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High-Accuracy Real-Time Monitoring of Solar Radiation Attenuation in Commercial Solar Towers

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Abstract. The main objectives of this work are twofold, the immediate objective is to provide current commercial solar towers with a system able to monitor accurately the solar radiation attenuation, the midterm objective is to acquire, with the adequate and precise measurements, the necessary knowledge about the different phenomena involved in the atmospheric attenuation in order to correlate it with meteorological and weather conditions when possible. The purpose of this paper is to describe the basic design features and operational capabilities of a new system designed by CENER and the University of Zaragoza (patent P201830758) for measuring real-time atmospheric attenuation of solar radiation at surface level. It performs a direct measurement without needing any previous assumption about atmospheric conditions. The work will be complemented with the analysis of the influence of atmospheric aerosols and meteorological conditions at surface level in atmospheric attenuation (at the lower ~300 m atmospheric layer).

INTRODUCTION

A sustainable electricity generation system is crucial for the mitigation impacts on regional climatic conditions and environmental degradation, and ultimately for securing the energy supplies in the future. In this scenario, Concentrating Solar Power (CSP) technologies, which are expected to be one of the leading renewable energy technologies, must be designed and optimized for the local conditions of the plant site to make optimum use of their capabilities [1]. The performance of a promising CSP technology, Central Receiver (CR) systems, is influenced by the optical performance of the heliostat field and the subsequent atmospheric attenuation of the solar rays reflected by them to the receiver. This is a remarkable, and not well understood, phenomenon influencing the performance of these CR plants, especially in low visibility days. There are already different models [2-6] to estimate the influence of the atmospheric attenuation of solar radiation in CR plants. Even if all of them point out the great influence of this phenomenon in the final performance of these plants, there are relevant differences found when comparing these models. Figure 1 shows the attenuation losses estimated from these models (under a visibility of 23 km), revealing remarkable discrepancies between them. These differences have a strong impact not only while designing and optimizing solar fields, but also and even more important in final plant performance. Having this in mind, it is easy to conclude that the final cost of electricity and the uncertainty in the financial model might be affected in the same range of percentages. Existing models already mentioned above do not take into account the specific meteorological and weathering conditions of each site that, as it will be explained below, might have also an important influence in the final results.

Summarizing, the existing uncertainty in the estimation and prediction of atmospheric attenuation of solar radiation (ATM) is significant. The impact of this uncertainty on the levelized cost of energy (LCOE) is significant.

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This work carries out a proper and detailed measurement of this effect that will provide us with the appropriate knowledge to allow us a better understanding of all phenomena involved in the ATM. Our ambition with respect to this knowledge is to help to:

- Reduce uncertainty in final performance of CR systems
- Improve existing models and validate them
- Establish a clear relationship between the existing meteorological conditions in a specific site and their effect in ATM
- Quantify at any site the ATM thought the measurement of meteorological conditions

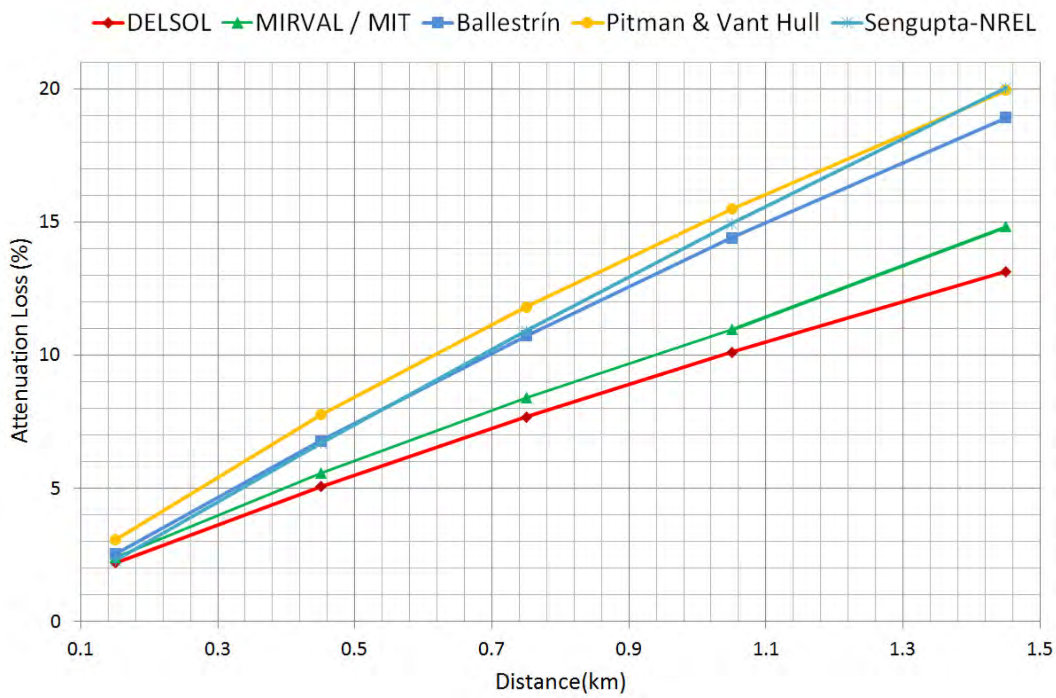

FIGURE 1. Attenuation losses estimated from different models.

The purpose of this paper is to describe the basic design features and operational capabilities of the ATM measurement system, a new system designed by CENER and the University of Zaragoza for measuring real-time atmospheric attenuation of solar radiation at surface level (patent P201830758). It performs a direct measurement without needing any previous assumption about atmospheric conditions.

METHODOLOGY

The atmospheric attenuation of the rays reflected by the heliostats on their way to the central receiver is caused by several phenomena such as atmospheric scattering (or diffusion) and absorption by aerosols and gases in the lower atmospheric layer. This attenuation is a function of the type and number of particles and molecules present in the path of the reflected sun's rays and can vary significantly with time and site. Moreover, these losses can be remarkable in desert locations, and maybe underestimated by standard and constant atmospheric conditions which are usually considered in ray-tracing or plant optimization tools. The primary source of atmospheric attenuation in the path of these rays is aerosols (small particles, solid or liquid, in suspension) [6]. Aerosols are difficult to model and predict, and come from a wide variety of sources (such as dust in suspension, sand storms, urban and industrial pollution, marine mists, etc.). The main attenuating phenomenon in the case of aerosols is dispersion, which shows a strong spectral dependence as a function of their size distribution. In particular, aerosol dispersion has a higher incidence in the ultraviolet and visible area of the solar spectrum.

In addition to this, the atmospheric gases present in the trajectory of reflected solar rays produce both dispersion and absorption (water vapor, ozone, NO_2 and other gases), being in this case the absorption the main attenuating phenomenon. Also, there are spectral bands associated with the specific absorption bands of different atmospheric gases where the absorption is significant (for example, water vapor has specific absorption bands in the infrared region at 820, 940 and 1120 nm, among others). Meteorological conditions largely determine the extent and speed with which pollutants disperse, and thus have a major effect on atmospheric attenuation at surface level. For example, wind carries atmospheric air pollutants and fine particles to distant places. Unfortunately, the effects of meteorological and physical phenomena associated with the attenuation processes in the very near surface layer (i.e., within the lower ~ 300 m of the surface layer), is poorly understood. Therefore, the air mass present in the path of the solar rays reflected by the heliostats on their way to the receiver element constitutes a spectral filter that can vary throughout the day, depending on the variation of aerosols, chemical composition of the air and even meteorological parameters [7]. For that reason, a spectral measurement and analysis of the attenuation phenomenon is necessary for its adequate characterization and modeling based on atmospheric components (including aerosols) at terrestrial level. A simultaneous measurement of the spectral atmospheric attenuation as well as other meteorological variables will allow modeling this effect (ATM) as a function of other common variables in meteorology. This precise modelling will enable solar community not only with a better estimation but also to a better prediction of ATM at different sites. These estimations will be based on the measured historical values of these meteorological variables what will help to make a better selection of the location of solar power plants.

In the state of the art there are experimental proposals for the measurement of ATM, i.e. those based on the use of a heliostat and several aligned radiometers [8] or CCD cameras [9]. Unfortunately, these systems neither measure the whole spectral range of the solar radiation (only about 73% of extinction is covered by the spectral range of the CCD camera) nor allow the monochromatic measurement in all and each wavelengths. As a result, the final achievable accuracy in measuring and/or estimating total atmospheric attenuation, as well as its quantification from other meteorological variables, is limited. The main advantage of the equipment developed and tested is that allow the accurate measurement of the ATM at each wavelength along the solar Spectrum in the range of 300 to 1650 nm, what provide us with a powerful ATM measurement tool in order to gather the necessary knowledge. Only by discriminating the total and monochromatic measurement of the ATM, and by applying spectroscopic analysis techniques is it possible, among the possible phenomena causing the extinction, to discern which of them is really the one taking place at a given moment, and thus to reach conclusions based on contrasted and measured facts and not on theoretical models or hypotheses whose validity may be more limited.

The objectives of this work, intended to go one step beyond the state of the art, are twofold: a) the immediate objective is to provide current commercial solar towers with a system able to monitor accurately the solar radiation attenuation, and b) the midterm objective is to acquire, with the adequate and precise measurements, the necessary knowledge about the different phenomena involved in the atmospheric attenuation in order to correlate it with meteorological and weather conditions when possible. In the following chapter a detailed description of the equipment, its functionalities and accuracy are described in detail.

EQUIPMENT DESCRIPTION, FUNCIONALITIES AND ACCURACY

Description of the Equipment

The ATM measurement system consists of a reflective screen used as a source of electromagnetic radiation emission and at least two devices for measuring the emitted radiation. The electromagnetic radiation source can be both artificial and natural (the sun, both directly and/or reflected by heliostats). Using the sun as the light source simplifies the optical system and ensures a spectral range and distribution suitable for modelling the attenuation phenomenon at the site itself (or any other site), both for prediction purposes and for estimating resources in the absence of recorded data. The system designed is used to characterize in real-time the causes of the atmospheric attenuation of electromagnetic radiation in the solar spectrum by means of the spectral measurement of solar radiation on a terrestrial level. The system is based on the separate arrangement of at least two light-catching devices, associated with measuring devices and aligned with a light source, to infer the attenuation of solar energy in the distance separating these devices from the light source by means of the difference in real time of the spectral energy incident on them (Fig. 2).

It is worth noting the presence of scattered radiation in the path from the screen to the optical device that does not come from the beam that travels from the screen to the optical device (which is the one of interest in the measurement of attenuation). So that the signal does not influence the final measurement, it is advisable to measure it and then consider its discount on the attenuation measurement. This can be done by aligning the telescopic devices to a black target or absorber screen. In addition, a heliostat can be pointed at the display to provide a brighter light signal as shown in Fig. 2.

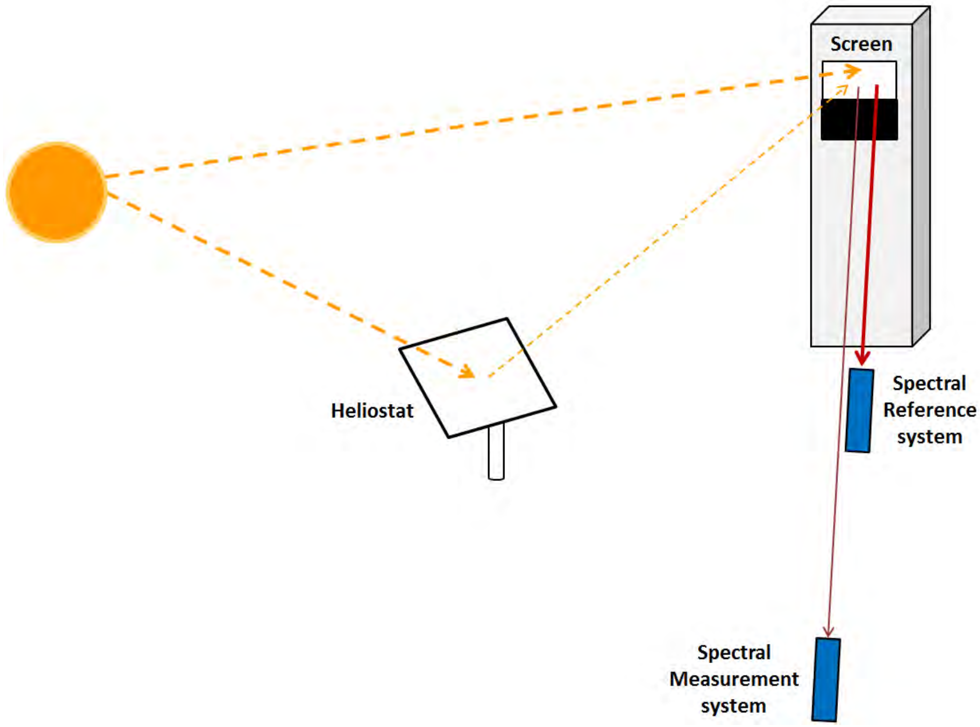

FIGURE 2. Schematic view of the system designed for the spectral measurement of the solar radiation attenuation.

The optical devices for capturing electromagnetic radiation are telescopic and ensure a capture of electromagnetic radiation only from the source, which is achieved by adapting the angle of acceptance (maximum angle at which the incident light beam is trapped) to the geometric considerations of the system (size of the screen, and distance between the screen and the detector system). It should be noted that the screen has a hemispheric reflectance to avoid the presence of privileged directions in the reflection and thus have a spatially uniform source. The value of the input aperture of the measurement system is determined by the focal length of the lens and the field aperture. Once the light signal is captured by the optical reference and measurement devices of the attenuated light signal, it is optically transmitted to a photodiode array spectrometer for simultaneous real-time measurement of its spectrum by both telescopic systems. Also, a calibration of the spectrometer linearity has been carried out in order to assure the measurement accuracy in the whole spectral range considered.

The screen is large enough to ensure that the telescopic optical device of the dimmed light signal, the farthest one, only captures light from the screen and thus avoids variable background signals which would lead to uncertainties in the measurement. In addition, the optical system must ensure that both the reference and the measurement systems capture the radiation coming from the same portion of the source. Specifically, for a distance of 1600 m and an aperture of 1 mrad, the size of the screen has to be larger than a circle with a diameter of approximately 1.6 m. Figure 3 shows the spectral (left) and reference (right) measurement systems.

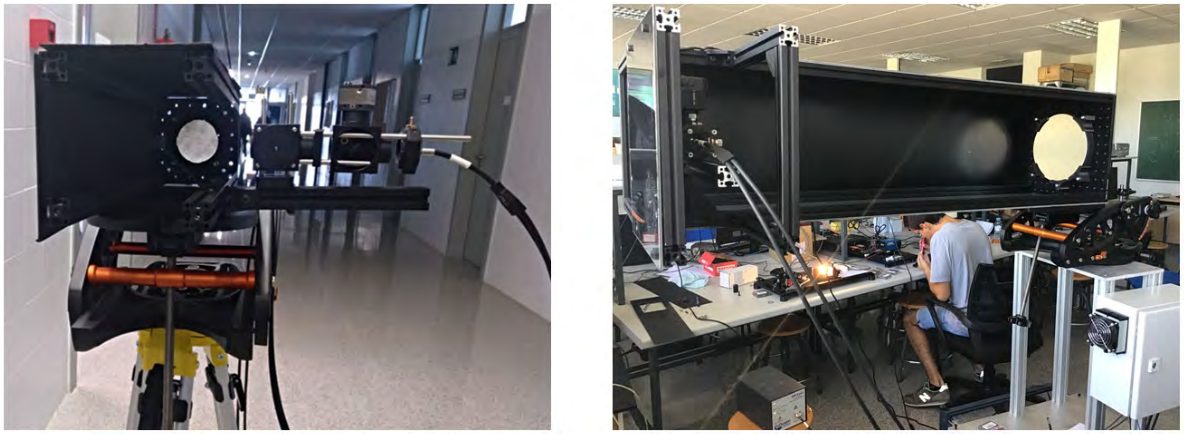

FIGURE 3. Frontal (left) and lateral (right) views of the device for measuring the solar radiation attenuation.

Noteworthy is the use of reflector telescopes (which make use of mirrors instead of lenses to focus light and form images), which prevent the angle of acceptance from changing with the wavelength (Fig. 3, right). The electromagnetic radiation emitted from the source and captured by the telescopic optical devices are conducted to real-time detection and measurement devices which provide simultaneous measurements of its spectrum in real time and over a spectral range that is sufficiently wide for the application under consideration.

System Functional Description

The comparison of the spectral curves obtained from the measurements of each detection and measurement device will provide the relative spectral atmospheric attenuation of the electromagnetic radiation concerned. The measurement procedure comprises the following steps:

- Alignment of at least two telescopic optical devices, located at different distances from the source, to the source of electromagnetic radiation
- Capture of a beam of electromagnetic radiation reflected from the source by means of each of the telescopic optical devices
- Monochromatic detection and measurement in the different spectral regions covered by the devices for detecting and measuring captured radiation
- Real-time calculation of monochromatic, spectral and total atmospheric attenuation by comparison of monochromatic spectral measurements

Also, to calibrate the ATM measurement system, prior to the alignment of the telescopic optical devices, it is advisable to calibrate the detection and measurement devices by placing the telescopic optical devices at the same distance from the source of electromagnetic radiation.

Figure 4 shows the spectral reference (orange) and measurement (purple) curves (left), as well as the telescopic image obtained of a sign of a white background with black letters located at 500 m (right). The comparison of the measurements provides the relative monochromatic atmospheric attenuation of the considered electromagnetic radiation between 300 nm and 1650 nm at 0.5 nm spectral resolutions. This attenuation is applied to the solar spectrum for obtaining the solar radiation attenuation.

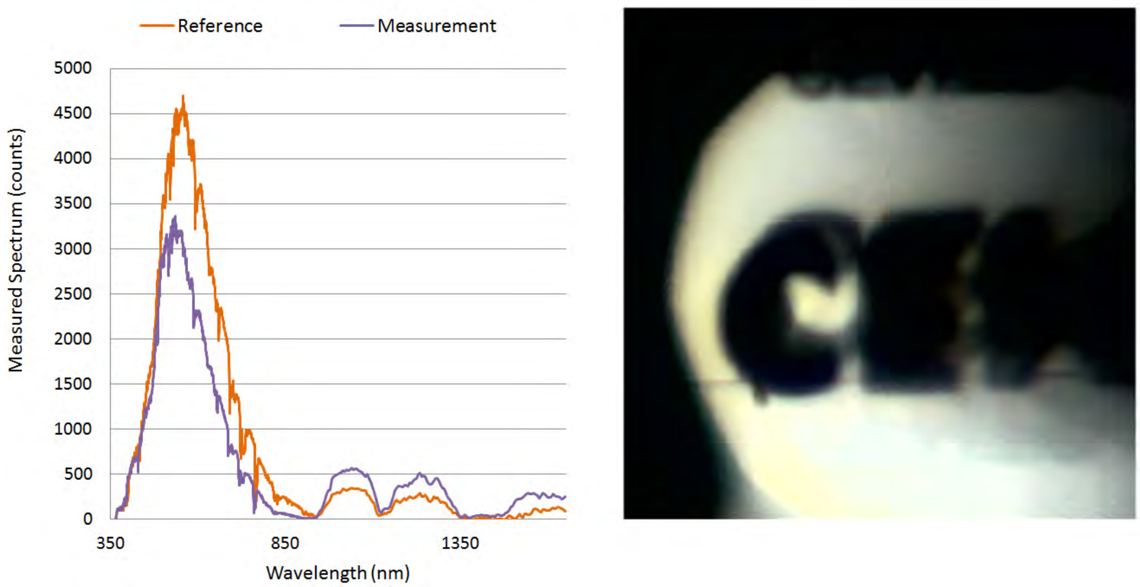

FIGURE 4. Spectral reference (orange) and measurement (purple) curves (left), and the telescopic image of a sign located at 500 m (right).

Finally, as Earth's atmosphere is a continuously changing filter that modifies the sunlight that travels through it, an actual solar spectrum must be used to obtain accurate results (either spectral measurements or the output of precise models). In this work, we have used SMARTS2 (Simple Model of the Atmospheric Radiative Transfer of Sunshine) [10], which computes spectral clear sky spectral irradiances (including direct beam) for specified atmospheric conditions (from any of 10 standard atmospheres) and solar geometries.

Accuracy of the Measurement

The ATM measurement system allows increasing the accuracy of the attenuation measurements with respect to state-of-the-art systems. The designed system allows the capture of radiation from the source with an angle of acceptance (maximum angle at which the incident light beam is captured and measured by the measuring device) in the order of 1 to 3 mrad to ensure that at a distance of 1 km only light is captured from the useful source of the system. This is because the telescopic optical device comprises an optical system that acts as a lens with a large focal length and a very small input diaphragm, so that the angle of acceptance of the optical system is very small (~1 mrad). In this way, a telescopic optical device arranged at a distance of 1 km from the source only captures the light reflected by an object of a size of 1 m. If the acceptance angle is not limited, the system will capture light from outside the system's useful source, which can lead to measurement errors. In the case of state-of-the-art systems that use cameras as sensors, they limit the angle of acceptance with the camera pixels they use to calculate the light output. This causes problems if there is chromatic aberration, as each wavelength can go to different pixels than the digital camera.

The proposed system is based on reflectors as optical imaging elements to ensure that there is no chromatic aberration and therefore to ensure that all wavelengths form image in the same image plane. Chromatic aberration can lead to errors in the case of the use of digital cameras as sensors, as each wavelength can form images in different pixels than the camera, so there will be pixels in which light from the useful light source or target and light from outside the useful light source is detected. The system envisages the possibility of preferably using two targets as a light source, a highly reflective or white target used as a useful light source for the measurement of atmospheric attenuation and a zero or black reflection target used as a background light measurement in the atmospheric attenuation measurement system. In state-of-the-art digital camera-based measurement systems, only one light source is used, which is a target that reflects sunlight. This can be a problem because the measuring system is not only supplied with light from the target but also with part of the diffuse light that reflects the atmosphere that is in the direct path from the camera to the target, and that forms a background of light that is variable with the conditions of the atmosphere and that is added to the light from the target. In the ATM measurement system, the same thing happens, that is to say, the light of the target and part of the diffuse light that is in the direct path from the target to the measurement system is detected, and for this reason, to eliminate the background of diffuse light, the system proposes to use a dark target that does not reflect any sunlight. Thus, when the measurement system is directed at the dark target, only the scattered light is measured, which is the background that is deducted from the measurement. In the current configuration, there is a white target as a source and, below it, a black target. Consequently, in order to take the measurement, the telescopic optical device should first be directed at the black target to measure the diffuse light background, and then the telescopic optical device should be directed at the white target to measure the useful light source by discounting the measurement of the black target.

As mentioned above, measuring the attenuation over the entire solar spectral range, i.e. in the ultraviolet, visible and near-infrared range, avoids significant errors that occur in the state-of-the-art attenuation measuring devices, since the non-visible spectral regions of the atmospheric attenuation do not have to be assumed from the atmospheric attenuation in the visible one. The fact of measuring the power exclusively in the visible spectrum, due to the use of exclusively silicon sensors or digital cameras whose sensor elements are made of silicon, limits the detection of a spectral range of up to 1050 nm. However, an important fraction of solar radiation is present in the non-visible spectrum region, and its atmospheric attenuation does not have the same weight that the visible region. By measuring across the entire solar spectrum, significant errors are avoided as far as state-of-the-art systems are concerned.

EXPERIMENTAL RESULTS

One of the main features that may fulfill this kind of systems is the long-term stability of the measurement. So, 24 h stability tests have been carried out to ensure that the final system will meet the appropriate requirements for a continuous measurement for at least one day in a solar plant, without a new calibration. To guarantee a proper light source during the entire test, a stabilized halogen lamp is used. Light from this lamp is directly captured by the fibers of the two optical systems (reference and measurement systems), detected and spectrally analyzed in both visible (VIS) and near-infrared (NIR) photodiode array spectrometers of each system. The stability obtained from these measures is better than 99%. As an example of these results, Fig. 5 shows the percentage of the ratio variation between reference and measurement systems over 24 h measured every 30 min, at eight different wavelengths in the VIS and NIR of the measured spectra.

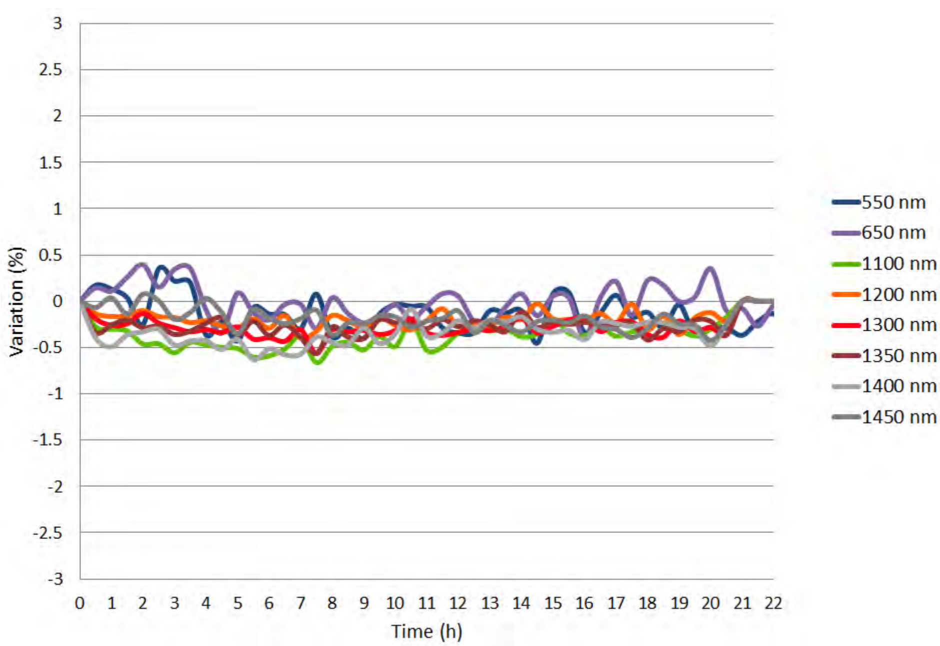

FIGURE 5. Variation (%) of the ratio between the spectral reference and measurement systems at different wavelengths.

For all wavelengths, variations are below 1%, which assures a suitable stability behavior of the system along the measurement times required by atmospheric attenuation characterization in solar plants. Note that in the case of the global attenuation coefficient parameter (which is calculated integrating over entire weighted solar spectra), the averaging over the whole spectrum reports better stabilities, with variations lower than 0.5%. Even so, longer terms stability tests (several days, weeks) will be carried out in the near future.

Another important feature of the system is the attenuation measurement accuracy that can be achieved. Unfortunately, it is not possible to have adequate atmospheric conditions having a well-known attenuation value as a standard for a proper accuracy test. So that, to simulate different attenuation conditions, we have used standard glasses with different attenuation coefficients. Figure 6 shows the attenuation curve measured for a 10 mm thick sample of fused silica glass (red curve). This curve has been measured by using as light source the sunlight reflected from a large white wall in a building located at a distance of 500 m from the measurement system. Measurement wavelength step is 1 nm, whereas spectral width is 5 nm in the range 450 nm to 750nm and 10 nm in the rest of the spectral range. For comparison, the figure shows the attenuation curve of the sample that was measured in laboratory bench spectrophotometer equipment (blue curve). One measured spectrum is also shown (purple curve) for a better understanding.

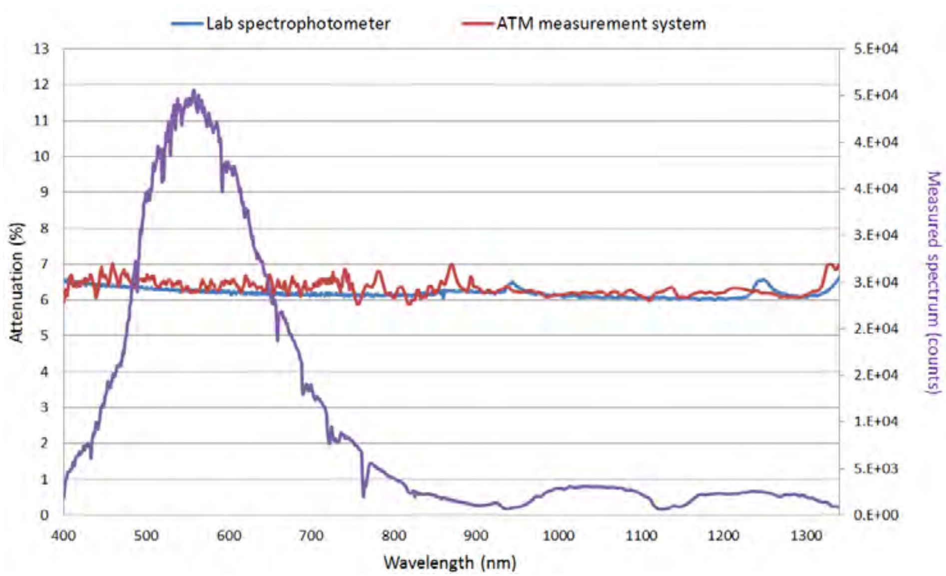

FIGURE 6. Attenuation (%) of a fused silica glass measured with a laboratory spectrophotometer (blue) and with the spectral measurement system (red), using as a source the sunlight reflected by a building at a distance of 500 m (purple).

The accuracy of the spectral measurement system compared to the laboratory measurement is noteworthy (the difference between them is below 1% at each wavelength in the whole spectral range analyzed).

CONCLUSIONS

Accurate measurement of the atmospheric attenuation is very relevant to the final real performance of solar tower technology. The precise knowledge of this phenomenon could have influence in the final design of future CSP plants depending on the site conditions. An innovative equipment for high precision measurement and characterization of atmospheric attenuation in real time has been developed by CENER and the University of Zaragoza (patent P201830758). This equipment measures the monochromatic ATM in the spectral range 300 - 1650 nm, which allows not only its characterization but also the correlation of the total ATM with the phenomena that cause it, either by the dispersion produced by the aerosols (with greater incidence in the UV-VIS zone of the spectrum) or by the presence of gases in the atmosphere (for example, water vapour with greater incidence in the IR zone of the solar spectrum).

Initial measures carried out, as well as theoretical estimates, reveal great stability of the device in operating conditions as well as low uncertainty (< 1%) of the atmospheric attenuation at surface level. No assumptions about atmospheric conditions are required. This equipment allows, on the one hand, to improve the accuracy of previous ATM measurement systems (this equipment achieves an accuracy in the order of 1%) and on the other hand to correlate the ATM with the existing meteorological variables (by applying spectroscopic techniques to meteorological measurements). In particular, critical relationship between atmospheric visibility, surface level aerosols and attenuation factors will be determined under different meteorological conditions. These, in turn, can be used for evaluating the attenuation phenomenon in solar resource assessments for site selection and prefeasibility studies, as well as for its forecasting in operating plants. In summary, the equipment and methodology presented in this paper will significantly improve the quality of the ATM measurements as well as the scientific knowledge of this important phenomenon what will help to get better CSP plants performance and reduce their cost.

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