PREDICTION AND VALIDATION OF CLOUDLESS SHORTWAVE IRRADIANCE SPECTRA FOR HORIZONTAL, TILTED, OR TRACKING RECEIVERS

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ABSTRACT

The SMARTS spectral model can advantageously be used to predict clear-sky irradiance spectra on surfaces of any tilt and orientation, e.g., for the simulation of spectrally-selective technologies. To evaluate the intrinsic accuracy of the model, its current version undergoes here a sophisticated three-step validation exercise, involving reference radiative transfer codes, and two series of sophisticated spectral and ancillary measurements performed at different locations. Provided that the most important inputs are known with sufficient accuracy, it is concluded that the model performance is very high, with typical differences of 1–2% when compared to reference models, and uncertainties largely within the overall experimental error when compared to spectroradiometric measurements.

1. INTRODUCTION

Many biological, chemical and physical processes are activated more powerfully at some wavelengths than at others. This is especially true and important in the field of solar energy engineering, where spectrally-selective systems such as PV devices, coated glazings, and biological reactors play an increasing role. For such systems, spectral radiation data are more appropriate than the more common broadband irradiance data. Unfortunately, spectral irradiance is not measured routinely, but only sporadically at a few experimental sites in the world. Consequently, the only way to accurately simulate the instantaneous energy production or overall performance of a spectrally-selective system is to rely on appropriate modeling. (For system rating considerations, it is possible to use some pre-determined reference spectra, usually imposed by an ad-hoc standard, but this method cannot be used to simulate a system under *variable* conditions, which is the purpose of this contribution.)

Most spectral radiation models have been developed for atmospheric research (e.g., MODTRAN and SBDART). Even though they are highly considered in the climate change community because of their accuracy and physical capabilities, it appears that their complexity (conducive to slow execution), specialized inputs, and their lack of support for the prediction of spectral irradiance on tilted surfaces make their utilization inappropriate for energy applications. Engineering models (e.g., SPCTRAL2) are much simpler and more adapted to the problem at hand. However, they have not been updated since the early '80s and their accuracy has not been tested against modern atmospheric models. In the last few years, the more recent and sophisticated SMARTS model (1, 2) has gained acceptance in both the atmospheric and engineering fields, due to its versatility (3), ease of use, execution speed, and various refinements.

MODTRAN, SBDART and SMARTS are three of six models that have been recently chosen to conduct an innovative radiative closure experiment (4). This study demonstrated that: (i) when detailed and accurate input data are available, such models can predict the clear-sky direct and diffuse *broadband* irradiances with great accuracy; and (ii) SMARTS's broadband irradiance predictions are comparable to those of reference radiative transfer codes.
These results also suggest that the current breed of radiative models can be used for quality control purposes, to test the consistency of long time series of broadband irradiance measurements made with different instruments, for instance. However, the present study is aimed at determining to what extent these same models can be useful in predicting *spectral* irradiance on surfaces of various geometries.

Because spectrally-selective technologies such as PV and thin-film coatings are very sophisticated and require considerable investments to develop and put into application, it is of paramount importance that the models used to predict the performance of these systems be of dependable accuracy under a variety of atmospheric conditions. The validation methodology followed here is threefold and consists in comparing the spectral predictions of SMARTS to: (i) those of four reference atmospheric models, under common and ideal atmospheric conditions for direct normal irradiance and global or diffuse horizontal irradiance; (ii) experimental spectroradiometric measurements of direct normal irradiance and global or diffuse horizontal irradiance; and (iii) experimental spectroradiometric measurements of global tilted irradiance that have been conducted specifically for this project.

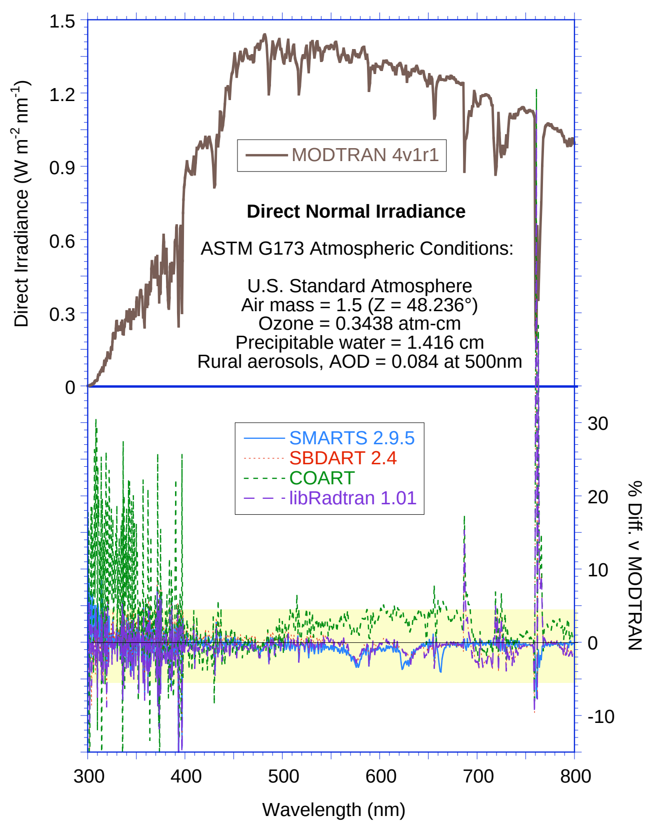

Fig. 1 Direct normal irradiance predicted by MODTRAN for *Case 1* (top panel), and spectrally-resolved percent difference between the irradiance predicted by four models and that of MODTRAN (bottom panel). The color-shaded area corresponds to an uncertainty of ±5%.

2. THEORETICAL VALIDATION

The first step into validating a model is to compare its predictions to those from more advanced or “reference” models. This is accomplished here by comparing SMARTS to four advanced radiative transfer codes: MODTRAN (5), SBDART (6), COART (7), and libRadtran (8). Some of these models have participated in detailed model intercomparison exercises (4, 9). With the exception of COART, which is used with its original extraterrestrial spectrum (ETS) throughout, all models are here forced to use the same ETS (10). Identical atmospheric conditions are also selected from the default vertical profiles they have in common. This guarantees that any model-to-model difference in irradiance prediction can be attributed entirely to differences in modeling the various extinction processes of the atmosphere (except with COART).

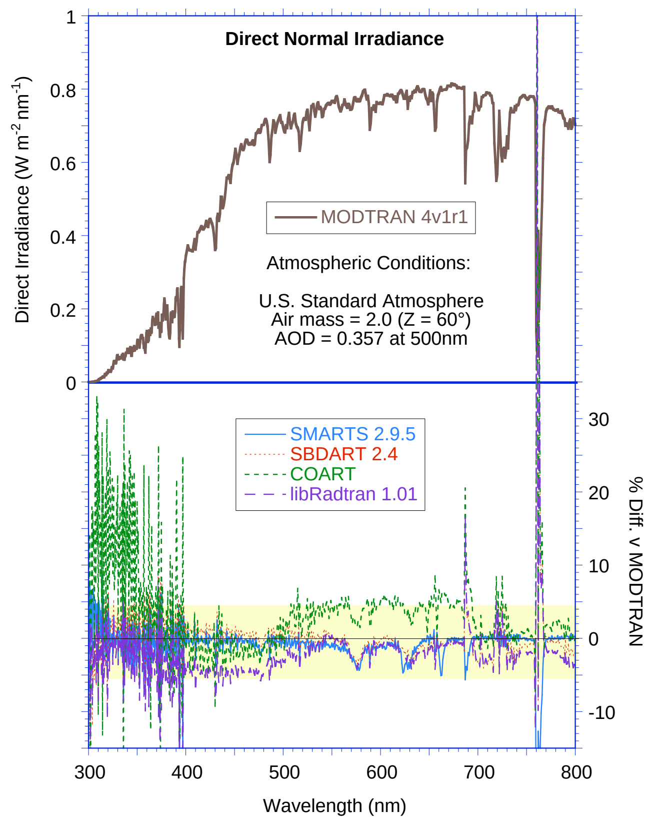

Fig. 2 Same as Fig. 1, but for *Case 2*: larger zenith angle (60°) and hazy conditions (AOD = 0.357 at 500 nm).

A variety of ideal atmospheric conditions have been considered, so as to create a real validation framework, but due to space limitations only two typical cases are discussed here. These two cases both consider a U.S. Standard Atmosphere with its corresponding columnar amounts of ozone (0.3438 atm-cm) and water vapor (equivalent to 1.416 cm of precipitable water), and an ideal ground with a spectrally-constant reflectance of 0.2. *Case 1* is for a zenith angle of 48.24° (air mass 1.5) and relatively low turbidity, reproducing the ASTM G173 standard conditions (11) nearly exactly. (The only exception being ground albedo, considered spectrally flat here rather than variable in G173.) *Case 2* differs from

Case 1 in two respects only: zenith angle increases to 60° (air mass 2) and turbidity increases 4.25 times, to an aerosol optical depth (AOD) of 0.357 at 500 nm.
Figures 1–4 illustrate some results of this first step, using MODTRAN's spectral predictions (downgraded to match SMARTS's resolution) as the reference. This selection of MODTRAN as the reference is based on the fact that, by default, it has the highest resolution among all models. It is still an arbitrary decision, which does *not* imply that MODTRAN is closer to the truth than any other model. Therefore, the relative results presented here cannot provide the absolute accuracy of SMARTS, but can at least address its consistency relative to more advanced models.

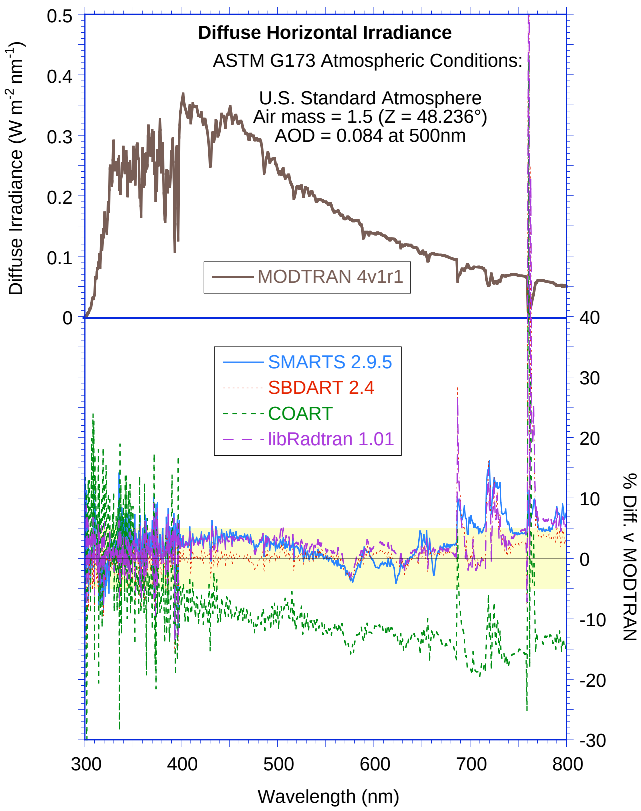

Fig. 3 Same as Fig. 1, but for diffuse irradiance.

Figures 1 and 2 pertain to direct normal irradiance, and show excellent agreement between all four models that share the same ETS. The SMARTS-predicted spectrum is normally well within ±2% of MODTRAN's, and often closer to it than SBDART's or libRadtran's. The disagreement between these three models and MODTRAN is only noticeable in strong absorption bands (due particularly to ozone, oxygen and water vapor), but these high-frequency spikes would disappear with moderate spectral smoothing. The differing COART results suggest that the uncertainty in ETS may far outweigh modeling differences in this class of models.

Results for diffuse irradiance appear in Figs. 3 and 4, showing slightly larger relative differences than in Figs. 1 and 2. This could be expected because diffuse irradiance is more difficult to model and involves more variables than direct irradiance. In both figures, the spectra predicted by SMARTS are close to those by libRadtran, whereas SBDART agrees more closely with MODTRAN. With the exception of COART, all irradiances are within ±5% of each other over the main part of the spectrum, at least outside of the main absorption features.
Results for global irradiance are not shown, but are similar to those for direct irradiance since, under clear skies, global irradiance is mostly made of its direct component.

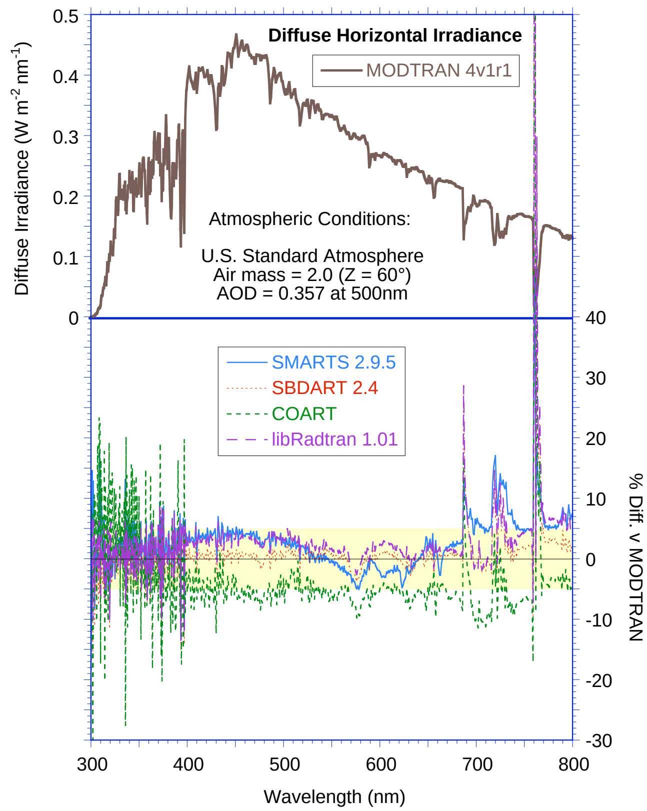

Fig. 4 Same as Fig. 2, but for diffuse irradiance.

3. EXPERIMENTAL VALIDATION

3.1 Conventional measurements

Conventional measurements and validation refer here to direct normal irradiance and diffuse or global irradiance on a horizontal surface. Most, if not all, spectral measurements currently performed are of this type. Comparisons between SMARTS's predictions and measured spectra have always been an important part of the model's development process to guarantee its relevance and accuracy (1–3, 11). This earlier work already demonstrated the high level performance of the model. Therefore only a few recent and more advanced sources of data are discussed here.

The main difficulty in any experimental validation undertaking of this type is that, *ideally*, very stringent requirements must be met if one wants to evaluate the accuracy of the model alone: (i) the spectrometer must have a better absolute accuracy than the model under scrutiny (otherwise the model actually tests the performance of the instrument); (ii) all the inputs required by the model must be measured simultaneously with independent instrumentation; and (iii) these inputs should be "perfectly" accurate to avoid propagation of errors.

Conditions for this ideal closure experiment unfortunately almost never happens, due to various limitations. For most validation exercises, only a few important input variables can be measured independently, and their accuracy is not always excellent nor well known.

In recent years, the Southern Great Plains (SGP) facility of the Atmospheric Radiation Measurement (ARM) program (located near Lamont, OK) has maintained a wealth of collocated radiometric and meteorological instruments. The high-quality and redundant measurements obtained during the Aerosol Intensive Operational Period (AIOP) of May 2003 currently offer one of the best opportunities to compare model predictions to irradiance measurements (4). The AIOP ancillary measurements include AOD from various sensors, aerosol single-scattering albedo, aerosol asymmetry parameter, and precipitable water.

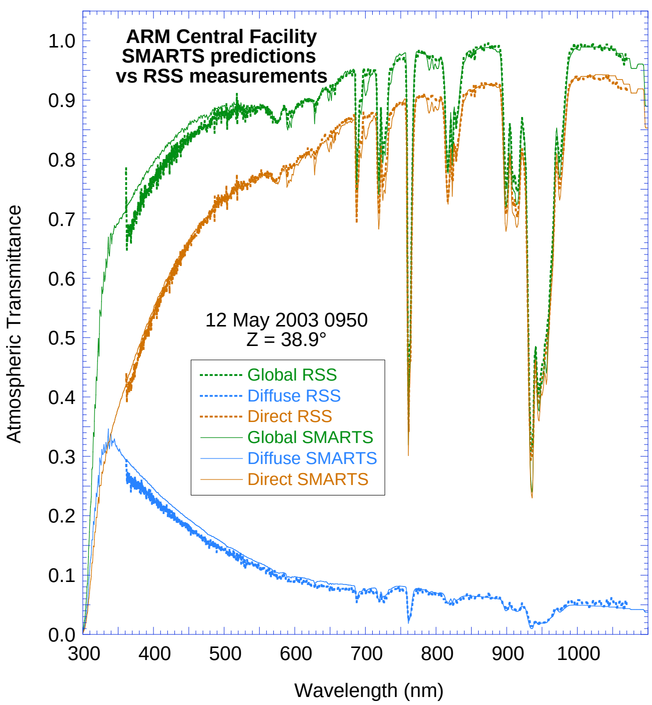

Fig. 5 Predicted vs measured direct normal, global and diffuse transmittances at ARM-SGP for a clear day.

SMARTS predictions are here compared to rotating shadowband spectroradiometer (RSS) measurements at the SGP site. This instrument uses a 1024-pixel CCD, measures global and diffuse horizontal irradiances alternatively (nearly simultaneously), and calculates direct irradiance by difference between them, in the spectral range 360–1070 nm (12). A sophisticated calibration technique, based on frequent Langley plots and detailed statistical analysis (13), has recently produced a method to obtain highly accurate *transmittances* from the irradiance dataset available from http://iop.archive.arm.gov, thus avoiding uncertainties in the instrument's absolute calibration and in the ETS. To better simulate the RSS, the SMARTS predictions are smoothed with a Gaussian filter of variable bandwidth, increasing (0.38–3.8 nm) non linearly as a function of wavelength (13).

For all these comparisons, the most important atmospheric variables were determined from collocated instruments, as summarized in (4).

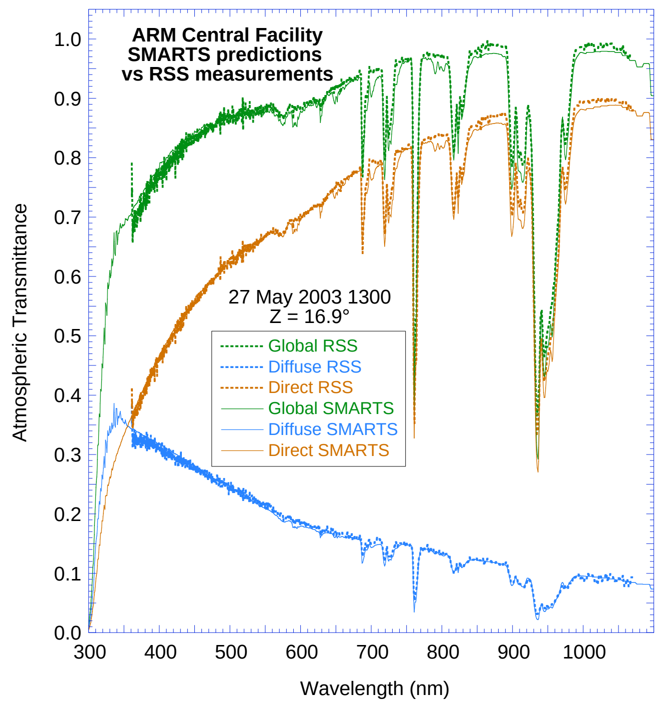

Fig. 6 Same as Fig. 5, but for a hazy day and higher sun.

Typical results appear in Figs. 5 and 6 for two of the 30 cases that were studied in (4), covering a day with low AOD (12 May 2003) and a day with high AOD (27 May 2003), respectively. Both figures show a nearly perfect agreement over most of the spectrum. Nevertheless, such a match can happen only if the main aerosol optical properties are known with sufficient accuracy. This may not be perfectly the case in Fig. 5, explaining the slight biases below 700 nm, where aerosol scattering is most intense.

Fig. 7 Left: Deployment of an ASD field spectrometer at NREL in 2005. Right: Ground cover seen by the instrument in inverted position. (Photos courtesy Daryl Myers.)

Fig. 8 Partial scene viewed by a vertically mounted sensor when facing south. (Photo courtesy Daryl Myers.)

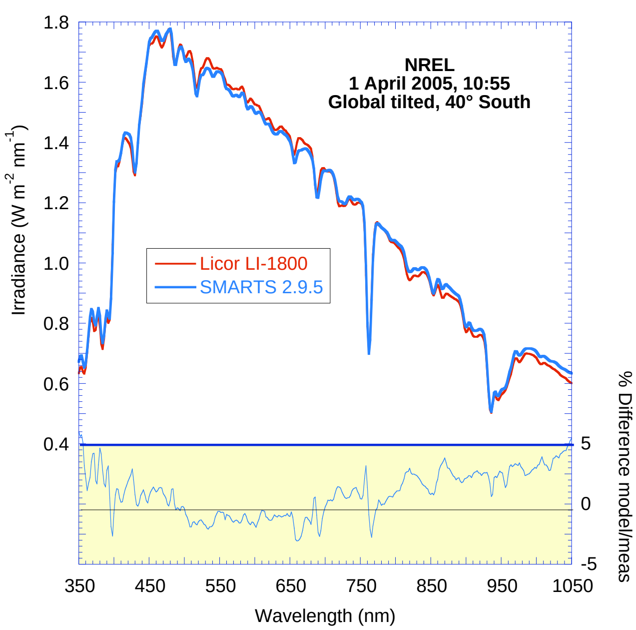

Fig. 9 Modeled vs measured spectrum on a 40°-tilted plane facing south under very clear conditions.

3.2 Measurements on tilted planes

Figure 7 shows a part of the experimental setup that was purposefully deployed at the Solar Radiation Research Laboratory of NREL (Golden, CO) during four separate days of April-May 2005 to undertake this final part of the study. The photo on the left shows a portable ASD Field-Spec spectrometer capable of acquiring spectra between 350 and 2500 nm at high speed. A laboratory-grade Optronic OL-754 was also deployed to acquire spectral scans between 300 and 800 nm in 3 minutes. All this is in addition to a fixed Licor LI-1800 field instrument, installed on a 40°-tilted plane facing south, that is routinely taking spectral scans every five minutes. Langley plots conducted on April 1, a very clear day, allowed to recalibrate the sunphotometers and retrieve the AOD at four wavelengths.

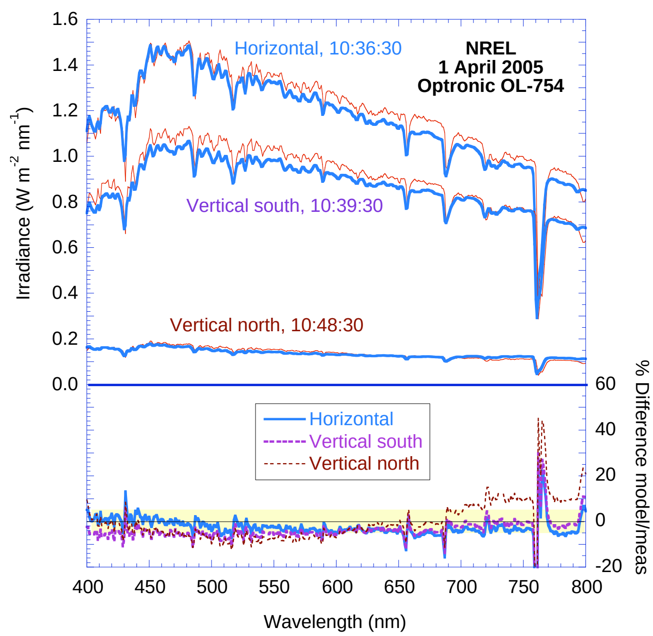

Fig. 10 Predicted vs measured global spectra at NREL (top), and percent difference between them (bottom).

Contrarily to the two ARM cases described in Section 3.1, no measurement of the other important aerosol optical properties (single-scattering albedo and asymmetry parameter) is made at NREL, so that default values were used in SMARTS. Similarly, precipitable water had to be estimated from temperature and humidity (14). An estimate of the ground's spectral reflectance was obtained by ratioing the upwelling and downwelling global fluxes measured by the FieldSpec instrument on one mid-day occasion (Fig. 7). This simple measurement, however, is not precisely representative of the real foreground reflectance facing a tilted instrument. For instance, the partial scene viewed by a tilted sensor facing south appears in Fig. 8. Not only the ground cover is globally different than in Fig. 7, there is also significant sky shading above the horizon, where radiance is quite high under clear skies. All this greatly increases the uncertainties when comparing measured and predicted spectra, relatively to the simpler cases of Section 3.1.

A typical comparison between SMARTS and a measured global spectrum on a 40°-tilt south-facing plane appears in Fig. 9. The difference between the two spectra is within ±5%, which is excellent, and its wavy structure can be explained in great part by known instrumental limitations (11, 15). Finally, three spectra measured with the OL-754 instrument in a 12-minute timeframe are compared to the model's predictions in Fig. 10. For that morning AOD was particularly low (0.027 at 500 nm). Combined with reduced Rayleigh scattering due to the site's high altitude (1829 m), little diffuse radiation is produced, hence the very low irradiance on the north-facing vertical plane. Despite all the modeling and experimental difficulties of this exercise, predictions are still mostly within ±5% of measurements. For other orientations, results are not always consistent because large reflecting obstructions exist at this site.

4. CONCLUSION

This study confirms the excellent accuracy of the SMARTS spectral model by comparison to predictions from reference models and to high-end experimental data at the SGP site. Validating modeled spectra for tilted, tracking or vertical planes is more challenging because additional variables are introduced, and some are difficult to model or control in practice (e.g., horizon shading or reflectance characteristics). Despite these difficulties, the special measurements carried out at NREL have shown that it is indeed possible to obtain accurate irradiance spectra on tilted or vertical planes with SMARTS. This is fortunate because it liberates the end-user from the extreme complexity of Monte Carlo models, which are required in remote sensing applications over steep terrain, for instance. These results are all the more important and original that no similar undertaking with such a large scope has been found in the literature.

For any receiver geometry and under any cloudless atmospheric condition, SMARTS therefore appears ideal to help simulate the output of spectrally-selective devices. The accuracy of this model is normally within 2% when compared to more sophisticated atmospheric models, and within the instrumental uncertainty (e.g., 5%) when compared to high-quality measured irradiance spectra.

For real conditions and under cloudless skies, the most important variable that conditions the accuracy of the predicted spectra is AOD. For optimum results, this variable needs to be measured in real time with a collocated sunphotometer. For steep receivers, precise evaluation of the foreground's reflectance properties and of horizon shading is essential too. Lack of such data may hinder the model's performance.

5. ACKNOWLEDGMENTS

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