Sub-minute PV generation prediction from sky image sequences

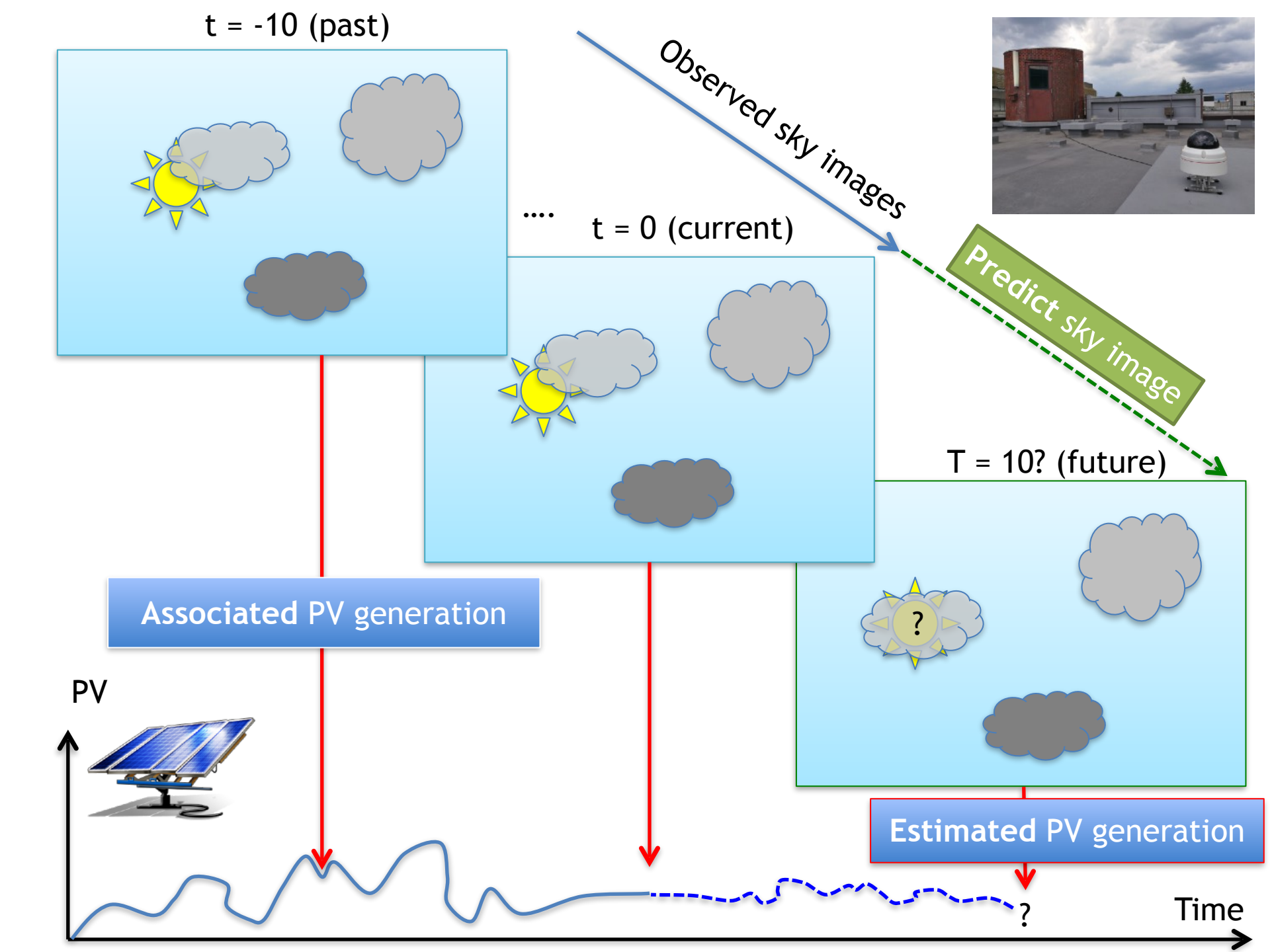
Rodrigo Verschae
Institute of Engineering Sciences
O'Higgins University

[IEEE PVSC-44, Washington DC, 2017]
[MIRU, Hiroshima, 2017]

Motivation

- Need of PV Prediction for Energy Management:
  - Local
  - Sub-minute
  - Accurate
  - Low-cost

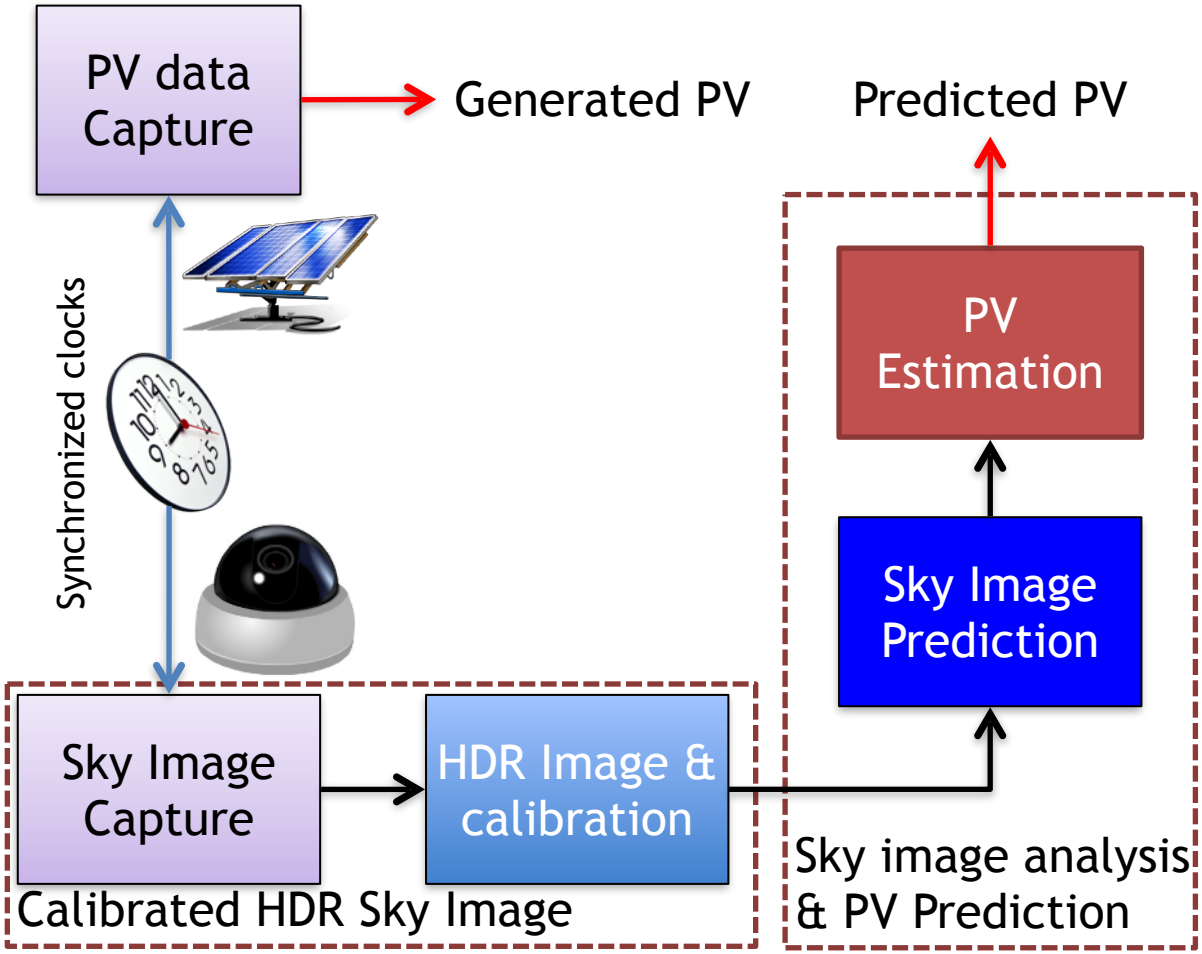
Sky Image-based prediction


t = -10 (past)
....
t = 0 (current)
Observed sky images
Predict sky image
T = 10? (future)
?
Associated PV generation
Estimated PV generation
PV
?
Time

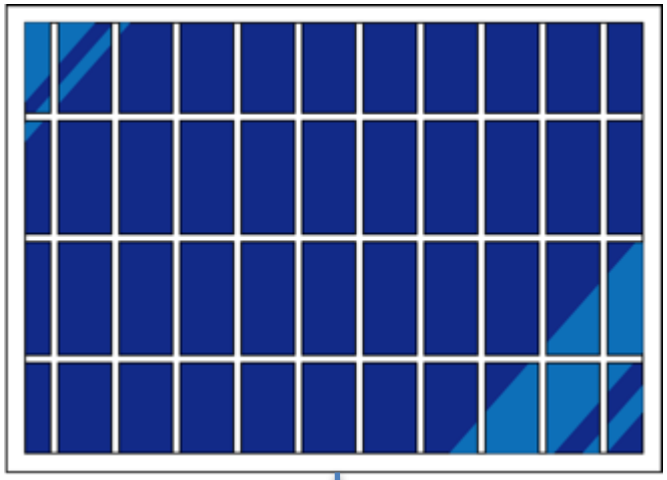
Main Challenges

- Dynamic cloud motion
- Cloud “transparency”
- Image saturation

System diagram



Solar power & sky image measurement



Outdoor observation dome housing

Fish eye lens

CMOS Camera

Power conditioner

Power generation measurement

Breaker

Small PC

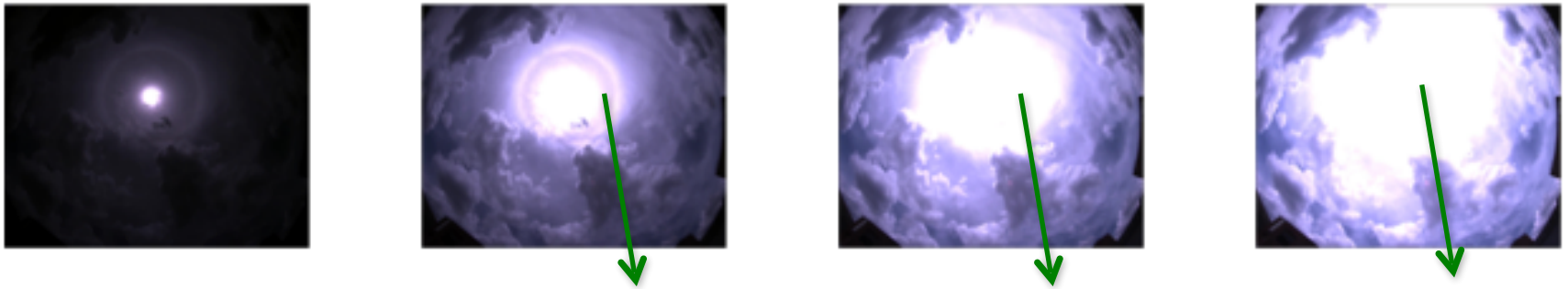
PC

Synchronization

Camera comparison (sunny day)

First system

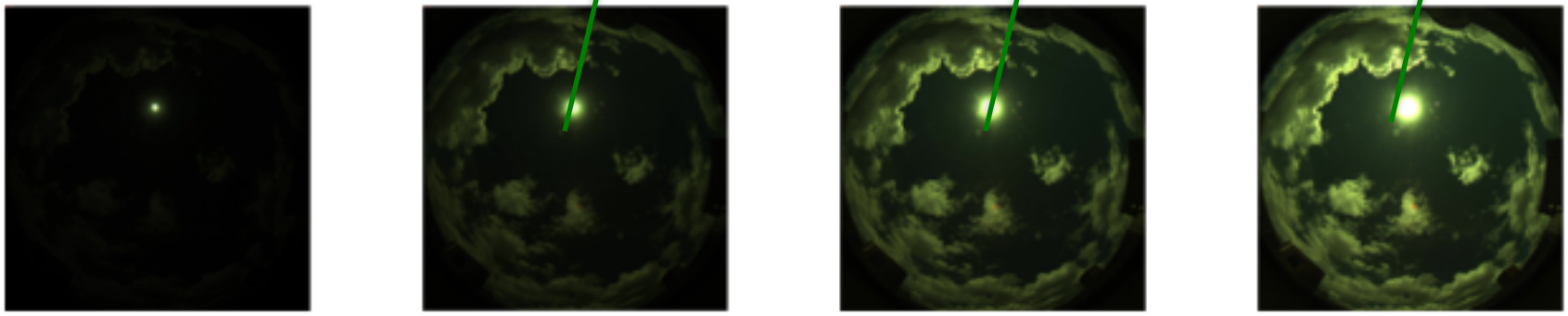
2016/07/10, 12am



Reduced saturation at non-sun pixels

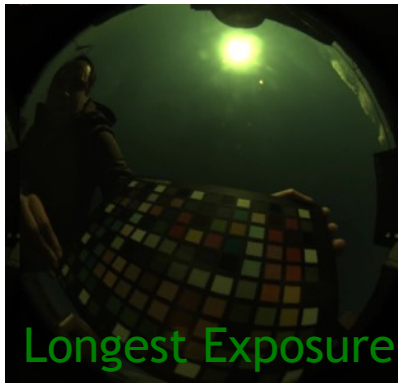
Updated system

2016/07/30, 11am



Color Calibration

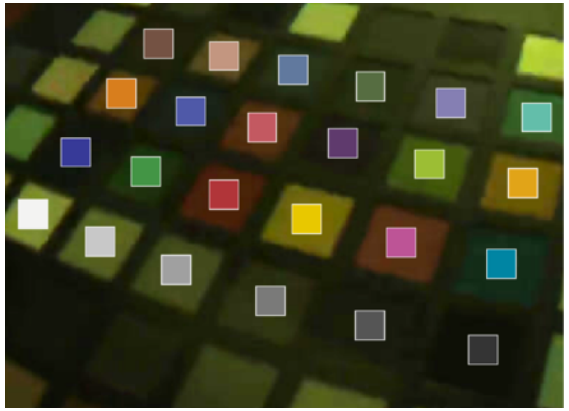
Color checker image



Calibration Target

No.	Number	sRGB R	sRGB G	sRGB B	CIE L*a*b* L*	CIE L*a*b* a*	CIE L*a*b* b*	Munsell Notation Hue Value / Chroma
1.	dark skin	115	82	68	37.986	13.555	14.059	3 YR 3.7 / 3.2
2.	light skin	194	150	130	65.711	18.13	17.81	2.2 YR 6.47 / 4.1
3.	blue sky	98	122	157	49.927	-4.88	-21.925	4.3 PB 4.95 / 5.5
4.	foliage	87	108	67	43.139	-13.095	21.905	6.7 GY 4.2 / 4.1
5.	blue flower	133	128	177	55.112	8.844	-25.399	9.7 PB 5.47 / 6.7
6.	bluish green	103	189	170	70.719	-33.397	-0.199	2.5 BG 7 / 6
7.	orange	214	126	44	62.661	36.067	57.096	5 YR 6 / 11
8.	purplish blue	80	91	166	40.02	10.41	-45.964	7.5 PB 4 / 10.7
9.	moderate red	193	90	99	51.124	48.239	16.248	2.5 R 5 / 10
10.	purple	94	60	108	30.325	22.976	-21.587	5 P 3 / 7
11.	yellow green	157	188	64	72.532	-23.709	57.255	5 GY 7.1 / 9.1
12.	orange yellow	224	163	46	71.941	19.363	67.857	10 YR 7 / 10.5
13.	blue	56	61	150	28.778	14.179	-50.297	7.5 PB 2.9 / 12.7
14.	green	70	148	73	55.261	-38.342	31.37	0.25 G 5.4 / 8.65
15.	red	175	54	60	42.101	53.378	28.19	5 R 4 / 12
16.	yellow	231	199	31	81.733	4.039	79.819	5 Y 8 / 11.1
17.	magenta	187	86	149	51.935	49.986	-14.574	2.5 RP 5 / 12
18.	cyan	8	133	161	51.038	-28.631	-28.638	5 B 5 / 8
19.	white (.05*)	243	243	242	96.539	-0.425	1.186	N 9.5 /
20.	neutral 8 (.23*)	200	200	200	81.257	-0.638	-0.335	N 8 /
21.	neutral 6.5 (.44*)	160	160	160	66.766	-0.734	-0.504	N 6.5 /
22.	neutral 5 (.70*)	122	122	121	50.867	-0.153	-0.27	N 5 /
23.	neutral 3.5 (1.05*)	85	85	85	35.656	-0.421	-1.231	N 3.5 /
24.	black (1.50*)	52	52	52	20.461	-0.079	-0.973	N 2 /

Annotation & expected output

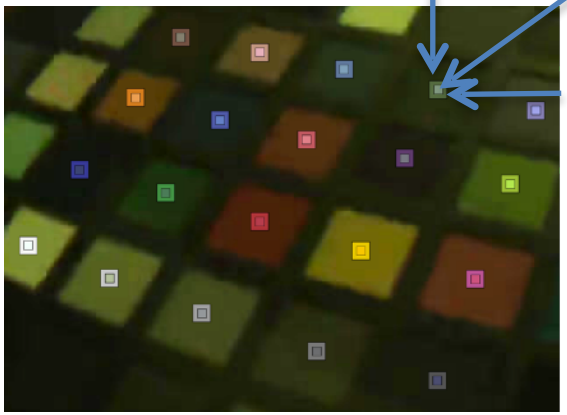


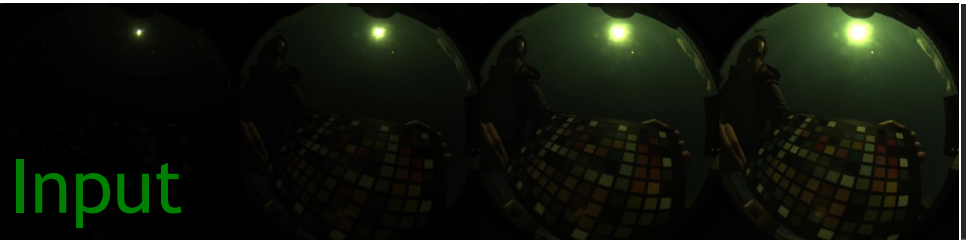
Linear Model

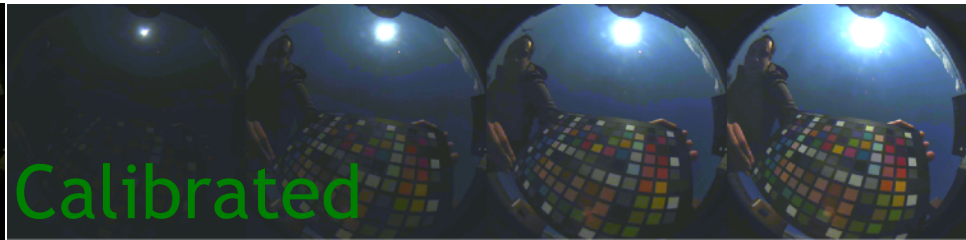
$$y_c = A_c x + b_c$$

$$c \in \{r, g, b\}$$

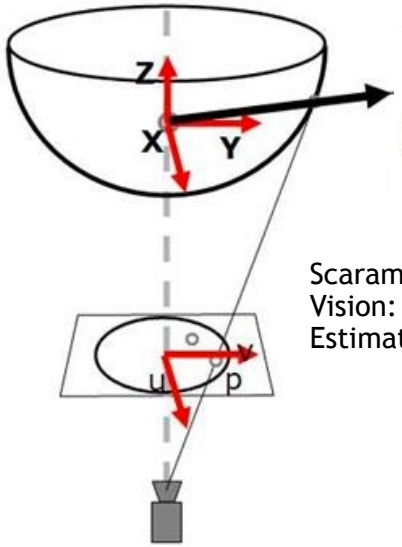
Calibration results







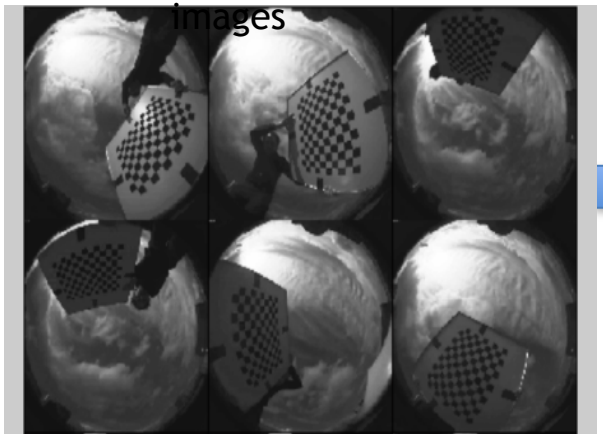
Camera model



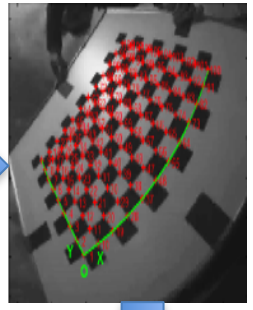
$$\mathbf{p} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} u \\ v \\ f(u,v) \end{bmatrix} = \begin{bmatrix} u \\ v \\ f(\rho) \end{bmatrix}$$

Scaramuzza, D. (2008). Omnidirectional Vision: from Calibration to Robot Motion Estimation

Check board images

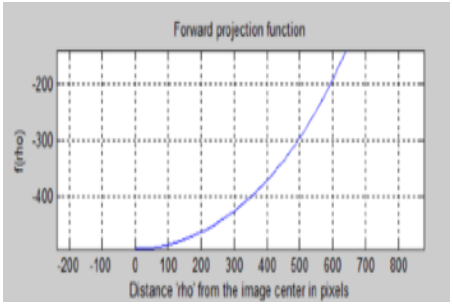


Extracted Corners

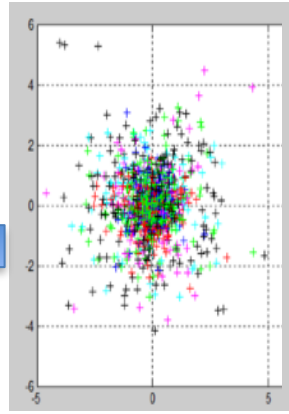


Polynomial model

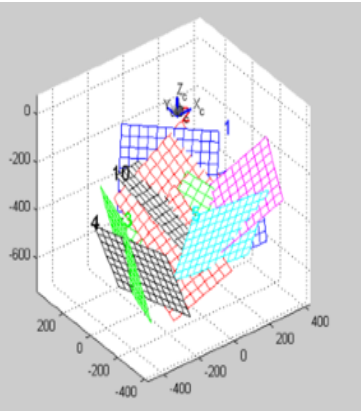
$$f(\rho) = a_0 + a_1\rho + a_2\rho^2 + a_3\rho^3 + a_4\rho^4 + \dots$$

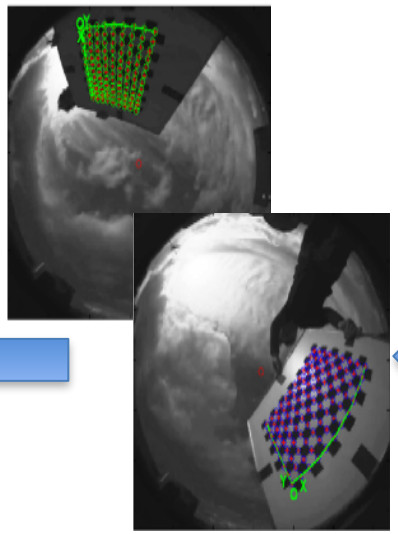


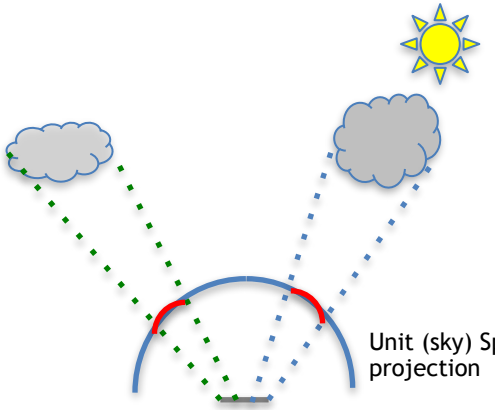
Error



Extrinsic Parameters





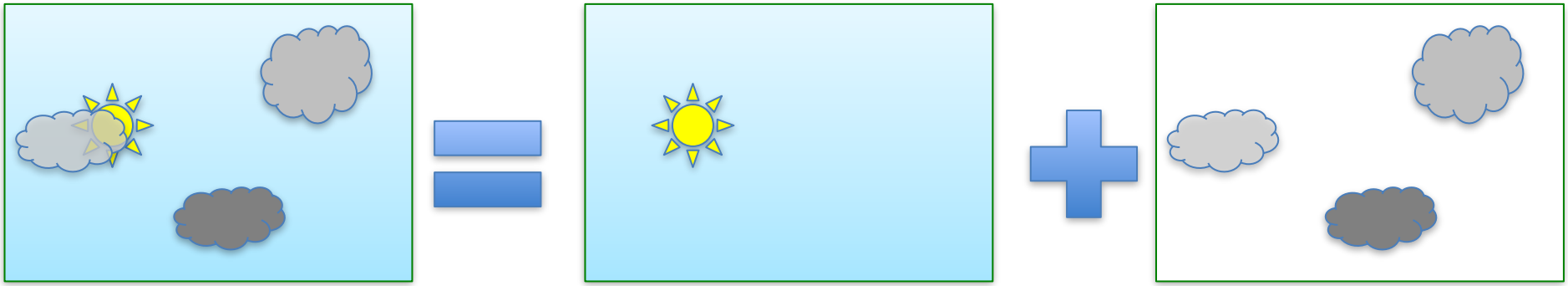


SKY MODEL

Sky Model

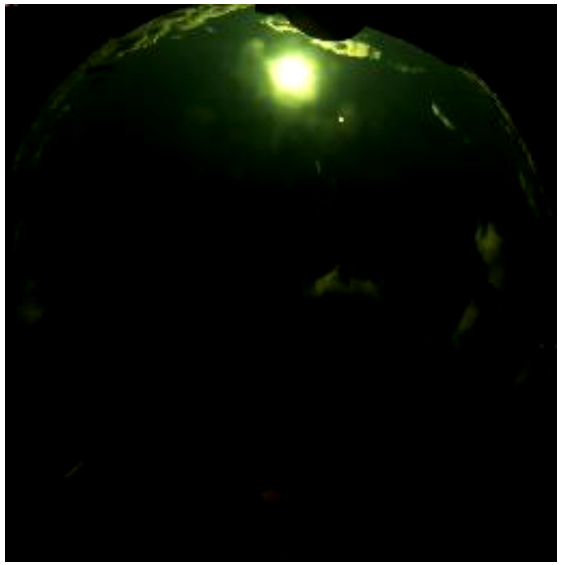
Sky + sun

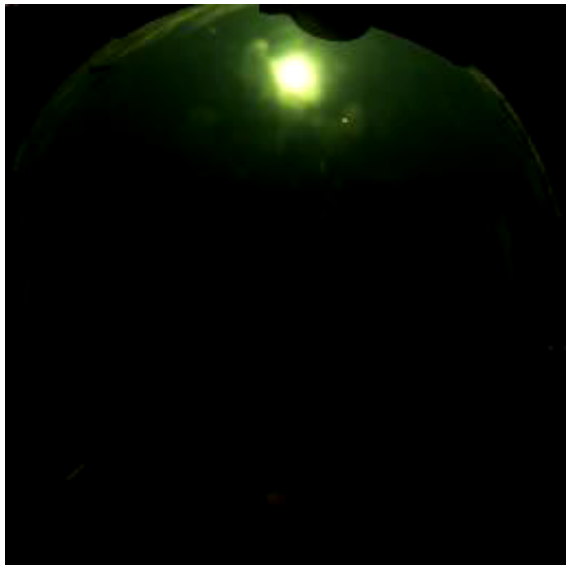
Cloud

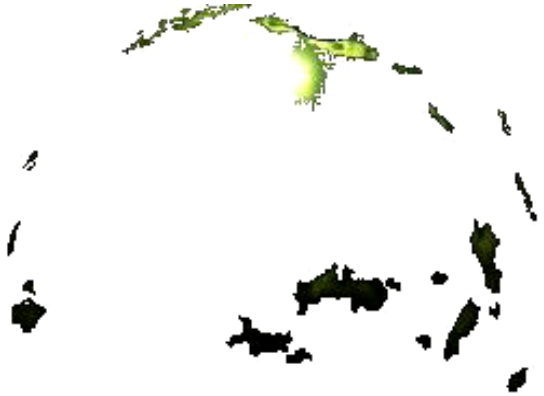


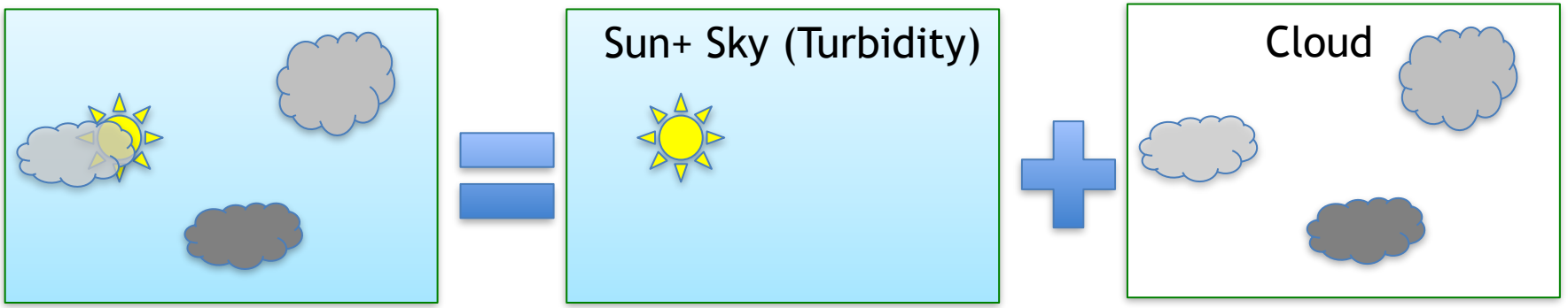
Robust PCA for movement decomposition

Input **Background (sun+sky)** **Foreground (cloud)**









Sky model (Preetham model)

(Needs color corrected image)

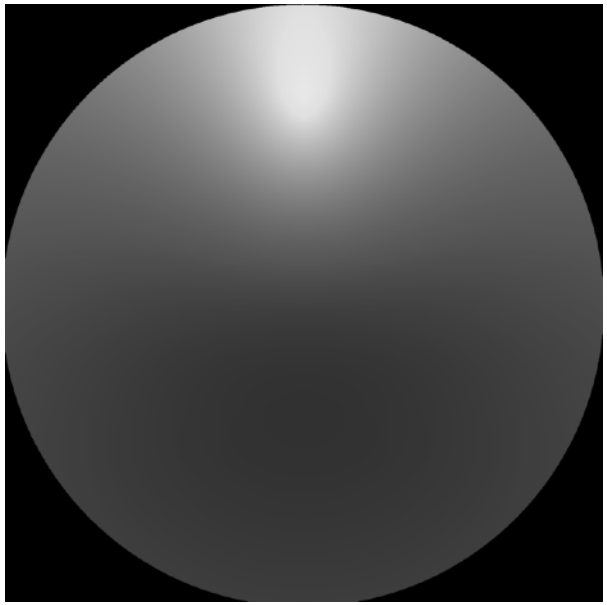
$$f_{sky}(\theta,\gamma,t) = (1 + t_1 e^{t_2/\cos\theta})(1 + t_3 e^{t_4\gamma} + t_5 \cos^2\gamma)$$

θ: zenit angle

γ: angular different with sun

t: turdidity

$$\begin{bmatrix} t_1 & t_2 & t_3 & t_4 & t_5 \end{bmatrix} = f(t)$$



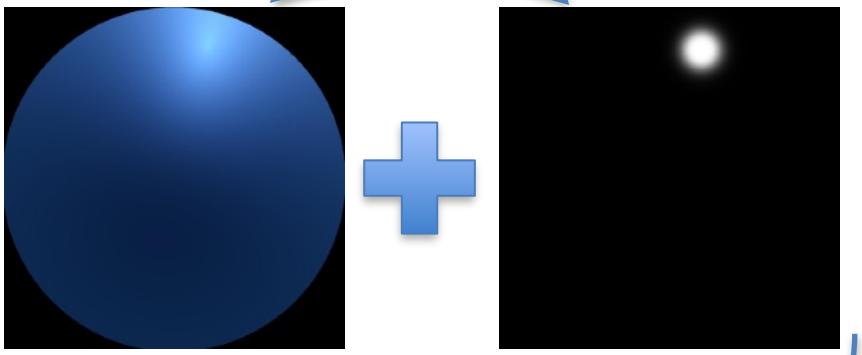
Input (saturated)

Clouds (foreground)

Sky + Sun (background)

Sky

Sun



Sky + Sun (unsaturated)

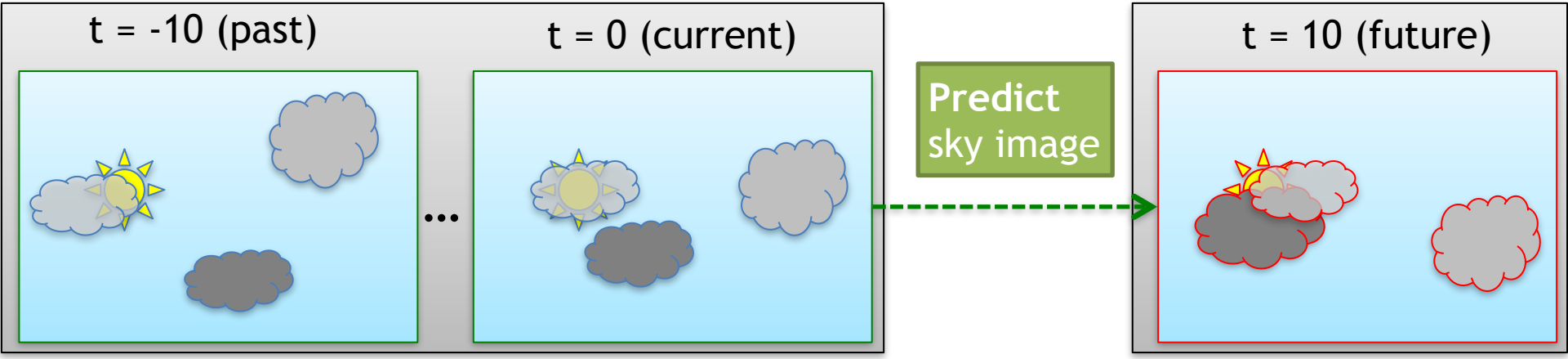
Sky model decomposition

2016/12/10, 10:30

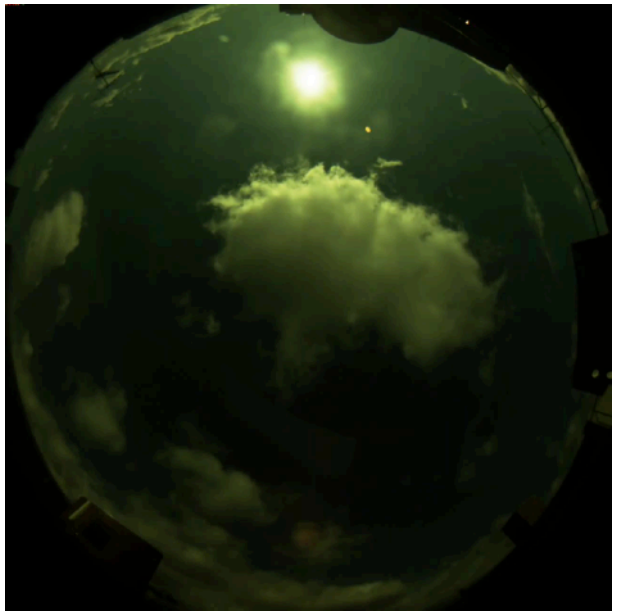
SKY IMAGE PREDICTION

Sky Image Prediction

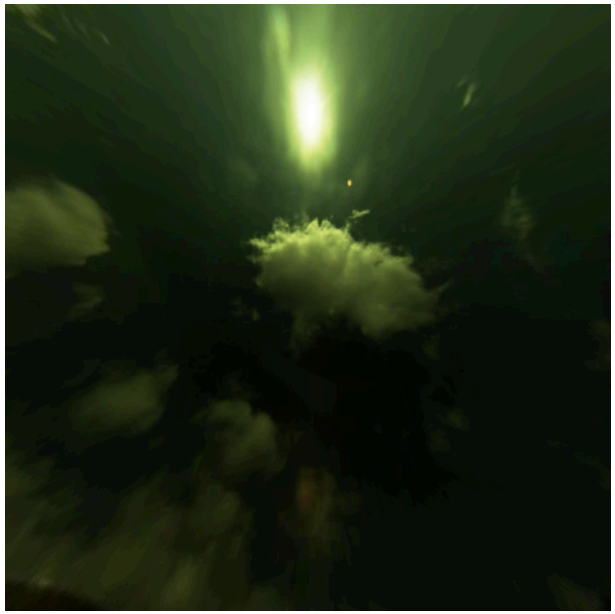
- From observed sky image sequence



Original video (1280 x 1280)

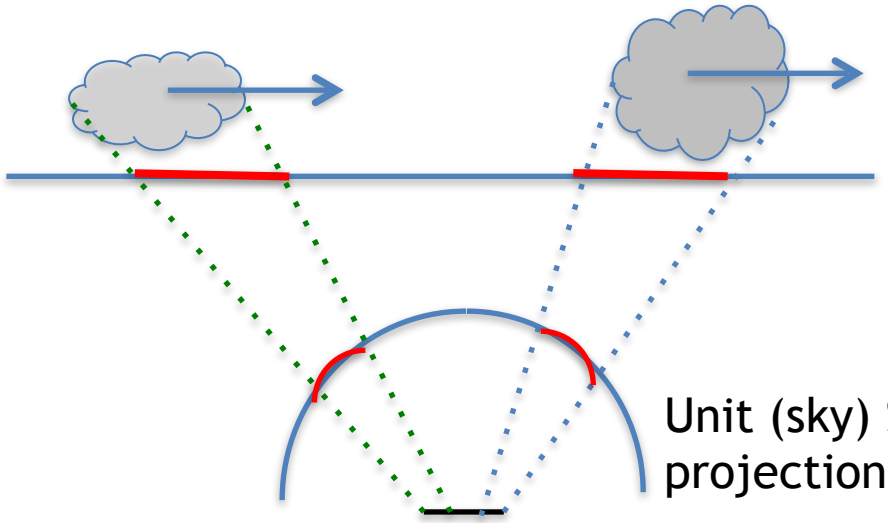


Projected video (2560 x 2560)



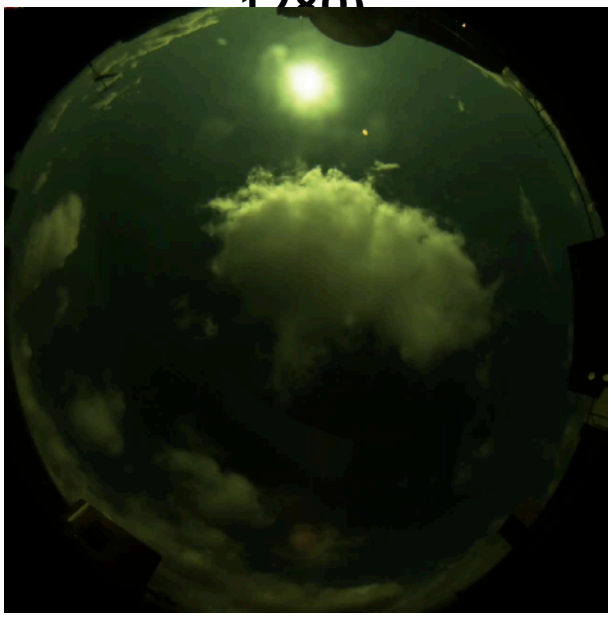
No sun movement
(short time)

Sky Plane Projection & cloud movement



Sky Plane Projection

Original video (1280 x 1280)

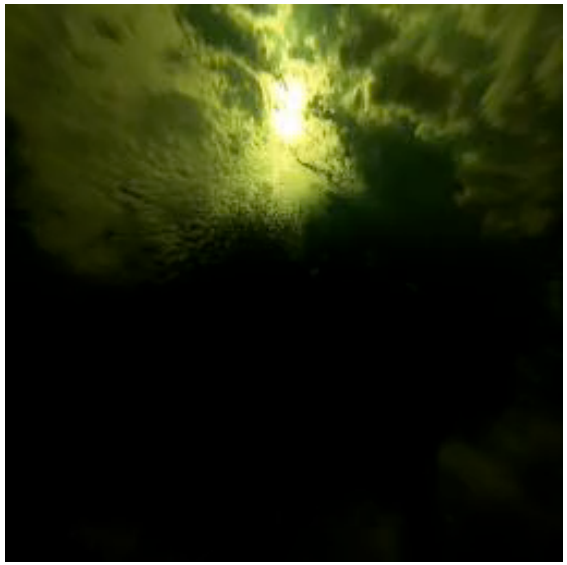


Projected video (2560 x 2560)

Cloud movement is linear

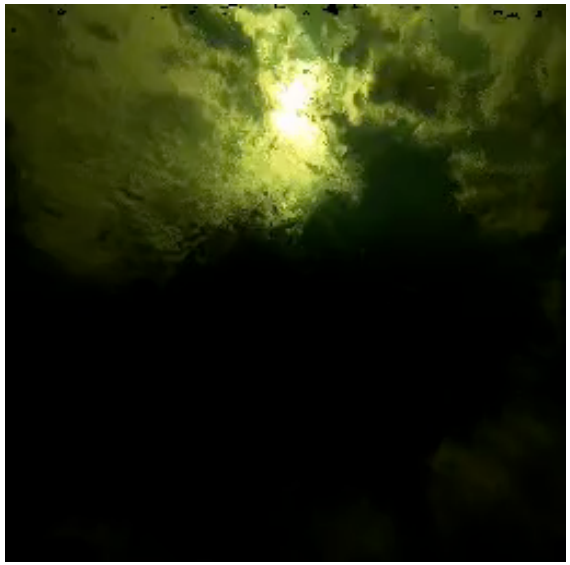
Robust PCA movement decomposition + prediction in Sky plane projection (10 sec)

Ground truth



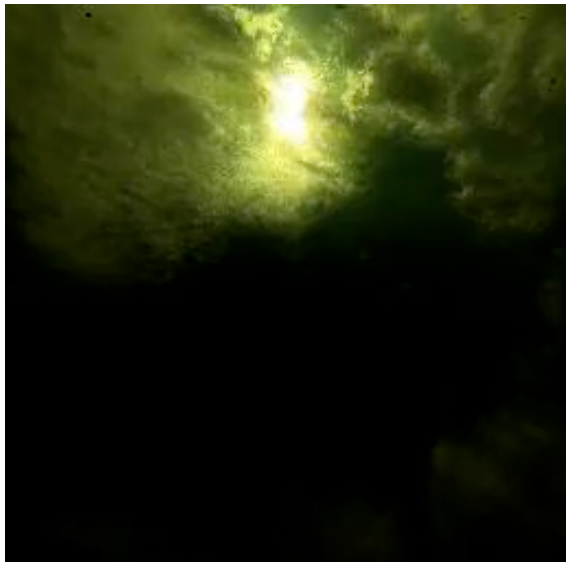
Directly Predicted

Average error: , SSIM



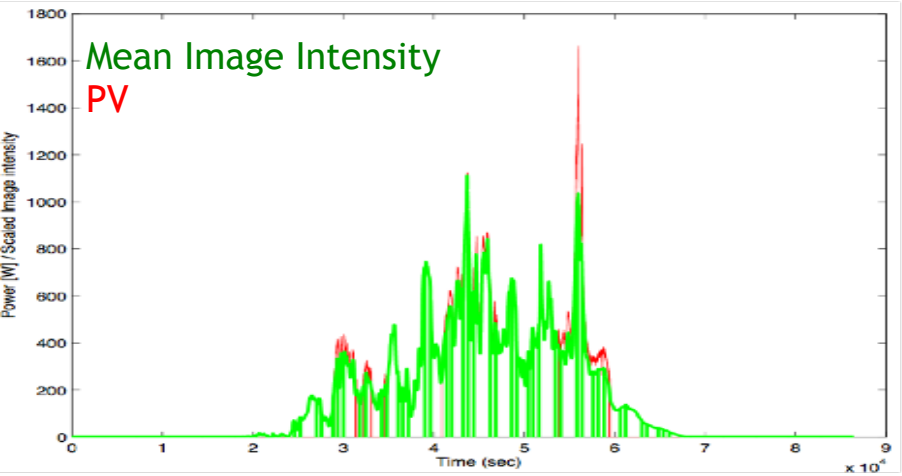
Prediction with Sky+Cloud decomposition

Average error: , SSIM

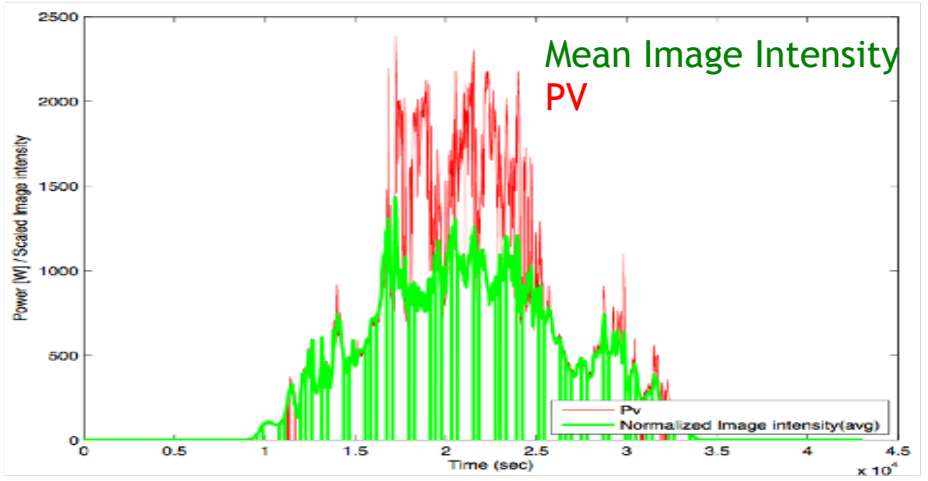


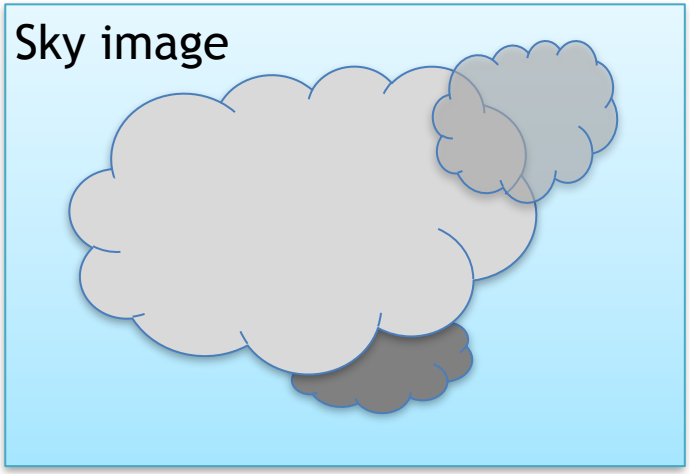
PV ESTIMATION FROM SKY IMAGE

Cloudy, 2016/07/12

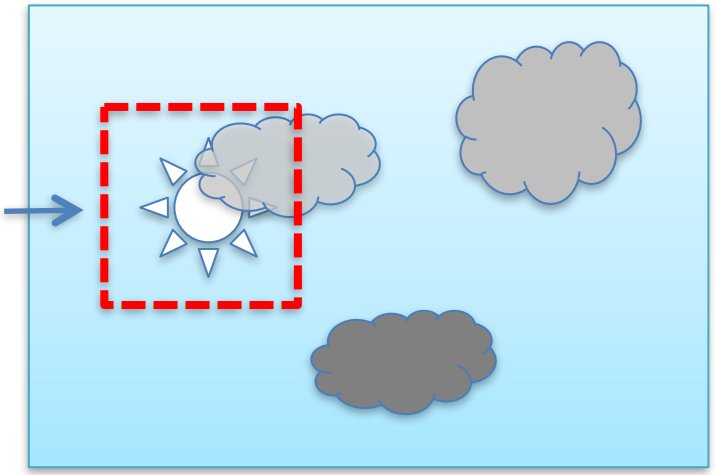


Sunny,2016/07/10



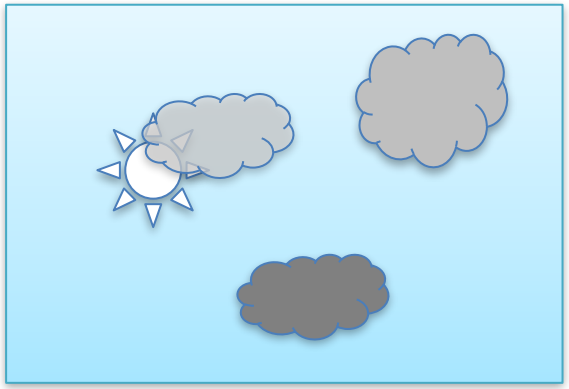


Sun pixels saturate the camera sensor

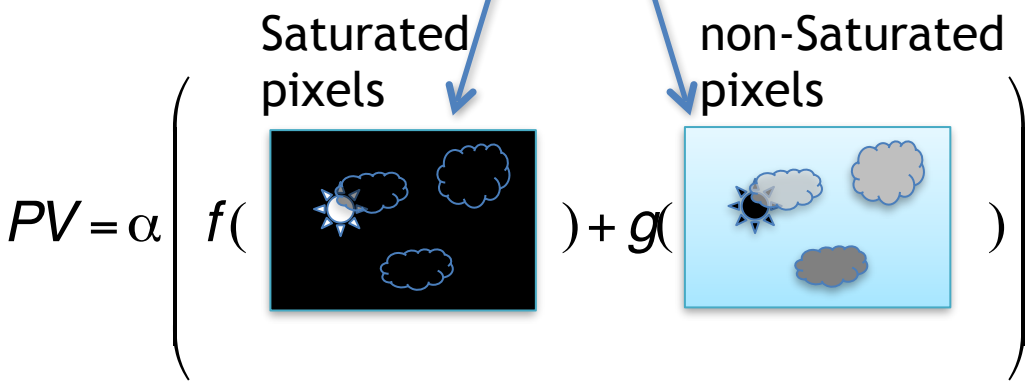


Estimation Approach

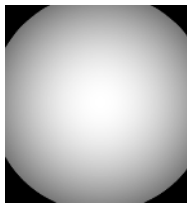
- SKY image



- PV Estimation



PV estimation



Weight of pixel (u,v)

$$w(u,v) = w_a(u,v)w_b(u,v)$$

Linear model

$$PV_{\text{sp}} = \sum_{c \in \mathbb{C}} \alpha_c \sum_{(u,v)} I_c(u,v)w(u,v)$$

Color Channel weight

Pixel intensity

Depends on PV cell angle

Depends on lens model (constant in our case)

$$w_a(u,v) = \cos\theta$$

with $\tan(\theta) = \rho / f(\rho)$

But, pixel saturation?

$$\mathbb{S}_c = \{(u,v) | I(u,v) = I_{\max}\}$$ Set of saturated pixels

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

Unknown saturated values

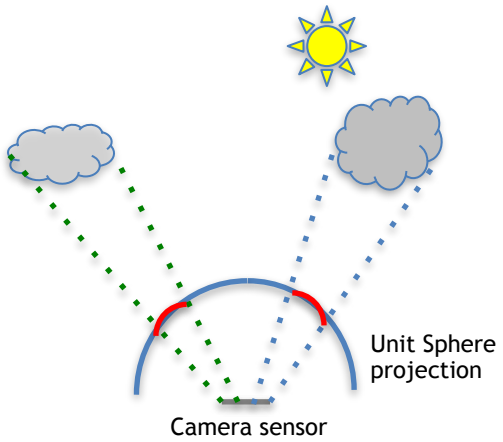
Non-Linear model

Weight of saturated values

$$\hat{y} = F\left(\sum_{(u,v) \in \mathbb{N}_c} I_c(u,v)w(u,v), \sum_{(u,v) \in \mathbb{S}_c} w(u,v), |\mathbb{S}_c| \right)$$

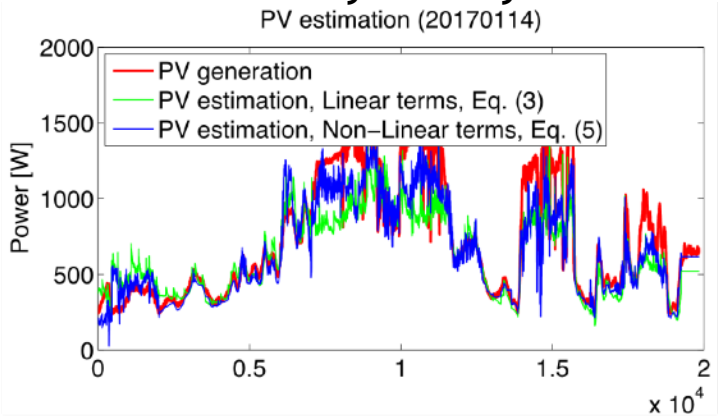
PV_{sp}

Number of saturated values

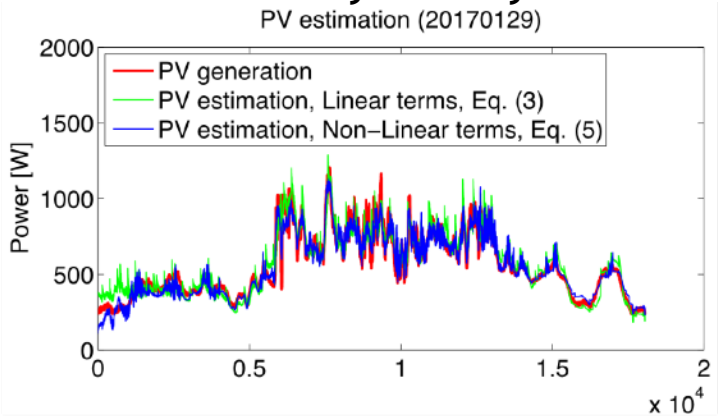


PV Estimation results (large data set)

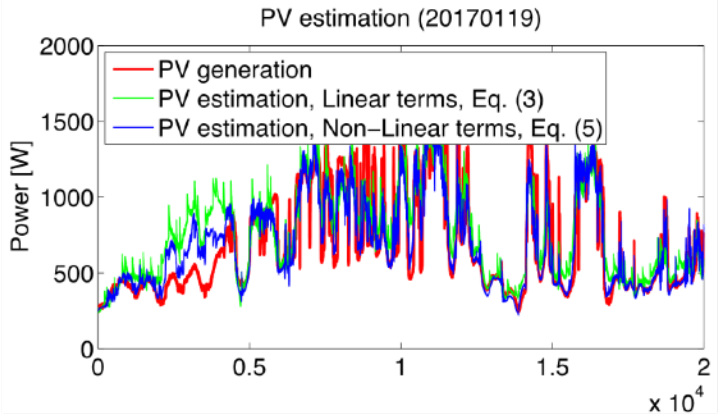
Mostly cloudy



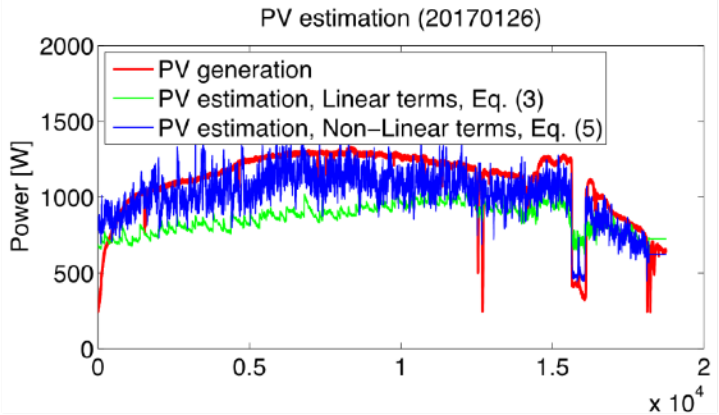
Partly Cloudy



Partly Sunny



Mostly Sunny



(Model learnt using ~70 days)

	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

Summary

- Capturing system:
  - Camera, lens, software, PC
  - Lens model calibration & Color calibration
- Approach: Sky image prediction + PV Estimation
  - Movement analysis:
    - Interpolation, Sky plane projection, Prediction,
    - Sky / Sun / Cloud decomposition
  - Model based PV estimation
    - Taking into account saturated pixels & lens model