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Effects of leveling error on the measurement of global radiation

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Abstract—Pyranometers are fundamental instruments widely used for measuring global irradiance. When operating weather stations without continuous manning, pyranometer may tilt from horizontal position. Error caused by inclination of a few degrees was calculated for the annual, daily, and instantaneous global radiations. Global irradiance incident on both horizontal and tilted surfaces were calculated from the direct beam, diffuse and ground-reflected irradiances. These components were measured by accurately leveled and regularly supervised instruments. The second purpose of this paper was to determine the minimum tilt angle that is detectable by calculating certain quantities. To detect the east-west inclination, the sum of the global radiation before and after the solar noon was compared. To detect the north-south inclination, it was tested whether the global irradiance measured at a fixed solar elevation with a horizontal and a tilt pyranometer is stochastically equal. Our findings show that tilt angle of 1° in east-west direction is already detectable. Tilting to the direction at an angle of 15° from the north-south is the most difficult to detect. Here 3° is the smallest detectable tilt angle.

Key-words: global radiation, global irradiance, pyranometer, tilt error, detection of tilt, leveling of pyranometer

1. Introduction

The demand for high-precision global radiation measurement has risen steadily in recent decades. Global radiation data with high spatial and temporal resolution are required in different fields including meteorological and climate models, active and passive solar energy systems, agriculture, and the solar architecture. Consequently, the instruments measuring solar radiation have shown significant progress. The number of weather stations equipped with solar instruments continues to grow, and the use of pyranometers for industrial purposes became general. In spite of this, compared to other meteorological variables, the measurement of solar radiation is more prone to errors *(Moradi,* 2009*). Younes et al.* (2005) classified the most general types of errors into two major categories: (1) equipment error and uncertainty, and (2) operational related problems and errors. The former includes the cosine response, azimuth response, temperature response, spectral selectivity, stability, non-linearity, and dark offset long-wave radiation error. The latter includes the incorrect sensor leveling, shading caused by objects above the horizon, electric fields in the vicinity of cables, mechanical loading of cables (piezoelectric effects), dust, snow, dew, bird -droppings, etc. A variety of useful procedures for post-measurement quality control have been published in the past years *(Geiger et al.,* 2002*; Muneer* and *Fairooz,* 2002;*, Younes et al.,* 2005*; Shi et al.,* 2008; *Moradi,* 2009;*, Tang et al.,* 2010; *Journée* and *Bertrand,* 2011*; Miras-Avalos et al.,* 2012*)*. These methods define an upper and a lower threshold and remove values being outside the acceptance range. So the extremely low or high values are eliminated, however, a value between the thresholds may also be erroneous. The correction of the equipment errors are dealt with in several papers as well *(Stoffel et al,* 2000*; Reda,* 1999;*, Bush et al.,* 2000*; Reda et al.,* 2005*; Lester* and *Myers,* 2006;*, Ji,* 2007*; Marquez et al.,* 2010*).*

Our aim is to develop a method to detect the tilt of the pyranometer without additional measurements. This paper is the first step in the program. One purpose is to quantify the effects of the tilt. The second purpose is to estimate the minimum tilt angle which is detectable from the time series of global irradiance alone.

To help the accurate leveling of the pyranometer, the instrument is supplied with a spirit level. In case of careful mounting, the angle between the plane of the sensor and the horizontal is less than 1° or 0.1°, depending on the type of the pyranometer. In case of tilt, posterior correction is not possible, since neither the direction nor the extent of the tilt are known. Global radiation incident on a tilted surface is essential for different uses of solar energy, so numerous studies focus on its estimation. In such cases, the angle between the absorbing surface and the horizontal is considerably greater than in the case of pyranometer leveled incorrectly. If the latter is tilted over 5°, it is already visible to the naked eye. Therefore, the effects of tilt angle not greater than 10° were investigated.

Bacher et al. (2013) presented a method to correct systematical errors, including tilt error. The sensor output level under clear-sky conditions is estimated directly from the observation by means of quantile regression. This is compared to solar radiation calculated with a clear-sky model. The different types of systematical errors are not examined separately, all of them are corrected in the same step.

Tilt error is particularly common if solar irradiance is measured from ship, buoy, aircraft, or other moving platforms. Correction methods developed for moving platforms is presented in *Long et al.,* (2010) and *Boers et al.,* (1998). The error due to the rocking motion and preferential tilt were calculated using the assumption that the diffuse to direct ratio was constant (*Katsaros* and *DeVault,* 1986). The novelty of the present study is that instead of estimating this ratio, a full-year time series of direct, diffuse, and reflex irradiances are used.

2. Material and methods

The error caused by tilt depends basically on the solar position, direction and magnitude of the tilt, and the diffuse to direct ratio. Carrying out measurements with pyranometers tilted in different directions and to different degrees would be extremely lengthy and costly. Therefore, both the global irradiance incident on horizontal and that incident on inclined surface were calculated from diffuse horizontal irradiance, direct normal irradiance, and ground-reflected irradiance. The data used in this paper were measured in the György Marczell Main Observatory (47°25’45”N and 19°10’56”E) of the Hungarian Meteorological Service from January 1, 2011 to November 27, 2011 and from December 8, 2011 to December 31, 2011. Both the diffuse irradiance and the ground-reflected irradiance were measured with Kipp&Zonen CM11 pyranometers while the direct normal irradiance was measured by Kipp&Zonen CH1 pyrheliometer. All measurements were carried out with precisely leveled instruments with continuous supervision. Sampling took place in every two seconds and their means were recorded on ten minute basis. The solar coordinates were calculated for the middle of the ten-minute intervals by the algorithm proposed by *Reda* and *Andreas* (2004).

In case of horizontal pyranometers, the global irradiance was calculated as the sum of the diffuse sky irradiance and the vertical component of the direct solar irradiance.

$$G_H = B \cdot \sin\varphi + D, \tag{1}$$

where G_H is the global irradiance incident on horizontal surface, B is the direct normal irradiance, D is the diffuse sky irradiance, and φ is the solar elevation.

When the pyranometer is tilted, it loses irradiance from a portion of the sky and instead receives radiation from below the horizon. So, in such a case the global irradiance was calculated by

$$G_t = B_t + D_t + R_t, \tag{2}$$

where G_t is the global irradiance incident on tilted surface, B_t, D_t, and R_t are the components of direct normal, sky diffuse, and ground-reflected irradiances, respectively. These components are perpendicular to the plane of the pyranometer and calculated by

$$B_t = B \cdot [\sin\varphi \cdot \cos s + \cos\varphi \cdot \cos(\alpha - \gamma) \cdot \sin s], \tag{3}$$

$$D_t = D \cdot \frac{1 + \cos s}{2}, \tag{4}$$

$$R_t = R \cdot \frac{1 - \cos s}{2}, \tag{5}$$

where s is the tilt angle that the plane of the pyranometer makes with the horizontal surface (s is always positive and represents the slope in any direction), γ is the azimuth angle of the tilt, where γ=0 for slopes oriented to south and it increases in clockwise direction. α is the solar azimuth and R is the ground-reflected irradiance measured by a horizontal, downward facing pyranometer. Eqs. (3), (4), and (5) are detailed in *Iqbal* (1983). Both the sky diffuse and ground-reflected irradiances were considered as isotropic, since the investigated tilt angle was restricted below 10°. Eqs. (4) and (5) show that if s is small then $D_t \approx D$ and $R_t \approx 0$. Consequently, the direct component is mostly affected by the inclination.

If a measured value or the calculated B_t component was negative it was replaced with zero.

The relative error caused by the tilt was calculated by

$$E = \frac{G_t - G_H}{G_H}, \tag{6}$$

where γ was varied between 0° and 330° by 30°, as well as s was varied between 1° and 10° by 1°. Annual, diurnal, and instantaneous global radiations were calculated for each case. The tilt of the pyranometer was assumed to be constant all year.

Quantities appropriate to detect the tilt of the pyranometer were looked for. Tilt towards the east or west causes diurnal asymmetries in the global radiation. Asymmetry may also be caused by diurnal variation of the atmospheric transmittance. Whereas the direction of the asymmetry caused by the tilt is the same on each day, that caused by the variation of the transmittance varies stochastically. To detect the inclination, those days shall be used when the direct to global ratio is high and the diurnal variation of the atmospheric transmittance is low. Three days where the diurnal global radiation was the highest were selected in each month. Sum of the global radiation measured before and after the solar noon were compared with paired samples t-test. The assumption underlying this test is that the difference of the two variables follows a normal distribution. Normality was tested with Shapiro-Wilk test. Statistical significance level was accepted to be $p<0.05$.

Tilt towards the north or south does not cause diurnal asymmetry. However, it causes distortion in the annual course of global irradiance corresponding to a given solar elevation. The lower the sun, the higher the angle of incidence and the greater the tilt error. At low solar elevation angles, around the winter solstice the sun is in the southern sky, and around the summer solstice it is in the northern sky. Consequently, the global irradiance measured by a pyranometer tilted towards the south is higher in winter and lower is summer compared with those measured by a horizontal pyranometer. This effect decreases with the increase of solar elevation in summer, because the sun moves away from the north. That is why the days around the winter solstice are the most suitable to detect the north-south tilt.

Sixty days before and after the winter solstice were used. These days were randomly divided into two groups of equal size. On the days being in the first and second group, the global irradiance measured with the horizontal and the tilted pyranometer was modeled, respectively. The highest 20 values corresponding to a given solar elevation were selected from both groups. Since these data did not follow the normal distribution, they were compared with the nonparametric Mann-Whitney U test. Statistical significance level was accepted to be $p<0.05$. Global irradiance corresponding to the solar elevation of 8°, 10°, 12°, 14°, 16°, 18°, 20°, and 22° were examined one by one. In order to eliminate the effect of randomness, the days when the pyranometer was assumed to be horizontal and tilted, respectively, were interchanged. The statistical test was repeated in this way. The difference was considered to be due to the tilt only if it was found significant in both cases.

If there is not a sufficient number of clear-sky measurements, the twenty highest values may include partially cloudy measurements too. It may reduce the power of the method. Therefore, the whole procedure was repeated with the highest 10 values corresponding to the given solar elevation.

The measurements were not carried out at the same solar elevation on each day. Therefore, the values of solar elevation expressed in degree were rounded to the nearest whole number. Hence, the global irradiance was corrected with linear interpolation as follows. When the solar elevation was rounded up before the solar noon or rounded down after the solar noon, then

$$G_t^{\text{int}} = G_t + \frac{G_{t+1} - G_t}{\varphi_{t+1} - \varphi_t}\left(\varphi_t^{\text{int}} - \varphi_t\right). \qquad (7)$$

When the solar elevation was rounded down before the solar noon or rounded up after the solar noon, then

$$G_t^{\text{int}} = G_t + \frac{G_{t-1} - G_t}{\varphi_{t-1} - \varphi_t}\left(\varphi_t^{\text{int}} - \varphi_t\right), \qquad (8)$$

where G_t^{int} is the global irradiance corresponding to the rounded solar elevation, G_t, G_{t+1}, and G_{t-1} are the global irradiance corresponding to the actual, 10 minutes later, and 10 minutes earlier measurements, respectively.

3. Results

3.1. Annual total global radiation

The relative error of the annual total global radiation was found to be directly proportional to the tilt angle in case of a fixed tilt direction (*Fig. 1*) in the examined range. It was found to be estimated by

$$E_{year} = s(-0.00054 + 0.0070\cos\gamma), \qquad (9)$$

where E_{year} is the relative error of the annual total global radiation and s is expressed in degree. The goodness of fit of the model was excellent, R^2=0.99. Tilt towards the north and south results in a relative error of –0.0075 and 0.0065 per degree, respectively. The lowest error, 0.0005 per degree, was found in the case of tilt towards the east or west.

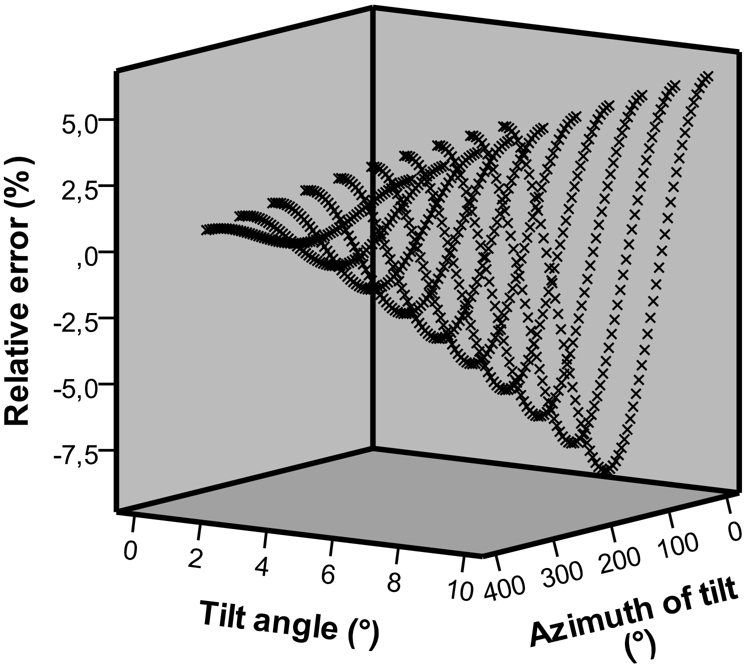

Fig. 1. Relative error of the annual total global radiation in 2011.

3.2. *Daily total global radiation*

The annual course of the error of the daily total global radiation has a typical pattern. The two most different cases are shown in *Fig. 2.* As it was expected, the lowest relative error was found on clear-sky day in winter with pyranometer tilted towards the north. In case of tilt angle of 1°, this error was lower than –4.5% (*Fig. 2a*). The same tilt caused an error about –0.3% around the summer solstice. The errors around zero were observed on the overcast days when the direct normal irradiance was zero or negligible. There were some days on summer, when the error was positive. It occurred on the days, when the direct normal irradiance was high in the morning and in the evening, and the sun was in the northern sky, and it was low around the solar noon when the sun was in the southern sky. The lower envelope of the scatter plot (*Fig. 2a*) shows the relative error corresponding to the clear-sky days.

In case of pyranometer tilted towards the east or west, the relative error was about zero both on the clear-sky and the overcast days (*Fig. 2b*). The relative error with the highest absolute value was found on the days when the morning was overcast and the afternoon was clear-sky or vice versa. On these days the absolute value of the relative error caused by tilt angle of 1°was about 1%, while on clear-sky days it was about 0.1%.

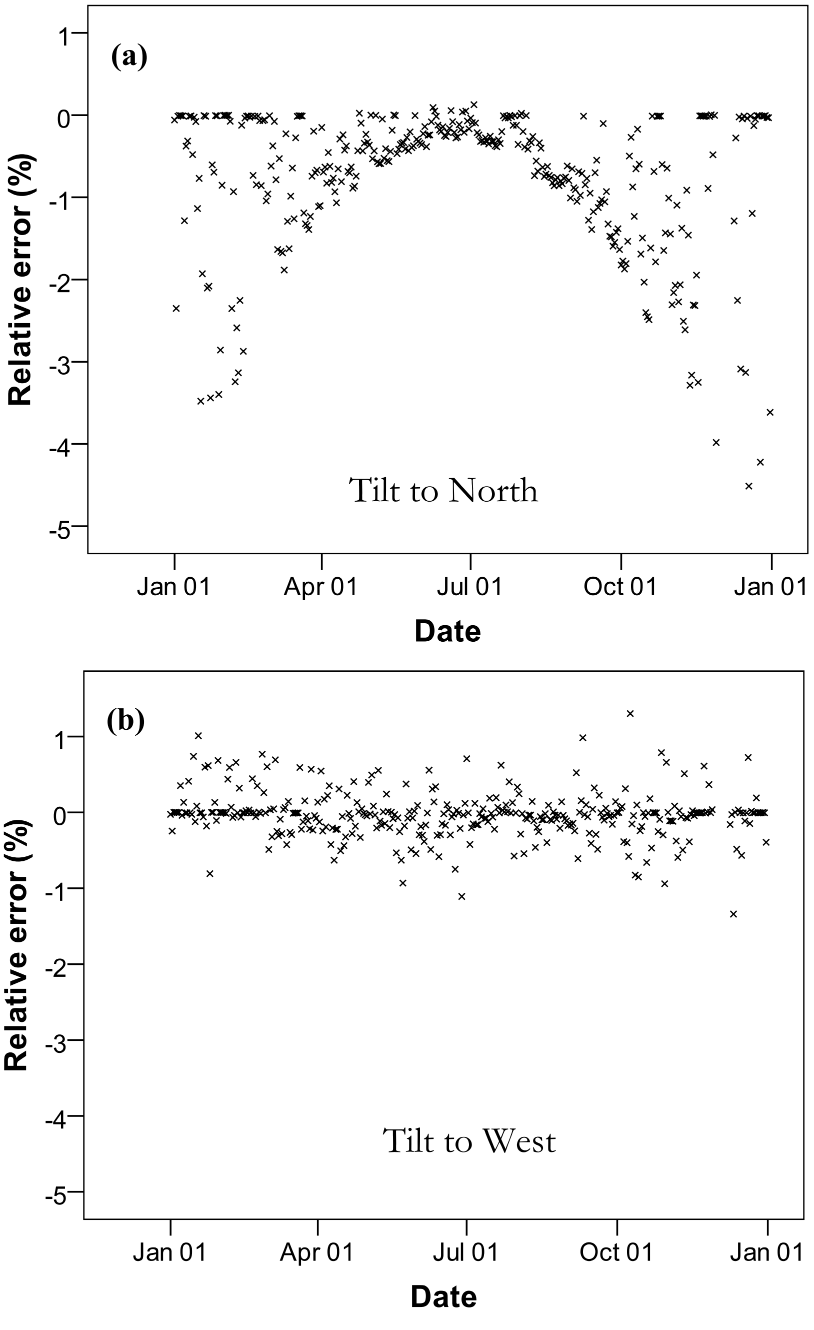

Fig. 2. Relative error of the daily total global radiation for tilt of 1° (a) to the north and (b) to the west, in 2011.

3.3. Global irradiance

The daily course of the relative error of the global irradiance depends strongly on the apparent daily path of the sun. To present the three most different cases, a clear-sky day was selected from around the summer solstice, autumn equinox, and winter solstice (*Fig. 3*). Compared to the annual or daily total, the relative error of the 10-minute average, caused by the same tilt, was notably higher. Around the winter solstice at low solar elevation angles, the error caused by the tilt of 1° to the south exceeds 8%. At solar elevation angles higher than 30°, even if the pyranometer is tilted towards the sun, the error caused by the tilt of 1° is lower than 1% (*Fig. 3a*).

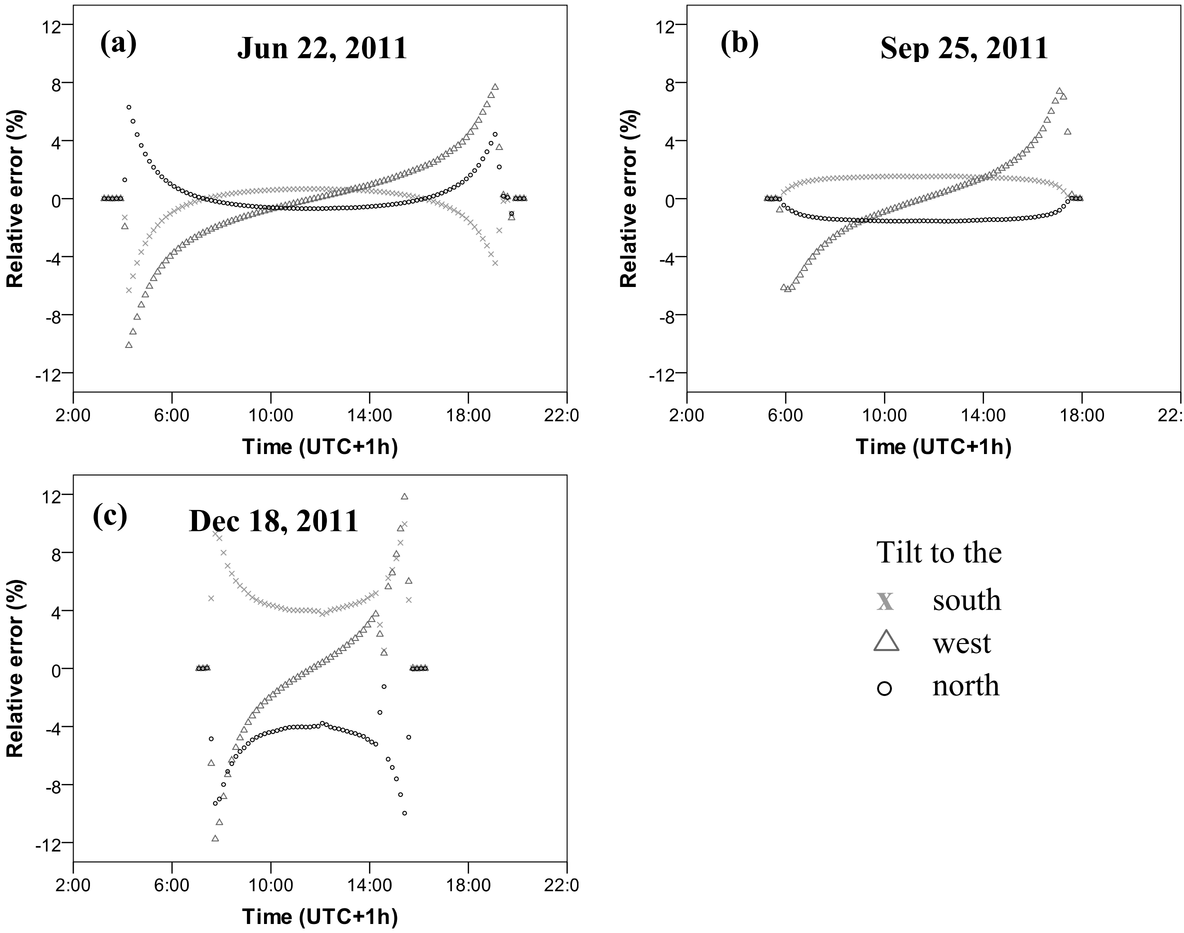

Fig. 3. Relative error of global irradiance, caused by the tilt of 1° around the (a) summer solstice, (b) autumnal equinox, and (c) winter solstice.

3.4. Comparison of the total global radiation measured before and after the solar noon

The tilt angles and the azimuth angles at which the comparison was carried out are shown in *Table 1* and *Table 2*. The difference of the two quantities followed normal distribution in each case. The results, as shown in *Table 1*, indicate that even tilt of 1° resulted in significant asymmetry if the azimuth of the tilt was within the range of 60° to 120° or 240° to 300°. For tilt angle of 1.5°, the asymmetry was significant when the azimuth of the tilt ranged from 30° to 150° or from 210° to 330°. The closer the tilt direction to the north or to the south, the less the asymmetry expected to be significant. If the direction, of the tilt makes an angle of 15° with the south-north direction the tilt angle must be at least 3° to result in significant asymmetry (*Table 2*).

Table 1. Difference of the total global radiation measured before and after the solar noon (kJ/m^2) in case of tilt angles smaller than 2°

tilt angle	**0°**	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**
0.5°	27	92	139	157	139	91	12	–101	–149	–166*	–149	–52
1.0°	18	149	253**	287**	251**	155	11	–166*	–262**	–296**	–262**	–178*
1.5°	19	216*	366**	417**	364**	220**	10	–232**	–374**	–427**	–389**	–244**

(*:p<0.05; **:p<0.01)

Table 2. Difference of the total global radiation measured before and after the solar noon (kJ/m^2) in case of tilt angles of 2° and 3°

tilt angle	**15°**	**165°**	**195°**	**345°**
2°	155	144	–171*	–169*
3°	194*	209**	–238**	–242**

(*:p<0.05; **:p<0.01)

3.5. Global irradiance corresponding to a given solar elevation angle

This quantity has a typical annual course due to the annual variation of the Sun-Earth distance and the atmospheric transmittance. It was modified by the tilt of the pyranometer (*Fig. 4*). The closer the solar azimuth corresponding to the given solar elevation angle to the azimuth of the tilt, the higher the relative error. Consequently, the error with the highest absolute value was found around the winter solstice in case of tilt to north-south (*Fig. 5a*). In case of tilt to east-west, it was found sometimes after the spring equinox as well as sometimes before the autumn equinox (*Fig. 5b*). Obviously, the exact date depends on the solar elevation angle in question.

Global irradiance corresponding to a given solar elevation was expected to show the tilt to the south-north direction. That is why the global irradiance incident on the horizontal and the tilted surface was only compared when the azimuth of the tilt was within the ranges of 0°–30°, 150°–210° and 330–360°. Due to the high number of the comparisons, only the significance of the difference is reported. Let a particular tilt be called detectable at a given solar elevation angle if the difference corresponding to the given solar elevation angle was found statistically significant regardless of which days were considered horizontal. These cases are highlighted with dark background in *Table 3*. The tilt of 1.5° to south was detectable at none of the solar elevation angles. Even the tilt of 2° to south was detectable at only two solar elevation angles. Tilt of 3° within the ±30° range around the south-north direction was already detectable at four different solar elevation angles. These results indicate that tilt to south-north is harder to detect than the tilt to east-west. The smallest detectable tilt angle in each tilt direction is presented in *Fig 6*.

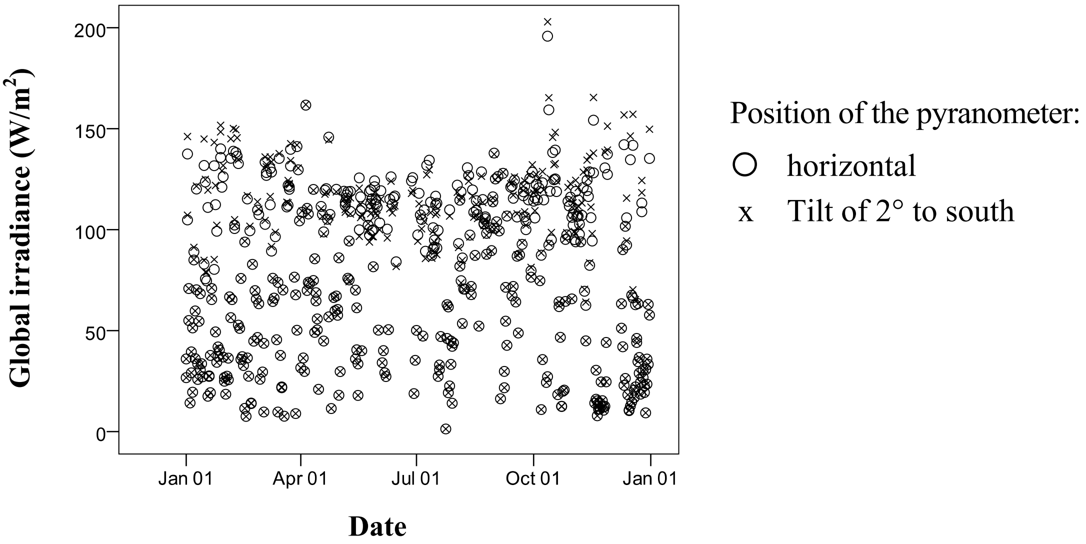

Fig. 4. Global irradiance corresponding to the solar elevation of 10°, in 2011.

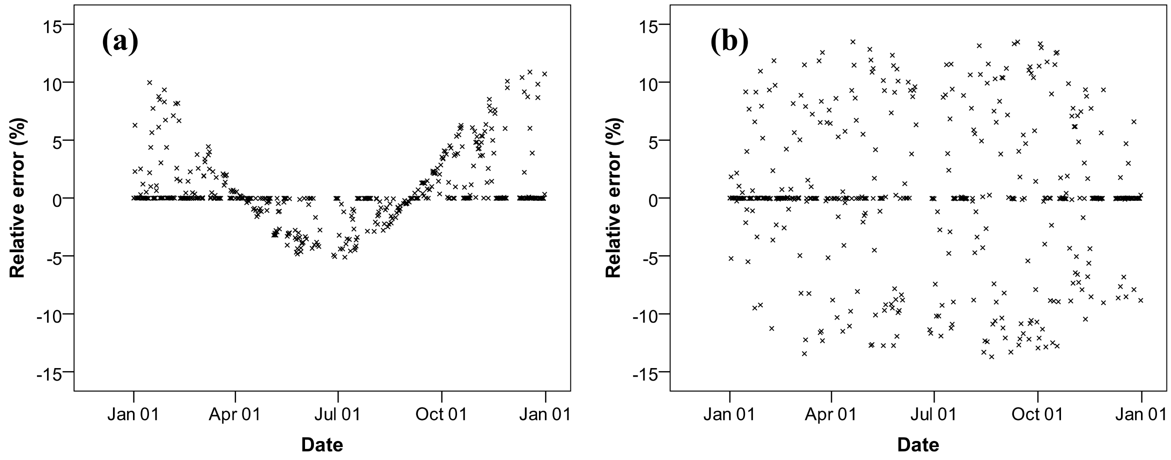

Fig. 5. Relative error of the global irradiance corresponding to the solar elevation of 10° in case of a 2° tilt (a) towards the south and (b) west, in 2011.

Table 3. Significance of the difference of global irradiance incident on the horizontal and the tilted surface. At tilt azimuth of 15°, 165°, 195°, 345°, the test was carried out at tilt angle of only 3°.

tilt angle	**sol. elev.**	**0°**	**15°**	**30°**	**150°**	**165°**	**180°**	**195°**	**210°**	**330°**	**345°**
1,5°	8°	* d		* d	* d		*dd		* d	* d	
	10°	* d		* d	* d		* d		* d	* d	
	12°	* d		* d	* d		* d		* d	* d	
	14°	* d		* d	*		*		*	* d	
	16°	* d		* d	*		*		*	*	
	18°	* d		* d	* d		* d		* d	* d	
	20°	*		* d	* d		* d		* d	* d	
	22°	*		* d	*		*		*	*	
2°	8°	* dd		* d	* d		*dd		*dd	*dd	
	10°	* d		*d	* d		*dd		* d	* d	
	12°	* d		*d	* d		* d		* d	* d	
	14°	* dd		*dd	* d		*dd		*	*dd	
	16°	* d		*d	*		**d		*	* d	
	18°	* d		*d	* d		* d		* d	* d	
	20°	*		*d	* d		* d		* d	*	
	22°	* d		d	*		*		*	*	
3°	8°	* dd	* d	* d	* d	**dd	**dd	**dd	**dd	*dd	*dd
	10°	* dd	*dd	* d	*dd	*dd	*dd	*dd	* d	* d	* d
	12°	* dd	*dd	* d	* d	*dd	* dd	*dd	* d	* d	*dd
	14°	* dd	*dd	*dd	**d	**dd	**dd	**dd	*dd	*dd	*dd
	16°	**dd	**dd	*dd	**d	*dd	**dd	* dd	**dd	*dd	**dd
	18°	**d	**d	**d	**d	**d	**d	**d	**d	**d	**d
	20°	* d	* d	* d	* d	* d	* d	* d	* d	* d	* d
	22°	**dd	** dd	** dd	**	*dd	**dd	** d	** d	**dd	**dd

*: p<0.05 with the 20 highest values; d: p<0.05 with the 10 highest values;
**: p<0.05 with the 20 highest values regardless of which days were considered horizontal; dd: p<0.05 with the 10 highest values regardless of which days were considered horizontal. ** and dd are denoted with grey background.

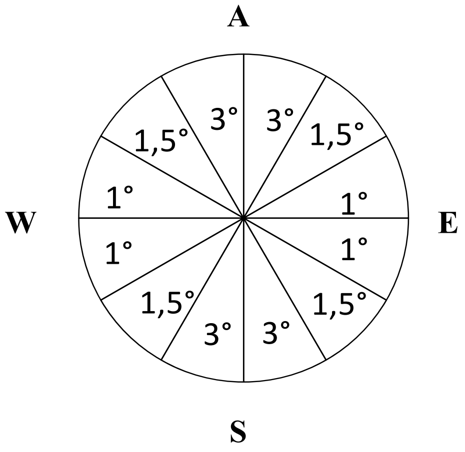

Fig. 6. The smallest detectable tilt angles in each tilt direction. Sectors represent ranges of 30°.

4. Discussion

The uncertainty of the daily total global radiation shall not exceed 2%, 5%, and 10% in cases of the secondary standard, first class, and second class pyranometers, respectively, according to the ISO standard (*ISO,* 1990). Our findings show that even a tilt of 1° can cause greater variation in the daily total values than the inherent uncertainty of a secondary standard pyranometer. The effect of a tilt of 2.5° can exceed the inherent uncertainty of even a second class pyranometer. It indicates that developing a method that assesses the data series of global irradiance with respect to the leveling would be very useful.

The aim of this paper was to find quantities that are calculated only from global radiation and suitable to assess the leveling of the pyranometer. The difference of the total global radiation measured before and after the solar noon has been shown to be very sensitive to the tilt to east-west. As small as tilt of 1° to east-west can be detected. The method is adaptable to any latitude, but the value of 1° refers only to the latitude of around 47°N. The selection of clear-sky days is a key element in the process. Refinement of the selection method is expected to shorten the length of the measurements necessary for the detection of a tilt.

The highest error in both the annual and the daily total global radiation is caused by the tilt to south-north, yet it is the most difficult to detect. Three degrees as the smallest detectable tilt seems like a lot. Assessing the global irradiance corresponding to a given solar elevation angle requires reference data that is considered as horizontal global irradiance. In the current study it was calculated from measurements of a few days. Future work will involve a multi-annual high accuracy measurement series. It will give the opportunity to analyze the annual course of the solar irradiance corresponding to a given solar elevation angle rather than the 10 or 20 highest values measured around the winter solstice. It is expected to allow smaller tilts to become detectable.

Overall, the power of the method using the twenty highest values is greater than that using the ten highest values. However, half of the cases showed by the twenty highest values were not showed by the ten highest values. It proves that both procedures were reasonable to use. The strength of investigating the solar irradiance corresponding to a given solar elevation angle is that it does not require clear-sky days, only shorter clear-sky periods of time. Its drawback is that the power to detect the tilt is not the same in each part of the year. Investigating the morning and afternoon solar irradiances separately can contribute to the detection of the tilt to east-west.

It has been shown that there is a good chance to detect a tilt as small as 1° to east-west, and we hope that as small as 2° will be detectable in any other directions by the refinement of the method. Future works will carry out measurements with tilted pyranometers to verify these findings.

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