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Evolution of Methods for Solar Radiation Mapping Using Satellite Data

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ABSTRACT

Since the first successful data acquisition from the first meteorological satellite in 1959 a number of methods to estimate solar radiation reaching the ground surface using satellite data have been developed worldwide. A review of these methods is presented in this paper to assist in selecting an appropriate method for the economically lagging countries. Although most of the methods give an acceptable level of accuracy for estimated data, they require expensive equipment for an operational radiation mapping system. Only a few are of low cost and are acceptable.

BACKGROUND

Methods of extraction of quantitative and qualitative cloud parameters (cloud type; optical behavior; coverage; structure and texture; motion, etc.), from satellite data have been developed since the onset of multispectral observations through meteorological or other satellites. Different models for calculating these parameters have been developed for different end uses. Two basic end uses are: meteorological forecasting and land use planning. Cloud screening from satellite data is used to obtain clear sky land use maps for various purposes such as vegetation monitoring, land erosion mapping, water resource monitoring and so on. Among the meteorological applications, regional or global cloud cover mapping or mapping of daily cloudiness or identifying cloud types or cloud motion to observe circulating events like storms, hurricanes, etc. are important. Clouds are assumed to be the prime attenuator of solar radiation coming towards the earth's surface. Molecular or particulate absorption and scattering in the atmosphere are second order attenuators. The methodology for cloudiness measurement, therefore, applies to the new fields such as solar radiation mapping.

During the 1960's clouds were measured from satellite data using only the visible channel. Single or multiple thresholds were used to detect cloud height and types. A pixel is called filled with cloud of the type whose reflectance exceeds the thresholds of that cloud type. The fractional cloud cover is then estimated as the ratio of cloud covered pixels to the total number of pixels in the scene. (AMS, 1990).

Later, around the 1970's, when infrared sensors came into use, only infrared data were used and similar threshold methods were applied. The accuracy of these methods depends mainly upon the selection of the threshold and the diversity of cloud types in the scene. In the late 1970's it was found that joint use of infrared and visible channels from polar or geostationary satellites could provide better cloud cover and cloud height during daylight hours. This is called the bi-spectral method (AMS, 1990).

During the 1980's and in recent times, more than two bands have been used to obtain more precise cloud parameters. To obtain pure cloud properties a number of pixels which are completely overcast with one type of cloud, should be examined. For cloud classification, the spectral response in different bands from different cloud types must be known (Yamanouchi and Kawaguchi et al., 1992). Raschke (1991) found that techniques for cloud identification which solely use longwave infrared data yield higher biases and underestimate the cloud cover in most cases. For identifying cloud and estimating cloud cover the multispectral AVHRR data are suitable and five channels of AVHRR data are used in many researches (Saunder and Kriebel, 1988; Karlsson, 1989). However, 100% accurate cloud parameterization has never been possible even using multispectral images.

NATURE OF METHODS

Statistical methods apply empirical formulas derived from basic principles of radiative transfer in the atmosphere but use ground measurement for calibration of the formulas. This is more locality dependent and requires ground truth data. However, most researchers prefer this method, because it does not require well calibrated satellite data and formulation is simple. This method is also called the **empirical** method. Examples: Sorapipatana et al. (1988), Tarpley (1979) and Cano et al. (1986).

Physical methods require more detailed physical analysis of radiative processes in the atmosphere in the passage of solar radiation from the source (the sun) to the target (the earth). Cloud parameterization is done from satellite data. Atmospheric extinction parameters are sometimes taken from other ancillary climatological data. This method requires well calibrated satellite data and also the process should be monitored regularly. The accuracy of this model can be poor if ancillary information is inaccurate or out of date. This method is also called the **theoretical** method. Examples: Gautier et al. (1980) and Moser and Raschke (1983 and 1984).

CHRONOLOGICAL DEVELOPMENTS OF DIFFERENT METHODS

During the 1960's

Fritz et al. (1964) found good correlation between the ground measured transmissivity of the atmosphere and the satellite derived reflectivity of the earth atmosphere. That was the first attempt of an empirical method leading to the possibility of estimating solar radiation reaching the earth's surface from satellite data. Data from the polar orbiting satellite TIROS-II, the precursor of the NOAA series, were used for that purpose.

Hanson et al. (1967) derived atmospheric transmittance functions when they were calculating the planetary reflection and surface and atmospheric absorption from measurements at the ground by pyranometers and space by flat plate radiometers of the TIROS-IV satellite. They used other climatological data to calculate atmospheric properties.

During the 1970's

In 1971 Hanson formalized the atmospheric transmissivity as a function of satellite measured planetary reflectivity, relative absorptivity of the earth atmospheric system and the surface albedo using the principle of energy conservation for the solar energy band of the electro-magnetic spectrum that he had used in 1967.

Vonder Haar et al. (1973) used data from NIMBUS-II, the second generation of operational NOAA polar orbiting satellites, to calculate the net radiation budget of the earth atmosphere. The quantity reaching the surface was not calculated. From the energy conservation principle, solar energy absorbed (G'_a) in the earth atmosphere system is the difference between the solar energy which enters into the system (G_o) and the quantity of it reflected from the system (G_r).

$$G_o - G_r = G'_a \tag{1}$$

Then the net radiation G_n is given by:

$$G_n = G'_a - I_r \tag{2}$$

Broad band visible radiance (0.3-3 μm) and cloud images data from the meteorological satellite along with conventional climatological measurements were used by Vonder Haar and Ellis (1978) to develop empirical relationships between satellite observations and surface insolation.

The basic energy conservation principle is again applied to calculate the surface albedo from clear sky measurements of radiation by the satellite and at the ground. The absorption was calculated from the optical path length using empirical relation (Equation 3) from Hanson (1967 and 1971). The error of estimation was 10-15% for daily total global radiation. The method can be called semi-physical and semi-empirical.

$$G_a/G_o = 0.117 + 0.031^* d^{1/2} \ln d \quad \text{(Vonder Haar and Ellis, 1975)} \tag{3}$$

The use of geostationary satellite data for insolation estimation began in 1978 (Tarpley et al.). Tarpley (1979) addressed the problem in two broad directions:

1. To determine how accurately daily total insolation can be inferred from satellite (polar or geostationary) and supplementary surface data for agricultural needs, where expected ground resolution would be 25-50 km and accuracy 10-15%.
2. To assess the possibility of an operational system for insolation estimation in real time.

Visible channel data (0.55-0.75 μm) of the GOES satellite of about 8km ground resolution in 64 grey levels were used without internal calibration from grey number to radiance. Surface pressure and precipitable water contents in the atmosphere were used to calculate the transmission function of the atmosphere in clear skies. Tarpley extracted cloud brightness, cloud cover and planetary brightness from the visible channel of satellite data. Solar zenith angle data were combined with this information to correlate with ground measured radiation data in different expressions for different cloudy conditions.

Tarpley found that, the variation of solar zenith angle explains 85% of the variation of solar radiation in clear sky conditions, and again it plays a significant role in cloudy skies, where target brightness makes the dominant contribution. He also observed that, the ancillary information although statistically significant, makes a smaller contribution to the accuracy of estimation than the satellite data. The resulting accuracy was better than 10% of the measured mean of daily total insolation using seven or more observations per day. According to Tarpley, averaging satellite data over a larger area is equivalent to averaging point measurements (by pyranometer) over a longer time period.

During the 1980's

In the workshop "Satellite and Forecasting of Radiation", in 1981, by the Solar Radiation Division of the American Section of ISES, a number of methodologies for estimating solar radiation from satellite images were assembled. The technology had seemed feasible and emerging for short and long term resource assessment of solar radiation (Bahm, 1981). For a number of applications, the demand for an operational mesoscale mapping system was suggested to depict the mesoscale variation.

Gautier (1980) presented a physical model considering in detail the radiative processes in the atmosphere, in clear sky and cloudy sky separately. She also used geostationary satellite data in the visible channel to calculate cloud and surface albedos. Other atmospheric properties like, absorptance, reflectance, (or scattering coefficient) were incorporated from surface climatological data. The cloudy atmosphere was divided into two separate layers and atmospheric properties were used separately for each layer. Scattering was assumed mostly above cloud. The accurate calibration of satellite data were required. Using this sophisticated physical model, she obtained an accuracy within 9% for daily or hourly total insolation. Scattering and reflections were assumed isotropic and absorption was assumed to be only due to water vapor.

Hiser and Senn (1980) presented a different approach to produce mesoscale maps of available solar energy at the earth's surface using GOES single band (visible) data. They were actually looking for solar radiation data measured at the ground for selecting solar power stations and for other purposes. Geographical distribution of this data was also essential. They tried to use sunshine and cloud cover data measured at climatological stations. They then switched to use satellite data for extracting cloud cover or sunshine distribution over a bigger surface area. Surface measured data of solar radiation and sunshine or cloud cover were fitted into a relationship between these two parameters from distributed ground stations over a long period of time. Knowing the cloud cover from satellite data, solar radiation data were calculated using those relationships. This is obviously an empirical method.

Brakke and Kanemasu (1981) obtained standard errors of estimates of total radiation at the ground within 11% using single band (visible) data from GOES satellite applying an empirical method similar to Tarpley (1979) but for a different geographical location.

Davis and Charters (1981) used TOVS low resolution data from NOAA polar orbiting satellite, to estimate hourly and daily insolation using a statistical method. Ground measured radiation data were correlated with two independent parameters, cloudy sky atmospheric transmittance T_{cl} and total precipitable water along the air mass U. Cloud cover N was estimated from satellite data which was combined with a preclassified cloud transmittance function to obtain T_{cl} after attenuation by clouds. The U was calculated from existing empirical expressions using surface pressure and vapor pressure, normalized by the cosine of the solar zenith angle. Then global solar radiation was determined by the following relation:

$$G_t/G_o \;=\; \exp\left(-\left(a + b\,U + c\ln T_{cl}\right)\right) \tag{4}$$

Coefficients a, b and c were obtained by least error fitting. The r.m.s differences were 3.26-4.67 MJ/m^{2}d.

Geostationary satellite data from METEOSAT in two bands, visible and thermal infrared were used by Moser and Raschke (1983 and 1984) to estimate daily or hourly solar radiation. The object was to establish an operational mapping system. The radiative transfer calculations were employed to determine the cloud and atmospheric transmittance of the solar radiation at different zenith angles.

The visible channel (0.4-1.1 μm) was used as an indicator of cloudiness. Additional information on cloud height and on the homogeneity of cloud height was extracted from simultaneously measured infrared radiance (10.5-12 μm). The two-stream approximation was applied where cloud and atmospheric layers were assumed solid plane-parallel. No ancillary surface data were required but boundary conditions on atmospheric parameters (water vapor content, turbidity, absorption, reflection, etc.) were calculated from a number of statistics of satellite data which were then fed back to the main radiative calculation. So the method can be classified as semi-physical and semi-statistical. The mean of the standard error of the estimate of daily total insolation was 11.8% with a range of 10%-14%. The mapping system needs a mini computer for all processing.

Nunez (1984) derived a very simple form of empirical relation between ground data and satellite measured reflectivity in the visible channel (0.55-0.73 μm) of GMS geostationary satellite scanned over Queensland, Australia, from a data set in the period August 1982 - January 1983, namely

$$T = a + b\,(G_r/G_o) \qquad (5)$$

where *a* and *b* are constants. The standard error for estimating daily total global radiation from three daily images was within 11%.

Cano et al. (1986) estimated G_t/G_o as a linear function of target cloud cover index *N* obtained from satellite image in a statistical method using data from GOES:

$$T = a + bN \qquad (6)$$

The index *N* was derived from the scene albedos *A* for each pixel weighted by the boundary albedos that would come from two conditions, fully clear sky and fully overcast cloudy sky, thus

$$N = (A - A_{cs})\,/\,(A_{cl} - A_{cs}) \qquad (7)$$

for which A_{cs} and A_{cl} were found as the minimum albedo and maximum albedo respectively of the scene from a time series of satellite images. The mean of r.m.s. errors from 27 stations was 422 kJ/m^{2}h.

Nunez (1987) again used his simple statistical model for Tasmania, further south of Queensland from GMS visible data for a period of August-December 1983; he obtained errors around 13%. The ground resolution of image over Tasmania was less than over Queensland. One of the reasons for higher error may be due to the higher viewing angle over Tasmania compared with Queensland.

Sorapipatana et al. (1988) developed an empirical bi-spectral method to estimate hourly and daily total global radiation for the first time in southeast Asia from two observations in a day from the GMS satellite in two simultaneous bands, visible and infrared, of HRFAX data. In his method a parameter called cloud effectiveness is calculated from the satellite image which is statistically correlated with the ground measured solar radiation data in the following relation:

$$T = a + b\,\{\,N\,(A_{cl}/A_{cs} - 1)\,\} \qquad (8)$$

where *N* is the fractional cloud cover of the sky and "a" and "b" are the regression coefficients of the statistical model. The term $N\,(A_{cl}/A_{cs} - 1)$ is called the cloud effectiveness. If I_m is the target mean thermal radiance measured at the satellite sensor, *N* is calculated from the infrared data as:

$$N = (I_{cs} - I_m)\,/\,(I_{cs} - I_{cl}) \qquad (9)$$

Daily effective cloudiness was calculated by averaging two hourly cloud effectivenesses at 9:45 and 12:45 hrs. The r.m.s. errors of estimates for daily global solar radiation using this method was 12-14% from only two images in a day. This bi-spectral model is unable to calculate the cloud effectiveness where the clear sky albedo is very low or equals zero such as in the case of large water bodies like lakes and oceans.

Frulla et al. (1988) used Tarpley's (1979) statistical method with further simplification for estimating hourly and daily radiation from GOES single band (visible) data acquired over Argentina. They obtained higher error (15-20% of mean) than Tarpley (1979) in daily total values. The error was in order of 8% for clear sky but very high errors (14%-33%) were obtained in partly clear and cloudy conditions. According to these authors, the mathematical formulation of the regression model perhaps does not adequately describe the real physical process in cloudy conditions, or the independent variables do not contain enough information to account for all processes depleting incoming radiation.

Diabate et al. (1989) present the first successful operational solar radiation mapping system (hardware and software included) which is claimed to be inexpensive. It is based on a micro computer. This system is called "Heliosat Station". It uses the statistical method of Cano et al. (1980) with modification. The analogue WEFAX data from a geostationary meteorological satellite is received by an HF receiver through a parabolic antenna. After digitization the data are passed to an IBM-PC compatible personal computer for processing and for color and monochrome outputs. The accuracy of estimation is claimed to be better than that obtained using some of the older methods. The advantage of this system is that, it produces maps of hourly radiation at the times of satellite observations and cumulative maps of daily total values pixel by pixel from the original maps. Therefore, the radiation map has a very high resolution in order of the resolution of the image. But the receiver system is still costlier than a small receiver of APT images from polar orbiting satellites and data volume is also high. The system cannot be used where geostationary satellites do not cover well, or where the low resolution image is only in the infrared band.

During the 1990's

Ferreira et al. (1991) used the model of Moser and Raschke (1983 and 1984) improved by Stuhlmann et al. (1991) using geostationary satellite (METEOSAT) data over Brazil. Even with the improved model, they obtained higher error in estimation of daily total global solar radiation (7-14% of mean) than the original. Two reasons were given by the authors:

1. The conflict in ground data and satellite data. There might be cloud during satellite scanning and no cloud at other times.
2. Reduced number of satellite images available for the period of study to obtain the representative boundary conditions (minimum and maximum radiances).

It was not known before 1990 that data from the Indian geostationary satellite (INSAT) could be received outside India. Recently, Malik et al. (1991) used INSAT VISSR visible data (0.55-0.75 μm) to produce maps of incident solar radiation (daily and monthly mean of daily) over Pakistan. A single band physical model of Dedieu et al. (1987) was modified and used for this study. Standard meteorological balloon sounding data of water vapor content was used to simulate the clear sky transmission factor accounting for atmospheric absorption and scattering. Quantitative estimates of error of the study were not given but it was explained that the estimation of solar energy correctly followed the real climatological conditions.

Another low cost system was developed very recently by Islam Md. Rafiqul (1993) to produce solar radiation maps on an operational basis using APT images transmitted from the NOAA satellites. The system comprises a small image receiver attached to an IBM compatible PC, a monochrome TV monitor, a monochrome computer monitor and a small dot matrix printer. The coverage of the map with smallest target size of 111 km x 111 km can be as big as 15° latitude and 20° longitude centered on the receiver station. An improved bi-spectral statistical model is used. Three cloudiness factors are calculated from three images in a day (morning, afternoon and evening) which are combined using variable weights to obtain the daily cloudiness factor. The weights are determined by multiple regression between cloudiness and the atmospheric transmissivity of solar radiation measured at the ground. The basic model is:

$$T \;=\; a + b\,Ç, \text{ where } Ç = \text{cloudiness factor} = N\,(A_{cl} - A_{ct})$$

The fractional cloud cover N is obtained from IR data and the albedos are from VIS data (conventional name, channel 2 of AVHRR). The mean standard error of estimate of daily global solar radiation is 12.9% with a range of 6-19% of the measured mean. Total cost of the system is about 11,000 US$. The APT image is receivable all over the globe free of charge.

The cloudiness at a time around noon is more important than at other times of the day when the sun's angle is low. Unlike the bi-spectral method of Sorapipatana et al. (1988) the allocation of variable weights to different cloudinesses at different times seems to give better results. Because the study area is sufficiently large, the spatial variability was included. Whereas Sorapipatana (1988) pooled the ground truth radiation data from four sites of the study area to determine the regression coefficients for a particular time (one month) that give the global influence of the whole area, in Islam's method (1993) the model coefficients are generated for each radiation station separately. Islam's method can also be used to estimate radiation over the ocean surface.

SUMMARY

During more than three decades of operating meteorological satellites, the determination of solar radiation reaching the ground using satellite data has been explored all over the globe. Researchers have used a variety of methods depending upon the resources available to them. The types of source data and desired application usually determines the methodology to be followed. The information associated with such methodologies can be divided into seven categories:

1. Satellite: Polar orbiting or Geostationary
2. Imaging: Resolution (Low, Medium or High)
   Spectral band (Single; VIS or Double; VIS and IR)
3. Formulation: Statistical or Physical
4. Coverage: Local, Regional or Global
5. Ancillary Data Requirement: None, Low, Medium or High
6. Product Accuracy: Acceptable or Unacceptable
7. Temporal Resolution of Product: Hourly, Daily, or Monthly mean.

Combinations of these seven factors were studied in many places. Results of individual studies are unique. But factors like economical, technological and skill limitations as well as national development policy of any country which also play a vital role in selecting a method were not considered.

Measurement of surface and atmospheric parameters like sea surface temperature, atmospheric temperature profile, surface reflectivity, etc., from satellite data were the starting point in the 1960's. Cloud parameterization evolved through the 1960's and continued up to the present by introducing multispectral analysis of precision cloud properties at different spectral and geometric resolutions.

When clouds were assumed the main attenuator of incoming solar radiation towards the surface, the methodologies evolved into estimation of solar radiation reaching the ground from satellite images beginning in the 1970's. Experiments continued through the 1980's to obtain higher accuracy of estimation using different methodologies and different data from different platforms. But improvement was irregular.

The development of operational solar radiation mapping systems was one of the objectives for their usefulness in solar radiation data applications. However, from the end of the 1980's and through the early 1990's, the cost optimization of such a system was chosen as the latest objective for any new research in this field.

It now seems that, the accuracy of estimates of solar radiation by satellite methods depends upon so many factors that some of them still remain unknown. When the same methodology with the same source data was used at different times for different geographic locations, the accuracy was different (Frulla et al., 1988 and Ferreira et al., 1991). No standardization is possible that could make selection criteria clear. So the best selection should be judged on the basis of:

a. Target application (importance of accuracy)
b. Target geographic location
c. Availability of source data
d. Availability or limitation of hardware and human resources
e. Affordability of the target user.

Normal accuracy was limited to 9-15% of mean values. Accuracy does not improve significantly (or optimally) using sophisticated models or adding ancillary information (Tarpley 1979 and Vonder Haar and Ellis 1975 and 1978). The "Solar Energy Data Workshop Report and Recommendation", November, 1973, Maryland, suggested that the systematic error of solar radiation measurement should be within ±5%, however, for most engineering purposes, 10-15% error is acceptable.

Statistical methods are much simpler than physical models but give equivalent results. The number of daily measurements can vary from one to seven. Although diurnal variation of cloudiness can be correctly obtained using a high frequency of observation, the net benefit is not significant when estimating daily totals from two or more measurements in a day (Tarpley, 1979).

Polar orbiting satellites offer global coverage but have lower frequency, whereas geostationary satellite data are most suitable for the areas within the coverage at low latitudes but have high daily frequency. Note that both geostationary satellite data and high resolution images are expensive.

CONCLUSIONS

When the highest emphasis is given to national activities which are directly related to or which directly benefit the developing countries, enlarging old methods or cultivating new methods for estimating solar radiation at the ground from satellite data is not important. Instead, using established methodologies for a low cost operational mapping system for the same purposes is desirable.

The present methodologies depending upon the existing satellite image data quality are sufficient for producing a solar radiation database on an operational basis. The database will be useful for engineering applications involving the development of energy technologies and assessments of environmental, climatological and agricultural parameters for the sustainable development of the economically lagging countries. Some of the methods offer excellent accuracy but their instrumental cost is high. Therefore, the need of an economically viable methodology and technology which could be most appropriate in the light of the present state of the target countries should be appreciated.

LIST OF ABBREVIATIONS

APT	Automatic Picture Transmission
AVHRR	Advanced Very High Resolution Radiometers (NOAA instrument)
GOES	Geostationary Operational Environmental Satellites (the USA geostationary satellites)
GMS	Geostationary Meteorological Satellite (the Japanese geostationary satellite)
HRFAX	High Resolution Facsimile from GMS
INSAT	Indian Satellite
IR	InfraRed (electromagnetic spectrum band name)
ISES	International Solar Energy Society
METEOSAT	The European geostationary satellite
NOAA	National Oceanic and Atmospheric Administration
TIROS	Television Infra-Red Observation Satellite
TOVS	TIROS Operational Vertical Sounder
VIS	VISible band of the electro-magnetic spectrum.
VISSR	Visible and Infrared Spin-Scan Radiometer
WEFAX	Weather Facsimile

LIST OF SYMBOLS

Terms in the parantheses are the units commonly used in this paper.

A	Visible albedo (dimensionless)
A_{cl}	Cloud albedo (dimensionless)
A_{cs}	Clear sky albedo (dimensionless)
A_{s}	Ground surface albedo (dimensionless)
$Ç$	The cloudiness factor of the sky (dimensionless)
G_a	Radiation absorbed by the atmosphere (MJ/m^2 per unit time)
G'_a	Total absorption into earth and atmosphere $G_a + (1 - A_s)\, G_s$ (MJ/m^2 per unit time)
G_n	Net radiant energy into the planet from space (MJ/m^2 per unit time)
G_o	Extraterrestrial solar radiation flux (MJ/m^2 per unit time)
G_r	Reflected radiation towards the space from earth-atmosphere (MJ/m^2 per unit time)
G_s	Downward solar radiation on the earth surface (MJ/m^2 per unit time)
I	Thermal infrared radiance (MJ/m^2 per unit time) or equivalent temperature (°K)
I_{cl}	Planetary thermal radiation in cloudy sky (MJ/m^2 per unit time)
I_{cs}	Planetary thermal radiation in clear sky (MJ/m^2 per unit time)
I_r	Net planetary thermal radiation to the space (MJ/m^2 per unit time)
N	Fractional cloud cover (dimensionless)
T	Atmospheric transmissivity of solar radiation (dimensionless)

T_{cs}	Clear sky transmissivity of solar radiation (dimensionless)
T_{cl}	Cloudy sky transmissivity of solar radiation (dimensionless)
d	Optical path length (cm).

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