Remote Sensing in Transition, Goossens (ed.)

Survey of the main databases providing solar radiation data at ground level

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Keywords: solar radiation, database, information system, climatology

ABSTRACT: Solar radiation at ground level is a necessary input for several applications such as primary production and agronomic related studies or potential solar energy assessments. The user needs consist generally in values of global daily or hourly irradiation with a spatial resolution of approximately 10 km. Relative errors (RMSE) of daily irradiation should be less than 20 %. Spatial coverage (continent) and temporal coverage are of importance. The data must be available conveniently at low cost. Several regional solar atlases have been made by interpolation of ground measurements, taking into account the local variation of climate. Satellite data produce irradiation maps offering a regular sampling in space and a wide geographical coverage. Time-series are also obtained by weather forecast models. Digital atlases have been created as integrated information systems. They comprise a database and software to exploit it. The co-operative systems are connected with other servers that provide necessary weather data to compute solar radiation quantities. This survey of solar databases showed that in a general case, there is a discrepancy between users needs and available databases. This conclusion supports the efforts made in integrating information systems and co-operative systems to overcome the technical limits of measurements by using the information and communication technologies.

1 INTRODUCTION

Incident downwelling solar radiation at ground level is a key input for several applications. Solar energy engineering, optimization of daylight use in building applications, biomass production and crop forecasting, oceanography and limnology applications and urban air quality studies or even the sizing of space borne sensors are among the various domains needing solar radiation information.

Researchers and engineers are facing the problem of solar radiation data retrieval on land or on oceanic surfaces. Their needs consist generally in values of hourly or daily global irradiation and its derived quantities (diffuse component, spectral distribution, spatial structure of the radiation) for various parts of the world. Accordingly, databases should be available that cover the whole earth surface for several years. These data should be available in a high spatial resolution (about 10 km in size) with a relative accuracy of 20 % in root mean square error (RMSE) for the daily irradiation. The data should present a convenient and low cost access.

The access to the relevant information is poor for many reasons. The number of stations measuring irradiation is too small to achieve an accurate worldwide coverage. Access is generally complicated by the various types of data, various storage standards, various units, various ways of expressing time … Space and time characteristics of presently available data are often unsatisfactory. Most often, raw measurements stored and supplied by the present databases are not matching to actual users needs.

Nevertheless, efforts have been made to collect, store and disseminate such information with respect to the user needs.

This paper presents a survey of the main possibilities offered for retrieving solar irradiation values at ground level. This study has been performed by analyzing different information sources of focused data and their characteristics having major interest to users.

2 SOLAR RADIATION RETRIEVAL FROM GROUND MEASUREMENT STATIONS

2.1 *The world radiometric network*

Solar radiation is measured by ground networks of measuring stations. Well controlled measurements have only been available in a limited number of sites, and since the middle of the 20th century or so. Various types of data are measured: sunshine duration, cloudiness, global irradiation and more rarely

its diffuse and direct components, spectral distribution etc. Ground based measuring networks have been established but investments and maintenance costs for each site are of importance. Consequently, national networks often comprise only a few stations, even in Western Europe and North America. In other parts of the world, measures are more rare. Oceanic surfaces are almost totally deprived of measuring sites.

The exact number of stations measuring irradiation throughout the world depends on sources of information. Stations belonging to a national network are not necessarily part of the World Radiation Network supervised by the World Meteorological Organization (WMO). According to the list of stations available from WMO in May 2002, there are 10930 measuring stations, of which 2900 measure the sunshine duration and 751 the global irradiation. Between 1966 and 1993, 1195 stations were measuring the sunshine duration and the global irradiation (WRDC/WMO). As shown in figure 1, the spatial distribution of stations is strongly heterogeneous through the world.

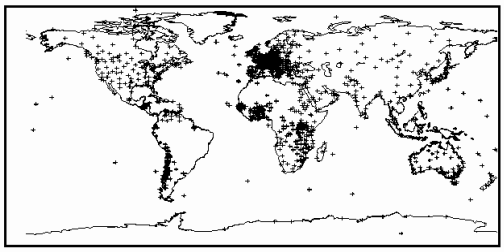

Figure 1. The World Radiometric Network for the period 1966-1993 (source WRDC)

One can see that some regions are better covered than others. The network is very dense in Western and Central Europe and Japan. The coasts of Australia are well covered but not the inland. There are large parts of the world that are mostly not covered.

Estimation of the solar irradiation at each point of a zone needs consequently to proceed with interpolations or extrapolations of measurements. This method induces some errors due to the distance between two stations. Climatic zone differences between measurement sites is also a source of errors.

Several studies have been performed to retrieve solar radiation in this way (Hay 1981, 1984; Hay, Hanson 1985; Perez *et al.* 1997; Supit 1994, 1998; Zelenka *et al.* 1992). It was shown that daily values measured at a station may be considered valid in an area of 30 km radius. The validity area of a daily measurement is taken as a square of 0.5 degrees (approx. 60 km) in size. If we limit ourselves to the land masses (30 % of the Earth surface), and assuming that the 751 stations were equally distributed (which is wrong as shown in the map on figure 1), the probability of being in the vicinity of a station is equal to 1 %. In other terms, in 99 % of cases, the stations are too far to deliver an accurate information to users. Considering only Western and Central Europe, outside Scandinavia, the number of stations is large: 2030 stations, of which 214 are measuring the global irradiation and 890 the sunshine duration. In that case, the probability of being in the vicinity of a station amounts to 7 %. That is 93 % of sites are too far from stations.

These numbers should be considered with care. In many countries, more radiometric stations are available than those reported to the WMO. For example, Germany and the United Kingdom total more stations than the 214 reported above for Europe. In addition, parallel networks exist, e.g. for agriculture or hydrology purposes, that are unknown to the WMO and not managed by the weather bureaus. Their data are usually available to other users. However, it remains that the density of the networks is too small for the delivering of accurate data according to users needs.

2.2 *Access to the data*

Getting the data physically is not always simple. They are usually provided by the weather bureaus in each country. Sometimes, centralized access is possible. For example, the World Radiation Data Center (WRDC) offers an on-line access to archived data for many countries.

Measurements are most often made on a daily basis and not hourly basis, except for a limited number of countries. Users should find models that synthesize hourly irradiation from a daily irradiation. These models call upon statistical knowledge on the hourly profile that is not available at most stations and should be inferred from other stations performing hourly measurements. A good point is that long series of records are most often available in stations.

Another good point is that data are in digital form, even for the past years which have been digitized. The accuracy is excellent if the instrument is well maintained.

Access is further complicated by the various types of data (hourly or daily measurements, global and diffuse irradiation, sunshine duration) that are available for the countries of interest. If collected in several countries, these data have various storage standards and various units (e.g., J/cm^2, J/m^2, Wh/m^2, cal/cm^2). Various ways of expressing time (coordinated universal time, mean solar time, true solar time, local time) are used. A standard exists within the World Meteorological Organization for defining hourly measurement: the hour allotted to the data is the end of the measuring period (e.g., data at 12h is the measurement made between 11 and 12h). It is not always the case in other networks, where the hour may be the beginning of the measuring period or the middle of the period.

2.3 *A particular case: The Baseline Surface Radiation Network*

The Baseline Surface Radiation Network (BSRN) is a project of the World Climate Research Programme (WCRP). It aims at detecting important changes in the earth's radiation fields which may cause climate changes. At a small number (less than 40, see figure 2) of stations in contrasting climatic zones, covering a latitude range from 80°N to 90°S, solar and atmospheric radiation is measured with instruments of the best accuracy available and at a very high (minutes) frequency. The radiation data are stored together with collocated surface and upper-air observations in an integrated database.

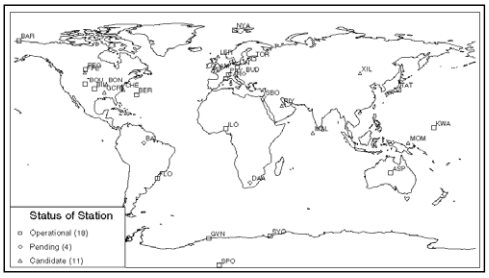

Figure 2. The Baseline Surface Radiation Network (May 2002)

3 SOLAR RADIATION SATELLITE-DERIVED ASSESSMENTS

Several initiatives are operationally producing assessments of the global radiation at ground level for large geographical areas. Satellites are routinely observing the Earth; their data may be processed to provide estimates of the global irradiation. Large geographical regions are such covered and the irradiation is known at every location within these regions. These maps offer a regular sampling in space (pixellated form). The size of the cells varies and ranges from 1 km to 300 km. Time-series originate from 1980 approximately. The situation varies depending upon the source of information.

The relative accuracy (relative rms) of such assessment of daily irradiation is approximately 20 %. The bias is usually very small. Compared to the models based on cloud cover or sunshine duration, the accuracy seems to be similar in regions with very dense radiometric networks (Perez *et al.* 1997; Zelenka *et al.* 1992). In other parts, while the accuracy of the models degrades with usually an increase in bias, that of satellite-derived assessments remains the same.

Probably the most known of these initiatives is the ISCCP program (International Satellite Cloud Climatology Project) and its brother, the SRB (Surface Radiation Budget) program which freely provide maps of the monthly-averaged daily irradiation for the entire world on cells of 280 km in size. These satellite-derived maps offer knowledge of the radiation at any site in the world. The SRB data are of easy access and are delivered by the NASA (Figure 3). They are monthly means of daily irradiation, available for several years and covering the whole world.

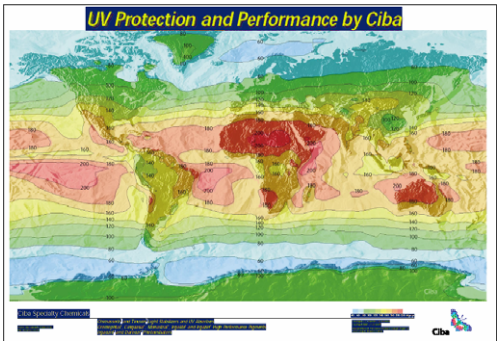

Figure 3. Example of information that is available for the whole world derived from the NASA Surface Radiation Budget project. This is the annual irradiance (energy flux). Units are kLangley. Values are to be multiplied by 1.33 to obtain W/m^2. Copyright CIBA.

The NASA Surface Solar Energy Data Set is derived from the SRB data set and intends to serve solar energy purposes. Figure 4 is an example of the maps that can be obtained through this server for Brazil. The spatial description is coarse due to the large size of the cell.

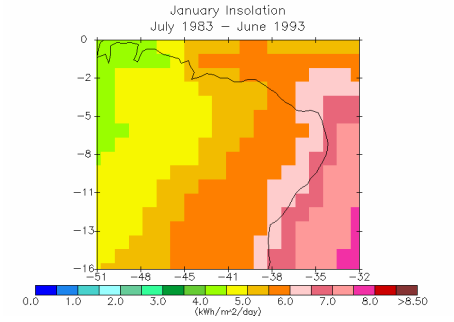

Figure 4. Example of output of the NASA Surface Solar Energy Data Set server. Map of the ten-years average of the monthly mean of daily irradiation for January for Brazil, expressed in kWh/m^2. Note that the displayed units (kWh/m^2/day) are incorrect.

Apart from these international programmes and the NASA programme, several weather bureaus are performing routine processing of satellite images to derive hourly or more frequently maps of irradiation over large areas. These data are used for weather

forecasts and can be delivered to users. Australia, France, Germany, Hungary or United States are known weather bureaus offering products of high quality. Australia delivers such information free of charge on the Internet (figure 5). The spatial resolution of the maps is better than those provided by the international programmes. The spatial distribution of the radiation is much more detailed.

Such maps are more than nice pictures. They show the spatial distribution of the solar radiation at ground level. They demonstrate the relationships between the radiation and latitude, geographical features and orography.

Apart from the weather bureaus, several initiatives established databases that can be accessed by customers, on a free basis or at moderate costs. The Satel-Light server delivers information of statistical type (i.e., cumulative frequencies) for Europe. The server of the University of Siegen (Heidt *et al.* 1998) provides global hourly irradiation over Europe. The SoDa server offers time-series of daily irradiation over Europe, Africa and the Atlantic Ocean.

Several servers deliver maps of irradiation. However, these maps cannot be integrated in the softwares used for modelling the solar systems, except integrated information systems. It follows that most servers propose an access to their satellite-derived databases in the form of time-series for a given location.

4 RE-ANALYSES OF WEATHER FORECAST

Models for weather forecasts are used in a reanalysis mode to reproduce what was effectively observed. The global radiation, called downward shortwave radiation in such models, is one of the modelled parameters. It is usually expressed as irradiance (energy flux, W/m^2) instead of irradiation (energy, J/m^2). Models may deal with the whole world or be of regional impact. The grid cell is approximately 1 – 2 °. Daily values are usually offered. Time-series originate from 1960 approximately.

The SoDa server offers an access to the global daily irradiation derived from the outputs of the NCEP/NCAR re-analyses together with other meteorological parameters.

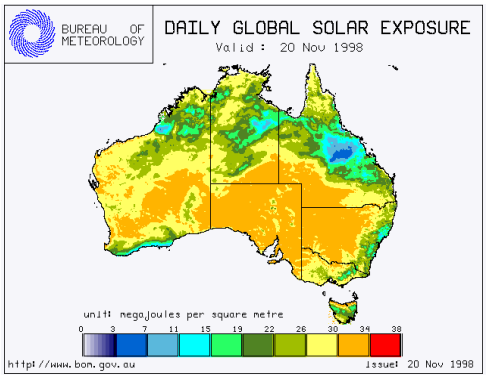

Figure 5. Example of output of the Australian Global Solar Radiation Archive server. This is a map of daily irradiation for the 20th November 1998, derived from satellite images. Units are MJ/m2.

5 INTEGRATED INFORMATION SYSTEM

An integrated information system is a database completed by a software. Digital atlases have been recently created which are more relevant to the field of renewable energies. Presented on CD-ROMs or online through the web, they comprise a database (maps, time-series of ground measurements, synthetic reference years, geographical information...) and software to exploit it (user interface, data management, result presentation, import-export capabilities...). The software also includes models for the computation of parameters of higher level as direct and diffuse components or spectral distribution of irradiation or photosynthetically active radiation (PAR).

5.1 *Meteonorm*

Meteonorm (2000) is a digital solar atlas presented on CD-ROM. It contains a database of ground stations measurements made by a combination of several databases from different parts of the world (Swiss meteorological institute, GEBA, WMO …). The main period of the measurement is from 1961 to 1990. Other climatological data useful for renewable energy engineering are also available (temperature, humidity, wind speed, precipitation).

The software included in this atlas permits to retrieve radiation data by a model of interpolation. It contains also algorithms to calculate radiation on inclined surface. Radiation data provided by this tool are available in various units according to user needs.

5.2 *Satel-light*

The European Union funded Satel-Light project offers a database of solar radiation data derived from satellite images, which can be accessed through the world wide web and produces value-added information mostly for daylighting purposes (Fontoynont *et al.* 1998; Reise *et al.* 1999). The database covers the European continent for a period between 1996 and 2000.

Though limited to the solar energy domain, these atlases and servers are excellent examples of what can be done to bring to users the information they require starting from basic meteorological measurements.

5.3 *The European Solar Radiation Atlas (ESRA)*

This atlas is an instrument dedicated to providing knowledge and aiding exploitation of the solar resources across a wide sweep of Europe, from the Urals to the Azores and from North Africa to the Polar Circle. The input data are based on the period 1981-1990.

This atlas provides a broad overview with supporting maps. It starts by describing the course of the Sun across the sky as it varies throughout the year with geographical location. Then the interactions of the solar radiation with the atmosphere and its components (haze, turbidity, clouds, etc.) and the separation of the solar radiation into the direct and diffuse parts are discussed. Sixteen coloured maps provide data on the monthly mean global, beam, diffuse irradiation on horizontal surface and the clearness index for March, June, September and December. The mapped values are averaged over the 10-year period 1981-1990. Additionally there are the corresponding four annual maps, also a country-based relief map and a map of ground observing stations used. There are two special maps giving zones of similar irradiation and zones of similar biomass productivity.

The CD-ROM contains a database, which offers spatial (every 10 km approximately) and temporal climatic information for different time scales (from climatological means - more than 700 stations - to hourly values - 7 stations). It includes the solar resources: irradiation (global and its components), sunshine duration, as well as air temperatures, precipitation, water vapour pressure, air pressure for a number of stations. The CD-ROM also contains the software to exploit the database.

The software uses either a “map” or a “station” mode at user choice. In the first case, any geographical site can be designated. In the second mode, only the available measuring stations can be selected. The software includes algorithms covering the following fields: solar geometry, optical properties of the atmosphere, estimation of hourly irradiation on slope under cloudless skies, estimation of solar irradiation values (going from daily to hourly values, conversion from horizontal to tilted surfaces), spectral irradiance, illuminance, daily mean profiles of temperature and other statistical quantities (central moments, extremes, probability, cumulative probability and utility curves). Graphics can be displayed in two or three dimensions. Applications in solar engineering can be handled. A few new algorithms were developed. Among them is a model for the assessment of the irradiance and irradiation under clear-sky conditions developed by Page (1995), which was proved to perform in checks by independent authors (Rigollier *et al.* 2000).

Maps are one attractive aspect of the ESRA. Spatial interpolation techniques do not lead to satisfactory results for meteorological parameters. For a start, terrain height has a great impact. Hence, maps were constructed only for solar radiation, its components and the clearness index. An innovative method was developed, following the path shown by Zelenka (1994), and based on the fusion of ground-measured data and satellite-derived maps of radiation (Beyer *et al.* 1997).

The ESRA continues, at enlarged scale, the previous work of the European Commission on solar radiation mapping (Commission of the European Communities, 1984a, b, 1997) and complements similar works in other European programmes, e.g., the European Wind Atlas (Troen, Petersen 1989), the Solar Radiation Atlas of Africa (Raschke *et al.* 1991). These atlases are on paper only. Compared to them, the ESRA benefits from the advances in information technologies. Databases are available, digital values can be exported, interactivity is everywhere, complex computations can be performed. The elevation of any geographical location is embedded in the database. In addition, the ESRA offers map capabilities, which are presently unique in solar radiation atlases

The CD-ROM-based atlases have their advantages and limitations. Further progress in the dissemination of information on solar radiation and resources is expected due to the world wide web capabilities. This approach is already demonstrated by the co–operative information systems.

6 CO-OPERATIVE INFORMATION SYSTEM

Such an information system is essentially based on the benefit of an interactivity between different web servers. Information-delivery system is co-operating with other servers that provide the necessary weather data. The two following examples present clearly the advantages of such co-operation.

6.1 *The RETScreen system*

The RETScreen system calls upon data from the NASA Surface Solar Energy Data Set. The user is invited to copy outputs of the NASA server and paste them into the input table of the RETScreen software. The RETScreen International Photovoltaic Project Model (version 2000) can be used worldwide to easily evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction for three basic PV applications: on-grid, off-grid, and water pumping. For on-grid applications the model can be used to evaluate both central-grid and isolated-grid PV systems. For off-grid applications the model can be used to evaluate both stand-alone (PV-battery) and hybrid (PV-battery-genset) systems. For water pumping applications the model can be used to evaluate PV-pump systems.

The RETScreen International Online Weather Database provides users access to weather data from more than 1,000 ground monitoring stations around the world. These data can be "pasted" to the pertinent cells within the RETScreen software. The database is provided free-of-charge and it is accessed directly through each of the 8 software models available for free download from this Website. As an alternative the user can use satellite data, particularly for the case when the project location is not close to a ground monitoring station. The NASA Surface Meteorology and Solar Energy Data Set provides RETScreen users access to satellite derived weather data for the entire surface of the planet. Via a direct Internet link to the NASA website, the user may simply "copy" this data from the NASA Website and then "paste" it into the RETScreen spreadsheets.

6.2 *The SoDa web server*

The project SoDa is based on the previous experience gained in the realisation of the ESRA product and the servers Satel-Light, Avalanche and SWITCH, and uses it as a springboard to answer customer needs by an efficient use of advanced information and communication technologies. An integration of information sources of different natures within a smart network is realized (see online at http://www.soda-is.com). These sources include databases containing solar radiation parameters and other relevant information. Several of these databases originate from an advanced processing of remote sensing images. Several were available separately and the SoDa Intelligent System builds smart Internet co-operation between sources. The information sources also include application-specific user-oriented numerical models and advanced algorithms. The system is being validated through user trials. The project SoDa focuses on several applications: energy-conscious building design, daylighting, vegetation, environment, climate change, oceanography, health and industrial use of renewable energies.

7 CONCLUSION

In most cases, accuracy of solar radiation information available is not that expected by users. Nevertheless, solar radiation data at the ground level are retrievable by a diversity of tools. Ground station measurements are far from being the only answer to user needs. Real efforts have been performed to provide irradiation values in various parts of the world in a satisfactory way. Satellite-derived assessments represent an accurate solution for the mapping of the solar radiation over a wide geographical area. Moreover, combining measured or assessed data and physical models permits a convenient access to the information. Co-operation between several sources of information provides fruitful results. Efforts made in integrated information system and co-operative system have to be pursued to overcome the technical limits of measurements by using information and communication technologies.

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