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MODELLING SOLAR RADIATION IN THE ARCTIC AN IMPROVED METHOD FOR THE SUBDIVISION OF GLOBAL RADIATION (U)

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MODELLING SOLAR RADIATION IN THE ARCTIC AN IMPROVED METHOD FOR THE SUBDIVISION OF GLOBAL RADIATION (U)

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ABSTRACT

From an analysis of solar radiation data collected at Alert, N.W.T., it was shown previously[2] that existing solar energy models overestimate slope irradiance at low solar elevation angles. In this technical note it is shown that this overestimation results from the breakdown of the relationship between sky condition and atmospheric transmittivity. In particular, at low solar elevations, the portion of the global radiation being attributed to direct radiation is overestimated. A new empirical relationship for the subdivision of global radiation at low solar elevations has been developed.

RESUMÉ

Une analyse des mesures de radiation solaire obtenues à Alert, T.N.O. a montré que les modèles solaires existant surestiment le rayonnement sur une inclinaison quand l'angle d'élévation solaire est bas. Dans cette note technique, il est démontré que cette surestimation est un résultat de la défaillance de la relation entre la "condition du ciel" la transmittivité de l'atmosphère. En particulier, pour les angles d'élévation bas, la portion de la radiation globale qui est attribuée à la radiation directe est surestimée. Une relation nouvelle pour la subdivision de la radiation globale à des angles d'élévation bas est proposée.

EXECUTIVE SUMMARY

The results presented in this paper were collected as part of a study to examine the feasibility of using solar energy to power the High Arctic Data Communications System, which runs from Alert to Eureka, N.W.T., during the summer months. A knowledge of the solar energy that is available is crucial if the components of the solar power system are to be sized correctly.

During the course of our studies , it was discovered that the existing solar energy models overestimated the amount of solar energy that was available when the sun is close to the horizon - a condition that is common in the High Arctic. A new empirical relationship that improves the prediction of solar energy availability under Arctic conditions is developed in this technical note.

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1.0 INTRODUCTION

The high cost of transportation and the need for high reliability make the provision of power to remote sites in the Arctic extremely expensive. It has been estimated[1], for example, that the annual cost of replacing the batteries at the six remote sites on the High Arctic Data Communications System (HADCS) is approximately $830K in 1983$. In such situations the use of a renewable energy source such as solar energy can become economically attractive.

In 1984, under task DCEM 58, experiments were initiated to examine the feasibility of employing a photovoltaic(PV)/battery system to supplement the non-rechargeable zinc-air batteries that were being used to power the HADCS sites. As part of these experiments an extensive data base of the availability of solar energy on a horizontal and a 80° south facing inclined surface was collected. This data was used to assess[2] the suitability of various models that were available to predict solar irradiance on inclined surfaces in the Arctic.

A knowledge of the quantity of solar radiation received on inclined surfaces is essential to ensure proper sizing of any photovoltaic systems that are installed as well as for thermal solar applications. It is also important[3] in understanding the performance of tents in the Arctic as well as the effects of sunlight on the comfort of military personnel who must operate under harsh climatic conditions.

In this technical note, a new method for the subdivision of global radiation into direct and diffuse components when the solar elevation angle is small (less than 10°) is proposed.

2.0 BACKGROUND

In a recent paper[2], the experimental results obtained for irradiance on a south facing 80° inclined surface at Alert, N.W.T., were compared with results obtained using the models of Hay[4] and Klucher[5]. Global radiation was subdivided into direct and diffuse components empirically using the Liu and Jordan[6] relationship as expressed by Klein[7]. The coefficients used were those derived for high latitudes by Boswarva[8].

Although the models provided reasonable estimates of slope irradiance when solar elevation angles exceed 8°, they seriously overestimate slope irradiance at lower elevation angles. The poor performance of the models at low solar elevations was attributed to the breakdown of the relationship between sky condition and atmospheric transmissivity (K_t). In particular, at low solar elevations, the portion of global radiation being attributed to direct radiation was over estimated.

The influence of solar elevation on the distribution of diffuse and direct radiation has been discussed by a number of authors. Iqbal[9] demonstrated that, under clear sky or partly cloudy conditions, solar elevation had a marked effect on the fraction of diffuse radiation when solar radiation was less than 30°. Garrison[10] noted similar effects in his extensive analysis of data collected at a large number of U.S. sites. Recently, Skartveit and Olseth[11] proposed a model that related the hourly diffuse fraction of global radiation in terms of solar elevation and atmospheric transmissivity. This analysis did not however include data for solar elevations less than 10°. In this note, the effect of solar elevation on the fraction of diffuse radiation is examined using integrated hourly averages of radiation data collected at Alert 82.50°, and using data collected at Resolute 74.72°, N.W.T., by the Canadian Atmospheric Environment Service (AES).

3.0 RESULTS

3.1 The Relationship Between Sky Condition and Atmospheric Transmissivity at Low Solar Elevations. Analysis of Radiation Data from Alert, N.W.T.

Solar radiation intensities have been recorded at Alert on a horizontal surface using an Eppley Black and White pyranometer, and on an 80° south facing inclined surface using an Eppley PSP, from June 1984 until May 1987. Radiation intensities were sampled at 5 minute intervals and hourly averages calculated and stored on magnetic tape using a Fluke 2280 data logger. The results obtained in this way agree well (MBE = -2.5%) with integrated hourly values of global radiation recorded by AES at the Alert weather station which is located a short distance away from our experimental site.

Although a direct measurement of the ratio of diffuse to global radiation on the 80° incline was not made, an estimate of I_d/I can be obtained from the data that was collected if it is assumed that one of the solar radiation models is adequate to describe sky condition. For simplicity, the isotropic model of Liu and Jordan[12] was chosen in this analysis. As shown in Figure 1, although not quite as good as the anisotropic models of Hay[4] or Klucher[5], good agreement is still obtained between measured and predicted solar radiation intensities for large solar elevations using the isotropic model.

Assuming the isotropic sky model of Liu and Jordan[12] to be sufficient in describing sky condition, the irradiance (I_β) on a south facing slope tilted at an angle β is given by:

$$I_\beta = (I - I_d)Rb + I_d[(1 + \cos\beta)/2] + \rho I[(1 - \cos\beta)/2] \quad (1)$$

where I is the global radiation, I_d the diffuse component, ρ the surface albedo and R_b the ratio of extraterrestrial radiation on a south facing surface tilted at an angle β to that on the horizontal (ie. $R_b = I_{o\beta}/I_o$). The ratio (I_d/I) is obtained using the experimental data for irradiance on the horizontal and the 80° inclined surface. In this case $I_\beta = I_{80}$ and I_d/I is determined by:

$$Id/I = [R_b + 0.4132\rho - (I_{80}/I)]/[R_b - 0.5868] \quad (2)$$

Using equation (2) and using the average monthly surface albedos given in Table 1, hourly values for I_d/I were calculated from the measured ratio of I_{80}/I. The results of these calculations are shown in Figure 2 as a function of atmospheric transmissivity ($K_t = I/I_o$) for various intervals of solar elevation. These results show clearly that the relationship between I_d/I and K_t is strongly dependent on solar elevation.

3.2 The Relationship Between Sky Condition and Atmospheric Transmissivity at Low Solar Elevations. Analysis of Radiation Data from Resolute, N.W.T.

The relationship between sky condition (I_d/I) and atmospheric transmissivity (K_t) was also studied using data obtained from AES for Resolute. At Resolute, AES makes a direct measurement of the diffuse and global radiation on a horizontal surface and the approximate method of analysis used to analyze the Alert data does not need to be used. The results presented are based on matched pairs of diffuse and global integrated hourly data for the period 1984 - 1985, recorded and archived according to true solar time (TST). Figure 3 shows the results when I_d/I is plotted as a function of K_t for the same intervals of solar elevation as in Figure 2. It should be noted that these results show the same dependence on solar elevation as in Figure 2. This provides confidence in the method that was used to extract I_d/I from the Alert data.

3.3 Empirical Relationship Between I_d/I and K_t at low solar elevations

It has been found that the results shown in Figures 2 and 3 can be described quite well by the expression:

$$I_d/I = 1 - k(\theta)*\theta*K_t^3 \quad (3)$$

where θ is the solar elevation angle,

$$k(\theta) = 0.09715 + 0.00323*\theta - 0.00016*\theta^2 \quad (4)$$

and $I_d/I \geq 0$.

The coefficients for this expression were determined by a least squares fit to the Alert data. Figure 4 shows the relationship determined for I_d/I (equation 3) as a function of K_t for various values of solar elevation. This equation provides a reasonable fit to the data shown in Figures 2 and 3. At low elevation angles, the agreement between the experimental and calculated values for irradiance on a tilted surface is greatly improved when the above relationship is used instead of the Klein[7] equation with Boswarva's[8] coefficients. Figure 5 compares the results of October 1985, calculated using equation (3), with those determined using Boswarva's coefficients. The relationship has been derived using data having a maximum solar elevation of 31° and it should not be used beyond this range without further validation.

A statistical comparison of model performance while using equation (3), with that using the Boswarva expression[8], is given in Table 2. In this table, a comparison is made of the mean bias error (MBE) and root mean square error (RMSE) as commonly defined [13]. There is a substantial improvement for March and September, months in which solar elevation angles remain low. Also included in Table 2 are the results for a hybrid model that uses equation (3) when the solar elevation angle is less than 8°, and the Boswarva expression for higher elevation angles. The hybrid model produces the best overall fit to the experimental data.

4.0 DISCUSSION

The results presented in Figures 2 and 3 indicate that the relationship between sky condition and atmospheric transmissivity is strongly dependent on solar elevation when the sun is close to the horizon (ie. θ is less than 10°). The need to adjust the coefficients[8] in the Klein[7] equation for higher latitudes is probably due, at least in part, to this dependency. However the effect of surface albedo on multiple reflection is also important [14].

The results presented in this note show that, at low solar elevation angles, there is a greater contribution of diffuse radiation to the total than at higher solar elevation angles for the same K_t value. When the sun is on the horizon ($\theta = 0^{\circ}$) all of the radiation is diffuse and in general it can be expected that $I_d/I \rightarrow 1$ when $\theta \rightarrow 0^{\circ}$.

5.0 CONCLUSIONS

The analysis of solar radiation data collected at Alert, N.W.T. (82.5 N) and obtained for Resolute, N.W.T.(74.7 N) from AES demonstrates that there is a serious breakdown of the Liu and Jordan relationship at low solar elevation angles. A new empirical relationship was determined for the subdivision of global radiation that takes into account the effect of low solar elevation angles. This new relationship shows a marked improvement over the Liu and Jordan relationship at low elevations.

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TABLE 1: Average Monthly Surface Albedo

March	April	May	June	July	August	September
0.8	0.8	0.8	0.6	0.2	0.2	0.8

TABLE 2: Statistical Performance of Radiation Subdivision Models

		METHOD OF RADIATION SUBDIVISION					
MONTH	ALL-SKY MODEL	LIU-JORDAN		EQUATION 3		HYBRID	
		MBE %	RMSE %	MBE %	RMSE %	MBE %	RMSE %
MARCH	HAY	130.7	280.9	90.2	274.0	65.2	182.2
	KLUCHER	72.2	158.2	65.7	248.3	27.5	110.2
APRIL	HAY	-5.4	45.2	3.7	59.5	-5.4	47.1
	KLUCHER	-10.7	42.6	1.6	56.2	-10.5	43.6
MAY	HAY	-3.6	22.3	5.1	30.5	-3.6	22.3
	KLUCHER	-1.7	20.7	8.4	28.3	-1.7	20.7
JUNE	HAY	7.4	22.2	8.6	28.7	7.3	22.8
	KLUCHER	11.7	25.1	12.5	27.8	12.1	24.2
JULY	HAY	-0.5	20.0	5.5	22.2	-0.4	20.0
	KLUCHER	2.8	24.6	8.3	23.0	2.8	24.6
AUGUST	HAY	-3.0	35.6	9.7	42.8	-2.7	35.7
	KLUCHER	-5.2	34.5	8.6	41.1	-5.0	34.5
SEPT	HAY	43.6	110.3	35.5	134.5	30.9	113.4
	KLUCHER	19.0	63.7	17.8	111.3	9.6	76.0
OCT	HAY	932.0	2171.0	205.3	940.0	215.0	962.0
	KLUCHER	564.0	1272.0	41.1	231.0	44.9	229.4

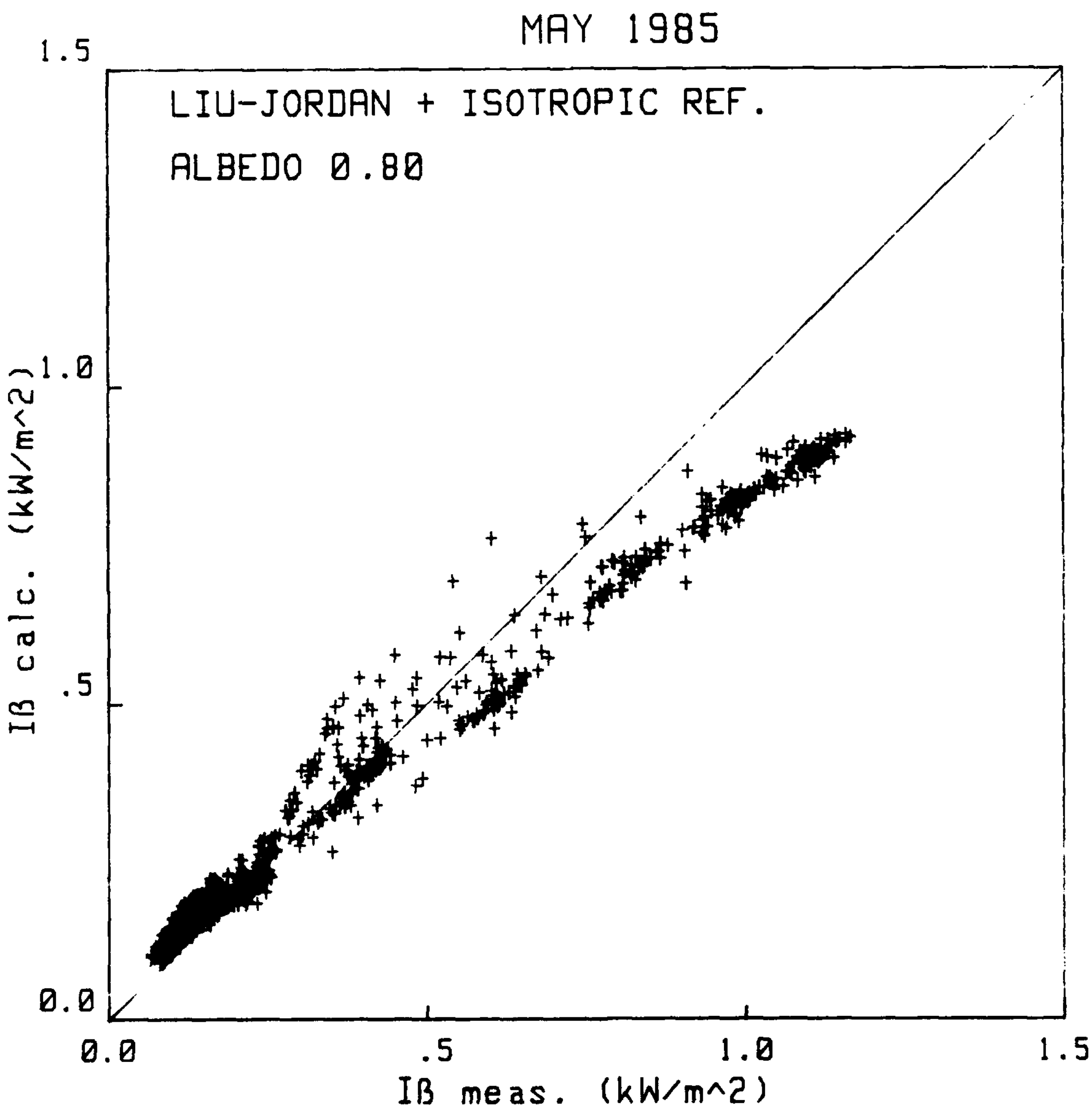

FIGURE 1: Hourly performance of the Liu and Jordan model during May 1985

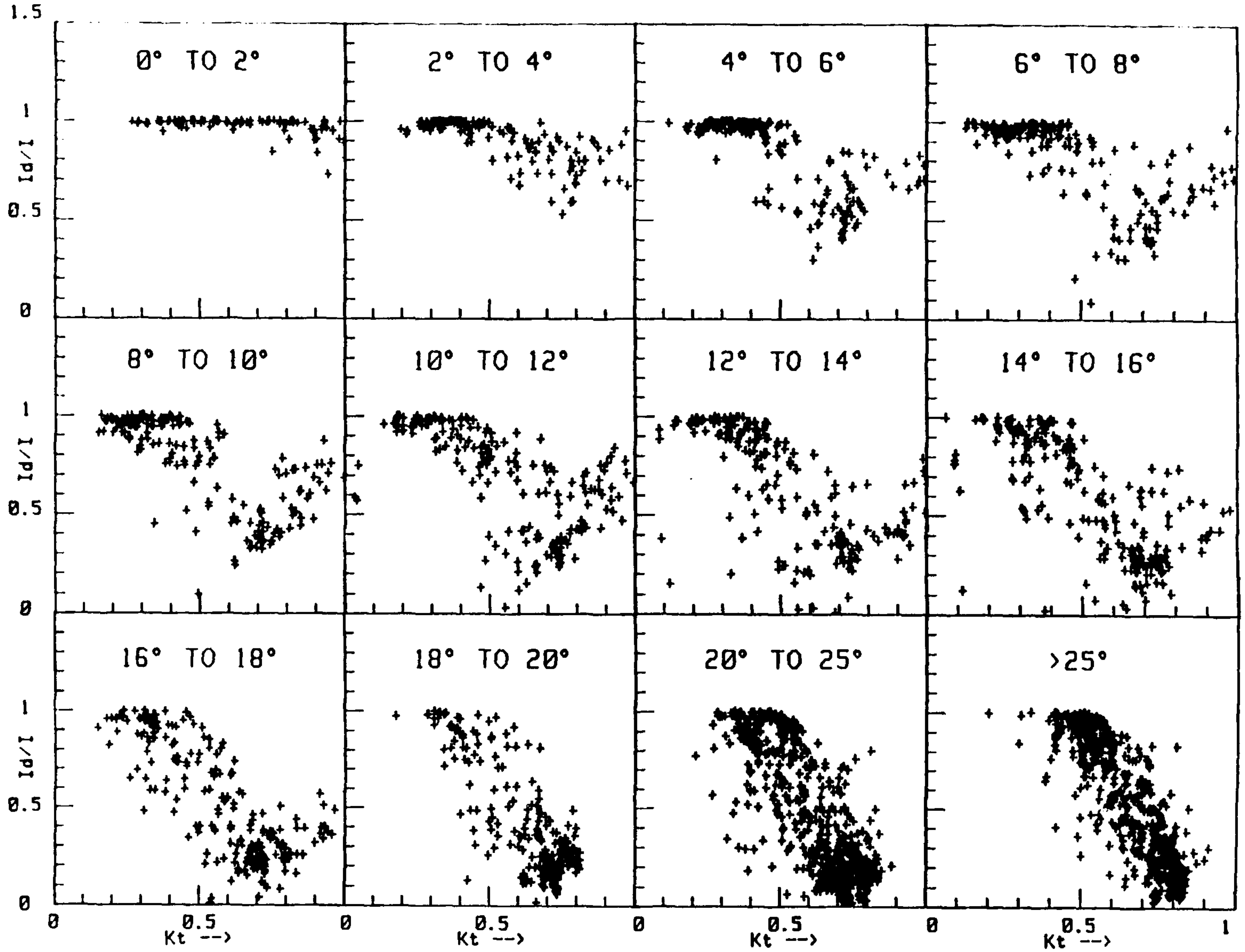

Figure 2: Hourly comparisons of I_d/I vs Kt for various solar elevation angle groups at Alert, N.W.t.; June 1984 through May 1987.

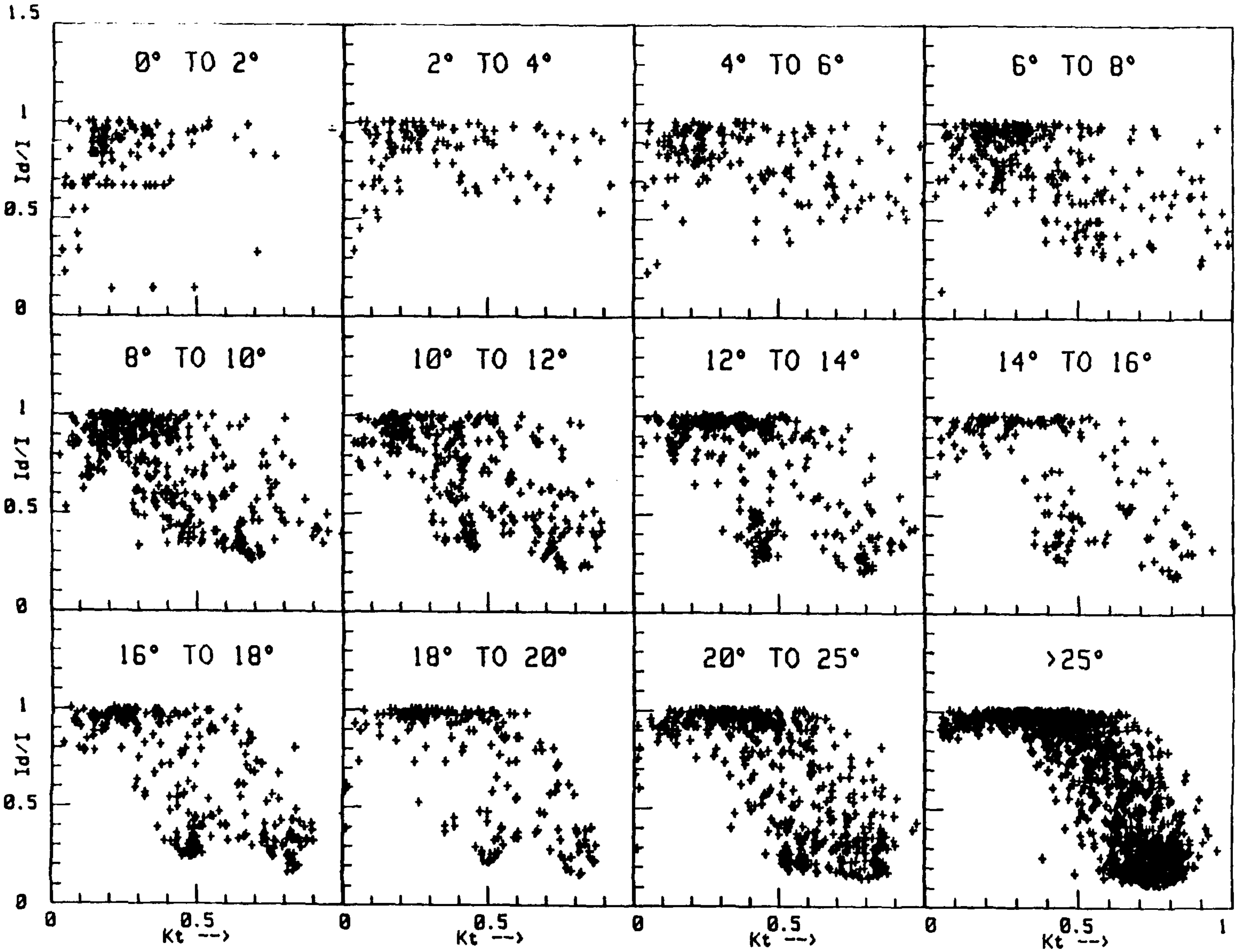

Figure 3: Hourly comparisons of I_d/I vs Kt for various solar elevation angle groupes at Resolute, N.W.t.; January 1984 through December 1985.

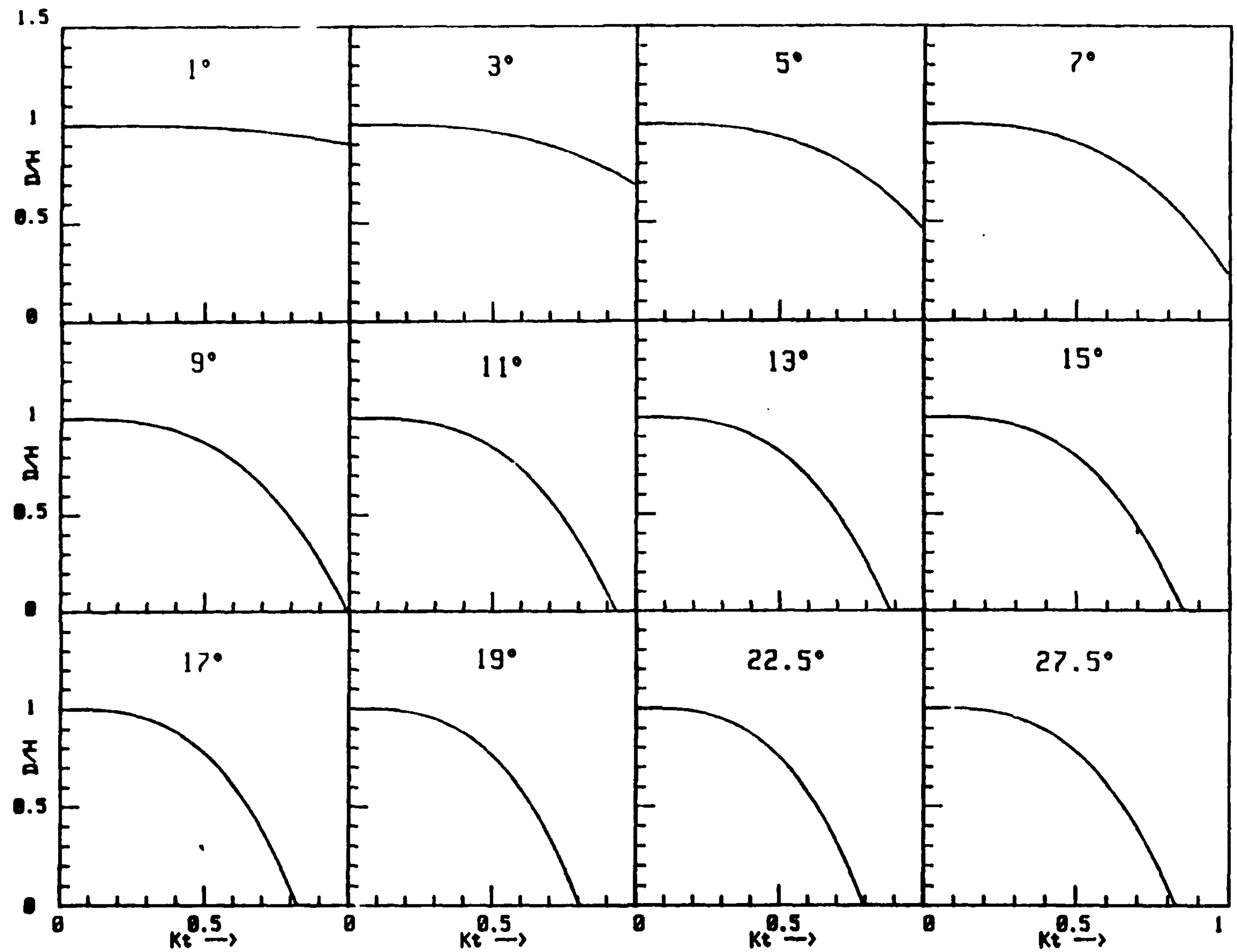

Figure 4: I_d/I vs. Kt as determined by equation 3.

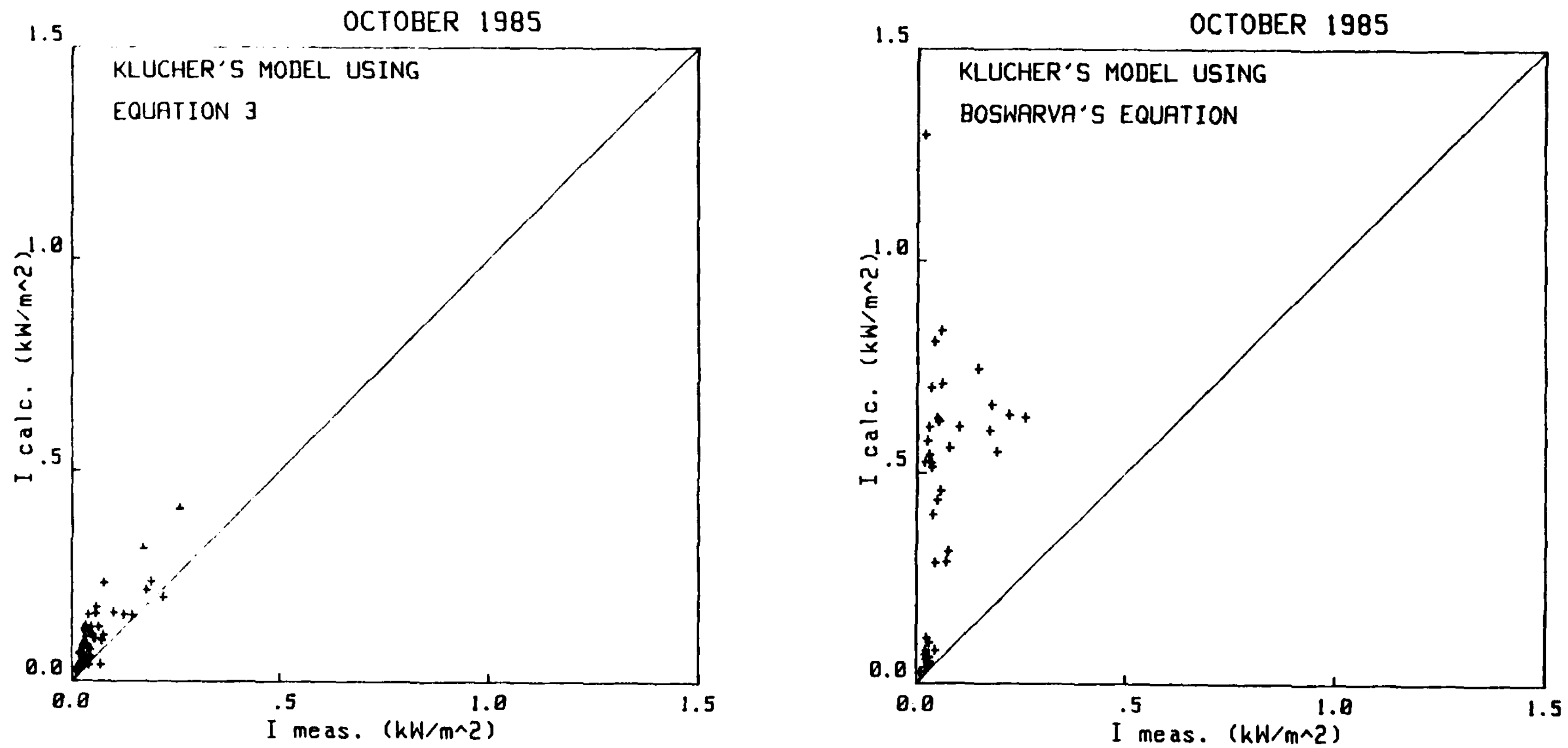

Figure 5: A comparison of model performance using equation 3 vs the Klein equation using Boswarva's coefficients for October 1985.

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