CORRELATIONS FOR A MEDITERRANEAN CLOUD COVER MODEL

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ABSTRACT

Relationship between sky cloud cover and solar radiation is presented in order to give informations about solar radiation attitude varying with cloudiness, useful to optimize solar devices. Meteorological and solar data were recorded by Environmental Technical Physic Laboratories, at University of Rome Tor Vergata from April 15th 2009 to May 31th 2010. Those data were associated to hourly cloud observation recorded in the same site in order to calculate the ratio of global radiation at total cloud amount (N okta) G(N) to global radiation at cloudless sky G(0). The comparison between Kimura and Stephenson (1967) work, and Kasten and Czeplak (1980) parameterization were evaluated to characterize Tor Vergata's site. The model of clear sky condition proposed by Duffie and Beckman (1980), Spena (1996), and Duchon and O'Malley (1998) were used to determinate the transmission coefficient for global radiation at cloudless sky. Monthly and seasonal formulas has been developed using power and polynomial functions: correlation coefficients were shown for each trend. The correlation coefficient R^2=0,9 showed that the best approximation is given by polynomial function. The results has indicated that the curve shape of G(N)/G(0) ratio has a maximum for N=3, almost half cloud cover condition, for Rome's latitude. The meaning for this behavior is that global radiation grow with scattered radiation growth. This correlation represent a new element useful to characterize Rome's site and to compare radiation trend with others of different latitudes site, and climate.

Keywords: Cloud Cover, global radiation, scattered radiation, latitudes.

1. INTRODUCTION

An important issue for the prediction of actual solar energy available at ground is to correlate the amount of radiation to the simultaneous cloudiness of the sky. This topic is relevant because of the strong bond between cloud cover and the fraction of solar radiation convertible in electric or thermal power.

Clouds play a key role in the radiative energy budget of the earth and in transfer of energy between the surface and the atmosphere. For this reason, a model that includes clouds variety and variability is important to produce real assessment of energy available for solar devices. In fact an overestimation of solar power during the circuit design can generate electrical losses in particular while the inverter transform alternating-current into direct-current.

However the dependence of radiation fluxes on cloud amount and type has been parameterized by some authors in the past, in particular for buildings engineering project.

In 1969 Kimura and Stephenson [1] proposed an estimating method to value solar intensities for the design of air-conditioning building system. Their main purpose was to determine the relationship between solar intensity on a horizontal surface and hourly observation of cloud cover for Ottawa, Ontario (45° 27' N, 75° 37' W). Their cloud cover observations have been made every hour (Standard Time) by experienced observers who estimate the amount of cloud on a scale of 0 to 10. The analysis were made in 1967, for March, June, September and December months to see if there was a seasonal variation in the relationship between the ratio of global solar radiation for a specific value of cloud cover and global solar radiation for clear sky condition (I_{rec}/I_{TH}), and the cloud cover (CC). For this relationship they proposed a second order polynomial function.

Some years later Kasten and Czeplak [2] presented a work based on the records of hourly sums of solar and terrestrial downward and upward radiation flux densities that has been evaluated with regard to simultaneous hourly cloud observations. Their investigation was intended to give additional information on the correlation between solar radiation and sky cloudiness, using continuous measurements of solar data, made in Hamburg (53° 33'N, 9° 58'E) from 1964 to 1973. The authors proposed seasonal and annual trend for the ratio of global radiation at total cloud amount N okta

(G(N)), to global radiation at cloudless sky (G(0)); they carried out a power function wherein coefficients are site dependent.
Both works were based on the estimation of global solar radiation at ground in cloudless sky condition. In the present work the clear-sky irradiance models for standardizing irradiance measurements were investigated to evaluate which model gives the best approximation for the latitude of Rome using meteorological and solar data recorded by the station of FTA Laboratories of the University of Rome Tor Vergata (41° 51' 28.17'' N, 12° 37'23.9'' E), since April 15th 2009. Those data were associated to hourly cloud human observations recorded in the same site, in order to calculate the ratio of global radiation at the actual total cloud amount N (okta), G(N), over the global radiation at cloudless sky, G(0). The purpose was to find out a model in overcast sky condition for Rome, and verified if it is in agreement with the previous models.

2. INSTRUMENTS AND EXPERIMENTAL PROCEDURE

FTA Laboratories of the University of Rome Tor Vergata include a meteorological-solar station, located on the rooftop of the building hosting the Department of Enterprise Engineering. Solar instruments consist of one Kipp&Zonen 2AP sun tracker that supports a shaded ventilated pyranometer (CM 21) for diffuse radiation measurements and a pyrheliometer (CH 1)for direct radiation measurements; global and reflected fluxes were measured by two pyranometers (Kipp and Zonen CM 21) mounted on a dedicated plate [6].
Meteorological instruments consist of one MP101A barometer for pressure measurements; one thermoigrometer and relative humidity (RH) measurements. A SKPS810/I barometric pressure sensor was used to measure the local pressure and one ARG100/LX pluviometer to gather and measure the amount of liquid precipitation. Data are collected by a Campbell Scientific CR1000 data logger via RS485. All the facilities are connected to the web and data are downloaded every 30 minutes in a database of a dedicated server.
In the present work only hourly data were use according to clouds observations, performed by human observer in the same site. Meteorological data were used to calculate global radiation at clear sky condition, following two different methods. Duchon and O'Malley [4] model used the formula:

$$G(0)= I_0 * \cos\theta * \tau_R * \tau_g * \tau_w * \tau_a \qquad (1)$$

where I_0 is the irradiance at the top of the atmosphere normal to the solar beam; θ_z is the solar zenith angle; and the τ_i's are transmission coefficients for Rayleigh scattering (*R*): permanent gas absorption (*g*), water vapor absorption (*w*), and scattering by aerosols (*a*). A simplified approach proposed and validated by Spena [4], was investigated and shown in Eq. (2):

$$G(0)= I_0 * \cos\theta * \tau \qquad (2)$$

where τ is total atmospheric transmission coefficient, as function of the air mass.
Duchon and O'Malley model was developed using a constant value of I_0 of about 1370 W/m^2, instead of Spena [5] model where it was calculated by:

$$I_0 = C * \left\{1+0.033*\cos\left[(i-3) * \frac{360}{365.25}\right]\right\} \qquad (3)$$

Where *i* is a progressive day counter.
As results Spena's formula give the best approximation and this approach was used for the next computation.

Hourly cloud observations were performed from April 15th 2009 to May 31th 2010 using the World Meteorological Organization cloud-type-code at the beginning of each hour on weekdays during most daylight hours. Total cloud amount (N) was evaluated in okta.

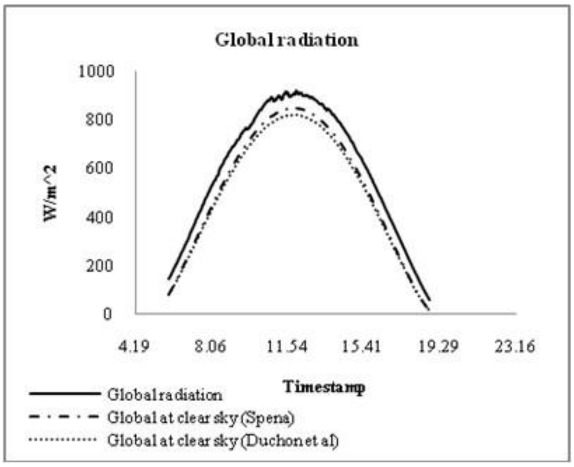

Figure 1. Comparison between both models to evaluate the best behavior for Rome latitude, during a completely cloudless day.

The G(N)/G(0) ratio was calculated for each hour where N was estimated and all this values were analyzed in monthly, seasonal and globally range. In the same way the D(N)/G(N) ratio was carried out. For both ratios power and polynomial fitting were achieved, to make a comparison with the previous described models.

2.1 Global radiation data analysis

As shown in Figure 2, total mean data set trough power and polynomial functions were investigated and their both correlation coefficients were compared. Standard deviation of the recorded data was also shown for each value of N. Therefore, could be evident the higher value of the correlation coefficient related to power function than the polynomial one, but it does not take in account the high value of G(N)/G(0) between 1 otka and 3 okta. This behavior is interesting because give additional information about the bond between global and scattered radiation, successively discussed. The comparison with Kasten and Czeplak power function for the ratio G(N)/G(0) was proposed in Figure 2 with polynomial trend and power trend that best approximates Tor Vergata's data. Polynomial trend has a maximum value (1.13) for N=3 (partially overcast) and decrease till 0,44 for N=8 (overcast condition). Power fit starts from 1.1 at N=0 and decrease till 0.34 for N=8.

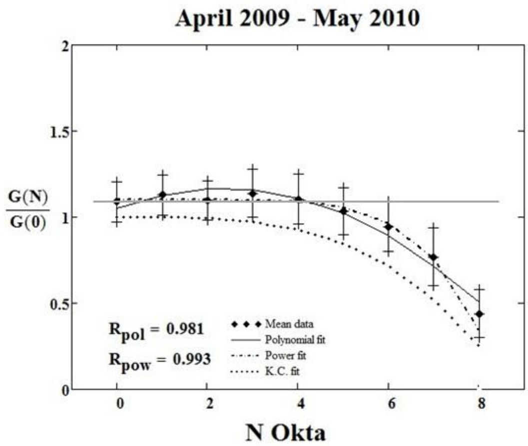

Figure 2. Data trend of global radiation are presented with their standard deviation. Polynomial and power function related to mean data plot are presented. In addition Kasten and Czeplak fit is shown.

Otherwise the function's trend of Kasten and Czeplak has a maximum value (1) for N=0 (clear sky condition) and decrease till 0,25 for N=8 (overcast condition).

The equations produced through a Mathcad 14.0 regression estimate using the data collected in Rome are shown below:

$$\frac{G(N)}{G(0)} = 1.049 + 0.098 * N - 0.021 * N^2 \quad (4)$$

$$\frac{G(N)}{G(0)} = 1.1 - 0,757 * \left(\frac{N}{8}\right)^6 \quad (5)$$

$$\frac{G(N)}{G(0)} = 1 - 0,75 * \left(\frac{N}{8}\right)^{3,4} \quad (6)$$

Equation (4) is the second order polynomial function proposed by the author; equation (5) is a function in which coefficient were generated by power regression of all the data collected in Rome, as proposed by Kasten and Czeplack (6) but in which coefficient has been calculated in Hamburg. The high value of the exponential coefficient give a wider flat trend and a low decrease that starts at 4 okta instead of 2 okta as Kasten's trend. This behavior is known in literature, but often not so extensively with respect to N values: when compared with the classical curves from Kasten and Czeplak [2], the results obtained for Rome show as a matter of evidence a wider platform of high values of G(N)/G(0). For a complete comparison between different climates we propose also another Italian work carried out in Bologna (44°29′N 11°20′E, norther Italy) by Nardino and Georgiadis [8].

Table 1. Coefficients of the power function proposed by Kasten and Czeplak, for G(N)/G(0) ratio calculated in three different sites.

G(N)/G(0)	Hamburg	Rome	Bologna
a	-0,75	-0,757	-0,99±0,06
b	3,4	6	1,3±0,1

2.2 Diffuse radiation data analysis

The diffuse radiation rate was also investigated. In this case are represented polynomial and power fit in order to make a complete comparison with Kasten and Czeplak work. Correlation coefficient shows that the fit that best approximate Tor Vergata's data is polynomial. The comparison with Kasten and Czeplak trend shows, moreover, the overestimation that their formula performs in Mediterranean climate. The equation of the D(N)/G(N) ratio for Hamburg and Rome are proposed below:

$$\frac{D(N)}{G(N)} = 1.049 + 0.098 * N - 0.021 * N^2 \quad (7)$$

$$\frac{D(N)}{G(N)} = 0,3 + 0,15 * \left(\frac{N}{8}\right)^2 \quad (8)$$

$$\frac{D(N)}{G(N)} = 0,7 + 0,65 * \left(\frac{N}{8}\right)^2 \quad (9)$$

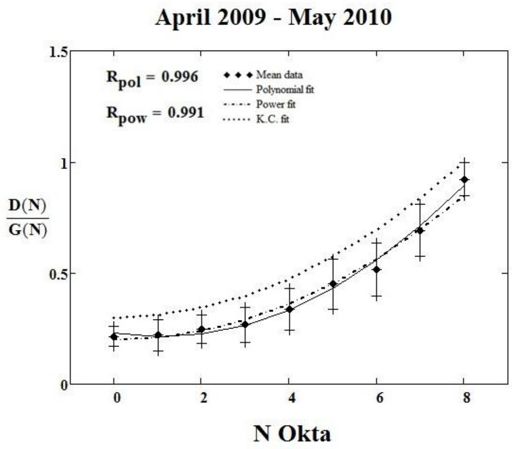

Figure 3. Data trend of diffuse radiation are presented with their standard deviation. Polynomial and power function related to mean data plot are presented. In addition Kasten and Czeplak fit is shown.

Again the best approximation is given for polynomial fit. Two consideration were necessaries: during summer time D(N)/G(N) decreases for $1 \leq N \leq 3$ because direct component is strongest than the scattered one. During coldest season the decrease for $1 \leq N \leq 3$ is lower because the scattered is strongest than the direct component. The comparison with Kasten and Czeplak trend shows, moreover, the overestimation that their formula performs in Mediterranean climate.

Is important to put in evidence that this correlation does not include any model, as happen for global radiation: both D(N) and G(N) are measured value, so their trend is not affected by model's errors.

2.3 Applications

An useful application of this graphs is that the knowledge of one parameter (as example D(N)/G(N) ratio Figure 3) could be used to find the corresponding N value and then find the provisional G(N)/G(0) ratio using the other graph (Figure 2), as shown in Figure 4.

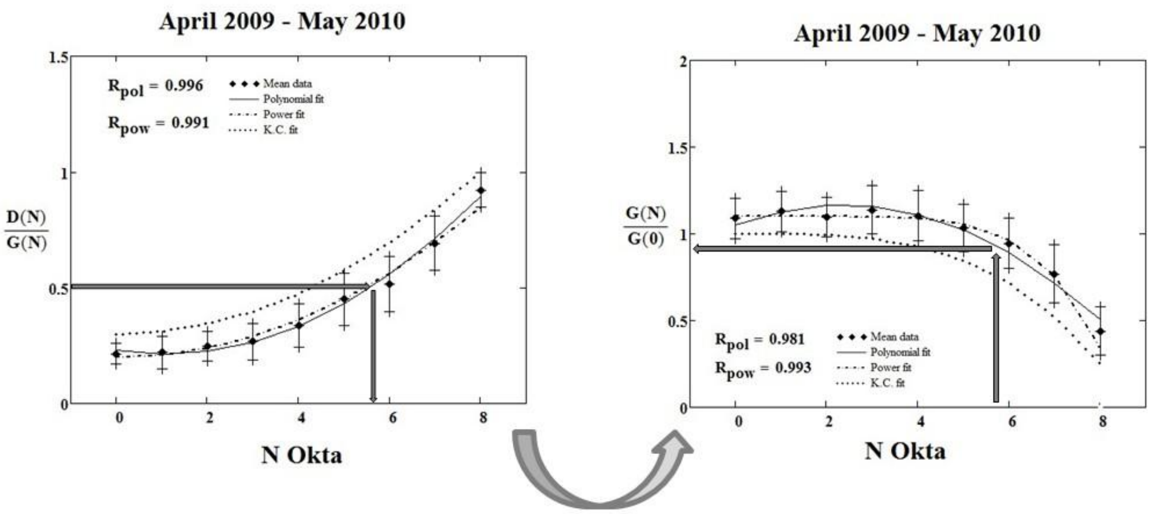

Figure 4. Example of correlation's application.

The same procedure could be done by inverting the parameter's choice to evaluate the scattered rate.

For a complete comparison between different climates, the work carried out in Bologna by Nardino and Georgiadis [8] is again considered:

Table 2. Coefficients of the power function proposed by Kasten and Czeplak, for D(N)/G(N) ratio calculated in two different sites.

D(N)/G(N)	Hamburg	Rome
a	0,3	0,15
b	0,7	0,65

A possible explanation of this fact is attempted in the paper, by means of the role played by the simultaneous effects of either water vapor content of the air (high), and wind speed (low), both at the ground level.

2.4 Seasonal data trends

Seasonal data were investigated to give additional information about the influence of clime variability during the year. Little differences in seasonal data trends help to understand why the authors chose the polynomial function as the best approximation for Rome's latitude.

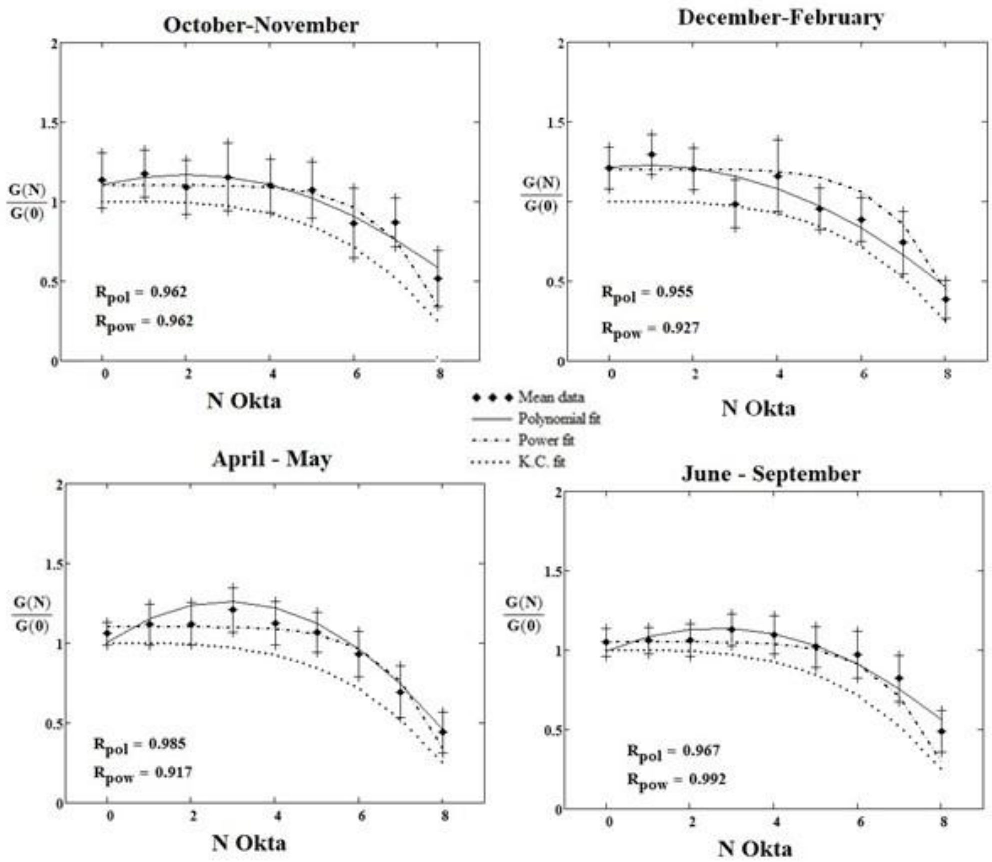

Figure 5. Data trend of global radiation from April 15th 2009 to May 31th 2010 are presented with their standard deviation. Polynomial and power function related to mean data plot are presented. In addition Kasten and Czeplak fit is shown.

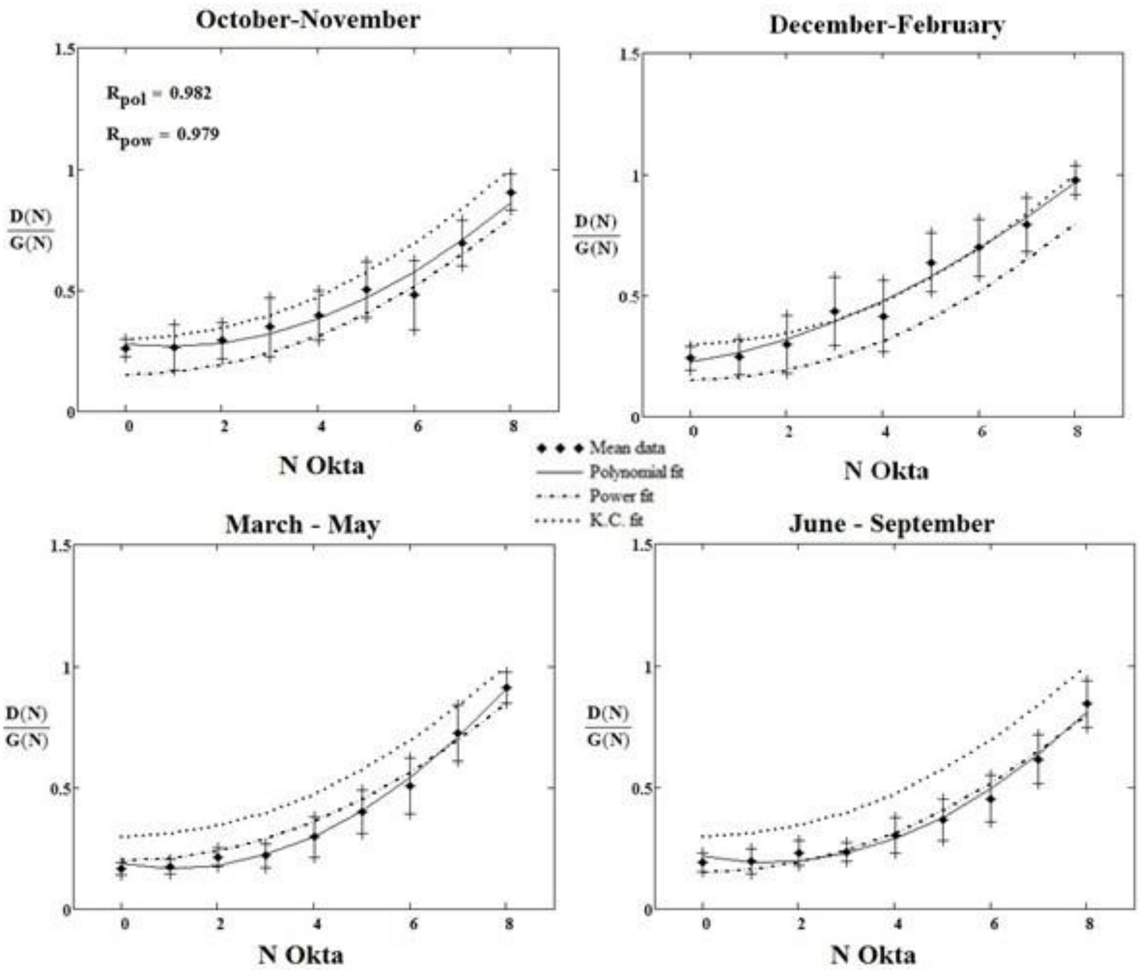

Figure 6. Data trend of diffuse radiation from April 15th 2009 to May 31th 2010 are presented with their standard deviation. Polynomial and power function related to mean data plot are presented. In addition Kasten and Czeplak fit is shown.

As shown in Figure 5 spring time gives a pronounced polynomial fitting, while winter time is more close to power fitting. It probably depends on the different kind of cloud that are prevailing in every seasons. In fact is more presumable that during spring cumulus clouds occurs, while during winter stratus clouds are more frequent. Usually cumulus clouds does not cover the whole sky and scatter radiation in all directions. Otherwise stratus often cover uniformly the whole sky, reducing reflection and scattering phenomenon.
Equation for every season of polynomial fit are presented in Table 3 and in Table 4:

$$\frac{G(N)}{G(0)} = A + B*N + C*N^2$$

Table 3. Seasonal coefficient of polynomial fit of G(N)/G(0) ratio.

Season	Coefficient A	Coefficient B	Coefficient C
Autumn	1.108	0.06	-0.016
Winter	1.213	0.028	-0.015
Spring	1.008	0.176	-0.031
Summer	0.997	0.106	-0.02

$$\frac{D(N)}{G(N)} = D + E*N + F*N^2$$

Table 4. Seasonal coefficient of polynomial fit of D(N)/G(N) ratio.

Season	**Coefficient D**	**Coefficient E**	**Coefficient F**
Autumn	0.276	-0.02	0.012
Winter	0.225	0.033	0.0074
Spring	0.186	-0.034	0.015
Summer	0.216	-0.038	0.014

Winter period does not show the decrease of diffuse rate for 1 okta as other months. As already said before it probably depend on the quantity of clouds observations achieved in that period.

3. RESULTS AND DISCUSSIONS

This work gives information about the relationship between solar radiation and clouds in Mediterranean climate (between the latitudes of 30° and 45°) which is characterized by warm to hot, dry summers and mild, wet winters with moderate temperatures and changeable, rainy weather.

The second order polynomial correlations proposed in this work were representative of Mediterranean climate and high value of standard deviation for winter period are probably dependent on the nature of the observations, made empirically out by the authors, and because of the short time of observation in itself (little bit more than 1 year at the time of this paper).

Clouds observation still on going to achieve appropriate quantity of data in order to refine on the correlation here proposed.

Future develop will enclose the analysis of all others solar radiation component, direct and reflected. Correlation results are going to be usefully enriched with more cloud cover and solar radiation experimental data, and with radiometric spectrum analyses.

4. NOMENCLATURE

Symbol	Quantity	SI Unit
N	Cloud cover	okta
G(0)	Global radiation in clear sky condition	W/m^2
G(N)	Global radiation calculated for a given N	W/m^2
D(N)	Scattered radiation calculated for a given N	W/m^2
I_0	Irradiance at the top of the atmosphere	W/m^2
T	Transmission coefficient	non dimensional
Θ	zenith angle	rad
R	Correlation coefficient	non dimensional

5. REFERENCES

[1] Kimura K., Stephenson D.G., 1969, *Solar radiation on cloudy days*, ASHRAE Transaction, Vol. 75, 227-234.

[2] Kasten F., Czeplak G., 1980, Solar and Terrestrial Radiation dependent on the Amount and Type of Cloud, Solar Energy, Vol. 24, 177-189.

[3] Duffie, J. A., Beckman W. A., 1980, *Solar Engineering of Thermal Processes*, John Wiley, New York, pp. 1-109.

[4] Duchon C.E., O'Malley M.S., 1998, *Estimating Cloud Type from Pyranometer Observations*, Journal of Applied Meteorology, Vol. 38, 132-141.

[5] Spena A., 1996, *Fondamenti di Energetica*, Cedam, Vol. I, Padova, pp 49-119.

[6] A. Spena, C. Cornaro, G. Intreccialagli, D. Chianese, *Data Validation and Uncertainty Evaluation of the ESTeR Outdoor Facility for Testing of Photovoltaic Modules*, 12th EU PV SEC, Hamburg, September 2009.

[7] A. Spena, S. Bartocci, C. Cornaro, G. D'Angiolini, C. Di Tivoli, C. Strati, *Advanced results of modelling, experiments, and innovative solar energy components conception at FTA laboratories*, ASME-ATI-UIT 2010 Conference on Thermal and Environmental Issues in Energy Systems, 16-19 May, 2010, Sorrento, Italy.

[8] Nardino M., 2003: *Effetti della copertura nuvolosa nella ripartizione dell'energia solare: studio del microclima locale per scopi Agrometeorologici*, PhD Thesis, Facoltà di Agraria, Università di Sassari.