



# Module Characterization

## Spectral Response of FS Series PV Modules

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### Purpose

The information presented in this document provides supplemental information about the response of First Solar FS Series PV Modules to different wavelengths of light and a summary of how spectral response affects module field performance. The data is intended to support the proper design of systems using the FS Series modules as well as the development of more accurate models for energy prediction. All data reported in this document is representative of First Solar FS Series cadmium telluride (CdTe) PV Modules, although some variation of performance between modules is normal and to be expected.

### Introduction

First Solar modules are rated under Standard Test Conditions (STC) assuming a spectral distribution (i.e. amount of irradiance at each wavelength) as defined by ASTM G173. Much like temperature and total irradiance, the spectral distribution of irradiance will affect module performance in the field as atmospheric conditions change. The performance effect of spectrum will depend on the material properties of the PV module technology, indicated by the module's spectral response as characterized under lab conditions (described in the first half of this document). The second half of this document provides a literature review of spectral response and spectral modeling, indicating how a module's spectral response will affect energy yield under field conditions.

### FS Series PV Module Spectral Response

The spectral responses of different FS Series CdTe PV Module types, provided in the form of external quantum efficiency (EQE), are shown in Figure 1. The EQE is limited in the short wavelength region by absorption of photons in the soda-lime glass superstrate material, transparent conducting oxide (TCO) layer, and window layer of the CdTe heterojunction. At wavelengths greater than 830nm, the EQE rapidly drops. This behavior is associated with the bandgap of the CdTe absorber layer. Photons of wavelength greater than 870nm have energies less than the bandgap energy (approximately 1.44eV), and therefore are unable to create electron-hole pairs. Such photons do not contribute to the current produced by a CdTe PV module.

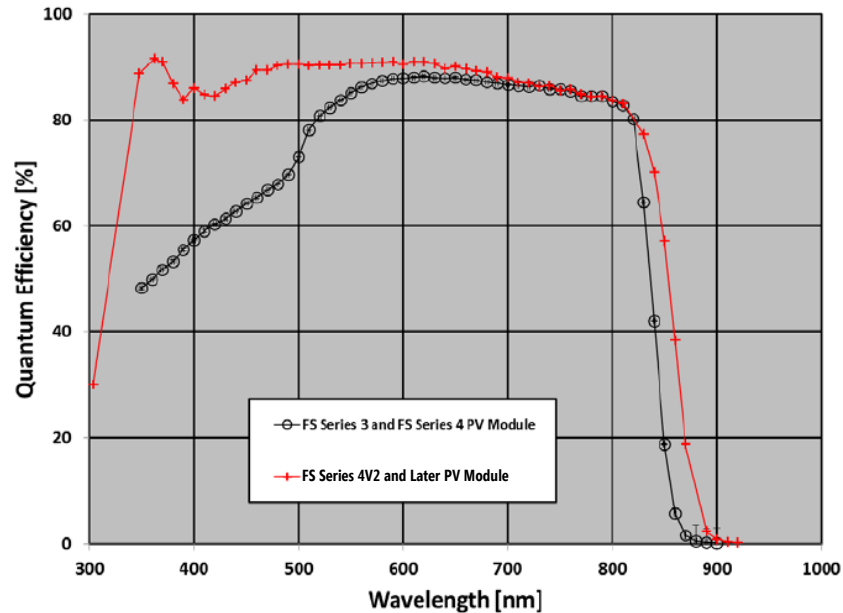


Figure 1. External quantum efficiency of a First Solar FS Series 3, FS Series 4, FS Series 4V2/Series 4V3, and FS Series 6 PV Module types.

### ***Spectral Response Comparison***

In order to make a comparison with the conventional silicon PV module quantum efficiency characteristic, Figure 2 provides overlaid EQE curves for First Solar FS Series CdTe PV Module types, along with the curve of a monocrystalline silicon (Si) PV module. All of the EQE curves have been normalized with respect to the peak response value to highlight the difference in EQE response from one PV module type to the next. In the wavelength region from 430nm to 550nm, the EQE of the Si PV module shows greater response than the FS Series 3 and FS Series 4 CdTe PV modules for several reasons. The Si module’s cover glass is thinner and has less iron content than the soda-lime glass used in FS Series 3 and Series 4 CdTe PV modules. In addition, the Si module has no transparent conducting oxide layer, nor window layer (as is used in a heterojunction CdTe type solar cell), so more of the short wavelength photons are able to get to the PN junction region and contribute to the Si module’s photo-generated current.

The FS Series 4V2/Series 4V3/Series 6 EQE shows significantly better response in the 350nm to 550nm wavelength range than both the earlier FS Series CdTe PV module types and the Si PV module. This improvement in EQE is made possible by changing the design of the transparent layers in front of the CdTe absorber layer in the CdTe PV module. The net result is an increase in the photocurrent delivered by the PV module, when compared to the photocurrent of FS Series 3 and FS Series 4 CdTe PV module types.

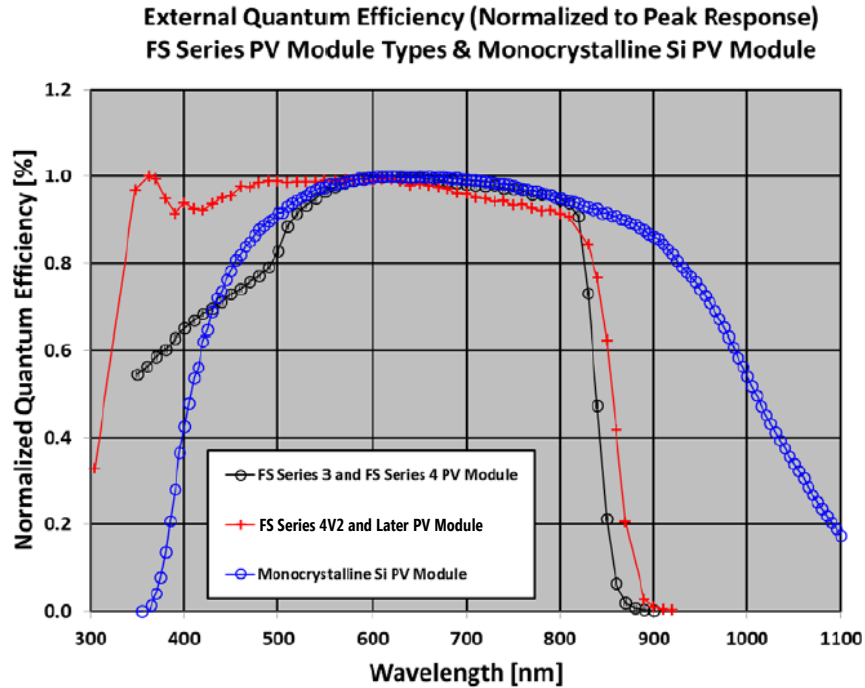


Figure 2. Normalized external quantum efficiency of First Solar FS Series 3, FS Series 4, FS Series 4V2/Series 4V3, and FS Series 6 CdTe PV Module types, compared with that of a monocrystalline Si PV module.

Figure 2 also shows that for photons of greater than 870nm, the Si module produces electron-hole pairs, since the bandgap of Si is lower than that of CdTe. The Si response approaches zero at about 1100nm, which corresponds to the bandgap of Si (approximately 1.12eV). The gradual decrease of the Si module's response from 900-1100nm is due to the fact that Si has an indirect bandgap, whereas CdTe is a semiconductor of the direct bandgap type. This property of First Solar CdTe PV modules yields a sharp cutoff in EQE response at the bandgap energy, with good response evident at wavelengths just shorter than the critical wavelength. Photons with energy slightly higher than the bandgap are strongly absorbed in CdTe, whereas the absorption coefficient for similar photons in the Si case is less, and becomes smaller still as photon energies approach the bandgap energy.

While the Si module's response in the 900-1100nm region enables it to make use of more near infrared (NIR) light in the solar spectrum than FS Series CdTe PV Modules can, the amount of energy available in this wavelength region is limited, and decreases with increasing photon wavelength (see Figure 3 for the spectral irradiance distribution of a typical reference solar spectrum). In addition, atmospheric water vapor strongly absorbs in this region (seen as a notch in the standard spectrum around 950nm in Figure 3). The overall contribution of NIR radiation to the total energy produced by a PV system is limited by these characteristics of the solar spectrum, and thus the value of NIR quantum efficiency in PV modules may not be the most important consideration when evaluating the energy yield of a PV system.

## First Solar's Solar Simulator

Figure 3 illustrates both the ASTM G173-03 standard spectrum for hemispherical (global) solar radiation on a 37° tilted surface, and the output of xenon arc solar simulators used at First Solar. As can be seen in the figure, there is close agreement between the standard spectrum and the solar simulator output over much of the wavelength range to which FS Series PV Modules respond (approximately 350nm to 850nm). The simulator shows a higher output in the 300-500nm range and a large spike in output around 823nm. Such spikes occur at wavelengths of characteristic emission lines of xenon and other gases used in the arc lamp source. Since FS Series PV Module EQE falls to zero at around 870nm, disagreement between the spectra shown in Figure 3 at wavelengths greater than 870nm has no impact on the electrical output of the module. First Solar's calibration procedure takes the impact of the higher short wavelength output and the 823nm spike into account, so results of measurements made on PV modules correspond to the output of the modules under the standard spectrum.

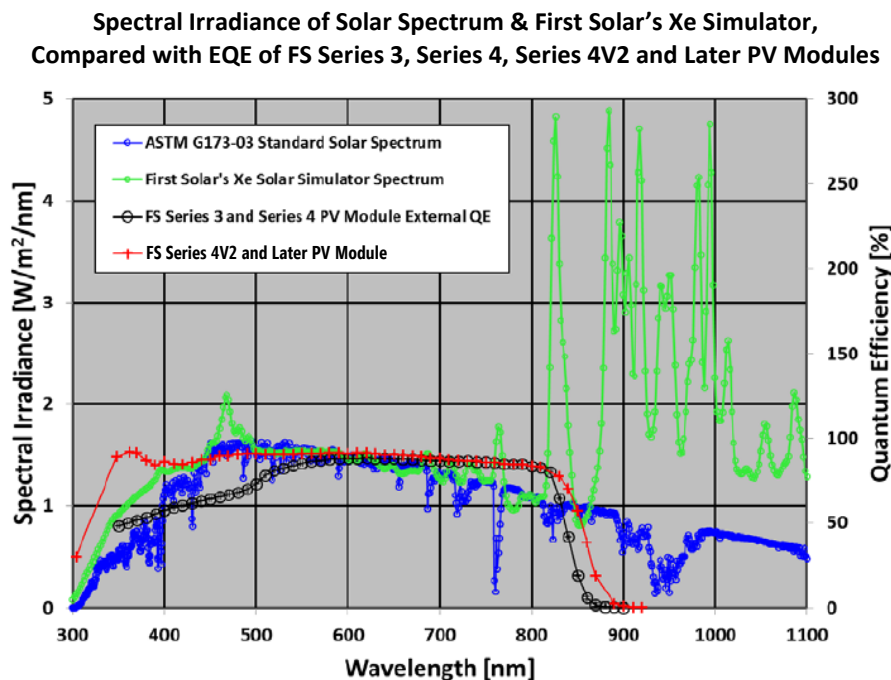


Figure 3. Comparison of the ASTM G173-03 standard solar spectrum and First Solar's continuous xenon arc solar simulator spectral output. The external QE data from Figure 1 are included for reference, and indicate that good agreement exists between spectral irradiance distributions over the response range of First Solar PV modules.

## Spectral Response under Field Conditions

The differing lab-measured spectral responses of technologies described above can have significant impacts on relative energy yield as atmospheric conditions change from the standard ASTM G173-03 spectrum. Different atmospheric constituents absorb and/or reflect irradiance at different wavelengths, which results in changes in the relative irradiance at each wavelength under field conditions. Significant constituents include precipitable water ( $P_{wat}$ ) and air mass (AM). Of these factors CdTe

module performance is most sensitive to  $P_{wat}$ , whereas crystalline silicon (c-Si) PV modules are more sensitive to Air Mass<sup>1-2</sup>.

First Solar has extensively researched the effects of spectrum on PV performance. This research, which has been published in academic journals and conference proceedings<sup>1-4</sup>, reaffirms the need for spectral corrections in PV performance modeling. Seasonal and short-term weather related changes in solar spectrum cause a shift in the performance of PV systems as large as 5% from nameplate<sup>2</sup>. Spectral shift (M) is a metric used to indicate variation in PV performance from nameplate due to deviations from ASTM G173 spectrum (AM1.5), and can be predicted using the SMARTS model<sup>1-4</sup>. SMARTS model results can be parameterized into simple functional forms that can easily be implemented into PV simulation software. Analysis of PV performance data from a variety of climates, over all seasons, illustrate that both the SMARTS model, and parameterizations thereof, match measured data<sup>1,3-4</sup>.

### ***A History of Spectral Correction Methods***

Spectral shift effects vary with PV technology due to the range of spectral responsivity of the module. Historically, the most commonly used spectral correction method was an air mass modifier proposed by Sandia National Labs<sup>5</sup>. The model was intended to be applicable to all PV technologies. However, this air mass function requires module testing outdoors under clear skies. Moreover, follow-up work has suggested that use of the air mass modifiers yielded errors larger than when no corrections were applied. The subsequent research hypothesized that precipitable water caused the seasonal and geographic disparities in the modifier value<sup>6-7</sup>.

Given that  $P_{wat}$  is the primary driver of spectral effects on CdTe PV technology, First Solar first proposed an empirical correlation for CdTe technology that was a function of precipitable water only<sup>3,4</sup>. Water vapor absorbs irradiant light in the wavelengths outside the CdTe QE (above 900nm)<sup>4</sup>, therefore module performance increases relative to a broadband irradiance measurement when  $P_{wat}$  is high. Hot humid climates such as the South Eastern United States and most of India indicate expected energy gains of 3%-5% over nameplate with First Solar Series 4V2, Series 4V3, and Series 6 modules due to the high  $P_{wat}$  content<sup>2</sup>.

### ***The Current State of Spectral Modeling***

More recently, First Solar improved upon the model by adding terms to account for secondary AM affects<sup>1</sup>. For CdTe, the new two parameter spectral model produces results comparable to the earlier  $P_{wat}$  only model; however, it has the added advantage of also being applicable to c-Si technologies. Other recent publications by a c-Si manufacturer<sup>8</sup> and a national lab<sup>9</sup> have suggested correlations that also include both precipitable water and air mass, with other considerations of aerosols and clearness index.

The inclusion of spectral variation into energy models has the potential to improve prediction accuracy which will lower the risk of projects failing performance commitments, making projects more bankable and financing easier.

### ***Spectral Research in Scientific Literature***

In addition to the First Solar internal publications, a considerable number of external documents support the sensitivity of PV performance to spectrum.

- Higher band-gap PV technologies display a large seasonal dependence over multiple locations. Low AM values and high  $P_{\text{wat}}$  positively impact the performance of CdTe technology<sup>10</sup>.
- One spectrum can result in spectral gains for one technology, but also spectral losses for another one<sup>11</sup>.
- CdTe and a-Si based samples indicate advantages for blue shifts of the solar spectral irradiance<sup>12</sup>.
- Technologies with a narrow range of wavelengths are more sensitive to  $P_{\text{wat}}$  amounts, which a single AM correction factor does not address<sup>13</sup>.
- It is reasonable to expect that the solar spectral content can vary apart from broadband irradiance and air mass; for example, due to water vapor content or atmospheric turbidity<sup>6</sup>.
- CdTe technology exhibits a greater spectral sensitivity than CIGS and c-Si due to its narrow spectral response. CdTe shows a net gain in current density during the summer months when the days are longer and higher electrical demand during peak times<sup>14</sup>.
- Sensitivity to spectral irradiance can be predicted by determining spectral irradiance variation as a function of input atmospheric conditions<sup>15</sup>.
- The difference between the incident spectral distribution and the reference spectrum assumed by broadband instruments is found to result in daily energy yield predictions that are incorrect by as much as 15%.<sup>16</sup>

### ***Spectral Model Implementation in Software***

First Solar introduced PlantPredict, a cloud-based web application that allows users to develop solar energy estimates for utility scale PV applications<sup>17</sup>. PlantPredict has the spectral correction method proposed by Lee and Panchula natively included<sup>1</sup>. First Solar recognizes that PVsyst, a commonly used commercial software for performing energy predictions does not contain a relative humidity parameter which is essential to calculating spectral shift for PV modules. Therefore an adjustment to monthly soiling factors external to PVsyst is required to accurately model spectral shift. Until such time as PVsyst permits the application of a mismatch loss due to spectral shift, please see PD-5-423 and PD-5-423EX for instructions and sample calculations.

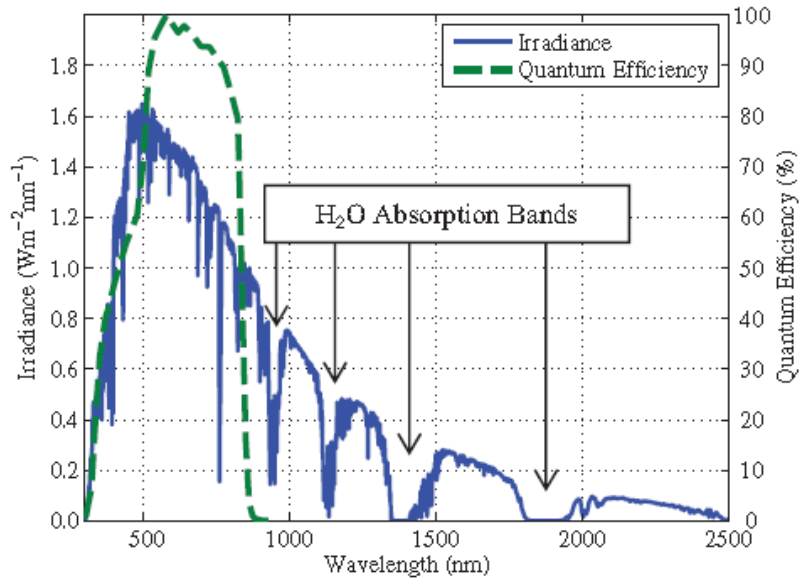


Figure 4. Global irradiance spectrum defined by ASTM G173 and an example QE curve normalized to 100% for a CdTe PV cell.<sup>3</sup>

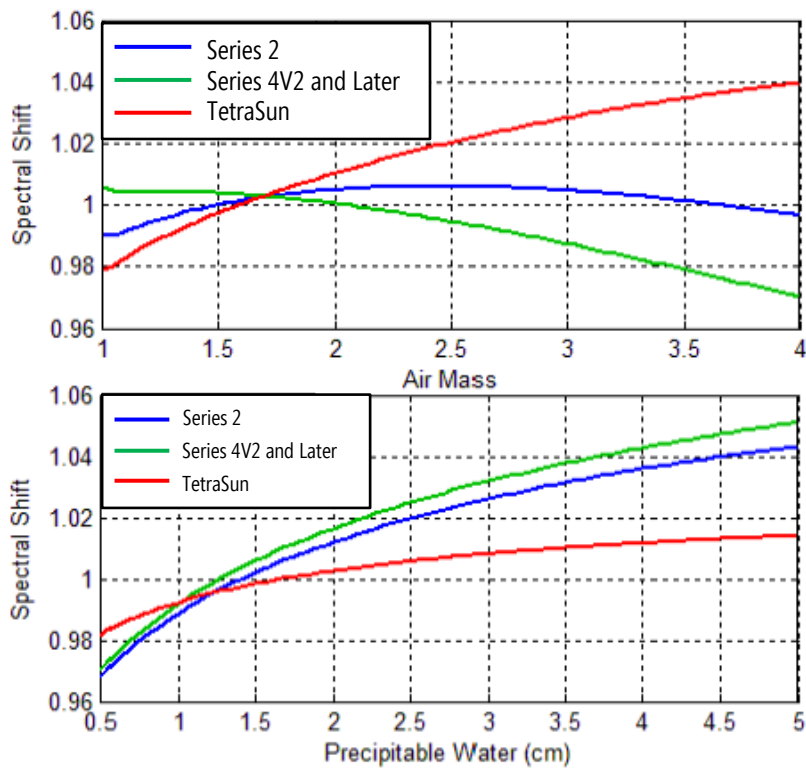


Figure 5. Sensitivity of Series 2 and Series 4V2 and Later CdTe modules and Tetrasun mono-Si modules to Pwat and AMa.<sup>2</sup>

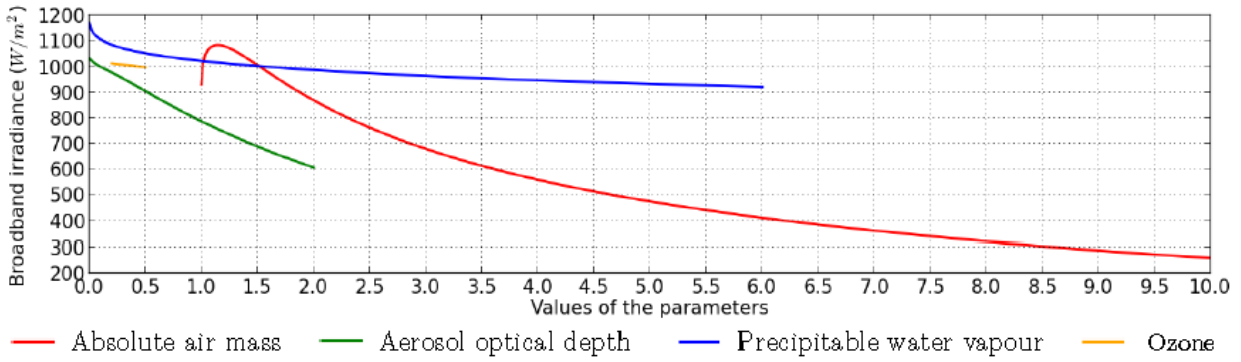


Figure 6. Effect of influencing parameters on the broadband irradiance.<sup>11</sup>

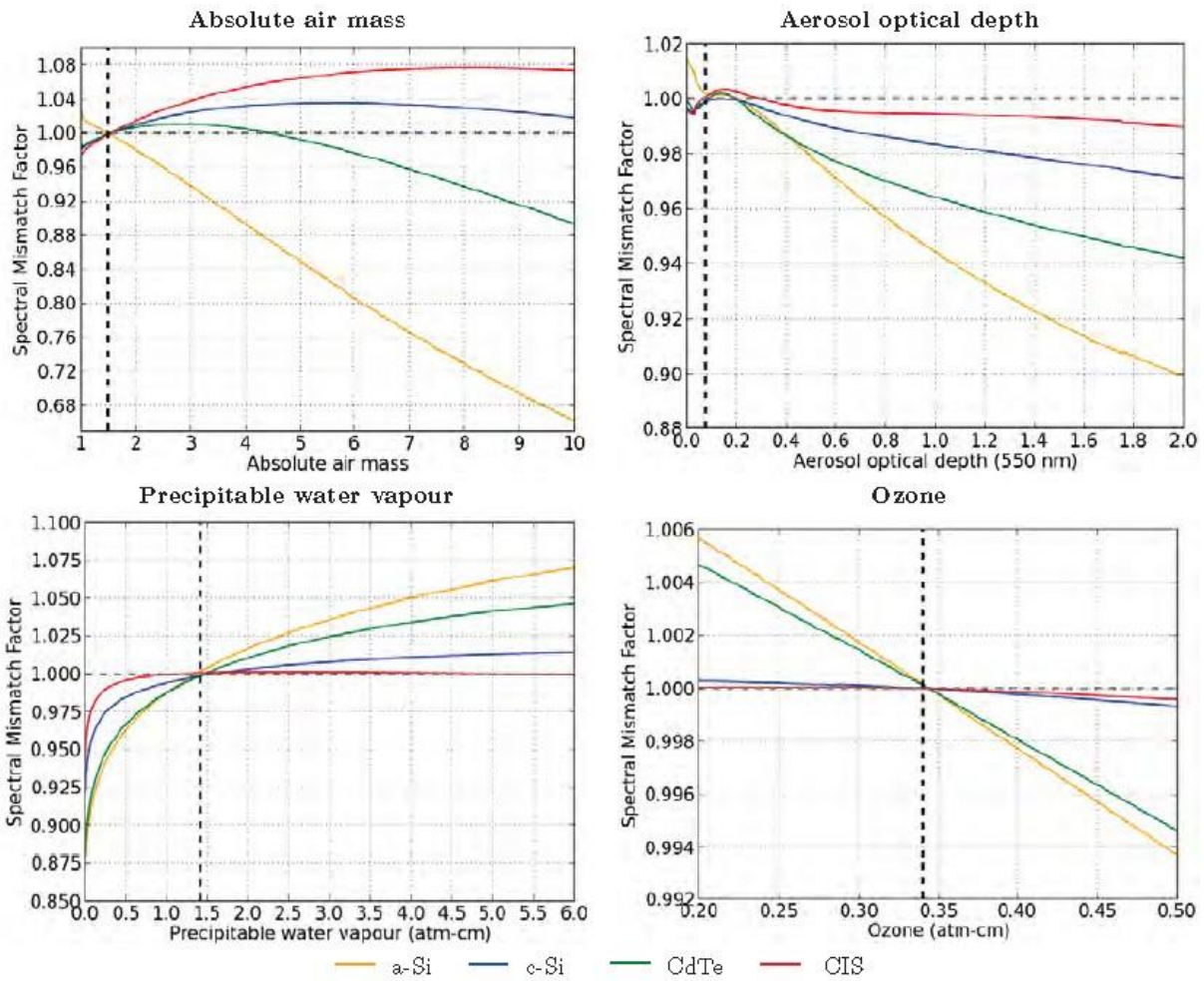


Figure 7. Effect of multiple influencing parameters on spectral mismatch.<sup>11</sup>



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