A Sky Image Analysis System for Sub-minute PV Prediction

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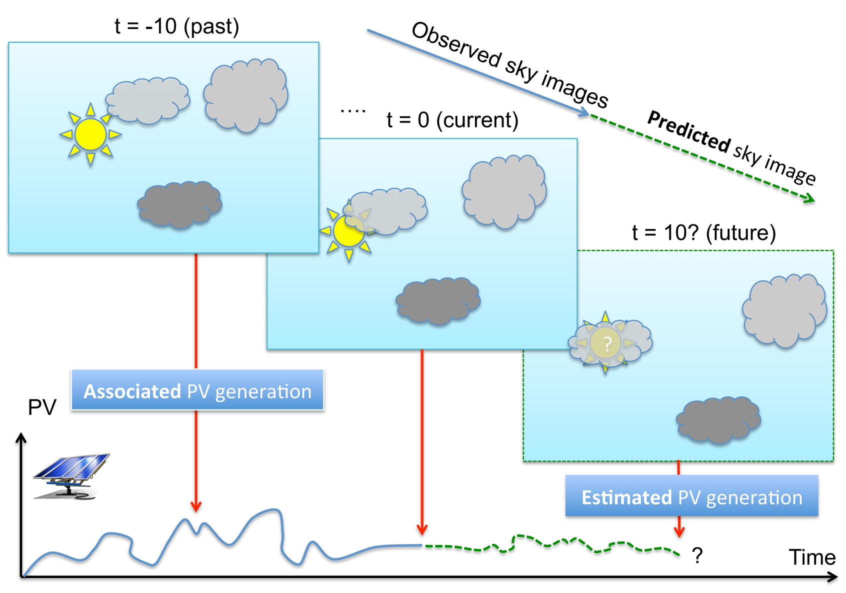
1 Motivation & Approach

1.1 Why sub-minute prediction?

- Enhance energy management systems (at homes, factories, etc.).
- Improve the management of distribution & transmission networks.
- Reduce the need of backup generation capacity.

Sky & cloud analysis can be useful for weather prediction and atmospheric studies.

1.2 Proposed Approach

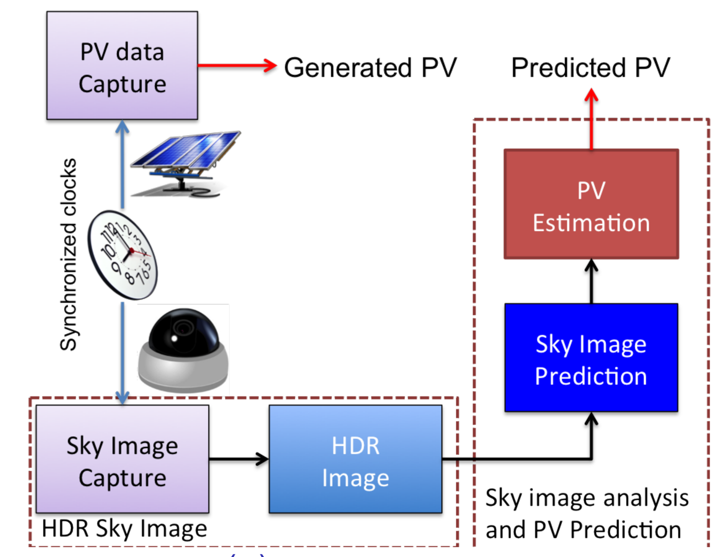


- To predict the PV generation, future sky images are predicted & the PV power associated to the predicted sky image is estimated.
- The system does not require a historical data nor geo-location information.

1.3 Existing approaches

	Time Horizon	Resolution	*RMSE*
Weather model	Hour-ahead	1 hour	20-60%
Satellite imaging	Hour-ahead	1 minute	20%
Dynamic PV model	Intra-hour	15 minute	20%

2. System diagram



(a) System diagram

(b) Camera system

Figure: System diagram & camera system.

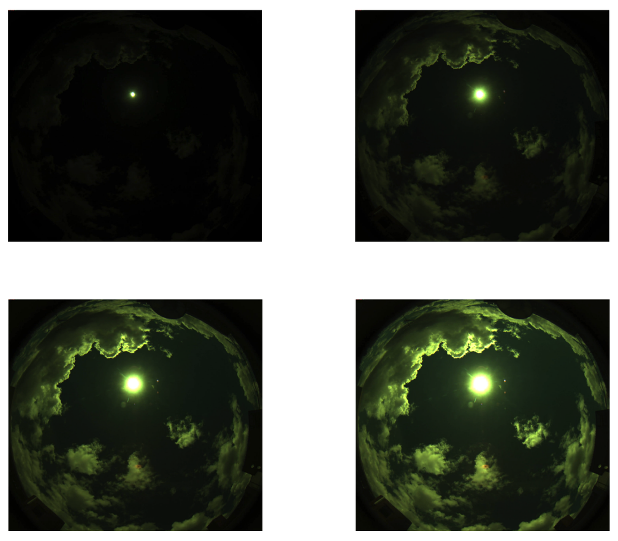


Figure: Multiple exposures for HDR.

2.1 Hardware

- Chameleon3 PointGrey Camera (Sony IMX265, 1/1.8", Color, 2048x1536 (3.2MP), USB3).
- Spacecom TV1634M, F1.4, **180** Fish-eye lens.
- Intel i7, 8 cores, 4 GHz, 32GB RAM PC (Ubuntu).

2.2 Software

- Bracketing mode every 1/2 second. Four exposure times in $\{1, 8, 16, 24\}$ x 11ms)) are captured at 8 fps.
- Capture program (C++) uses multi-thread programming to improve throughput and reduce I/O blocking.
- Images cropped in camera (1280x1280 pixels).

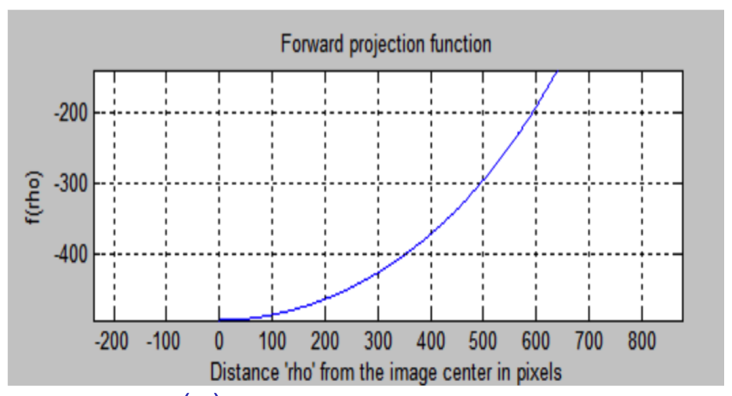
3. Sky Image Capture System

3.1 Camera model & Lens calibration

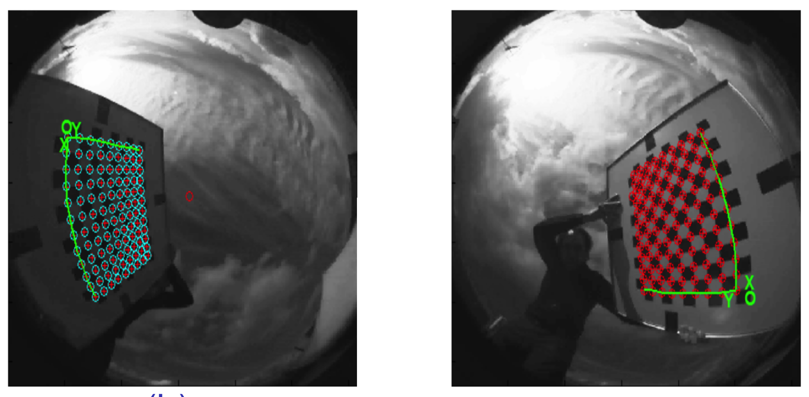
The lens is modeled using a 4th degree polynomial:

$$f(\rho) = a_0 + a_1\rho + a_2\rho^2 + a_3\rho^3 + a_4\rho^4 \text{ with,} \tag{1}$$

- $\rho = \sqrt{u^2 + v^2}$: distance from the image center, and (u, v) the coordinates in the sensor plane (pixels).
- $f(\rho)$ gives the coordinate of the 3D point $[u, v, f(\rho)]$ associated to pixel (u, v).
- We estimate the light direction θ from $\tan\theta = \rho/f(\rho)$.



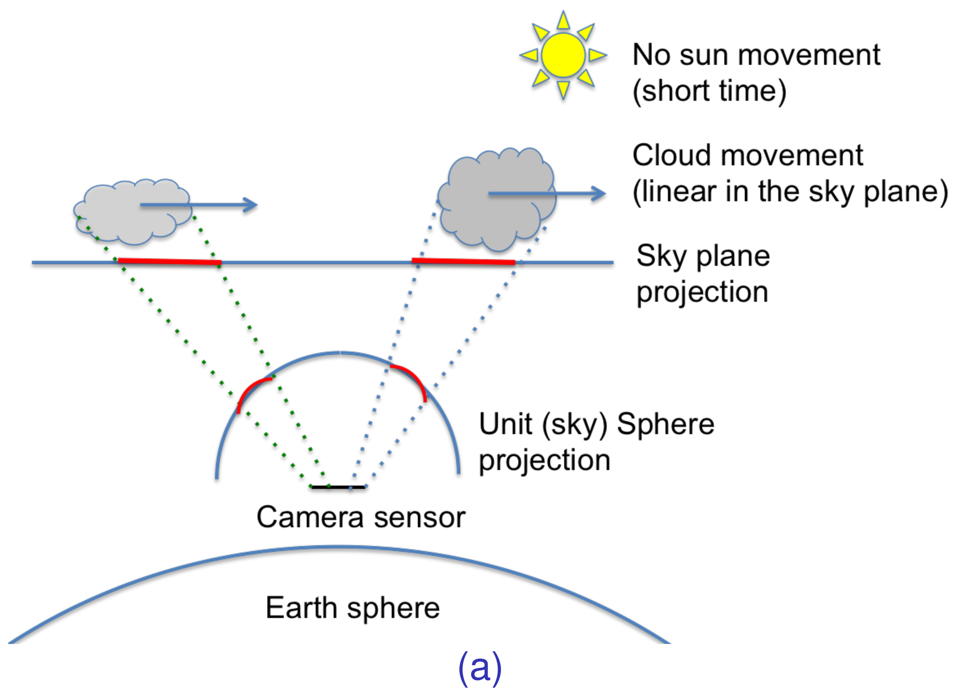
(a) Mapping function $f(\rho)$



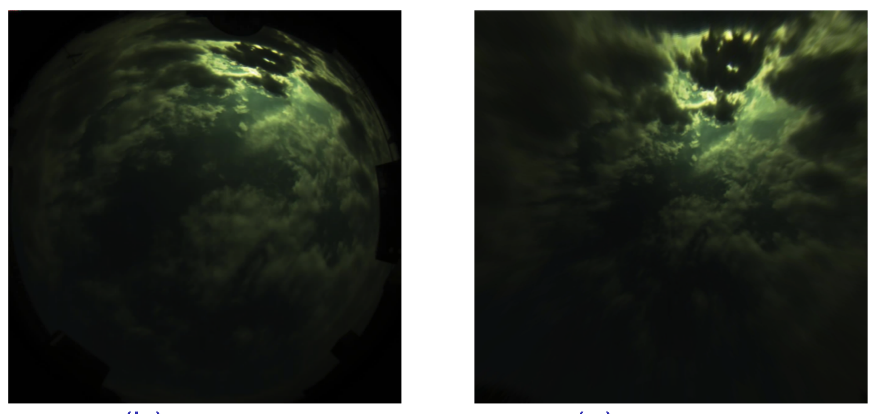
(b) Checkboard and projected lines.

Figure: Lens calibration. The calibrated model closely matches the checkboard patterns (lines (green) in (b)).

3.2 Projection Model



(a)



(b) Original (c) Sky plane

Figure: (a) Light projection model: sensor, sphere & sky plane projections.

4. Sky Image Analysis and Prediction

4.1 Motion Analysis

- Optical flow is used to calculate the movement of each pixel (see Fig)
- The (cloud) movement is assumed to be linear in the sky plane.
- The predicted image is projected back to the original image plane for PV Estimation.

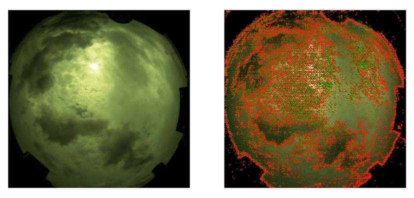
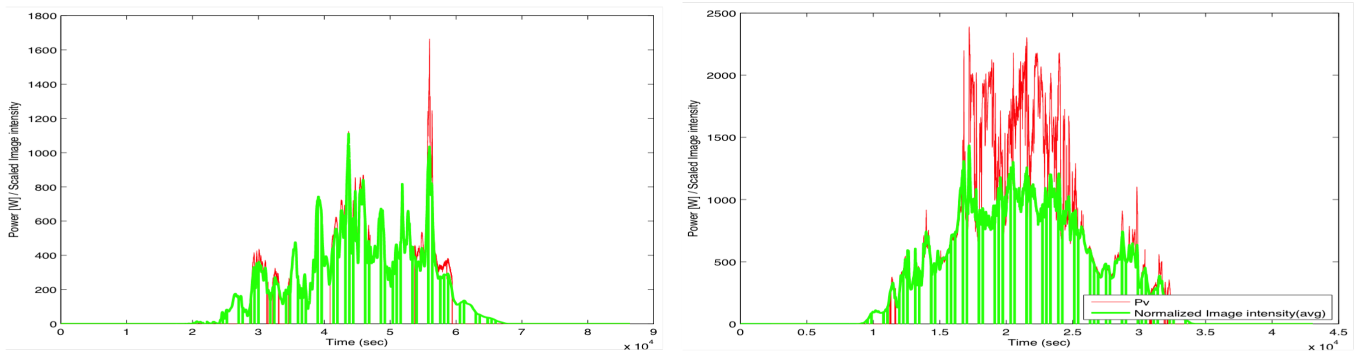


Figure: Optical flow

4.2 Simple matching of PV generation and image data



(a) Cloudy day (b) Sunny day

Figure: PV generation (red) vs average image intensity (green).

4.3 PV estimation

- *Spectral response & light incidence angle*

$$PV_{sp} = \sum_{c \in \mathbb{C}} \alpha_c \sum_{(u,v)} I_c(u, v) w(u, v), \text{ with } w(u, v) = w_a(u, v) w_b(u, v), \text{ where ,} \tag{2}$$

$w_b(u, v)$: weight of the spherical sector sampled by pixel (u, v); light angle of incidence in the pixel).
$w_a(u, v) = \cos\theta$: weight associated the angle of incidence in the PV cell, with $\tan(\theta) = \rho/f(\rho)$.

- *Saturation*

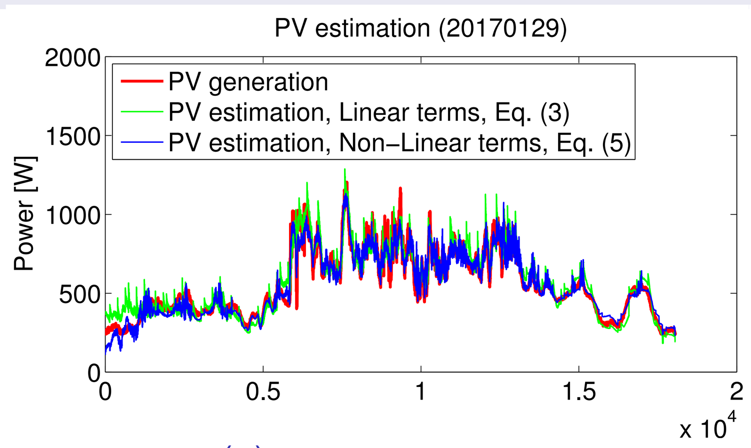
Let us call $\mathbb{S}_c = \{(u, v) | I(u, v) = I_{max}\}$ the set of saturated pixels,
$\tilde{I}_c(u, v)$ the pixel intensity if there was no saturation, and I_{max} the saturation value, then:

$$PV_s = PV_{sp} + \sum_{c \in \mathbb{C}} \alpha_c \sum_{(u,v) \in \mathbb{S}_c} (\tilde{I}_c(u, v) - I_{max}) w(u, v), \tag{3}$$

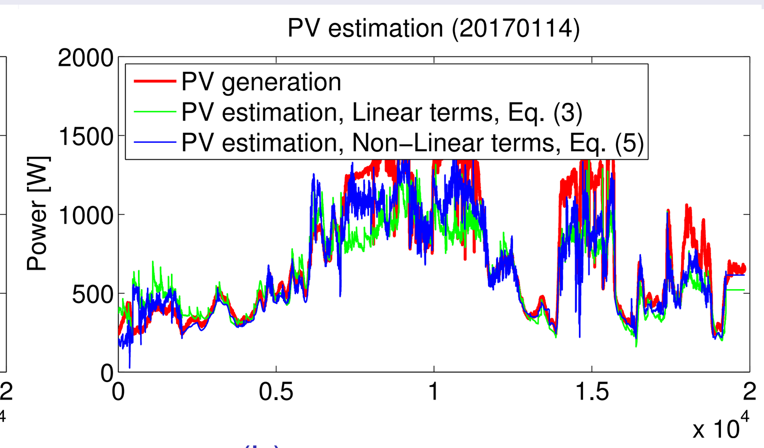
- Linear and non-linear regression of:

$$\hat{y} = F\Big(\sum_{(u,v) \in \mathbb{N}_c} I_c(u, v) w(u, v), \sum_{(u,v) \in \mathbb{S}_c} w(u, v), |\mathbb{S}_c| \Big). \tag{4}$$

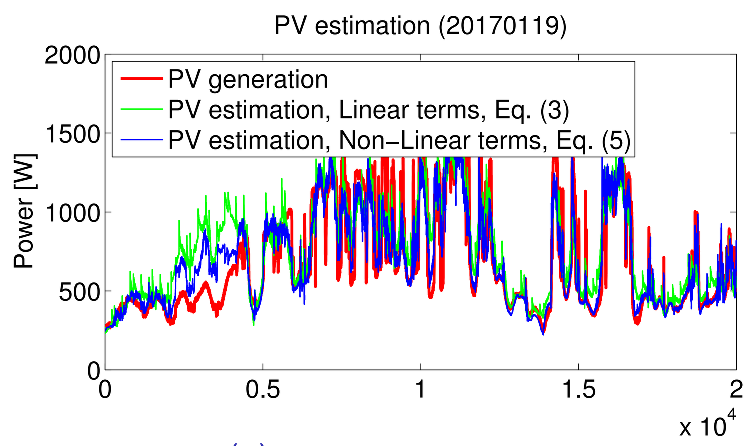
5. Results



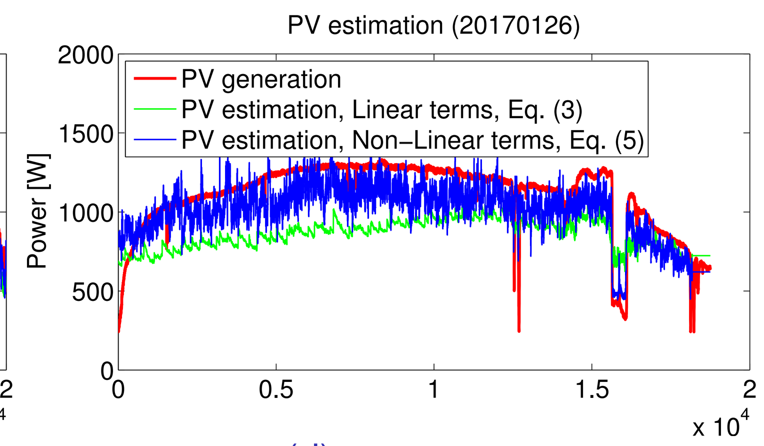
(a) Mostly cloudy day



(b) Partly cloudy day



(c) Partly cloudy day



(d) Sunny day

Figure: PV estimation using linear regression.

5. Results

Table: PV estimation evaluation.

	RAE E_1 [%]		RMSE E_2 [%]	
Data (Figure)	**Linear**	**Non-Linear**	**Linear**	**Non-Linear**
Cloudy (7a)	11.85	7.78	13.71	9.68
Partly cloudy (7b)	20.11	14.14	30.97	22.58
Partly cloudy (7c)	24.67	14.34	28.64	20.11
Sunny (7d)	25.63	13.36	26.59	14.37
Complete test set	25.52	18.27	32.9	24.16

- Relative absolute error rate (RAE):

$$E_1 = 100 \frac{1}{T} \sum_t |y(t) - \hat{y}(t)| / y(t).$$

- Root mean squared error rate (RMSE):

$$E_2 = 100 \sqrt{\frac{1}{T} \sum_t (y(t) - \hat{y}(t))^2} / \bar{y},$$

$y(t)$: PV ground truth. $\hat{y}(t)$: PV prediction.

6. Future directions

- Layered cloud movement analysis,
- Cloud transparency estimation, prediction of sun occlusion, and
- Sky image intensity model that takes into account Mie scattering and Rayleigh scattering.

Acknowledgments

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