Solar Energy Incident at the Tower Receiver of a Solar Thermal Energy Plant, Derived from Remote Sensing: 1. Computation of both DNI and Slant Path Transmittance

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Solar Paces 2016, Abu Dhabi,
11-14 October 2016

1. Aerosols decrease the solar plant production

Solar Thermal Energy (STE) plants are an important component of the renewable energy market. They are built where solar resource is maximum, which usually occurs in dry areas of the tropics, where cloud cover is relatively sparse, atmospheric content of water vapour is small, and the sun can reach the zenith. The other important factor on solar resource is the extinction by aerosols, tiny particles in suspension in the atmosphere.

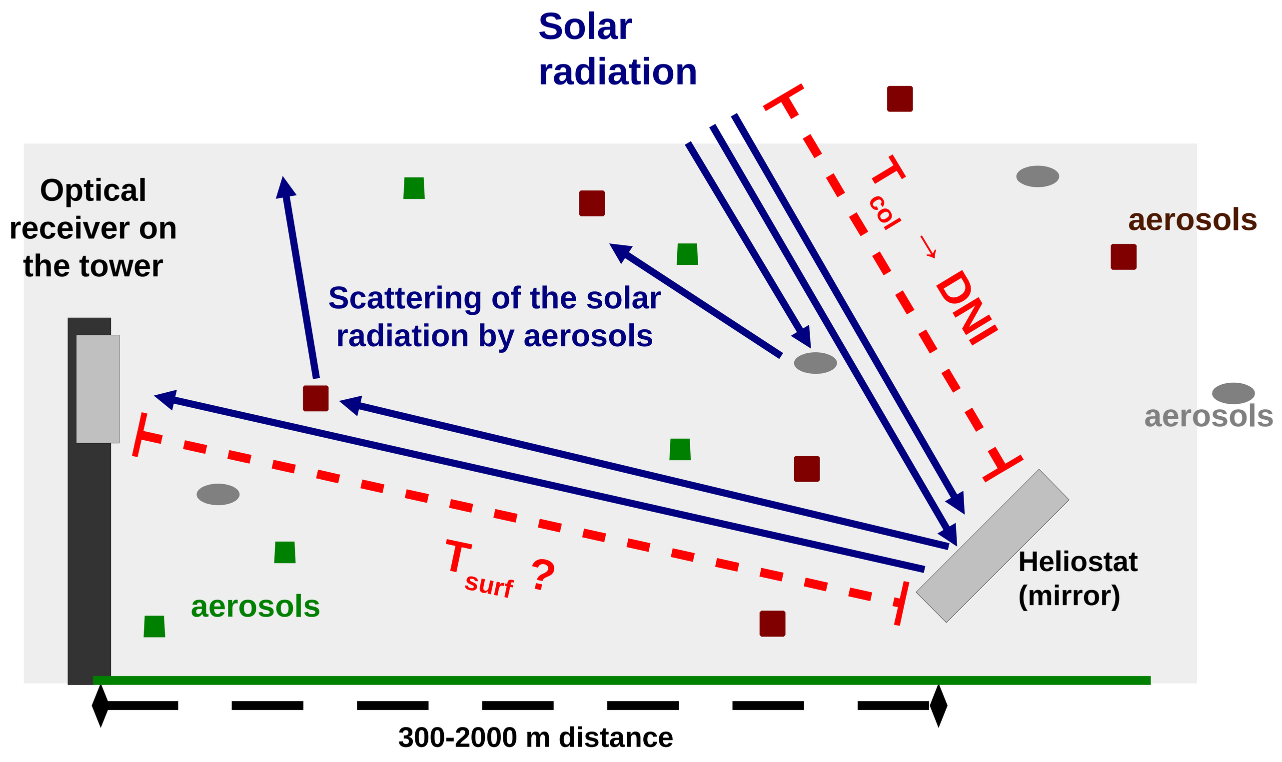

Figure 1. *Schematic view of the two optical pathways in a tower STE plant, and the scattering effect by aerosols.*

Mostly by scattering but also by absorbing solar radiation, aerosols have a strong impact on Direct Normal Irradiance (DNI). It is consequently important to correctly model the aerosol optical properties for the bankability of solar thermal plants. Moreover, the collected solar radiation depends not only on the atmospheric column transmittance governing the *DNI*, but also on the slant path transmittance between the heliostats and the receiver. The slant path contribution can be significant as it increases with the heliostat-receiver distance, and as aerosols are mostly found close to the ground level. ***Fig. 1*** shows the schema of a tower STE plant.

2. Regional maps of DNI and slant path attenuation

The MODerate resolution Imaging Spectroradiometers (MODIS) are used to show the aerosol impact and its spatial heterogeneity, in the region extending from southern Iberia to Sahara, beyond the High Atlas, on 16 August 2012. The contribution by aerosols on accumulated *DNI*, $\Delta SEH_{aerosol}$ (for Solar Exposure at the Heliostat) is computed (***Eq. 1***), as well as the slant path broadband attenuation caused by aerosols, A_{surf} (***Eq. 2***), with MODIS aerosol optical thickness (AOT) and ECMWF boundary layer height (BLH) [Elias *et al.*, 2016].

Equation 1:

$$\Delta SEH_{aerosol} = \sum_{\Delta t} DNI(Rayleigh, gas) \times \Delta t - \sum_{\Delta t} DNI(Rayleigh, gas, aerosols) \times \Delta t$$

Equation 2: $A_{surf} = 100 * (1 - T_{surf})$ *(transmittance T_{surf} represented in* ***Fig. 1****)*

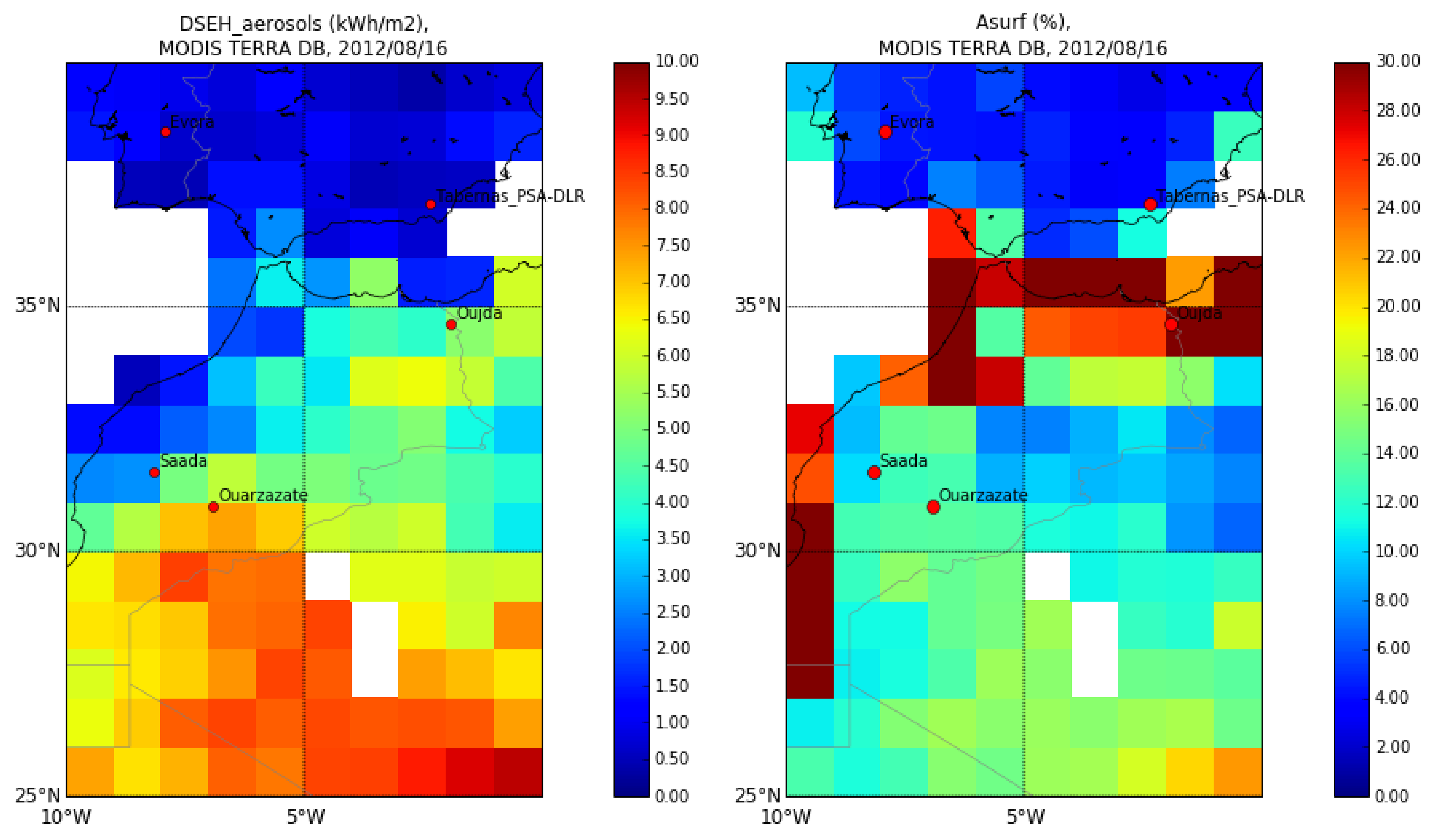

Figure 2. *Solar resource parameters computed with MODIS AOT (Collection 6, Level 3, Deep Blue algorithm), MODIS water vapour content, MODIS ozone content, ECMWF ERAinterim BLH, on 16 August 2012 at around noon. $\Delta SEH_{aerosol}$ (kWh/m²) is showed on the left, and A_{surf} (%) on the right. No clouds are considered in the coloured pixels, while white pixels indicate cloud presence. AERONET stations are indicated.*

$\Delta SEH_{aerosol}$ (***Fig. 2, left***) was highly contrasted on 16 August 2012 in the region. The aerosols had little impact along the coast and over the Iberian Peninsula, and on contrary 7 to 10 kWh/m² was attenuated by aerosols south-east of Ouarzazate. On this specific date, aerosols could attenuate half of the extraterrestrial solar energy.

A_{surf} was little varying from 15% to 25% inland and strongly decreased along the coasts because of decreasing *AOT* (***Fig. 2, right***). A_{surf} was larger in the Iberian Peninsula than on the coast because *AOT* was as small but *BLH* larger.

3. Time variability of the slant path transmittance

When a location is chosen for a tower STE plant, a ground-based instrument can provide a better accuracy on *AOT* than a satellite instrument, with a better representativity of the aerosol variability and of the tower STE plant running conditions, and a higher time resolution. An AERONET station is running at the Ouarzazate airport (Morocco) since 2012.

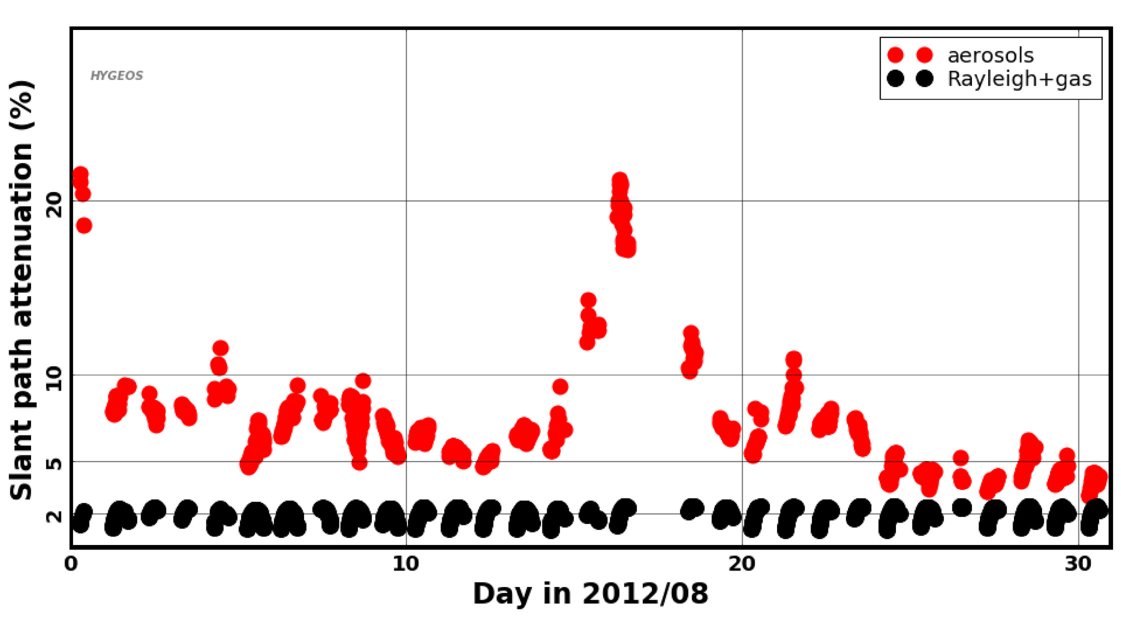

Figure 3. *The slant path attenuation in the broadband solar spectrum, at Ouarzazate in August 2012, computed with 15-minute AERONET AOT and ECMWF BLH of 4.7 km, for a heliostat-receiver distance of 1 km. Attenuation is showed separately for aerosols (red) and for both Rayleigh scattering and water vapour absorption (black).*

Fig. 3 shows the variability of the attenuation (***Eq. 2***) for 1-km distance in the slant path. In August 2012, the attenuation caused by aerosols could reach 20% during a few hours (17/08), when *AOT* was close to 1.0 at 500 nm, and also be smaller than 5% during cleaner days (e.g. 26/08). Rayleigh scattering and water vapour absorption had minor but non negligible influence in the slant path, with around 1.5% attenuation.

The monthly average of the slant path broadband attenuation caused by aerosols was 6.9±3.0% in August 2012, because of desert dust aerosols. *AOT* was 0.36±0.17 and the Ångström exponent was 0.27±0.07. Aerosols in the slant path reduce the incident energy by 7.5 kWh/m² in August 2012.

4. Validation

The monochromatic-to-broadband conversion is validated by comparing computed *DNI* with local measurements made at Ouarzazate. The root mean square difference was 42 W/m² in *DNI* and 0.32 kWh/m² in *SEH* (over 1 day). ***Fig. 4*** shows comparisons of *DNI* for two days with contrasted aerosol loads. *DNI* is satisfyingly reproduced. Largest differences were caused by heterogeneities in the cloud cover or the aerosol plumes.

On 28 July 2012, *AOT* was fairly constant (0.06 at 500 nm) during the day, but on 22 March, it was highly variable, by a factor of 4 from sunset to sunrise. The changing impact of *AOT* was correctly computed, even if some time delays were observed, caused by heterogeneities in the aerosol plume spatial extent.

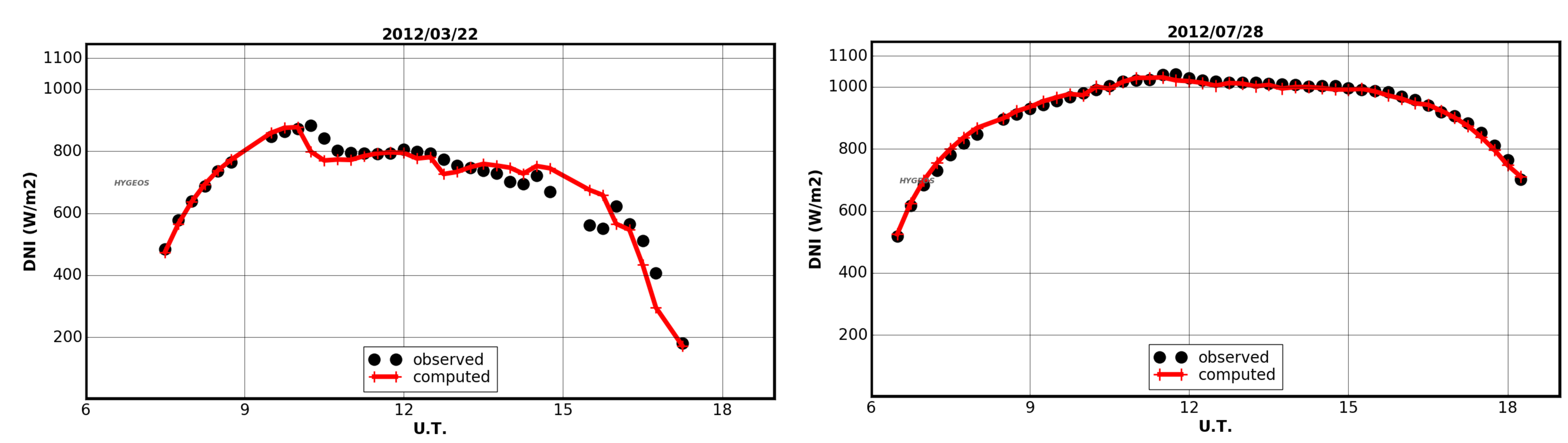

Figure 4. *Computed and observed DNI during 2 days at Ouarzazate. AOT is constant on 28 July 2012 (right) but the standard deviation is 0.10 on 22 March 2012 (left).*

The BLH approach was validated using ground-based measurements by a nephelometer at Ouarzazate, and further data is necessary to ensure the validation.

Acknowledgments: The authors are very grateful to the AERONET site operators and instrument owners, to the MODIS team, and to EDF-EN to provide the *DNI* data. The authors also acknowledge ECMWF for providing the boundary layer data.