

# Comparison and analysis of two measurement systems of horizontal atmospheric extinction of solar radiation

F. J. Barbero<sup>a,\*</sup>, G. López<sup>c</sup>, J. Ballestrín<sup>d</sup>, J. L. Bosch<sup>a</sup>, J. Alonso-Montesinos<sup>a, b</sup>, M. E. Carra<sup>d</sup>, A. Marzo<sup>e</sup>, J. Polo<sup>f</sup>, J. Fernández-Reche<sup>d</sup>, F. J. Batlles<sup>a, b</sup>, R. Enrique<sup>d</sup>

<sup>a</sup> Department of Chemistry and Physics, University of Almería, 04120, Almería, Spain

<sup>b</sup> CIESOL, Joint Centre of the University of Almería-CIEMAT, 04120, Almería, Spain

<sup>c</sup> Department of Electrical and Thermal Engineering, Design and Projects, University of Huelva, 21004, Huelva, Spain

<sup>d</sup> Concentrating Solar System Unit (Plataforma Solar de Almería, CIEMAT), 04200, Almería, Spain

<sup>e</sup> CDEA, University of Antofagasta, 02800, Antofagasta, Chile

<sup>f</sup> Photovoltaic Solar Energy Unity (Renewable Energy Division-CIEMAT, 28040, Madrid, Spain)

\* Corresponding author. E-mail address: jbarbero@ual.es

## Abstract

Direct normal irradiance is the component of solar radiation exploited by concentrating solar power plants. However, solar radiation reflected by heliostats can be partially extinguished on its way to the receivers in solar power tower plants. These energy losses are accentuated with the distance travelled by the light. The growing development of solar power tower plants has highlighted the interest in determining this phenomenon. This paper presents the results of a six-month intercomparison campaign of the two most promising extinction measuring systems. The system developed at Plataforma Solar de Almería (SE Spain) is based on a direct measurement methodology by using two digital cameras. The second system indirectly estimates the extinction from forward-scatter meter (FSM) measurements. Two FSMs were used in this study. Both FSMs provided the same Meteorological Optical Range (MOR) trends, with differences into declared error margins. A selected number of days corresponding to medium to high aerosol loads have been used to assess the performance of both types of systems. Results show that, in these days, the atmospheric extinction coefficient values derived from the two-camera system were on average 2.1 times higher than those determined with the FSMs. Semi-empirical and empirical corrections for the aerosol spectral characteristics and for the content of water vapour in the atmosphere have been applied to the FSM measurements so that both systems provide similar values of horizontal attenuation.

**Keywords:** Solar resource assessment, Solar power tower plant, Atmospheric extinction, Forward-scatter meters, Digital cameras.

## Nomenclature

$\alpha$	Aerosol Ångström exponent
$\sigma_w$	Water vapour absorption extinction coefficient
$\sigma_{CSys}$	Extinction coefficient from the CIEMAT-System
$\sigma_{FSM}$	Extinction coefficient from the FSM
$\sigma_{FSM, BB}$	FSM extinction coefficient corrected to broadband
$\sigma_{FSM-c}$	Corrected FSM extinction coefficient ( $\text{km}^{-1}$ )
$\sigma_{m, \lambda}$	Molecular Rayleigh extinction coefficient at $\lambda$
$\rho_{w0}$	Water vapour density at the surface ( $\text{g cm}^{-3}$ )

46	<i>Acf</i>	Aerosol absorption correction factor
47	AERONET	Aerosol Robotic Network
48	$AOD_{\lambda}$	Aerosol optical depth at wavelength $\lambda$
49	$Att_{CSys}$	Attenuation at 1 km from the CIEMAT-System
50	$Att_{FSM}$	Attenuation at 1 km from FSMs
51	<i>BMod</i>	Correction parameters set from Biral M&O manual
52	CIEMAT	Spanish Center for Energy and Environment Research
53	<i>EMod</i>	Correction parameters set from Elias et al. model
54	$F_{\lambda}$	Correction factor to change the spectral range
55	FSM-UAL	Forward-scatter meter from University of Almería
56	FSM-UHU	Forward-scatter meter from University of Huelva
57	MOR	Meteorological Optical Range (km)
58	PSA	Plataforma Solar de Almería (CIEMAT- Center for solar power development)
59	SSA	Single scattering albedo
60	STEP	Solar Thermal Energy Plant
61	<i>StF</i>	Aerosol scattering to fog scattering ratio
62	VR	Visibility Range (km)
63	<i>w</i>	Precipitable water content (cm)
64	WMO	World Meteorological Organization

65

## 66 **1. Introduction**

67

68 With society's increasing energy consumption, fossil fuels and their use to generate energy have multiple  
69 disadvantages, whether due to depletion, economic issues, or their negative effect on the environment. In this  
70 sense, renewable energies are presented as a clear alternative, having a lower impact on the environment  
71 compared to other energy sources. The generation through some renewable energies, such as solar or wind,  
72 has an intermittent character that varies depending on the location and its weather conditions which, in turn,  
73 vary seasonally. Therefore, its performance is conditioned by its variation in time and weather conditions. Over  
74 the next few years, it is expected that there will be an increasing dependence on the energy supply from  
75 renewable resources. In this context, concentrating solar thermal technologies, such as parabolic troughs or  
76 solar tower power plants, stand out thanks to the thermal storage that allows them to produce continuously  
77 without depending on variations in the solar resource.

78 A solar power tower plant basically consists of a receiver on top of a tower, surrounded by a field of  
79 heliostats. The heliostats, large mirrors that track the movement of the sun, reflect solar beam radiation towards  
80 the receiver, which absorbs the radiation and converts it into process heat. Both heliostats and receivers  
81 typically operate in the 300-2500 nm spectral range of solar radiation. The process heat produced can be used  
82 for a variety of applications, including the production of electricity using turbines. It can also be stored for later  
83 use.

84 It is well known that the atmosphere interacts with the beam radiation, or Direct Normal Irradiance (DNI),  
85 causing its attenuation through the processes of absorption and dispersion. This interaction determines the  
86 amount of solar resource available at ground level for use in Concentrated Solar Power (CSP) plants. To  
87 measure the amount of solar resource available at a specific location in real time, radiation sensors, such as  
88 pyrhemometers, are used. Model retrievals and satellite images also help to obtain information about the solar  
89 resource available at a specific location.

90 In the case of large solar power tower plants, the reflected solar radiation from the outermost heliostats must  
91 travel distances longer than 1 km to the receiver. In this second propagation through the lower layer of the  
92 atmosphere, solar radiation suffers additional attenuation processes of absorption and scattering, which can  
93 cause losses of up to 40% depending on the atmospheric conditions ([Ballestrin & Marzo, 2010](#)). This additional  
94 attenuation occurs in the optical path between the heliostats and the receiver and has a spectral character, i.e.,  
95 it depends on the wavelength. It is mainly due to atmospheric aerosols and water vapour, components that are  
96 more concentrated in this lower layer of the atmosphere, which further exacerbates their effect. This attenuation  
97 translates into power losses compared to what is expected. This is a crucial aspect in the design and operation  
98 of solar power tower plants. The actual amount of useful solar radiation available at the place of interest, that  
99 which reaches the receivers, may differ from those estimated from the site's solar resource databases. It is  
100 therefore crucial to quantify these losses.

101 The first studies on the estimation of these power losses were carried out in the 70s and 80s based  
102 exclusively on modelling techniques ([Pitman & Van't-Hull, 1982](#)). Recently, with the increase in size and power  
103 of solar tower plants, the determination of power losses due to atmospheric attenuation has become essential.  
104 Different methodologies have been developed over time for estimating power losses ([Hanrieder et al., 2017](#));  
105 [Hanrieder et al., 2019](#)). These include modelling techniques and direct or indirect measurement of the  
106 atmospheric extinction using different instruments (satellites, digital cameras, ceilometers, etc). For example,  
107 power losses have been modelled using radiative transfer codes and different sets of input parameters: tower  
108 height, slant range between heliostats and the receiver, precipitable water content, or aerosol type and  
109 concentration ([López et al., 2017](#); [López et al., 2018a](#)). A methodology to estimate the extinction of radiation in  
110 the first 150 m of the lower atmosphere and its impact on the generated electricity cost has been recently  
111 published ([Marzo et al., 2021](#)).

112 Due to its special characteristics, transmissometers and forward-scatter meters (FSMs), which were  
113 designed to provide information on visibility conditions on airports or highways, have been considered of interest  
114 in determining the horizontal attenuation in solar plants ([Hanrieder et al., 2012](#)); [López et al., 2017a](#)). These  
115 equipment provide information about visibility through a related parameter: the Meteorological Optical Range  
116 (MOR), defined as: "*The length of path in the atmosphere required to reduce the luminous flux in a collimated  
117 beam from an incandescent lamp at a colour temperature of 2700 K to 0.05 of its original value, the luminous  
118 flux being evaluated by means of the curve of spectral luminous efficiencies for photopic vision given by the  
119 International Commission on Illumination (C.I.E.)*" ([WMO, 2014](#)).

120 The Kochsmieder approximation of this definition ([Kochsmieder, 1924](#)), derived from the Beer-Lambert law,  
121 allows for the atmospheric extinction coefficient at around 550 nm to be obtained from the MOR value, using:

$$\sigma_{ext} [\text{km}^{-1}] = \ln(0.05) / \text{MOR}[\text{km}] \quad (1)$$

123  
124 The physical principle on which the design of a transmissometer is based is very similar to the definition of  
125 Meteorological Optical Range. The most common transmissometers consist of an emitter, which has a luminous  
126 source that meets the above cited conditions (light sources today are white light LEDs, whose spectrum ranges  
127 from 400 to 750 nm, with colour temperature of 2700 K) and a receiver, both separated by a distance ranging  
128 from 10 to 300 m. Light is sent from emitter to receiver, and visibility is calculated from the attenuation of the  
129 transmitted light. The atmospheric extinction in the spectral range of the instrument is derived from this

130 measurement. However, transmissometers can present several drawbacks: 1) short distances used to perform  
131 the measurement; 2) the corresponding small sensitive atmospheric volume is a considerable source of  
132 uncertainty when the measurement is extrapolated at longer distances, and 3) they need frequent maintenance  
133 and calibration.

134 Monochromatic transmissometers have also been utilized to determine monochromatic horizontal  
135 atmosphere attenuation, such as the long-path LPV4 transmissometer ([OPTEC, 2011](#)). A LPV4 uses as emitter  
136 a LED at 532 nm, with 10 nm bandwidth, and it can work with large distances between transmitter and receiver,  
137 up to 20 km. It records extinction by aerosols, but needs to correct its measurement to broadband extinction.  
138 Drawbacks are that it is very sensitive to vibrations, alignment and dirt. This transmissometer has been tested at  
139 the PSA, using a distance among emitter and receiver of 487 m ([Hanrieder et al, 2015](#)).

140 A flip-up LIDAR system could be useful to detect irregularities in aerosol concentrations at lowermost  
141 atmosphere layers, but it would have to meet the basic condition of having a full overlap between the solid  
142 angles of emission and reception of radiation at short distances, say, one hundred meters. However, estimating  
143 the aerosol extinction coefficient along a path in that layer is a difficult task. A LIDAR system records the  
144 backscatter coefficient which is not very sensitive to the type of aerosol, and therefore to determine the aerosol  
145 extinction coefficient from the backscatter value the *lidar ratio* of the specific aerosol type is needed. Finally, if  
146 these difficulties could be avoided, the result is still a monochromatic extinction coefficient, and some algorithm  
147 must be used to have a broadband extinction value.

148 Because of the novelty of the problem, which was highlighted a decade ago with the advent of large tower  
149 plants, there are not many techniques for measuring atmospheric attenuation. However, quality measurements  
150 are necessary not only to measure losses in real-time, but also to generate and validate models that allow their  
151 estimation from other parameters. Two of the most promising atmospheric attenuation measurement techniques  
152 are the CIEMAT-System and those based on forward-scatter meters. The CIEMAT-System was developed at  
153 the Plataforma Solar de Almería and is based on a direct measurement methodology using two digital cameras.  
154 The second system indirectly estimates the extinction from the forward scattering meter (FSM) measurements.  
155 This paper presents the results of a six-month intercomparison campaign of the two extinction measurement  
156 systems mentioned above: CIEMAT-System and the FSM based methodology. Before that, the following  
157 section provides a literature review and contextualisation of the FMS and the CIEMAT-System. This will help to  
158 better understand the basis for the functioning of each methodology, its application and to evaluate the results  
159 of the intercomparison. Subsequently, the materials and methodology will be described, followed by the results  
160 and conclusions.

161

## 162 **2. Forward-scatter meters and CIEMAT-System**

163

164 FSMs were developed for the same purpose as transmissometers, to provide a value of visibility, but being  
165 cheaper and with lower maintenance needs. A FSM consists of an emitter, usually a narrow band LED  
166 operating in the near-infrared band (i.e. 850 nm), and a receiver located at an angle of about 45° with respect to  
167 the beam of the emitter. The receiver collects the scattered light in a sensitive volume of about 400 cm<sup>3</sup>, at a  
168 scattering angle of about 45°. This arrangement was adopted because it was experimentally demonstrated  
169 ([Middleton, 1952](#)) that in the range of angles between 35° and 55°, the scattering coefficient has a low  
170 dependence on the size of the dispersing particles. The FSM design and operation is based on two

171 assumptions: absorption phenomena can be neglected, and the radiation detected in the range of selected  
172 scattering angles is proportional to the total scattering extinction coefficient ([Biral VPF Series, 2017](#)). Therefore,  
173 the MOR value supplied by a FSM accounts for the scattering by the atmospheric constituents. Since the MOR  
174 is a parameter related to the visual spectral range, for a FSM to fulfill the task of providing a visibility value, it  
175 must be calibrated against a transmissometer which works in the visible spectral range. The primary calibration  
176 is usually performed in reference installations in order for both technologies to match under atmospheric  
177 conditions which may cause a significant degradation of visibility, such as fog, haze or rain ([Bloemik, 2006](#)),  
178 ([Tjugum et al., 2005](#)).

179 In the WMO definition, Fog is “*a suspension of very small, usually microscopic water droplets in the air,*  
180 *reducing visibility at the Earth’s surface*”, while Haze is “*a suspension in the air of extremely small, dry particles*  
181 *invisible to the naked eye and sufficiently numerous to give the air an opalescent appearance*”.

182 FSMs have been designed primarily to provide visibility values under mist and fog conditions, and therefore  
183 the comparison of their measurements with those by a transmissometer is mainly performed under low visibility  
184 conditions.

185 Considering the low cost and low maintenance of FSMs, these devices could be used to estimate the  
186 atmospheric attenuation of solar radiation between the field of heliostats and the receiver in Solar Thermal  
187 Power Plants (STP). In this respect, ([Hanrieder et al., 2015](#)) developed a methodology to estimate the horizontal  
188 attenuation losses using MOR measurements from a FSM Vaisala-FS11 ([Vaisala, 2010](#)) at near IR, and  
189 transmittance values from a LPV4 transmissometer working at 532 nm ([OPTEC, 2011](#)), and using the  
190 *libRadtran* software package for radiative transfer to calculate the water vapour absorption. Statistical values of  
191 atmospheric transmittance at 1 km at three locations were obtained with that methodology ([Hanrieder et al.,](#)  
192 [2019](#)).

193 In the case of the FSM Biral-SWS250 ([O&M SWS Manual, 2014](#)), their MOR measurements (or equivalent  
194 extinction coefficients) have been well correlated with the relative humidity, pressure, air temperature and direct  
195 and diffuse irradiances, into an artificial neural network (ANN) structure. But it is worth noting that the inclusion  
196 in the ANN of the radiative variables does not result in a noticeable improvement of the fitting ([López et al.,](#)  
197 [2018b](#)).

198 Also, MOR measurements from the same instrument have been simulated using as input variables the  
199 relative humidity and the aerosol optical depth (AOD) at different wavelengths derived from a collocated  
200 spectroradiometer. The correlation versus AODs only is very poor, but a significant improvement is reached with  
201 the incorporation of the relative humidity as an input variable ([López et al., 2018b](#)).

202 FSMs have been used along with systems based on digital cameras as an automated reference instrument  
203 that may also determine the Visibility Range (VR, a parameter equivalent to 4/3 of MOR) according to the WMO  
204 definition. [Chen et al. \(2013\)](#) recorded visibility values using a digital camera and a Vaisala FSM FD12. They  
205 found a high level of agreement between both systems for visibility (VR) values between 1.5 and 3.0 km. [Wang](#)  
206 [et al. \(2013\)](#) also performed an intercomparison of the horizontal visibility values using three systems: a digital  
207 camera, a FSM-FD12 and a trained human observer. Results showed that the three methods display the same  
208 trends and a reasonable agreement in non-rainfall situations for VR values below 3.0 km. The goal in the two  
209 above cited works was to develop measurement systems based on digital cameras suitable to determine the  
210 visibility. But the performance analysis of these systems was undertaken under very low visibility conditions,  
211 less than 3 km. These extreme cases are not usual in the day-to-day STEP operation.

212 A system has been developed at Plataforma Solar de Almería (PSA), southern Spain, to measure the  
213 horizontal atmospheric attenuation of solar radiation in STP. It uses two identical cameras, one placed near to a  
214 black and white Lambertian target and the other one far away from the target (CIEMAT-System). A complete  
215 and detailed description of all aspects and configuration of CIEMAT-System is in [\(Ballestrin et al., 2018a\)](#).  
216 Attenuation measurements by the CIEMAT-System have been correlated with the relative humidity and  
217 concentration of particles [\(Ballestrin et al., 2020\)](#). Result shows a normalized root-mean-square deviation of  
218 5.5% and a Pearson's coefficient of 0.92. This close dependence shows that, in principle, these two variables  
219 would be enough to explain the atmospheric attenuation. Unfortunately, particle counting systems are rare to  
220 find in the scope of a STEP.

221 CIEMAT-System extinction values at PSA have been well estimated (correlation coefficient  $R = 0.88$ ) from  
222 radiative and meteorological variables (direct normal irradiance, atmospheric pressure, relative humidity and  
223 temperature) using ANN techniques [\(Alonso-Montesinos et al, 2021\)](#). This shows that the standard variables  
224 conventionally measured in solar plants can serve as a first good estimate of horizontal atmospheric extinction.

225 A six-month measurement campaign was undertaken at PSA, where the CIEMAT-System and two identical  
226 FSMs were jointly used. This document summarizes the comparison between both systems. Also the  
227 differences between the extinction values provided by both systems are shown, together with the possible  
228 causes that could explain them and the corrections that could be done to obtain a better agreement between  
229 both systems.

230

### 231 **3. Material and methods**

232

233 The comparison test was carried out at PSA (SE Spain; 37.0970 N, 2.3647 W, altitude 500 m a.s.l.) from  
234 February 2<sup>nd</sup> to July 22<sup>nd</sup> 2018. PSA is a Singular Scientific-Technical Installation, which belongs to the Spanish  
235 System of Science and Technology, and in which different solar receiver prototypes have been evaluated in the  
236 past two decades [\(PSA Annual Report, 2018\)](#). The test site is located in the desert of Tabernas (Almería,  
237 Spain), between two ranges, *Sierra de los Filabres* to the north and *Sierra Alhamilla* to the southeast, which  
238 isolate it from the humid currents of the nearby Mediterranean Sea. Its climate ranges from semi-arid to  
239 Mediterranean, with scarce rainfall (less than 200 mm per year). The southeast of the Iberian Peninsula is  
240 sometimes affected by African dust episodes with large mineral dust particle loads. But visibility conditions at  
241 PSA are otherwise excellent [\(Carra et al., 2018\)](#); [\(Ballestrin et al., 2018b\)](#).

242

#### 243 **3.1 Equipment and features**

244

##### 245 *3.1.1 Two-digital camera system (CIEMAT-System)*

246

247 It uses two identical Hamamatsu® ORCA cameras, one located at 83 m and other at 825 m from a  
248 Lambertian target being the distance between cameras of 742 m. The target has one half painted white with  
249 Amercoat 741 with 70% weighted solar reflectance and the other half painted black using Zynolyte® with 95%  
250 weighted solar absorptance. Both cameras simultaneously record the target image, and the horizontal extinction

251 is derived at the distance between both cameras using a contrast formulation ([Ballestrin et al., 2018a](#));  
252 ([Ballestrín et al., 2018b](#)).

253 The CIEMAT-System essentially consists of the camera's optical system, CMOS detector, cabinet  
254 borosilicate windows and neutral filters. It has been checked that all the elements have a high value of  
255 transmittance throughout the whole spectral range covered by the camera (400-1000 nm). The combination of  
256 the responses of all elements (camera, windows, filters and paint), gives a CIEMAT-System spectral response  
257 centered on 550 nm. The spectral response of the CIEMAT-System, ranging from 400 to 1000 nm, includes  
258 three water vapour bands at 720 nm, 810 nm and 940 nm, with the strongest one centered at 940 nm, whose  
259 response is around 10% of its maximum value at 550 nm. Due to this system's design, it can be stated that it  
260 records the extinction between cameras by air molecules (Rayleigh scattering), aerosols (absorption and  
261 scattering) and water vapour.

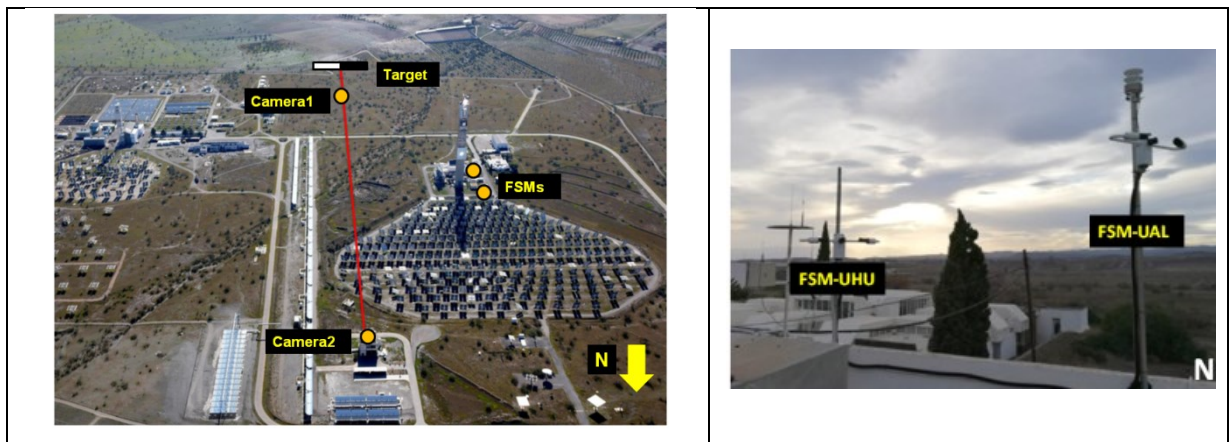
262 The CIEMAT-System is fully automatic and is running at PSA since June 2017 working in a supervised  
263 manner, subject to strict control of operation and verification, so that data is only taken in working days. The real  
264 time attenuation value provided by this system is displayed on the control panel of the CESA-1 thermosolar  
265 plant of the PSA.

### 266 3.1.2 Forward-scatter meters

269 Two Biral FSMs model SWS-250 ([O&M SWS Manual, 2014](#)) have been used in this study: one belonging to  
270 the University of Almería (UAL) and another to the University of Huelva (UHU). The SWS-250 emits an infrared  
271 light beam at wavelength of 850 nm and bandwidth around 40 nm; the receiver collects the light scattered by the  
272 atmosphere in a sensitive volume of about 400 cm<sup>3</sup>, and at a dispersion angle of 45° with ± 6° cone angle. The  
273 SWS-250 also provides information on the meteorological situation, as the type and amount of precipitation.

274 Both FSMs were placed on the roof of one of the PSA buildings (Figure 1), separated by a distance of  
275 several meters, well above ground level, and oriented according to the assembly standards of this type of  
276 equipment. The selected emplacement is in the same area in which the CIEMAT-System operates (Figure 1).

277



278  
279 Figure 1. Left: layout of the CIEMAT-System and the two FSMs at PSA. Right: Biral SWS-250 FSMs belonging to the  
280 UAL and the UHU, placed at PSA facilities  
281

282 To ensure the reliability of measurements, the calibration of both FSM was checked just before the  
283 beginning of the experimental campaign using the respective calibration plates provided by the manufacturer.

284

### 285 **3.2 Data**

286

287 The Biral SWS-250 provides MOR values in a range from 10 m to 75 km. The MOR measurement error  
288  $\epsilon_{\text{MOR}}$  is given by the manufacturer ([O&M SWS Manual, 2014](#)) up to MOR 30 km, but uncertainties for values  
289 above 30 km are unknown. Nevertheless, a first approximation of the uncertainties can be derived by linear  
290 extrapolation of documented uncertainty values in the whole range of 0-75 km, according to the following  
291 expression:

292

$$\epsilon_{\text{MOR}} (\%) = 4.46 + 0.52 \text{ MOR (km)} \quad (2)$$

293

294 Throughout the test period, around 250 000 one-minute records corresponding to each one of the FSMs are  
295 available. Each MOR value is calculated as the average of 60 one-second values.

296 The CIEMAT-System takes data every minute between 10 to 15 h (local time), and supplies the value of the  
297 horizontal atmospheric attenuation (in %) for a distance of 742 m, along with its absolute error. During the test,  
298 18 000 attenuation values were available from that system. A small amount of attenuation data was rejected  
299 due to undesirable situations, such as spurious radiation incidences on the target or reflections on the cameras  
300 coming from bright clouds.

301 During the period of time in which both systems were available, which covered about 160 days, there are  
302 simultaneous records of both systems in 91 days.

303 A collocated radiometric and meteorological station has also been used. It consists of a spectroradiometer  
304 EKO MS-700 ([EKO, 2016](#)) mounted on an EKO automatic solar tracker model STR-22G, and sensors for  
305 atmospheric variables (temperature, relative humidity, atmospheric pressure and wind speed and direction).

306

### 307 **3.3 Data processing and selection**

308

309 All data records were referred to the UTC time, and the days were referred to the first day of the year; thus,  
310 April 24<sup>th</sup> is day 114.

311 The data derived from the FSMs and the CIEMAT-System have been homogenized to represent the  
312 atmospheric attenuation of the solar radiation at 1 km distance, which is a representative distance in the tower  
313 plants. Therefore, the attenuation data of the CIEMAT-System, derived for a distance of 742 m, were converted  
314 to attenuation values at 1.0 km, through the extinction coefficient  $\sigma_{\text{CSys}}$ :

315

$$\sigma_{\text{CSys}} [\text{km}^{-1}] = -\ln(1-\text{Att}(0.742))/0.742 \quad (3)$$

316

$$\text{Att}_{\text{CSys}}(1.0 \text{ km}) = 1-\exp(-\sigma_{\text{CSys}}) \quad (4)$$

317

318 MOR values supplied by the FSMs were also converted to attenuation values at the distance of 1.0 km with  
319 the following expression:

320

$$Att_{FSM}(1.0\text{ km}) = 1 - \exp(\ln(0.05) / MOR) \quad (5)$$

321

322 Water vapour density at the surface,  $\rho_{w0}$ , has been used as an independent variable; although there is not a  
 323 very significant difference with the relative humidity,  $RH$ , it is a variable proportional to the density of water  
 324 vapour molecules. The following equations were used to calculate it ([Gueymard, 1994](#)):  
 325

$$\rho_{w0} [\text{g cm}^{-3}] = 216.7 RH(\%) * p_s(\text{hPa}) / T(\text{K}) \quad (6)$$

326

327 where  $T$  is the ambient temperature, and  $p_s$  is the saturation pressure, calculated as:  
 328

$$p_s [\text{hPa}] = 6.112 \exp(17.67 * T(\text{°C}) / (247.5 + T(\text{°C}))) \quad (7)$$

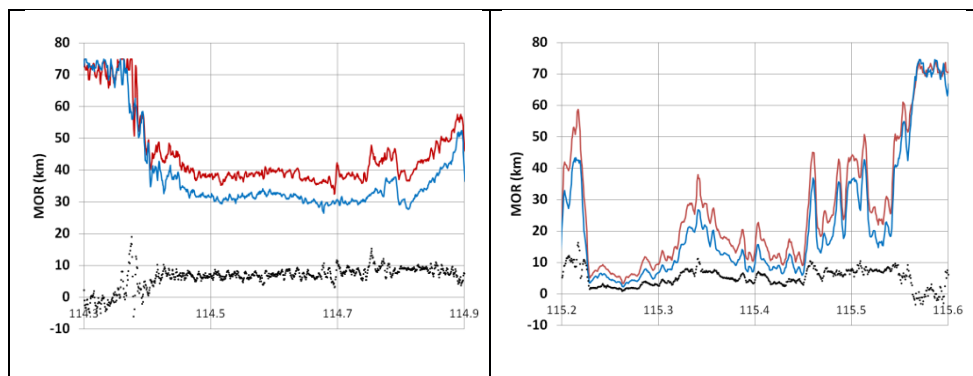
329

### 330 3.4. Intercomparison between forward-scatter meters

331

332 During the test campaign, FSMs frequently detected situations of very high visibility, displaying its limit value  
 333 of  $MOR = 75$  km. The equivalent atmospheric attenuation at 1 km then was less than 3.9%, as derived from Eq.  
 334 (5). As the FSM only detects aerosol scattering at its sensitive volume, this is the minimum attenuation by  
 335 aerosols at 1 km in the case of a homogeneous atmosphere equal to that surrounding the FSM. As a high  
 336 variability was observed in the MOR measurements each minute, since they measure very local conditions,  
 337 these measurements have been filtered by a 5 minute moving average filter.

338 The first step was to verify the consistency of the MOR data from both FSMs. Simultaneous data from both  
 339 FSMs have been compared throughout the entire trial period. Figure 2 shows MOR records on April 24<sup>th</sup> and  
 340 25<sup>th</sup>, days included in an episode of dust intrusion. As it can be seen, a notorious decrease of visibility appeared  
 341 in the morning of April 24<sup>th</sup>, reaching MOR values around 30 km. At the subsequent night, MOR values were as  
 342 low as 2 km.  
 343



344

345 Figure 2. MOR values (km) for FSM-UAL (Red) and FSM-UHU (Blue) during April 24<sup>th</sup> (left) and April 25<sup>th</sup> (right), and  
 346 difference between both FSMs (Black dots). Abscissa is day-of-year fraction (UTC).  
 347

348 Figure 2 shows the general behaviour of both FSMs observed throughout the trial, which is summarized in:

- 349 • The remarkable parallelism between both time series and the simultaneity of specific episodes.

- 350 • MOR values from FSM-UAL are systematically higher than the ones from FSM-UHU, up to 10 km for  
351 intermediate MOR values, but within the respective uncertainty limits.
- 352 • When both FSMs approach their detection limit of 75 km, there are no significant differences in  
353 measurements between them.

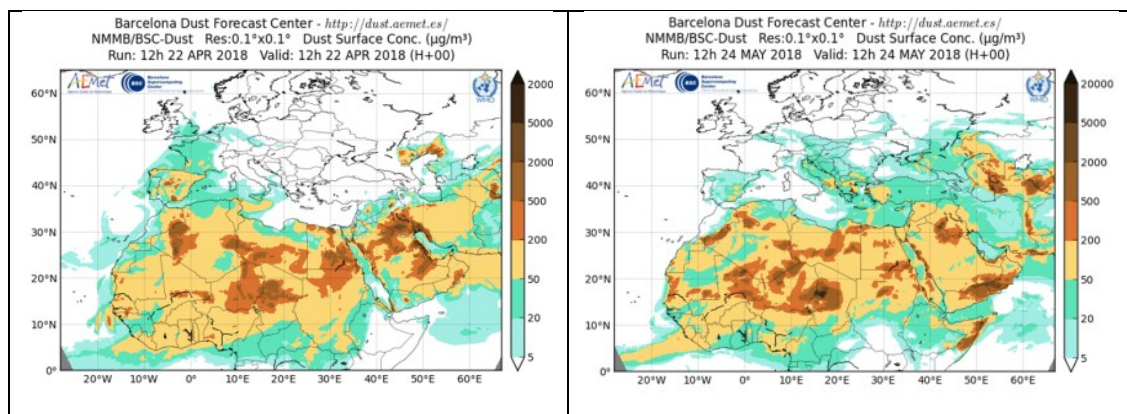
354  
355 Due to the similar behaviour observed from both FSM, that the differences between their measurements are  
356 within the stipulated uncertainty ranges and the lack of additional criteria to decide which FSM has the best  
357 performance, a *virtual* FSM has been defined averaging the simultaneous MOR measurement from both FSMs.  
358

### 359 **3.5 Data selection**

360  
361 A set of days were selected to compare both systems. Only days that met the following conditions for most  
362 of the daytime were selected: CIEMAT-System attenuation values were taken in cloudless situations or with low  
363 presence of clouds, and FSMs' MOR values remained below 75 km most of the time. Only 11 days meet these  
364 requirements.

365 During the test campaign there have been some episodes with a medium to high aerosol load. Special  
366 attention was paid to these situations of high atmospheric extinction, as they represent the best opportunity to  
367 study the response of both systems. These episodes happened around April 20<sup>th</sup>, May 22<sup>nd</sup> and June 23<sup>rd</sup>.  
368 Another episode, although not as strong, happened from July 10<sup>th</sup>; in this case the CIEMAT-System registered  
369 attenuation values up to 13%. Only 8 days from the selected set of days that met the requirements are included  
370 in the cited episodes.

371 Figure 3 shows the Europe and North-Africa dust surface concentration ( $\mu\text{g m}^{-3}$ ) maps provided by the  
372 AEMET-Barcelona Dust Forecast Center ([BDFC, 2020](http://dust.aemet.es/)) for the mentioned dust incursion episodes.  
373



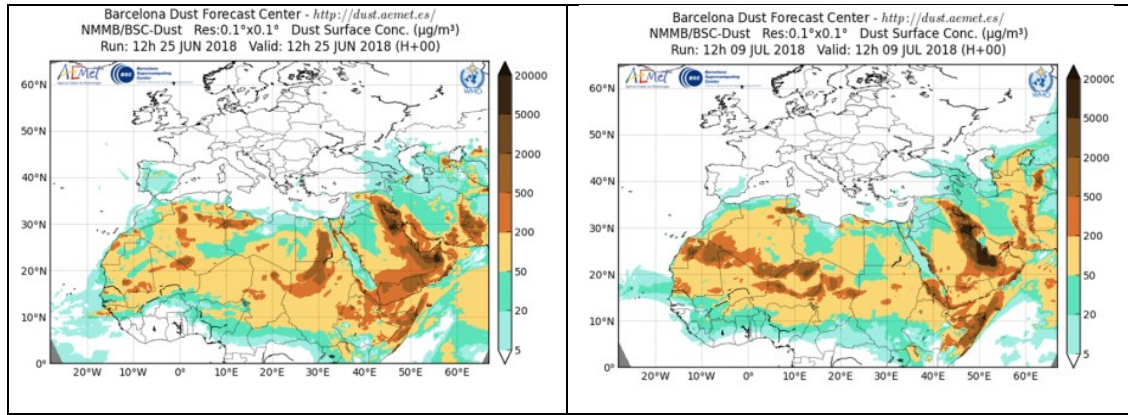


Figure 3. Dust surface concentration for days 22/4, 24/5, 25/6 and 9/7 of 2018. Source: AEMET-Barcelona Dust Forecast Center.

Table 1 summarizes the average values from the weather station and the collocated spectroradiometer for the 11 days that meet the requirements. Only 8 days included into the episodes were selected to develop the methodology and the other 3 days (in italic in Table 1) were used to check the derived algorithm.

Table 1. Average values from 10 to 13 h (local time) for air temperature, relative humidity, water vapour density at surface, aerosol optical depth at 500 nm and aerosol Ångström exponent. Data in parentheses is from AERONET\_Murcia

Day	$T(^{\circ}\text{C})$	$RH(\%)$	$\rho_{w,0}$ ( $\text{g cm}^{-3}$ )	$AOD_{500}$	$\alpha$
April 20	16.7	56.6	8.2	0.43	0.35
April 24	23.0	34.5	7.0	0.28	0.21
April 27	20.7	59.4	10.4	0.23	0.81
<i>May 18</i>	20.4	47.6	8.3	0.06	1.54
<i>May 21</i>	20.1	46.8	8.6	0.17	1.38
May 25	21.8	51.5	9.7	0.21	0.70
May 29	21.8	46.9	8.8	0.17	1.01
June 26	28.8	44.6	12.4	0.29	0.39
June 29	26.9	53.4	13.4	0.30	1.05
July 10	30.5	35.1	10.6	0.14	0.54
<i>July 12</i>	30.7	30.2	9.3	(0.21)	(1.3)

$AOD_{500}$  and aerosol Ångström exponent ( $\alpha$ ) have been derived from the direct normal irradiance spectra registered by the spectroradiometer, using the “window method” (Martínez-Lozano et al., 1998) in situations when the sun was not covered by clouds. On July 12<sup>th</sup>, when the spectroradiometer and also the AERONET\_Tabernas station were unavailable,  $AOD_{500}$  and aerosol exponent registered at AERONET\_Murcia (~150 km away) were used as reference.

#### 4. Results

This section will present the results of the intercomparison between the previously presented atmospheric extinction measurement systems, which will also include a discussion of the most important and determining facts.

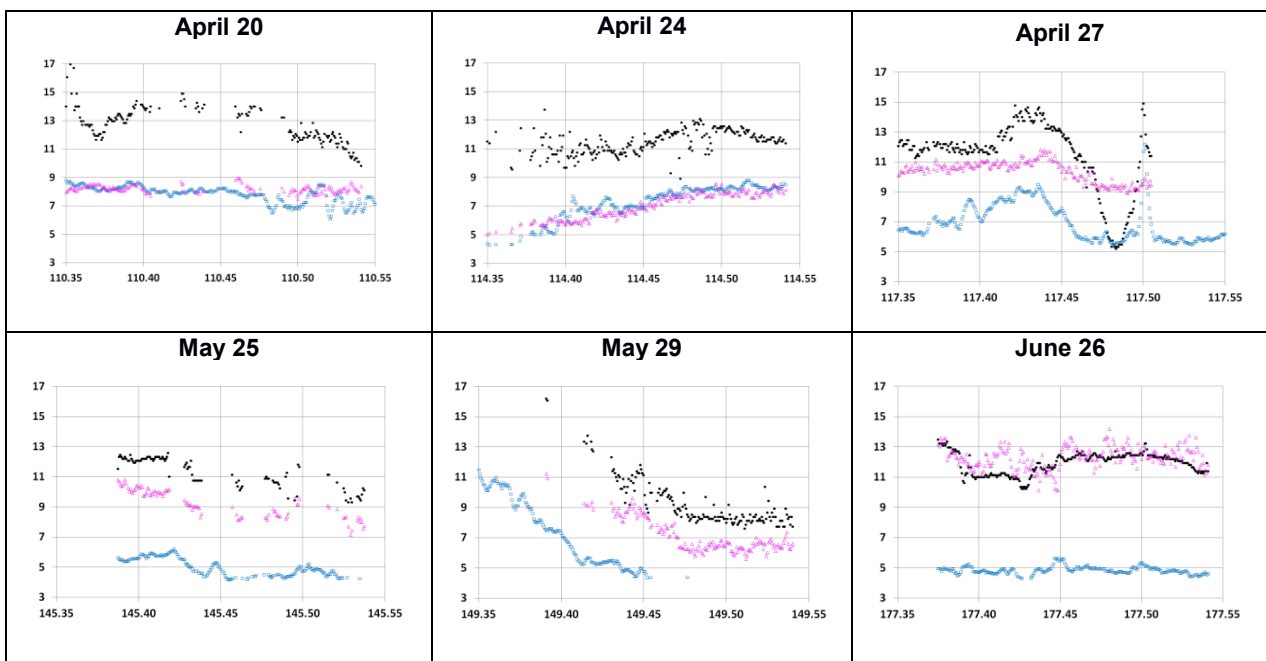
398 **4.1 Attenuation measurement systems intercomparison.**

399  
400 Since the CIEMAT-System records the total extinction between cameras by air molecules (Rayleigh  
401 scattering), aerosols (absorption and scattering) and water vapour, it has been considered, in this test, as a  
402 reference equivalent to a long-base transmissometer. The reliability of the attenuation values provided by the  
403 CIEMAT-System at PSA has been tested against yearly horizontal attenuation values derived from a typical  
404 aerosol year (TAY) using the AOD values at different wavelengths from the AERONET\_Tabernas station at  
405 PSA. Results show similar statistical values (histograms, mean and extreme values) for the TAY analysis and  
406 for the CIEMAT-System (Carra et al., 2018).

407 In the case of real-time values, an independent method has been used. Said method allows determining the  
408 attenuation value with a single digital camera, using landscape images which include the black side of the target  
409 and the sky just above the target. Attenuation values obtained during a test campaign on several July 2018 days  
410 were similar for the CIEMAT-System and single camera systems, always within the margins of error of both  
411 methodologies (Barbero et al., 2020).

412 Figure 4 shows daytime evolution of attenuation values provided by the CIEMAT-System and attenuation  
413 from the averaged FSM for the 8 selected days. The time interval spans from 8:30 to 13:30 (UTC), a somewhat  
414 broader range than the daily working time period of the CIEMAT-System. The attenuation uncertainty for the  
415 CIEMAT-System device has been estimated to be lower than 2.0% (Ballestrín et al., 2018a). For the FSM, using  
416 the extrapolated relative uncertainty data (Eq. 2), an absolute uncertainty at 1 km of 2.3% has been derived for  
417 MOR values between 20 and 70 km.

418  
419



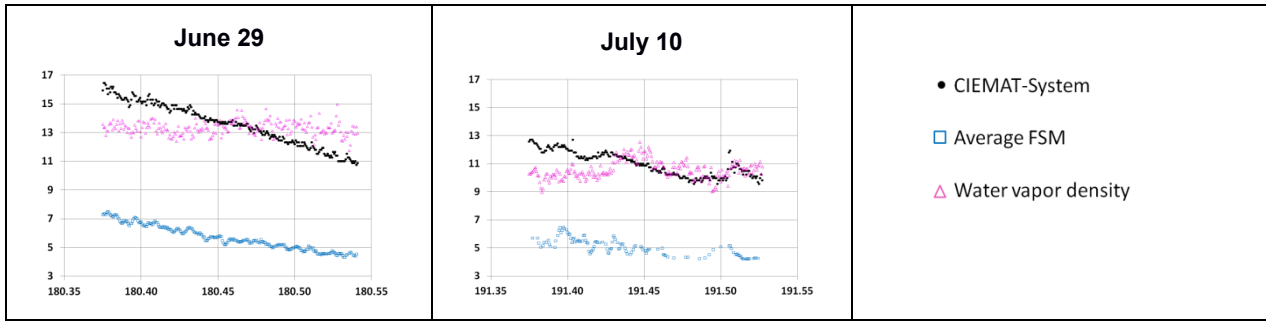


Figure 4. Attenuations (%) at 1 km: CIEMAT-System (black), average FSM (blue). Water vapour density at surface ( $\text{g cm}^{-3}$ ) (purple) for the selected days. Abscissa in day-of-year fraction (UTC).

There is a lack of attenuation data in Figure 4 from the CIEMAT-System in some intervals; these data were rejected mainly due to saturation of images by high radiant flux from the target due to bright clouds behind the cameras. The existence of these clouds was confirmed by the discontinuous DNI records from pyrheliometers.

It is worth noting that the prevailing winds on the selected days have been from directions E and SW, induced by the topography of the valley in which the PSA is located. But no clear correlation has been found between fluctuations in wind speed and the visibility measured by the FSMs.

Several conclusions can be drawn from Figure 4 about the behaviour of both systems in the selected days:

- FSM attenuations at 1 km are always lower than the ones from the CIEMAT-System.
- When the CIEMAT-System gives attenuations below 9%, the FSM provides attenuation values of 3.9% that correspond to the MOR limit of 75 km.
- Attenuation values from the CIEMAT-System follow in most cases the long-time evolution of the water vapour density at the surface, and even some of the short-term water vapour variability (April 27<sup>th</sup>, May 29<sup>th</sup>).
- In the case of April 27<sup>th</sup>, just before 12:00 h, FSMs detected a brief episode of weak rain of about 10 minutes, although it was not registered by the PSA rain gauge. Consequences of this episode on the attenuation values were captured by both systems and CIEMAT-System and FSM systems provided very similar results.

#### 4.2 Extinction coefficients ratio

Differences between the attenuation values at 1 km derived from the averaged FSM and the CIEMAT-System, shown in Figure 3, can be better expressed in terms of the ratio between their respective extinction coefficients. This ratio is written as follows:

$$\sigma_{CSys} / \sigma_{FSM} = \ln(1-Att_{CSys}) / \ln(1-Att_{FSM}) \quad (8)$$

where attenuations  $Att_x$  are defined in equations (4) and (5).

To evaluate the behavior of this relationship on each of the days, a time range has been selected from 10 to 13 h (local time). Using equation (8), the values of the ratio between both extinction coefficients were calculated for the time intervals in which there were measurements of both systems; then the average value of all of them was calculated. The results of this average, together with the standard deviation, are shown in Table 2.

454  
455  
456

Table 2. Average and standard deviation values of CIEMAT-System extinction coefficient ratio to the extinction coefficient from the averaged FSM, calculated from 10 to 13 h (local time).

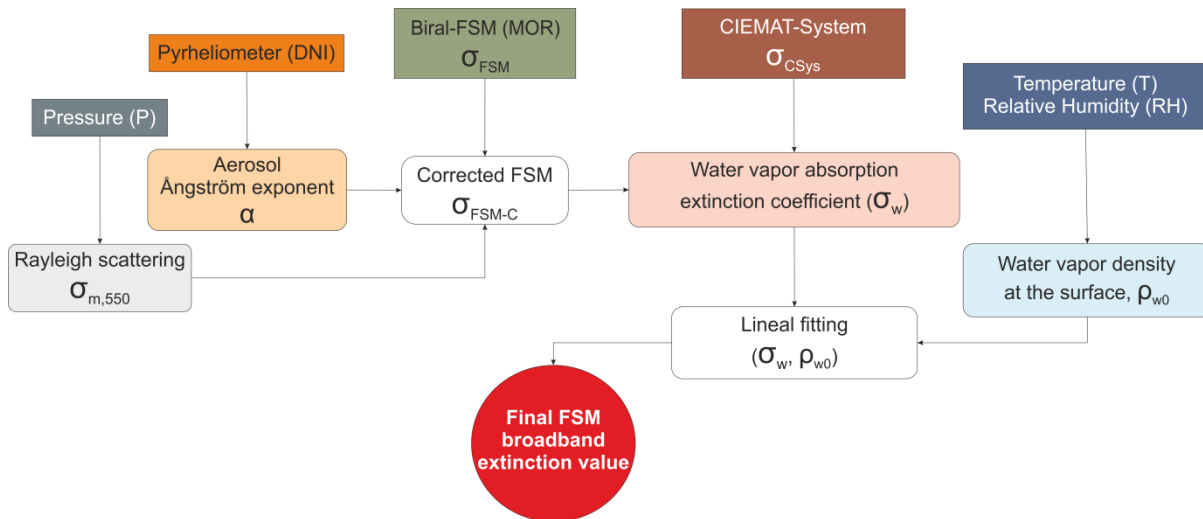
Day	$\sigma_{CSys} / \sigma_{FSM}$	StdDev
April 20	1.81	0.07
April 24	1.73	0.19
April 27	1.64	0.11
May 25	2.32	0.14
May 29	2.29	0.14
June 26	2.58	0.11
June 29	2.52	0.07
July 10	2.25	0.05

457

458 An average value for all the selected days results in:  $\sigma_{CSys} / \sigma_{FSM} = 2.1$ , with standard deviation of 0.4. Then  
459 the extinction coefficient values derived from the CIEMAT-System are, in average, around 2.1 times those  
460 derived from the FSMs. This remarkable discrepancy between the extinction coefficient values from both  
461 systems, also observed in Figure 4, deserves a detailed analysis.

462 The CIEMAT-System has a long baseline and wide spectral range, while the FSM samples over a small  
463 volume and it is almost monochromatic. FSM records only scattering by particles while the CIEMAT-System (or  
464 a broadband system working with a long baseline) can detect scattering and absorption by aerosols, molecular  
465 Rayleigh scattering and water vapour absorption. All these causes, related to the design and the operational  
466 characteristics of each one of the systems will be described in detail below. Figure 5 summarizes the process to  
467 be followed so that the Biral FSM monochromatic measurement may be validated against that broadband one  
468 provided by the CIEMAT-system.

469



470

471 Figure 5. Flowchart showing the process to correct the FSM measurements. Both input extinction coefficients are  
472 referred to the distance of 1 km

473

474 The basic elements of this flow chart are developed in the following sections. An expression will be obtained  
475 that allows correcting the FSM measurements by parameters that come from the FSM design itself, and by  
476 other absorption and scattering phenomena detected by the CIEMAT System. Corrections to be made are: the  
477 Rayleigh scattering by air molecules (Section 4.3) and the dependence of the FSM measurement on the type of

478 aerosol (Section 4.4). Once these corrections were made, a further correlation of  $\sigma_{CSys} - \sigma_{FSM-c}$  with the water  
479 vapour density at the surface will be found (Section 4.5). Using this correlation, the FSM measurement can also  
480 be corrected for water vapour absorption.

481

### 482 **4.3 Rayleigh scattering by air molecules**

483

484 Given the small sensitive volume of the FSM, it does not register the Rayleigh scattering by air molecules,  
485 whereas the CIEMAT-System does due to its much greater operating distance. Then, the extinction coefficient  
486 derived from the FSM must be corrected with the Rayleigh scattering extinction coefficient modified according to  
487 the actual atmospheric pressure value.

488 A standard value of  $\sigma_{m,550} = 0.01149 \text{ km}^{-1}$  was taken from literature ([Bucholtz, 1995](#)), and then corrected by  
489 the measured value of the atmospheric pressure at site. At PSA site, 500 m a.s.l., with average pressure of 967  
490 mbar, attenuation values at 1 km due to Rayleigh scattering were 1.1%. At sea level this attenuation at 1 km is  
491 an offset of 1.2%.

492

### 493 **4.4 FSMs data correction under haze conditions**

494

495 In this section the corrections in the measures when haze conditions are present in the atmosphere are  
496 analyzed.

497

#### 498 **4.4.1 Correction factors from FSM M&O manual**

499

500 A important cause to explain these discrepancies may come from the own design of the FSM. Primarily  
501 designed to provide visibility values in fog or mist conditions, FSMs would not provide adequate MOR values in  
502 haze situations. The scattering angles selected in the FSM design are between 30° and 50°. At these angles, an  
503 FSM provides scattering values that are almost independent of particle size, but the value of the scattering  
504 function that is used to convert the FSM output to the integrated scattering at all angles is that for fog, which has  
505 a lower value than that for fog.

506 In the basic manual of its operation, the manufacturer refers to some corrections that must be made to have  
507 adequate values in cases of haze when an FSM Biral has been calibrated in fog conditions. In case of a haze  
508 situation, the value of the extinction coefficient provided by the FSM must be multiplied by the relation between  
509 the dispersion phase function at 45° for the haze with that corresponding to fog. This haze-to-fog conversion  
510 factor ( $StF$ ) is 0.58 in case of FSM Biral ([Biral Present Weather Sensors, 2017](#)).

511 Additionally, because of the aerosol scattering coefficient depends on wavelength, a further correction factor  
512 must be applied to change from the infrared spectral range where the SWS-250 registers scattering (850 nm) to  
513 visible range (550 nm) as follows:

514

$$F_{\lambda} = (550/850)^{-\alpha} \tag{9}$$

515 where  $\alpha$  is the aerosol Ångström exponent.

516

517 It is worth to note that the spectral range correction factor almost exactly compensates the haze-to-fog  
 518 conversion factor in the case of atmospheric aerosols with Ångström exponent 1.3 ( $F_\lambda = 1.76$ ). This is equivalent  
 519 to saying that in case of small aerosol particles, according to its M&O manual, this FSM should provide direct  
 520 aerosol attenuation values. But in the general case, the correction to the FSM measurement shall depend on  
 521 the type of aerosols present.

522  
 523 *4.4.2 Correction factors derived from the FSM modelisation*

524  
 525 In another line of research (Elias et al., 2017), the response of three different FSM models to different types  
 526 of aerosols (dry mist, hydrated aerosols, mist and desert dust) has been modeled using Mie's theory. These  
 527 three FSM were: Biral-VPF710 at 875 nm ([Biral Present Weather Sensor, 2017](#)), Vaisala-FS11 ([Vaisala, 2010](#)),  
 528 at 850 nm and Degreane-DF20+ at 550 nm ([Degreane, 2007](#)). They obtained correction parameters for the  
 529 measurements of each one of the referred FSMs, with special emphasis on the FSM Biral-VPF710, which is  
 530 very similar to Biral-SWS250

531 Some results are in agreement with the referred Biral M&O manual, e.g. that the corrections to be applied in  
 532 case of haze depend on the type of aerosol present. But they also conclude with some differences: 1) a  
 533 correction factor should be applied to take into account the aerosol absorption (which can be calculated from the  
 534 aerosol single scattering albedo, SSA); 2) the parameter to correct the FSM measurements from fog to haze  
 535 seems to be also depends on the aerosol type.

536  
 537 *4.4.3 Correction Algorithm to FSM MOR data, including Rayleigh scattering*

538  
 539 Considering both the dependences on aerosol type and Rayleigh scattering, a whole correction of the FSM  
 540 extinction coefficient can be performed with the following algorithm:

541  

$$\sigma_{FSM-c} [\text{km}^{-1}] = \ln(0.05)/MOR * StF * F_\lambda * Acf + \sigma_{m,550} \tag{10}$$

542  

$$K_{tot} = StF * F_\lambda * Acf \tag{11}$$

543  
 544 The corresponding aerosol Ångström exponent value for the aerosol column in Table 1 has been used to  
 545 compute the wavelength dependent correction factor defined in equation (9),  $F_\lambda$ .

546 The first term of the sum on the right side of equation (10), corresponds to the correction on the FSM  
 547 measurement changing to the visible range and including aerosol absorption. The aerosol absorption correction  
 548 factor has been taken as 1.06, corresponding to a SSA = 0.94, which is an adequate value for the typical  
 549 aerosols at PSA (rural, tropospheric and maritime) and also for STEP emplacements ([Shettle & Fenn, 1979](#)).

550 Table 3 shows the values of  $StF$ ,  $F_\lambda$ ,  $Acf$  and  $K_{tot}$  parameters for the Biral FSM for different aerosol  
 551 exponent values corresponding to standard (fine) aerosols (*BMod-fine*);  $\alpha = 0.0$  aerosols (*BMod-coarse*) and  
 552 any exponent (*BMod*), and also using the model *EMod* ([Elias et al., 2017](#)).

Table 3. Correction factor  $K_{tot}$  for the Biral FSM values for different aerosol models.

	Haze
--	------

	$StF$	$F_{\lambda}$	$Acf$	$Ktot$
<i>BMod-fine</i> , $\alpha = 1.3$	0.58	1.76	1.06	1.08
<i>BMod-coarse</i> , $\alpha = 0.0$	0.58	1.00	1.06	0.62
<i>Bmod</i>	0.58	$F_{\lambda}$	1.06	$0.62 F_{\lambda}$
<i>EMod</i>	0.49	2.8	1.06	1.45

555 As it can be seen, the  $Ktot$  value for the *Bmod-fine* case (1.08) leaves the FSM measurements almost  
556 unchanged, and in case of coarse aerosols the correction gives even lower attenuation values than the  
557 measured ones prior to the addition of the Rayleigh scattering extinction coefficient  $\sigma_{m,550}$ .  
558

#### 559 **4.5 Water vapour density at surface dependence**

560 The FSM measurements have been corrected for each day using the algorithm of equation (10) in three  
561 situations; applying *EMod*, *BMod-fine* and *BMod*, the latter being the one that uses the Ångström exponent  
562 values in Table 1.  
563

564 Scattering and absorption by aerosols and also scattering by air molecules have already been considered in  
565 the corrected FSM values at equation (10). The discrepancies that continue to be observed between the  
566 CIEMAT-System and corrected FSM extinction coefficients could be explained by the contribution of the water  
567 vapour absorption at the surface, which is detected by the CIEMAT-System but not by the FSM.  
568

569 The relationship between the horizontal attenuation of the reflected radiation by the heliostats and the water  
570 vapour content in case of an aerosol free atmosphere has been modeled using a radiative transfer code ([López  
571 et al., 2018a](#)). The water content ranges from a extreme dry atmosphere ( $w = 0$  cm) to a subtropical atmosphere  
572 ( $w = 4.5$  cm). One of the main results is that the horizontal attenuation is not linearly correlated with the water  
573 vapour content; transmission losses for high  $w$  values only slightly increase respective to medium  $w$  values. The  
574 explanation is that for high  $w$  values the incident solar spectrum on the heliostat has already been severely  
575 attenuated by the atmosphere in the water vapour absorption bands; therefore the water vapour between  
576 heliostat and receiver scarcely contributes to the attenuation in high water vapour content situations. In that  
577 study, an attenuation value of 3.5% was calculated at 1 km for an aerosol free atmosphere with  $w = 1.42$  cm,  
578 equivalent to a water vapour density at surface of  $6.8 \text{ g cm}^{-3}$  for water vapour scale height of 2.1 km ([Gueymard,  
579 1994](#)). As the Rayleigh scattering attenuation at 1 km was around 1%, the contribution of water vapour must  
580 account for the remaining 2.5%.

581 Although the relationship between both variables is not linear, we consider that for the water vapour content  
582 values in the selected days, between 1.3 and 3.5 cm, it is possible to find a linear relationship between the  
583 water vapour extinction coefficient and the water vapour density at surface in the form:  
584

$$\sigma_w = \sigma_{CSys} - \sigma_{FSM-c} = a \rho_{w0} + b \quad (12)$$

585 The relationship has been calculated for the selected days, resulting in 862 pairs of data for each model.  
586 Table 4 shows the results for the linear correlation coefficients.  
587

588 Table 4. Linear fitting parameters for different models to derive the water vapour absorption coefficient at PSA  
589  
590

	$a (10^{-3})$	$b (10^{-2})$
<i>EMod</i>	7.48	- 4.98
<i>BMod</i>	3.81	2.74
<i>BMod-fine</i>	6.68	- 2.08

591

592 When compared with the previous cited value of 3.5% [López et al. \(2018a\)](#), it was found that the *BMod*  
593 model gave the most similar approach to the water vapour contribution.

594 Then, the algorithm which would translate the FSM MOR measurement to a broadband extinction  
595 coefficient,  $\sigma_{FSM, BB}$ , taking into account all corrections, may be written as:

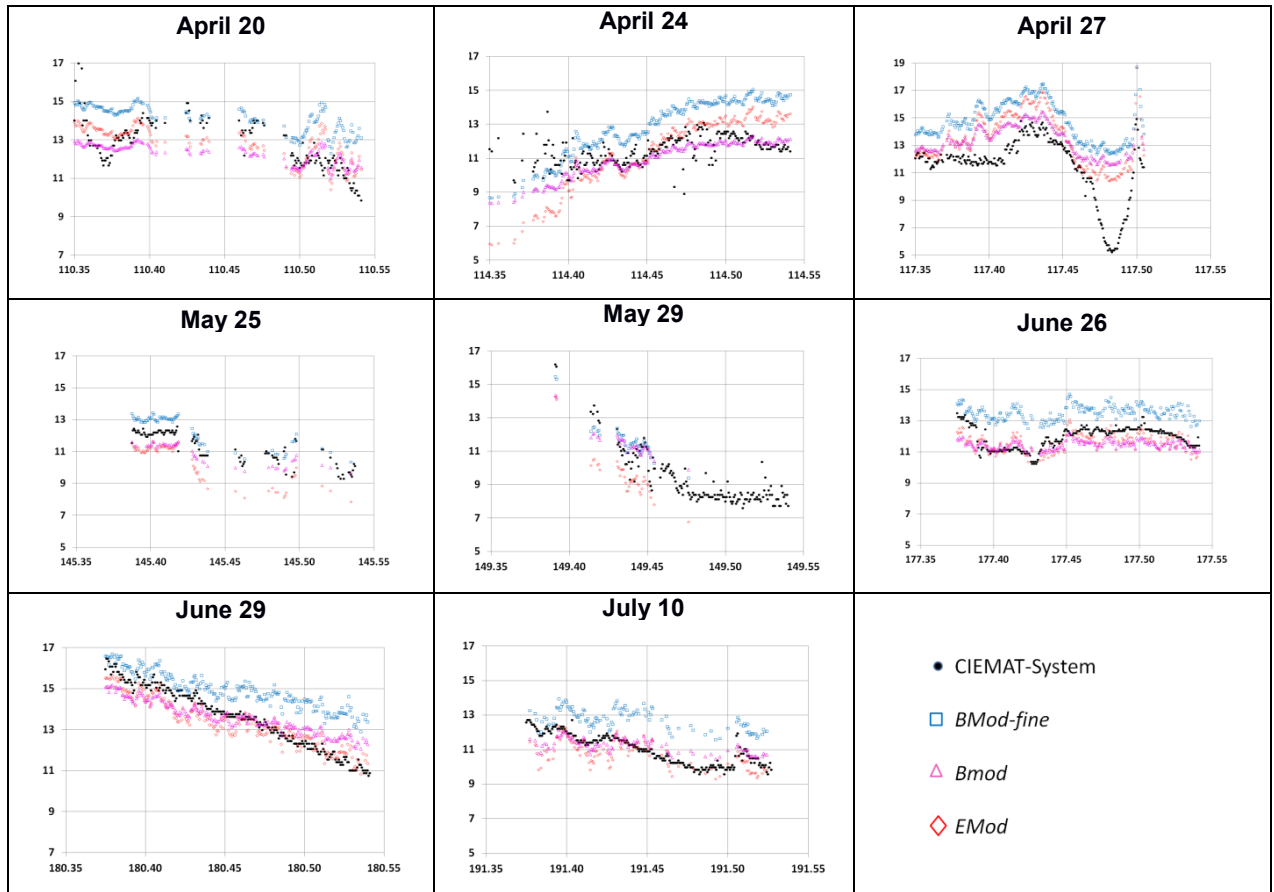
596

$$\sigma_{FSM, BB} [\text{km}^{-1}] = \ln(0.05)/MOR * StF * F_{\lambda} * A_{cf} + \sigma_{m, 550} + (a \rho_{w0} + b) \quad (13)$$

597

598 Figure 6 shows the comparison between the CIEMAT-System attenuation at 1 km and those derived from  
599 the full corrected FSM measurement for *EMod* and *BMod* models, including the corresponding to water vapour  
600 density at surface values obtained from parameters in Table 4.

601



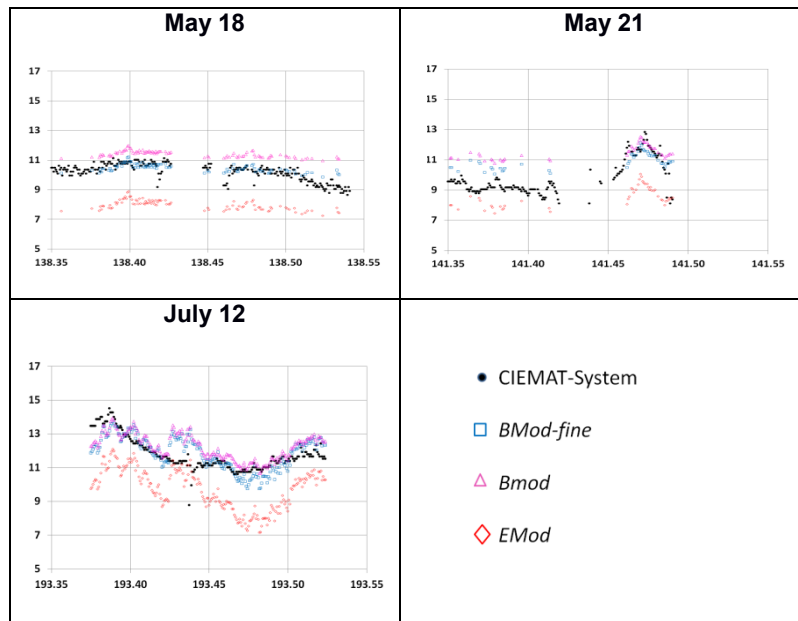
602

603 Figure 6. Horizontal attenuations at 1 km (%): CIEMAT-System (Black) and FSM corrected models *EMod*, *BMod* and *BMod-*  
604 *fine*. Note that the ordinate scale is not as in Figure 4, but expanded to better see the differences among models.

605

606 To test the goodness of the different models, an independent set of days not used to carry out the process  
607 described above, has been utilized. These days are May 18<sup>th</sup>, May 21<sup>st</sup> and July 12<sup>nd</sup>. Averaged daytime values

608 for meteorological relevant variables can be found in Table 1. It is worth noting that in these days the Ångström  
 609 exponent correspond to fine aerosols.  
 610



611  
 612 Figure 7. Horizontal attenuations at 1 km (%): CIEMAT-System (Black) and FSM corrected models *EMod*, *BMod* and  
 613 *BMod-fine* for validation days  
 614

615 Table 5 resumes the total extinction coefficient ratio CIEMAT-System to each one the corresponding to the  
 616 models for all the selected days. “Set 1” is for the eight days in Figure 4 and “Set 2” is for the three test days.  
 617

618 Table 5. Average and standard deviation values from 10 to 13 h (local time) of CIEMAT-System extinction coefficient ratio to  
 619 the extinction coefficient from each one of models for all the selected days.  
 620

Set	$\sigma_{CSys} / \sigma_{BMod-fine}$	$\sigma_{CSys} / \sigma_{BMod}$	$\sigma_{CSys} / \sigma_{EMod}$
Set 1	0.92 (0.03)	1.06 (0.04)	1.10 (0.06)
Set 2	0.99 (0.06)	0.92 (0.06)	1.18 (0.03)

621  
 622 Figure 6 and data in Table 5 show how the *BMod* model, that considers the correction due to the derived  
 623 aerosol Ångström exponent at the atmospheric column and from the corresponding coefficients in Table 4,  
 624 seems to be the best one (averaged extinction coefficients ratio 1.06) to approach the CIEMAT-System  
 625 attenuation measurements for the Set 1 days. But, the *EMod* may also give reasonable results. The *BMod-fine*  
 626 seems to be the worst performing in these dusty days, with low aerosol Ångström exponent values.

627 In case of Figure 7 and data in Table 5, it is shown how the fit with *BMod* and also with *BMod-fine* are good  
 628 for the determination of the horizontal attenuation. The similarity of behaviour of both models is not surprising  
 629 because the Set 2 days were days in which the aerosols showed a Ångström exponent of the order of 1.0, while  
 630 the *BMod-fine* model was for aerosol exponent 1.3. Results with *EMod* underestimate the extinction coefficient  
 631 around 20 %.

632 We are considering only horizontal extinction measurements at the surface but, at this point, it is important  
 633 to evaluate also the contribution of the vertical extinction, because in a STP of 100 MW, the central receiver is  
 634 located as high as 250 m above the surface or even more. To estimate the influence of the receiver height on

635 the total extinction some published results ([Ballestrín et al. 2016](#)) can be used. DNI spectral radiative transfer  
636 calculations with MODTRAN code ([Anderson et al. 1996](#)) at the base of the tower and at 100 m above have  
637 been carried out for three different visibilities (VR = 5 km, 23 km and 50 km) and for a homogeneous rural  
638 atmosphere. Results show that attenuation values of solar spectra were 3.5%, 0.6%, 0.25%, respectively. It can  
639 be estimated that, in the case of VR = 23 km (MOR = 17 km) and a receiver height of 200 m, there would be a  
640 vertical attenuation of 1.5%. For a STEP with heliostats 1 km away, and under the same conditions, these would  
641 suffer much higher horizontal attenuation levels, so the vertical contribution would be negligible. This vertical  
642 component could be relevant in the case of the closest heliostats, generally at horizontal distances equivalent to  
643 the height of the tower, but their number is small, so their influence on the final contribution to the energy  
644 produced would be very low.

645 It is usual to work with the hypothesis of atmosphere homogeneity of the lowest aerosol layer up to heights  
646 above the receiver. However, knowing the height profile of the aerosols could be important in the referred case  
647 of a receiver 200 m above the level of the heliostats. Using a Vaisala CL51 ([Vaisala CL51, 2010](#)) ceilometer,  
648 concentration fluctuations with root-mean-square error up to 10% around 1-hour moving average have been  
649 observed at 100 m above ground in case of high dust density near the surface ([Barbero et al. 2018](#)). This  
650 ceilometer is characterized by having a full overlap height around 80 m. The use of a collocated lidar with this  
651 feature could report in near real time the profile of the aerosols from full overlap height to well above the  
652 receiver.

653

## 654 **5. Conclusions and outlook**

655

656 Determination of the attenuation of solar radiation between the heliostats and receiver in a STP is important  
657 to evaluate the efficiency of the heliostat field and, therefore, the efficiency of the plant itself. Quality  
658 measurements are necessary to quantify the attenuation in real time but also to generate and validate models  
659 that allow estimation of attenuation from other parameters. In this context, an intercomparison campaign has  
660 been carried out between two methodologies for determining the extinction of solar radiation in the lower layers  
661 of the atmosphere.

662 One of the methodologies, developed at PSA-CIEMAT, consists of a set of two cameras (CIEMAT-System),  
663 spaced at a distance of 742 m, which simultaneously acquires the image of a Lambertian target, painted in  
664 white and black. This methodology directly provides values of horizontal atmospheric attenuation using a  
665 baseline close to 1 km.

666 The other methodology is based on FSMs, monochromatic instrumentation that are commonly used to  
667 measure visibility conditions in airports and highways. Two identical FSMs and the CIEMAT-System PSA-  
668 CIEMAT system were used in the intercomparison.

669 In the case of the two FSM it was observed that they fitted to each other within the respective uncertainty  
670 margins. However, the extinction coefficients obtained from their MOR values were on average a factor 2.1  
671 lower than those provided by the CIEMAT-System. This discrepancy can be explained because an FSM  
672 measures particle scattering in a small volume and it is designed to provide the most reliable output in low  
673 visibility fog and mist situations but it overestimates visibility in haze conditions. From the underlying physical  
674 phenomena, the discrepancy occurs because an FSM records only scattering, while the CIEMAT-System (or a  
675 broadband system in general) can detect scattering and absorption by aerosols, Rayleigh scattering by air

676 molecules and water vapour absorption. The process to correct the measurement of an FSM for all these effects  
677 has been summarized in the flowchart in Figure 5.

678 To correct the values of  $\sigma_{FSM}$ , several correction factors must be applied: some are documented for each  
679 FSM model, and others depending on the emplacement. Although general guidelines can be given:

680 The haze-to-fog correction factor,  $StF$ , depends on the angle between the emitter and the receiver of the  
681 FSM. In general, this design angle is between  $30^\circ$  and  $50^\circ$ , because in this range of angles the scattering  
682 coefficient has a very low dependence on the size of the aerosols. See as an example in Table 3 the calculated  
683 values of this factor for two different infrared FSMs.

684 The wavelength correction factor  $F_\lambda$  depends on the Angstrom exponent of the aerosols (equation 9)  
685 however, since IR FSMs all work at very similar wavelengths, this factor will be almost identical for all of them.

686 The corrective term for aerosol absorption,  $Acf$ , for sites with rural, tropospheric or maritime aerosols, and  
687 with relative humidity around 50%, this value is between 1.0 and 1.06. However, for urban type aerosols this  
688 value increases to 1.54 ([Settle & Fenn, 1979](#)).

689 The correction for the Rayleigh scattering of air molecules depends on the atmospheric pressure at the site,  
690 but can be considered as an offset. At sea level, represents an attenuation of 1.2% at 1 km

691 Finally, absorption by surface water vapour is conditioned by the characteristics of the site, and is calculated  
692 according to equation 12. In the case of PSA, in these episodes has been between  $5.5$  and  $14.7 \text{ g cm}^{-3}$ ; these  
693 values correspond to a precipitable water amount in the atmosphere between 1.3 and 3.5 cm, for a water  
694 vapour scale height of 2.4 km.

695 In the analyzed cases, the best solution for estimating real-time attenuation values from Biral FSM  
696 measurements should be to correct these values using equation (13) with the model *BMod* parameters, when  
697 the aerosol Ångström exponent is known (from a collocated spectroradiometer or a near AERONET station),  
698 and the corresponding correction by water vapour density at surface obtained from Table 5. But horizontal  
699 attenuation at 1 km forecasting with 2% of absolute error could be also achieved using *BMod* with  $\alpha = 1.0$ .

700 FSMs allow estimating the aerosol concentration in the local atmosphere, but its use to get reliable  
701 horizontal attenuation values (even with considerable error margins) is very complex. The corrections to be  
702 applied to the visibility provided by that equipment are based on empirical or semi-empirical models, which need  
703 to know the nature of the aerosol present. This information is not commonly known at the location of a solar  
704 plant and, in the best case, is obtained from the direct normal solar radiation through the atmospheric air  
705 column, and not from surface-level aerosol data.

706 The best solution is to have instrumentation that directly provides broadband horizontal attenuation, such as  
707 the CIEMAT-System. But it is possible to maximize the utility of a FSM to determine real-time values at a solar  
708 central tower plant including its MOR measurement in an artificial neural network structure, along with other  
709 meteorological and radiometric variables (direct solar radiation, relative humidity, temperature and pressure).

710

## 711 **Acknowledgements**

712

713 This work is included in the activities of the PRESOL project (Forecast of Solar Radiation at the Receiver of  
714 a Solar Power Plant) funded by the Spanish Government (Ref. ENE2014-59454-C3-1, 2, 3-R). And also the  
715 PVCastSOIL Project (Ref. ENE2017-83790-C3-1, 2, 3), funded by the Spanish Government and co-financed by  
716 the European Regional Development Fund.

717 The authors acknowledge the financial support provided by the Innova Chile - CORFO, PROJECT CODE:  
718 17BPE3-83761, as well as CONICYT/FONDAP/15110019 "Solar Energy Research Center" SERC-Chile.

719 The authors wish to thank to the investigators involved in the stations at AERONET\_Tabernas and  
720 AERONET\_Murcia, for delivering so useful data.

721 And also wish to thank the PSA's Maintenance and Instrumentation staff for the excellent work during the  
722 preparation of the intercomparison tests.

723

## 724 **References**

725

726 Alonso-Montesinos, J, Ballestrín, J, López, G, Carra, E, Polo, J, Marzo, A, Barbero, J., Batlles, F.J.. 2021. The use of ANN  
727 and conventional solar-plant meteorological variables to estimate atmospheric horizontal extinction. Journal of Cleaner  
728 Production 285, 125395

729 Anderson, G.P., et al., 1996. Reviewing atmospheric radiative transfer modeling: new developments in high and moderate  
730 resolution FASCODE/FASE and MODTRAN. Proc SPIE 2830, Optical Spectroscopic Techniques and Instrumentation  
731 for Atmospheric and Space Research II, 1996; <https://doi.org/10.1117/12.256105>

732 Ballestrín, J. Marzo, A. 2012. Solar radiation attenuation in solar tower plants, Sol. Energy 86, 388-392.

733 Ballestrín, J., Monterreal, R., Carra, M.E., Fernandez-Reche, J., Barbero, J., Marzo, A. 2016. Measurement of Solar  
734 Extinction in Tower Plants with Digital Cameras. AIP Conference Proceedings 1734, 130002; doi: 10.1063/1.4949212

735 Ballestrín, J., Monterreal, R., Carra, M.E., Fernandez-Reche, J., Polo, J., Enrique, R., Rodríguez, J., Casanova, M., Barbero,  
736 F.J., Alonso-Montesinos, J., López, G., Bosch, J.L., Batlles, F.J., Marzo, A. 2018. Solar extinction measurement system  
737 based on digital cameras. Application to solar tower plants. Renew. Energy 125, 648-654. ISSN: 0960-1481,  
738 <https://doi.org/10.1016/j.renene.2018.03.004>.

739 Ballestrín, J., Carra, E., Enrique, R., Monterreal, R., Fernández-Reche, J., Polo, J., Casanova, M., Barbero, F.J., Marzo, A.  
740 2018. Diagnosis of a Lambertian target in solar context, Measurement 119, 265-269. ISSN: 0263-2241,  
741 <https://doi.org/10.1016/j.measurement.2018.01.046>.

742 Ballestrín, J., Carra, E., Monterreal, R., Enrique, R., Polo, J., Fernández-Reche, J., Barbero, F.J., Marzo, A., Alonso-  
743 Montesinos, J., López, G., F.J. Batlles, F.J. 2019. One year of solar extinction measurements at Plataforma Solar de  
744 Almería. Application to solar tower plants. Renew Energy 136, 1002-1011

745 Ballestrín, J., Carra, E., Alonso-Montesinos, J., López, G., Polo, J., Marzo, A., Fernández-Reche, J., Barbero, F.J., Batlles,  
746 F.J. 2020. Modeling solar extinction using artificial neural networks. Application to solar tower plants. Energy. DOI:  
747 <https://doi.org/10.1016/j.energy.2020.117432>

748 Barbero, J., Alonso-Montesinos, J., Batlles, F. J., Polo, J., López, G., Bosch, J. L., Ballestrín, J., Carra, M. E., Fernández-  
749 Reche, J. 2018. Evolution of the aerosol extinction coefficient at 100 m above ground during an episode of Saharan dust  
750 intrusion as derived from data registered by a ceilometer in Almería (SE Spain). AIP Conference Proceedings 2033,  
751 190002; <https://doi.org/10.1063/1.5067187>

752 Barbero, F.J., Alonso-Montesinos, J., Ballestrín, J., Carra, E., Fernández-Reche, J. 2020. Atmospheric horizontal extinction  
753 determined with a single digital camera-based system in the scope of solar power tower plants. Measurement 149,  
754 107025, ISSN: 0263-2241 <https://doi.org/10.1016/j.measurement.2019.107025>.

755 Barcelona Dust Forecasting Center. <https://dust.aemet.es/>. Access 2021.

756 Biral VPF Series. Present Weather Sensors. Manual Number: 102186. 2017.

- 757 Bloemink, H.I. 2006. KNMI visibility standard for calibration of scattermeters.  
758 [https://www.wmo.int/pages/prog/www/IMOP/publications/IOM-94-TECO2006/P3\(26\)\\_BloeminkMs\\_Netherlands.pdf](https://www.wmo.int/pages/prog/www/IMOP/publications/IOM-94-TECO2006/P3(26)_BloeminkMs_Netherlands.pdf)
- 759 Bucholtz, A. 1995. Rayleigh-scattering calculations for the terrestrial atmosphere. *Applied Optics*, 34 n15, 2765.
- 760 Carra, E., Ballestrín, J., Polo, J. Barbero, F.J. Fernández-Reche, J. 2018. Atmospheric extinction levels of solar radiation at  
761 Plataforma Solar de Almería. Application to solar thermal electric plants. *Energy* 145, 400-407.
- 762 Chen, X., Lu, C., Liu, W., Zhang, Y. 2013. A New Algorithm for Calculating the Daytime Visibility Based on the Color Digital  
763 Camera. *IJCSI International Journal of Computer Science Issues*, Vol. 10, Issue 1, No 1. ISSN (Print): 1694-0784 | ISSN  
764 (Online): 1694-0814.
- 765 Degreane Horizon. User's Manual DF20+. 2007
- 766 EKO. MS-700 Spectroradiometer.pdf. <https://eko-eu.com>. 2016.
- 767 Elias, T., Ramon, D., Dubus, L., Brau, J., Langouet, H. 2017. Instrumental Set-up to Estimate the Atmospheric Attenuation  
768 along the Slant Path of Concentrated Solar Plants. In *Proceedings of the Poster, SolarPACES2017*, Santiago de Chile,  
769 Chile, 26–29 September 2017.
- 770 Gueymard, C. 1994. Analysis of monthly average atmospheric precipitable water and turbidity in Canada and Northern  
771 United States. *Sol. Energy* 53, 57-71.
- 772 *Guide to Meteorological Instruments and Methods of Observation*. World Meteorological Organization, 2014. 291-309.
- 773 Hanrieder, N., Wilbert, S., Mancera Guevara, D., Buck, R., Giuliano, S., Pitz-Paal, R. 2017. Atmospheric extinction in solar  
774 tower plants-A review. *Sol. Energy* 152, 193–207.
- 775 Hanrieder, N., Wehringer, F., Wilbert, S., Wolferstetter, F., Pitz-Paal, R., Campos, A., Quaschnig, V. 2012. Determination of  
776 beam attenuation in tower plants. In: *SolarPACES*. Marrakech, Morocco
- 777 Hanrieder, N., Wilbert, S., Pitz-Paal, R., Emde, C., Gasteiger, J., Mayer, B., Polo, J. 2015. Atmospheric extinction in solar  
778 tower plants: absorption and broadband correction for MOR measurements. *Atmos. Meas. Tech.* vol. 8, no. 8, 3467–  
779 3480.
- 780 Hanrieder, N., Ghennioui, A., Merrouni, A., Wilbert, S., Wiesinger, F., Sengupta, M., Zarzalejo, L., Schade, A. 2019.  
781 Atmospheric Transmittance Model Validation for CSP Tower Plants. *Remote Sens.* 11 (2019)1083
- 782 Koschmieder, H. 1924. Theorie der horizontalen Sichtweite. *Beitraege zur Physik der freien Atmosphäre*, 12, 33–53.
- 783 López, G., Bosch, J.L., Pulido-Calvo, I., Gueymard, C.A. 2017a. Visibility estimates from atmospheric and radiometric  
784 variables using artificial neural networks. *WIT Transactions on Ecology and The Environment*, Vol 211,  
785 [www.witpress.com](http://www.witpress.com), ISSN 1746-448X (on-line). doi:10.2495/AIR170131
- 786 López, G., Gueymard, C.A., Bosch, J.L. 2017. Evaluation of Solar Energy Losses for the Heliostat-to-Receiver Path of a  
787 Tower Solar Plant for Different Aerosol Models. *SWC 2017 / SHC 2017 / ISES Conference Proceedings*.  
788 doi:10.18086/swc.2017b.23.03.
- 789 López, G., Gueymard, C.A., Bosch, J.L., Rapp-Arrarás, I., Alonso-Montesinos, J., Pulido-Calvo, I., Ballestrín, J., Polo, J.,  
790 Barbero, F.J., 2018a. Modeling water vapour impacts on the solar irradiance reaching the receiver of a solar tower plant  
791 by means of artificial neural networks. *Sol. Energy* 169, 34–39
- 792 López, G., Christian A. Gueymard, Juan L. Bosch, Joaquín Alonso-Montesinos, Igor Rapp-Arrarás, Jesús Polo, Jesús  
793 Ballestrín, Javier Barbero, Manuel J. Caro-Parrado, Francisco J. Batlles. 2018b. Estimation of Visibility from Spectral  
794 Irradiance Using Artificial Neural Networks. *AIP Conference Proceedings* 2033, 040023;  
795 <https://doi.org/10.1063/1.5067059>. Published Online: 08 November 2018.

796 Martínez-Lozano, J.A., Utrillas, M.P., Tena, F., Cachorro, V.E. 1998. The parameterisation of the atmospheric aerosol  
797 optical depth using the Ångström power law. *Solar Energy*. Volume 63, Issue 5, November 1998, Pages 303-311

798 Marzo, A., Salmon, A., Polo, J., Ballestrín, J., Soto, G., Quiñones, G., Alonso-Montesinos, J., Carra, E., Ibarra, M., Cardemil,  
799 J., Fuentealba, E., Escobar, R. 2021. Solar extinction map in Chile for applications in solar power tower plants,  
800 comparison with other places from sunbelt and impact on LCOE. *Renewable Energy* 170, 197-211 ISSN 0960-1481.  
801 Doi: <https://doi.org/10.1016/j.renene.2021.01.126>.

802 Middleton, W.E.K. 1952. *Vision through Atmosphere*. University of Toronto Press.

803 Pitman, C.L., Vant-Hull, L.L. 1982. Atmospheric transmittance model for a solar beam propagating between a heliostat and a  
804 receiver. *ASES Progress in Solar Energy* 1247-1251.

805 Operations and Maintenance Manual: SWS Present Weather Sensors. 2014. Bristol Industrial and Research Associates  
806 Limited (BIRAL).

807 OPTEC. 2011. Model LPV3 and Model LPV4. Long Path Visibility Transmissometer, Technical Manual for Theory and  
808 Operation and Operating Procedures, Technical report, 1-72.

809 Plataforma Solar de Almería. Annual Report 2018. <http://www.psa.es/en/techrep>.

810 Shettle, E., Fenn, R. 1979. Models of the atmospheric aerosols and their optical properties. *Environ. Res.* 94.

811 Tjugum, S.A., Vaagen, J.S., Jakobsen, T., Hamre, B.. 2005. Use of optical scatter sensors for measurement of visibility. *J.*  
812 *Environ. Monit.* 7, 608-611

813 Vaisala. 2010. User's Guide: Present Weather Sensor FS11P.

814 Vaisala ceilometer CL51. User's guide. Functional description. 2010.

815 Wang, J., Liu, X., X. Yang, X., M. Lei, M., Ruan, S., Nie, K., Miao, Y., Liu, J. 2014. Development and evaluation of a new  
816 digital photography visiometer system for automated visibility observation. *Atmospheric Environment.* 87, 19-25.  
817 <https://doi.org/10.1016/j.atmosenv.2013.12.045>

818 WMO, 2018. Guide to Instruments and Methods of Observation.  
819 [https://library.wmo.int/index.php?lvl=notice\\_display&id=12407#.YOR1nDNxeMo](https://library.wmo.int/index.php?lvl=notice_display&id=12407#.YOR1nDNxeMo)

820