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A Rapid Method of Estimating the Solar Irradiance Spectra with Potential Lighting Applications

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Abstract

Diverse solar irradiance spectra can be observed under different conditions of time, date, location, weather, etc. Since the solar irradiance spectrum is required by certain scientific and engineering applications, obtaining accurate spectral data is essential. Measurements by spectrophotometers are able to achieve accurate real-time data with high resolution, but at high expense. While in some engineering applications, the requirements on accuracy and resolution are much lower than that in a typical scientific research. Therefore, a rapid method of estimating the solar spectrum is proposed based on an available spectral model in this paper. In order to achieve fast estimation, we simplify the input parameters of this model into five key inputs, including latitude and longitude, altitude, date and time, sky and ground type. The first three parameters are easy to obtain from GPS and the internet. Sky and ground types include common types of sky and ground, which can be input manually or processed automatically by analyzing a digital image of target sky or ground. The automatic input is realized through dominant color extraction or by training an artificial neural network. Results show that the proposed rapid method can generate different spectral power distributions based on distinct input conditions. Two device frameworks are also proposed to implement the rapid method, which is applicable to many fields. LED lighting is one of the most prominent applications. Users can easily share local sunlight with each other through an APP in mobile phones.

1. Introduction

In regard to terrestrial solar spectra, the most frequently used data set among energy science and industry is the air mass 1.5 (AM 1.5) standard (or reference) spectrum. Air mass coefficient here indicates the relative optical path of the direct solar beam through the Earth's atmosphere [1]. As shown in Fig.1 (a), AM 0 refers to the solar spectrum outside the atmosphere, i.e. extraterrestrial solar spectrum, which usually serves for space power applications. After filtered by the atmosphere with the sun directly overhead, i.e. a zero solar zenith angle, the solar spectrum is weakened selectively, denoted as AM 1.0. Since we're rarely in the condition of exact "one atmosphere" thickness, AM 1.5 is defined as the spectrum under a solar zenith angle of 48.2°, as illustrated in Fig.1 (a), representing the common condition at mid-latitudes with the world's major population. Therefore, the reference solar spectra as shown in Fig. 1 (b) are the results based on the analysis of massive data, but not necessarily to be the sunlight observed with naked human eyes in daily life. In reality, the solar irradiance spectra vary with conditions of time, date, location, weather, etc. The reference solar spectra result from industrial standardization purposes, which are the opposite of our aim to explore the diversity of solar irradiance spectra under various conditions in this paper.

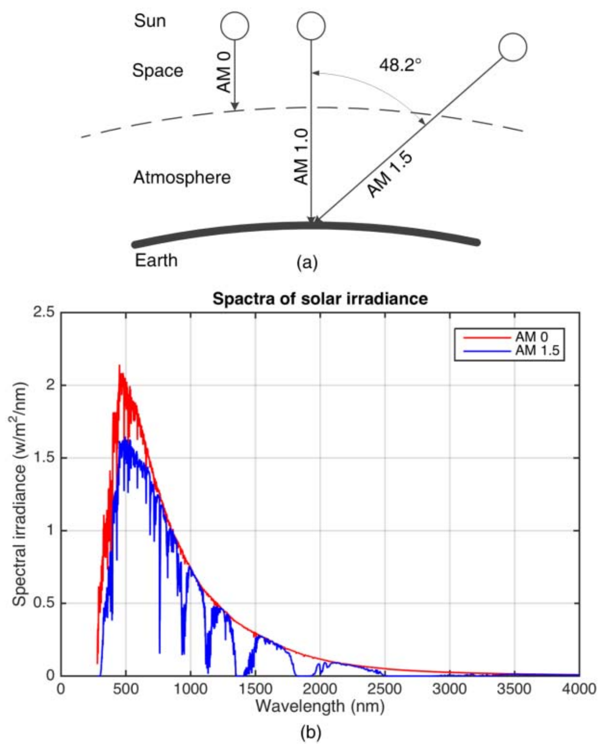

Fig. 1 (a) Definition of AM (Air Mass) 0, AM 1.0, and AM 1.5. (b) Spectral solar irradiance of AM 0 and AM 1.5.

Why the real solar spectrum is important for us? That's because the sunlight is a critical input parameter for many fields associated with solar energy, e.g. photovoltaic industry, meteorology, architecture, agriculture, vision science, etc. For instance, light therapy, such as exposure to the artificial light that mimics a specific solar spectrum, can treat circadian rhythm disorders, jet lag, or seasonal affective disorders [2]. Before we can reproduce the sunlight of a certain region at a certain time, we have to find a way to obtain the target spectrum.

Currently, we use spectrophotometers to measure the local spectral solar irradiance. Such field measurements are able to achieve accurate real-time data with high resolution. Considering the cost of equipment, however, only few institutes are able to perform such routine measurements. While in some engineering applications, the requirements on accuracy and resolution are much lower than that in a typical scientific research. Therefore, a rapid method of estimating the solar spectrum is of interest to engineers of many different fields.

In this paper, an indirect solar spectrum estimation method was proposed based on an available spectral model called SMARTS (Simple Model of the Atmospheric Radiative Transfer of Sunshine). SMARTS is a spectral model developed by C. Gueymard in order to predict sky spectral irradiances for specified conditions [3]. We simplified the complicated input parameters of SMARTS into five key inputs, which can be quickly accessed with current available technologies. Results show that the proposed rapid method is able to generate distinct spectra by changing input parameters. To implement such rapid method, possible hardware structures were introduced to collect necessary information. At last, we discussed potential lighting applications of the proposed method with current LED technologies.

2. SMARTS Model Description

SMARTS model can generate solar spectral irradiances, including direct beam, hemispherical diffuse, etc., with fewer than 20 input parameters under certain atmospheric conditions. Algorithms and models used by SMARTS are developed based on lots of parameterized models such as spectral transmittance functions of specific components in the Earth's atmosphere. It is also the basis of ASTM (American Society of Testing and Materials) reference spectra used for testing photovoltaic performance.

The accuracy of this model has been assessed by comparing with both rigorous codes and measured data of good quality in a professional report [3]. Results show that SMARTS performs well in a variety of atmospheric conditions and spectral bands. With sufficient auxiliary atmospheric variables, it can even be used to detect some instrumental problems. Therefore, SMARTS fully meets the requirements of accuracy and resolution in our study.

We will downplay numerous derivations and functions of this model since that's not the main point of our research. Details can be found in previous publications and instruction manuals [3-5]. The source code of SMARTS compiled in FORTRAN language is available for PC platforms free of charge. Input configurations can be customized through 20-30 lines of codes or a graphical interface.

The input parameters of this model include solar position (including year, month, day, hour, latitude, longitude, etc.), atmosphere (including site pressure, water vapor, Ozone, carbon dioxide, etc.) and terrestrial (including tilt surface and local albedo) conditions. Though SMARTS requires fewer complex inputs than previous models, it still needs some technical parameters, such as carbon dioxide concentration, to estimate the solar spectrum. Hence, simplified inputs are investigated in this paper in order to achieve rapid estimation.

3. Rapid Input

As mentioned above, so many detailed parameters are considered in SMARTS model that it is difficult for users without background knowledge or measuring devices to perform a fast calculation. Typically, we would use a spectrophotometer to measure the real-time solar spectrum if high accuracy and resolution are put in the primary consideration. In our case, however, the top priority is the quick access to all necessary parameters at a low cost of time and equipment. Therefore, five critical inputs are summarized from the model. They're latitude and longitude, altitude, date and time, sky and ground type, as shown in Fig. 2. The first three inputs can be easily obtained via GPS and internet. For the sky type, factors of atmospheric media, such as Ozone, water vapor, carbon dioxide, etc., influence the absorbing, scattering and transmitting effects of sunlight. Here, instead of meteorological data, we take typical weather conditions (i.e. clear, cloudy, etc.) as an overall sky input for the sake of convenience. Though the contents of interested gases vary in the atmosphere even under the same weather condition, the sacrifice of accuracy is worthy and acceptable for rapid-estimation applications.

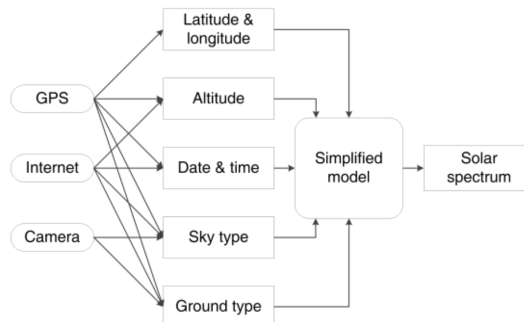

Fig. 2 Five main input parameters of the simplified model for estimating solar spectrum.

Two alternatives are able to determine the sky type. One is manual input, which is suitable for those with a professional background and do not trust "smart" technologies so much. The other is automatic identification with image processing technology. The core algorithm is to build relations between sky images, as shown in Fig. 3, and corresponding sky types. Dominant color extraction and artificial neural networks are able to establish such relations. Details of these methods can be found elsewhere [6-10]. Through this method, users can achieve the input of sky type by taking a photo of the sky overhead.

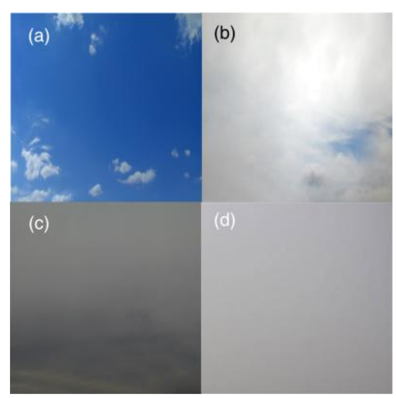

Fig. 3 Digital images of sky under typical weather conditions: (a) clear, (b) partly cloudy, (c) cloudy, and (d) fog (or smog).

The same method and technology are applicable to the input of ground type. Here, ground refers to the Earth's surfaces, such as concrete slab, green grass, snow, sea water, etc. as shown in Fig. 4. Comparing to sky types, ground has more complicated categories. But most of them reveal a similar reflection feature unless snow ground or desert with white sands is involved.

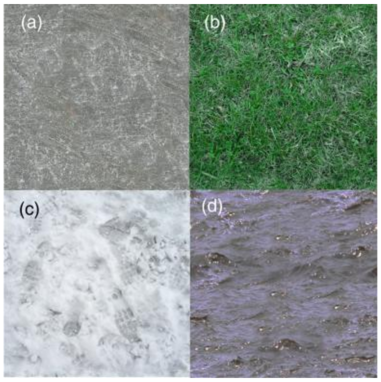

Fig. 4 Digital images of four ground types: (a) concrete slab, (b) green grass, (c) snow, and (d) sea water.

4. Results

To better understand how input parameters of the model affect the solar spectrum, we conduct experiments with controlled variables. For example, we choose three locations in the torrid, temperate, and frigid zones in order to investigate solar spectra at different locations. Coordinates of each location and other conditions are shown in Table 1. The spectral power distributions (SPD) of visible sunlight are presented in Fig. 5. In general, irradiance drops with the increase of latitude, but not proportionally for each wavelength.

Table 1 Rapid input parameters with different location conditions and for concrete slab type of ground.

Location	Coordinates	Altitude	Date	Time	Weather
Sanya	(18.2° N, 109.7° E)	0	2015-02-04	12:00	Clear
Beijing	(39.92° N, 114.46° E)	0	2015-02-04	12:00	Clear
Arctic Circle	(66.5° N, 114.46° E)	0	2015-02-04	12:00	Clear

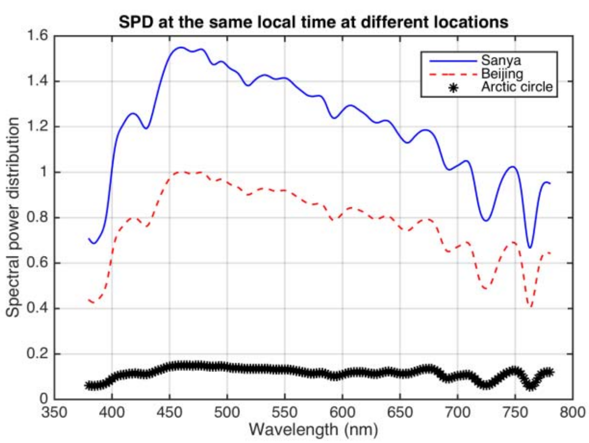

Fig. 5 Solar spectral power distribution generated by the rapid estimation method with conditions in Table 1.

Likewise, Fig. 6-8 illustrate the trend of SPD changing under different conditions of local time, sky and ground types. The diversity of sunlight can be used to explain some visual experience. For example, snow blindness is a painful eye condition caused by traveling outside in snowy terrain without wearing proper sunglasses or goggles. That is because snow can reflect more than 80% of the ultraviolet rays. In Fig. 7, though the UV band is not shown, we can still see that the snow reflects more sunlight than other ground types.

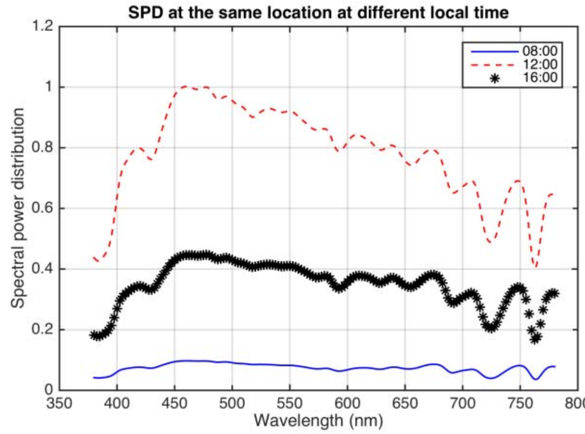

Fig. 6 Solar spectral power distribution generated by the rapid estimation method at different local time with the same conditions of location (39.92°N, 114.46°E), altitude (0 m), date (2015-02-04), sky type (clear), and ground type (concrete slab).

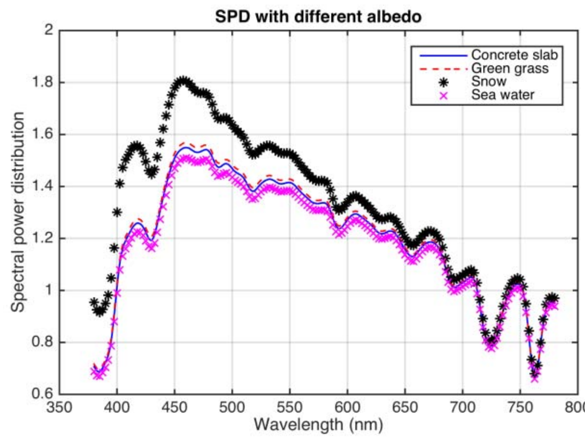

Fig. 7 Solar spectral power distribution generated by the rapid estimation method with different ground types and the same conditions of location (18.2°N, 109.7°E), altitude (0), date (2015-02-04), time (12:00), and sky type (clear).

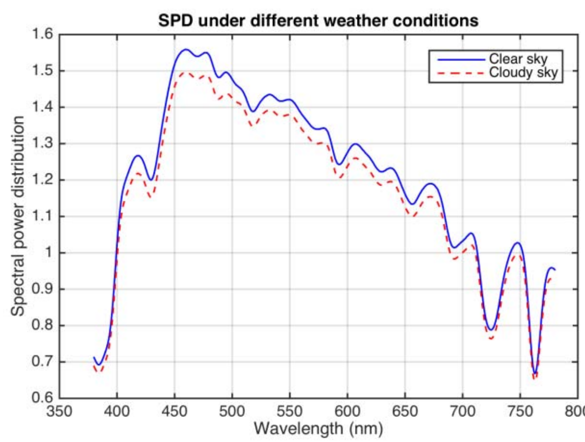

Fig. 8 Solar spectral power distribution generated by the rapid estimation method with different sky types and the same conditions of location (18.2°N, 109.7°E), altitude (0), date (2015-02-04), time (12:00), and ground type (concrete slab).

The solar spectra generated by the simplified model are not comparable with measurement data. Deviation mainly derives from SMATRS model and the simplification of its inputs. The performance assessment of SMARTS is provided in [3] as mentioned above. However, we're not capable to validate the deviation caused by the simplified inputs due to the lack of massive atmospheric data. From the above results, what can be confirmed is that the proposed rapid method is able to provide with distinguishing solar spectra based on different inputs. For relevant applications which do not claim high requirements of accuracy and resolution, estimated spectra can be considered as reference datasets.

5. Potential Lighting Applications

To implement the rapid method in this study, two device frameworks are proposed as shown in Fig. 9 and 10. The main difference between two devices is where the core algorithm is run, in the processor or in the cloud server. The so-called "device" can be a customized hardware, or your smart phone with an APP. By opening the APP and taking photos of the sky and ground, users can easily obtain, storage and share an estimated real-time solar spectrum.

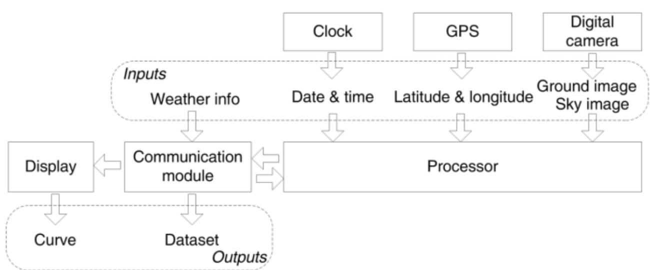

Fig. 9 Schematic diagram of a handheld device which is able to estimate and display real-time solar spectrum.

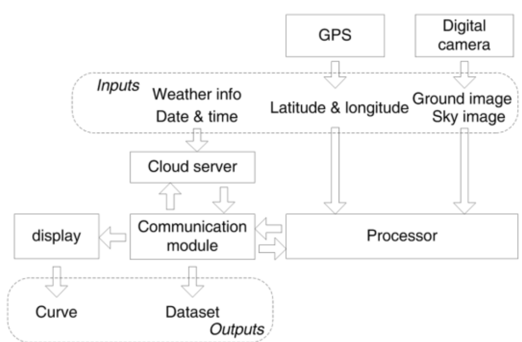

Fig. 10 Schematic diagram of a handheld device and a cloud server

This technology brings more possibilities of interesting interaction between users and LED lights. Without travelling abroad, a resident in Shanghai can just relax in the living room with LED lights, enjoying the artificial lighting with visible solar spectrum sent by a friend on Miami Beach, regardless of the gloomy or smoggy sky outside. Similarly, a family living in high-latitude areas is able to experience the bright summer sunlight stored in the APP, even in a dark winter evening.

It is noteworthy that our rapid estimation method provides with solar SPD, which is a relative intensity in visible range. The actual light intensity of LED lights should be set according to relevant standards of interior artificial lighting, or users' demand. As to commercial products, more potential functions should be developed based on this technology in order to enhance user experience.

6. Conclusions

Current spectrally tunable LED light sources [11] are usually integrated with remote control by smart phones. In this study, we proposed a rapid method of estimating solar spectrum based on available models. Input parameters are simplified through image processing and artificial neural networks so that the estimation can be done by an APP in mobile phones, which allow users to share local sunlight with each other.

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