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Enhancing satellite derived irradiance data for taking into account sub-pixel structures relevant for solar energy system analysis – current practice and future options

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Abstract

Satellite derived irradiance information currently approaches the status of a standard source for irradiance data used in solar energy system analysis. Due to intrinsic limitations in both spatial and temporal resolution, these data fail to give information of the full dynamics of the irradiance field in space and time. The analysis of systems comprising a sensibility to details of the temporal evolution of the irradiance field (i.e. systems comprising short-term storage elements) and of systems with sensibility to the spatial inhomogeneity of the irradiance field (i.e. large photovoltaic- or CSP-power plants) require knowledge of the "fine-structure of the irradiance field. Thus, methods for a respective enhancement of the satellite derived data are needed. This contribution presents various approaches discussed for setting up fine scale input data for the study of solar energy systems.

Keywords: fine scale irradiance data, irradiance field, temporal and spatial structure

1. Introduction

With the increasing availability of satellite derived irradiance information, this type of data set is more and more in use for the design and operation of solar energy systems, most notably PV- and CSP-systems. By this, the need for data measured on-site is reduced. However, due to basic limitations of the satellite-derived data, several requirements put by the intended application cannot be coped with this data type directly.

Grid integration studies and studies for systems involving either short-term storage devices (batteries) or show a sensibility to large power gradients, require data on the generated power - and thus on the irradiance - with a time resolution as short as one minute or even one seconds. With respect to spatial resolution, for a reliable modeling of both small and large solar installations, which can cover area from a few square meters up to square kilometers, respectively, information on the evolution of the area averages of the irradiance as well as on the inhomogeneity of this field is required. In this regard, the satellite-derived data are currently confined to a temporal sampling of - at best - a 10-15 min resolution. The spatial resolution is at best in the kilometer scale (depending on satellite type and data set), presenting spatially averaged information for the respective area, i.e. the pixel). Thus, in view of the requirements mentioned, the raw satellite information has to be enhanced in both space and time resolution by additional information to be fully applicable for all aspects of the system modeling.

2. Approaches

2.1 Enhancing the temporal resolution of irradiance information

The most direct approach concentrates on the temporal information, with the aim to paste synthesized high-resolution data into the low-resolution original sets. Pre-requisite is an appropriate model for temporal structure extracted from respective measurements. The models are mostly based on information directly

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extracted from ground measured data. Basic work in this field was done by Skarveit and Olseth 92 by a detailed analysis of statistical properties of short term (here: down to 1 minute) values of the clears sky index. Models to describe the probability density function (PDF) and the autocorrelation characteristics of the sets are identified. Based on this, universally applicable tools to generate appropriate short term time series of global and diffuse irradiances with pre-described hourly averages have been developed, see e.g. Remund and Müller 2011. An alternative approach presented by Bright et al. 2015 is based on first describing the temporal evolution of the cloud cover given in octa and handling the distribution of clear sky index in dependence of the cloud cover. The temporal evolution of the cloud cover is modelled by a Markov approach (which could be extended to a spatial field). Fig. 1 gives examples for the resulting time series.

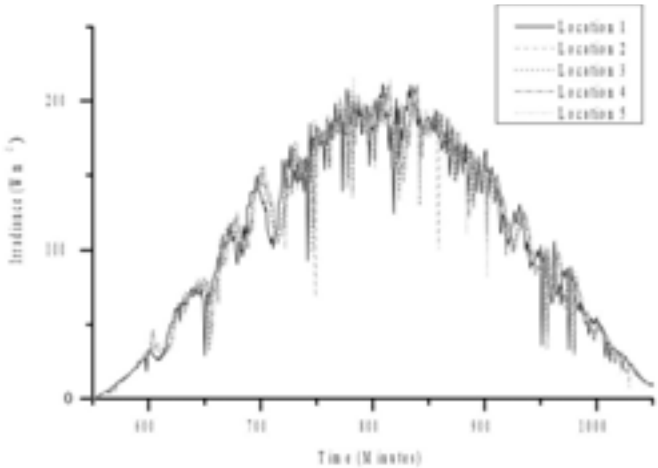

Fig. 1: Examples for daily time series of irradiances at different locations generated by the Bright et all 2015 model (taken from Bright et al. 2015). The mutual correlation of the series is up to now not tested.

Other more direct derivatives of the Olseth and Skartveit 1992 approach developed to cope with the direct normal irradiance as well are given by e.g. Beyer et al. 2010, Polo et al. 2011 and Fernández-Peruchena et al. 2015. Fig.2 gives examples for respective daily evolutions of the 1 min. global and direct normal irradiances.

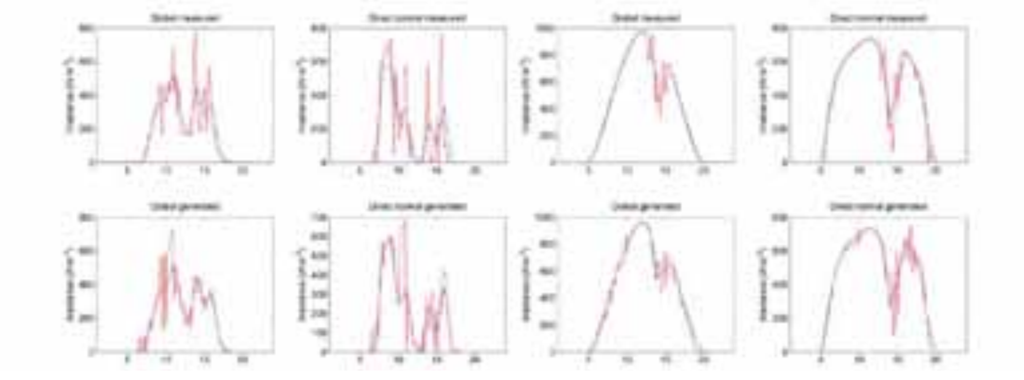

Fig. 2 Examples of daily evolution of global and direct normal irradiance with low (blue) and high (red) time resolution, Upper row presents measured data, data with high time resolution in lower row are synthetic (taken from Polo et al. 2009).

Validation of these schemes can be done by comparing simulations of the performance of solar energy systems for real and synthetic input data (see e.g. Beyer et al. 2010). When applying this approach to spatially distributed systems e.g. CSP-systems limitations are given by the fact, that it has to be assumed that the system is affected by a homogeneous irradiance field – which in general is not the case. This calls for additional information on the spatial statistics of the irradiance field.

2.1 Analysis of the spatial structure of the irradiance field based on fleets of point measurements

To gain the information on the time and space structure of the irradiance, dedicated measuring campaigns had been set up. Early examples as e.g. given by Beyer et al. 1993 and 1994 investigating the space/time structure of the irradiance field on scales of 100m and 1s respectively. More actual examples are e.g.

reported by Kuszamaul et al. 2010, Sengupta and Andreas 2010, Madhavan et al. 2015. Luger et al 2013 and Öchsner et al. report on a campaign analyzing both, the small scale structure of the irradiance field covering a MW scale PV system as measured by fleet of irradiance sensors and the reaction of the PV system. Based on the set of irradiance data, Luger et al. 2013 propose a method for the reconstruction of the field cased on the time series of the point measurements and (see figs. 3,4).

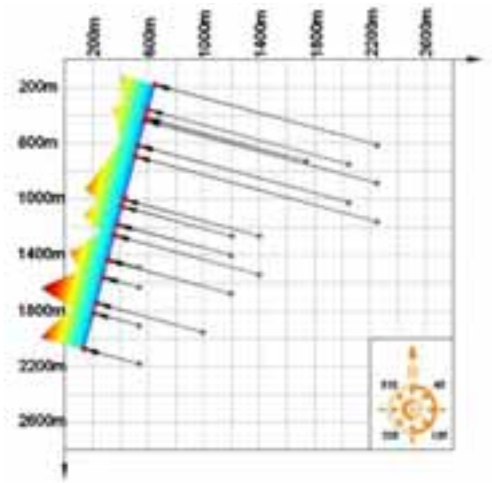

Fig. 3: Generating an irradiance field driven by measurements of a fleet of irradiance sensors. From the cross-correlation structure of the point data a cloud drift vector is derived. Assuming rigid clouds and an appropriate interpolation techniquwtime coherent irradiance bands can be constructed (taken from Luger et al. 2013).

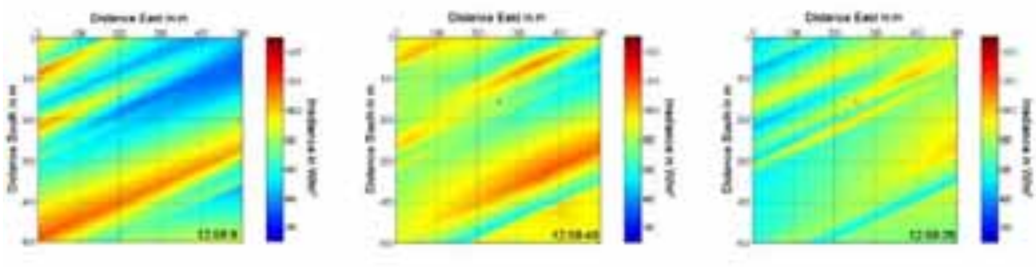

Fig. 4: Consecutive irradiance field situations generated by the method presented by Luger et al. 2013 (taken from Luger et al. 2013).

The procedure makes use of the assumption that the temporal evolution of a highly fluctuating irradiance the field is governed by the movement of shadow casting clouds, and is thus linked to the spatial structure of the cloud field and its displacement over time.

2.2 Analysis of the space/time structure of the irradiance field based on sky image analyses and models for the synthetizations of irradiance fields derived

As the structure of the irradiance field is governed by the evolution of the cloud field, the explicit analysis of cloud field geometry comes into the focus. With information on cloud field geometry and dynamics, the modulation of the irradiance by this field can be modelled with space and time resolution according to the resolution of the spatial cloud features.

As data source, ground based cameras proved useful. Fig.5 gives an example for raw and processed sky images presented by Nitche et al. 2014. The processing used here aimed at the separation of the pixels containing clouds. This cloud image offers the basis for an analysis of the clouds as two dimensions spatial structure.

As tool for the structural analysis, the description of the clouds as fractal object proved helpful. The fractal characterization of the cloud circumference was applied by e.g. Beyer et al. 1996. Based on the fractal dimension of the cloud circumference for a cumulous cloud field a scheme for the generation of a synthetic field with similar characteristics was set up. Fig. 6 shows a synthetic cloud shadow band. By assuming a cloud drift speed, the shift over a (Generator-) area of interest can be modelled, resulting in a cloud modified irradiance time series at each point at the ground effected by the cloud field (see Fig. 7 for a single point series). It could be shown, that the resulting irradiance field can reflect statistical properties of the ground measured irradiance field (Beyer et al., Hammer and Stolzenburg 1993).

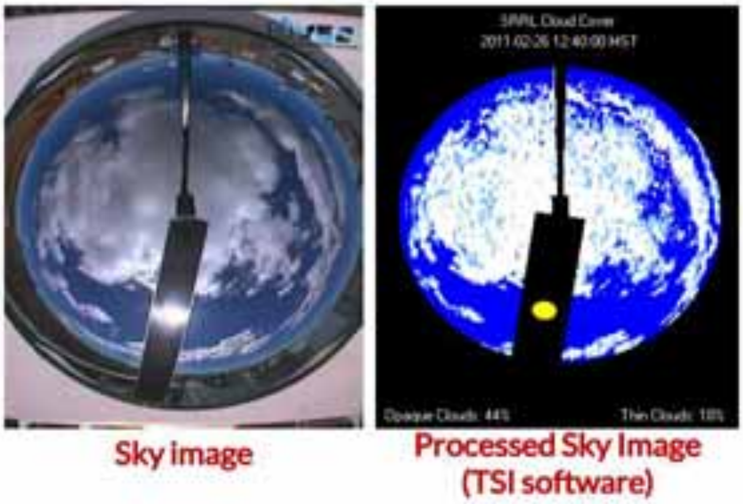

Fig. 5: Photographs taken by a sky imager. The image on the right is processed for cloud/clear sky separation. (taken from Nitsche et al. 2013).

Fig. 6: 2D Cloud band generated according to a fractal dimension of the cloud circumference (taken from Beyer et al. 1993).

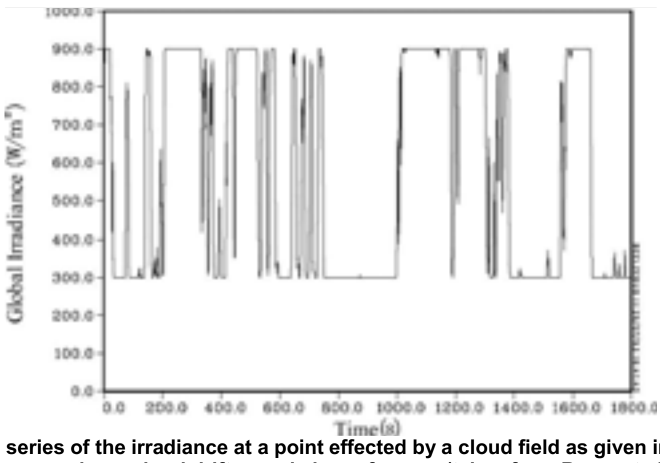

Figure 7: Time series of the irradiance at a point effected by a cloud field as given in Fig. 6. , drifted across assuming a cloud drift speed circumference (taken from Beyer et al. 1993).

This approach has been taken up by Cai 2014. An irradiance field modulated by a fractal cloud field generated similar to the abovementioned approach is shifted over a housing area area with high PV penetration of aprox 2*2 km^2 extension. Fig.8 gives an example for the cloud band and the resulting shadow pattern generated here. Fig.8 gives an example for the for the system reaction concerning the PV effected power at the substation and the voltage reaction of the grid.

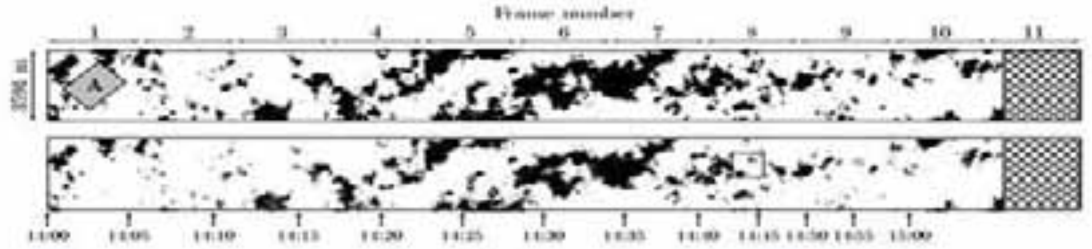

Fig. 8: A cloud band and resulting shadow pattern a given by Cai 2014. The time marks at the bottom are linked to the cloud drift speed assumed. The study area is marked by A (taken from Cai 2014).

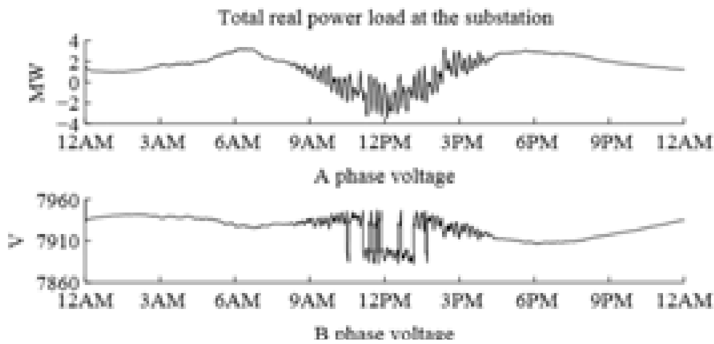

Fig. 9: Grid reaction to the passing cloud field. The upper graph the time pattern of the load of the substation effected by the PV generation, the lower graph gives the respective voltage response (the sharp transitions are caused by actions of transformer tap changes (taken from Cai 2014).

2.2 Other Methods for cloud field generation stemming

Another scheme for the generation of 2D cloud fields is based on information on cloud fraction, cloud and gap cords applying of cellular automata is suggested by Alexandow et al.2010. These automata give a procedure to populate a prescribed mesh with clouds according to the selected distribution properties and can be applied on various spatial scales. This procedure can be performed in steps of consecutive resolutions. Fig. 10 shows the result of such process.

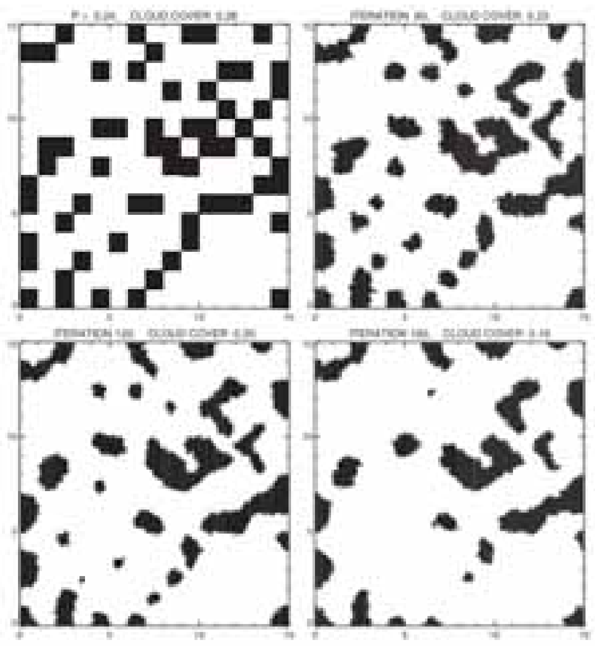

Fig. 10: The generation of a cloud field by a cellular automata scheme as given by Alexandrov et al. 2010. The resolution of the field increase with iteration (from top left to top right to bottom left to bottom right) (taken from Alexandrov et al. 2010

2.3 Methods for the synthetization of 3D cloud fields based on detailed distribution of cloud constituents

Based on detailed information of the structure of cloud fields, as e.g. liquid and ice water content derived from radar observations the 3D spatial structure of the respective fields can be extracted and be used for the generation of respective synthetic fields. Kew 2003 has set up a scheme for the generation of cirrus cloud fields. The model is based on 3D presentation of the spatial power spectral densities of the parameters inspected. The spectra form the basis of an inverse Fourier transform, which by randomly selected phases results in a stochastic filed. Fig. 10 shows an example for a 3D field of the ice water content covering 200km*200km with a resolution of 1km. This field generated according to desired large scale properties can form the basis for detatailed radiative transfer calculations giving a pattern of the irradiance at ground level.

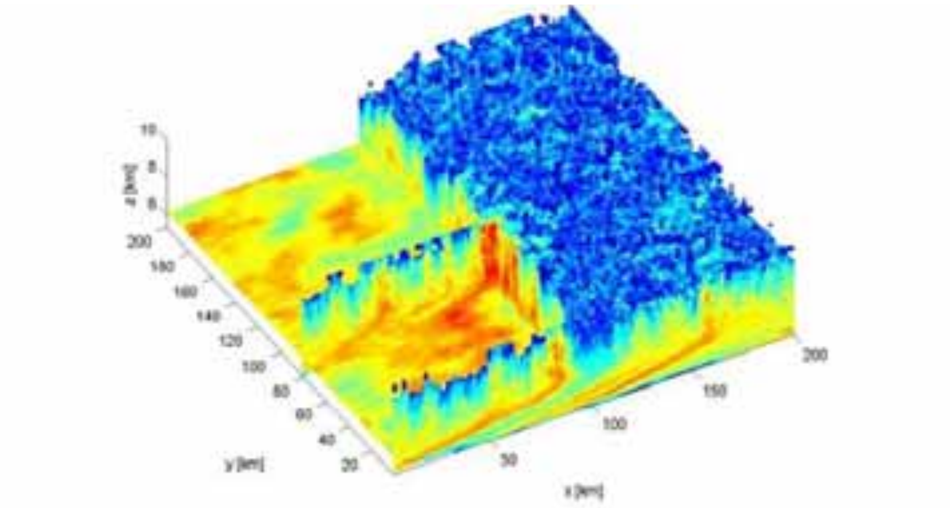

Fig. 10: Presentation of a synthetic 3D field of the ice water content (IWC). For demonstration a section is cut away (taken from Kew 2003).

2,4 A general procedure for the generation of cloud fields with arbitrary optimization goals

A more general scheme for construction of 3D clouds, that can handle various goal values for the statistical properties of the field is given by Venema 2005. It uses evolutionary algorithms to iteratively modified an initial field until is statistical properties approach the goal characteristics (e.g. power spectra). In fig.11 two examples for the outcome of this procedure are given, concerning a 2D field of cloud water content generated based on 1D measured power spectrum. The panel on the right shows the evolution of a cloud, constructed based on selected measured statistical cloud properties.

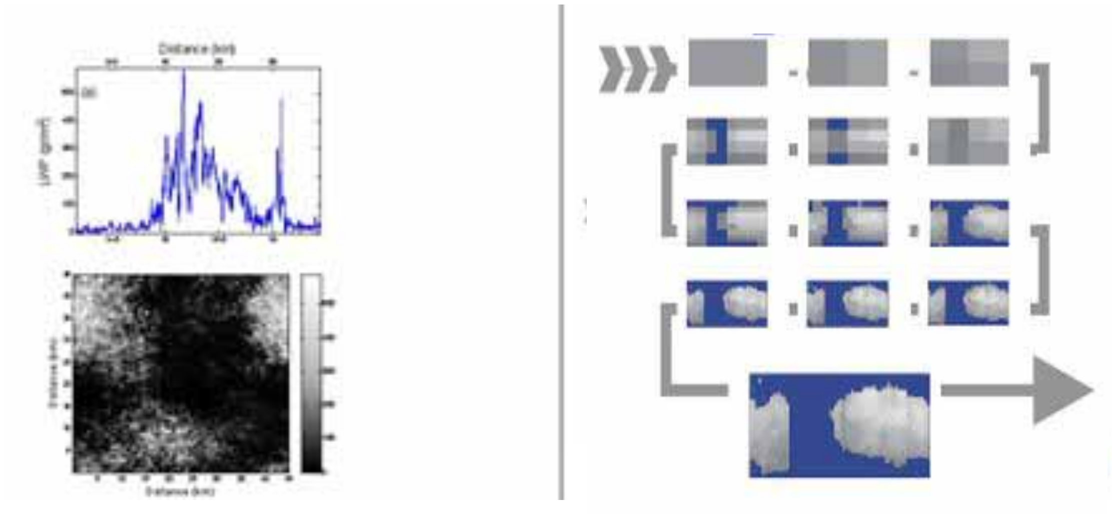

Fig. 11: Outcomes of a procedure of Venema 2005 to modify initial fields iteratively to present prescribed statistical characteristics. In the left panel a 2D field of cloud water content generated on the basis of a 1D spectrum is given. The right panel presents the evolution of a 3 D cloud structure by consecutive refining (starting upper lef) aimed to present selected measured statistical properties (taken from Venema 2005).

3 Conclusion

Over the years a variety of procedures had been developed to generate synthetic high-resolution (e.g. showing minutely resolution) irradiance time series that can be merged in sets with lower resolution (e.g. the seies derived from satellite information). For the generation of respective 2D fields, additional information on the spatial statistics have to be added. For this task most work is done be approaching the spatial structure of the irradiance field via the analysis of the spatial structure of the cloud field causing the statistical disturbance of the irradiance field. Various schemes for the generation of 2D cloud fields showing statistical properties close to the cloud characteristics derived from e.g. sky images. For application key parameters of the cloud field e.g. the average cloud cover ration must be extractable from the large scale information. New developments from basic meteorological research more directly tied to the modelling of the cloud physics offer new ways for an extension to the handling of 3D fields and the application of radiative transfer calculations to derive detailed spatial information of the irradiance field and, with information on spatial cloud dynamics (drift), detailed temporal information.

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