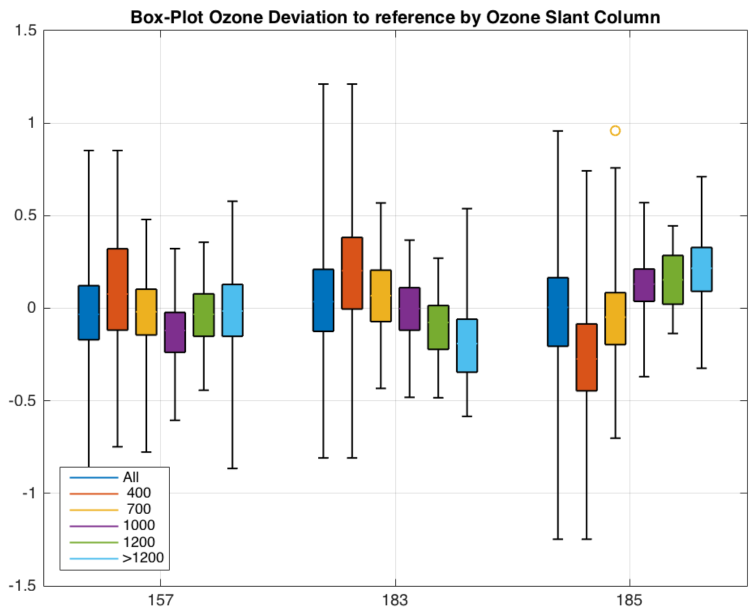

Figure 6. Box plot of the ozone percentage deviation from the mean before the X RBCC-E campaign at El Arenosillo in 2015.

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 then described by the Standard Lamp correction:

$$ETC_{new} = ETC_{old} - (SL_{ref} - SL_{measured}) \tag{11}$$

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. Some instruments showed deviations of R6 values to the reference larger than 20 units (Fig. 10). The comparison with a standard instrument is the only way to assess whether the SL correction properly tracks changes on the calibration constants or the changes observed are just due to changes of the lamp's spectral emission (Fig. 9). In some instruments, for example Brewer #075, the SL correction improves the comparison, whereas for others like #165 the opposite happens. This will determine if a re-evaluation of the ozone observations between calibrations are required after an analysis of the history of the instrument.

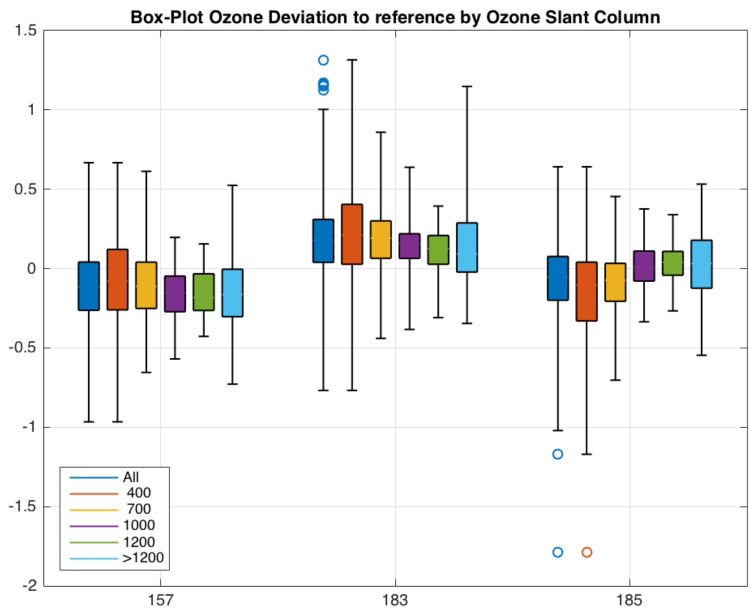

Figure 7. Box plot of the ozone percentage deviation from the mean after the X RBCC-E campaign at El Arenosillo in 2015.

Table 1 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 stray-light-free OSC region. With the exception of Brewer #151, that can not be considered an operational instrument, the maximum difference found is 1.5%. This is a really good result considering that most of the instruments were calibrated two years ago. 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.

3.3 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 tried 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. 11 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.

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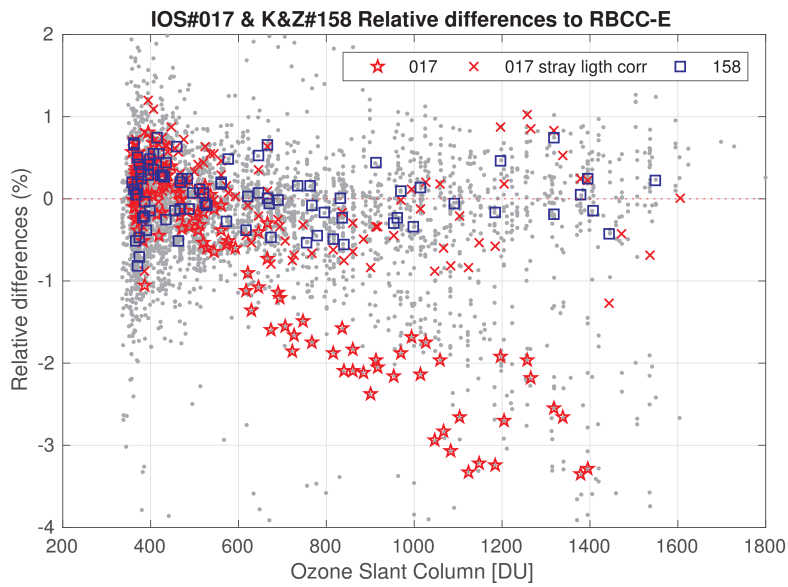

Figure 8. Comparison of reference instruments during the X RBCC-E campaign: relative differences with respect to the IZO reference using the initial configuration during the campaign, in red for the IOS Brewer #017 (stars are used for the original observations and crosses for the stray light corrected 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

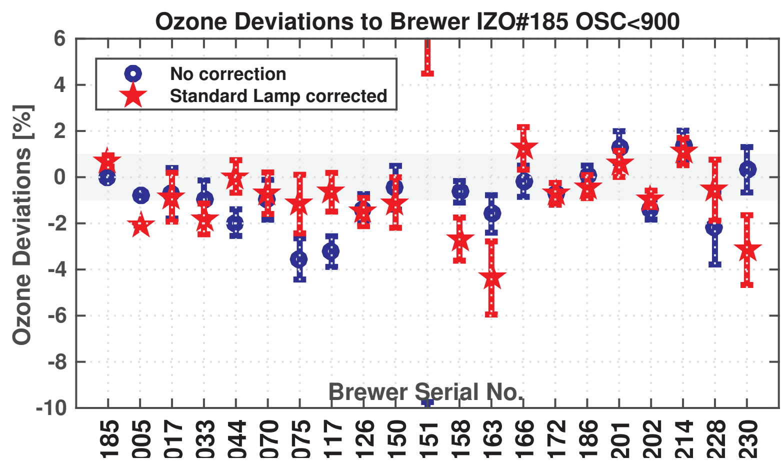

Figure 9. Percentage mean difference for the simultaneous direct sun measurements with the reference for all the participating instruments, with and without the standard lamp correction, in the stray-light-free OSC region (OSC<900).

Deviations of ozone values for all the participating instruments with respect to the RBCC-E travelling standard Brewer #185 are shown in Fig. 12 and summarized in Table 1. 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 Sec. 2.

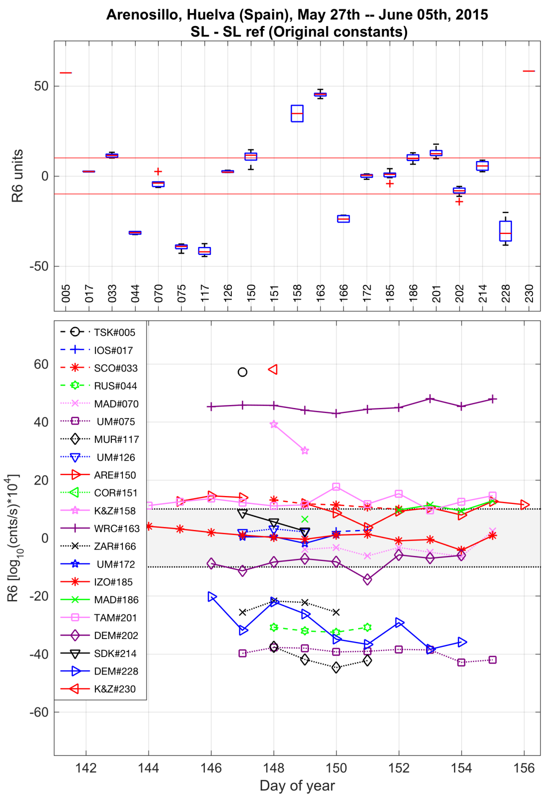

Figure 10. Standard lamp R6 difference with respect to the R6 reference value from the last calibration during the blind days, before the maintenance. Variations within the ±10 units range (∼1% in ozone) are considered normal, whereas larger changes would require further analysis of the instrument performance.

It should be noted that all Brewers were calibrated using the one parameter ETC transfer method, i.e., the ozone absorption coefficient was derived from the wavelength calibration (dispersion test) and only the ozone ETC constant was transferred from the reference instrument. The so-called "two parameters calibration method" Staehelin et al. (2003), where the ozone absorption coefficient is also calculated from the reference, is also used as a quality indicator. 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. 12 and Table 1. With the application of the stray light correction to the single Brewer spectrophotometers, all instruments are within the ±0.5% agreement range.

Table 1. 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	-

4 Conclusions

To summarize the calibration results of the X 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 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 13), in this period 85 spectrometers has been calibrated: 59 (69%) shows an agreement better than 1% , 32 (38%) within 0.5% and 7 (8%) shows a discrepancy greater than 2%.

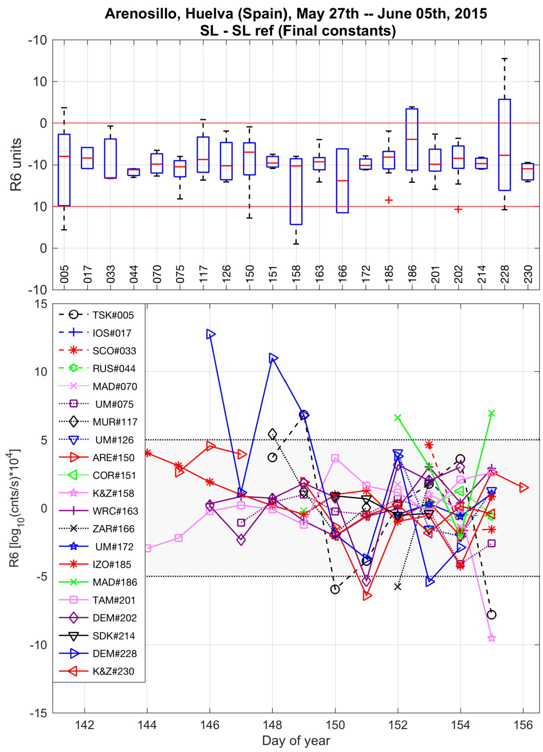

Figure 11. Differences between the daily standard lamp R6 ratio and the proposed R6 reference value during the final days.

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.

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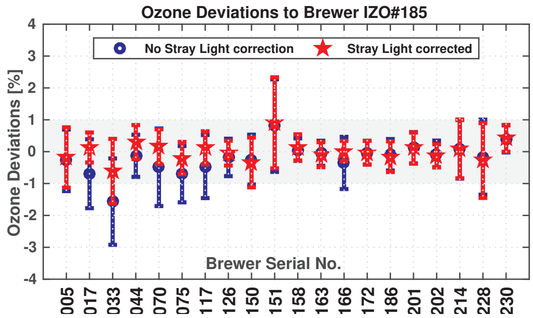

Figure 12. Final days mean percentage difference with respect to the reference Brewer for the simultaneous direct sun measurements for all the participating instruments, blue circles shows results without the stray light correction and red starts show results with the correction applied to single Brewer spectrophotometers.

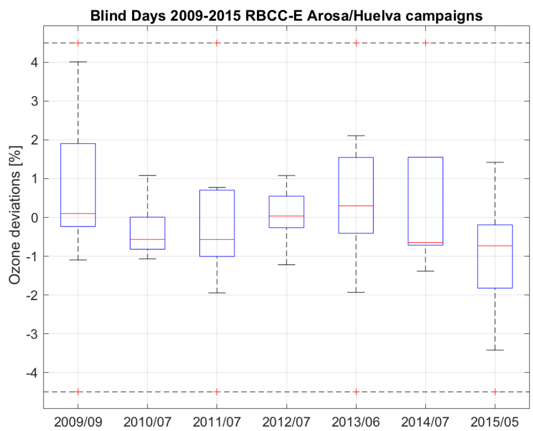

Figure 13. Ozone deviations for the Blind Days with respect to the reference Brewer for the simultaneous direct sun measurements for all the participating instruments during the RBCC-E regular campaigns 2009-2015, the campaigns performed in odd years correspond to Arosa (Switzerland) and in odd years in Huelva (Spain). This results correspond to the stray light free region OSC< 700 DU, the outliers (red cross at +/- 4.5% levels) generally correspond to no operating instruments.

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Table 2. 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”
	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 Groebner	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	212	Tomi Karprinen	Finnish Meteorological Institute
20	Denmark	228	Niss Jepsen	Danish Meteorological Institute,
21	Netherlands	230	Keith M. Wilson	Kipp & Zonen