Validation of F-matrix and six-phase method

Radiance Workshop, August 29-31, 2016

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Contents **Work in progress…**

Strategic Goals

Overall objectives

Support development of technological solutions that can help us meet aggressive carbon emission goals

Encourage market adoption to achieve significant widespread impacts within 2020-2030 timeframe

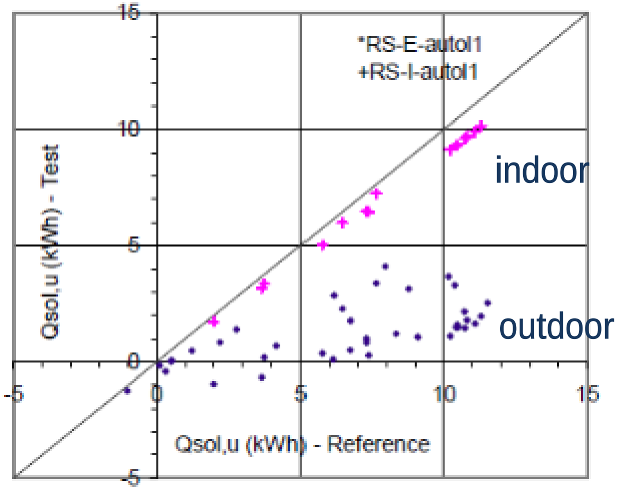
One approach

Shading/ daylighting window "attachments" can be applied at a relatively low cost for the retrofit construction market →
tools development for optically complex systems

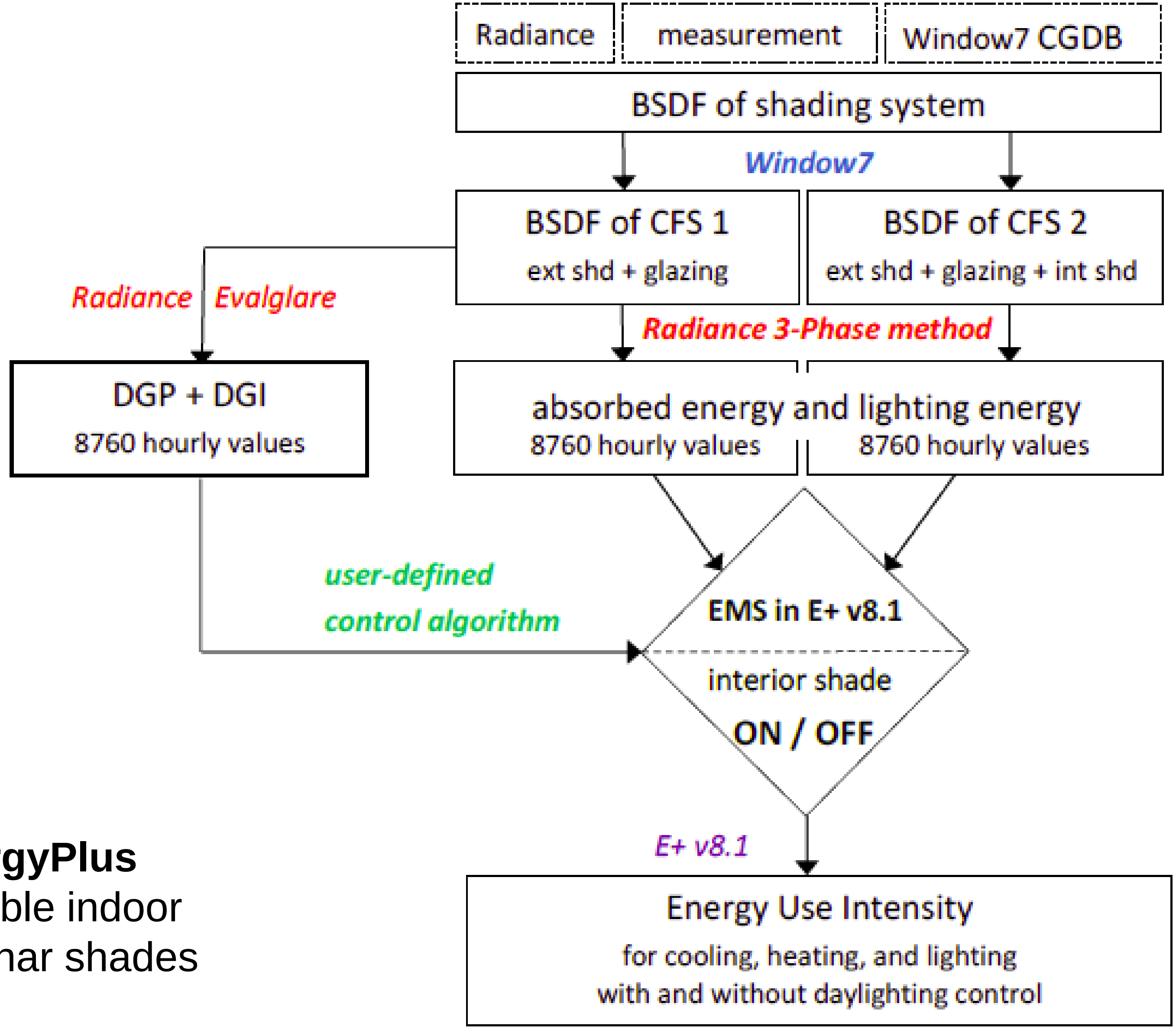
Mitigate climate change

Motivation

Between 6 types of exterior shades:
78-94% reduction in window heat gains
-25% to 36% reduction in lighting energy use
2-32% of day with glare compared to low-e glazing with indoor shade



E.S. Lee et al., High Performance Building Façade Solutions, Final project report, California Energy Commission, CEC 500-06-041 (2009), Table 6.

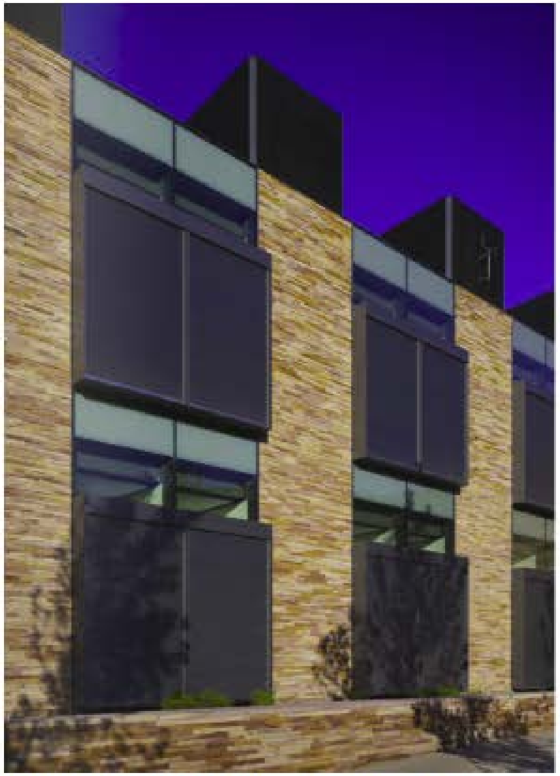


Radiance → EnergyPlus
workflow for operable indoor and outdoor coplanar shades

[ugh@!]

E.S. Lee et al., High Performance Building Façade Solutions – Phase II, Final project report, California Energy Commission, CEC 500-2015-033.

Coplanar exterior shading



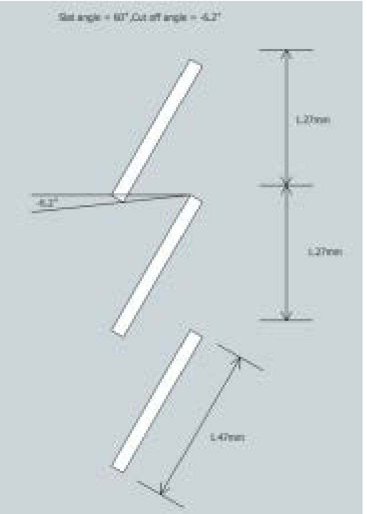
Hilton Foundation, Agoura Hills
Stainless steel roller shade (shd 6)
(picture: ZGF architects)

Li Ka Shing, UC Berkeley campus
Aluminum louvers above window
Aluminum louvers in shutters (shd 8)
(picture: ZGF architects)

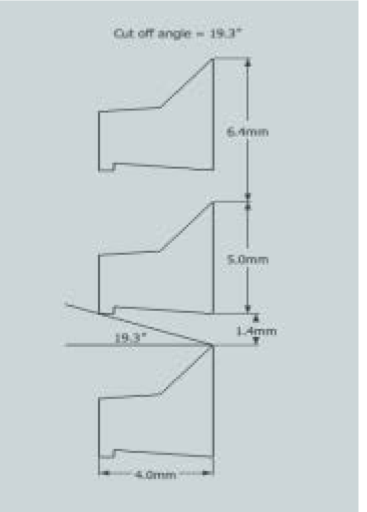
Federal Building, San Francisco
Metal mesh (similar to shd 10)
(picture: Morphosis architects)

Sabine Hoffmann et al., Energy and Buildings 112 (2016): 279-298

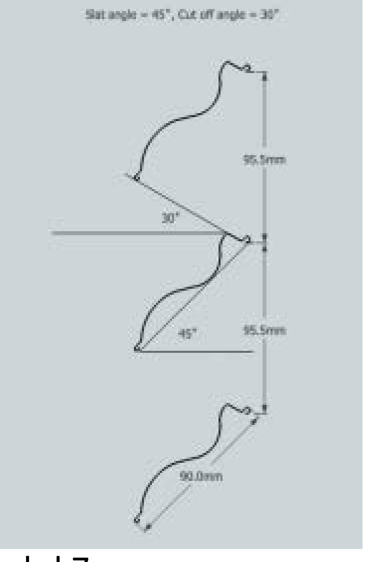
Coplanar exterior shading



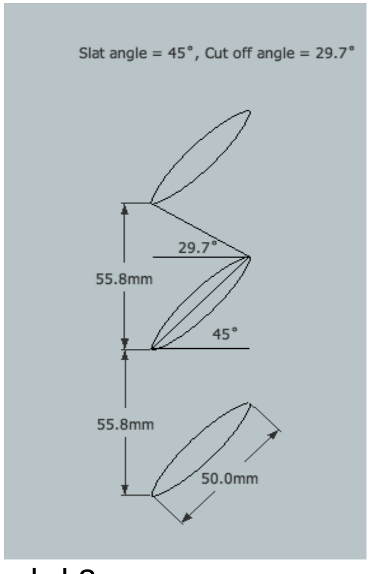
shd 5



shd 6



shd 7



shd 8

Number of hours indoor shades are lowered to control discomfort glare

Discomfort glare: DGP ≥ 0.38 or DGI ≥ 24

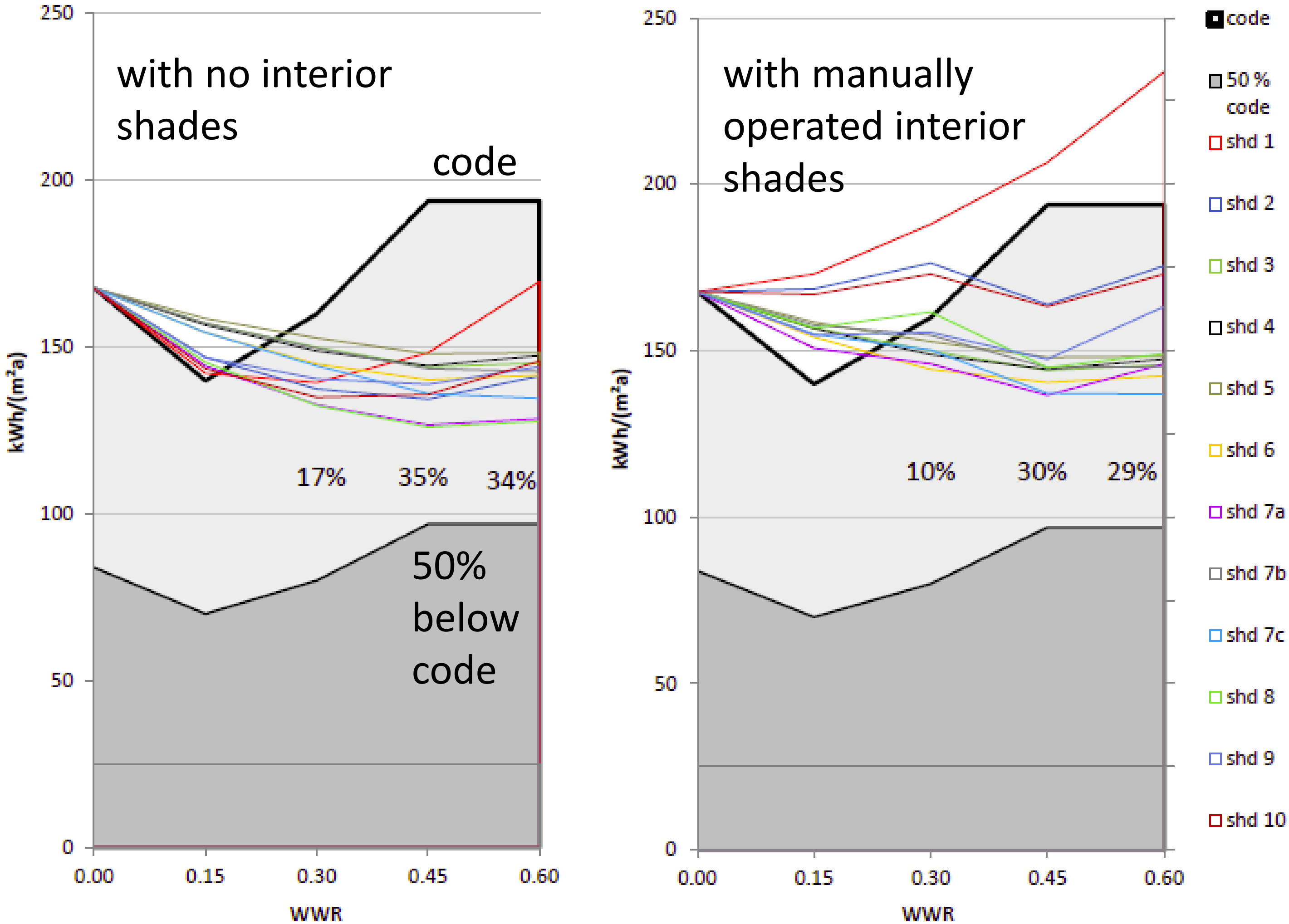
	Burbank, California			Oakland, California		
	East	South	West	East	South	West
no shade	3569	3575	3640	3338	3324	3428
shd 1	3623	3300	3648	3375	3088	3436
shd 2	1296	1385	1346	1072	1312	1264
shd 3	212	0	121	127	0	89
shd 4	0	0	0	0	0	0
shd 5	0	0	0	0	0	0
shd 6	257	0	190	177	0	170
shd 7a	862	660	970	706	597	802
shd 7b	432	14	472	349	14	378
shd 7c	469	9	409	385	21	336
shd 8[1]	1145	1089	1199	954	1021	1071
shd 9[5]	1036	922	1097	878	884	977
shd 10[5]	1387	1587	1490	1212	1547	1367

Rvis and cut-off angle of exterior shades affects number of hours

Sabine Hoffmann et al., Energy and Buildings 112 (2016): 279-298

Which in turn reduces….

annual energy use savings



Sabine Hoffmann et al., Energy and Buildings 112 (2016): 279-298

Strategic Goals revisited – why the matrices approach?

Develop technological solutions that can help us meet aggressive carbon emission goals →

- Manufacturers: need for <u>parametric</u> tools for rapid prototyping and evaluation
- Architects: similar need for exploratory design and optimization (e.g., grasshopper/ rhino + honeybee/ ladybug)

Encourage market adoption to achieve significant widespread impacts within 2020-2030 timeframe →

- Regulators: need <u>parametric</u> analysis for development of codes, standards, guidelines, rating and labeling systems that encourage informed decisionmaking by consumers

Single design? Use DC approach…

Non-coplanar exterior shading:
the final frontier…

Static systems: Parametric design for material selection, geometry

Operable, automated systems: potential to optimize solar control, daylight, & views?

Tongji University, Shanghai

Li ka Shing Center, UC Berkeley

Shading with non-Lambertian projections

(not accommodated in California Title-24 Standards or ASHRAE 90.1)

Genentech Building 35, South San Francisco. McNeil et al. 2014

http://eetd.lbl.gov/sites/all/files/lbnl-1005151_0.pdf

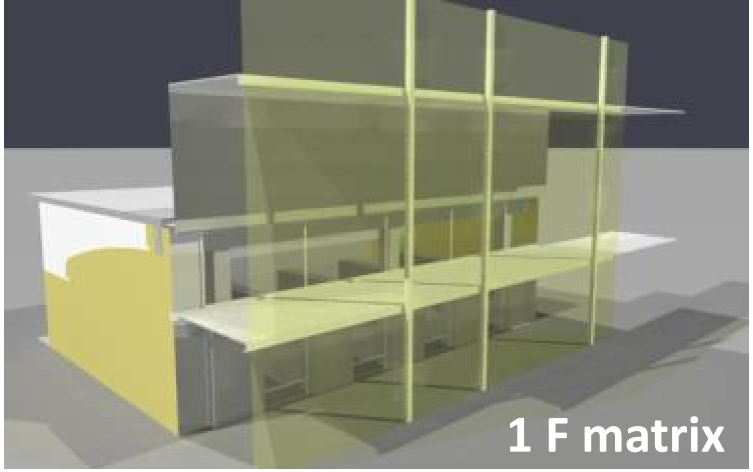
F-matrix for non-coplanar exterior shading

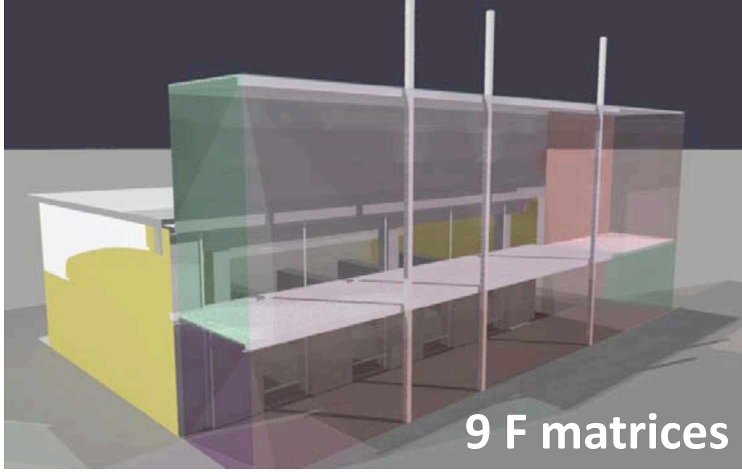
i = **VTFDs**

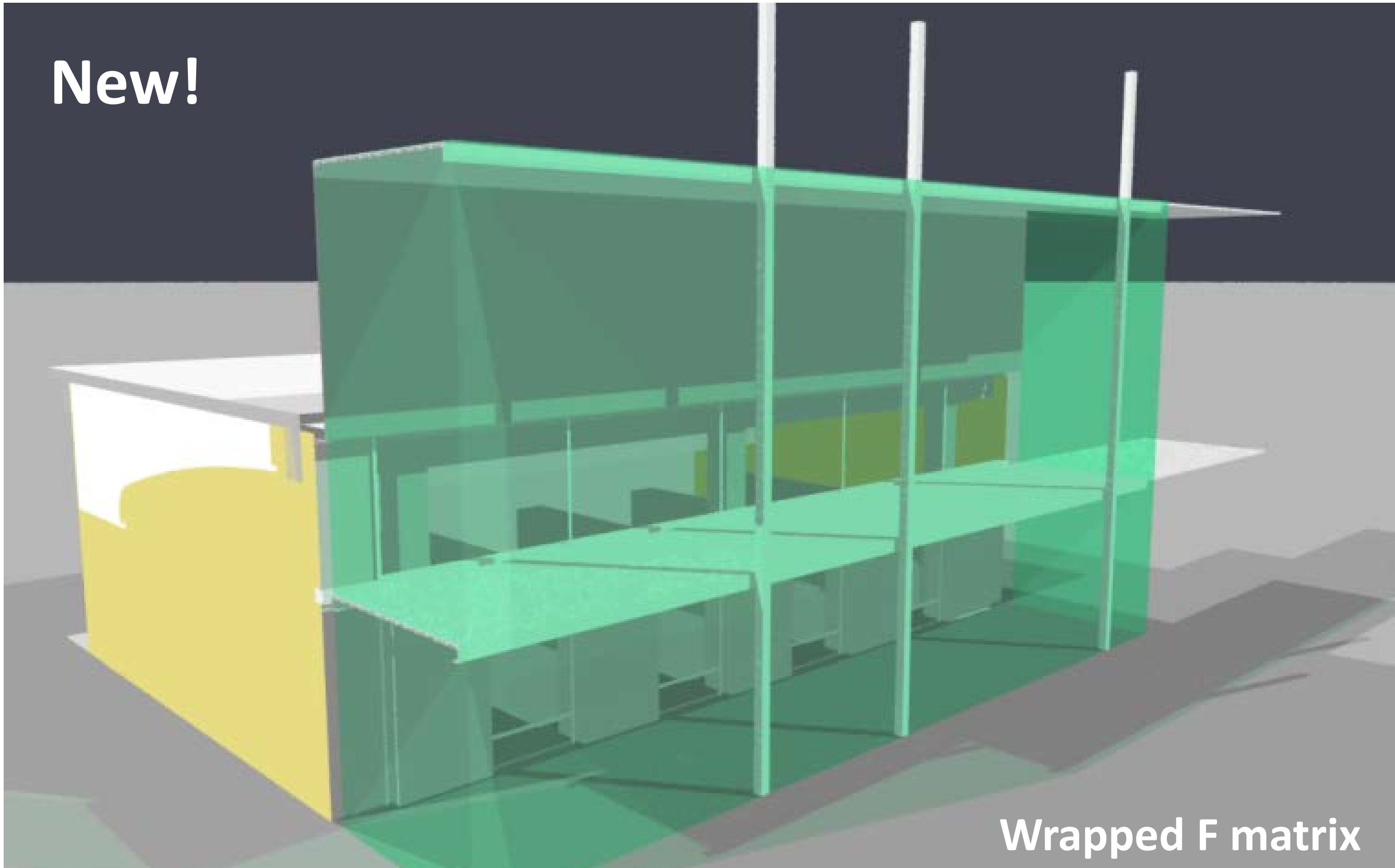
where:

i	is the desired result vector (radiances, irradiances, etc.)
V	is the "View" matrix defining the lighting connection between results and exiting directions for a window group
T	is the "Transmission" matrix defining the BTDF of the window group
F	is the “Facade” matrix defining the flux transfer of exterior shading
D	is the "Daylight" matrix defining the coefficients between incoming directions for the window group and sky patches
s	is a vector of sky patch luminances for a particular time and date

Defining the F-matrix







Greg Ward & Andy McNeil introduced F-matrices in prior Radiance workshops (2012-2013)

UC San Diego Biomedical II building example

F-1 matrix

```
# Compute D matrix from exterior aperture
rfluxmtx -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 portF1.rad \
skyglow.rad -i octs/model_3ph.oct > matrices/F1/facade.dmx
# Compute F matrix connecting clerestory glazing to exterior aperture
rfluxmtx -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 glass_clerestory.rad \
portF1.rad -i octs/model_3ph.oct > matrices/F1/clerestory.fmx
# Compute F matrix connecting vision glazing to exterior aperture
rfluxmtx -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 glass_vision.rad \
portF1.rad -i octs/model_3ph.oct > matrices/F1/vision.fmx
# Compute V matrix corresponding to illuminance points
rfluxmtx -faf -o matrices/%s.vmx -I+ -ab 7 -ad 50000 -lw 1e-7 \
- glazing.rad -i octs/model_3ph.oct < points.txt
# Followed by dctimestep or similar….
```

F wrapped matrix

Compute **D** matrix from exterior aperture (4 surfaces)
rfluxmtx -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 portF1H.rad \
skyglow.rad -i octs/model_3ph.oct > matrices/F1H/facade.dmx
Compute **F** matrix connecting clerestory glazing to exterior aperture
rfluxmtx -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 glass_clerestory.rad \
portF1H.rad -i octs/model_3ph.oct > matrices/F1H/clerestory.fmx
Compute **F** matrix connecting vision glazing to exterior aperture
rfluxmtx -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 glass_vision.rad \
portF1H.rad -i octs/model_3ph.oct > matrices/F1H/vision.fmx
Compute **V** matrix corresponding to illuminance points*
rfluxmtx -faf -o matrices/%s.vmx -I+ -ab 7 -ad 50000 -lw 1e-7 \
- glazing.rad -i octs/model_3ph.oct < points.txt
Followed by **dctimestep** or similar….

Comments

- For this example, we expect the F9-aperture calculation to be more accurate because it matches the original test condition more closely.
- In general, the F1 single aperture might be preferred if the model is a section of a larger façade.
- FH wrapped aperture is a compromise that can produce better results than a single face (F1) while still using only a single matrix.

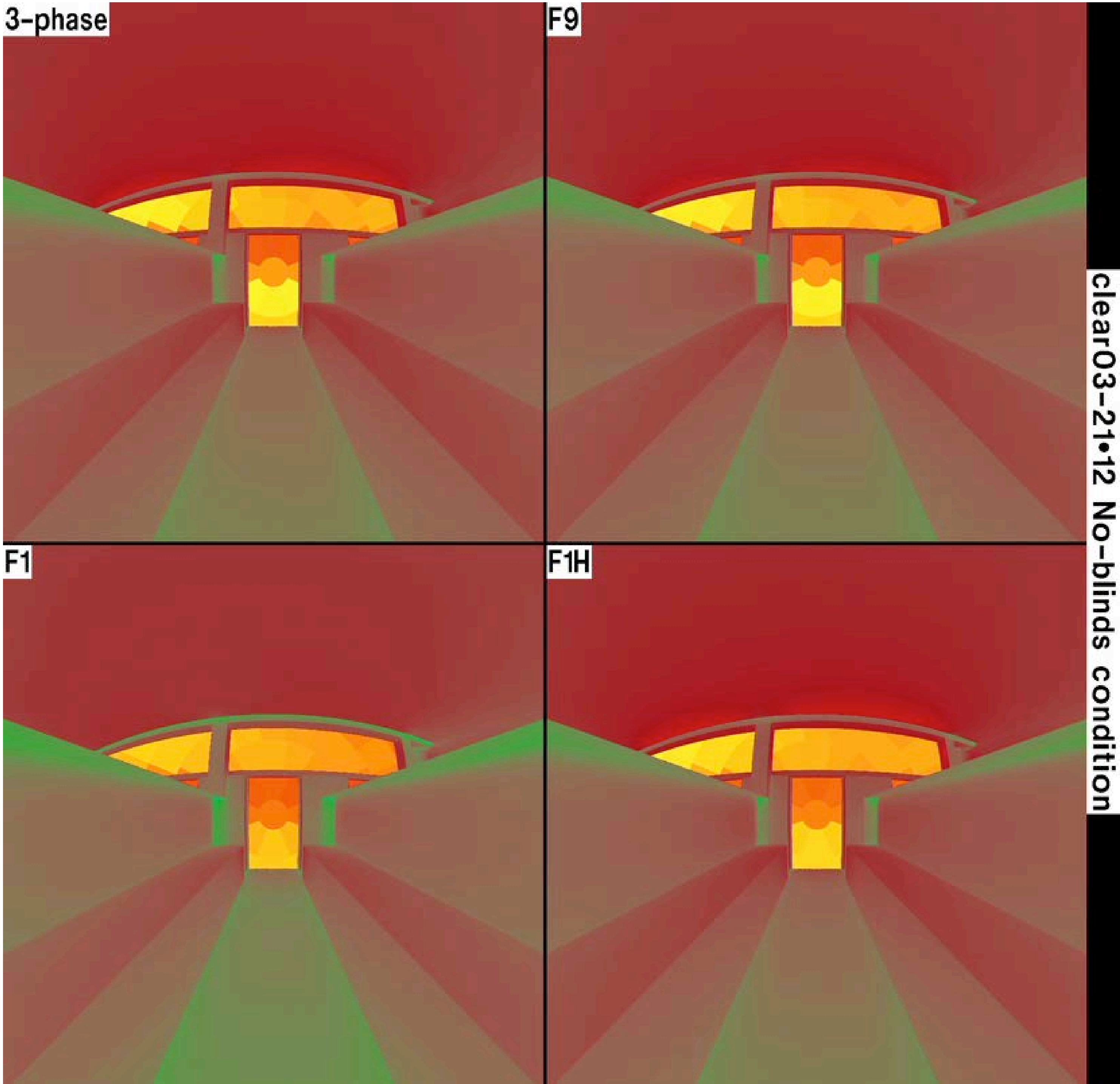
Error analysis

Compared F-matrix calculations to original 3-phase method in west-facing structure

- 576 workplane illuminance test points
- No blinds and 5 venetian blind angles
- On 21st for each of 7 months, solstice-to-solstice
- One-hour intervals over daylight period

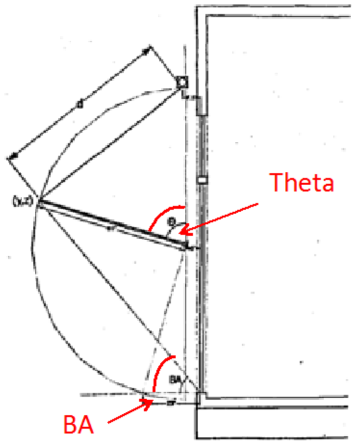
Relative Error	Avg.	Max.
Single **F** matrix	22%	33%
Wrapped **F** matrix	11%	21%
Nine **F** matrices	6%	10%

Comparison between 3PH, F1, F1H, & F9 (all with no blinds)



Field Validation

Drop-arm awning



summer test

6 7 8 9 10

Initiated field testing Summer 2016 at Position 3

6 7 8 9 10

BSDF of awning fabric

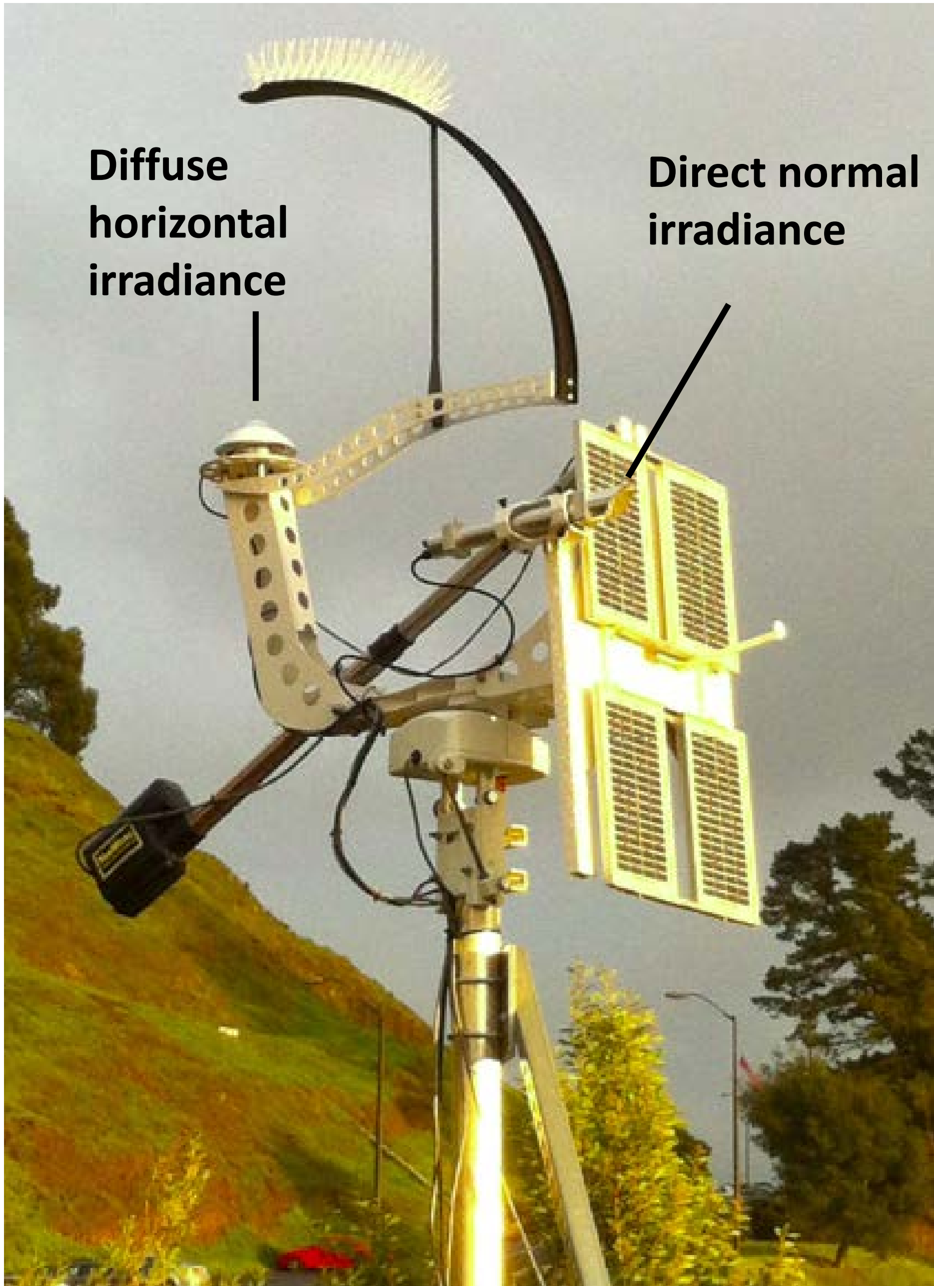
Flat weave fabric (Sunbrella 4633-0000, Linen)
Manufacturer's data:
T_v,n-n = 0.08
T_v, n-h = 0.044
ρ_v, n-h = 0.40

LBNL BSDF measured data:
Lambda 950 spectrophotometer with 150 mm integrating sphere plus
angle tube accessory for Lambda 950

Measure diffuse and direct transmittance & reflectance at nine angles of incidence

Jonsson, J., Measurement procedure for optical and thermophysical properties of fenestration shading fabrics to be used in WINDOW, July 23, 205.
N. Kotey, J. L. Wright, and M. Collins, Determining off-normal solar optical properties of drapery fabrics, ASHRAE Transactions, 115, 2009.

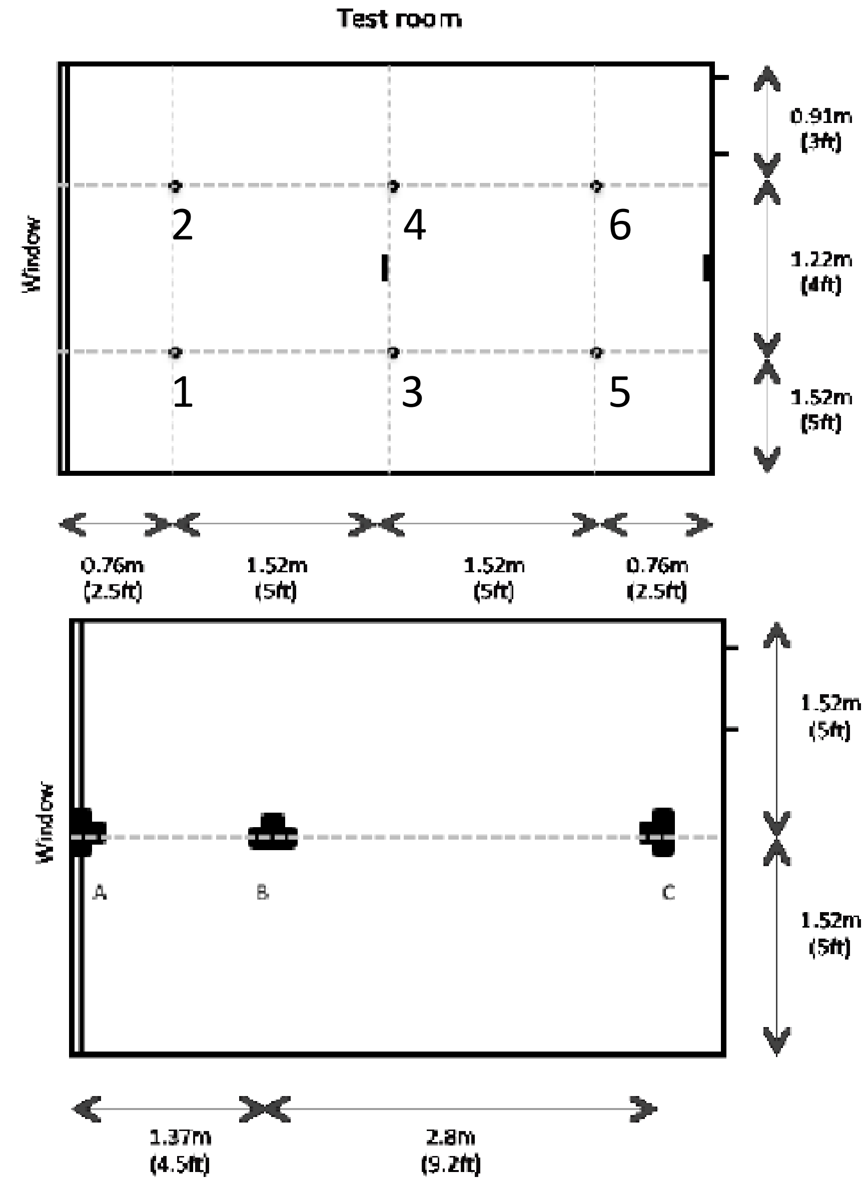
Solar instrumentation (at the Advanced Windows Testbed)




Skycam at FLEXLAB: skydome luminance distribution, global illuminance and irradiance
Plus separate sensors for direct and diffuse irradiance at FLEXLAB
terrestrial light

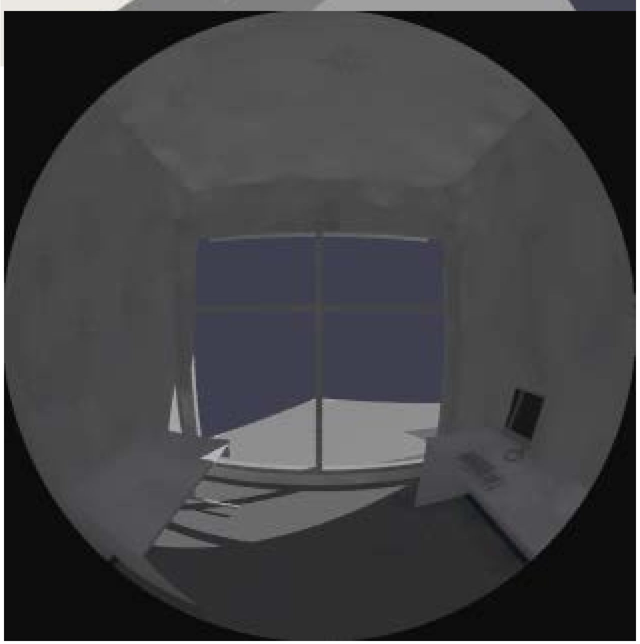

Incident vertical illuminance
1
2
3
4
5
6
7
8
9
10
11
12

Set-up: workplane illuminance and HDR imaging



Canon 5D with Sigma 8 mm f3.5 fisheye lens

MODEL PARAMETERS



	Tvis	Rvis (non specular)	Other
Wall		65%	
Ceiling		82%	
Floor		23%	
Desk		63%	
Door		55%	
Monitor	9%	36%	
Mullion		50%	
Glass	64.9%		
Awning			Primitive BSDF

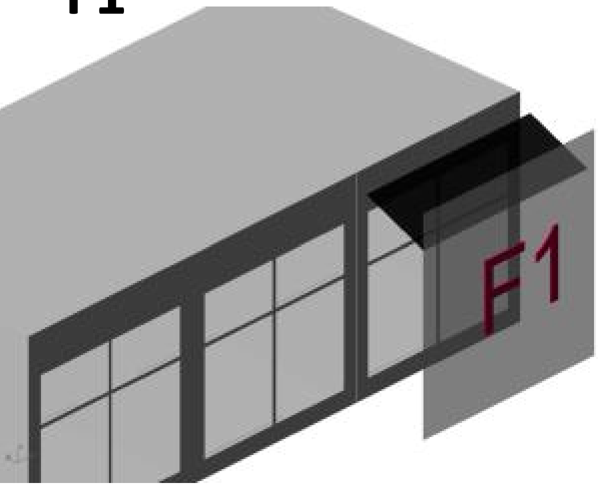
SIMULATION PARAMETERS

	View Matrix	Transmission Matrix	Daylighting Matrix	Façade Matrix
-ab	12		4	4
-ad	60,000		2000	10,000
-aa	0		0	
-as	0		0	
-lw	1e-42		1e-8	1e-5
-ds	0.05			
-dj	1			
-dt	0			
-dc	1			
-c			500	5000

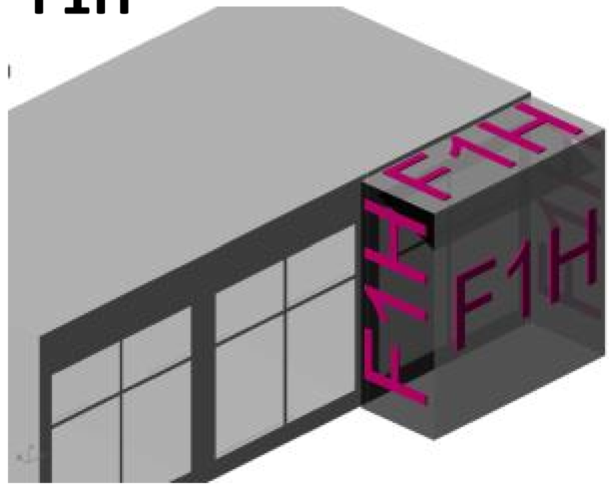
SIMULATION PARAMETERS

	DC	3-PHASE	4-PHASE METHOD			6-PHASE METHOD			
			F1	F1H	F4	F1	F1H	F4	DIRECT
Equation:	$I = Ds$	$I=VTDS$	$I = VTFDS$			$I = VTFDS - V_d T_d F_d D_d S_{ds} + C_{ds} S_{sun}$			
View Matrix	N X 2306	N X 145		N X 145			N X 145		
Transmission Matrix (CFS BSDF)	N/A	145 X 145		145 X 145			145 X 145		
Facade Matrix	N/A	N/A		145 X 145			145 X 145		Same as 5-phase method
Daylight Matrix	N/A	145 X 2306		145 X 2306			145 X 2306		
SKY	2306 X N	2306 X N		2306 X N			2306 X N		5612 X N

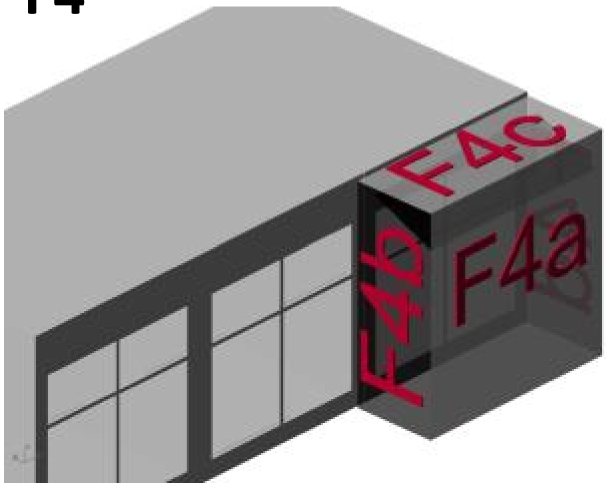
F1



F1H

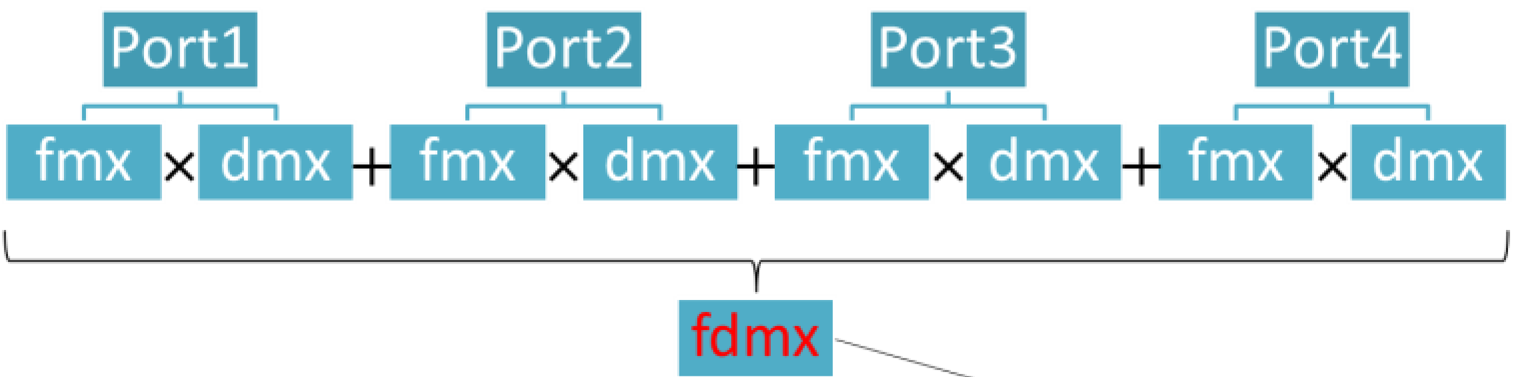


F4



F4

Multiplying matrices

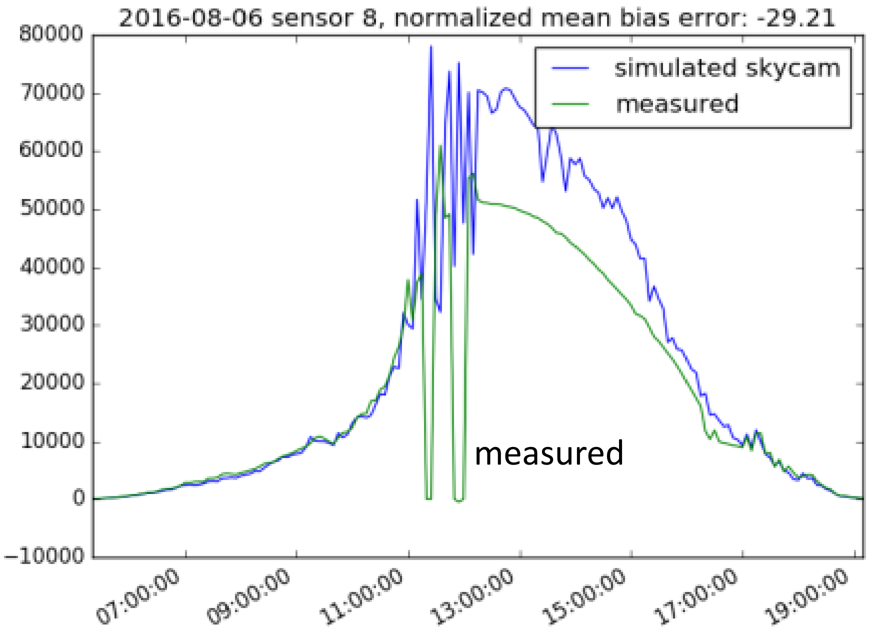



```
dctimestep matrices/glazings.vmx (CFS BSDF) fdmx
example.skv > output
```

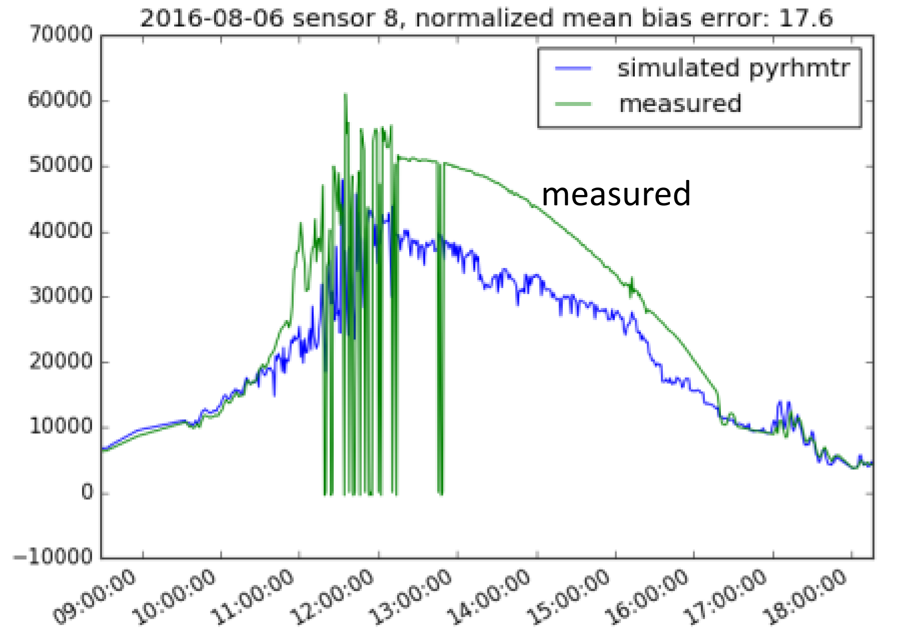
SKY SIMULATION (no awning)

Outdoor incident vertical illuminance

Simulations with skycam data
over predicts measured data (NMBE=-29%)

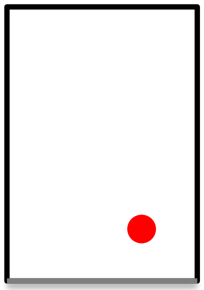


Simulations with pyroheliometer data
under predicts measured data (NMBE=18%)

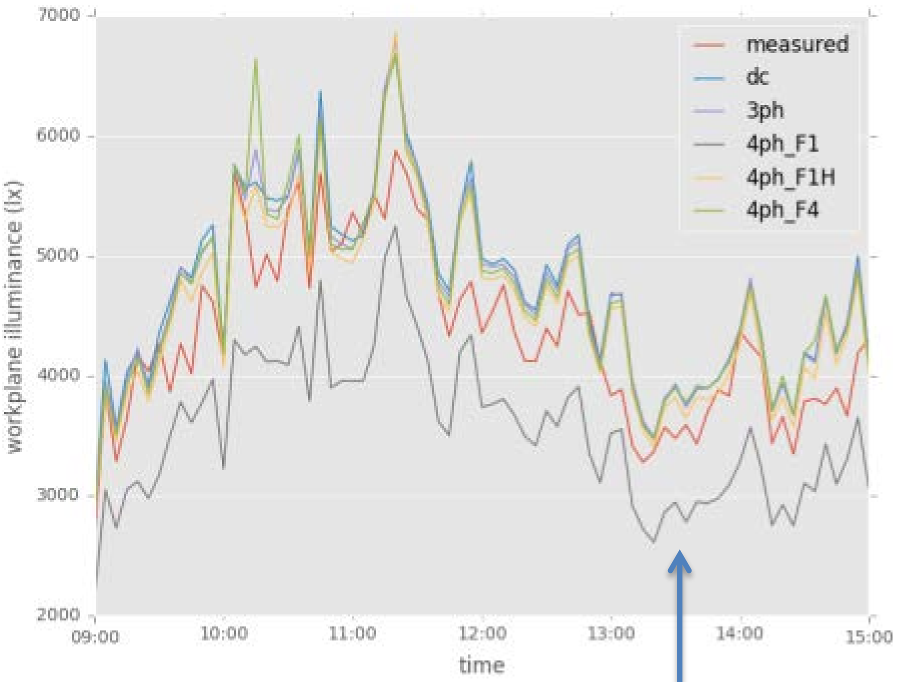


RESULTS | work-plane illuminance

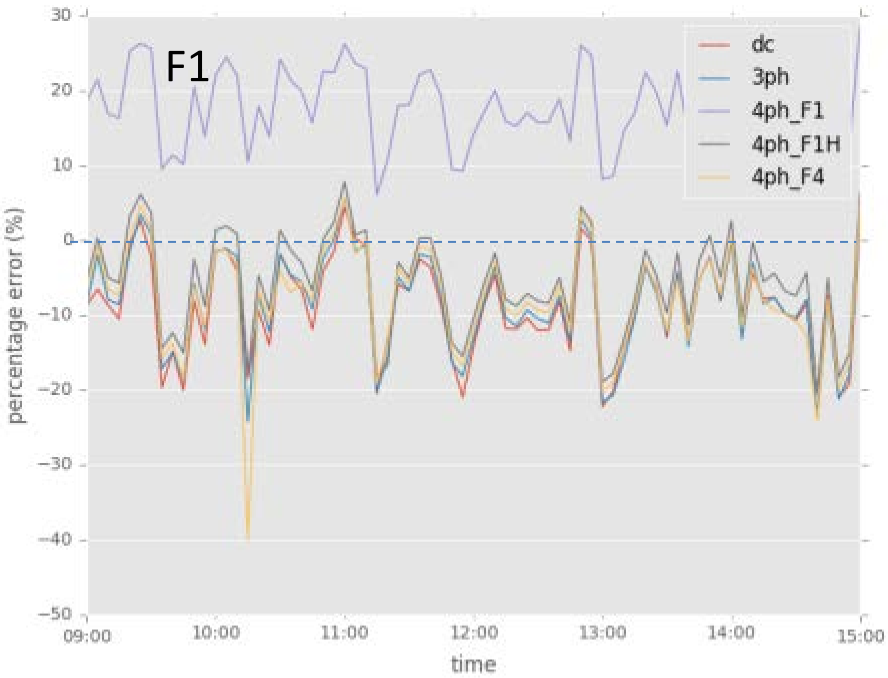
overcast sky | near window sensor | skycam (July 4)



Workplane illuminance (lux)



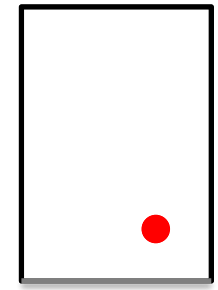
Percentage error (%)

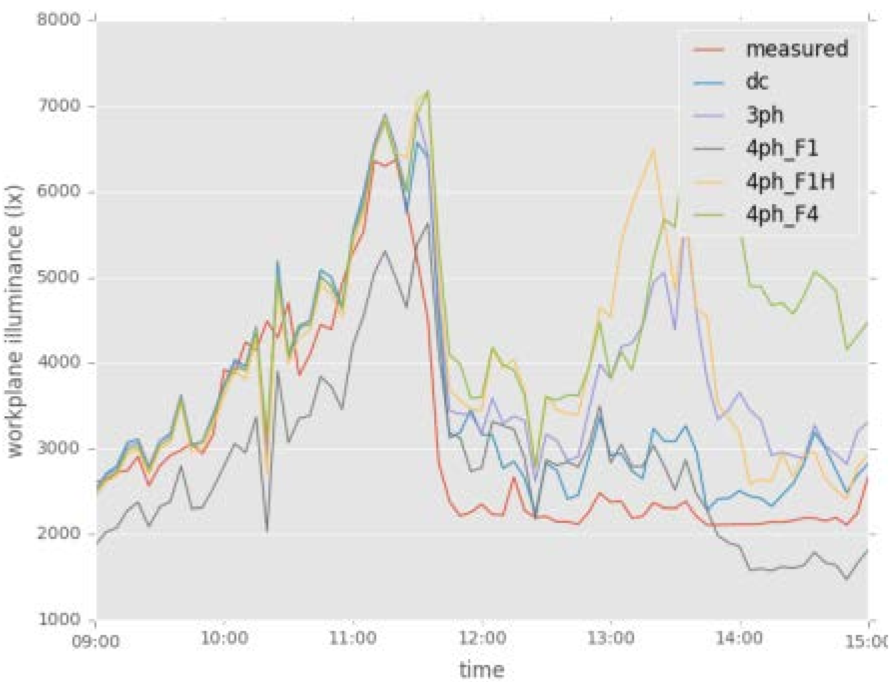


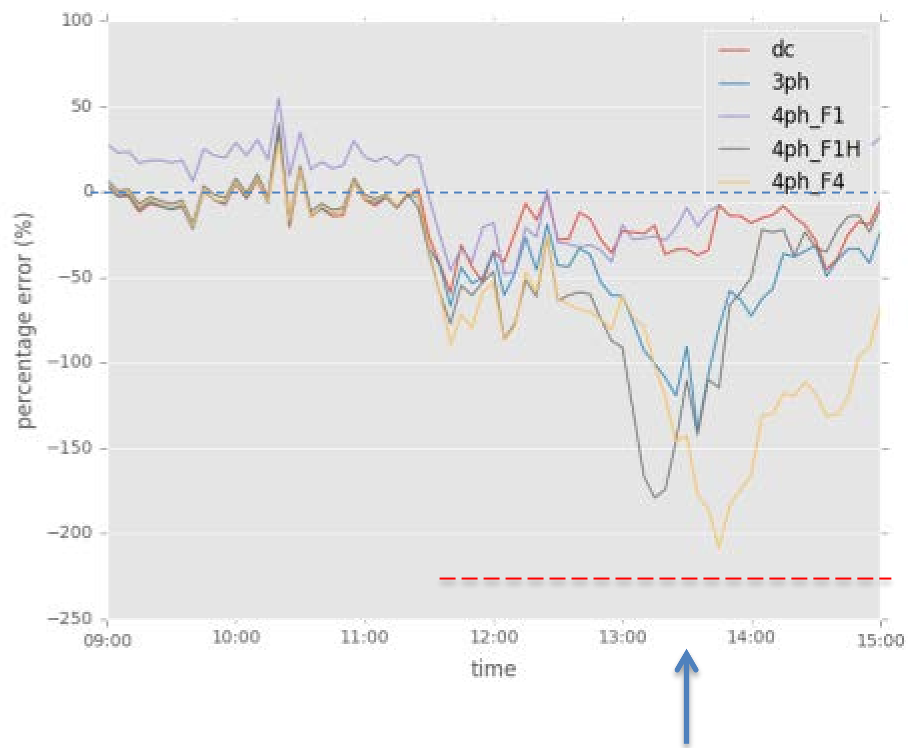
F1 is low due to "missing flux"

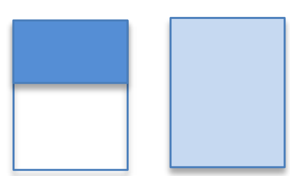
RESULTS | work-plane illuminance

sunny sky | near window sensor | skycam (July 16)





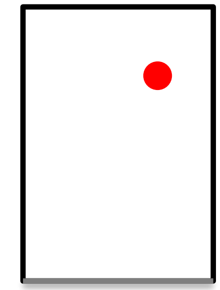


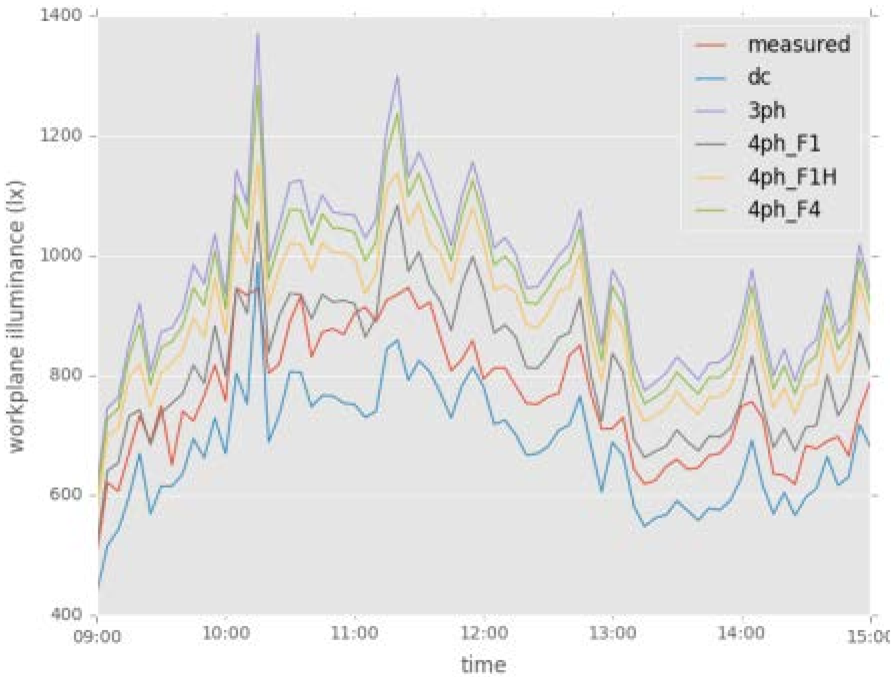


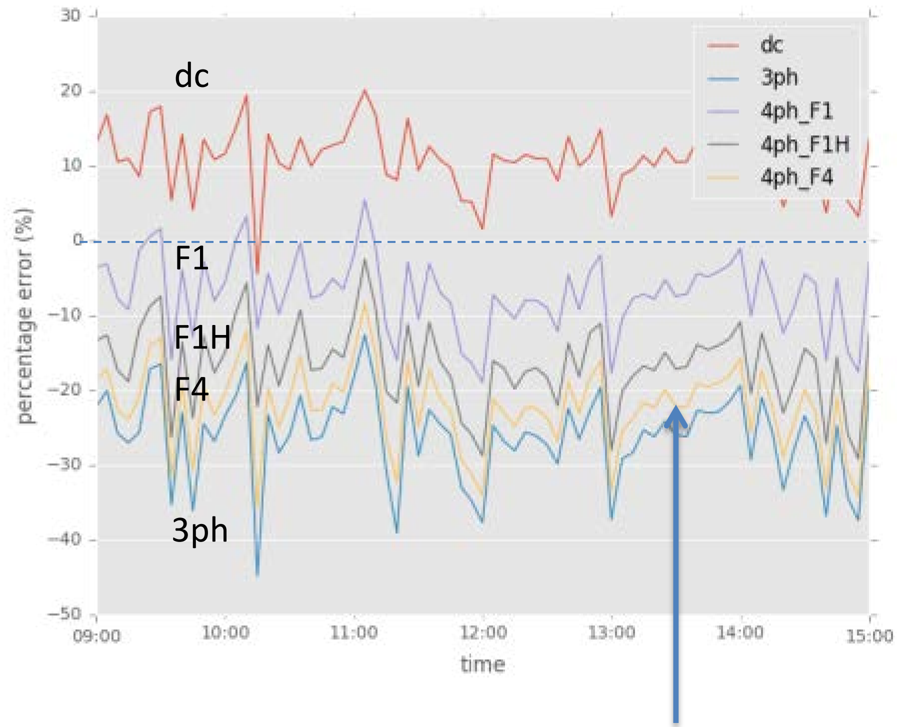
3- and 4-phase: Significant error due to spatial averaging over façade and/or direct-diffuse split by skycam

RESULTS | work-plane illuminance

overcast sky | back room sensor | skycam



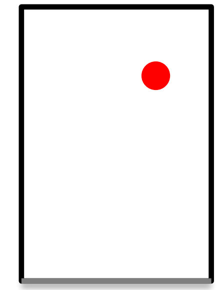


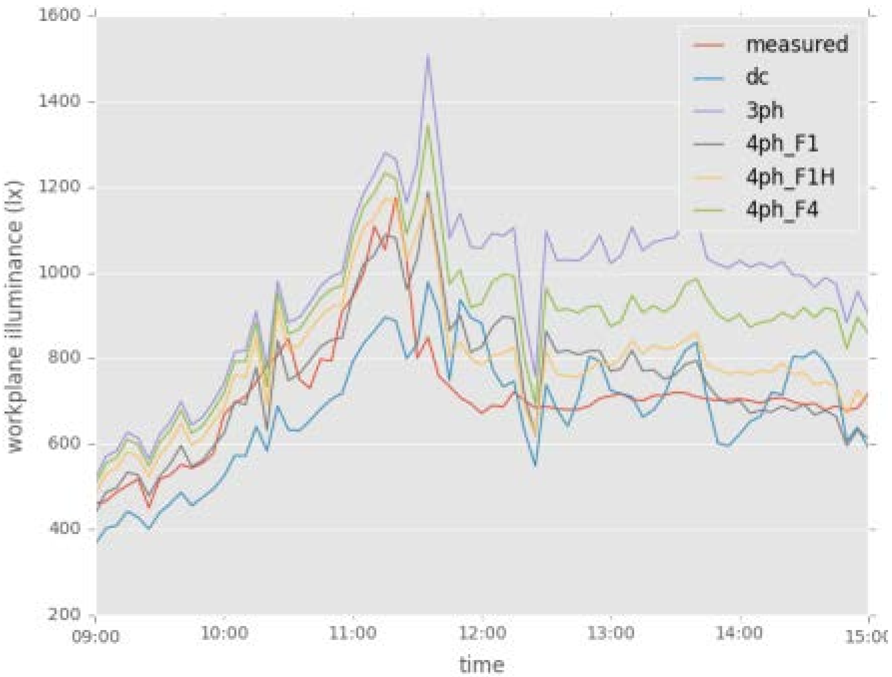


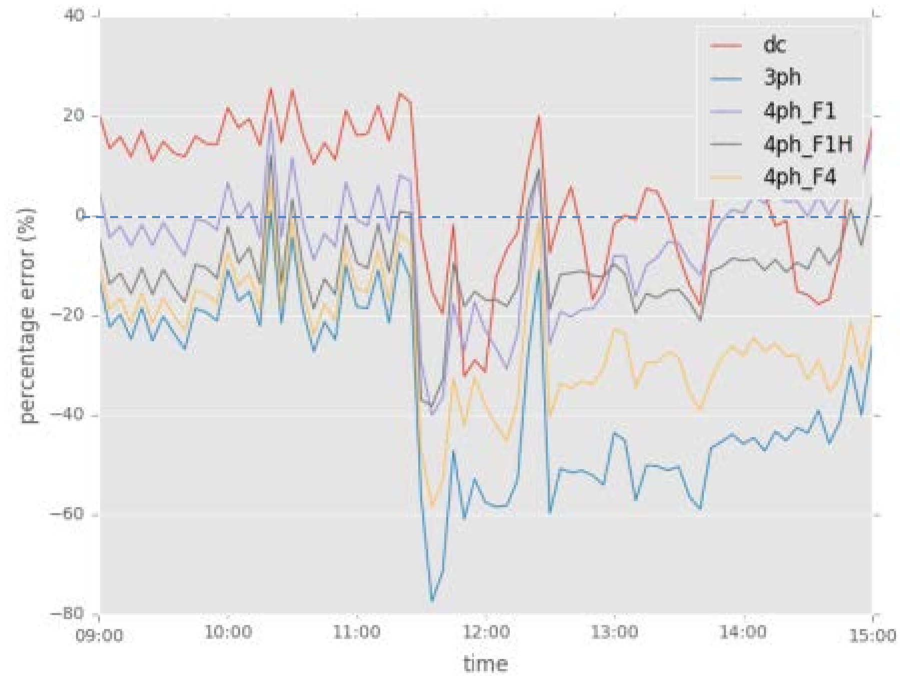
3- and 4-phase: over-prediction at rear of room (3.8 m, 12.5 ft from window)

RESULTS | work-plane illuminance

sunny sky | back room sensor | skycam



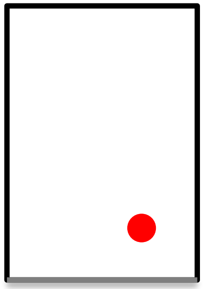




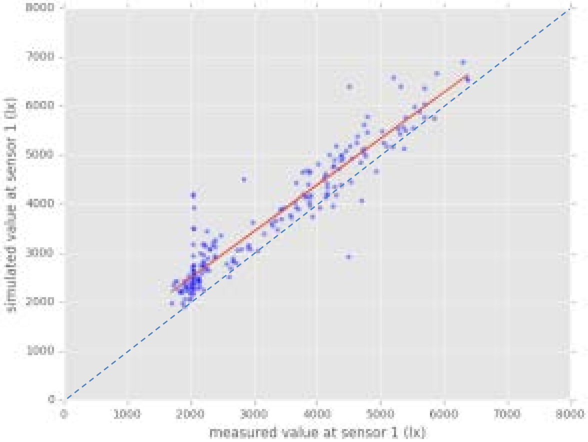
3- and 4-phase: over-prediction at rear of room (3.8 m, 12.5 ft from window)

RESULTS | work-plane illuminance

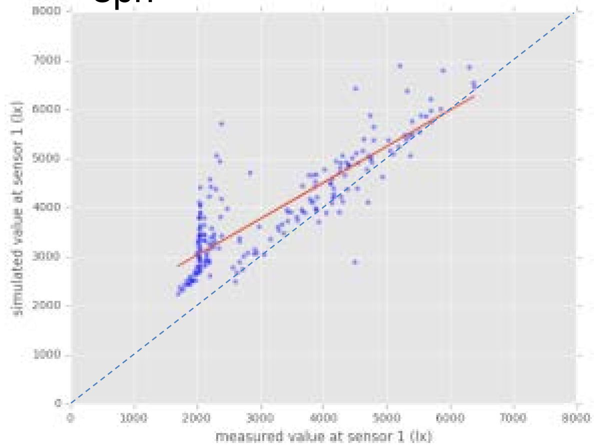
near window sensor | skycam (July 4 &16)



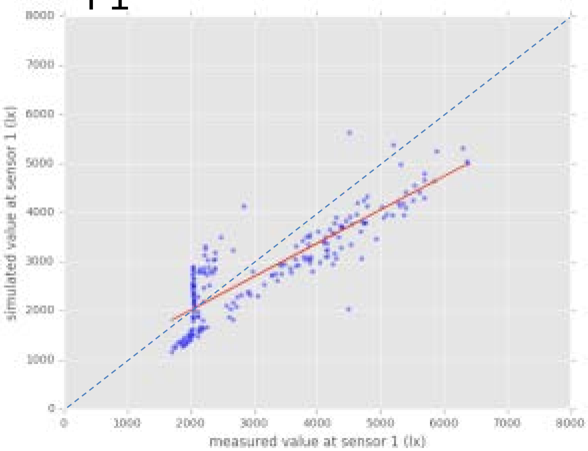
DC



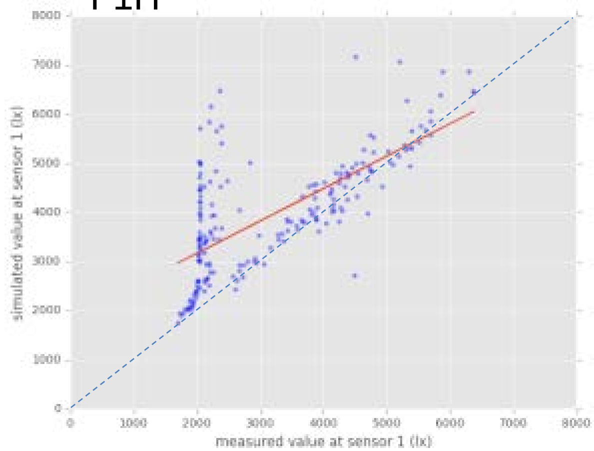
3ph



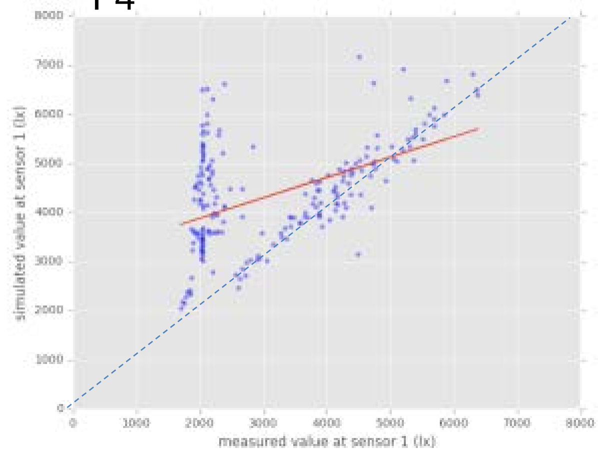
F1



F1H

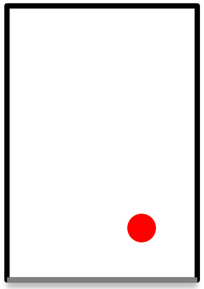


F4

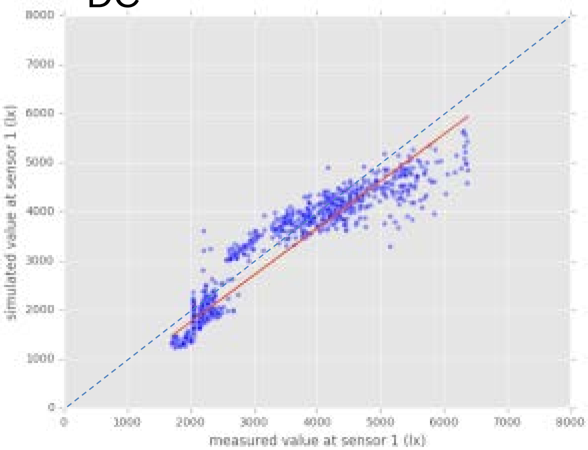


RESULTS | work-plane illuminance

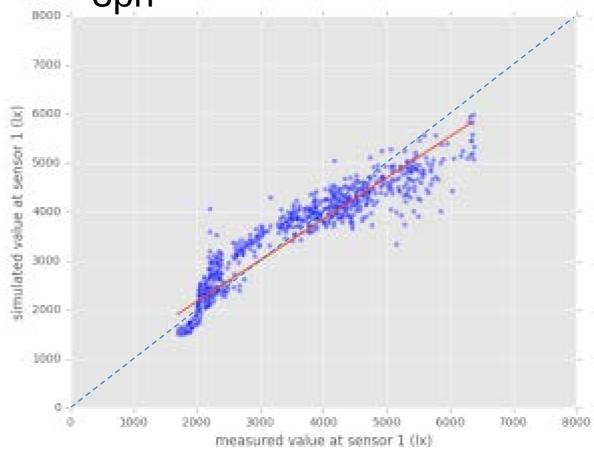
near window sensor | pyroheliometer



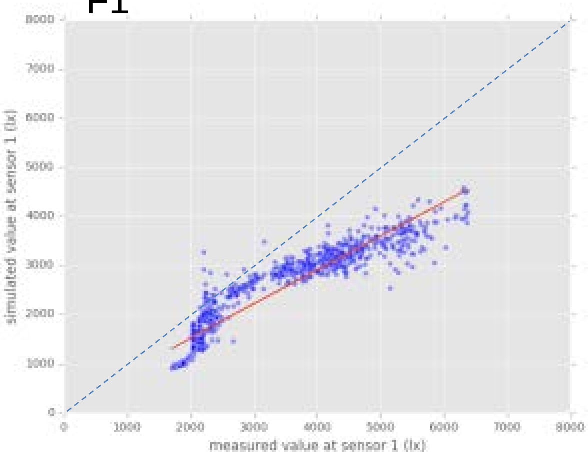
DC



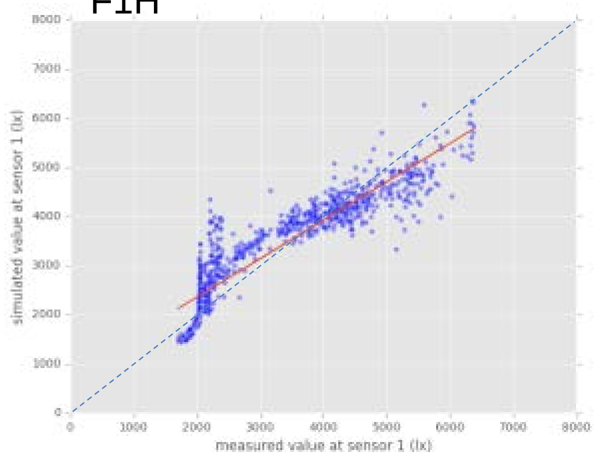
3ph



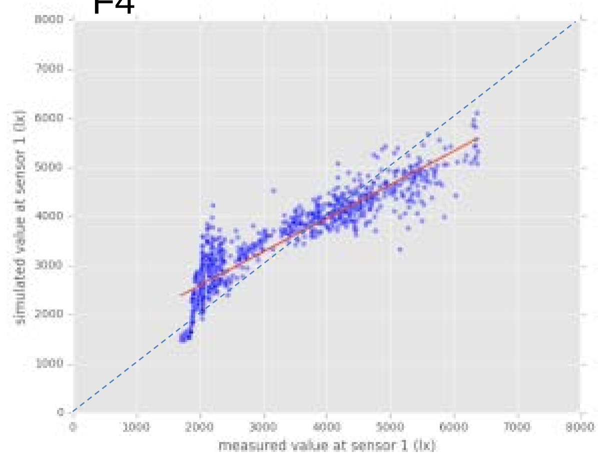
F1



F1H

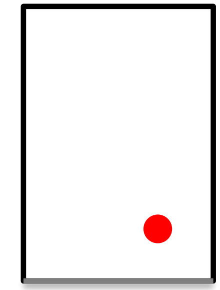


F4

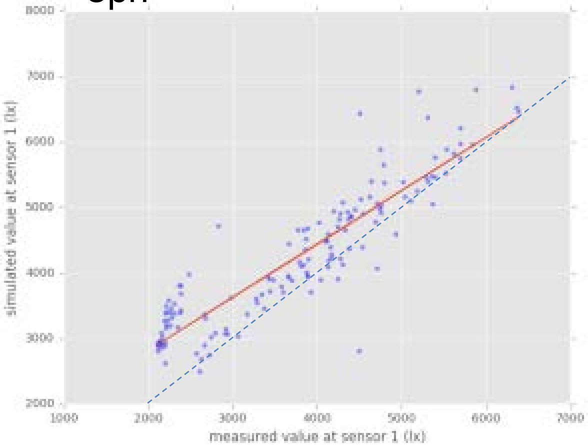


RESULTS | work-plane illuminance

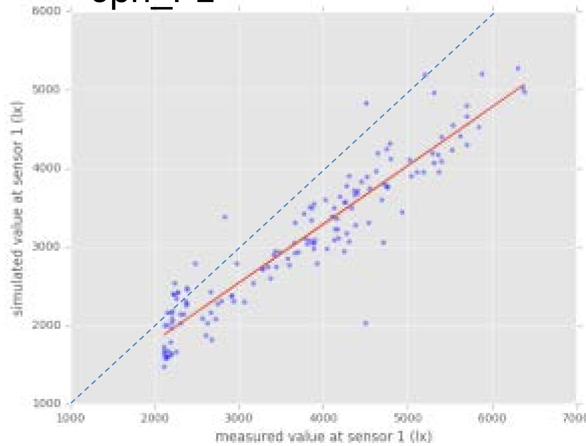
near window sensor | skycam | 6ph



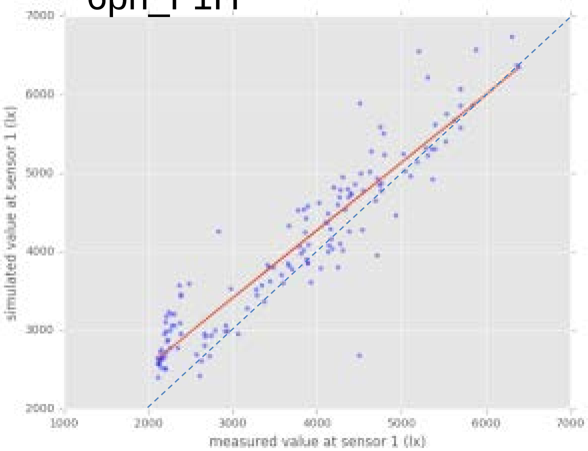
5ph



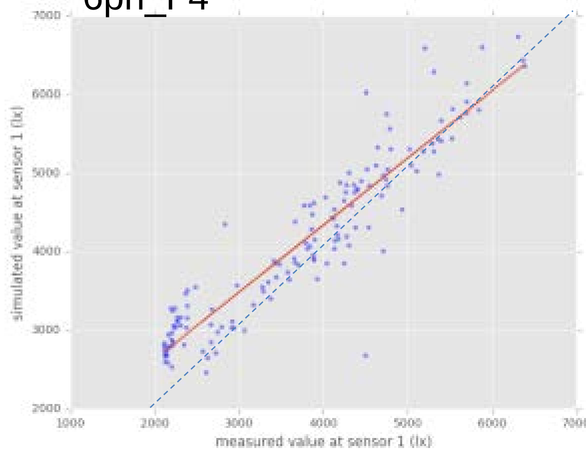
6ph_F1



6ph_F1H

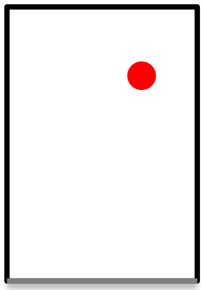


6ph_F4

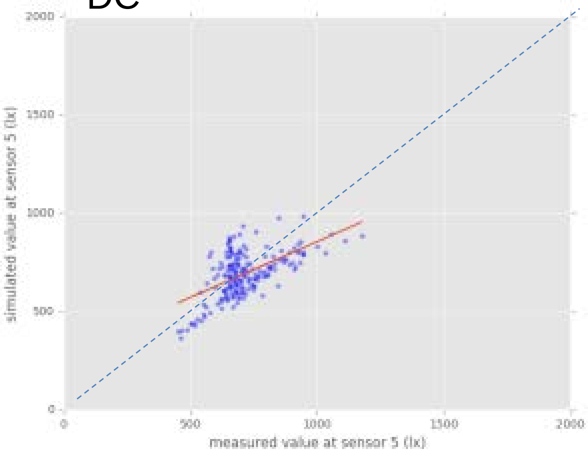


RESULTS | work-plane illuminance

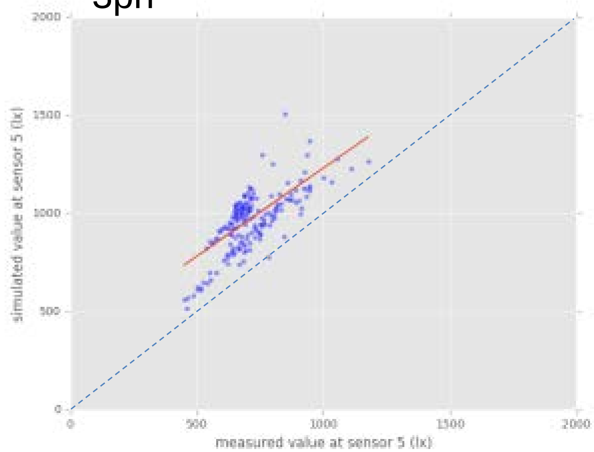
back room sensor | skycam



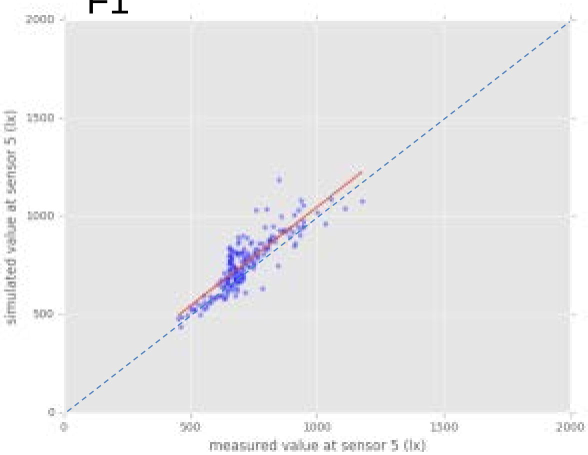
DC



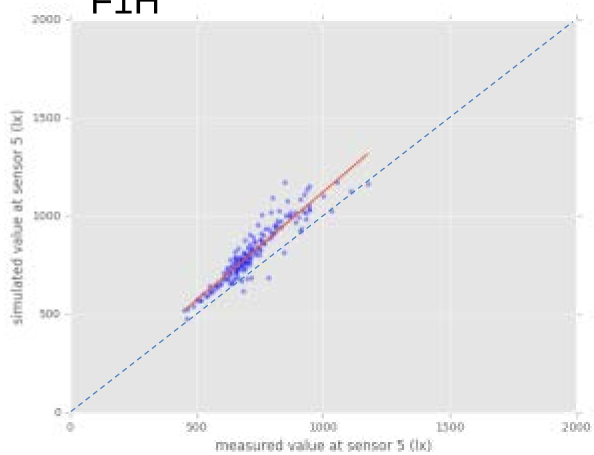
3ph



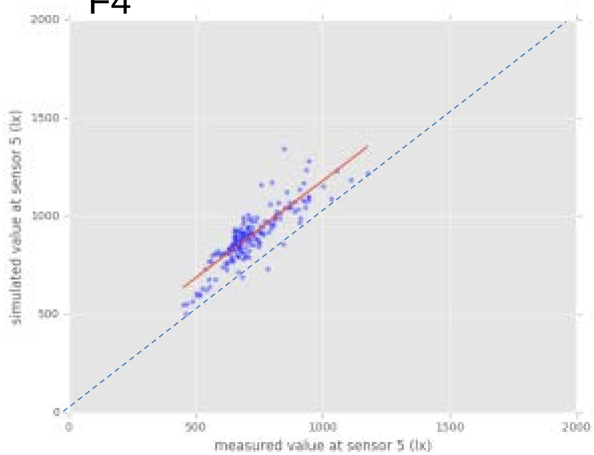
F1



F1H

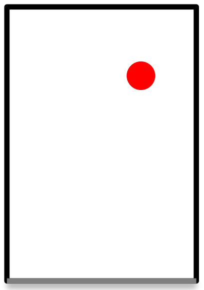


F4

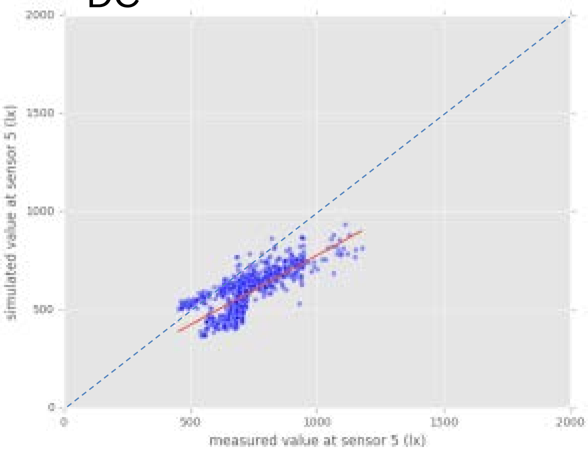


RESULTS | work-plane illuminance

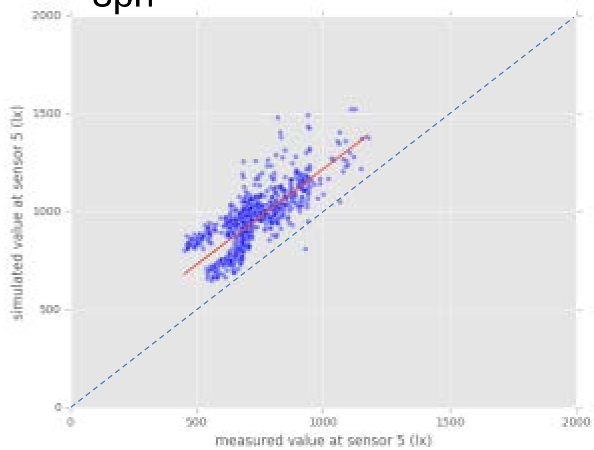
back room sensor | pyroheliometer



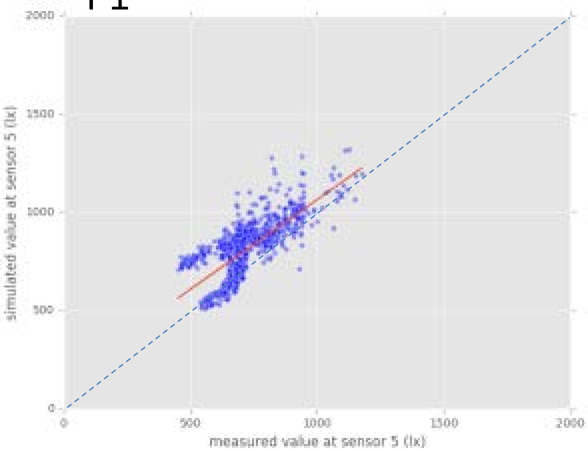
DC



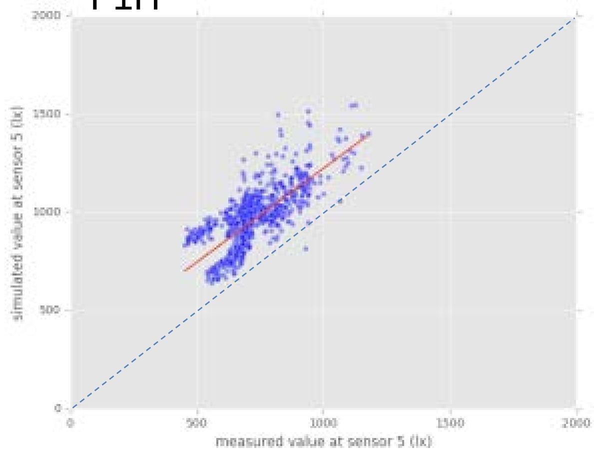
3ph



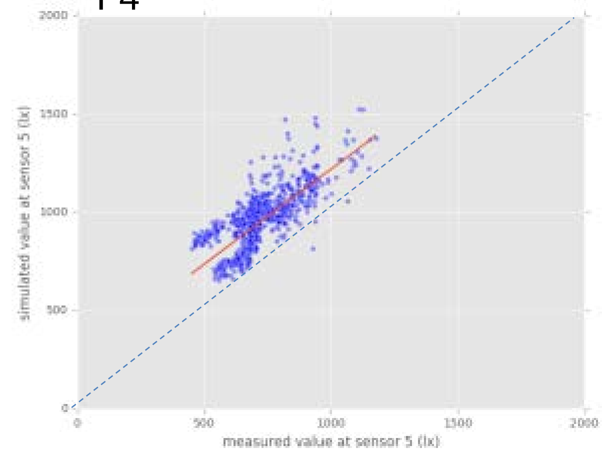
F1



F1H

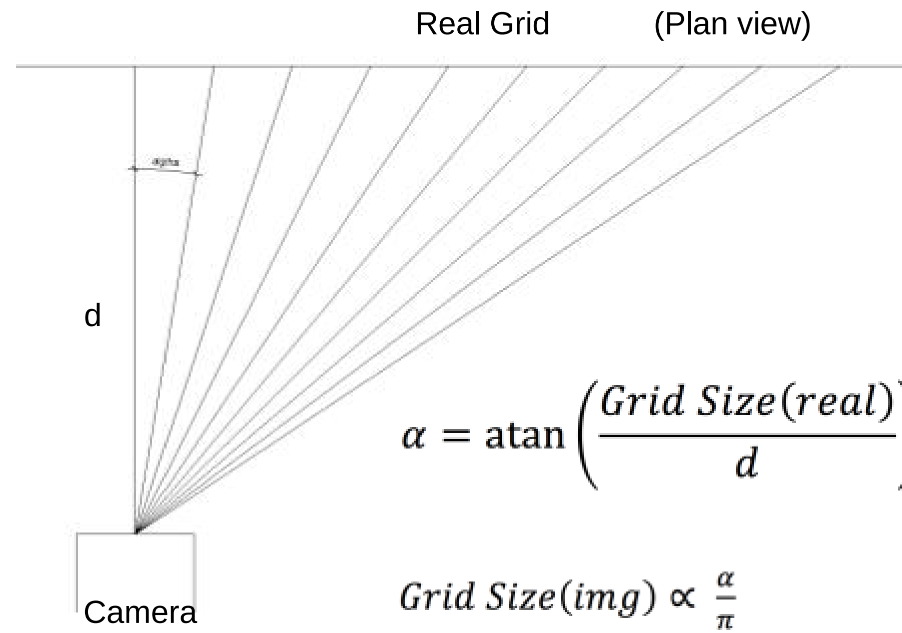


F4



FISHEYE LENS DISTORTION CORRECTION

Sigma 8mm F3.5 lens does not take a perfect angular projection fisheye image, which is needed to more accurately evaluate glare (using Evalglare)

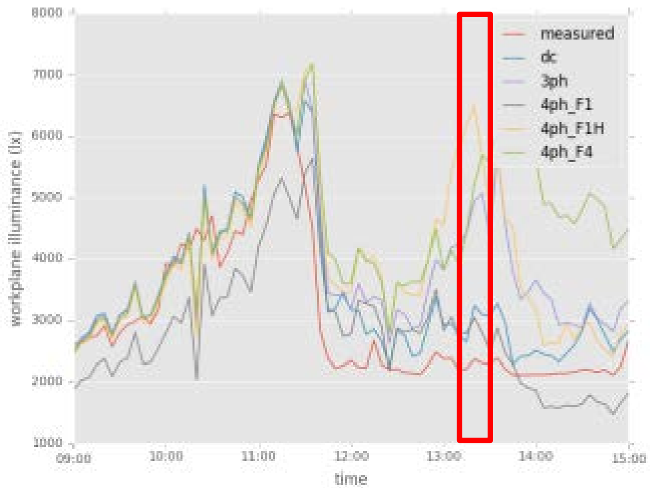


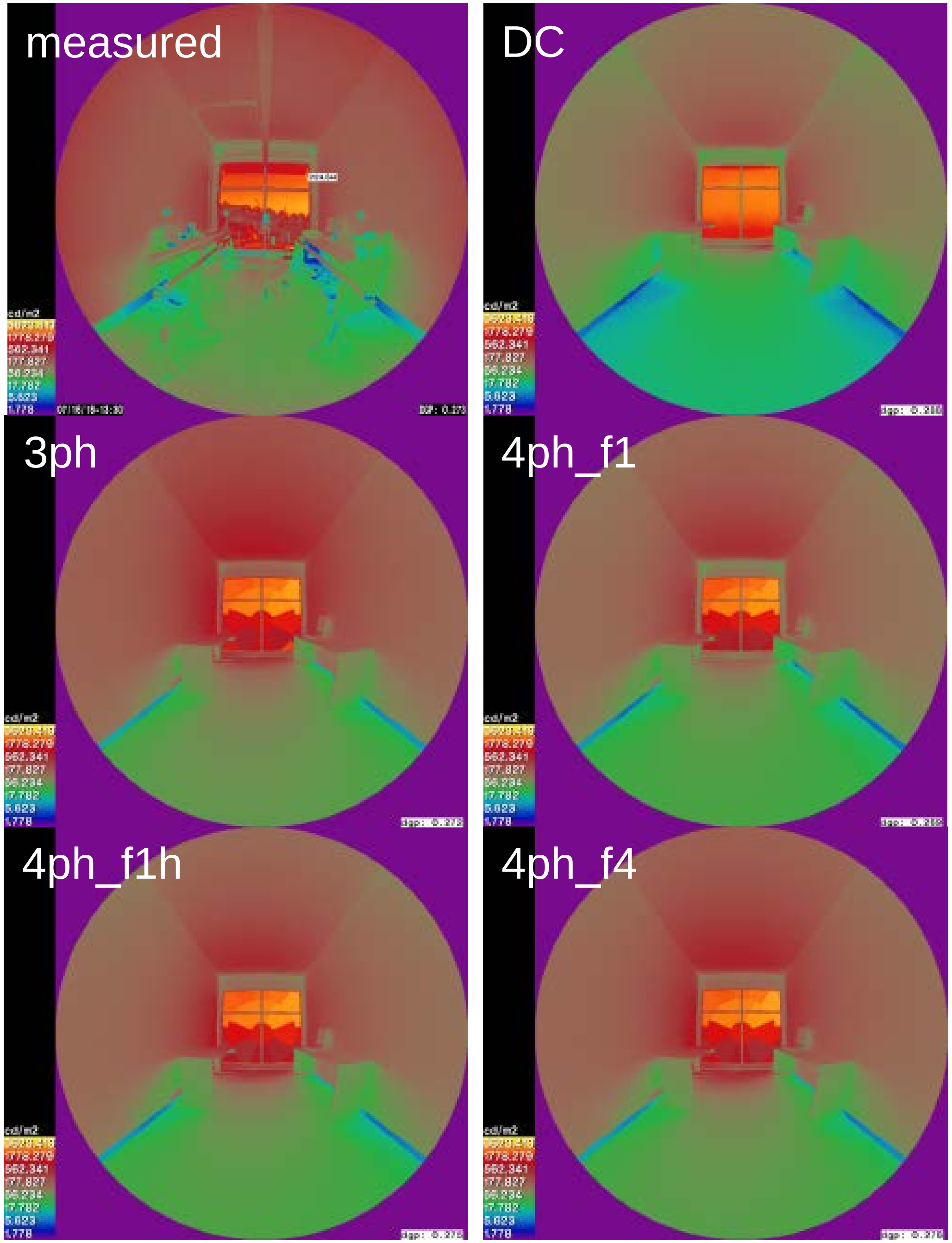
$$\alpha = \operatorname{atan}\left(\frac{Grid\ Size(real)}{d}\right)$$

$$Grid\ Size(img) \propto \frac{\alpha}{\pi}$$

RESULTS | luminance

sunny sky | Skycam |13:30



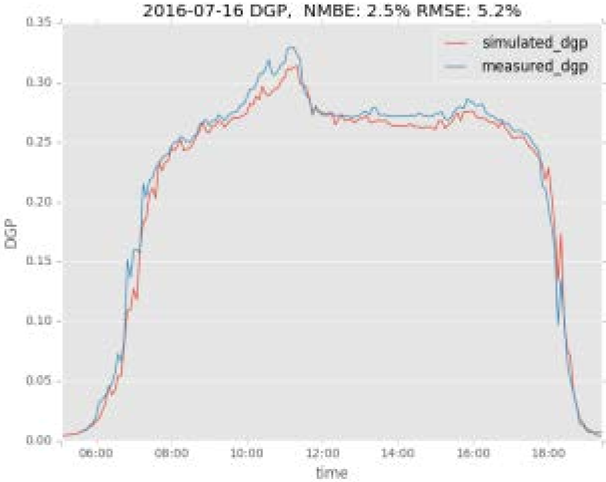


M & S PARAMS | INSTRUMENT |SKY SIMULATION | DC | 3-PH | 4-PH (F1) | 4-PH (F1H) | 4-PH (Fn) | 6-PH (F1) | 6-PH (F1H) | 6-PH (Fn)

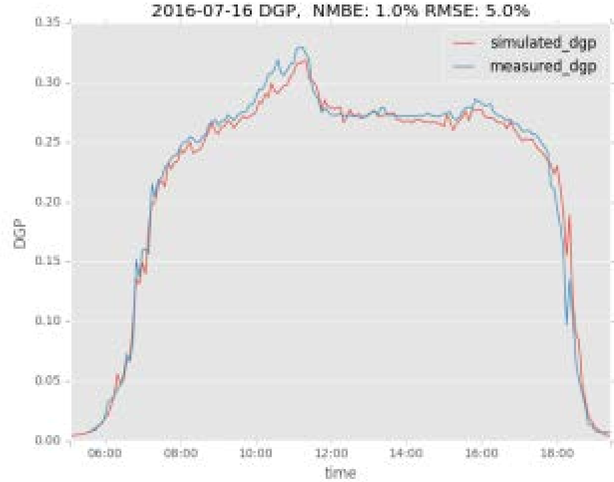
RESULTS | luminance

sunny sky | skycam

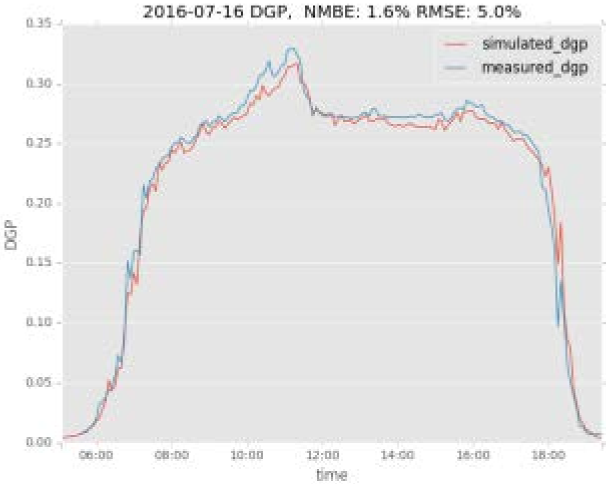
3ph



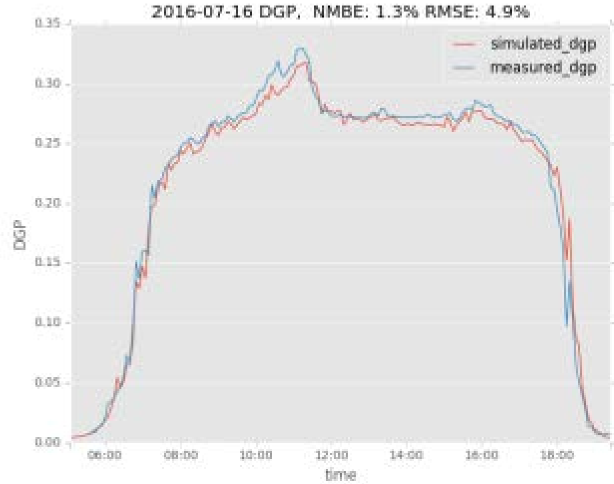
F1



F1H

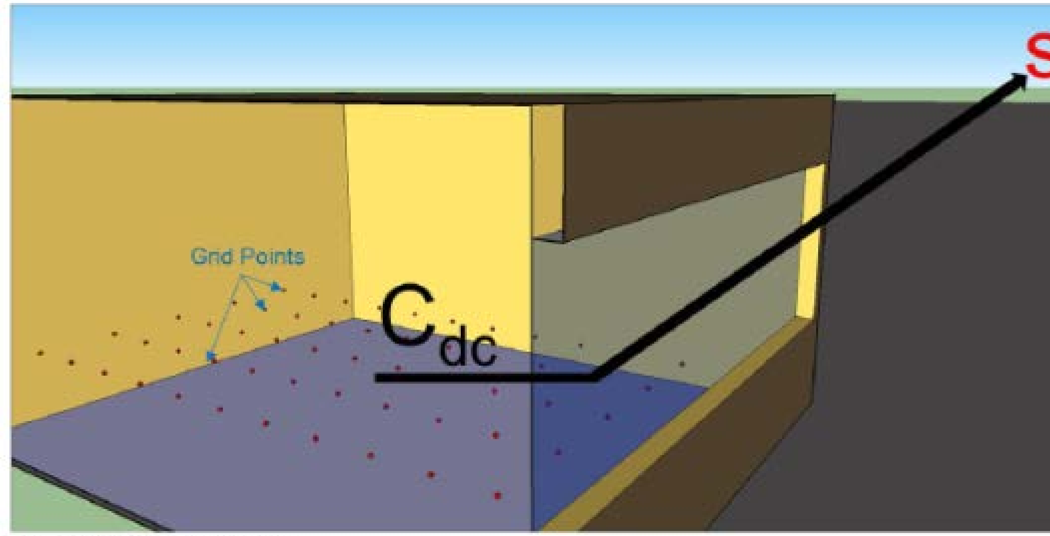


F4

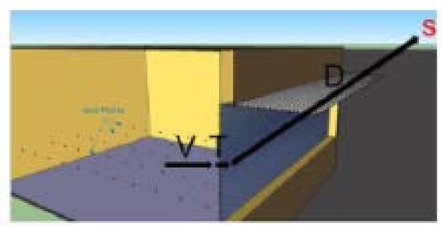


Next steps and related work

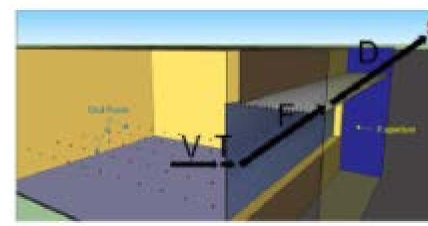
- Sort out sources of error
- Measure and validate with more exterior shading configurations, including low angle winter solstice period
- In the works: F-matrix Tutorial (and more), Sarith Subramaniam, Penn State University (looking for potential review/ testers!)



Daylight Coefficient Method



3 Phase Method



F Matrix Method

https://facades.lbl.gov/

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