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Soiled CSP solar reflectors modeling using dynamic linear models

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Abstract

Dust particles accumulation on the solar reflectors of concentrating solar power (CSP) plants, reduces the reflectance by absorbing and scattering the sunlight, which otherwise would be reflected onto the thermal receiver, causing optical losses to the solar field. The focus of this paper is to provide an adequate model capable of describing and forecasting the loss of reflectance of solar reflectors used in CSP plants. The approach adopted is based on time series analysis, using the dynamic linear Gaussian state space time series models. The modeled data are reflectance measurements of second surface glass mirrors, typically used in CSP plants, exposed outdoors in southwest Morocco. The data measurements campaign was conducted from 26 June to 29 December 2014 with an average measurement frequency of twice per week. After performing model selection criteria, the best fitted model describing the long term change in the cleanliness is the *local linear trend*, which performs even better when an optimal discount factor of 0.95 is considered.

Keywords: CSP; Silvered-glass mirror; Reflectance; Soiling; Time series; Dynamic linear model

1. Introduction

In the last decade, a growing energy demand was witnessed in the MENA (Middle East and North Africa) region, where nonrenewable resources of energy are not a sustainable solution (El-Katiri, 2014). The kingdom of Morocco has committed to making renewable energies a part of its energetic mix, by increasing the share of renewable energies to 20% in 2020 (Eichhammer et al., 2005), with CSP being a key technology. Projects such as ISCC Ain Beni Mathar (Fernández-García et al., 2010) and Ouarzazate Noor solar complex (MASEN, 2012) are the first steps in making this vision a reality. In the candidate sites chosen for the deployment of CSP plants in Morocco, harsh weather conditions can increase the probability of materials degradation (Karim et al., 2014) and also provoke severe dust accumulation which threaten to lower the expected output of CSP plants by reducing the reflectance of the large solar reflectors required to meet the aimed output production (NREL, 2013). The two mechanisms responsible of the reflectance reduction, and the subsequent optical losses of the solar field, due to dust and soiling accumulation on the reflector surfaces, are absorption and scattering of the sunlight reflected onto the thermal receiver.

Solar-weighted specular reflectance is the key parameter to quantify the optical quality of a mirror (Meyen et al., 2010). It is the primary factor for the cleaning decision and can provoke a severe drop in the power production of a CSP plant. A typical CSP plant requires the operation and maintenance (O&M) staff to monitor the reflectance of

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Nomenclature

Acronyms

MENA	Middle East and North Africa
ACF	autocorrelation function
AIC	Akaike information criterion
BIC	bayesian information criterion
CF	cleanliness factor
CSP	concentrating solar power
CV	cross validation
D&S	Devices and Services
DLM	dynamic linear model
EMB	expectation maximization bootstrapping
MAD	mean absolute deviation
MAPE	mean absolute percentage error
MAR	missing at random
MSE	mean square error
O&M	operation and maintenance
Q–Q	Quantile–Quantile
SD	standard deviation

Greek symbols

β_t	slope of the series at time t, in the second-order polynomial model
δ	discount factor
μ_t	level of the series at time t
ω_t	evolution error
ρ	reflectance
ρ_0	initial reflectance of a clean mirror
θ_t	state vector
υ_t	observation error

Roman symbols

a_t	mean of the prior distribution at time t
C_{t-1}	variance of the posterior distribution for the filtering process at time $t-1$
D_t	set of available information until time t
D_{t-1}	past observations until time $t-1$
e_t	forecast error
F_t	design matrix of known values
f_t	mean of the 1-step ahead prediction
G_t	evolution matrix
j	minimum number of observations needed for model fitting
L	maximized value of the likelihood function
m	number of samples in the EMB algorithm
m_{t-1}	mean of the posterior distribution for the filtering process at time $t-1$
n	number of observations
P_t	prior variance with null evolution error at time t
Q_t	variance of the 1-step ahead prediction
R_t	variance of the prior distribution at time t
S_t	variance of the posterior distribution for the smoothing process at time t
s_t	mean of the posterior distribution for the smoothing process at time t
T	the starting time point for the smoothing process
V_t	observation variance
W_t	evolution variance
Y_t	sequence of observed data
k	number of step ahead forecast
k'	number of estimated parameters in the model
K_t	gain matrix
$N[x_0, \sigma_x]$	normal (Gaussian) distribution with mean x_0 and variance σ_x
t	time index

the mirrors and to clean them regularly or rely on their knowledge to guarantee an acceptable level of cleanliness (Cohen et al., 1999). Measuring the reflectance of a solar field in dusty environments such as the MENA region in general and Morocco in particular is labor intensive and a time consuming task. Consequently, there is a crucial need to develop models that reliably monitor and forecast the soiling of solar reflectors, in order to achieve the targeted energy production.

Many studies have investigated different aspects of the soiling of CSP candidate mirrors, as can be found on Sarver et al. (2013). The properties of dust adhering to the surface of the mirrors is an interesting research area covered by Berg (1978), Roth and Pettit (1980), Morris (1980) and Biryukov et al. (1999). The changes in the level of reflectance over time were investigated in Pettit et al. (1981) and Fernández-García (2012). The study of reflectance loss of mirrors samples exposed in different locations was reported in Bethea et al. (1981), Heimsath et al. (2010), Tahboub et al. (2012) and Wolfertstetter et al. (2014). A predictive model accounting for the dirtiness of solar collectors was developed by Deffenbaugh et al. (1986).

None of these studies on reflectance loss have used time series dynamic modeling, which are advanced modeling and forecasting tools from the time series toolbox. This work is focused on applying these advanced tools to model the variation in the reflectance of soiled reflectors exposed to natural environment and to forecast their level of dirtiness.

2. Methodology

This section includes the description of the exposure site and the methodology followed to obtain the reflectance time series, that is, the measurement equipment and the measurement protocol used in the study. The experimental set up and the frequency of measurements are also described.