Multichannel radiometer calibration: a new approach

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The error in irradiance measured with Sun-calibrated multichannel radiometers may be large when the solar zenith angle (SZA) increases. This could be particularly detrimental in radiometers installed at mid and high latitudes, where SZAs at noon are larger than 50° during part of the year. When a multiregressive methodology, including the total ozone column and SZA, was applied in the calculation of the calibration constant, an important improvement was observed. By combining two different equations, an improvement was obtained at almost all the SZAs in the calibration. An independent test that compared the irradiance of a multichannel instrument and a spectroradiometer installed in Ushuaia, Argentina, was used to confirm the results. © 2005 Optical Society of America

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1. Introduction

Sun and lamp calibrations are the usual techniques for calibrating multichannel radiometers. In addition, some authors apply a combination of both,[1] and, for Sun-tracking and shadow-band multichannel instruments, Langley plots have been proposed.[2–4] Lamp calibrations are performed in dark laboratories and are subject to errors that may arise from differences in the spectral and spatial distribution of Sun and lamp radiation.[5] Sun calibration may be performed following two different procedures. One of them is to install the multichannel radiometer side by side with a spectroradiometer, and the other is to install it close to a reference multichannel radiometer that has already been calibrated against a spectroradiometer. The first procedure requires moving the radiometer from its site of deployment to the site where the spectroradiometer is located. The disadvantage of this method is that time series of the multichannel instrument will present a gap while the radiometer is being calibrated. The advantage is that the calibration is transferred directly from the spectroradiometer to the multichannel instrument. When following the second methodology, the instrument is calibrated on site, under the conditions under which it usually collects data, and it is not necessary to interrupt the collection of information. However, the error in calibration constants may be larger since the calibration is transferred from the spectroradiometer to the reference radiometer and from this to the mul-

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tichannel instrument. This procedure is usually applied when several instruments belonging to a network are calibrated. In this case, the reference radiometer travels to all the sites as a standard instrument.

In calculating the calibration, two approaches have been proposed: (i) The output voltage from each channel of the multichannel instrument is related to the calibrated irradiance measured by the spectroradiometer at the nominal central wavelength of the channel,[5] and (ii) the output voltage from each channel of the multichannel instrument is related to the calibrated irradiance measured by the spectroradiometer weighted by the responsivity function of the channel and integrated in the corresponding wavelength interval.[6,7] Following the first procedure, a calibrated monochromatic irradiance is obtained. With the second, the calculated value corresponds to a responsivity-weighted irradiance that is instrument dependent. Then, to standardize the data, the biologically weighted irradiance is calculated or spectral reconstruction is performed.

In this paper, Sun calibration using a traveling instrument and obtaining a monochromatic irradiance will be discussed. In both steps of the calibration, the spectroradiometer–reference and the reference–site radiometer, synchronized data from the instruments are collected. The data are processed using linear regressions in the corresponding wavelengths (channels) to obtain the calibration constants for that channel. When a radiometer is calibrated on site, summertime is usually chosen to perform the calibration under a large range of solar zenith angles (SZAs). On the other hand, when the radiometer is moved and the calibration is carried out against a spectroradiometer, the calibration is usually performed in a low-latitude or mid-latitude location to maximize the SZA range of values. This results in a different range of SZAs compared to the radiometer's deployment site. In either case, since the regression line is determined using least squares, the smaller values, which are usually measured at larger SZAs, have a smaller weight in determining the coefficients of the linear equation and will result in large errors in these calibrated irradiance values. Although this is probably not critical when considering daily integrated values and when using radiometers installed at low latitudes, it is of utmost importance for instantaneous values measured at large SZAs or at higher latitudes where SZAs during winter exceed 50°, even at solar noon.

Another factor that may produce a large variation in the calibration constant, mainly in the lower wavelength channels, is changes in the total ozone column. This is particularly important, for example, in southern-hemisphere high-latitude sites, where an ozone depletion of 60% from normal values may occur.

We propose a multiregressive methodology to improve the radiometer calibration. This approach involves ozone and the SZA in the calculation of the calibrated irradiance. In this case, the calibration is represented by a function rather than a constant.

2. Data and Methodology

With a multiregressive model, spectral irradiance may be derived from broadband instrument measurements, the total ozone column, and the SZA.[8] By considering one channel of a multichannel radiometer as a broadband instrument, a similar methodology was proposed to improve the calibration of the UV multichannel instrument GUV-511 against a spectroradiometer[9] (SUV-100) according to

$$\ln E_{SUV\lambda} = a_1 \ln E_{GUV\lambda} + a_2 O_3 + a_3 f(90 - \mathrm{SZA}) + b, \tag{1}$$

where $E_{SUV\lambda}$ is the calibrated spectral irradiance measured by the SUV-100 at wavelength λ; $E_{GUV\lambda}$ is the measurement of GUV-511 channel λ in volts; O_3 is the total ozone column; $f(90 - \mathrm{SZA})$ is a function of the SZA; and a_1, a_2, a_3, and b are the regression coefficients determined with least-squares methods. The function $f(90 - \mathrm{SZA})$ is determined by calculating the difference between $\ln E_{SUV\lambda}$ and $\ln E_{GUV\lambda}$ and then making a polynomial fitting of this function against the complement of the SZA.

Some instruments, such as Dobson photometers, calculate the total ozone column from the ratio of a pair of irradiances, one of them affected and the other unaffected by ozone changes. The same principle has been proposed to infer ozone amounts from multichannel radiometers.[6] Then, in Eq. (1), the ozone can be replaced by combining irradiances measured by different channels, as follows:

$$\begin{aligned}\ln E_{SUV\lambda} = {} & c_1 \ln E_{GUV305} + c_2 \ln E_{GUV320} + c_3 \ln E_{GUV340} \\ & + c_4 \ln E_{GUV380} + c_5 f(90 - \mathrm{SZA}) + d,\end{aligned} \tag{2}$$

where $E_{SUV\lambda}$, $E_{GUV\lambda}$, and $f(90 - \mathrm{SZA})$ are as in Eq. (1) and c_1, c_2, c_3, c_4, c_5, and d are the regression coefficients determined with least-squares methods.

The azimuth angle could also be included in Eq. (2) to correct for response differences in the horizontal plane between both instruments. In this case, the instrument orientation during calibration and data deployment needs to be consistent.

Since the logarithm of the measured values was used in Eqs. (1) and (2), smaller values have considerable weight when applying least squares, and that set of values shows a larger improvement in the calibration. To optimize values, also for smaller SZAs, another empirical relationship based on Eq. (2) is proposed:

$$\begin{aligned}E_{SUV\lambda} = {} & e_1 E_{GUV305} + e_2 E_{GUV320} + e_3 E_{GUV340} + e_4 E_{GUV380} \\ & + e_5 f_1(90 - \mathrm{SZA}),\end{aligned} \tag{3}$$

where $E_{SUV\lambda}$ and $E_{GUV\lambda}$ are as in Eq. (2); $f_1(90 - \mathrm{SZA})$ is a function of the SZA; and e_1, e_2, e_3, e_4, and

e_5 are the regression coefficients determined with least-squares methods.

In this case, the independent term is set to zero since all irradiances should tend to zero when the SZA approaches 90°. With this approach the error in irradiance corresponding to smaller SZAs also diminishes compared to the calibration performed with single regression.

Although this method was originally developed for Sun calibration of a multichannel instrument against a spectroradiometer, it was then applied to improve the calibration of a site radiometer against a reference multichannel with good results.[10] In this case, both instruments are supposed to have the same bandwidth, but, indeed, some slight differences may occur in bandwidth or the central wavelength because of normal manufacturing dispersion of the components that constitute the instrument. Then, for example, if during normal operation ozone conditions vary regarding the calibration situation, the relationship of the voltage measured by one instrument against the other could change, which is equivalent to a change in the calibration constant, resulting in larger errors in the calibrated values. Incorporating the SZA and the total ozone column in the calculation of the calibration constants can greatly reduce the errors, mainly for larger SZAs. In this case, Eq. (2) is replaced by

$$\begin{aligned}\ln E_{RGUV\lambda} = {} & f_1 \ln E_{GUV305} + f_2 \ln E_{GUV320} + f_3 \ln E_{GUV340} \\ & + f_4 \ln E_{GUV380} + f_5 f(90 - \mathrm{SZA}) + g, \qquad (4)\end{aligned}$$

where $E_{RGUV\lambda}$ is the irradiance measured by the reference GUV at channel λ; $E_{GUV\lambda}$ is the irradiance measured by the site GUV at channel λ; $f(90 - \mathrm{SZA})$ is as in Eq. (1); and f_1, f_2, f_3, f_4, f_5, and g are the regression coefficients determined with least-squares methods. Equation (3) is also adopted, in this case for smaller SZAs when calibrating the site radiometer against a reference.

This methodology was applied to the calibration of the Inter American Institute for Global Change (IAI) radiation network radiometers performed during 2000 as part of the IAI project entitled Enhanced Ultraviolet-B Radiation in Natural Ecosystems as an

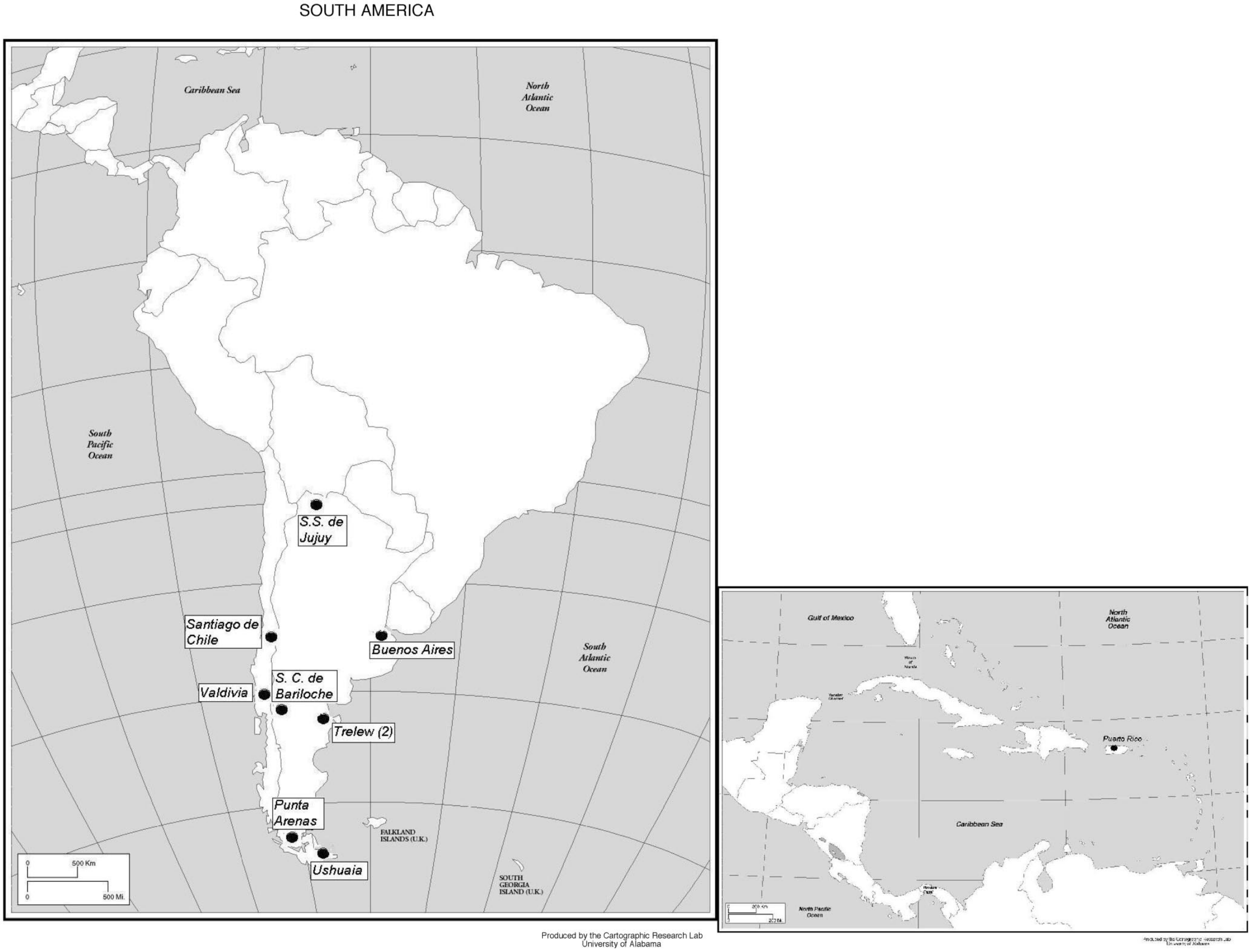

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Fig. 1. Stations of the IAI Network. Ten multichannel radiometers (GUV-511, Biospherical Instruments Inc.) have been installed in Central and South America and are being calibrated by one traveling reference radiometer.

Added Perturbation due to Ozone Depletion (CNR-26). These multichannel instruments (GUV-511, Biospherical Instruments Inc.) were installed by different efforts during the 1990s in South and Central America. One of the radiometers is located in Puerto Rico, three in Chile, and six in Argentina. Figure 1 shows the geographical location of the stations. The radiometers are Sun calibrated with a traveling reference instrument (RGUV-9287, also a GUV-511).

The traveling reference radiometer was calibrated against the SUV-100 located in San Diego (32°45′N, 117°11′W). Data from 1 to 26 June 2000 was considered for the calculation of the calibration. The RGUV-9287 radiometer collected data at 1 min frequency, and the SUV-100 performed a full scan in about 12 min every 15 min. We used data from both instruments, with matching time, as provided by Biospherical Instruments Inc. Calibrated SUV-100 irradiance and RGUV-9287 voltage after extracting the internal noise of the instrument (dark values) for SZAs between 9.79° and 85° were used.

The calibrations of the site instruments against the reference instrument were performed at each site, except Puerto Rico, during the austral summer (January–March) in 2000. During GUV–RGUV calibration, synchronized data were collected continuously for the reference and the on-site radiometer for between 1 and 8 days depending on the station. Data for each radiometer (reference and on site) were processed by subtracting dark (night) values. The minimum SZA considered in the calculation of the calibration varied with each site, and the maximum was limited to 85° at all the sites.

The GUV-511 is a temperature-stabilized multichannel radiometer that measures irradiances with moderately narrow bandwidth channels (near 10 nm) at 305, 320, 340, and 380 nm, plus photosynthetically active radiation (PAR) (400–700 nm)[1] (Fig. 2). The SUV-100 is a scanning spectroradiometer that covers the UV and part of the visible radiation (280–620 nm), with a 1 nm bandwidth, and is part of the National Science Foundation (NSF) UV Radiation Monitoring Network.[11]

3. Results

Single-regression and multiregressive approaches were applied to calibrate the RGUV-9287 against the SUV-100. When comparing the calibrated RGUV irradiances against the irradiance measured by the SUV-100, improvements were observed in the multiregressive procedure, mainly for channels 305 and 320 and for larger SZAs. Table 1 shows the rms error for different SZA intervals for channel 305. In the multiregressive approach Eqs. (3) and (2) were used for SZA $< 40°$ and SZA $\geq 40°$, respectively. The applied SZA function was a fourth-degree polynomial in both cases. The rms error over all the SZAs diminished from 27% for the single regression to 7% for the multiregressive method, but it showed dependence on the SZA. For SZAs larger than 50°, the error decreased from 41% to 9%.

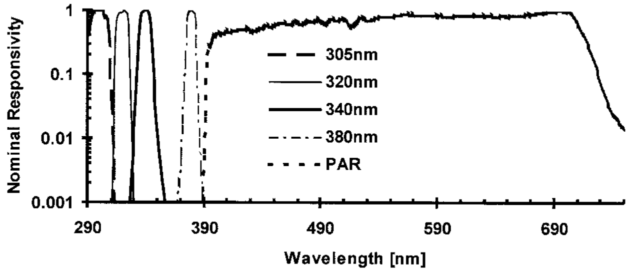

Fig. 2. Channels of the GUV-511. The radiometer has four moderate bandwidth interference filters (near 10 nm) centered at 305, 320, 340, and 380 nm, plus PAR (400–700 nm).

When the multiregressive method was applied to the RGUV–GUV calibration, encouraging results were obtained for all the sites and UV channels, as well as with visible corrections in residuals, the slope, and the offset. Figure 3(a) shows the irradiance from RGUV-9287 versus the irradiance from GUV-9221 (Bariloche, Argentina) estimated using single-regression calibration for channel 305. A double drawing and a nonlinear relationship was observed between the values. When applying the multiregressive calibration, both effects disappeared [Fig. 3(b)]. Also, the offset and systematic errors diminished considerably, as reflected by the ordinate at the origin and the slope (1×10^{-15} and 1.000000000000010, respectively). In Fig. 4, the relative errors in absolute value for both approaches are shown. Much lower errors are observed with the multiregressive method, mainly for SZAs larger than 50°. Table 2 shows the rms error for both approaches and for SZAs larger than 50° for the IAI sites and UV channels. The difference between both methodologies is more pronounced in some instruments than in others. In general, channel 305 improved the most and channels 340 and 380 showed low errors, even in the single-regression calibration.

4. Independent Test

An independent test was performed comparing the calibrated data from the GUV-9234 and the SUV-100 located in Ushuaia. This spectroradiometer is part of

Table 1. rms Error between SUV Irradiance and RGUV-9287 Calibrated Irradiance[a]

Range of SZA[b] (°)	rms Error Single (%)	rms Error Multi (%)
<20	3.29	3.39
$20 \leq$ SZA < 30	4.93	4.33
$30 \leq$ SZA < 40	6.13	5.59
$40 \leq$ SZA < 50	7.69	5.89
$50 \leq$ SZA < 60	11.83	5.28
$60 \leq$ SZA < 70	26.27	7.82
$70 \leq$ SZA < 80	58.08	8.54
$80 \leq$ SZA < 85	53.50	14.11

[a] The error is provided for different 10° SZA intervals at 305 nm with single-regression and multiregressive calibrations.

[b] In the multiregressive calculation, Eq. (3) was used for SZA $< 40°$ and Eq. (2) for larger SZAs.

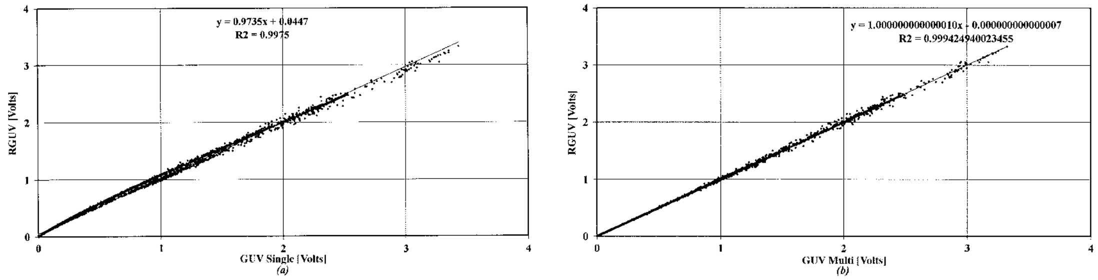

Fig. 3. (a) Single calibration of GUV-9221 (Bariloche) against RGUV-9287 and (b) multiregressive calibration. A double line is observed in (a) and disappears in (b). Also, an improvement is observed in the slope (closer to 1) and offset (ordinate at the origin near 0).

the NSF UV Radiation Monitoring Network. Data are consistent with the SUV-100 installed in San Diego. Since the GUV-9234 was calibrated using the RGUV-9287, which was calibrated against the SUV-100 in San Diego, the data from the GUV-9234 and SUV-100 in Ushuaia are independent but consistent.

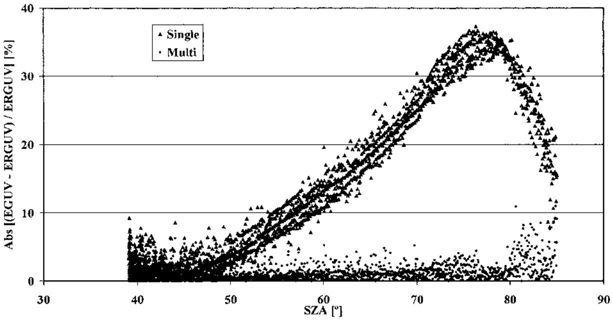

Fig. 4. Relative error, in absolute value, for single-regression and multiregressive calibration, GUV-9221 (Bariloche) against RGUV-9287.

Data from both instruments, under all weather conditions, for the period from 1 July to 31 December 2000 were used in the comparison. Data from the GUV-9234 calibrated with both methodologies were considered. Table 3 shows the error for single-regression and multiregressive calibrations of the GUV-9234 values in relation to the RGUV-9287 values during calibration for channel 305. Improvements were observed for SZAs above 60°. It should be pointed out that Ushuaia is under the influence of the ozone hole during spring, so data used in this test include irradiances measured under a wide range of total ozone columns, including values below 150 Dobson units (DU).

Taking into account the variation of the error with the SZA, in both steps of the calibration, GUV against RGUV and RGUV against the San Diego SUV-100, single regression was used for SZAs smaller than 60°

Table 2. rms Irradiance Error in Percent for Each of the UV Channels[a]

	Channel 305		Channel 320		Channel 340		Channel 380	
Site	S[b]	M[c]	S	M	S	M	S	M
Jujuy (GUV-9232)	9.72	5.53	2.22	1.82	2.38	2.17	2.31	2.01
Santiago (GUV-9258)	13.82	2.66	6.38	0.50	3.00	0.55	4.16	0.37
Buenos Aires (GUV-9236)	15.24	3.79	5.87	1.28	1.56	1.39	2.01	1.87
Trelew 1 (GUV-9233)	10.32	6.72	3.58	0.47	1.18	0.50	2.18	0.77
Trelew 2 (GUV-9299)	30.72	3.87	1.11	0.43	1.87	0.62	3.51	0.75
Valdivia (GUV-9259)	13.66	1.11	0.93	0.23	1.73	0.22	3.26	0.22
Bariloche (GUV-9221)	21.87	2.11	1.65	1.33	2.03	1.76	3.07	2.63
Punta Arenas (GUV-9210)	32.22	17.83	5.90	1.70	2.51	1.70	3.61	3.08
Ushuaia (GUV-9234)	6.09	2.85	4.37	1.90	2.01	1.85	2.55	2.36

[a] rms error for the GUV radiometers in the IAI Network calculated during 2000 with respect to the RGUV-9287 for SZAs larger than 50°.
[b] S, single regression.
[c] M, multiregression.

Table 3. Error for calibration of GUV-9234 (Ushuaia) against RGUV-9287[a]

Range of SZA (°)	rms Error Single (%)	rms Error Multi (%)
$50 \le \text{SZA} < 60$	2.08	1.92
$60 \le \text{SZA} < 70$	4.27	1.62
$70 \le \text{SZA} < 80$	9.53	2.37
$80 \le \text{SZA} < 85$	9.80	5.60

[a] rms values corresponding to error in channel 305. Note the improvement observed in particular for SZAs larger than 60°.

and multiregressive Eq. (2) was used for larger SZAs in both steps. The errors for instantaneous values of the GUV-9234 against the SUV-100 in Ushuaia for the above-mentioned 6-month period are shown in Table 4.

Since each instrument was installed in a different building roughly 30 m apart, instantaneous values may present errors due to timing problems and short-time cloud changes.[12] To filter these errors, hourly average irradiances were calculated for both instruments, and then the errors were calculated. The results are shown in Table 5, where smaller errors, in relation to the instantaneous values, are observed for all SZA intervals.

It should be pointed out that the GUV installed in Ushuaia showed smaller errors for the multiregressive calibration for only SZAs larger than 50°. For instruments like the GUV-9221 (Bariloche), where the improvement is more important for all SZAs, the total difference between both methods should be more pronounced.

Table 4. Error of GUV-9234 versus SUV-100 (Ushuaia) Instantaneous Values[a]

Range of SZA (°)	rms Error Single (%)	rms Error Multi (%)
<40	10.61	10.61
$40 \le \text{SZA} < 50$	9.94	9.94
$50 \le \text{SZA} < 60$	10.04	10.04
$60 \le \text{SZA} < 70$	22.24	14.61
$70 \le \text{SZA} < 80$	52.42	22.35
$80 \le \text{SZA} < 85$	77.81	41.18

[a] Values correspond to rms error for channel 305 for the period of July through December 2000. Considering the error during calibration, single calibration was applied in both steps for SZAs less than 60°. For larger SZAs the multiregressive logarithmic approach was applied in both steps.

Table 5. Error of GUV-9234 versus SUV-100 (Ushuaia) Hourly Average[a]

Range of SZA (°)	rms Error Single (%)	rms Error Multi (%)
<40	5.74	5.74
$40 \le \text{SZA} < 50$	5.95	5.95
$50 \le \text{SZA} < 60$	7.72	7.01
$60 \le \text{SZA} < 70$	19.52	13.09
$70 \le \text{SZA} < 80$	42.23	14.19
$80 \le \text{SZA} < 85$	73.17	37.06

[a] Same as Table 4 but considering hourly averages. The errors diminished considerably for most SZA intervals.

5. Conclusions

A multiregressive methodology that includes the total ozone column and SZAs has been proposed to improve Sun calibration of multichannel radiometers. The method has shown good results in both steps of the calibration (GUV against RGUV and RGUV against SUV-100). The proposed technique diminishes considerably the errors in values measured at SZAs larger than 50°. It would be particularly beneficial to apply this calibration method in radiometers installed at mid and high latitudes, where SZAs during winter are larger than 50°, even at noon. An independent test, performed comparing 6 months of data from the GUV-9234 and the SUV-100 installed in Ushuaia, showed better data agreement when multiregressive calibration was applied to the GUV-9234.

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