地理信息科学
Geographic Information Sciences
第一卷第一期 一九九四年十二月
Vol. 1, No. 1, December 1994

A Hybrid Geometric Optical and Radiative Transfer Approach for Modeling Pyranometer Measurements Under a Jack Pine Forest

Li Xiaowen†§, Curtis Woodcock§, Robert Davis¶

† Institute of Remote Sensing Application, CAS, Beijing 100101
§ Center for Remote Sensing, Boston University, U.S.A.
¶ Cold Region Lab. of U.S. Army Engineering Corp.

Abstract

Pyranometer measurement under old jack pine forest in the BOREAS experiment is analyzed through our new hybrid model. This application is an example to illustrate why we need hybrid model and how it works. The work presented here is a part of efforts for a GIS-based distributed hydrology-vegetation interaction model of drainage basin.

I. WHY HYBRID MODEL?

At the scale of a small volume in which leaves can be regarded as being homogeneously distributed, some recently developed RT (Radiative Transfer) theories are the best to model the phenomenon by using descriptors such as leaf scattering characteristics, leaf size, volume density of leaf area, etc. However, at the scale of a stand, GO (Geometric Optical) models catch the basic features of discontinuous canopies under sunlight, i.e., foliage are clustered into crowns and crowns cast shadows. Hence in practice up to now, simple pure GO models are the only models applicable to natural discrete crown canopies. However, pure GO models require signatures of sunlit and shaded crown surface and background as known parameters under given situation or to be determined in situ. This has been proven a major restricting factor in applications and model inversion. And it is also a drawback that these signatures have not been related to leaf descriptors, wavelength, and sky conditions.

We are now in process to develop a hybrid GO-RT approach to model the radiation climate in a discontinuous canopy (partially supported by Chinese National Natural Science Foundation 49331020). A key element in this approach is gap probability model which we developed earlier (Li and Strahler, [1]). Gap probability, on one hand, can be obtained through pure G-O model which reflects the structure at the stand scale. On the other hand, gap probability within crown is closely related to the process that radiation collides and is scattered by foliage. Hence it becomes a natural link between two kinds of models best at the corresponding scales.

Vertical distribution of sunlit crown surface is first obtained by GO method. Then the within-crown path length distributions and associated single scattering source distributions at different heights are obtained. Then successive order scattering are handled with a formulation more similar to radiative theories, with considering the "Openness Distribution" of discontinuous canopies.

Details of the model formulation and initial validation using field data acquired in Howland, Maine, USA, have been published recently (Li et al. [2], [3], [4]). While more validations are still needed, the BOREAS experiment provides some opportunity of model applications.

II. SOJP TEST SITE OF BOREAS AND PYRANOMETER MEASUREMENTS THERE

BOREAS (Boreal Ecosystem-Atmosphere Study) is a cooperative field and analysis study to improve our understanding of the interactions between the boreal forest biome and atmosphere, involving scientists from Canada, USA, and other countries. The study is centered on two 20x20 km sites within the boreal forest region of Canada, located near the northern and southern limits of the biome, being called Northern and Southern Study Areas respectively.

We acquired three days' pyranometer measurements in the BOREAS winter campaign 1994 at an old jack-pine forest stand (SOJP) of the SSA.

The SOJP site is also known as "Tower Flux Site", located at 53.916 N, -104.69 W. Nine Eppley pyranometers, Model PSP (0.35 - 2.5 μ), were placed randomly on snow surface beneath canopy. Positions were determined by drawing a random number for the azimuth and a random number for paces away from the Campbell data system. Radiation observations were taken at 10 second intervals, averaging over a period of 10 minutes. The radiometers were specially calibrated at Eppley Laboratory down to -50^0C.

Measurements were made from the Julian day (DY) 37 at 1520 to DY 40 at 1630. All measurements lied in a circle with radius 35 m, the center of which was located 60 ESE of flux tower. Pyranometers were shuffled randomly once, on DY 39 over period 1110 to 1130.

The total measurements of the 9 pyranometers in all three days are shown in Fig. 1, the X-axis is normalized to local solar time, i.e., 0.5 at the local noon, the Y-axis is of unit W/m^2.

III. EXPLANATION OF MEASUREMENTS BY HYBRID MODEL

The figure 1 looks quite interesting and typical in measurements for snow melt forecasting, but there has not been a good model to explain such data yet.

The easiest part is the spikes which are apparently the effect of sunlight directly shining on the pyranometer through gaps between the crowns, when sun crossed the sky, pyranometers got direct sunshine and shadows alternatively. But what is the baseline of these spikes?

By our hybrid model, the measured radiance is the sum of 3 components: 1) direct sunshine $I_0(\theta)$; 2) diffuse skylight J_{sky} through the gaps in all hemispherical directions (Openness); 3) multiple scattering between ground and canopies, excited by $I_0(\theta)$ and J_{sky}. That is,

$$y_i(t) = i_0(\theta) + j_0(t) + J_m(t), \qquad (1)$$

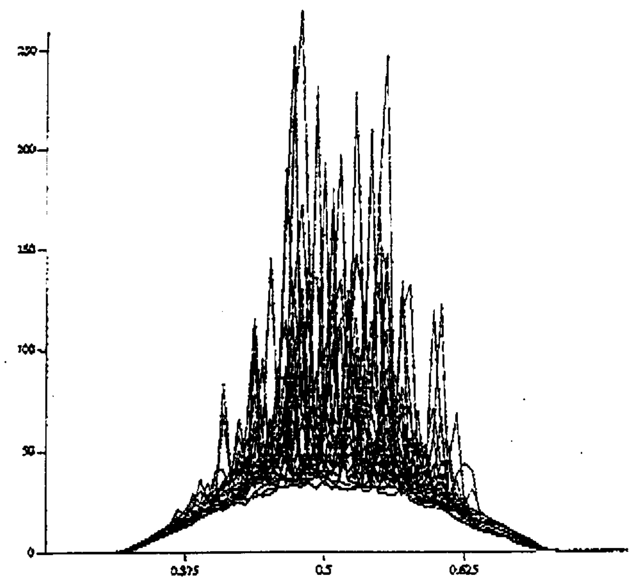

Fig. 1. Three day measurements of 9 pyranometers at SOJP, all normalized to local solar time, i.e., 0.5 at the noon.

where $y_i(t)$ is the measurement of individual pyranometer; $i_0(\theta)$ is the contribution from direct sunshine on pyranometer, which is determined by sun position, the random location of the pyranometer and the gaps above it, and therefore a random variable; $j_0(t)$ is contribution from direct skylight on pyranometer, and thus an average of random gaps over the hemisphere; a variable less random; and $J_m(t)$ is the contribution from multiple scattering; and therefore the least random among the three. The solar zenith angle θ is no doubt a function of time t, but we use it as variable for $i_0(\theta)$ to indicate that it is an immediate result of sun direction instead of diffused skylight or multiple scattering. The average of $i_0(\theta)$ is:

$$I_0(\theta) = I_{sun}(\theta)[P(n=0|\theta) + P_{gap}(n>0|\theta)], \qquad (2)$$

where $P(n=0|\theta)$ is intercrown gap probability and $P_{gap}(n>0|\theta)$ is within-crown gap probability.

$$P(n=0|\theta) = e^{-\lambda\Gamma_\theta}; \qquad (3)$$

and

$P_{gap}(n>0|\theta)$

$$= (1 - P(n=0|\theta))e^{-PLAI(\theta)}; \quad (4)$$

where λ is stem density, $PLAI(\theta)$ is the mean LAI along the projection θ within crown-shaded area, Γ_θ is the shadow area of an average crown on the ground. Since in DY 38-40 at the SOJP there was snow pack on crowns, $P_{gap}(n>0|\theta)$ can be ignored in eq. (2), though we need it later for determining the multiple scattering in canopies. The mean of $j_0(t)$ is:

$$J_0(t) = J_{sky}(t)K_{open}, \quad (5)$$

where K_{open} is the mean value on the ground, i.e., $h=0$ in general case $K_{open}(h)$ in [2].

The contribution from multiple scattering is excited by $I_{sun}(\theta)$ and $J_{sky}(t)$ and is therefore a function of $I_0(\theta)$, $J_0(t)$ and the vertical distribution of the single scattering source. Since snow packs on the crowns made crowns in fact opaque, we can simplify the problem by ignoring the vertical distribution of the single scattering source, regarding multiple scattering as being excited by $I_0(\theta)$ and $J_0(t)$ only.

$$J_m(t) = (I_0(\theta) + J_0(t)) \sum_{k=1}^{\infty}[\omega^2(1-K_{open})]^k$$
$$= \beta(I_0(\theta) + J_0(t)) \quad (6)$$

where ω is the mean albedo of canopies without between-crown gaps. If we ignore the reflectance of leaves comparing to snow, $\omega = \tau\rho$, i. e., product of mean within-crown P_{gap} over hemisphere and snow reflectance, and

$$\beta = \frac{\omega^2(1-K_{open})}{1-\omega^2(1-K_{open})}. \quad (7)$$

Then eq. 1 can be rewritten as:

$$y_i(t) = i_0(\theta) + \alpha J_0(t)$$
$$+\beta[I_0(\theta) + J_0(t)]. \quad (8)$$

Note that $i_0(\theta)$ changes approximately as $\cos\theta$ and subject to random gaps for $I_{sun}(\theta)$ to reach pyranometer, thus are the spikes in the Fig. 1. $J_{sky}(t)$ changes slowly and if always isotropic, the gap relation to the pyranometer won't change with time. Therefore though $j_0(t)$ is still random, depending on the location, it can be replaced by $\alpha J_0(t)$, where α is a factor of random location. the second and third terms altogether formed the slow changing lower boundary (i.e., base-line) in the Fig.1. Especially, when the sun angles are very low, the pyranometer measurements are resulted merely from $J_{sky}(t)$.

$$y_i(t) = (\alpha + \beta)J_0(t). \quad (9)$$

Ideally with measured $J_{sky}(t)$ and calculated $J_0(t)$, we can estimate $\alpha+\beta$ from these periods, and therefore $(\alpha+\beta)J_0(t)$ for all t, if neither α nor β changes with time. However, since the pyranometer were shuffled at 11:10am to 11:30am on the day 39, a sudden change of α may or may not occur. Fig. 2 shows the base-line of the pyranometer 3 has a sudden drop around the time of shuffling, while Fig. 3 shows the base-line of the pyranometer 1 quite stable.

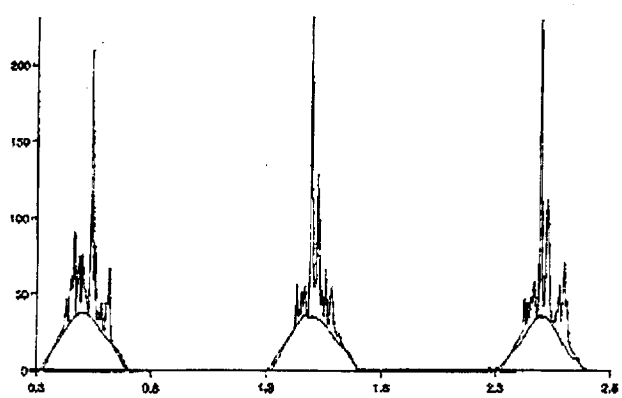

Fig. 2. Three day measurements of the pyranometer 3 in time sequence, and the fitted base-line (lower one). Random shuffling on DY 39 apparently changed value of α.

Because we have no separate measurements for $I_{sun}(\theta)$ and $J_{sky}(t)$ but total irradiance (Fig. 4) measured on the flux tower. We have to use 6S (Vermote et al. [5]) to calculated the I_{sun} and J_{sky}, a midlatitude gas model and a continental aerosol model are applied.

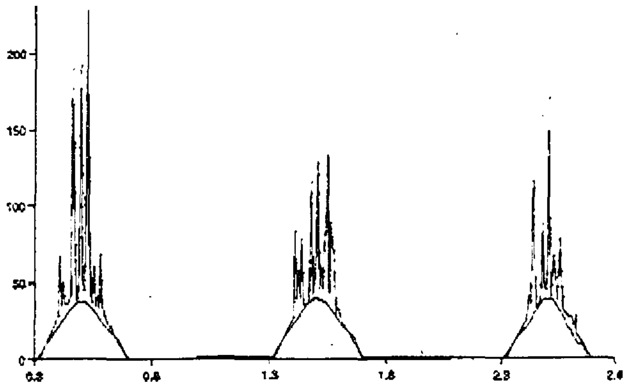

Fig. 3. Three day measurements of the pyranometer 1 in time sequence, and the fitted baseline (lower one). Random shuffling on DY 39 apparently did not change value of α.

DY:	Noon SZN	% of J_{sky} at noon
38	69.48	13%
39	69.17	14%
40	68.85	11%

The 6S code is invalid for SZN > 70 degrees, but we can use these percentages at noon to estimate the cases of other SZN angles. We considered the earth curvature and assumed no other changes except the path length in atmosphere is proportional to $\sin\gamma / \sin\theta$ instead of $\sec\theta$, where

$$\gamma = \theta - \arcsin(R\sin\theta / (R+H)), \qquad (10)$$

where R is the radius of the earth, H the thickness of the atmosphere, 60 km as used in 6S. The percentage of I_{sun} at any SZN is assumed a negative exponential function of optical path length, with its value at the noons fixed by the 6S estimations of I_{sun} above. By this way, we divided the total irradiance into $I_{sun}(\theta)$ and $J_{sky}(t)$ (Fig. 4). This is valid only if atmosphere kept clear during all three days, which was unfortunately not the case. The afternoon in the day 40 had apparently more diffused skylight and less direct sunshine than the previous two afternoons. Lacking of measurement $J_{sky}(t)$, we decided not to use the data in that afternoon, though no much difference if they are included.

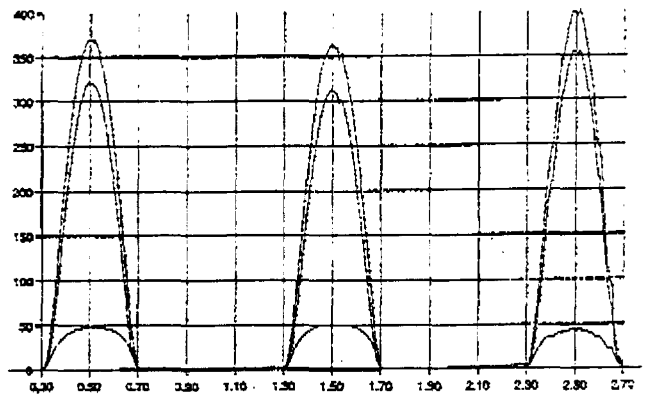

Fig. 4. The 3-day measurements of total irradiance in time sequence, W/m^2. The estimated I_{sun} (the second high one) and J_{sky} by modified 6S.

The openness of the site is $K_{open} = 0.255$, calculated based on the following structural parameters (from our own measurements and Chen et al., [6]):

b/r ratio = 10.0; (crown shape parameter, long spheroid)
r = 0.57; (crown radius)
h = 13.0; (center height)
dbh = 2* 0.084;
λ = 800/ha.; (stem density)

The gap probability $P(n=0|\theta)$ is also calculated based on these parameters for all SZN from noon to sunrise/sunset. Since K_{open} is assumed a constant, $J_0(t)$ has the same shape as $J_{sky}(t)$, but $I_0(\theta)$ is narrower than $I_{sun}(\theta)$ because of smaller $P(n=0|\theta)$ at large SZN's (Fig. 5).

With $J_0(t)$ and $I_0(\theta)$ available, we tried first to fit the base-line for all pyranometers by carefully adjusting β for all and α for individual pyranometer before and after shuffling (e.g. Fig. 2,3). It was proven time consuming and lack of quantitative criteria on what is the best fit of the baselines. Subjective judgement may cause β varies from 0.4 to 1, while α varies from 0.2 to 2. So we decided to take means of all $y_i(I_0(\theta)+J_0(t))$ for each value of $I_0(\theta)+J_0(t)$, regardless specific random values of α and do regression against $I_0(\theta)+J_0(t)$. The result is: $\beta = 0.65$, with coefficient of correlation 0.97.

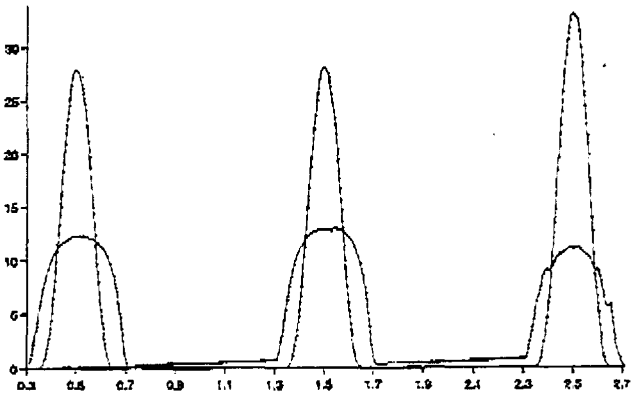

Fig. 5. The calculated $I_0(\theta)$, in time sequence.

When we tried to fit base lines for individual pyranometers, however, it was noted that pyranometers 1-5 and 6-9 may be under different canopy structure and may have different β and openness. This is because the five and four pyranometers were located respectively on the two sides of the flux tower, and the shuffling on DY 39 did not occur between these two sides where the canopy structures do look different. This difference is hidden in average-taking procedure. If we divide the data into two groups and apply the same regression for both, we have:

For the 1-5, $\beta = 0.83$, with coefficient of correlation 0.93;

for the 6-9, $\beta = 0.43$, with coefficient of correlation 0.91.

The coefficients look worse since less number of data are involved in mean-taking procedure for each group, therefore more deviation appears (Fig. 6). Since the canopy structure parameters we used for calculating $P(n=0|\theta)$ and K_{open} are our best estimates of overall mean values of the SOJP stand, they do not reflect the true difference in the two sides of the tower. For example, if the true $I_0(\theta)+J_0(t)$ in the group 6-9 is in fact less than what we used as the mean value, the above β is underestimated, and vice versa for the group 1-5. We tried to change the density of 1-5 group smaller, and that for 6-9 group higher. The result β values of two groups would converge and the regression look better (Fig. 7). But again because the information contained in pyranometer are limited, not enough to deduce too many uncertainties in canopy structure, we would prefer to halt here and validate this after we have more reliable structure measurement data. Presently, we are working on modifying our hybrid code so that it can handle this special case (snow on crowns) for investigating more detailed multiple scattering patterns. More specifically, how β is determined by the $P(n>0|\theta)$, leaf spherical albedo, and snow reflectance. The parameter ω in this study should be the most stable quantity among all other parameters. Once it is modeled and validated, we may be able to invert K_{open} directly from the pyranometer data. For the K_{open} we used in calculation, $\beta = 0.65$ implies an $\omega = 0.73$, a rather high albedo.

IV. CONCLUSION

The pyranometer measurement in the SOJP presents an interesting case because of its relatively weak $I_0(\theta)$ due to low sun and therefore relative apparent $J_{sky}(t)$ contribution. The snow packs on crowns and on ground further cause strong multiple scattering between the snow packs on ground and crowns. This makes hybrid model's features and potentials more obvious. From these data and initial analysis, seemingly we can at least conclude that in winter SOJP, the radiation absorbed by snow packs can be approximately $\beta + \sqrt{\beta(1-K_{open})(1+\beta)}$ (that is about 150% given $\beta = 0.65$ and $K_{open} = 0.26$) more than that calculated by using $I_0(\theta)+J_0(t)$ alone without multiple scattering. This may be one of the reasons why the distributed hydrology-vegetation model of Wigmosta et al. [7] has a systematic bias (though slightly) to underestimate the snow melt during the maximum snow pack period.

Though we are still waiting for other radiometric and more reliable tree measurements, the initial results show that the hybrid model is promising.

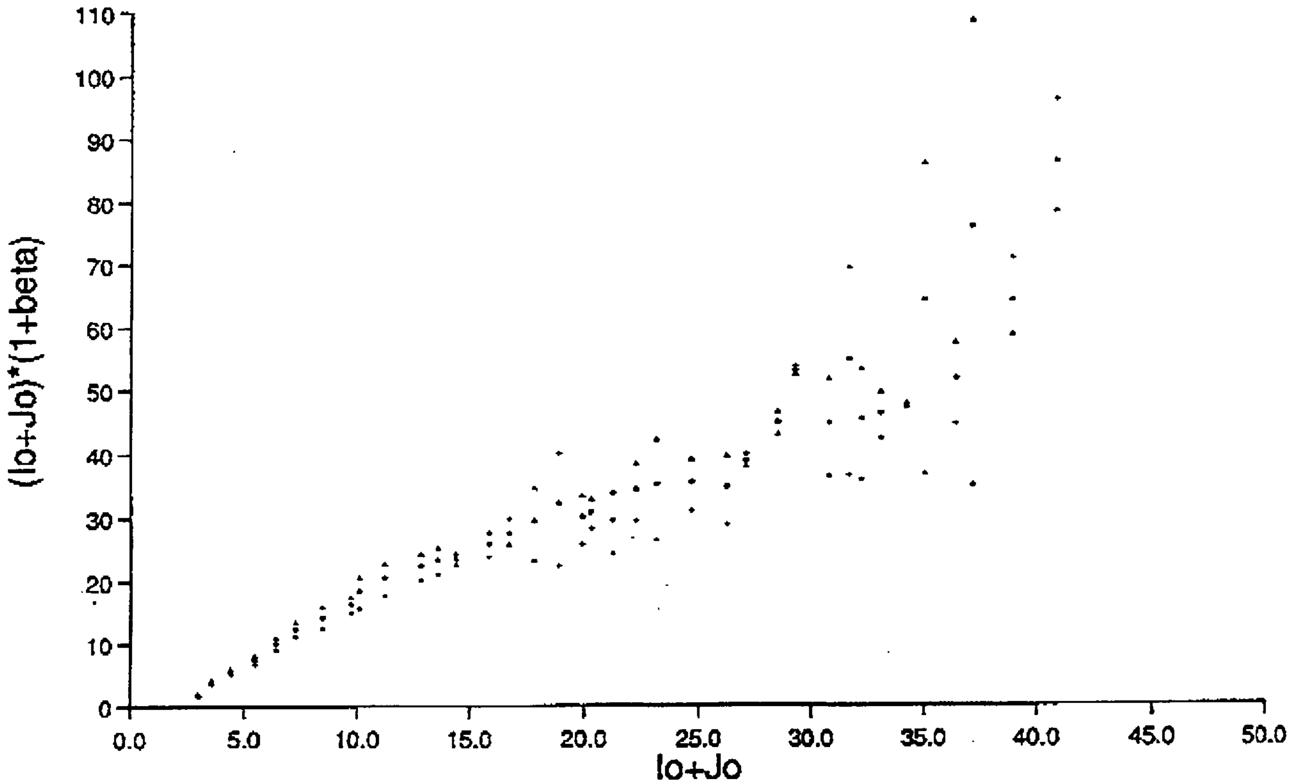

Fig. 6. The regression of β, for total and for two groups. Patterns: dot - all data; triangle - pyranometer #1-5; cross - pyranometer #6-9.

REFERENCES

[1] Li X. and A. Strahler, 1988. Gap Frequency in Discontinuous Canopies, *IEEE Trans. on Geoscience and Remote Sensing*, Vol. GE-26, No. 2, pp. 161-170.

[2] Li Xiaowen, A. Strahler, Wang JinDi, 1994. A Hybrid Geometric Optical and Radiative Transfer Albedo Model of a Forest Canopy, *China Science*, (in Chinese).

[3] C. B. Schaaf, X. Li, and A. H. Strahler, Validation of Canopy Bidirectional Reflectance Models with ASAS Imagery of a Spruce Forest in Maine, *Proceedings of IGARSS'94*, pp. 1832-1834.

[4] X. Li, A. Strahler and C. Woodcock, in press. A Hybrid Geometric Optical and Radiative Transfer Approach for Modeling Albedo and Directional Reflectance of Discontinuous Canopies, *IEEE Trans. on Geo. and Rem. Sens.*

[5] E. Vermote, D. Tanre, J. L. Deuze, M. Herman, and J. J. Morcrette, 1994. *6S User Guide*, Version 0.

[6] J. M. Chen and Josef Cihlar, in press. Qualifying the Effect of Canopy Architecture on Optical Measurements of Leaf Area Index Using two Gap Size Analysis Methods, *IEEE Trans. on Geo. and Rem. Sens.*

[7] Wigmosta, M. S., L. W. Vail, and D. P. Leftenmair, 1994. A Distributed Hydrology- Vegetation Model for complex terrain, *Water Resource Research*, 30:6, pp. 1665-1679.

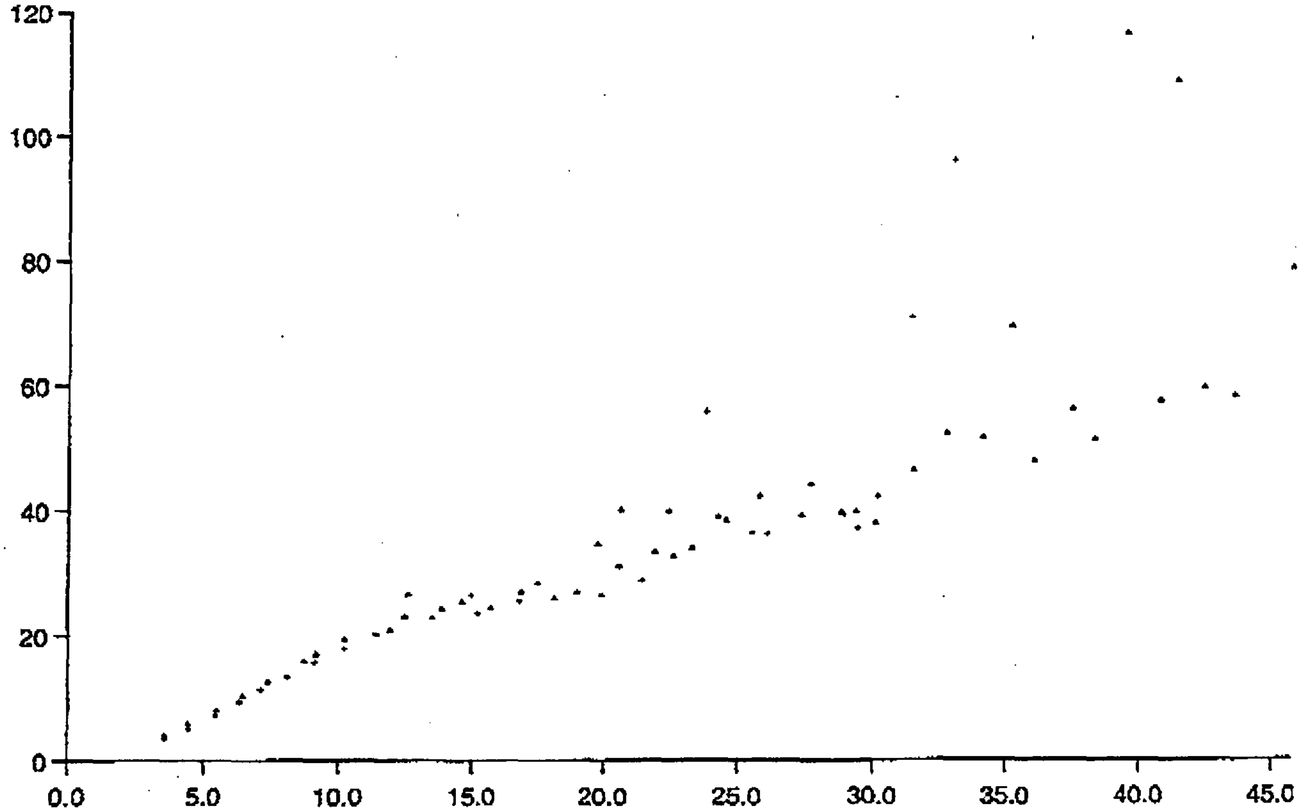

Fig. 7. The regression of β, for different K_{open} used for two groups. Patterns: triangle - pyranometer #1-5; cross - pyranometer #6-9.