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POTENTIALS OF IMAGES FROM GEOSTATIONARY SATELLITE DATA FOR THE ASSESSMENT OF SOLAR ENERGY PARAMETERS

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ABSTRACT

Images taken by meteorological geostationary satellites are currently used to map global radiation. Several methods exist which process these images. Among them, the Heliosat method ranks as one of the most accurate and one of the easiest to use. Typical uncertainties (rms.) of such assessment are about 10 % for the monthly mean global irradiance on the ground, about 10 % for the daily value, and about 20 % for the hourly value. Use of ground measurements and proper processing (e. g. kriging) increase the accuracy of the estimates in global radiation.

Splitting the global radiation into its direct and diffuse components is not currently made on an operational basis. This requires additional information, such as turbidity in clear skies and geometrical and optical properties of the clouds, which is not available from the current geostationary satellites. However, some methods have been proposed which make use of the sole satellite data and which rely on assumptions replacing the missing information. In assessing the components of the global radiation, one should take care of the space-time scales he is dealing with: they are of paramount importance in designing a method, of its usefulness, as well as in the evaluation of its accuracy. It is emphasized that satellite images are measurements taken by a radiometer and as such obey the theory of signal processing, particularly space-time sampling constraints. The application of such images and of their processing is limited to time scales equal or greater than 1 hour, and to space scale equal or

greater than two pixels (about 20 km). Therefore, we cannot treat the case of fragmented cloud coverage, unless additional external information is available. An important aspect to be taken into account when satellite-derived and ground-measured information are to be compared, either for calibration or validation, is the fact that satellite information is a snapshot over a large area, while ground information is a time-integrated pinpoint measurement.

Of course practical problems to be solved are strongly dependent upon the particular applications, with major effects of space and time samplings. For example, in daylighting for a peculiar building, detailed spatial distribution is required for a very accurate assessment of the luminance. The large size of a pixel prevents from having this information, and the best and most useful that can be got is likely a sky class together with some relevant probabilities.

In daylighting as well as in many other applications in solar energy, it is necessary to split the global radiation into its diffuse and direct components in order for example to be able to compute values on tilted surfaces. Keeping in mind the above-mentioned limitations, several works have been made to infer diffuse radiation from satellite images.

Some of these works are briefly presented, their principles and their uncertainties. Then future tracks are discussed which rely heavily on numerical models of the radiative transfer within the cloudy or cloud-free atmosphere. The advantages and drawbacks, as well as the pending questions are presented. Such approaches require additional information that are not available by the sole use of the data of the geostationary satellites. The supply of these data, the robustness of the method to these data are discussed, too.

It is shown that some properties, such as turbidity, geometrical and optical properties of the clouds, are predominant for the assessment of the diffuse and direct components. These properties are best estimated by some other satellites and it is recommended to use them in order to gain in accuracy. However this leads to a large increase in complexity of the processing chain as well of the fundamental problems to be solved with respect to the space-time characteristics.

1. INTRODUCTION - THE HELIOSAT METHOD

Images taken by meteorological geostationary satellites are currently used to map global radiation. Several methods exist which process these images. Among them, the Heliosat method ranks as one of the most accurate and one of the easiest to use. The Heliosat project has been developed at Ecole des Mines de Paris under the auspices of both the Commission of the European Union (DG XII-F) and the French Agency of Energy, beginning in 1978. It has two purposes: the estimation of incident solar radiation at ground level from images of the earth acquired by geostationary satellites, and the production of detailed maps of the spatial distribution of the global radiation (and of its components, if possible) in real time. A large number of works from Ecole des Mines de Paris (six Ph.D. theses), and also other institutes, have assessed many times the good accuracy of the Heliosat method by the means of comparison with ground-based pyranometers. They have also shown its simplicity, its reduced computing-time, its possible levels of automation, its acceptance of different kinds of geostationary satellites (Meteosat, GOES, GMS) and of data (raw data, B2 data, PDUS data and digitized WEFAX data), and its relevance in real-time and operational constraints.

The principle of the Heliosat method is the construction of a "cloud index" resulting from a comparison of what is observed by the sensor to what should be observed over that pixel if the sky were clear, which is related to the "clearness" of the atmosphere. In preparation to the determination of the cloud index, a reference map of the albedo for clear sky is constructed (Moussu *et al.*, 1989). Given a time-series of images, it is evaluated at each pixel in a recursive fashion by minimizing the variance between the measured radiances and those resulting from the clear sky model, the cloudy cases being eliminated at each step (Cano *et al.*, 1986). Figure 1 provides a diagram of the method.

At each pixel of the current image, the apparent albedo is computed as:

$$\text{apparent albedo} = \frac{(\text{DC} - \text{DC0})}{(\text{extraterrestrial radiation})\,(\text{geometry factor})(\text{clear sky transmittance})}$$

where

- DC means ‘digital count’, DC0 being what can be called the sensor zero (DC is not necessarily calibrated),
- the extraterrestrial radiation is computed for the current day,
- the geometry factor accounts for the illumination and the viewing geometry,
- the clear sky transmittance is provided by simple empirical models.

The cloud index $n^t(i,j)$ at point (i,j) for given time t is defined as a function of the characteristic reference albedo $\rho(i,j)$, the apparent albedo at the same point measured by the satellite $\rho^t(i,j)$, and the average albedo of the cloud tops ρ_c (see Figure 1). The computation of ρ_c is performed using the inverse of the algorithm used for determining the reference albedo map and retaining only the cloudy areas. The histogram of this "only cloud" image provides an estimation of ρ_c.

The clearness index KT(i,j) is defined as the ratio of global radiation at ground on an horizontal surface G(i,j) to the horizontal irradiance outside the atmosphere $G_o(i,j)$:

$$KT(i,j) = G(i,j) / G_o(i,j)$$

Several previous studies did show a linear relationship between the cloud index and the clearness index, where a and b are positive and have been determined once for ever:

$$KT^t = -a\, n^t + b$$

Then the hourly global radiation at ground level on a horizontal plane is determined according to: $G^t(i,j) = - KT^t(i,j)\, G_o{}^t(i,j)$

The Heliosat method can run in a fully automatic fashion on any kind of Meteosat visible data (Diabaté *et al*. 1989; Wald *et al*. 1992). It provides accurate hourly estimates of the global radiation at ground. Furthermore, it gives as by-product estimates of the cloud cover and also maps of ground albedo (Moussu *et al*. 1989). The latter have been employed to study the changes in albedo in the Western Africa during the whole year 1984 (Diabaté *et al*. 1989) or the hydrological regime of Lake Chad during the past years, including the 1970's drought (Wald, 1990).

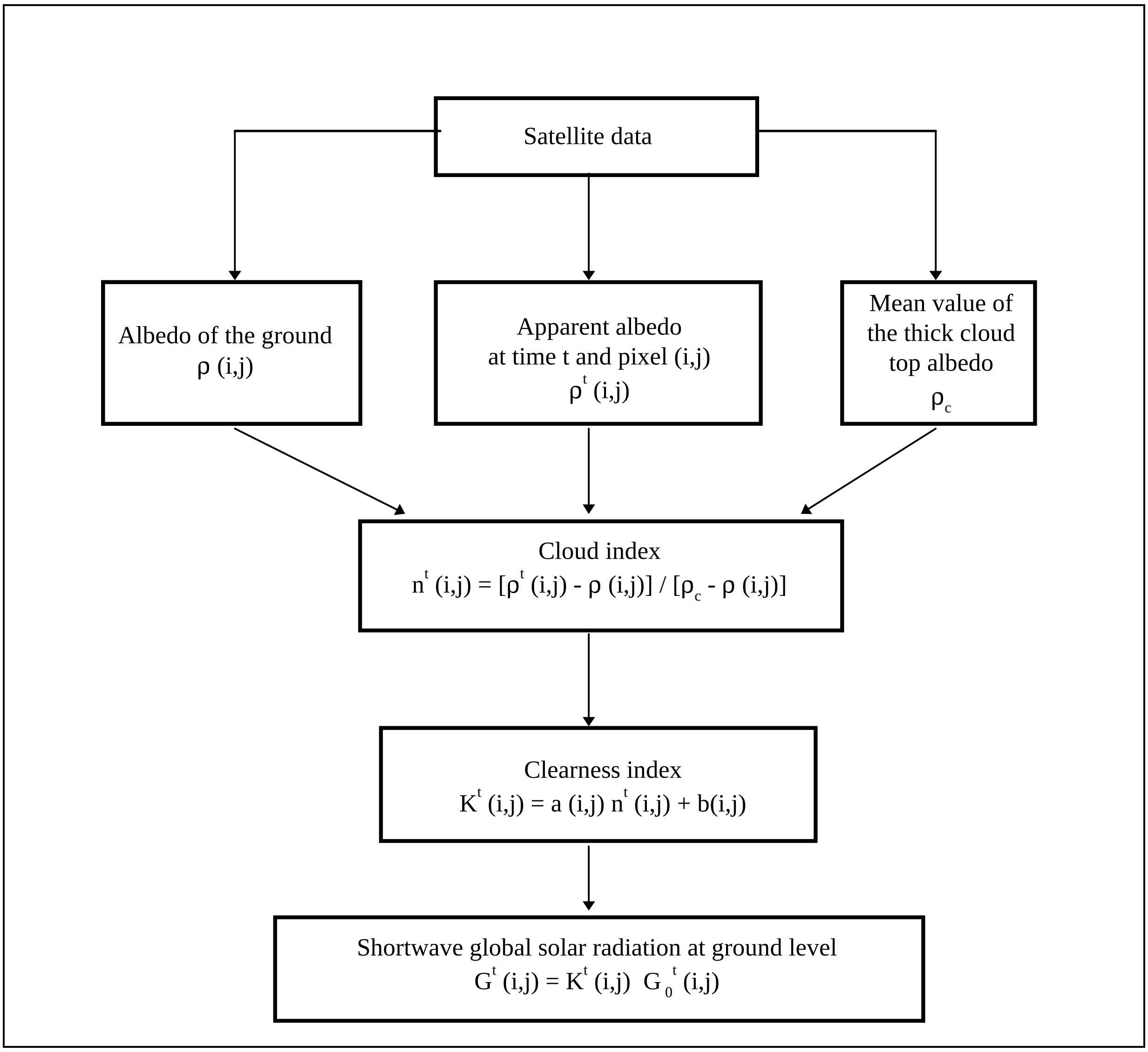

Figure 1. Diagram of the Heliosat method

A model has been proposed by Diabaté (1989) for the assessment of the monthly mean of daily sums. An analytical law has been fitted onto measurements taken by Météo-France for 10 years with a relative deviation (rms.) less than 1 %. This model has then be applied to hourly values derived from satellite data through the Heliosat method. Only three values are available per day. When compared to ground measurements, the relative error (rms.) in reconstruction is about 10 %. The larger the number of images used per day, the lower the level of error. The error depend also of the size of the pixel. Stuhlmann *et al.* (1990) applied their IGMK model to satellite images having a resolution of about 50 km (called B2-type data). Having five images per day, they found a similar error, *i.e.* 10 %.

Though the algorithm exists for about fifteen years, developments are still made. For example, Beyer *et al.* (1996) proposed some changes which may result into an easier use and installation of the Heliosat method and a better accuracy if confirmed by more experiments.

Many comparisons (several thousands) between Heliosat, other methods and ground measurements have been made by several independent research teams (see e.g. Diabaté, 1989; Diabaté *et al.*, 1988; Grüter *et al.*, 1986; *Solar radiation atlas for Africa*, 1991; Zelenka *et al.*, 1991). The results are independent of season - except in seasonally snow-covered areas -, of geographical areas and of satellites, type of data, and the quality (even the absence) of the calibration of the satellite data. Some very recent works have shown that merging a few ground stations measurement into the satellite-derived maps, make the errors decrease by a few per cent (Beyer, Wald, 1996; Zelenka *et al.*, 1991). The error is now a function of the distance to the closest station. The standard Heliosat method ranks as one of the most accurate. At pixel level (10x10 km^2) the relative error (rms.) is about

- 15 % or better for the assessment of the hourly value,
- 10 % or better for the monthly mean for a given hour,
- 10 % or better for the monthly mean of daily sums.

Heliosat also means a software, the Sun-UNIX version of it made at Armines / Ecole des mines de Paris being in public-domain and available on an Internet server (http://www-cenerg.cma.fr/tele). A PC-based package including a satellite data receiver has also been developed and is marketed and sold by a French company. The method is currently used by several institutes in Europe and elsewhere with geostationary satellites like Meteosat (Europe), GOES (USA) or GMS (Japan). A scientific network ensures collaboration between these institutes and improvements in the method.

2. LIMITATIONS IN ASSESSING ADVANCED SOLAR ENERGY PARAMETERS

Splitting the global radiation into its direct and diffuse components is not currently made on an operational basis. This requires additional information, such as turbidity in clear skies or geometrical and optical properties of the clouds, which is not available from the current geostationary satellites. However, some methods have been proposed which make use of the sole satellite data and which rely on assumptions replacing the missing information. But first of all, one should take care of the space-time scales he is dealing with in assessing the components of the global radiation. Such scales are of paramount importance in designing a method, including its usefulness, as well as in the evaluation of its accuracy.

The typical size of a pixel within images from geostationary satellites is about 10 km. Images are acquired every half-hour or every hour. It is then obvious that no one can expect to derive directly from such images parameters having smaller space-time scales, such as for example, the luminance entering a window facing a certain direction. Satellite images are nothing else that measurements taken by a radiometer. As such they obey the theory of signal processing, particularly to space-time sampling constraints. The application of such images and of their processing is limited to time scales equal or greater than 1 hour, and to space scale equal or greater than two pixels (about 20 km). It follows that for example, we cannot treat the case of fragmented cloud coverage or provide a detailed description of the cloud cover surrounding a peculiar building, unless additional external information is available.

Of course practical problems to be solved are strongly dependent upon the particular applications, with major effects of space and time samplings. For example, monthly means of daily sums of diffuse radiation over large areas are much easier to assess in an accurate way than the same radiation hour per hour for these places, and peculiarly if aerosols loading is highly variable. In daylighting for a peculiar building, detailed luminance distribution is required for a very accurate assessment of the luminance. The large size of a pixel prevents from having this information, and the best and most useful information that can be got is likely a class of skies, together with some relevant probabilities.

One of the major points when designing or validating methods which derive parameters from satellite data is the link between these parameters and the measurements of these same parameters by standard procedures at ground level (pyranometers, for example). The latter are used either for validation of the derived parameters and the assessment of their accuracy, or for calibration of the method, possibly on a routinely basis, or for both. Several problems arise. They are usually resolved by calling upon theories of atmospheric turbulence. I discuss briefly these problems and their effects on assessment of the accuracy of a method.

An important aspect to be taken into account when satellite-derived and ground-measured information are to be compared, either for calibration or validation, is the fact that satellite information is a snapshot over a large area, while ground information is a time-integrated pinpoint measurement. The first question is: should the ground information be similar to the satellite-derived information if the method were with no error ? What are the origins of the possible discrepancies and their level of magnitude ? Second question: taking into account that the model is not perfect, can we assess precisely the error only due to the model ?

Mixed to the previous aspect, is the accuracy of the geocoding of the pixels within the satellite image. Typical accuracy is 0.3 - 0.5 pixel for very well geocoded images. For the images of interest here, that means that the geographical location of a pixel is known with an error (rms.) of about 3 to 5 km. It follows that the exact position of the ground station is unknown. One may hesitate between several pixels when being deciding which pixel contain the ground station (Figure 2). Related to that point is the question of the variability of the parameter under concern within a pixel. If the parameter is homogeneous, and more exactly has an uniform value over the pixel, then the ground measurement has the same value than any other pin-point measurement that would be made over that pixel. That is the ground measurement is representative of the parameter.

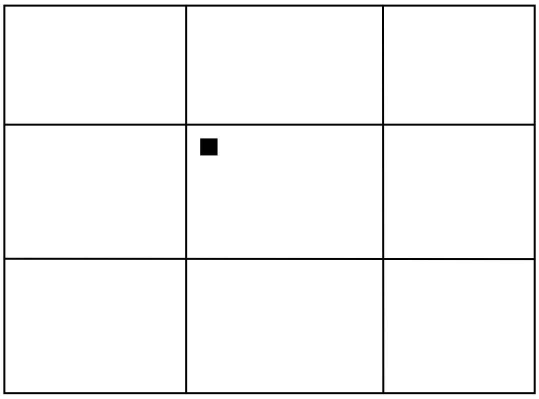

Figure 2. Location of a pyranometer within a pixel

However uniformity is obviously rarely encountered. Therefore one has to deal with weaker hypotheses. Before proceeding, we have to consider also that images are not acquired in the middle of the time-lapse of the ground measurement. For example, France is observed by Meteosat every half-hour plus 15 minutes (e.g. 10h15 UT, 10h45 UT, ...). Therefore assuming that one hour is the time-lapse that should be compared to the satellite-derived parameter, one has to construct an one-hour synthetic value by the means of interpolation using time-adjacent measurements made by the e.g. pyranometer. Indeed the justification in doing so is done exactly in the same way than for the space domain (*i.e.* the pixels). The same hypotheses are to be applied. The most common one is the stationarity of increments of the parameter in space and time. Let consider the parameter as a random variable in space. Let consider its difference between two points arbitrarily remote. This difference is also a random variable. Stationarity of increments means that the statistical properties of this random variable are independent in space and time.

It is assumed furthermore that the optical properties of interest are passive tracers of atmospheric velocity, and that their turbulent properties can be derived from that of the velocity. This is only fairly true for clouds since they have their own dynamics which may differ strongly from the wind dynamics. Such a hypothesis allow us to make use of well-known theories of turbulence.

Time-average, as performed by pyranometers, should be replaced by average in space, as performed by satellite sensor. In turbulence theory, Taylor proposed in 1938 the so-called hypothesis of ‘frozen turbulence’, according to which one can consider that the aggregates of turbulent eddies which govern oscillations of optical properties at a fixed point are translated without change with the mean velocity of wind. By this hypothesis, satellite-derived values averaged over several pixels within the neighborhood of the pyranometer can be compared to the ground measurements. More exactly the statistics of the satellite-derived parameter can be compared to the statistics of the ground measurements. This hypothesis is very convenient and often used. But still it remains a working hypothesis which is not always verified when possible. It may be valid for very small intervals of time relative to the variation of the turbulence, which is obviously not the case here.

The size of the pixel (~ 10 km) as well as the measurement lapse time (1 hour) are well within the critical range intermediate between small-scale and meso-scale turbulence. Within this range, there is generally no strong links between the fluctuations observed at one scale (e.g. 10 km) and another (e.g. 1 km). The statistical properties cannot be transposed from one scale to another as one can do in the so-called ‘inertial’ ranges in small- or meso-scale turbulence. It follows that we cannot claim that the satellite-derived information, averaged over a block of pixels or not, should match the ground measurement. A discrepancy is expected because of the natural variability of the radiation which cannot be predicted nor assessed in the general case.

Assuming a mean velocity of 10 m/s, one sees that satellite-derived values must be averaged over about 4 pixels in order to be compared to the 1-hour averaged ground measurement. This number of pixels depend strongly upon the wind velocity which is variable in space (x, y) and also with the altitude z. The latter problem may be solved by the computation of an average of the vertical profile of mean velocity weighted by the profile of the optical properties, as far as such information is available. This is barely the case. For the sake of the simplicity, one often averages the satellite-derived values over a square of 3x3 pixels centered on the location of the pyranometer. In doing so, one assumes the homogeneity of the random variable made up from the fluctuations of the velocity around the mean value for this block of pixels. As said before, this is only fairly true for several tens of kilometers, including the large variability of the optical properties in the lower part of the troposphere. Furthermore, it does not account for the prevailing direction of the wind. Taking a square means that the wind is blowing from all directions towards the central pixel or inversely! Putting it differently, this way of doing may be read as if some clouds which never passed in the field-of-view of the pyranometer during the 1-hour measurement influence this measurement. Of course, changing the size of the square to e.g. 7x7 or 11x11 pixels significantly change the results, the magnitude of it depending upon the case. Under uniform conditions, the results are the same. In the heterogeneous case, the results may differ significantly in an unpredictable way. Pinker, Laszlo (1991) studied the effect of different spatial sampling of satellite observations on retrieved surface global radiation using two different resolutions: 8 and 50 km. They found that, on the average, the results differed by about 8 - 9 %. Several other attempts, not published in international journals, found similar conclusions and demonstrated that there is not an unique size of pixel aggregate giving the best results. It is possible at one time to get better agreement with one resolution and at other times better agreement with a different resolution. Beyer *et al.* (1992) suggested that the local variance may used as a measure of the spatial heterogeneity and may serve to determine the most appropriate size.

From this discussion, some conclusions are drawn, which are valid only for the scales involved here:

- it is not true that the satellite-derived information should exactly match the ground measurement,
- the natural variability of the radiation may be important and induce a large discrepancy between assessed and measured radiation,
- turning spatial average into temporal average by the means of the Taylor hypothesis is not justified in the general case,
- however it greatly ease the burden in image processing complexity,
- it may have sensible effects on the results of the comparison between satellite-derived

parameters and ground measurements,
- the magnitude of these effects are difficult to predict.

3. ASSESSING DIFFUSE RADIATION

In daylighting as well as in many other applications in solar energy, it is necessary to split the global radiation into its diffuse and direct components in order for example to be able to compute values on tilted surfaces. Keeping in mind the above-mentioned limitations, some works have been made to infer diffuse radiation from satellite images.

One obvious way is to start from the satellite-derived global radiation and to apply a standard algorithm as in the case of ground measurement. In the framework of the European Solar Radiation Atlas, 2nd edition, several algorithms were tested by a group of experts. The algorithms of Erbs *et al.* (1982) have been selected. The first algorithm performs the assessment of the daily diffuse horizontal irradiation from the daily global horizontal irradiation. Typical relative rms. is about 15 % or less when entries are measured radiation. In the case of satellite-derived global radiation, one has to add the associate error. I assume that a crude assessment of the rms. may be given by the root of the quadratic sum of each rms., and thus we obtain a typical relative rms. of about 20 %. The second algorithm performs the same task but for monthly average of daily sums. It is applied to maps of global radiation obtained by the merging of ground-measurements and satellite-derived information, to provide maps of monthly means of diffuse radiation averaged over 10 years (1981-1990). Typical relative rms. is about 8 % or less when entries are measured radiation. In the case of satellite-derived radiation, it is estimated to about 13 %. Though crudely assessed, these rms. form a reference. Given the complexity of the processing of satellite data, a model can only be justified on an operational basis if the resulting errors are less than these references. Table 1 summarizes the errors (in relative rms.) that are currently attained by the processing of satellite images as exposed above.

Global	hourly	20 %
	daily sum	10 %
	monthly means of hourly values	10 %
	monthly means of daily sums	< 10 %
Diffuse	hourly	35 - 40 %
	daily sum	20 %
	monthly means of daily sums	13 %

Table 1. Summary of the errors (in relative rms.) that are currently attained by the processing of satellite images.

An attempt was made by Diabaté, Wald (1995) (see also Diabaté 1989) to assess the hourly diffuse radiation through the Heliosat method. An empirical relationship was seek between the Heliosat cloud index n and the diffuse radiation measured at eleven stations in France during 1984 and 1985. This relationship was a second-order polynomial function of n. According to the linear relationship between n and KT, this is equivalent to seek a relationship between clearness index KT and diffuse radiation. The task was very difficult since it was dealing with hourly values and not averages. Relative uncertainties (rms.) were about 38 % for both years. The larger errors were encountered for clear skies and very thick clouds. In both cases KT and the solar elevation are not sufficient to determine the diffuse radiation. The influence of the turbidity is predominant for clear skies (low cloud index, $n < 0.1$, $KT > 0.6$) and becomes negligible for cloudy skies ($n > 0.5$, $KT < 0.4$). For very thick clouds, it was found that additional information describing the type of cloud is required in order to gain accuracy.

Stuhlmann *et al.* (1990) introduced a model to assess the daily sum of the diffuse component into the IGMK model. The IGMK model was developed concurrently with Heliosat. In essence, both models are very alike and lead to similar results (Grüter *et al.*, 1986; *Solar radiation atlas for Africa*, 1991). Using climatological monthly means of the optical thickness for the atmospheric ozone, water vapor, and surface albedo, and prescribed values for aerosols type and loading, they computed the daily diffuse radiation for 31 stations for 1985 and 1986, by the processing of Meteosat B2-type images (every 3 hours, pixel size is about 50 km). Figure 3 is copied from this work and displays the ratio of daily diffuse to daily global radiation versus the clearness index KT for January 1985 and 1986. The relative error (rms.) in reconstructing the daily sum is about 25 % and is reduced to about 15 % for the monthly mean of daily sum of diffuse radiation. Differently to the work of Diabaté, Wald, one observe a large scatter for medium and small KT. The fact that these authors used low resolution data together with ground stations located in several different climates, is in perfect agreement with the introduction of climatological knowledge in the IGMK model. In the case of both an area of smaller extension and higher resolution satellite data, one would likely obtain larger errors.

Figure 3. Ratio of daily sum of diffuse to daily sum of global radiation versus daily clearness index, for January 1985 and 1986. (a) measurements (31 stations); (b) IGMK model results. Copied from Stuhlmann *et al.* (1990).

From the analysis of such works, I believe that a formal description of different optical processes within the atmosphere is a key to success in assessing advanced solar energy parameters. This is illustrated by the modified IGMK model which provides fairly acceptable results though crude approximations are made in optical properties of the atmosphere. Several models have been popularized like Lowtran, Modtran or 5S-6S. They have different purposes which differ from those pursued here. However they form the basis from which one can cautiously extract the various sub-models describing the fundamental processes. By bringing more physics into consideration, one expects to improve the accuracy in retrieving the diffuse radiation as well as the spectral information required for illuminance assessment.

However the major limit to these sophisticated models are the physical parameters to be input. Usually, these parameters are very difficult to know. I think that their knowledge is the second key to success.

Using models detailing the fundamental processes leads to:

- complexity increases
- number of input parameters increases,
- accuracy of input parameters should be high,
- whole system should be coherent, *i.e.* each piece (sub-model plus associated inputs) should have the same level of knowledge and accuracy than the others.

For example, one may use detailed description of the Rayleigh scattering and of aerosol scattering. Rayleigh scattering is a function of the air pressure at ground level. A relative change of 10 % in pressure induces a relative change of 1 % in radiation in the blue range. As for the aerosol scattering, assuming one type of aerosol instead of another leads to relative changes of 1 - 2 % in the same range. These errors may partly compensate or cumulate. In this example, we have increased the description of the processes, we have increased the complexity, we have increased the number of inputs but the lack of knowledge about these inputs leaves a possible relative error of several per cent.

The work of Stuhlmann *et al.* (1990) illustrates this point. Having designed a model requiring several input parameters, they affect crude values to them by lack of knowledge. In a certain way it is in contradiction with the sophistication of the model. For example, special treatment can be done for aerosols, but nobody knows the optical thickness, type and loading for the current conditions. They are using climatological data or simply archives (past measurements or maps), which are overall poor in accuracy because they do not correspond to the current conditions. This lead to an accuracy which is not better than simpler models, which are using statistical relationship between ground measurements and satellite-derived parameters. This limit in accuracy due to the poor accuracy of the input parameters is illustrated in Figure 3. One can see that for clear-skies there is a bias (difference between mean values) in KT between the observations and the estimates. This bias amounts to 0.04 in absolute value, which is about 10 % of the mean KT. It is mostly induced by the use of prescribed values for the aerosol properties (no seasonal nor geographical variation) or of climatological values for water vapor.

The previous works as well as runs of numerical models describing the radiative transfer within a cloudy or cloud-free atmosphere show that in a first approximation

- there are two difficult cases to solve: the clear-skies, and the overcast skies, including the case of superimposed layers of cloud, and the broken fields,
- in clear-sky, the main parameters are the aerosol loading and the water vapor content, or the visibility which is a more global parameter,
- in overcast skies, the most important parameters are the optical thickness, and the altitude of the cloud top.

According to the past experience, the following approach should be used in the Satellight program. This approach should be understood as one of the several steps towards a very accurate assessment of the diffuse component, not as a definite one. The Satellight program is sponsored by the European Commission, and aims at the retrieval of the diffuse component as well as improving the assessment of the illuminance. The approach is the following. One may use climatological or standard values for aerosol and water vapor and more generally for all parameters of interest. Cloud top height is assessed by the means of imagery taken in the thermal infrared band, providing measurements of the temperature of the targets. Given a standard vertical profile of temperature, one can derive the cloud top height. The profiles may possibly be supplied by the European Center for Medium Range Weather Forecast (ECMWF). This allows to take into account the current conditions, though cloud top height determination is limited by the fact that the vertical temperature profile may change rapidly within a ECMWF grid mesh, at least in the boundary layer. If the ECMWF profiles are used, account should be taken of the size of the grid mesh (about 0.6° at best, *i.e.* about 70 km) compared to the pixel size.

Then there is one degree of freedom: the optical thickness of the cloud. It is adjusted in an iterative way so that the reflectance output from the numerical model matches the reflectance observed by Meteosat. More precisely, this minimization problem is performed on a function of the distance between measured and assessed parameters. Attention should be paid on this parameter (or these parameters). For example, if the parameter is the reflectance observed by Meteosat, one should take into account the poor accuracy of the calibration of the sensors. This peculiar point can be solved by using reflectances relative to an arbitrary reference. For example, one can define a model cloud index in a similar way than for Heliosat. The matching is then performed on the cloud indexes. Compared to the previous works, one can expect better results because of this degree of freedom. Adjusting the optical thickness of the cloud to the observations allows to compensate for the errors arising from elsewhere. It is likely that the error on the optical thickness will be large, but the error of the whole approach to the diffuse radiation will be better. Of course the error in clear-skies is expected to be close to that observed by Stuhlmann *et al.* since the processing will be similar.

4. MERGING DATA FROM OTHER SATELLITES

However better accuracy is required for global radiation applications and also other parameters are required for several uses of in several domains: global, diffuse, direct, illuminance, APAR, cloud cover surrounding a spot, spectral composition of the radiation. According to the previous discussion, it follows that better accuracy is required on the input parameters, including their space and time distribution.

This can only be achieved by the means of space-borne sensors. Some may help in producing more detailed assessment of these input parameters. These satellites are future programs, some are current. For example, NOAA data are acquired in two visible and near-infrared bands. Darnell *et al.* (1988) used such data in a very satisfying way regarding accuracy. The multispectral capabilities permit a characterization of the optical properties of the atmosphere, including aerosols loading for clear skies. However the processing of such images is much more complicated than the Meteosat data. Furthermore, there is only one to three usable images per day as an average, at the beginning of the afternoon in mean solar time. This is not sufficient to derive daily sums. It follows that the NOAA imagery cannot be used alone for the assessment of solar energy parameters. When combined to geostationary images, it greatly improves the retrieval of these parameters, but at the expense of a much more complicated processing.

Future programs such as the European MeRIS, PolDER, and GOMOS and the USA EOS initiatives will better characterize and map the optical properties of the atmosphere. We can expect to have within a few years a more accurate description of the parameters to be input to the sophisticated models retrieving the direct or diffuse radiation. An approach such as the one envisioned for Satellight will be still valid, with possibly a minimization of a quantity which is now a function of several inputs allowed to slightly fluctuate.

When calling upon several sources of data, several problems arise, including the problem of data fusion. Some satellites like the Meteosat Second Generation program will give a large number of the required information. However it is likely that in order to increase our knowledge, we have to increase the number of relevant information. Therefore we have to deal with other satellites and sensors. These satellite data are of different types, different resolutions in space, different sampling in time, different geographical coverage, and then we enter a very difficult field of image processing called data fusion. That means that an advanced analysis of satellite data will require a close cooperation between people involved in optics of the atmosphere, image processing, applied mathematics, decision theory and so on. Advanced fusion techniques may call upon data assimilation and numerical models for predicting temporal changes of optical properties. Most of the work will be done by the space agencies but the solar energy community has a fundamental role to play. As today the solar energy community has to show that it is convinced about the potentials of the satellite data in order to foster the studies the space agencies may launch in that direction.

5. CONCLUSION

I have discussed the state-of-the-art in assessing diffuse and direct components of the radiation. Some methods are currently available but gain in accuracy is needed for solar energy applications. Discrepancies between ground measurements and satellite observations with respect to space and time characteristics are key issues. The variation in space and time of the radiation should be better understood in order to modelize it and furthermore to be able to compare (or merge) these different types of data in a more accurate way.

Some properties, such as turbidity, geometrical and optical properties of the clouds, are predominant for the assessment of the diffuse and direct components. It has been shown that advanced models should be employed for the radiative transfer but then the main limitation is the poor accuracy of the input parameters. These parameters are, or will be, best estimated by some other satellites and it is recommended to use them when possible in order to gain accuracy. However this leads to a large increase in the complexity of the processing chain and requires a better understanding of the fundamental problems to be solved with respect to the space-time characteristics.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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