Towards harnessing the Solar Energy

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Outline

- Motivations
- Challenges
- Modeling the Solar Irradiance
- Modeling the Harvested Power
- Results
- Conclusions

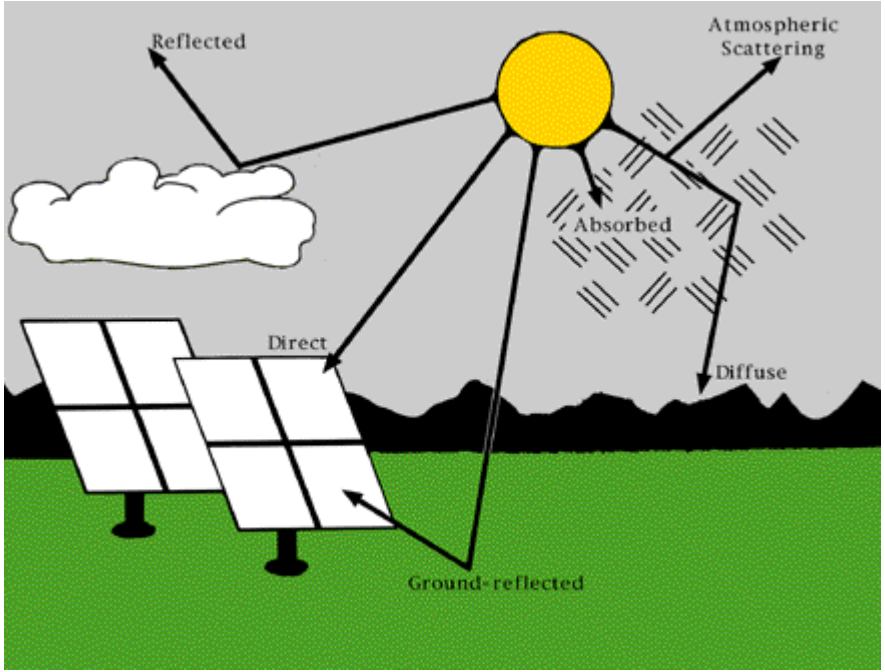
Motivations

- energy cost
- a means of reducing environmental footprint
- really essential for IT such as data centres, base stations, sensors etc.
- relative share of ICT products/services in total worldwide electricity consumption

about 3.9% in 2007 -> about 4.6% in 2012

Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., Demeester, P.: Trends in worldwide ICT electricity consumption from 2007 to 2012. Computer Communications 50, 64–76 (September 2014)

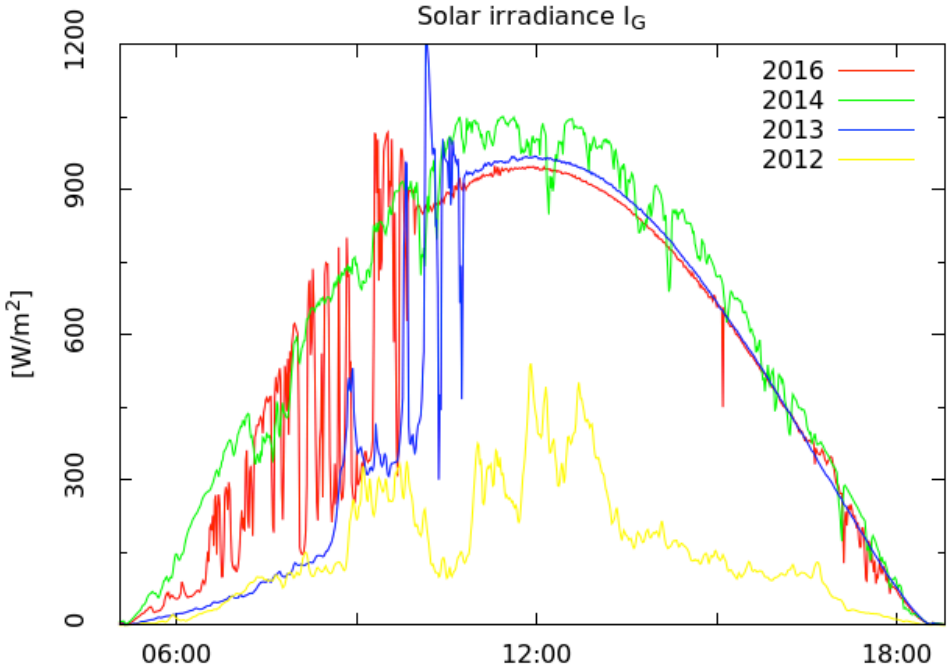
Solar Irradiance



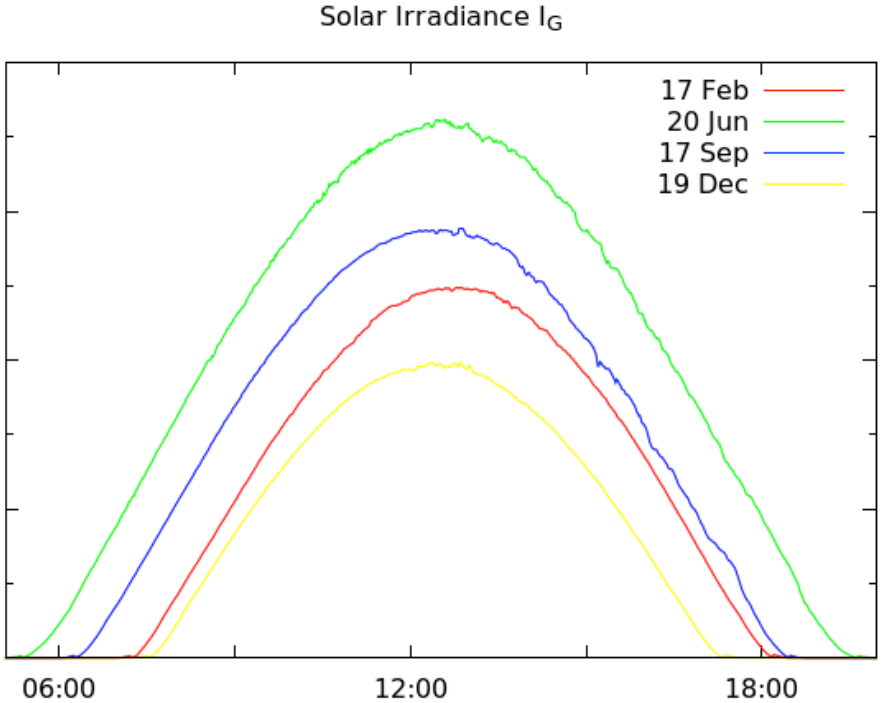
- Direct Normal
- Diffuse Sky
- Ground-Reflected

Global irradiance I_G = Direct Normal + Diffuse Sky

Challenges



(a) May 1st, different years



(b) Different days in 2012

Modeling the Solar Irradiance

The global irradiance I_G is a product of a ***multiplicative noise***, denoted **α,** by the clear sky solar irradiance I_{cs}

$$I_G = \alpha I_{cs}$$

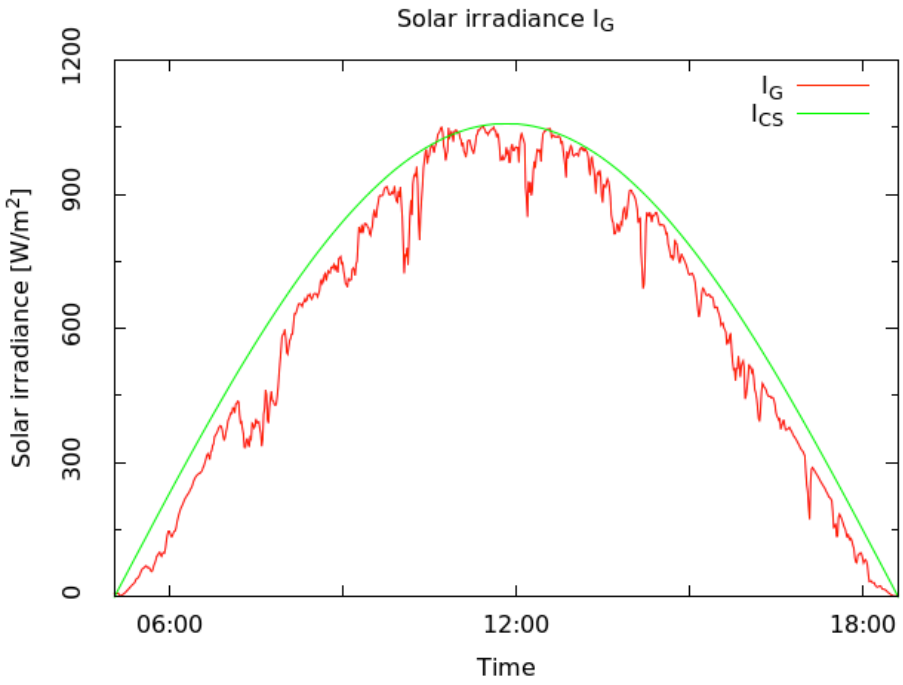
Idea: Model separately α and I_{cs}

Modeling the Solar Irradiance

- Modeling the clear sky irradiance I_{cs}

$$Ics(time) = MaxClearSky \cdot \sin\left(\frac{time - sunrise}{sunset - sunrise} \cdot \pi\right)$$

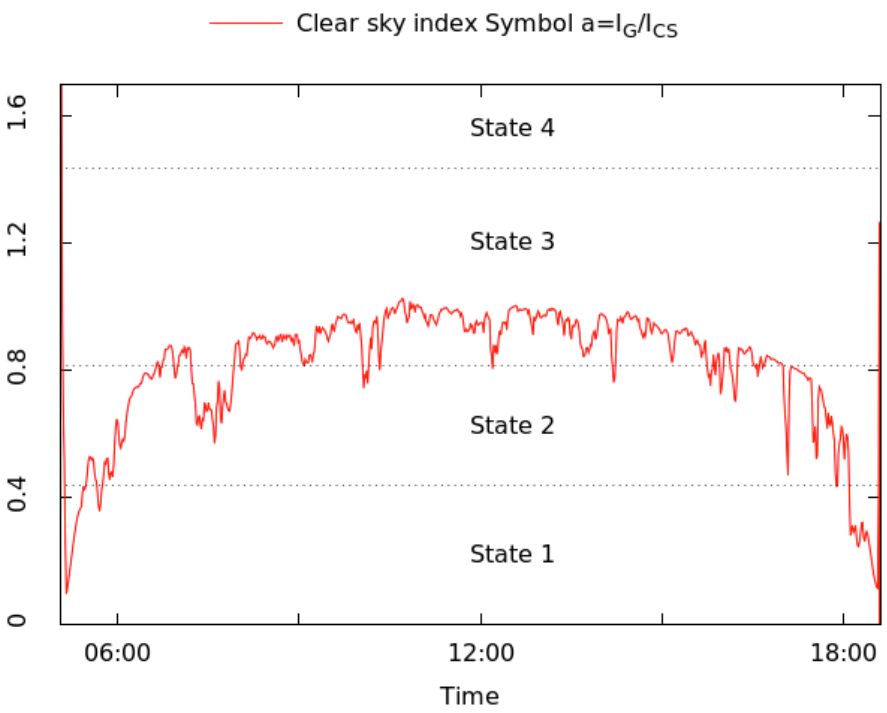
"sunrise", "sunset" and "MaxClearSky" -> astronomical data
Available for any date and many selected locations from https://ptaff.ca/soleil/



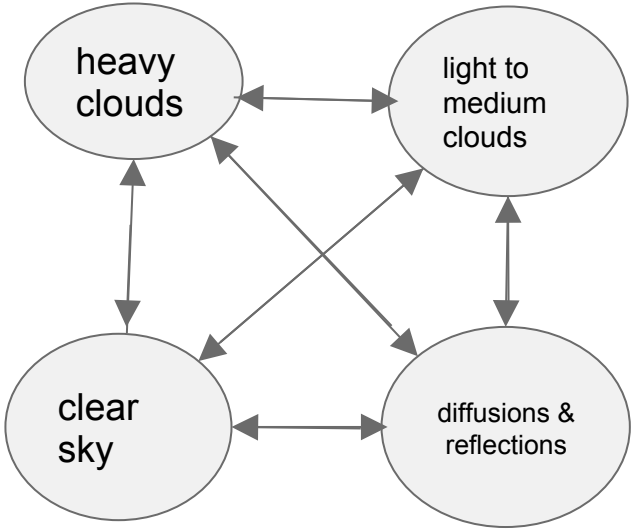
Modeling the clear sky index

- Clear sky index Symbol:
  - $\alpha = I_G / I_{cs}$
  - I_G : global irradiance & I_{cs} : clear sky irradiance

<u>Question</u>: How can we model α?



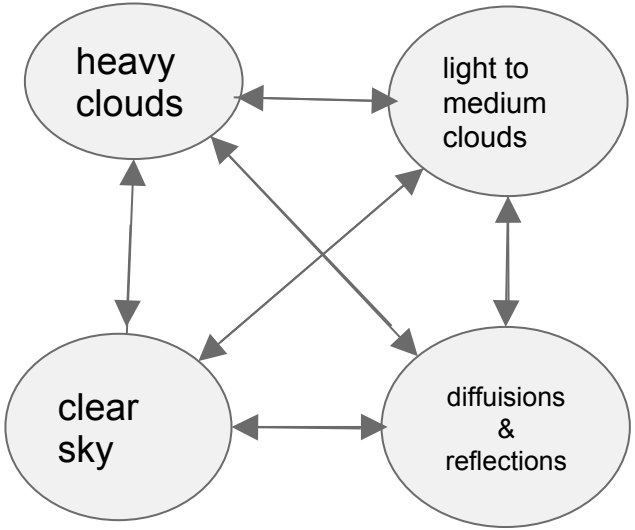
Discrete-time semi Markov process



- Sojourn time distribution for each state $\mathbf{f}_\iota$
- Distributions of values of α for each state: $\mathbf{g}_\iota$
- Transition Probability Matrix: P
- f_i and g_i , for $i \in \{1, 2, 3, 4\}$ will be fitted to empirical distributions of the sojourn times and values of α

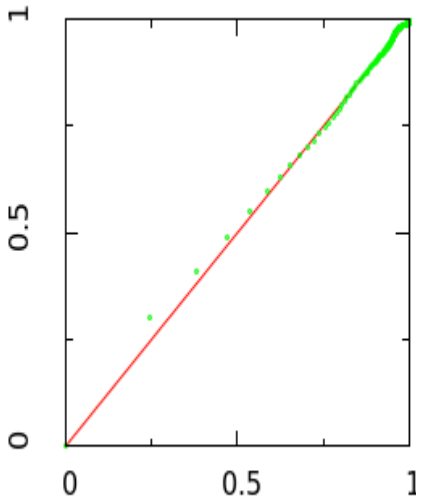
Validating model of clear sky index α

- NREL solar irradiance per minute, April 2010-March 2015, LA
- k-means for α to find the different clusters-> metric Davies doublin index -> k =4

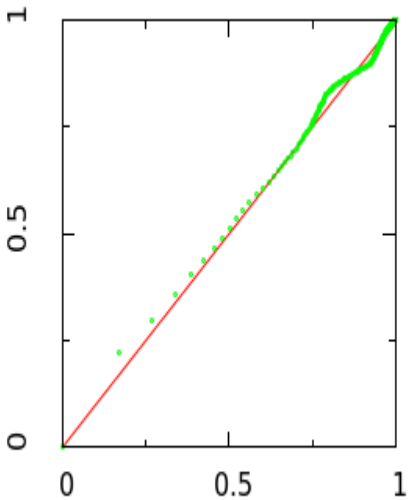


Range of values of α	State	Physical Interpretation
[0,0.44152)	1	heavy clouds between the sun and the surface
[0.44152, 0.81639)	2	medium to light clouds between the sun and the surface
[0.81639, 1.4343)	3	clear sky
[1.4343,3)	4	High reflection and diffusion in the atmosphere

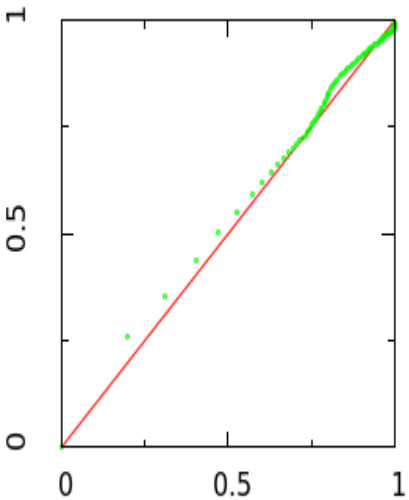
Probability plots of the phase-type fitting for sojourn times in each state



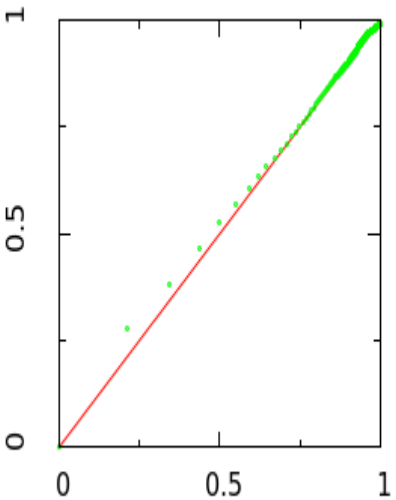
(a) State 1, PH-5 fit



(b) State 2, PH-6 fit

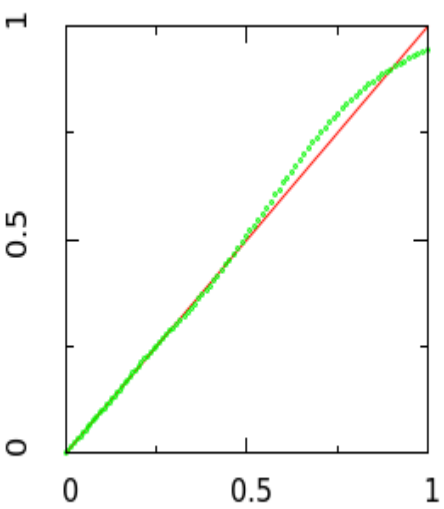


(c) State 3, PH-6 fit

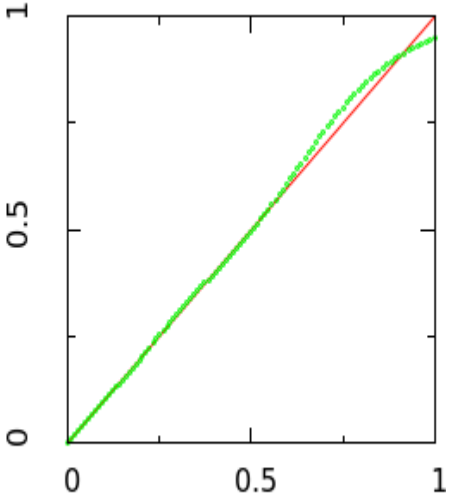


(d) State 4, PH-6 fit

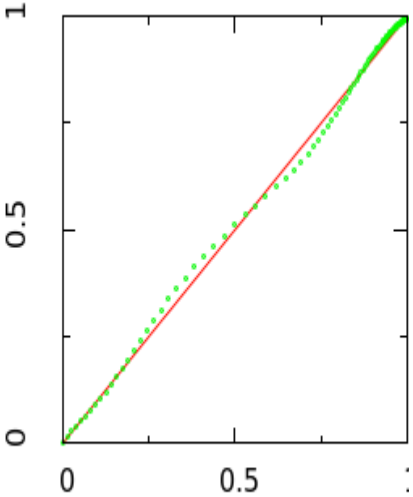
Probability plots of the phase-type fitting for α values in each state



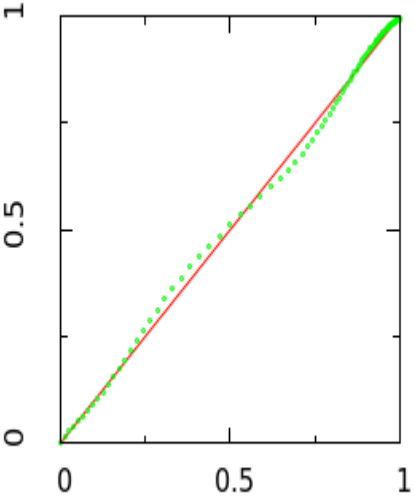
(a) State 1, PH-20 fit



(b) State 2, PH-20 fit

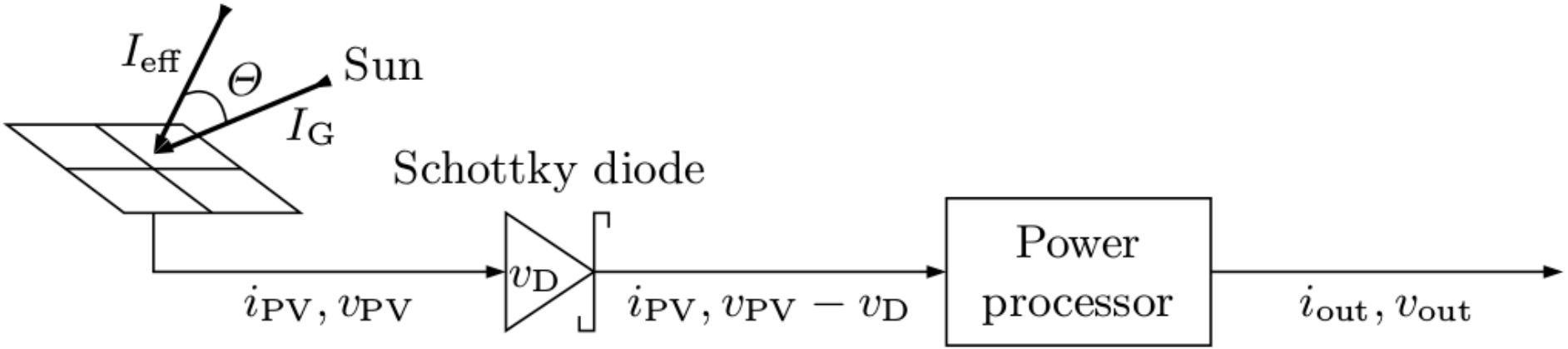


(c) State 3, PH-6 fit

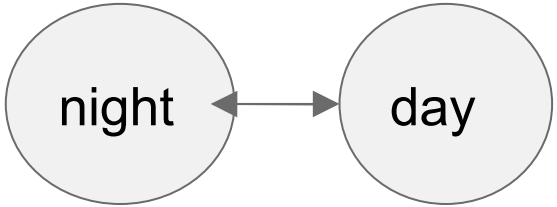


(c) State 3, PH-6 fit

Modeling the Harvested Power



On-off model [3]



- Per hour solar irradiance data for LA, from NREL [1]
- Model the output current (ι_{out})
- 2-state semi-Markov process
- Split the data according to an arbitrary threshold
- Output current grouped by month
- Kernel smoothing techniques to estimate time duration and output current distributions
- Day state -> generate current *constantly*
- Night state -> output current =0

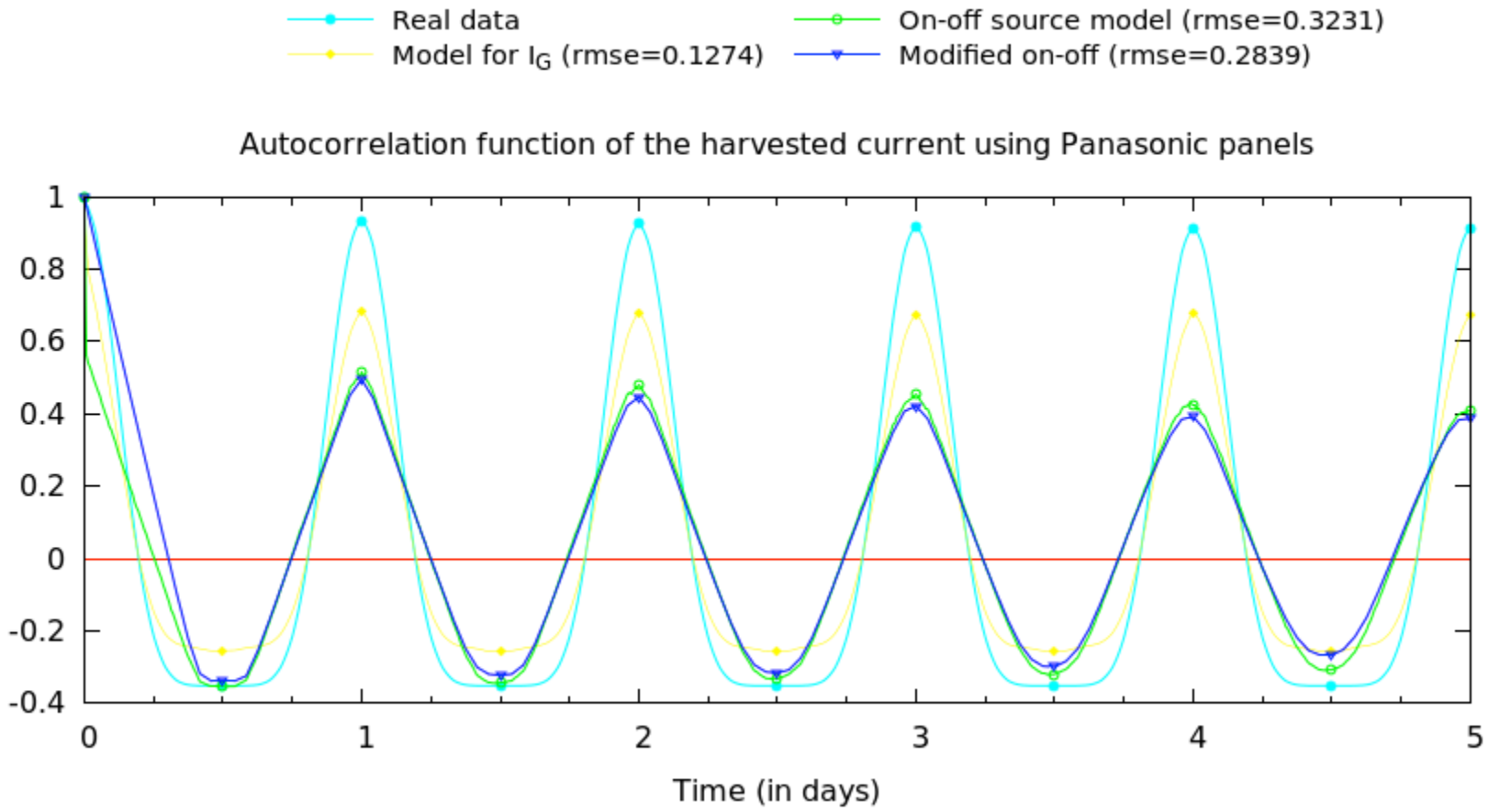
Modified on-off model

- Day state -> *resample* (every 10 minutes) from the current distributions until a transition occurs

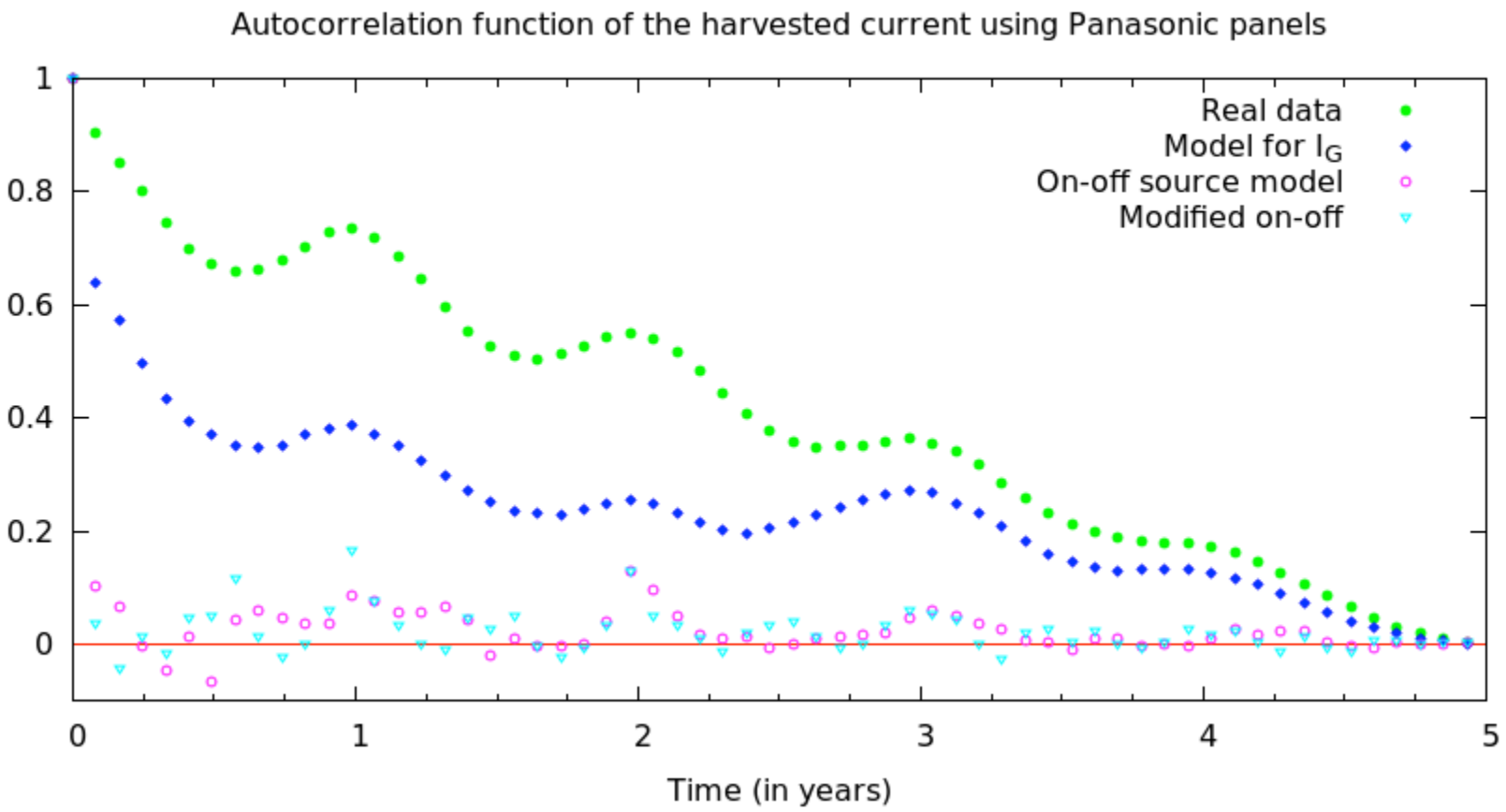
Comparison

- Use 5 years empirical data for LA from NREL
- Generate 5 years synthetic data from
  - Irradiance model
  - On-off model [3]
  - Modified on-off model
- Metrics
  - Autocorrelation
  - periodogram

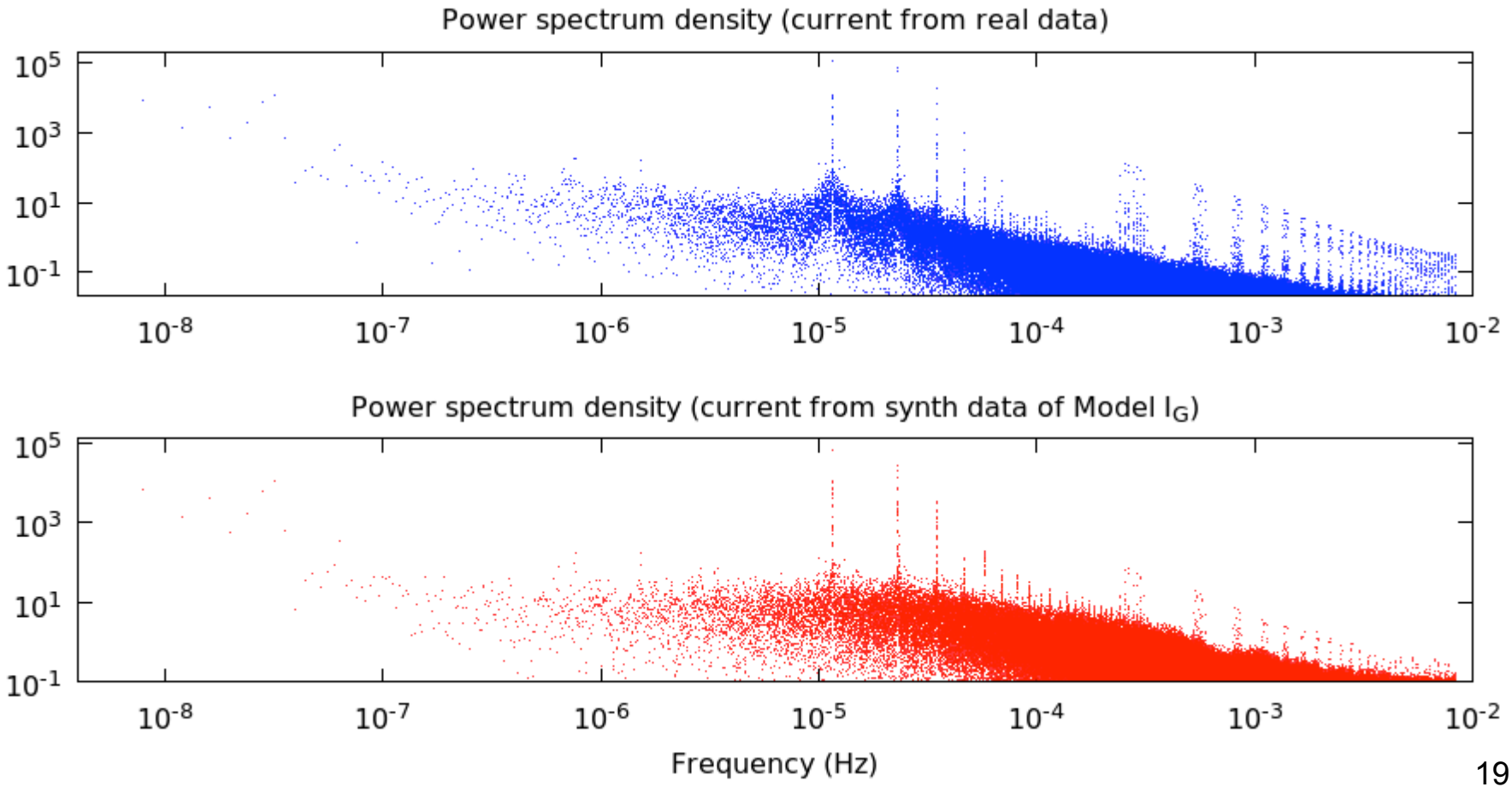
Results (1/3)


Real data
Model for I_G (rmse=0.1274)
On-off source model (rmse=0.3231)
Modified on-off (rmse=0.2839)
Autocorrelation function of the harvested current using Panasonic panels
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
1
2
3
4
5
Time (in days)

Results (2/3)


Autocorrelation function of the harvested current using Panasonic panels
Real data
Model for I_G
On-off source model
Modified on-off
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
Time (in years)

Results (3/3)


Power spectrum density (current from real data)
10^5
10^3
10^1
10^{-1}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Power spectrum density (current from synth data of Model I_G)
10^5
10^3
10^1
10^{-1}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Frequency (Hz)

Conclusions

- ➢ Our solar irradiance model is able to generate synthetic data that exhibits most of the frequency peaks of real data
- ➢ Our solar irradiance model captures small time scales fluctuations as would be needed by ICT applications
- ➢ Autocorrelation functions and periodograms of empirical and synthetic traces -> very well performance
- ➢ Our model can be used not only in the mathematical analysis of energy harvesting communication/computer systems and in their simulation.

Thank you!!!

References

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4. Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., Demeester, P.: Trends in worldwide ICT electricity consumption from 2007 to 2012. Computer Communications 50, 64–76 (September 2014)

5. Politaki D., Alouf S. (2017) Stochastic Models for Solar Power. In: Reinecke P., Di Marco A. (eds) Computer Performance Engineering. EPEW 2017. Lecture Notes in Computer Science, vol 10497. Springer, Cham