# Intra-hour forecasting with a total sky imager at the UC San Diego solar energy testbed

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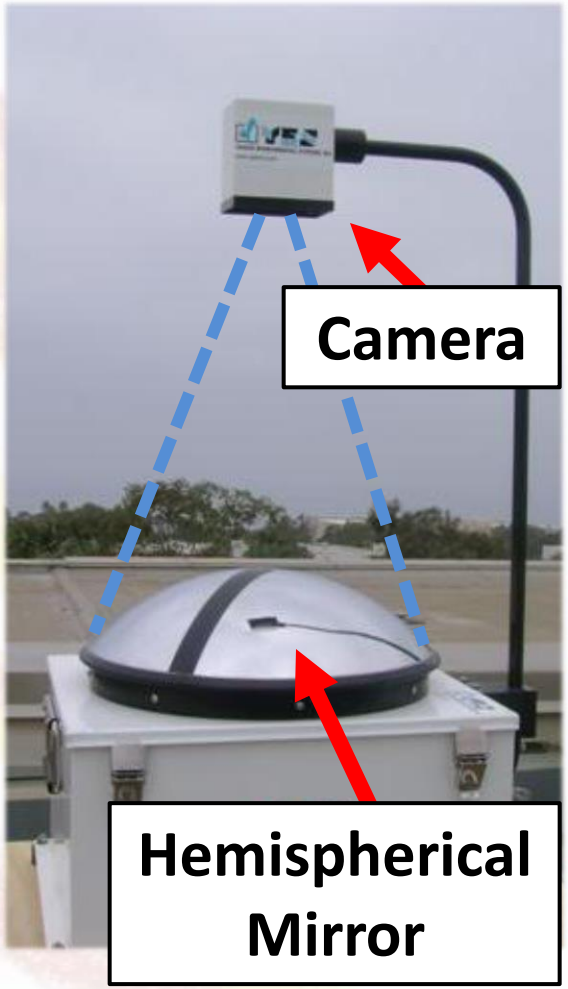
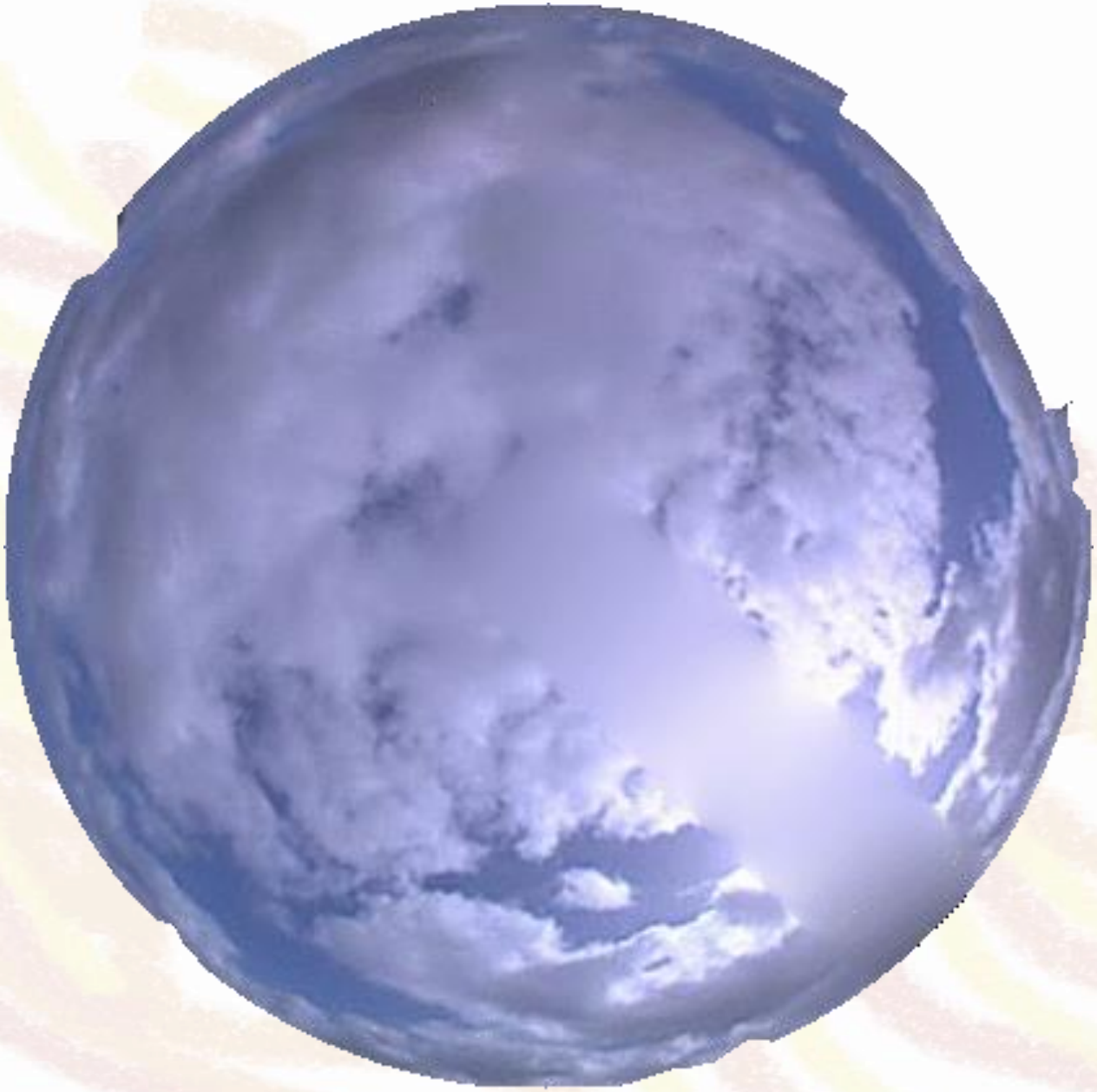
# Ground-Image Based Forecasting

- High time resolution coverage
  - Limited by computing power
- Granular spatial resolution
  - Multi-megapixel cameras
- Reasonable coverage
  - ~15 $km^2$ - cloud field dependent
- Short time-horizon
  - 10 to 20 minutes





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UC San Diego Sky Imager October 4, 2009 11:20:30

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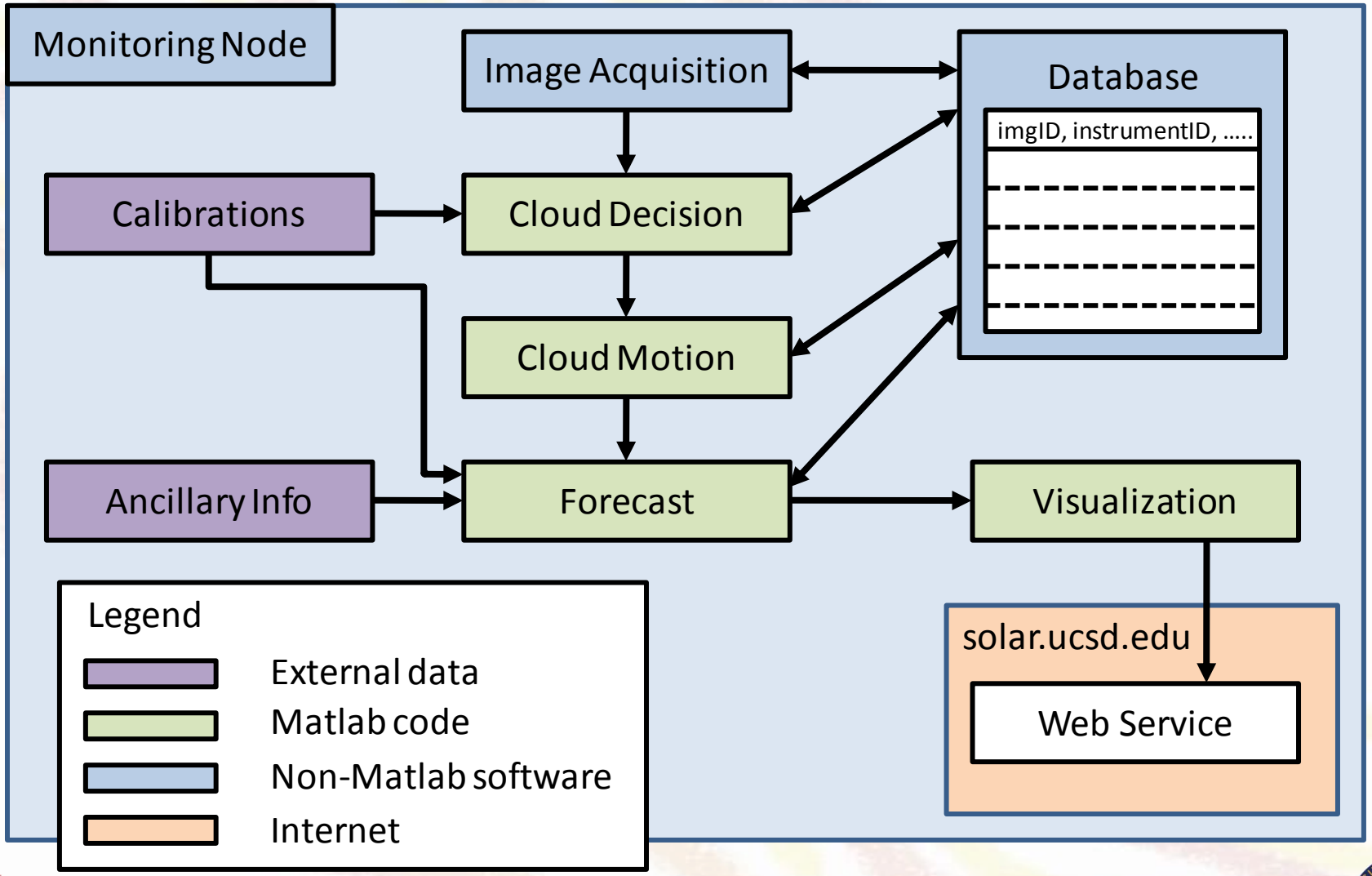
# Resource Assessment Scales

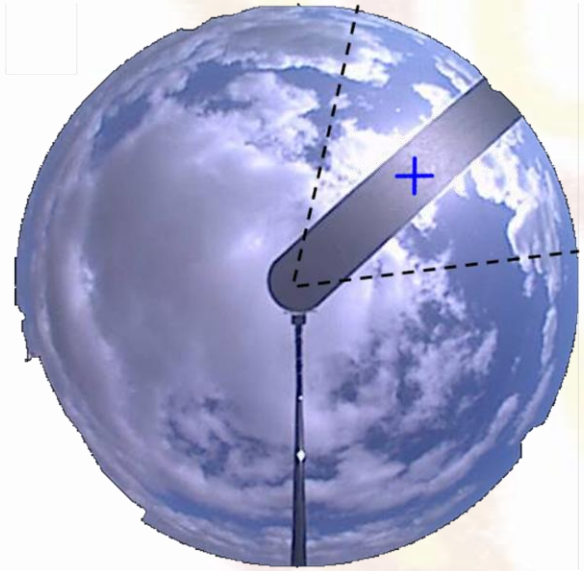
| | NWP (HRRR) | Satellite (GOES) | Sky Imager |
|---|---|---|---|
| Spatial Resolution | 3 km horizontal | 1 $km^2$ at nadir | 100 $m^2$ ground projected |
| Spatial Coverage | Continental | Continental | 15 $km^2$ |
| Temporal | Hourly | 15+ minutes (routine operations) | 30 seconds (or faster) |

# UCSD Operational Forecasting

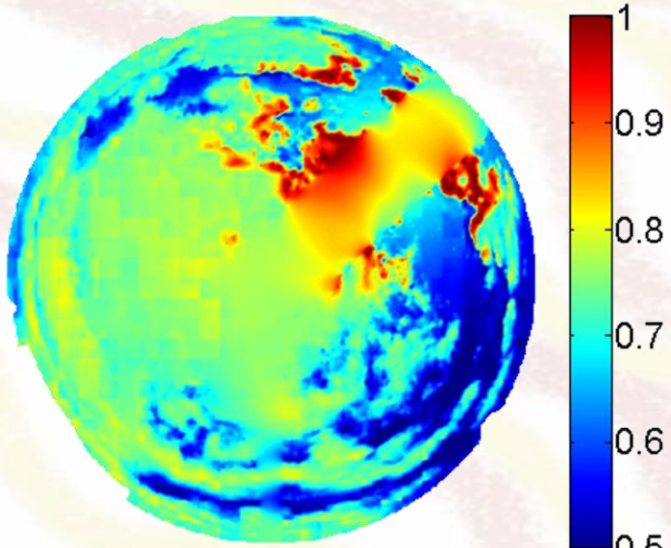


# Cloud Decision

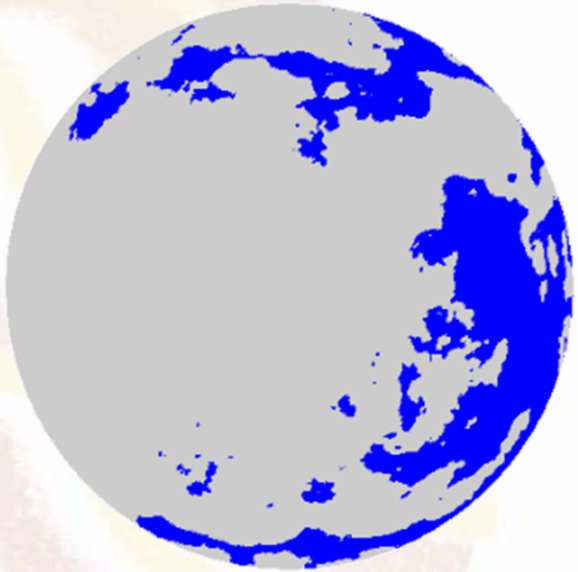
- Ratio of red content to blue content
  - Small values indicate clear sky
  - Values near unity indicate cloud



raw image



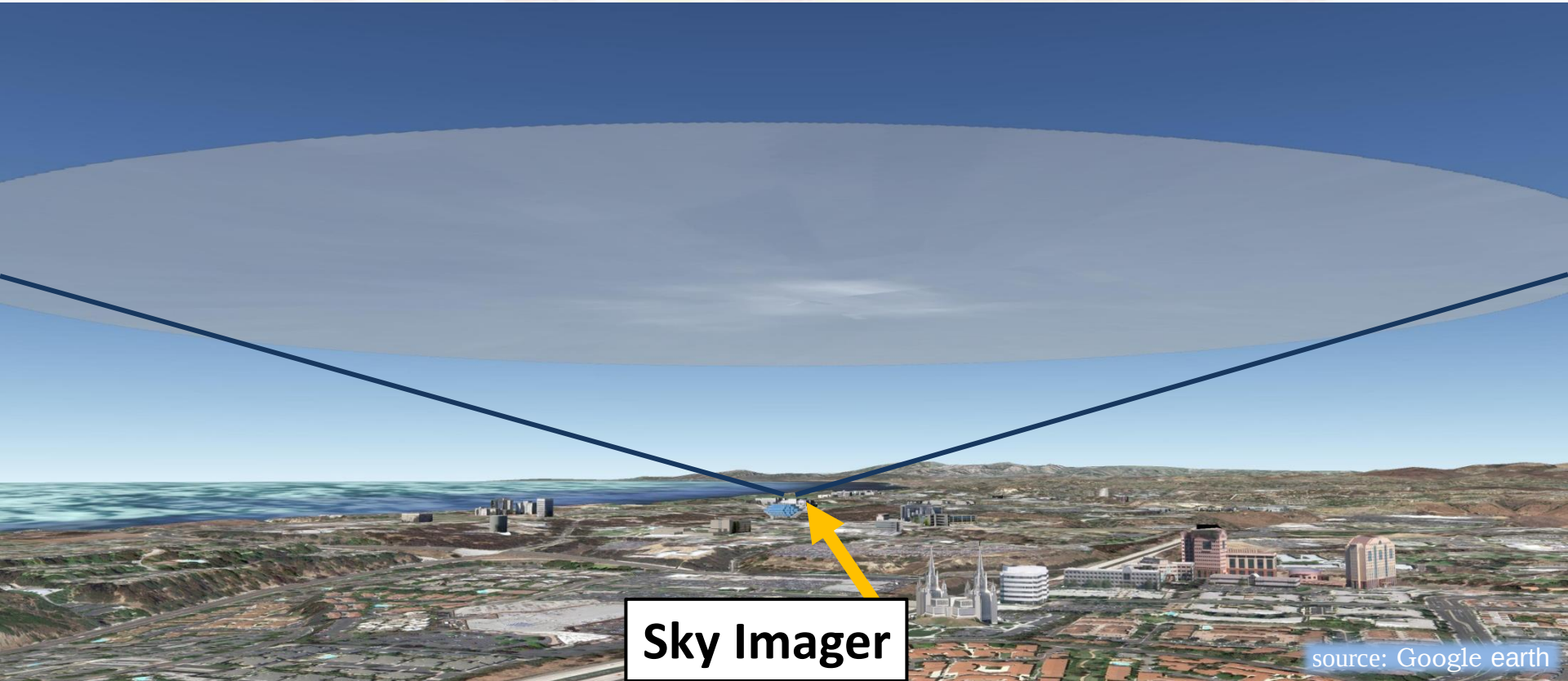

red-blue ratio

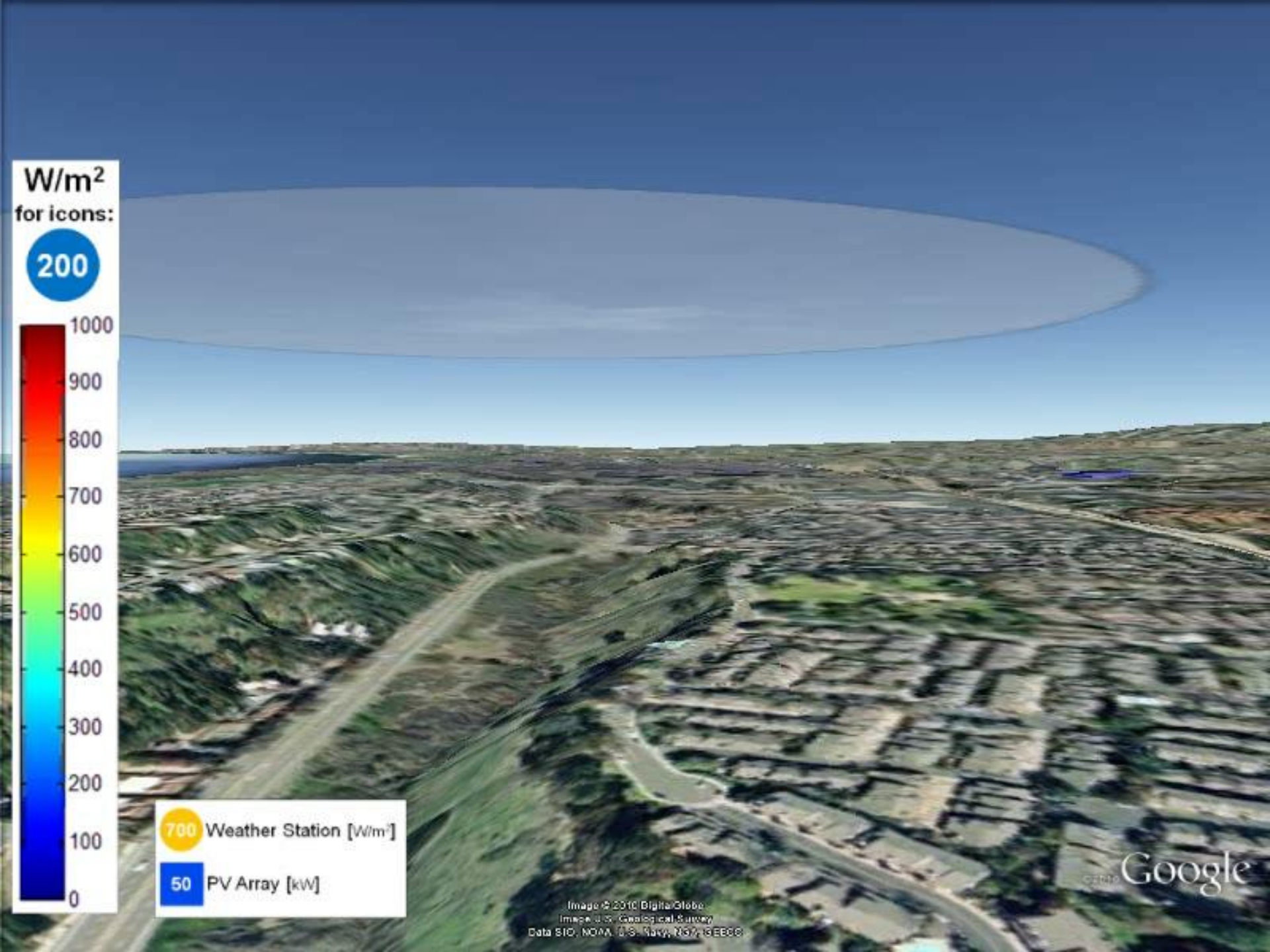


cloud decision

# Cloud Mapping

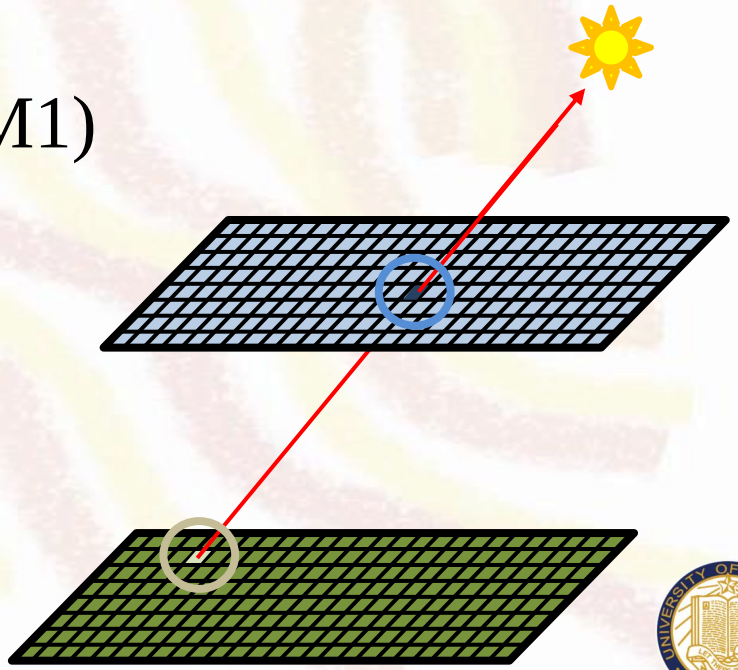
- Cloud projection
  - Plane formed by cloud base
  - Ceilometer used for height




W/m²
for icons:
200
1000
900
800
700
600
500
400
300
200
100
0
700 Weather Station [W/m²]
50 PV Array [kW]
Image © 2010 DigitalGlobe
Image U.S. Geological Survey
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google

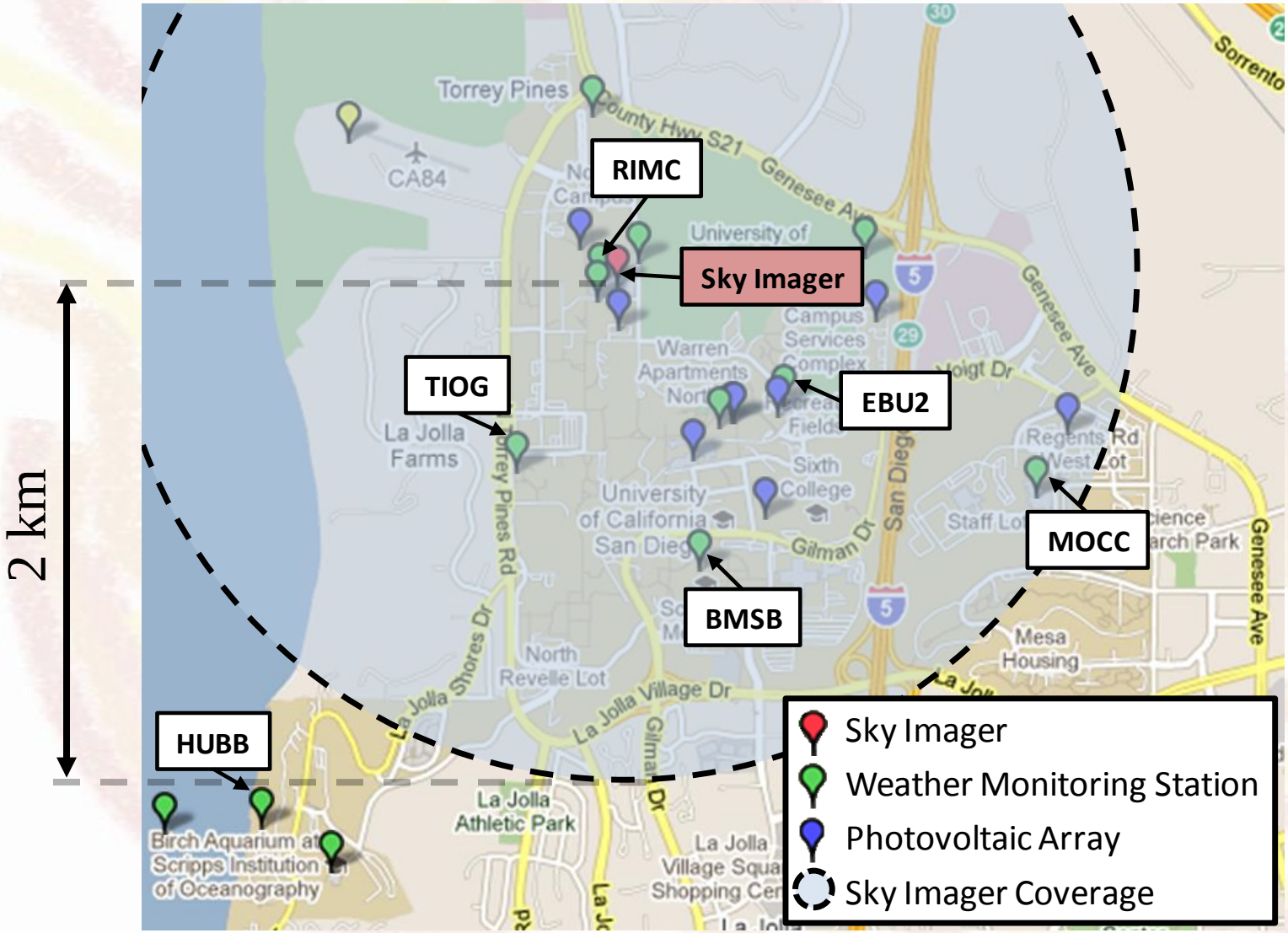
# Cloud Shadow

- Shadow is projected to ground from binary cloudmap using solar angles
  - binary: clear or cloudy
- Sky condition mapped to ground (“shadowmap”)
  - 10 × 10 m grid cells
  - Topography included (SRTM1)



topography not shown in shadowmap illustration

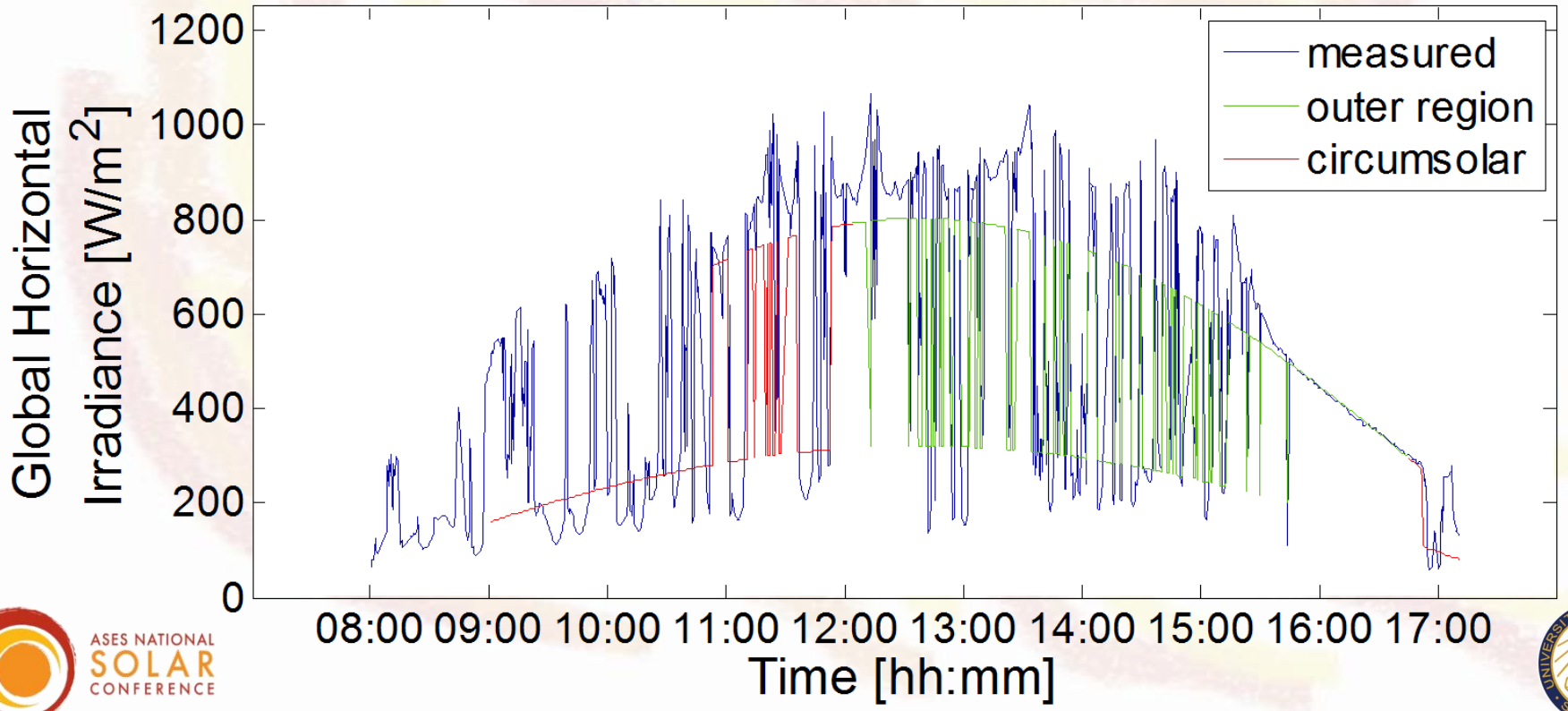
# Sensor Network Layout



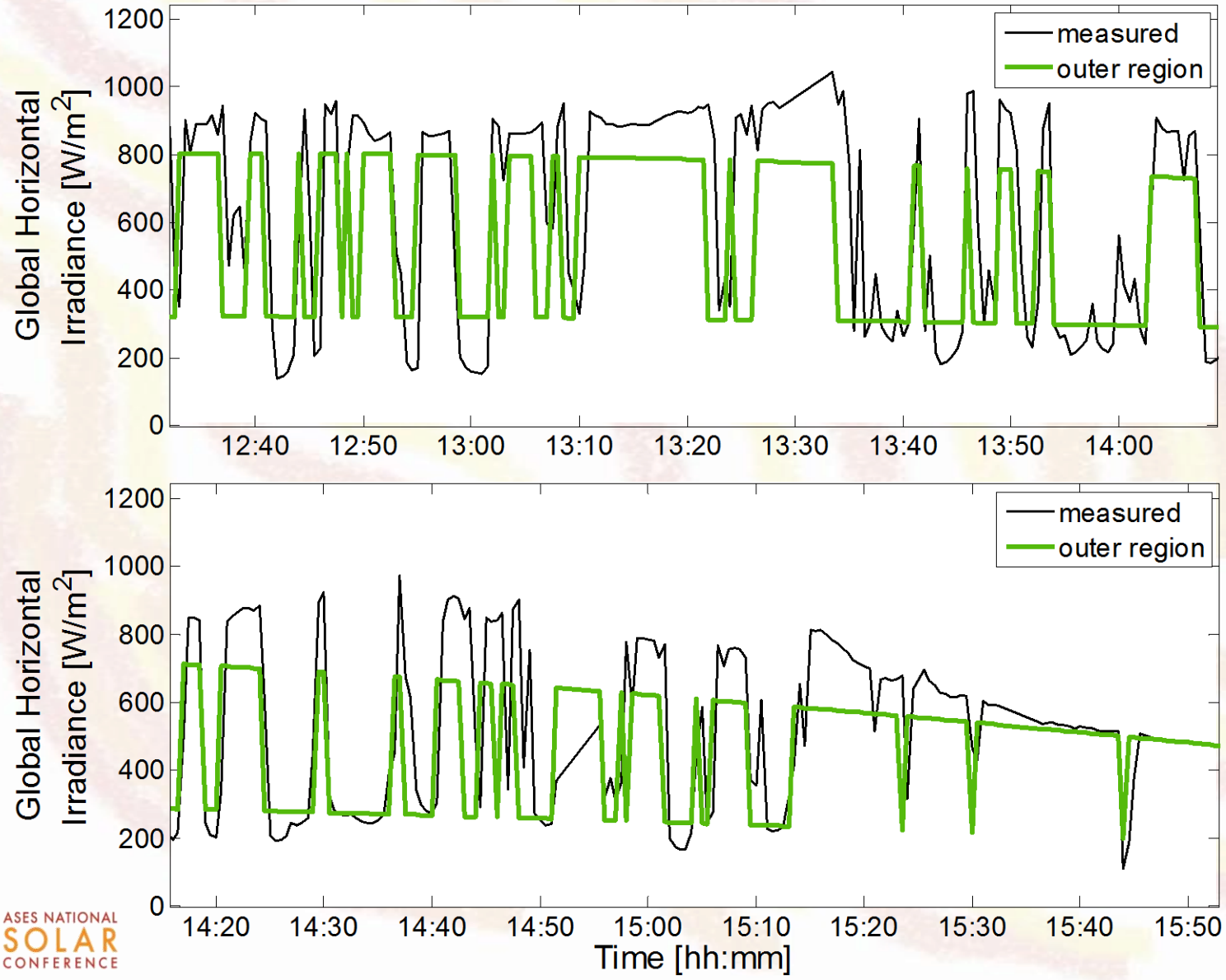
# Irradiance Parameterization

- Global Horizontal Irradiance (GHI) [W/m$^2$] parameterized as:

$$GHI = kt \cdot GHI_{csk}, \qquad kt = \begin{cases} 0.4 & cloudy \\ 1.0 & clear \end{cases}$$

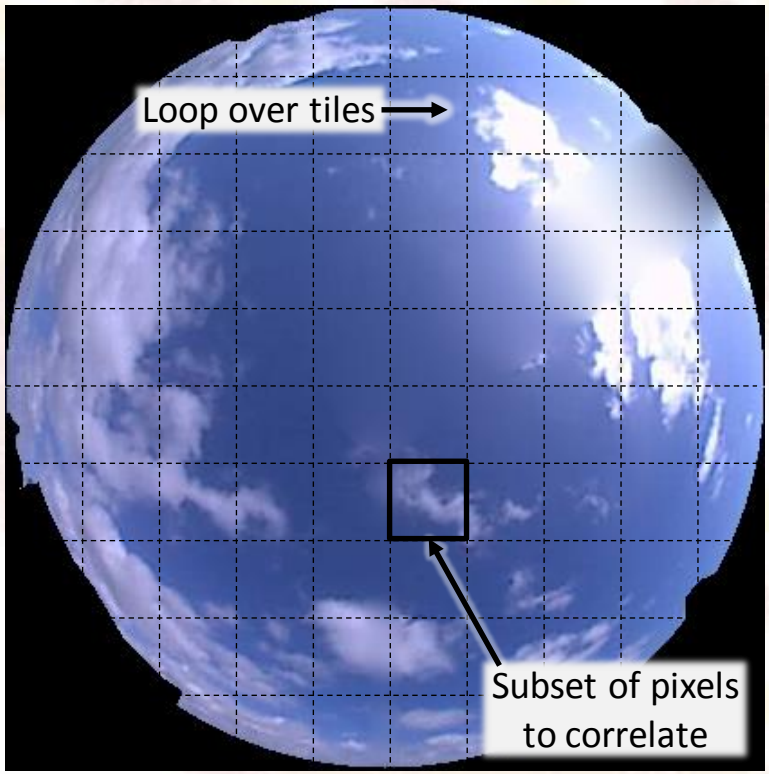


# Capturing ramps

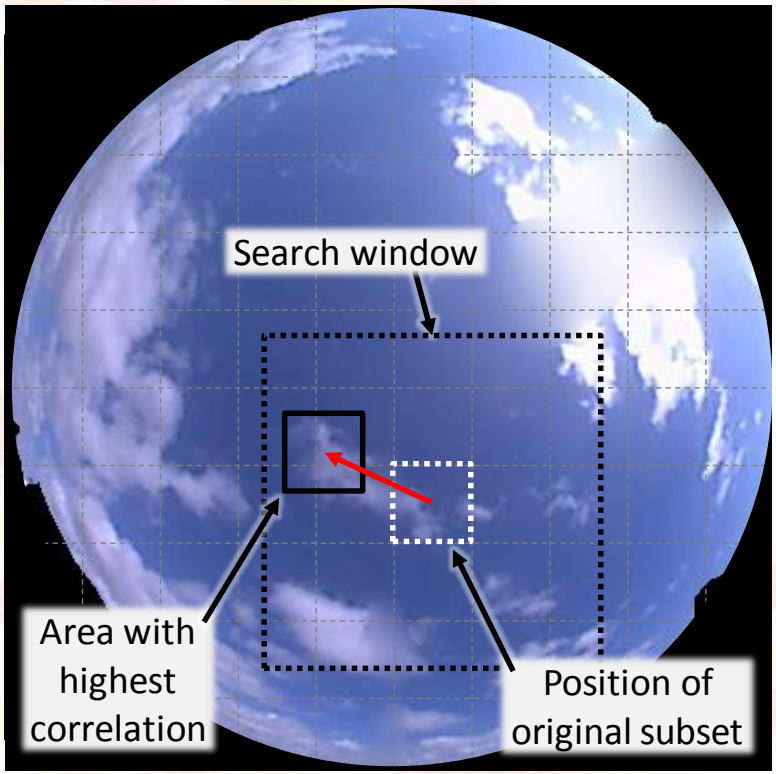


# Cloud Motion

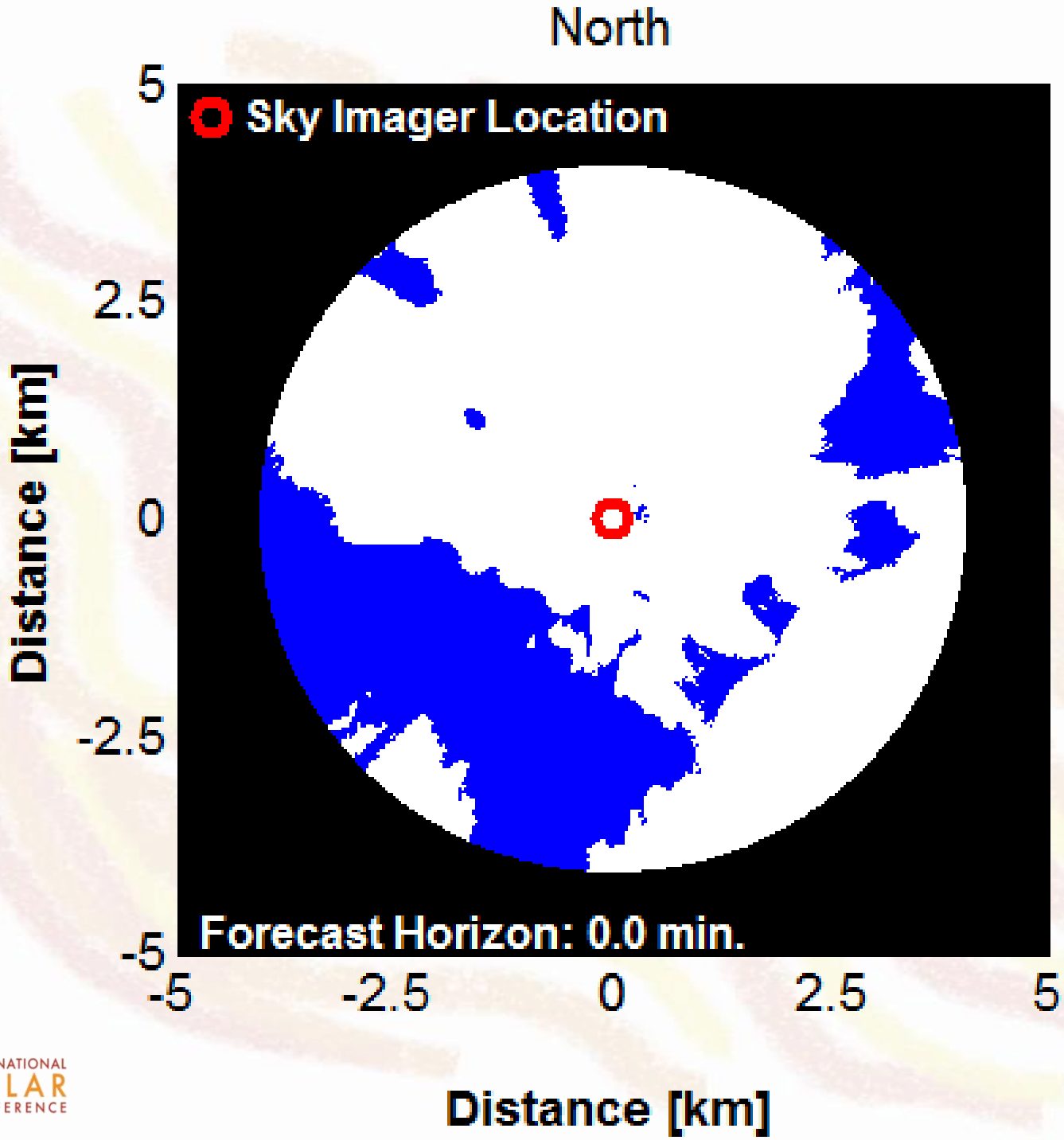
- Cross correlate image subsection within prescribed neighborhood

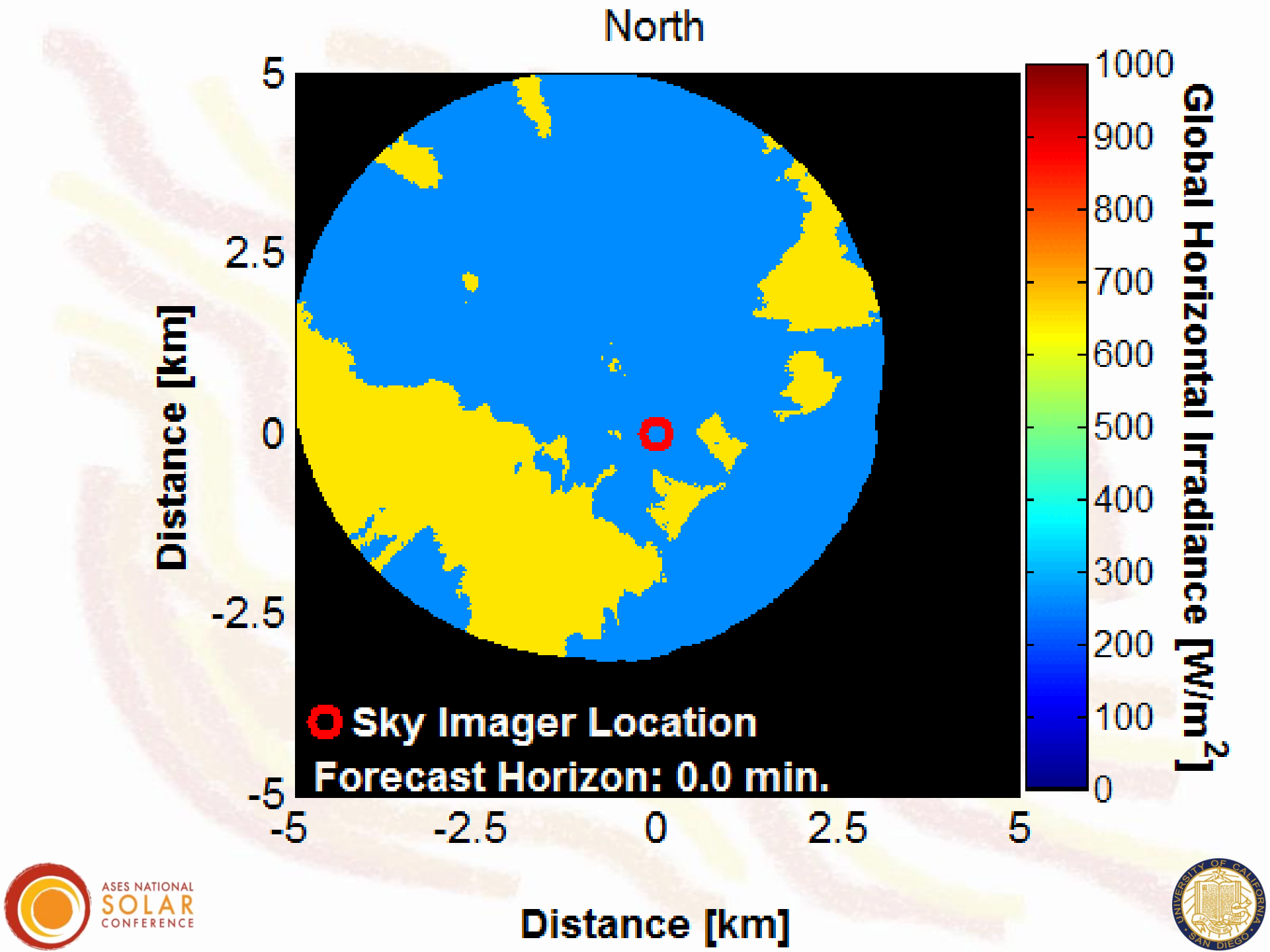



$t = t_o - 30\ sec.$




$t = t_o$


North
Sky Imager Location
Forecast Horizon: 0.0 min.
Distance [km]
5
2.5
0
-2.5
-5
-5
-2.5
0
2.5
5
Distance [km]



# Sky Condition Forecasting

- Binary cloudmap → binary comparison metric
  - Condition is **clear** or **cloudy**
- Sky imager derived condition determined from projected cloud shadows
- For pyranometer measurements:

$$clear \equiv kt > 0.7$$
$$cloudy \equiv kt \leq 0.7 \text{ ,} \qquad kt = GHI/GHI_{csk}$$

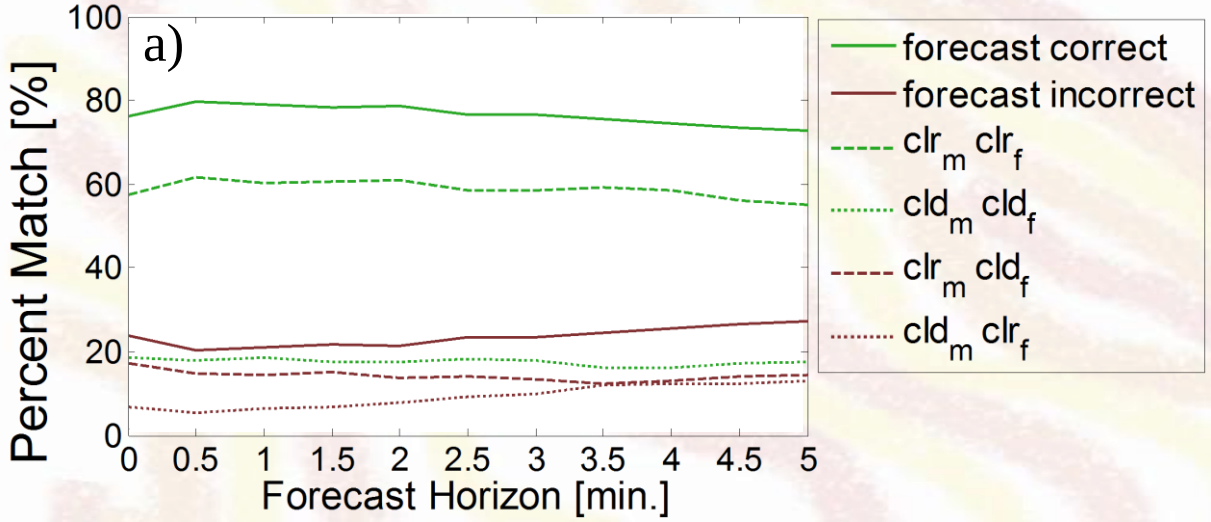
- Four possible outcomes:

| | Sky Imager Forecast | |
|---|---|---|
| Measured | Clear | Cloudy |
| Clear | $clr_m clr_f$ | $clr_m cld_f$ |
| Cloudy | $cld_m clr_f$ | $cld_m cld_f$ |

match:

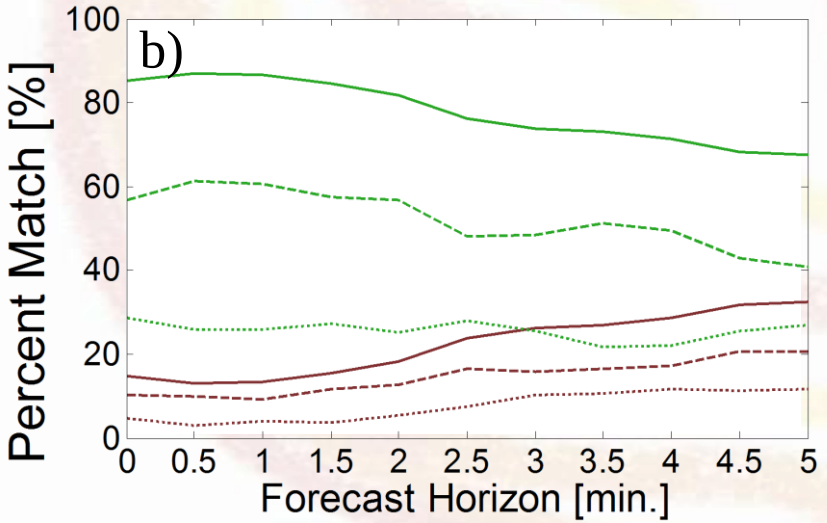
| |
|---|
| Positive |
| Negative |

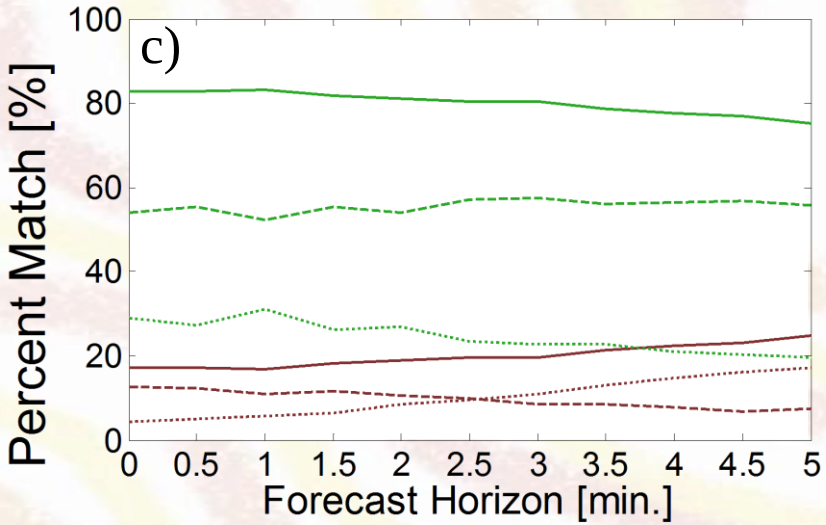
# 5-min Forecast Results




a) All 4 days†
b) October 4, 2009
c) March 10, 2010

| | Sky Imager Forecast | |
|---|---|---|
| Measured | Clear | Cloudy |
| Clear | $clr_m clr_f$ | $clr_m cld_f$ |
| Cloudy | $cld_m clr_f$ | $cld_m cld_f$ |

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†includes September 15, 2009 and March 04, 2010

# Acknowledgements


- DOE High PV Penetration Program
- Sanyo

# Thank you for your time


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