# Advanced Solar Resource Modeling and Analysis

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SunShot
U.S. Department of Energy

# *Advanced Solar Resource Modeling and Analysis*

This proposal aims to significantly reduce uncertainty in the solar resource by improving:

1. Methods for estimating global horizontal irradiance (GHI) from satellite observations;
2. Models that estimate direct normal irradiance (DNI) from GHI;
3. Methods for estimating spatially averaged irradiance over a plant's footprint/fleet of PV systems.

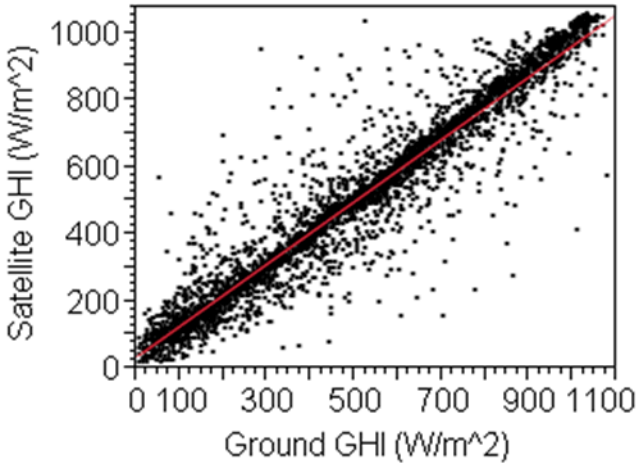
Reduced uncertainty in solar resource will increase accuracy of and confidence in power and energy estimates.

# Relevance to SunShot Goals

- Uncertainty in annual energy production (ratio of P90/P50) is a key factor in cost of financing
  - *Reducing uncertainty in solar resource will reduce financing costs (Tasks 1 and 2)*
- Reserve requirements increase due to variability in solar power output
  - Uncertainty in power modeling adds to output variability and thus to reserve requirements
  - *Reducing uncertainty (by improved models) will lower integration costs (Tasks 2 and 3)*

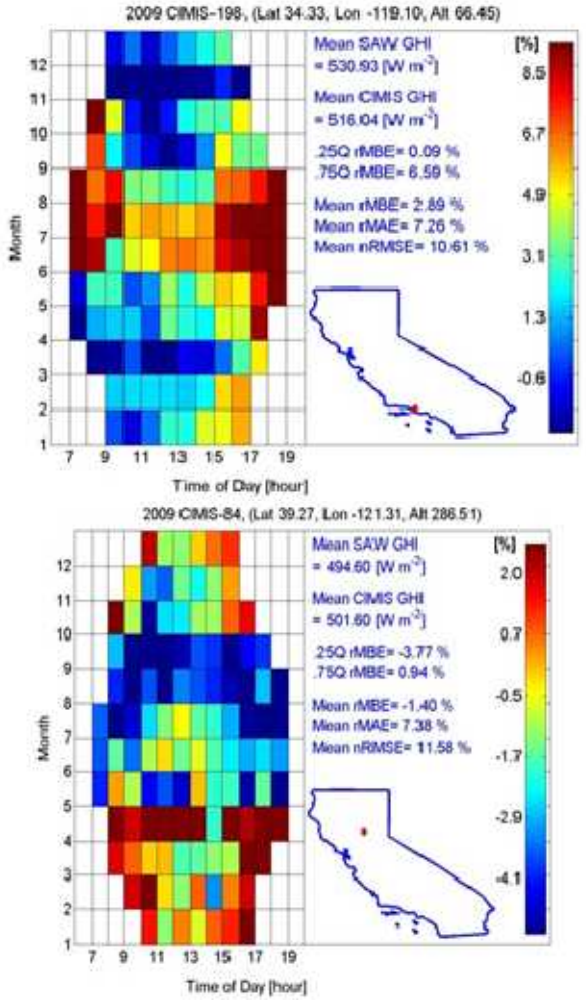
# Current Situation – Satellite GHI

- Analyses of satellite estimates of GHI show opportunities for improvement
- Systematic errors are apparent when individual locations/times are examined




MBE < 1 W/m$^2$
rMSE = 83 W/m$^2$

Stein et al., 2010




Jamaly and Kleissl, 2012

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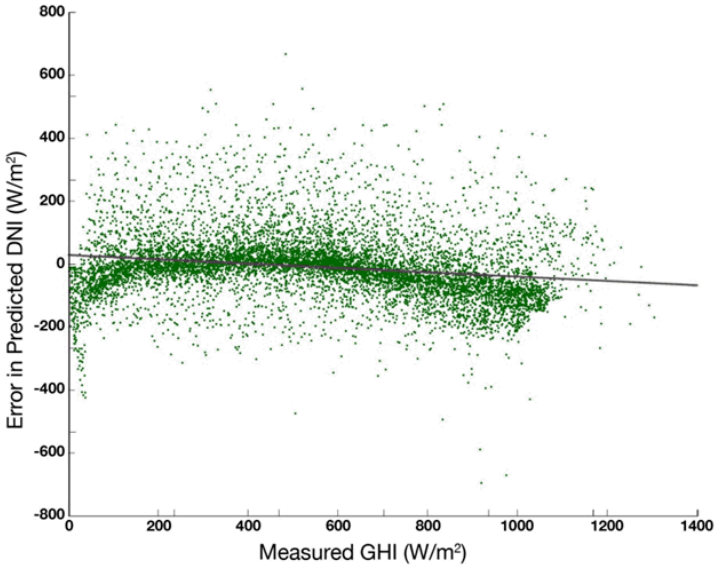
# Current Situation – DNI models

- More than 250 models have been proposed to separate GHI into components (Gueymard, 2010)
- No significant advances in model accuracy in last 20 years
- Models share common weakness:
  - Stationary, typically linear, empirical correlations
  - Relative few accurate measurements of DNI

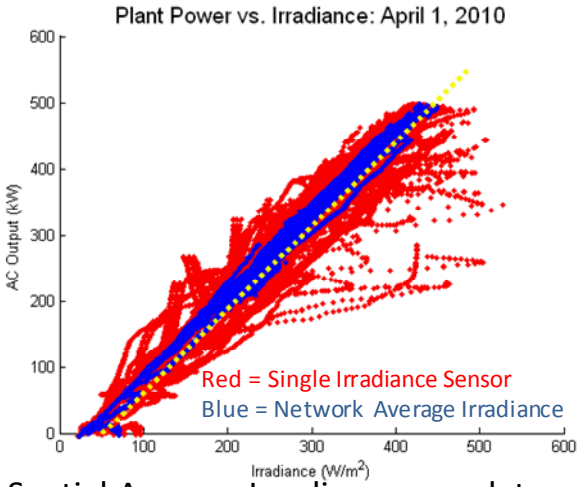



Error in modeled DNI

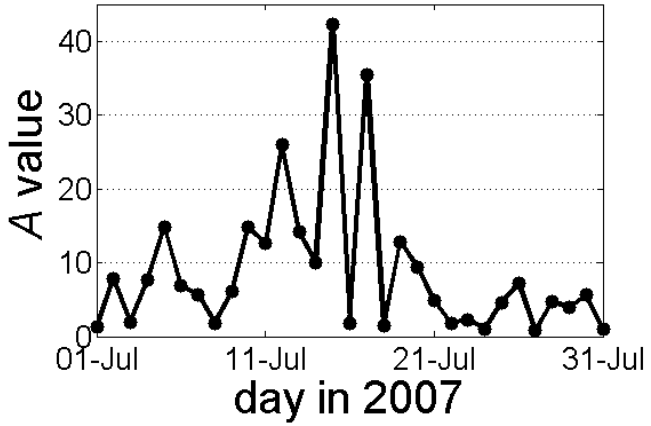
(DIRINT model, Perez et al. 1992)

# Current Situation – Spatial Smoothing

- Want to simulate output from a large plant.
  - Aggregate power correlates well with spatial average irradiance.
  - Typically we only have measured irradiance at a few locations.
  - Have to "smooth" irradiance over space.
- Similar challenges when simulating aggregate output for a fleet of plants
- Current smoothing methods rely on simple stationary filters, or a stationary calibration to spatio-temporal data.




Spatial Average Irradiance correlates with power (Kusmaul et al. 2010)




Smoothing model calibration is not stationary (Lave et al., 2012)

# Summary of Tasks

1. Improve satellite-based estimates of irradiance
2. Improve models that estimate direct normal irradiance (DNI) from global horizontal irradiance (GHI)
3. Better methods to represent reduction in irradiance variability due to geographic dispersion

Common themes:

- Apply advanced time series methods
- Leverage recent Sandia innovations:
  - Algorithm for automatically identifying clear-sky periods
  - Methods for cleaning lesser quality ground measurements

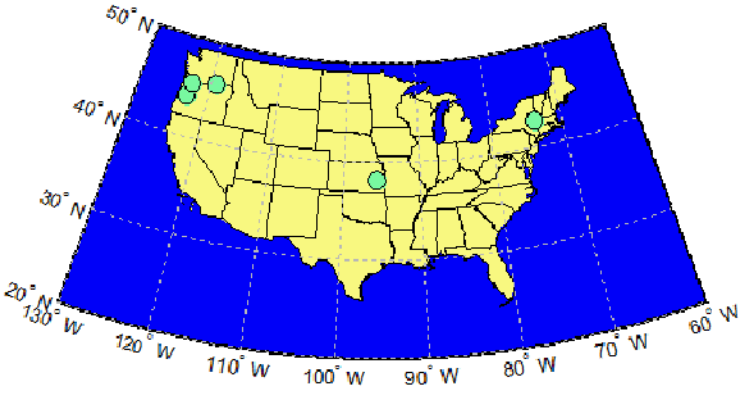
# Proposed Budget and Timeline

Total: $1.2M over 3 years

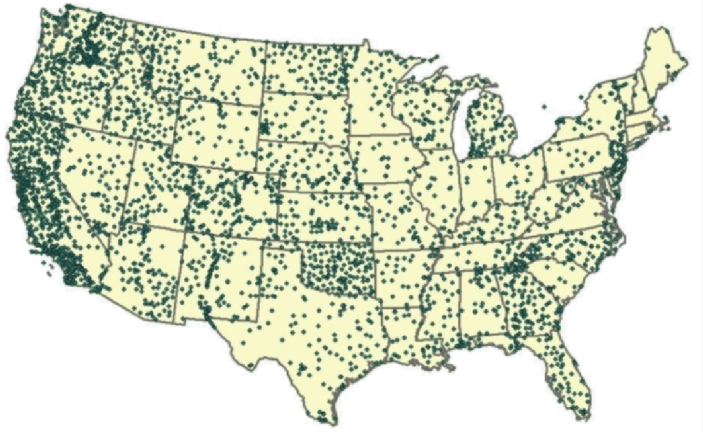
- Sandia: $840K, project leadership, data analysis, reporting, validation, interactions with utilities
- Baylor: $270K, statistical methods, data analysis and reporting
- CleanPowerResearch: $0, collaborative no-cost research partner:
  - —provides satellite-based irradiance data
  - —platform for prototyping and validating improvements

# 1. Improving satellite-based estimates

- Leverage regional ground measurements in irradiance model calibration:
  - Current models are calibrated nationally at a few locations.
  - We will calibrate on a regional basis leveraging additional data.
  - Analyze and model spatio-temporal errors (similar to Model Output Statistics (MOS)).
- Research partnership with CPR
- *Improved modeling will:*
  - *Reduce uncertainty in annual energy esp. regarding P90/P50*
  - *Reduce location-dependent error*



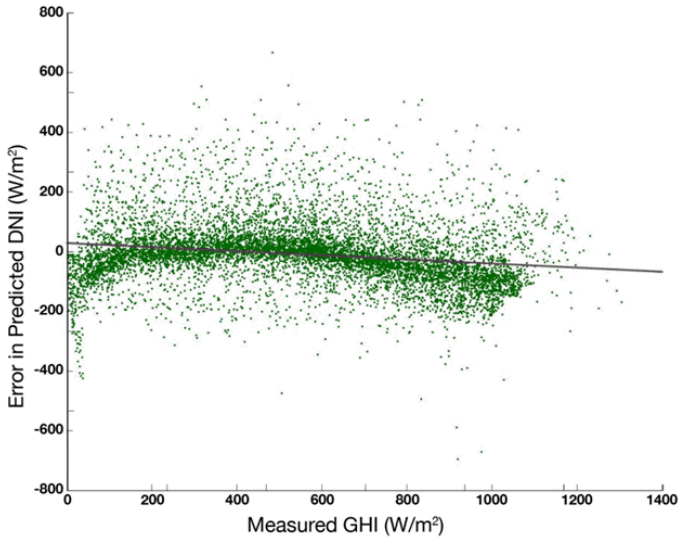

Locations used to Calibrate Satellite Irradiance Model (Perez et al, 2002)



Ground Measurements of Irradiance (SolarDataWarehouse, 2012)

# 2. Improve models for DNI

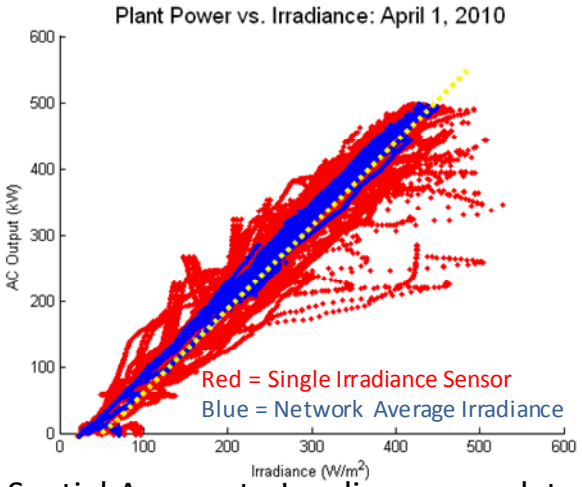
- Apply nonstationary time-series methods:
  - DNI is affected primarily by aerosols and precipitable water.
  - GHI is also affected by these quantities.
  - Time-series of GHI contain information about DNI.
  - Consideration of time-series is key to separating effects of shading (short-time transients) from atmospherics.
- *Improved DNI model will reduce uncertainty in CPV/CSP power prediction.*



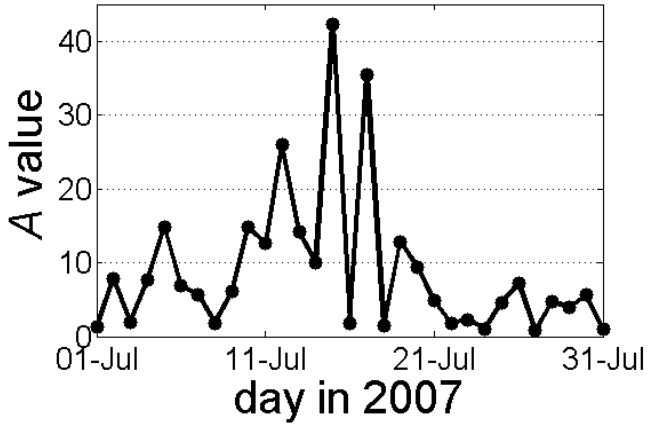

Error in modeled DNI (DIRINT model, Perez et al. 1992)

# 3. Better methods to represent smoothing

- Use vector-functional coefficient autoregressive (VCAR) methods to overcome stationarity.
- We will model the relationship between point measurements and spatial average.
  - Apply at various spatial scales, from an individual plant to fleets of distributed systems.
- Goal is to produce validated algorithms and efficient computational procedures.
- *Improve fidelity of power simulations for integration studies.*




Spatial Aggregate Irradiance correlates with power (Kusmaul et al. 2010)




Smoothing model calibration is not stationary (Lave et al., 2012)

# Coordination with Other SunShot Work

- Complementary to NREL's SRA proposals
  - —SNL focus is on modeling methods
  - —NREL focus is on measurements, uncertainty quantification and dissemination
- SNL SRA proposal supports grid integration
  - —Improving foundational input (irradiance) for power simulations
  - —Providing better methods to represent geographic correlations
- Collaborative with academic and industry leaders

# Why Sandia, Baylor and CPR?

- Sandia brings expertise in grid integration and trusted collaborative relationships with solar power and electricity industries
  - —Access to data sources
  - —Leverage recent innovations
  - —Ensure research is guided by its application
- Baylor brings deep expertise in spatio-temporal statistical modeling
- CleanPowerResearch develops and deploys state-of-the-art estimation of irradiance from satellite data

# Technical Challenges and Risks

- Proposed statistical methods have not previously been applied to model irradiance
  - Model forms may need adjustment, calibration can be more difficult than estimated
  - Even with excellent calibration, model improvements may be modest
  - Uncertainty in irradiance dominates uncertainty in annual energy
  - Potential for improvement merits taking a research risk
- Models may be computationally intensive
  - Mitigated by access to Baylor's and Sandia's HPC clusters
  - May complicate transition to industry where computing resources may be slim

# Summary

We intend to significantly reduce uncertainty in the solar resource by improving:

- Satellite estimates of GHI
- Models for DNI
- Methods for representing spatial smoothing

*Increased accuracy and confidence in power and energy estimates.*

# Questions?

# Backup - Satellite-based estimates of irradiance

- Current methods:

  From visible and IR channels*

  1. Convert pixel value to cloud index
  2. Simulate clear-sky GHI
  3. Scale clear-sky GHI using cloud index

- Coefficients determined by calibration at a few locations
- Spatio-temporal errors show evidence of systematic discrepancies

*IR channel data used to help distinguish clouds from snow cover

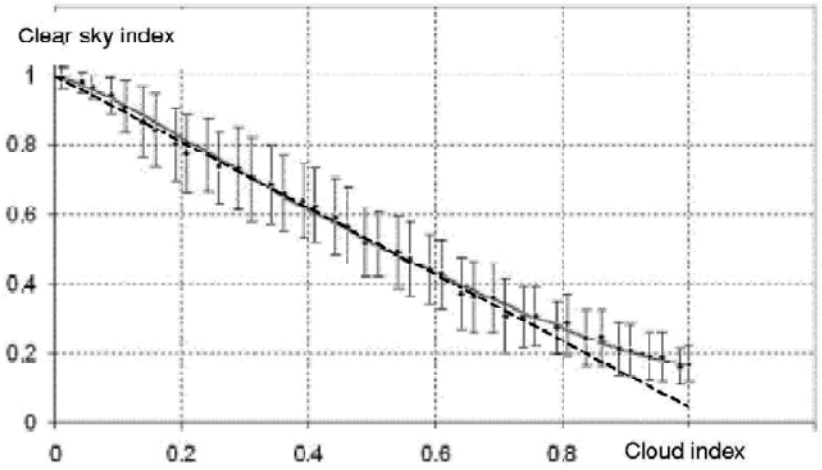
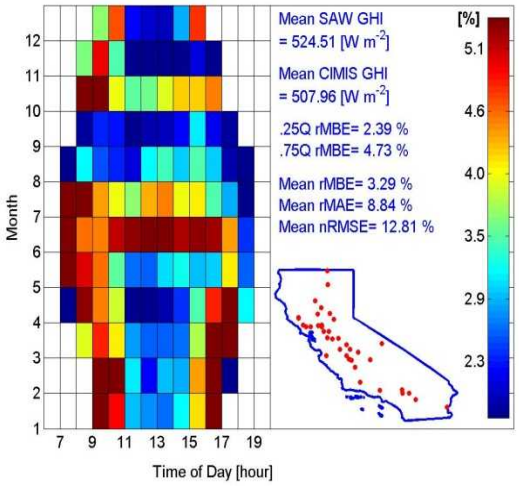



Fig.4, Perez et al. (2002)

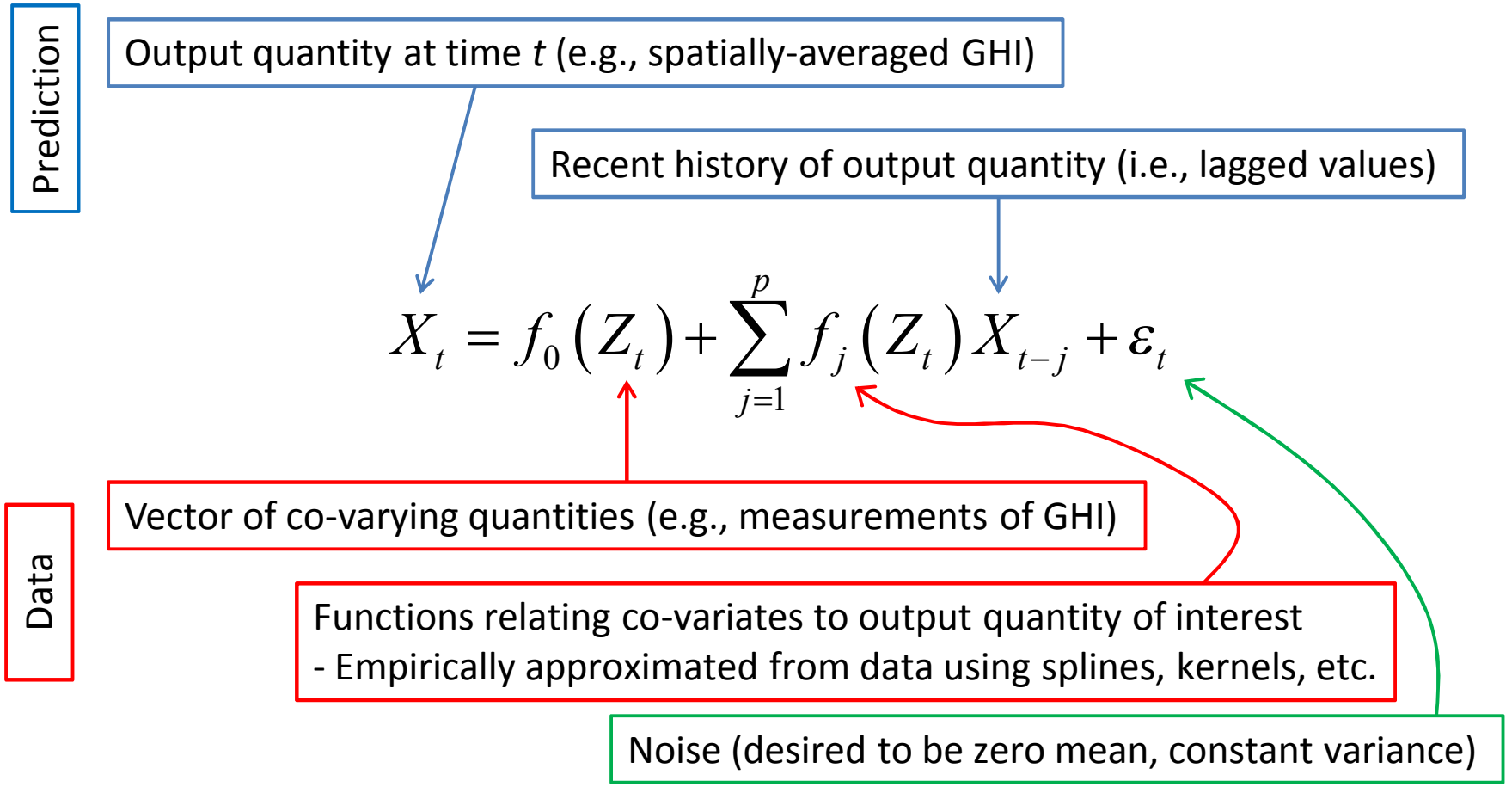



Spatially-Averaged Error in SolarAnywhere Daily GHI for 2009 (Jamaly and Kleissl, 2012)

# Backup – Valuing Additional/Improved Ground Measurements of Irradiance

- Satellite-to-irradiance conversion model will be improved through use of additional ground measurements
- Developed methodology can also be applied to quantify the value of additional/improved ground measurements
  - —Hypothesize new ground measurements
  - —Calculate improvement in satellite irradiance (reduced uncertainty)

# Backup – Vector functional coefficient autoregressive modeling



# Backup – Algorithm to identify clear-sky periods in irradiance data

- Calculate 5 simple statistics from GHI time series
  - Mean GHI, Max GHI, line length, variance of changes, maximum change
  - Compare with clear-sky model to detect clear perios
- Automated separation of GHI time series in clear and cloudy periods