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# A Simple Method of Estimating Photosynthetically Active Radiation at the Earth's Surface from Satellite

Thomas Eck  
ST Systems Corporation  
Goddard Space Flight Center  
College Park, Maryland 20742

Dennis Dye  
Department of Geography  
University of Maryland  
Greenbelt, Maryland 20771

## Abstract

A physically based method of estimating the photosynthetically active radiation (PAR) incident at the earth's surface is described. Ultraviolet reflectivity, inferred from the Total Ozone Monitoring Spectrometer (TOMS) onboard the polar orbiting Nimbus-7 satellite, is used to account for the effect of cloud albedo on the attenuation of PAR incident at the surface. The clear sky incident radiation for the PAR wavelengths (400-700 nm) is computed from the spectral model of Goldberg and Klein (1980). Monthly averages of incident PAR at the surface estimated from the satellite method differed from estimates of PAR from ground pyranometers by less than 6%. This method of PAR estimation can be applied globally over snow and ice free areas.

## INTRODUCTION

Solar radiation in the wavelength interval of 400-700 nm is used by green plants for photosynthesis. The amount of this photosynthetically active radiation (PAR) which is incident at the earth's surface is therefore an important variable for monitoring and modelling the photosynthetic activity of the earth's vegetation (Dye, 1985). Studies of global photosynthetic activity thus require accurate information about the spatial and temporal patterns of PAR insolation.

However, measurements of photosynthetically active radiation at the earth's surface with spectral pyranometers are made at only a few universities and research facilities. In many regions of the world there are no measurements of PAR at all or only for widely separated stations. In addition, frequent maintenance and calibration are required to maintain high data quality for regional studies or station comparisons.

Remotely sensed satellite measurements have the potential of overcoming these problems of sensor intercalibration and sparse or non-existent surface monitoring networks. They have the potential to provide estimates of PAR, from a single sensor, including its spatial and temporal distribution over a wide range of climatic regimens. In this study we present a satellite technique for estimating the amount of PAR incident at the earth's surface.

## METHOD

For the case of a cloudless atmosphere, including only background levels of atmospheric aerosol, the spectral model of Goldberg and Klein (1980) has been used to calculate clear sky potential insolation over the spectral range of 400-700 nm. The model was developed using 8 years of spectral pyranometer data from three surface stations: Rockville, Maryland, Barrow, Alaska, and the Panama Canal Zone. The Goldberg and Klein (1980) model for a cloudless atmosphere is given by

$$I = I_0 \cos z [0.5(1 + e^{-m^*R}) e^{-m^*(\tau + \alpha x)} + 0.05] \quad (1)$$

where

$I_0$  = extraterrestrial solar irradiance

$m^*$  = effective airmass for computing daily insolation

$\tau$  = aerosol scattering and absorption effects  
 $x$  = ozone amount in atm. cm.  
 $\alpha$  = ozone absorption coefficient  
 $R$  = Rayleigh scattering coefficient  
 $z$  = solar zenith angle

The extraterrestrial solar irradiance on a horizontal surface ( $I_0 \cos z$ ), is computed using the method of McCullough (1968). This value of irradiance for the complete solar spectrum is multiplied by 0.378 to account for the fraction of the energy in the PAR wavelengths and to adjust the value of the solar constant since McCullough's equation is based on a value which is larger than generally accepted. A Rayleigh scattering coefficient,  $R$ , of 0.131 and an ozone absorption coefficient of 0.053 was used for the 400-700 nm spectral interval, as given by Goldberg and Klein (1980). The amount of ozone,  $x$ , was set constant at a value of .300 atm. cm. for all locations and months. The value of  $\tau$  was also set constant at 0.02. This value was based on an estimate of approximate background aerosol effects for the clearest conditions from the annual cycle of  $\tau$  in Rockville, Maryland and Panama (Goldberg and Klein, 1980).

The variation in cloud type and amount is the dominant factor affecting the amount of PAR incident at the surface over most regions of the earth. Measurements of UV reflectivity at 370 nm from the TOMS instrument on the Nimbus-7 satellite were used to determine the presence of clouds and to account for the effects of cloud on the attenuation of PAR. The earth's surface reflectivity in the UV for cloudless scenes was studied by mapping the minimum reflectivity for a three month season (June-August) over the entire earth (Eck et al., 1987). For both land and ocean areas, which were free of ice and snow, the UV reflectance is uniform and low. Typical UV reflectivity over ocean ranged from 6-8%, and non-desert land surfaces have UV reflectances of 2-5%. The UV reflectance of clouds, however, is high, averaging 56.1% for cloud filled field of views from 60°N to 60°S for a one week period. The high contrast between earth surface and cloud reflectance in the UV allows for the effective detection of cloud over all earth surface types. The exception is when earth surface UV reflectivity is high due to snow or ice cover.

In our technique of PAR estimation we assume that clouds do not absorb radiation at wavelengths shorter than 700 nm and thus reflection is the only mechanism for PAR attenuation by clouds. It is also assumed that the reflectivity of clouds is the same across the UV and PAR wavelengths and the reflection is isotropic.

The application of the UV reflectance measured by TOMS in our technique assumes that the cloud albedo is represented by the measured reflectance above a threshold which is selected as a cloudless scene UV reflectance. We have selected a constant threshold of 5% for the TOMS inferred UV reflectivity for a cloudless scene. To account for the attenuation of PAR by cloud reflectance, the entire right hand side of eq. (1) is multiplied by  $(1 - (R - 0.05) / .90)$ , where  $R$  is the TOMS reflectivity. For reflectance greater than 0.50 the right hand side of eq. (1) is multiplied by  $(1 - R)$ . These formulations include the effect of a linear decrease in the earth surface reflectance contribution to the total scene reflectance as the cloud reflectance increases.

#### DATA AND APPLICATION

The method of PAR estimation, described in the previous section, was applied to monthly average UV reflectivity data from the archived CMATRIX data base of the Nimbus-7 cloud climatology program (Hwang, 1988). The CMATRIX data have a spatial resolution of approximately 500x500 km. A grid of

approximately 2070 fixed position target cells provides complete coverage of the earth. The spatial resolution of the TOMS instrument is 50x50 km in the nadir view direction, increasing to 150x200 km in the extreme off-nadir direction. Therefore, for each day there are typically several TOMS measurements which are averaged to fill the fixed, approximately equal-area CMATRIX target cells. We validated the algorithm estimates of incident PAR at the surface by comparing them with pyranometer measurements of total incident solar radiation adjusted for the percentage of total insolation which is in the PAR wavelength region.

Rao (1984) measured the fraction of the total incident solar radiation that is in the PAR band in Corvallis, Oregon. The monthly mean values of the irradiance in the 385-695 nm band (PAR) to total global solar irradiance (295-2800 nm) ranged from a minimum of 44.1% (February and November) to a maxima of 46.0% (June) for a three year measurement period. Howell et al. (1983) similarly measured the fraction of total insolation (285-2800 nm) in the PAR band (400-700 nm) near Fresno, California. They measured monthly average PAR fractions of total insolation ranging from 44.1% to 45.6% at one station and from 44.5% to 45.8% at a second station.

Given the observational evidence of relatively constant monthly average PAR fraction at mid latitudes from these studies, we have assumed a PAR fraction of 45% of total insolation in computing the estimate of PAR from global pyranometer data. The pyranometer data used in this study was obtained for selected mid latitude stations in the NOAA solar radiation network from April 1979 through December 1980. Three stations were selected for being relatively close to the centers of the 500x500 km fixed location CMATRIX target areas. Figure 1 shows a map of the CMATRIX target area boundaries for the contiguous United States and the locations of the three pyranometer stations. Satellite estimates of PAR for cloudless conditions were made for the latitude and longitude of the pyranometer stations. The monthly average UV reflectivity for the 500x500 km target area which encompasses the station were then used to compute the reduction in PAR insolation due to cloud reflectance.

## RESULTS AND DISCUSSION

A comparison between the satellite estimates of PAR incident at the surface versus the estimate of PAR from the global pyranometer (45% of total insolation) at Montgomery, Alabama is shown in Fig. 2. These are monthly totals of PAR in  $\text{kJ/m}^2$  for 14 months where pyranometer data were available from May 1979 through December 1980. The correlation coefficient for these two estimates is 0.985. The UV reflectivity from TOMS varied from a maximum of 52% in January 1980 to a minimum of 24% in July and August 1980. The root mean square (rms) difference between the satellite and surface estimates is  $13510 \text{ kJ/m}^2$  or 5.9% of the mean value of  $227098 \text{ kJ/m}^2$ . For the entire 14 month total of estimated PAR, the satellite estimate was only 0.5% greater than the pyranometer estimate, thus indicating very little bias.

Similar comparisons were made of PAR estimates for Dodge City, Kansas and Phoenix, Arizona. The rms difference for Dodge City was 5.8% of the mean and for Phoenix was 3.4% of the mean.

Sources of error in the satellite estimation of PAR include glint from ocean surfaces, although this effect is smaller in the UV than visible reflectances (Eck et al., 1987), and the presence of sea ice (or snow/ice on land). Diurnal cloud variability which is not characterized accurately by the TOMS once per day local noon overpass measurement of UV reflectance, and/or UV reflectance which is not representative of the PAR cloud albedo due to anisotropy, may also lead to errors in satellite estimates.



## SUMMARY

A simple, physically based technique for the estimation of PAR incident at the earth's surface has been developed. Measurements of UV reflectance inferred from the TOMS instrument on the polar orbiting Nimbus-7 satellite are used to account for the reflection by clouds in the PAR wavelengths. The UV reflectance over most earth surfaces (except snow and ice) is uniformly low and cloud reflectivity is generally high and similar to visible reflectivity. Validation of the technique was performed by comparing the satellite estimates of PAR insolation with PAR estimates from ground based pyranometer measurements of total insolation. The rms difference of monthly average incident PAR between the two estimates was less than 6% for three stations in different climatic regimes within the U.S.

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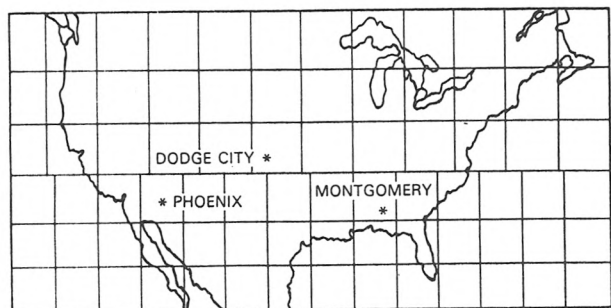


Fig. 1. Locations of the three pyranometer stations studied, showing the fixed 500x500 km CMATRIX target areas.

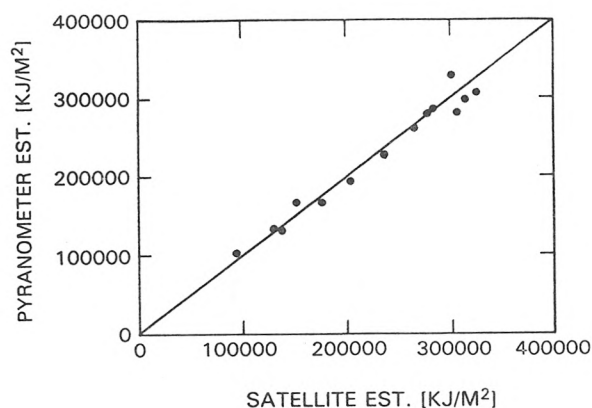


Fig. 2. Monthly total PAR incident at the surface estimated by satellite versus pyranometer estimates at Montgomery, Alabama.