COMPARISON BETWEEN LEBARON-PEREZ AND DAL PAI-ESCOBEDO CORRECTION METHODS FOR DIFFUSE IRRADIANCE MEASURED BY THE *MEO* SHADOWRING METHOD

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Abstract

This study aims to determine the effectiveness of two methods of correction of diffuse irradiance measured with shadowbands: LeBaron-Perez method and Dal Pai-Escobedo method. For the LeBaron-Perez method, we use the original coefficients and adjusted coefficients for the atmospheric conditions of Botucatu. Global, direct and diffuse solar irradiances were supplied by the Laboratory of Solar Radiometry of Botucatu. The period assigned for the study comprised the years 1996 to 2005. The results showed that the LeBaron-Perez correction model with the original coefficients are not suitable for correction of diffuse irradiance in Botucatu. Otherwise, the LeBaron-Perez model with adjusted coefficients and Dal Pai-Escobedo model are indicated for the correction of diffuse irradiance in Botucatu measured by shading ring with accuracy of 0.5%.

Keywords: Shading ring, diffuse irradiance, Correction Factors, anisotropy, Measurement Methods.

1. Introduction

Information of the solar potential are required in various industries and areas of society, with applications in climatology, architecture, agriculture, passive lighting, satellite studies, among others. In general, the information serves to supply solar energy conversion models, thermal comfort and energy balance.

Several weather stations, for practical reasons, measure, routinely, only the global radiation. Measures of direct and diffuse radiation are less frequent due to the high financial costs. However, it is possible to establish a database of global, diffuse and direct radiation with low financial investment. In this case, the global component is monitored by a pyranometer positioned in the horizontal plane of the locality, the diffuse component is monitored by a pyranometer placed under the shade of a shading ring and the direct component is obtained by the difference between the global and diffuse components.

This method of measuring diffuse radiation is known as shading ring method. Different assemblies are described in the literature and best known is the Drummond´s assembly (1956) (Fig. 1). In Drummond assembly, the pyranometer remains fixed and the shading ring moves parallel to the polar axis to compensate the variations in the solar declination. The Drummond assembly is currently the most widely used. An alternative assembly with low cost, easy operation and maintenance, was proposed by Melo and Escobedo (1994) - *MEO* assembly (Fig. 1). In this system, the shading ring is fixed with an inclined angle equal to the local latitude, and to compensate the solar declination, the pyranometer moves parallel to the local horizon plane on a moving base to stay under the shadow produced by the ring.

Despite having operational and financial advantage, shading ring method has the disadvantage of correction factors (CF) to offset the portion (LF) of diffuse irradiance barred by shading ring (Drummond, 1956; Kasten et al, 1983; Stanhill, 1985). 5% errors in the measurement of diffuse radiation can propagate up to 20% uncertainty in the estimate of direct radiation to high zenith angles (Lebaron et al, 1990). Correction factors are based on isotropic radiation, and consider only the use of geometric factors (radius and ring width) and geographic (latitude and solar declination).

doi:10.18086/swc.2017.23.01 Available at http://proceedings.ises.org

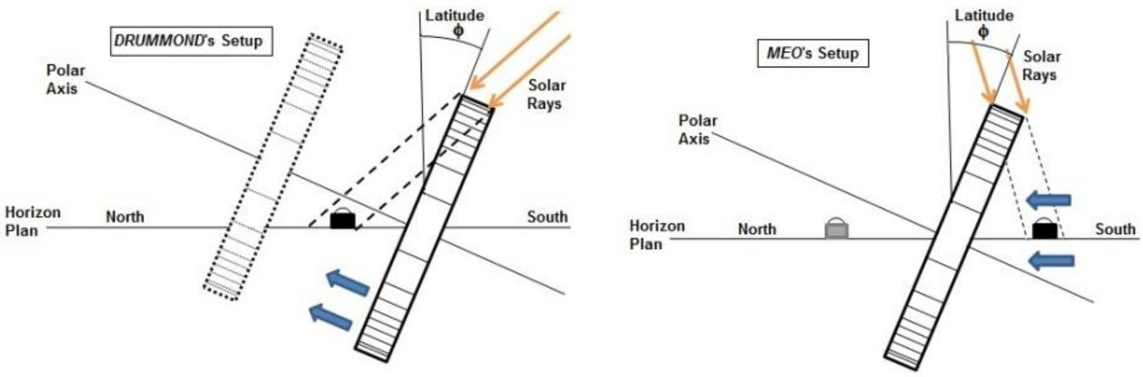


Figure 1 - Shading ring assembly: Drummond and MEO.

Several researchers have shown that the application of isotropic correction does not include atmospheric effects (turbidity, cloudiness, pollution, water vapor) that are responsible for anisotropy in the diffuse radiation. Kasten et al. (1983) and Pollard and Langevine (1988) introduced corrections based on anisotropic parameters such as K_T clearness index (ratio between the global irradiance I_G by the extraterrestrial irradiance I_O), zenith angle and atmospheric turbidity associated with isotropic correction to improve the accuracy of the measurement of diffuse irradiance by Drummond shading ring. Stanhill (1985) found that the anisotropic corrections showed spatial and temporal dependence, caused mainly by the different sizes and concentration levels of aerosols in the atmosphere. LeBaron et al (1990) proposed anisotropic correction models by combining three anisotropic parameters (zenith angle and brightness index) and an isotropic parameter (geometric and geographic), highlighting the K_T clearness index as the most significant parameter in the representation of anisotropic conditions. In this way, Iqbal (1983) recommends different anisotropic corrections to the ring as a function of K_T clearness index (3% to $0 < K_T < 0.30$; 5% to $0.30 < K_T < 0.65$ and 7% to $0.65 < K_T < 1$). Battles et al (1995) used the same parameters of LeBaron and developed two numerical correction methods through multiple linear regression: the first method uses all the parameters in a single equation, whereas the second uses geometric parameters, brightness and solar zenith angle grouped by four intervals of the K_T clearness index, a total of four numeric correction equations.

In this sense, the objective is to compare the efficiency of Lebaron-Perez and Dal Pai-Escobedo methods for correction of diffuse solar irradiance measured by the *MEO* shading ring assembly.

2. Materials and Methods

The study is based on global, direct and diffuse irradiance measurements provided by the Laboratory of Solar Radiometry, located at the Department of Bioprocess and Biotechnology, School of Agricultural Sciences / UNESP / SP (latitude 22º 54 'S, longitude 48º 27' W and altitude 716 m). There were used 10-years data (1996-2005), 75% intended for modeling and 25% for validation purposes. A computational routine was developed to separate the data, being three lines for modeling and 1 line for validation..

The city of Botucatu (Fig. 2) lies in a region of planting sugarcane and eucalyptus. It has about 130,000 inhabitants and is surrounded by an asymmetric embossing called Cuesta de Botucatu and the watersheds of the Tietê and Paranapanema. It has few industries and its economy is based on service delivery.

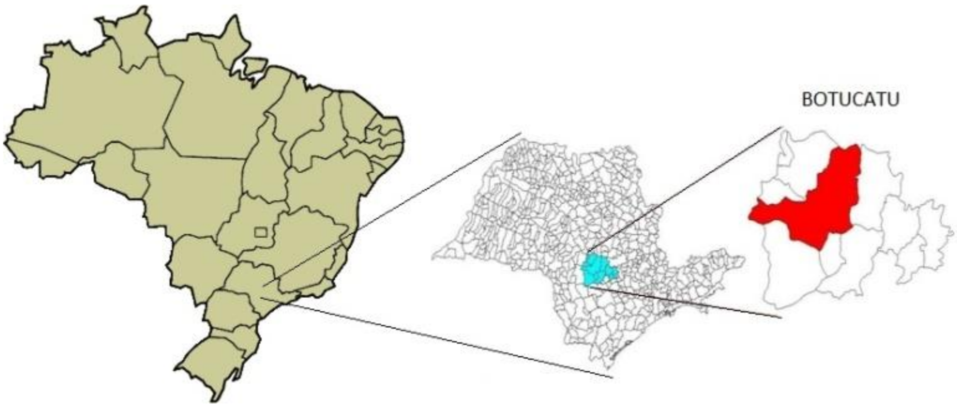


Figure 2 - Map of Brazil with state divisions showing the location of the study (Botucatu in the state of São Paulo)

According to the Köppen climate classification, the local climate is Cwa (humid subtropical climate), with hot, humid and rainy summers and dry winters and mild temperatures. The temperature and relative humidity values follow the astronomical variations, with maximum values of temperature and relative humidity in February (23.12 ° C and 78.25% respectively) and minimum temperature values in July (17.10 ° C) and relative humidity in August (63.97%). The rainy season occurs in the summer and spring, accompanied by high cloudiness. About 80% of the annual rainfall occurs during this period, with a maximum in January (246.2 mm). In the winter and fall seasons, the average rainfall is less than 100 mm per month, and minimum in August (36.1 mm). Regarding aerosols, industrial activity and motor vehicles are the largest emitters of aerosols in the atmosphere. However, as the Botucatu is full of sugarcane crops, the practice of harvest burning can emit large amounts of particulate matter in the atmosphere, especially in winter, where the removal by rain is minimal (Codato et al, 2008).

The global solar irradiance I_G was measured by an Eppley PSP pyranometer; the direct solar irradiance by an Eppley NIP pyrheliometer equipped with a ST-3 solar tracking device; and diffuse solar irradiance by an Eppley PSP pyranometer under the *MEO* shading ring (radius of 0.40 m width 0.10 m). Tab. 1 shows the operating characteristics of the measurement devices.

Table 1 - Operational characteristics of the global, direct and diffuse solar irradiance measurements.

Irradiance	**Global**	**Direct**	**Diffuse**
Sensor-brand	Eppley Precision Spectral Pyranometer	Eppley Normal Incidence Pyrheliometer	Eppley Precision Spectral Pyranometer
Sensibility	±7,45 μV/Wm²	7,59 μV/Wm²	±7,47 μV/Wm²
Spectral Range	295 – 2800 nm	295 – 2800 nm	295 – 2800 nm
Response time	1 s	1 s	1 s
Linearity	±0,5% (from 0 to 2800 W/m²)	±0,5% (from 0 to 1400 W/m²)	±0,5% (from 0 to 2800 W/m²)
Cosine effect	±1% (0º<Z<70º) ±3% (70º≤Z<80º)	–	±1% (0º<Z<70º) ±3% (70º≤Z<80º)
Temperature Dependence	±1% (from -20ºC to +40ºC)	±1% (from -20ºC to +40ºC)	±1% (from -20ºC to +40ºC)

Figure 3 – Global, diffuse and direct solar irradiance measurements.

The values of solar irradiance were monitored by an automatic data acquisition system model Datalogger 23X Campbell Scientific Inc with a 0.2 Hz frequency. Mean values were calculated every 5 minutes and stored in W/m^2 format.

The diffuse irradiance data measured by the MEO shading ring (Id_{ANEL}) were corrected using the geometric correction factors proposed by Oliveira et al (2002). True diffuse irradiance, called reference diffuse irradiance (Id_{REF}) was calculated as the difference between the global and direct irradiance. Of the 525 592 available data on ten years of monitoring, 47725 (representing 9.09% of total) were removed due to the application of filters shown in Tab. 2 (Kudish and Evseev, 2008). The cutoff values are due to misalignment, lack of electricity and internal reflections occurred in the shading ring caused by low solar altitude.

Table 2 - Quality control filters and results (Kudish and Evseev, 2008).

Solar Irradiance	**Filter**
Global	$I_G < I_O$
Direct	$I_b \leq Io$
Diffuse	$0,1\ I_G \leq Id_{ANEL} < I_G$
Diffuse Reference	$0 \leq Id_{REF} \leq I_o$

For LeBaron-Perez correction method (Lebaron et al, 1990), we calculated the zenith angle (Z), the clarity index Epsilon (ε) and the brightness index (Δ).

$$Z = \cos^{-1}[\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega] \quad (1)$$

$$\varepsilon = \frac{I_G - I_d}{I_d \cos Z} + 1 \quad (2)$$

$$\Delta = \frac{I_d . m}{I_o} \quad (3)$$

where ϕ is the local latitude, δ the solar declination, ω the hour angle, I_G the global irradiance I_d the diffuse irradiance uncorrected measured by the shading ring, m the optic mass and Io the extraterrestrial irradiance mass. The Dal Pai-Escobedo correction method (Dal Pai et al, 2011) uses the atmospheric transmissivity parameter K_T.

$$K_T = \frac{I_G}{I_o} \quad (4)$$

The original method of LeBaron-Perez used the geometric correction factors for Drummond assembly. As in Botucatu the diffuse irradiance measurement method uses the MEO assembly, the geometric correction factors were adjusted for such assembly. Equations (5) and (6) show the loss of fractions of assemblies Drummond (Drummond, 1956) and MEO (Oliveira et al, 2002), respectively, and the equation (7) the calculation of the geometric correction factors.

$$F_{lost-D} = \left(\frac{2b}{\pi R}\right).cos^3\,\delta \int_0^{w_z} \cos Z\, d\omega \tag{5}$$

$$F_{lost-MEO} = \left(\frac{2b}{\pi R}\right).\cos\delta.\left[\frac{\cos(\phi+\delta)}{\cos\phi}\right]^2 \int_0^{w_z} \cos Z\, d\omega \tag{6}$$

$$F_G = \frac{1}{1-F_{lost}} \tag{7}$$

where b is the width of the ring and R the radius of the ring. The evaluation of the correction model is based on MBE and RMSE statistical indicative (Stone, 1993) given by Eq. (8) and Eq. (9), respectively.

$$MBE = \left(\sum_i^N (y_i - x_i) \Big/ N\right) \tag{8}$$

$$RMSE = \left(\sum_i^N (y_i - x_i)^2 \Big/ N\right)^{1/2} \tag{9}$$

where y_i represents the ring diffuse irradiance, x_i the reference diffuse irradiance and N is the number of observations. The MBE is the simple deviation and a positive value indicates an overestimate, while a negative value indicates an underestimate. The RMSE is the standard deviation and is related to the dispersal of values from the average.

3. Results and Discussions

In this section are compared two methods of correction of diffuse solar irradiance measured by the shading ring. The first method used is based on LeBaron-Perez correction method (Lebaron et al, 1990), using four parameters for a sky conditions description (geometrical factor, zenith angle, clarity index and brightness index). The second methodology is based on the correction method of DalPai-Escobedo (Dal Pai et al, 2011), and used two parameters for description of sky conditions (geometric factor and atmospheric transmissivity).

The LeBaron-Perez correction model considers both isotropy and anisotropy conditions of the radiation. A geometric factor was proposed for isotropy conditions based on construction features of the ring, while zenith angle, clarity index and brightness index was assigned for anisotropy conditions. In this case, while zenith angle is responsible for the position of the sun in the celestial hemisphere and the optical path taken by the sun's rays, clarity index and brightness index are linked to measurements performed on surface and reflect the interaction of radiation with the atmosphere. Tab. (3) shows the parameter values used in the LeBaron Perez-correction model divided into four sets, which result in 256 sky categories. Two situations were present for geometric factors: one containing the values of the original model for Drummond assembly and one adjusted for *MEO* assembly at Botucatu.

Table 3 - Limit values used for the four parameters chosen to describe the corrections applied to the diffuse irradiance measured by the shading ring. The combination of these parameters allow 256 sky coverage categories.

Parameters			Groups 1	2	3	4
i	Zenith angle		0 to 35	35 to 50	50 to 60	60 to 90
j	Geometric factor	(*Original*)	1 to 1.068	1.068 to 1.100	1.100 to 1.132	1,132 to ---
		(*Adjusted*)	1 to 1.123	1.123 to 1.165	1.165 to 1.208	1,208 to ---
k	Epsilon		0 to 1,253	1.253 to 2.134	2.134 to 5.980	5.980 to ---
l	Delta		0 to 0,12	0.12 to 0.20	0.20 to 0.30	0.30 to ---

Once you have determined 256 categories of sky condition, corrections were calculated by the ratio of reference diffuse irradiance to not corrected diffuse irradiance. The advantage of Lebaron Perez-model is that these 256 classes represent a "scan" of more complex analytical formulas and, since these values are tabulated, the computational time in processing is more efficient. Tab. 4 and Tab. 5 show the correction factors obtained for Lebaron Perez-correction method. In Tab. 4 are shown the original coefficients developed using Drummond assembly. In Tab. 5 are shown the adjusted coefficients for Botucatu for *MEO* assembly.

Table 4 - Correction factors for each parameter category. (LeBaron-Perez model with original coefficients)

Categories (i j k l)

(i = zenith; j = geometric factor; k = epsilon; l = delta)

categ	**fc**	**categ**	**fc**	**categ**	**Fc**	**categ**	**fc**	**categ**	**fc**	**categ**	**fc**	**categ**	**Fc**	**categ**	**fc**
1111	1.051	*1311*	1.117	*2111*	1.051	*2311*	1.115	*3111*	1.069	*3311*	1.119	*4111*	1.047	*4311*	1.074
1112	1.051	*1312*	1.117	*2112*	1.051	*2312*	1.130	*3112*	1.073	*3312*	1.115	*4112*	1.058	*4312*	1.117
1113	1.051	*1313*	1.117	*2113*	1.051	*2313*	1.128	*3113*	1.076	*3313*	1.131	*4113*	1.060	*4313*	1.103
1114	1.051	*1314*	1.117	*2114*	1.051	*2314*	1.143	*3114*	1.085	*3314*	1.117	*4114*	1.069	*4314*	1.117
1121	1.051	*1321*	1.117	*2121*	1.051	*2321*	1.117	*3121*	1.161	*3321*	1.147	*4121*	1.076	*4321*	1.104
1122	1.051	*1322*	1.117	*2122*	1.051	*2322*	1.186	*3122*	1.086	*3322*	1.168	*4122*	1.074	*4322*	1.118
1123	1.051	*1323*	1.117	*2123*	1.051	*2323*	1.180	*3123*	1.135	*3323*	1.176	*4123*	1.092	*4323*	1.143
1124	1.051	*1324*	1.117	*2124*	1.051	*2324*	1.195	*3124*	1.132	*3324*	1.183	*4124*	1.118	*4324*	1.150
1131	1.051	*1331*	1.117	*2131*	1.051	*2331*	1.117	*3131*	1.051	*3331*	1.117	*4131*	1.187	*4331*	1.139
1132	1.051	*1332*	1.117	*2132*	1.051	*2332*	1.203	*3132*	1.080	*3332*	1.211	*4132*	1.140	*4332*	1.191
1133	1.051	*1333*	1.117	*2133*	1.051	*2333*	1.207	*3133*	1.169	*3333*	1.193	*4133*	1.150	*4333*	1.180
1134	1.051	*1334*	1.117	*2134*	1.051	*2334*	1.210	*3134*	1.144	*3334*	1.226	*4134*	1.117	*4334*	1.178
1141	1.051	*1341*	1.117	*2141*	1.051	*2341*	0.990	*3141*	1.015	*3341*	0.946	*4141*	0.925	*4341*	0.977
1142	1.051	*1342*	1.117	*2142*	1.051	*2342*	1.120	*3142*	1.182	*3342*	1.081	*4142*	1.057	*4342*	1.133
1143	1.051	*1343*	1.117	*2143*	1.051	*2343*	1.117	*3143*	1.051	*3343*	1.117	*4143*	1.089	*4343*	1.216
1144	1.051	*1344*	1.117	*2144*	1.051	*2344*	1.117	*3144*	1.051	*3344*	1.117	*4144*	1.024	*4344*	1.162
1211	1.082	*1411*	1.173	*2211*	1.104	*2411*	1.163	*3211*	1.082	*3411*	1.140	*4211*	1.063	*4411*	1.030
1212	1.082	*1412*	1.176	*2212*	1.095	*2412*	1.162	*3212*	1.089	*3412*	1.142	*4212*	1.076	*4412*	1.156
1213	1.082	*1413*	1.182	*2213*	1.082	*2413*	1.159	*3213*	1.088	*3413*	1.129	*4213*	1.085	*4413*	1.156
1214	1.082	*1414*	1.191	*2214*	1.105	*2414*	1.168	*3214*	1.093	*3414*	1.156	*4214*	1.082	*4414*	1.156
1221	1.082	*1421*	1.248	*2221*	1.082	*2421*	1.184	*3221*	1.161	*3421*	1.168	*4221*	1.078	*4421*	1.146
1222	1.082	*1422*	1.211	*2222*	1.082	*2422*	1.194	*3222*	1.130	*3422*	1.177	*4222*	1.102	*4422*	1.174

1223	1.082	*1423*	1.221	*2223*	1.171	*2423*	1.213	*3223*	1.148	*3423*	1.197	*4223*	1.119	*4423*	1.182
1224	1.082	*1424*	1.238	*2224*	1.148	*2424*	1.230	*3224*	1.160	*3424*	1.210	*4224*	1.116	*4424*	1.185
1231	1.082	*1431*	1.156	*2231*	1.082	*2431*	1.156	*3231*	1.082	*3431*	1.156	*4231*	1.167	*4431*	1.191
1232	1.082	*1432*	1.237	*2232*	1.082	*2432*	1.212	*3232*	1.195	*3432*	1.185	*4232*	1.098	*4432*	1.181
1233	1.082	*1433*	1.238	*2233*	1.160	*2433*	1.230	*3233*	1.191	*3433*	1.210	*4233*	1.133	*4433*	1.156
1234	1.082	*1434*	1.232	*2234*	1.206	*2434*	1.238	*3234*	1.178	*3434*	1.216	*4234*	1.155	*4434*	1.167
1241	1.082	*1441*	1.181	*2241*	1.082	*2441*	1.104	*3241*	1.016	*3441*	1.027	*4241*	0.967	*4441*	1.150
1242	1.042	*1442*	1.217	*2242*	1.082	*2442*	1.180	*3242*	1.115	*3442*	1.111	*4242*	1.119	*4442*	1.033
1243	1.082	*1443*	1.156	*2243*	1.082	*2443*	1.156	*3243*	1.082	*3443*	1.156	*4243*	1.194	*4443*	1.064
1244	1.082	*1444*	1.156	*2244*	1.082	*2444*	1.156	*3244*	1.082	*3444*	1.156	*4244*	1.025	*4444*	1.142

Table 5 - Correction factors for each parameter category. (LeBaron-Perez model with adjusted coefficients)

Categories (i j k l)

(i = zenith; j = geometric factor; k = epsilon; l = delta)

categ	**fc**	**categ**	**fc**	**categ**	**Fc**	**categ**	**fc**	**categ**	**fc**	**categ**	**fc**	**categ**	**Fc**	**categ**	**Fc**
1111	1.061	*1311*	1.137	*2111*	1.063	*2311*	1.103	*3111*	1.065	*3311*	1.100	*4111*	1.045	*4311*	1.062
1112	1.061	*1312*	1.138	*2112*	1.068	*2312*	1.132	*3112*	1.066	*3312*	1.108	*4112*	1.047	*4312*	1.068
1113	1.061	*1313*	1.148	*2113*	1.068	*2313*	1.137	*3113*	1.066	*3313*	1.121	*4113*	1.054	*4313*	1.060
1114	1.061	*1314*	1.159	*2114*	1.086	*2314*	1.141	*3114*	1.076	*3314*	1.109	*4114*	1.040	*4314*	0.934
1121	1.061	*1321*	1.249	*2121*	1.174	*2321*	1.208	*3121*	1.173	*3321*	1.170	*4121*	1.102	*4321*	1.159
1122	1.061	*1322*	1.249	*2122*	1.220	*2322*	1.233	*3122*	1.205	*3322*	1.165	*4122*	1.087	*4322*	1.151
1123	1.061	*1323*	1.250	*2123*	1.209	*2323*	1.225	*3123*	1.187	*3323*	1.190	*4123*	1.096	*4323*	1.142
1124	1.061	*1324*	1.257	*2124*	1.189	*2324*	1.232	*3124*	1.170	*3324*	1.204	*4124*	1.097	*4324*	1.150
1131	1.061	*1331*	1.470	*2131*	1.460	*2331*	1.479	*3131*	1.061	*3331*	1.187	*4131*	1.211	*4331*	1.241
1132	1.061	*1332*	1.338	*2132*	1.326	*2332*	1.342	*3132*	1.343	*3332*	1.320	*4132*	1.257	*4332*	1.224
1133	1.061	*1333*	1.314	*2133*	1.284	*2333*	1.306	*3133*	1.281	*3333*	1.299	*4133*	1.277	*4333*	1.292
1134	1.061	*1334*	1.318	*2134*	1.244	*2334*	1.295	*3134*	1.218	*3334*	1.261	*4134*	1.132	*4334*	1.172
1141	1.061	*1341*	1.384	*2141*	1.357	*2341*	1.394	*3141*	1.257	*3341*	1.290	*4141*	1.064	*4341*	1.055
1142	1.061	*1342*	1.372	*2142*	1.293	*2342*	1.371	*3142*	1.229	*3342*	1.309	*4142*	1.063	*4342*	1.110
1143	1.061	*1343*	1.187	*2143*	1.251	*2343*	1.328	*3143*	1.218	*3343*	1.292	*4143*	1.019	*4343*	1.142
1144	1.061	*1344*	1.187	*2144*	1.061	*2344*	1.187	*3144*	1.165	*3344*	1.304	*4144*	1.014	*4344*	1.145
1211	1.112	*1411*	1.185	*2211*	1.103	*2411*	1.151	*3211*	1.091	*3411*	1.109	*4211*	1.058	*4411*	1.039
1212	1.119	*1412*	1.183	*2212*	1.104	*2412*	1.162	*3212*	1.103	*3412*	1.122	*4212*	1.058	*4412*	1.041
1213	1.120	*1413*	1.186	*2213*	1.111	*2413*	1.163	*3213*	1.097	*3413*	1.125	*4213*	1.060	*4413*	1.045
1214	1.125	*1414*	1.193	*2214*	1.117	*2414*	1.160	*3214*	1.100	*3414*	1.133	*4214*	1.004	*4414*	1.005
1221	1.144	*1421*	1.245	*2221*	1.222	*2421*	1.212	*3221*	1.176	*3421*	1.202	*4221*	1.134	*4421*	1.187
1222	1.228	*1422*	1.267	*2222*	1.237	*2422*	1.219	*3222*	1.171	*3422*	1.202	*4222*	1.117	*4422*	1.188
1223	1.224	*1423*	1.284	*2223*	1.222	*2423*	1.230	*3223*	1.189	*3423*	1.204	*4223*	1.122	*4423*	1.189
1224	1.231	*1424*	1.292	*2224*	1.219	*2424*	1.257	*3224*	1.191	*3424*	1.232	*4224*	1.120	*4424*	1.190
1231	1.345	*1431*	1.445	*2231*	1.379	*2431*	1.420	*3231*	1.144	*3431*	1.240	*4231*	1.216	*4431*	1.254
1232	1.315	*1432*	1.362	*2232*	1.311	*2432*	1.349	*3232*	1.313	*3432*	1.321	*4232*	1.187	*4432*	1.229
1233	1.261	*1433*	1.360	*2233*	1.296	*2433*	1.344	*3233*	1.264	*3433*	1.317	*4233*	1.256	*4433*	1.246

1234	1.256	*1434*	1.344	*2234*	1.266	*2434*	1.337	*3234*	1.243	*3434*	1.316	*4234*	1.148	*4434*	1.207
1241	1.328	*1441*	1.426	*2241*	1.349	*2441*	1.405	*3241*	1.240	*3441*	1.312	*4241*	1.069	*4441*	1.177
1242	1.361	*1442*	1.355	*2242*	1.314	*2442*	1.360	*3242*	1.239	*3442*	1.310	*4242*	1.083	*4442*	1.161
1243	1.144	*1443*	1.230	*2243*	1.283	*2443*	1.322	*3243*	1.256	*3443*	1.305	*4243*	1.048	*4443*	1.155
1244	1.144	*1444*	1.230	*2244*	1.144	*2444*	1.230	*3244*	1.205	*3444*	1.287	*4244*	1.030	*4444*	1.169

The categories consist of the zenith angle parameters, geometrical factor, epsilon and delta, when combined, result in 256 categories. The groups was carried out by the indices "i", "j", "k" and "l", which represent, respectively, the zenith angle, geometrical factor, epsilon and delta, and each of these indices can take values from 1 to 4 depending on their range (Tab. 3). Thus, the cluster was determined by means of a number consisting of four digits in the format "ijkl". For example, the category 4321 describes a state with zenith angle ranging from 60 to 90, the geometrical factor of 1.100 to 1.132, epsilon 1.253 to 2.134 and delta 0 to 0.12. Some categories were not filled with solar irradiance data due to physical limitations of the parameters. In this case, the correction factor was adopted an average of the geometrical factor.

Tab. 4 shows the original correction factors proposed by LeBaron et al (1990), developed for the assembly of Drummond, ranging from 0.925 to 1.248. The largest corrections occurred for low cloudiness and high brightness index (delta), typical of the days of high solar declination. Minor corrections occurred for high cloudiness, wherein the isotropic behavior of the radiation is more evident.

We adjusted LeBaron-Perez's methodology for Botucatu atmospheric conditions and MEO shadow ring's assembly (LeBaron Perez-adjusted model). Tab. 5 shows the adjusted coefficients. Corrections ranged from 0.934 to 1.470. The largest correction also occurred for low cloudiness, showing great influence of the anisotropy. The lowest correction value occurred for high situation zenith angle and brightness index, probably linked to reflections inside the shading ring.

We also use the Dal Pai-Escobedo correction model, which is based on geometric factor (isotropy) and K_T atmospheric transmissivity (anisotropy). Tab. 6 shows the numerical factors used by the Dal Pai-Escobedo correction model for four K_T atmospheric transmissivity intervals.

Table 6 - Correction factors based on K_T atmospheric transmissivity intervals (*MEO* shading assembly).

K_T Interval	**Correction Factors**
$0 \leq K_T < 0.35$	0.975
$0.35 \leq K_T < 0.55$	1.034
$0.55 \leq K_T < 0.65$	1.083
$0.65 \leq K_T < 1$	1.108

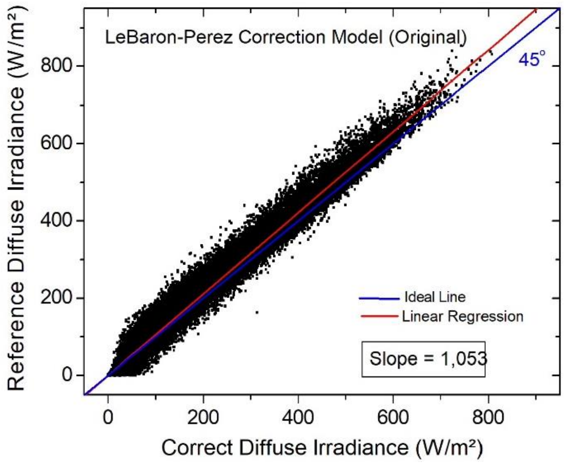
To validate the correction models, corrected diffuse irradiance were compared with reference diffuse irradiance by means of MBE and RMSE statistical indicators. MBE shows the long-term model behavior, with an underestimating or overestimating by the model. RMSE shows the dispersion of the model around the measure. Tab. 7 shows MBE, RMSE and slope, while Fig. 4 shows the graphs between reference diffuse irradiance and corrected diffuse irradiance by the correction models (LeBaron-Perez (Original), LeBaron- Perez (Adjusted) and Dal Pai-Escobedo).

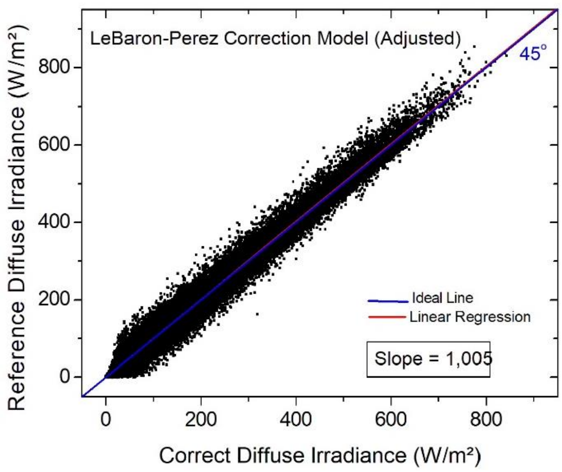
Table 7 - MBE, RMSE and slope for reference diffuse irradiance and corrected diffuse irradiance (LeBaron-Perez (Original), LeBaron-Perez (Adjusted) and Dal Pai-Escobedo).

Correction Model	**Statistical Indicators**				
	MBE (W/m^2)	**MBE (%)**	**RMSE (W/m^2)**	**RMSE (%)**	**Slope**

LeBaron-Perez - OR	-9,52	-5,93	22,87	14,24	1,053
LeBaron-Perez - AJ	-0,74	-0,46	17,32	10,79	1,005
Dal Pai-Escobedo	-0,02	-0,01	18,11	11,28	0,999

The worst performance was given to the model LeBaron-Perez correction with original coefficients, with an underestimation of 6% and dispersion of 14.3%. This result was expected, since the original model coefficients were developed for a different atmospheric condition of Botucatu, both aerosols, water vapor and clouds. This model was significantly improved when setting the coefficients for atmospheric situation of Botucatu, causing a reduction in MBE (~ 0.5%) and RMSE (~ 11%). A good performance was also attributed to Dal Pai-Escobedo correction model, with low values of MBE (- 0.01%) and RMSE (11.28%). With respect to slope, Lebaron-Perez adjusted and Dal Pai-Escobedo correction models had the same great performance, with slope closer to 1. Overall, LeBaron-Perez (Adjusted) and Dal Pai-Escobedo correction models exhibit the same order of accuracy in correction of diffuse irradiance measured by the shading ring. Dal Pai-Escobedo correction model takes a small advantage by presenting less parameters to classify the sky.





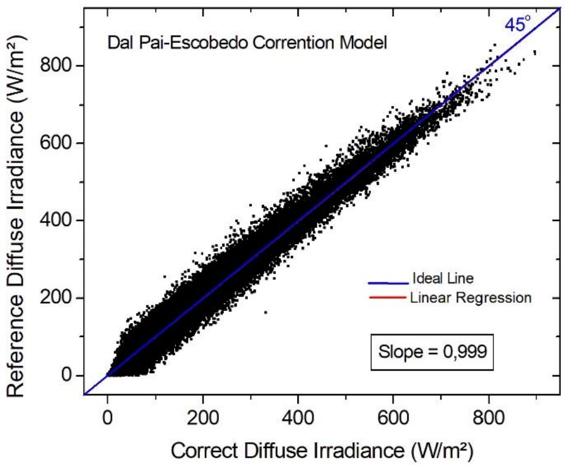


Figure 4 - Comparison between the diffuse irradiance reference and corrected diffuse irradiance by the correction models: a) LeBaron-Perez (Original). b) LeBaron-Perez (Adjusted). c) Dal Pai-Escobedo.

4. Conclusion

Our results allowed the following conclusions:

a) Lebaron-Perez correction model with the original coefficients, is not suitable to correct diffuse irradiance measured in Botucatu with the *MEO* shading ring method.

b) Lebaron-Perez correction model, when adjusted for Botucatu sky conditions, can be used to correct the diffuse irradiance measured by the *MEO* shading ring method.

c) Dal Pai-Escobedo correction model is suitable to correct diffuse irradiance measured by the *MEO* shading ring method.

d) Lebaron-Perez (Adjusted) and Dal Pai-Escobedo correction models has the same efficiency to correct diffuse irradiance.

e) We recommend Dal Pai-Escobedo correction model to correct diffuse irradiance because it uses fewer parameters.

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Acknowledgements. The authors acknowledge the financial support from FAPESP.