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A COMPUTATIONAL METHOD OF DETERMINATION OF THE SUNSHINE DURATION

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Abstract
The work deals with the method for determining the duration of sunshine based on meteorological data and model calculations of solar radiation. A comparative analysis of the features of pyranometric and pyrheliometric methods for determining the sunshine duration (SD) is carried out. To improve the accuracy of determining SD, the cubic spline function method is used to interpolate of direct solar radiation records. The features of the determination of SD based on global horizontal radiation and various algorithms are considered. All chains of calculation formulas of these methods are given. Calculations are based on data from the Parkent Weather Station for monthly monitoring.

Keywords: *sunshine, duration, solar radiation, direct radiation, global radiation, weather station, solar constant, declination, latitude, azimuth, altitude, zenith, clear sky, cloudiness, sunrise time, sunset time, interpolation, weather data, pyranometer, pyrheliometer, turbidity factor, Angstrom-Prescott.*

One of the important indicators of solar energy resources is the sunshine duration of the any terrain. This indicator can also be called the sunshine of the terrain or the parameter of the cloudlessness of the atmospheric sky. Note that some popular-science publications or travel booklets also use terms such as the number of sunny days, number of clear days or number of cloudless days, etc. However, if we take into account that often weather consist of sunshine interchanging with periods of clouds, there is a lack of clarity in the correct estimate of the sunshine duration in a long period. This is because of the fact that in this case, the unit of time measurement "day" is a large value and therefore the sunshine duration (SD) is measured in hours and minutes, sometimes as a percentage relative to the total daytime duration of a particular period. That is the time when the sun is above the horizon. This climatological indicator - the sunshine duration is used for a specific period, and usually monthly, seasonal or annual summation periods are considered. For a long-term period, the values averaged over years are used.

The sunshine duration is an important meteorological characteristic of the terrain, and data about it plays an important role in applied solar energy area, medicine, tourism, the agricultural sector and etc. [1-3].

It should be noted that in any weather, the solar radiation has some value, and therefore there is also ambiguity in determining the sunshine duration. For clarity, the World Meteorological Organization (WMO) has defined the sunshine duration as the sum of the intervals in which direct solar radiation value not less than 120 W/m^2. At the same time, depending on the value of the relative daily sunshine duration, three ranges of its values (0 ÷ 0.3; 0.3 ÷ 0.7; 0.7 ÷ 1.0) are considered with the corresponding conditional weather names - "cloudy sky", "scattered clouds" and "good weather" [1].

It should be noted that in applied solar energy area, SD is widely used to determine other characteristics of solar energy resources. For example, using data on SD, one can determine global solar radiation (a series of formulas of the Angstrem type, etc.), the interrelationship of SD and air temperature, etc. [4–13] have been studied.

Special instruments, so-called heliographs, measure the sunshine duration. Before, meteorological stations (MS) used Campbell Stoke (CS, 1879) [14] SD recorders everywhere. Currently, more modern SD instruments are used, such as, for example, CSD3 from Kipp & Zonen [15], BF5 from DeltaT Devices Ltd [16], and others.

In recent years, modern compact SD measuring instruments based on photo sensors have been developed. Such instruments are also manufactured in the CIS countries, for example, in Russia and Belarus. Unfortunately, many weather stations are not equipped with such instruments, particularly in Uzbekistan also.

As noted in [17], in recent years, modern methods of determining and automatic sensors for measuring the sunshine duration have replaced classical Campbell-Stokes (CS) solar recorders because of their high price, low measurement accuracy (7% in winter and up to 20% in summer) and other shortcomings in operation [18]. In Europe, equipped with the most density network of weather stations, such technical replacements have been carried out since 2000. For example, in Switzerland, the Czech

Republic, Iceland and Estonia such modern devices have been used since 2000, in Poland since 2014. In Belgium, Denmark, Luxembourg, Ireland, Great Britain, Sweden, Germany and the Netherlands, ordinary and modern automatic sensors are commonly used. In Greece, Croatia and Hungary, modern sensors are mainly used. Some national weather services (Switzerland, Denmark, the Netherlands, the UK and Luxembourg) have launched online services that provide access to sunshine duration data [17]. Nowadays, improved methods for determining SD based on weather data are also widely used.

For numerical determination of SD, the so-called pyrheliometric and pyranometric methods are used, which use a pyrheliometer and pyranometer measurement database. To determine SD by pyrheliometric method, the records of direct solar radiation are used, and for this reason the method is sometimes called the direct method. As the pyranometer measures a global horizontal solar radiation and, therefore, in this case, Angstrem-type mathematical formulas are used [7-13].In these methods, various algorithms for determining SD are developed. In [18–20], an overview and comparative characteristics of various methods for determining SD are presented. It may be noted well-known algorithms: (Glover & McGulloch, 1978), (Slob and Monna, 1991), (Alain Louche, 1991), (Bergman, 1993), (Campbell Scientific, 1998), (Schipper, 2004), (Jean Olivieri , 2004), (Hinssen-Knap linear algorithm, 2007) [18].

Note that almost all MS are equipped with pyranometers, since, as they are relatively inexpensive instruments. Pyrheliometers are currently about 4-10 times more expensive than pyranometers and therefore not all stations have such instruments. In addition, in many existing weather stations there are still no modern automatic sensors for measuring SD.

It is known that, despite of the important role of meteorological data on the sunshine duration for solving many problems, even for many large populated regions of the world, reliable, detailed and updated data on SD are not available. The reasons for these cases are the insufficient network of modern weather stations (MS) and measuring posts of solar radiation, the absence of modern SD measuring instruments. That is why, in most cases, there are no direct records of SD in meteorological databases, and this value is usually determined by the special algorithms listed above using archive records of solar radiation.

It should also be noted that there are some differences of instrument readings of various modern devices for measuring SD and in the results obtained by various methods. Therefore, the development of updated algorithms for determining SD based on weather data is an important task. Also for this reason, the disputable issue of the sufficiency of the measuring bases of pyranometers and pyrheliometers for determining SD with good accuracy is now being discussed in scientific communities.

On the example of the Republic of Uzbekistan, it can be said that the territory of the country has a high gross potential of solar energy. According to [21], the SD in the north of Uzbekistan is 2800 h/year at average. To the south, the values increase, and in the last south (Termez) the SD reaches 3050 h / year. In winter and spring, the SD is minimal - on average 80-100 h per month. Cloudy days without sunshine in Uzbekistan are rare. In the northern and mountainous regions, their number reaches 45–50 per year, decreasing in the last south to 25. The greatest number of such days is available in December-January: from 10 to 25 (a total of two months). From June to September inclusive it is observed from 1 to 4 days without sunshine on average over 10 years.

Analysis of the literature data shows that modern SD data are not available for Uzbekistan, SD measurements are not conducted at MS, and little attention has been paid to such studies. Unfortunately, the information given in the literature is based on outdated data. It seems that some general characteristics of solar energy resources, which are given in the literature, are correct in terms of average characteristics. However, for many applied tasks on the development of solar energy resources and the correct prediction of the expected results of perspective problems, detailed information is needed on this matter. For Uzbekistan, for this reason, the numerical studies of SD based on the MS data and model calculations of solar radiation are relevant matter.

In the Internet resources, one can find SD data for the capital of Uzbekistan (Tashkent city), based on estimates and/or outdated data (25 or more years old), also SD data from Khujand Meteorological Station (Tajikistan), probably due to the proximity of localities (167 km). According to these data, SD by months are as follows: 117.8; 127.1; 164.3; 216.0; 303.8; 363.0; 384.4; 365.8; 300.0; 226.3; 150.0; 105.4.

In the numerical calculations of this work, the database of the meteorological station MS4-12-01, located in Parkent region [22-23] is used. This station is located at the “Sun” object, at the Institute of Material Sciences (45 km from Tashkent). The station is equipped with modern solar sensors and other measuring devices (RSP-4G pyranometers, CHP1 pyrheliometers, Campbell Sci CS215 thermometers, Campbell Scientific CS100 barometers, etc.). The “Sun” object has the following geographic data: 41.32° - geographical latitude, 69.74° - longitude, 1081m - height above sea level.

At the station there are no instruments for direct measurement of SD and automatic calculation of SD is not implemented. The recording interval of solar radiation is 10 minutes, although measurements are made more frequently.

The task of the definition of SD is devoted to many works, in particular, the above references. Most of the papers relate to the definition of SD based on global horizontal radiation, i.e. pyranometric method. In particular, the above algorithms mainly relate to this method.

Let's consider the features of the algorithm for determining SD based on records of direct solar radiation, i.e. pyrheliometric method.

Note that in recent years, in many MS, archival records of direct solar radiation were made with intervals of $\boldsymbol{t_r}$ = 10 minutes. Even earlier records had $\boldsymbol{t_r}$ = 30 minute recording time interval. It should be noted that modern measuring devices in MS have a sampling frequency of 1 Hz, i.e. radiation records can be made every second [24]. According to the WMO recommendation, the requirements for the measurement accuracy of SD are 0.1 hour or 6 minutes [1].

The simplest algorithm for determining SD is to count the number of single intervals with radiation of more than 120 and multiply the obtained value by the values of the recording interval of radiation, for example, by 10 or 30 minutes. Obviously, the smaller the time interval of record, the greater is the accuracy of SD determination. If you look at a certain time interval $\boldsymbol{t_n} >> \boldsymbol{t_r}$, in which radiation is greater than 120 at all points, then the maximum inaccuracy of determining SD for a given time interval is, as is easy to see, equal to the value of $2\boldsymbol{t_r}$. Figure 1 shows the dependence of direct solar radiation on time during variable weather. In this case 3-hour fragment of time (station MS4-12-01, 10.29.2013, time 13^{00}-16^{00}) were considered. In case of changeable weather, when alternation of sunshine and cloudiness often occurs, the maximum inaccuracy of determining SD increases proportionally depending on the number of such alternations of weather.

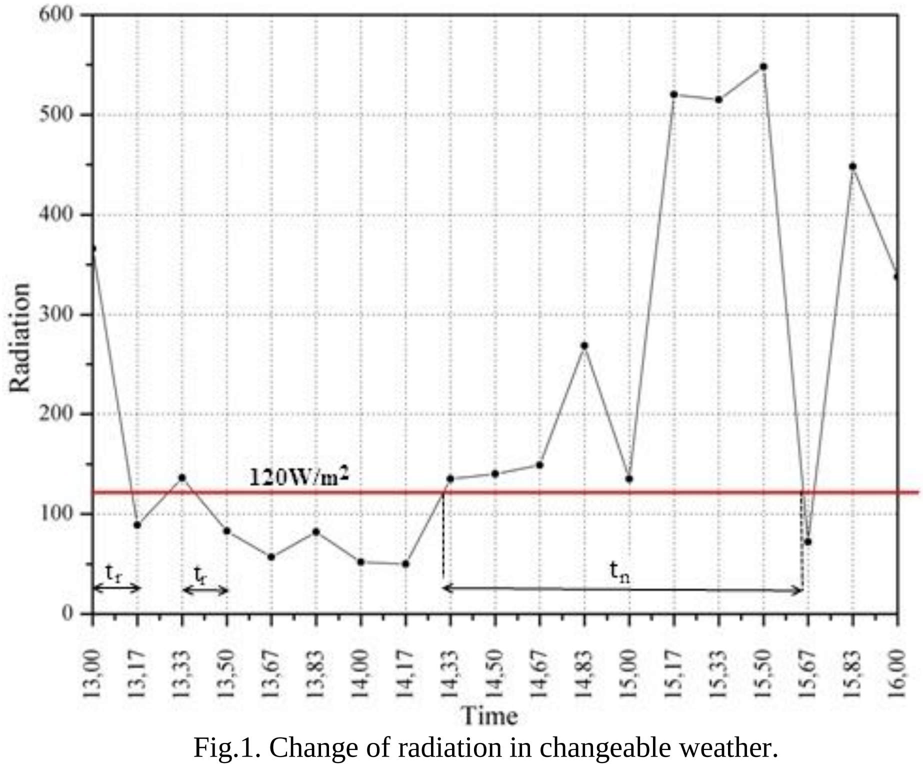

Fig.1. Change of radiation in changeable weather.

Thus, it is easy to see that when determining SD for large periods of time (for example, a month), a sufficient error can occur, which is mainly determined by the value of $\boldsymbol{t_r}$ and the nature of the weather variability. In this case, for the determination of SD, direct solar radiation $E_{bm}(t)$ is used the indications of the CHP1 pyrheliometer. Directly from these data, it can be only estimate the SD, and in changeable weather, the assessment deteriorates.

To the correctly determine of the daily SD, it is necessary to calculate the integral

$$SD = \int_{t_1}^{t_2} \xi(t) E_{bm}(t) dt \tag{1}$$

where the integrand $\xi(t)$ is equal to 1, if $E_{bm}(t)$ >=120 Wt/m^2, otherwise it is 0. t_1 , t_2 - the time of sunrise and sunset, or the beginning and end of the time interval. Note that the function $\xi(t)$ has a similar physical meaning, defined in [25] as the “sunshine number”. Thus, the function $\xi(t)$ should be interpolated. For this purpose, we have selected cubic spline interpolation. Algorithms from the book [26] were used (subprograms Spline and Seval). As an example to illustrate the method, two characteristic data (clear day and changeable weather) of Parkent meteorological station MS4-12-01 from 8.0.2013 and 10.29.2013 are considered.

The results of the interpolation are presented in Fig.2. In the figure, the meteorological data is plotted as large dots (1), and the curves are the results of interpolation (2). The figure shows that the interpolation results are good (there is no need to calculate the interpolation parameters). The interpolation step is 1 minute. Note that in this case, instead of integration, you can use a simple summation of 0 or 1 , taking into account the condition $E_{bm}(t) > 120$ in the interpolation results.

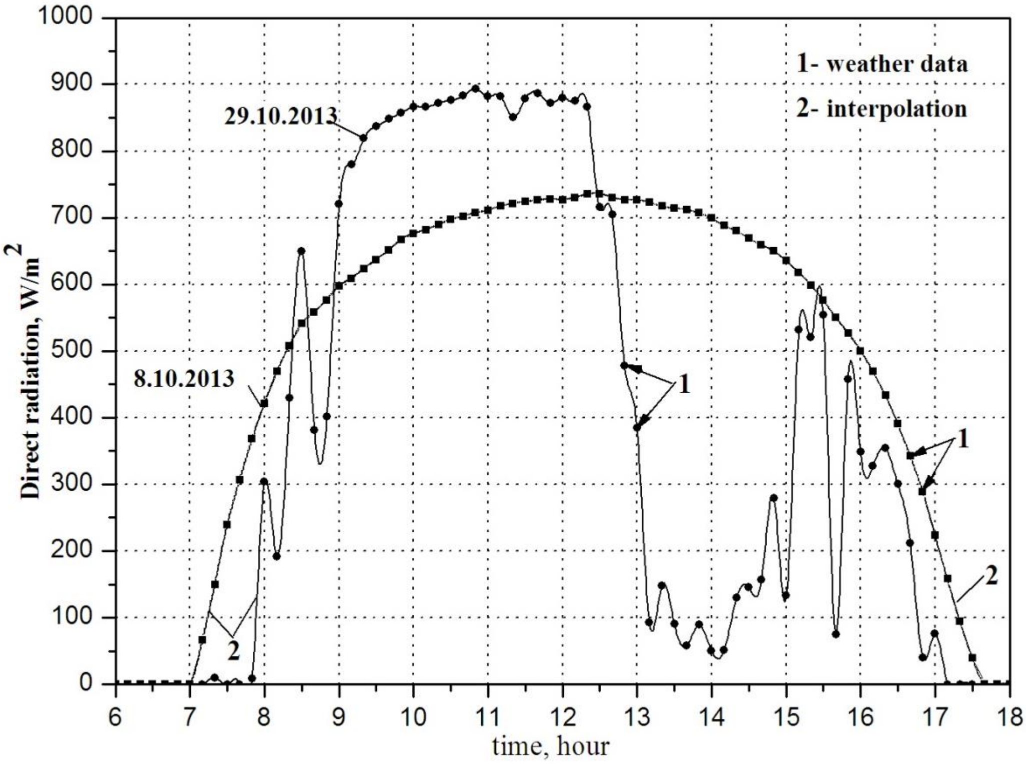

Fig.2. Interpolation of weather data

The results of the calculation of SD by days for the October month, 2013, according to the above integral are presented in Fig. 3 (curve 1).

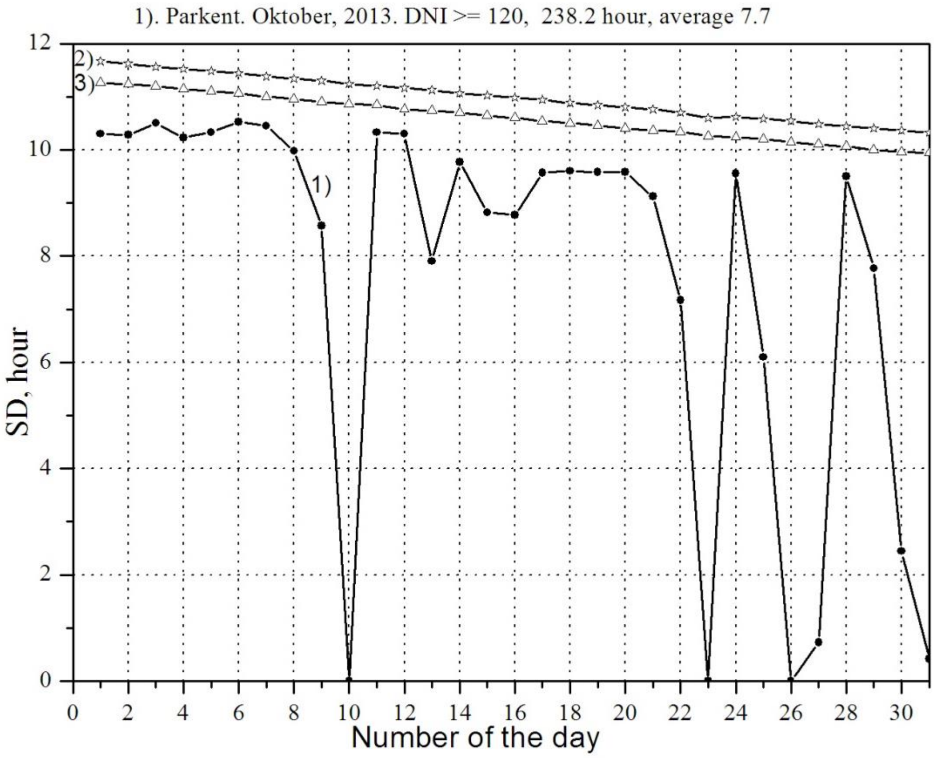

Fig.3. Dependence of SD on the day number

As already mentioned, SD is often presented in relative units. In some cases this may be relative to the total duration of days ($\boldsymbol{SD_{21}}$ - the time when the Sun is above the horizon, curve 2), in other cases relative to the theoretically possible duration of sunshine ($\boldsymbol{SD_{max}}$). In the last case, instead of the experimental data of direct solar radiation, it is necessary to use direct solar radiation on a clear, cloudless sky (model, hypothetical case). These definitions imply a specific date period (days, months, seasons, years). Relative SD values are determined by calculation

Now, if in formula (1) instead of experimental data (radiation) we use an empirical formula (there are many adequate empirical formulas), we can get the maximum possible sunshine duration $\boldsymbol{SD_{max}}$. In Figure 3, curve 3 corresponds to this case. The graph shows that the dependences of $\boldsymbol{SD_{max}}$ and $\boldsymbol{SD_{21}}$ on the day number are linear. The average deviation of these values for the month is 0.382, i.e. they do not differ much from each other and we have $\boldsymbol{SD_{max} = SD_{21} - 0.382}$.

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