National Renewable Energy Laboratory
Innovation for Our Energy Future

Estimating Solar PV Output Using Modern Space/Time Geostatistics

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Project Description - Motivation

- PV output data for any location in SW US, 10 minute time step are required to assess the grid environment under high penetrations of wind, CSP, PV
- Solar measured PV data is spatially sparse but temporally dense
- Satellite (modeled) PV data is spatially dense but temporally sparse
- New measurement stations are needed, but they must be sited effectively, and data must be assimilated into applications
- There is no current research using geostatistics and atmospheric science on PV modeling

Project Description

- **Mapping Situations**

  - Hourly inaccurate modeled data on 10km solar grids + 10-minute measured data at several locations

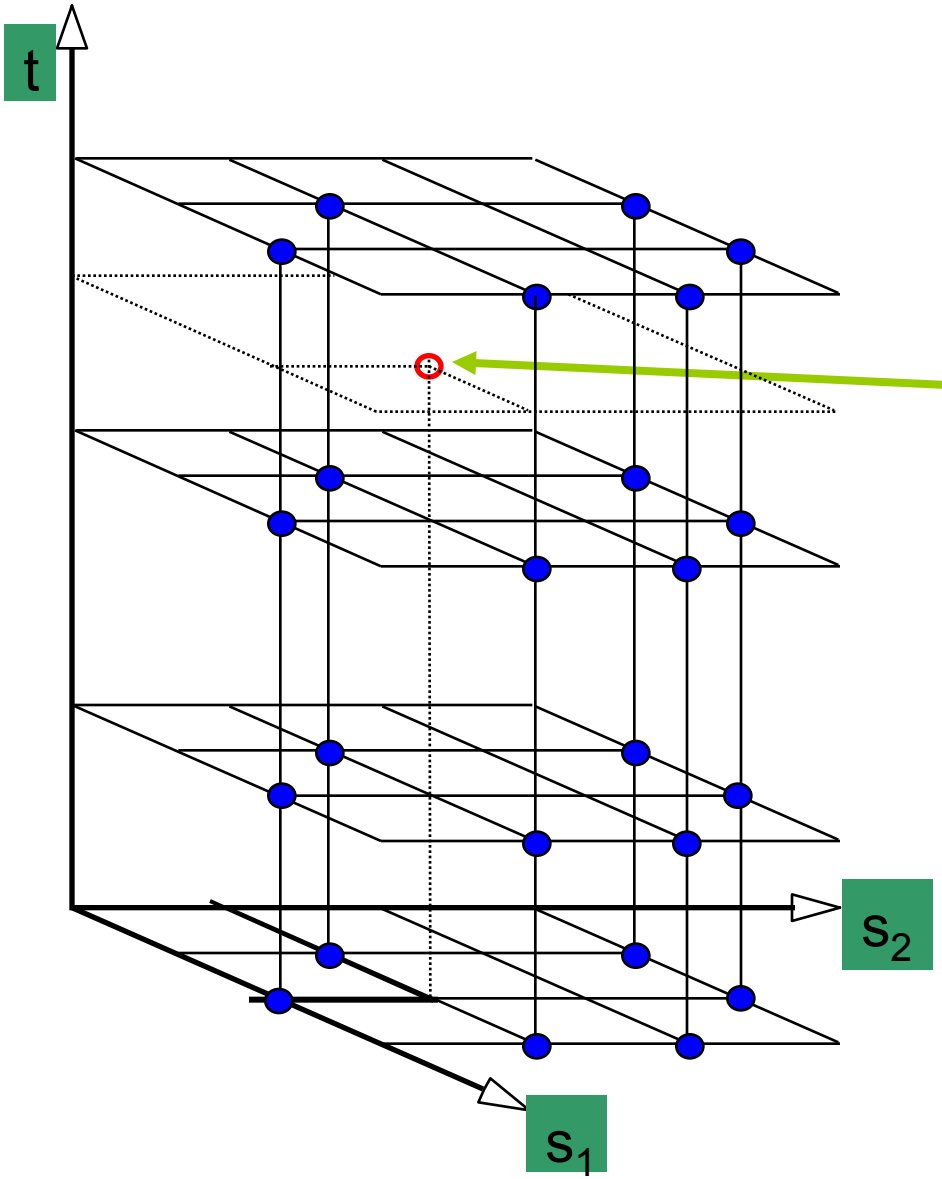
- **Goals**

  - Predict solar output at subhourly resolution at any spatial points (disaggregation & extrapolation)
  - Develop a methodology that is applicable to natural resources in general
  - Demonstrate capability of geostatistical techniques to predict the output of a potential solar plant

- **Technology-Transfer Opportunities**

  - Publication of the basic statistical methods in the open literature
  - Distribution of the computation-intensive geostatistical software
  - Application to “siting” for RE data collection

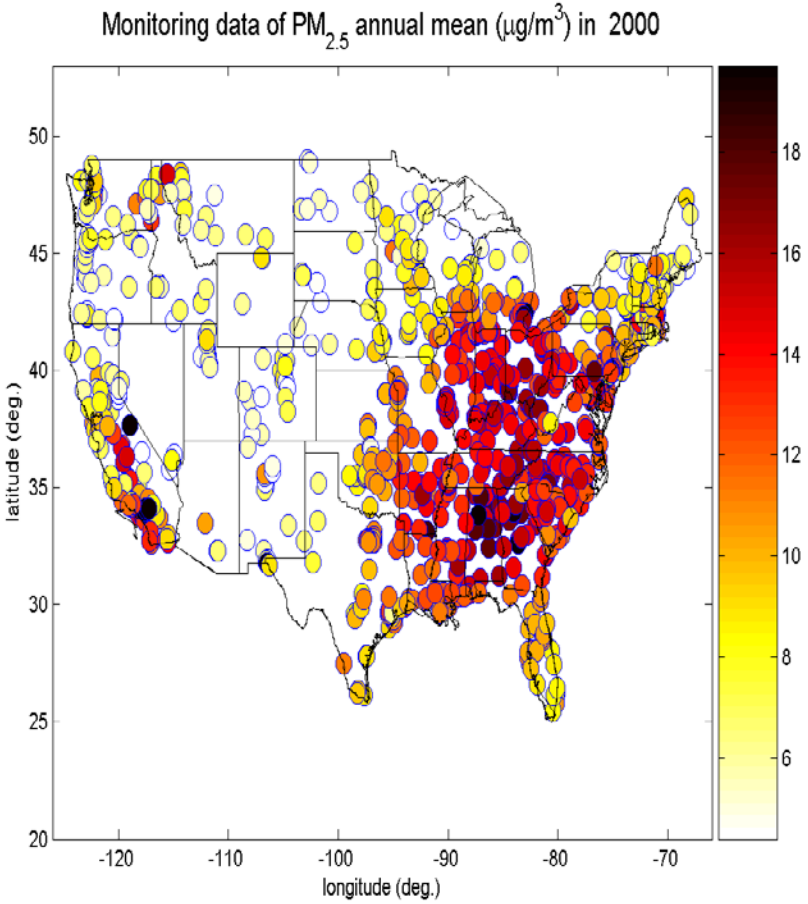
Space/time Geostatistics



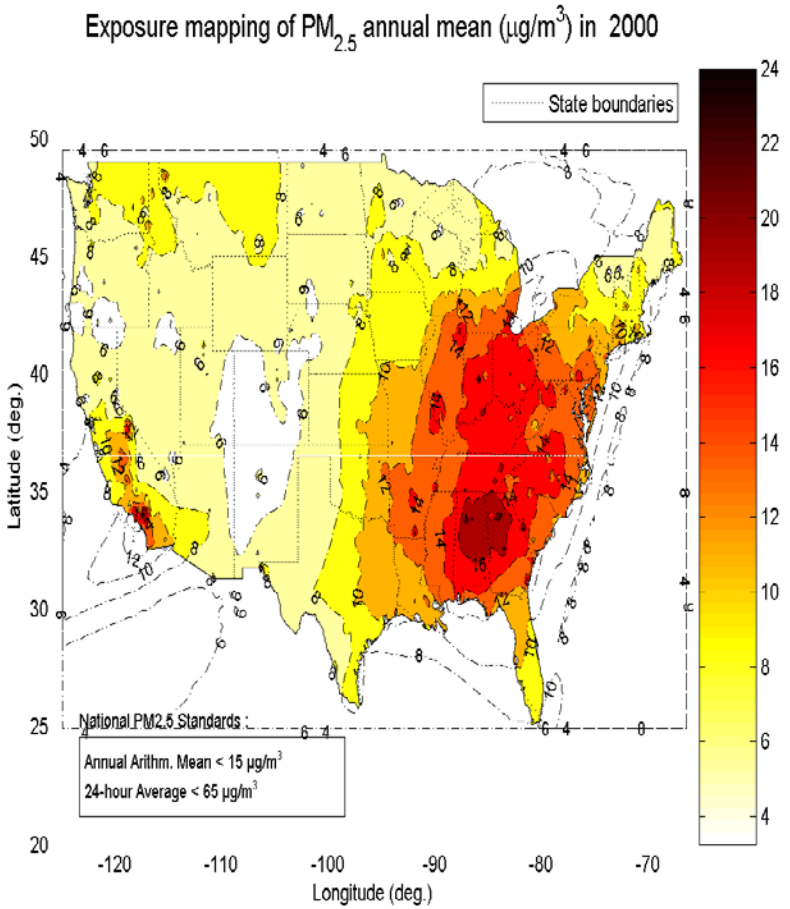
Its main job is to provide an estimate at an unsampled space/time coordinate

An Example of Geostatistics

$PM_{2.5}$ data over the U.S.



$PM_{2.5}$ estimates over the U.S.



Classical vs. Modern Geostatistics

Classical Approach

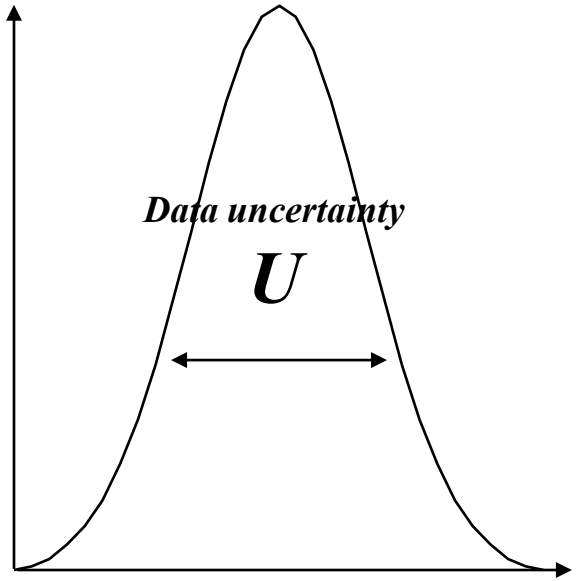
- Linear estimator
- Interpolation
- Integrates variability and randomness between samples
- Estimation error as a function of error-free measurements
- Gaussian assumption (mean & variance only)
- No incorporation of data uncertainty (hard only)

Modern Approach

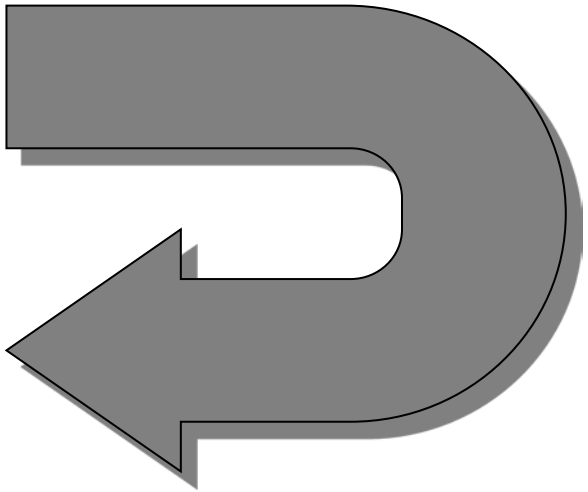
- Non-linear estimator
- Interpolation and extrapolation
- Integrates variability, randomness, and data uncertainty between samples
- Estimation error as a function of error-free or error-containing measurements
- No Gaussian assumption
- Incorporation of data uncertainty (hard and soft)

Hard vs. Soft Data

Probabilistic soft data



If U is neglected



hardened data; deterministic values

If U is accounted for

Modern Geostatistics

Process various physical knowledge available

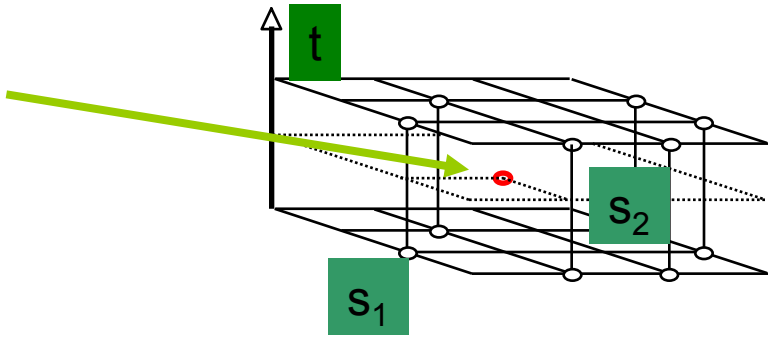
1. General knowledge
   - statistical moments (autocorrelation in space and time)
   - physical laws (fate and transport, chemistry, etc.)
2. Site-specific knowledge
   - exact measurements called hard data
   - measurement with uncertainty called soft data

Produce a complete stochastic characterization of variables at the estimation point in terms of the BME posterior probability density function (PDF)

$$Prob[\boldsymbol{x}_k < \boldsymbol{u}] = \int_{-\infty}^{\boldsymbol{u}} d\chi_k f_S(\boldsymbol{\chi}_k)$$

Modern Geostatistics

We estimate *x* at unsampled point across space and time



mean and covariance

error-free hard and uncertain soft data

Geostat.

Posterior PDF at the estimation point

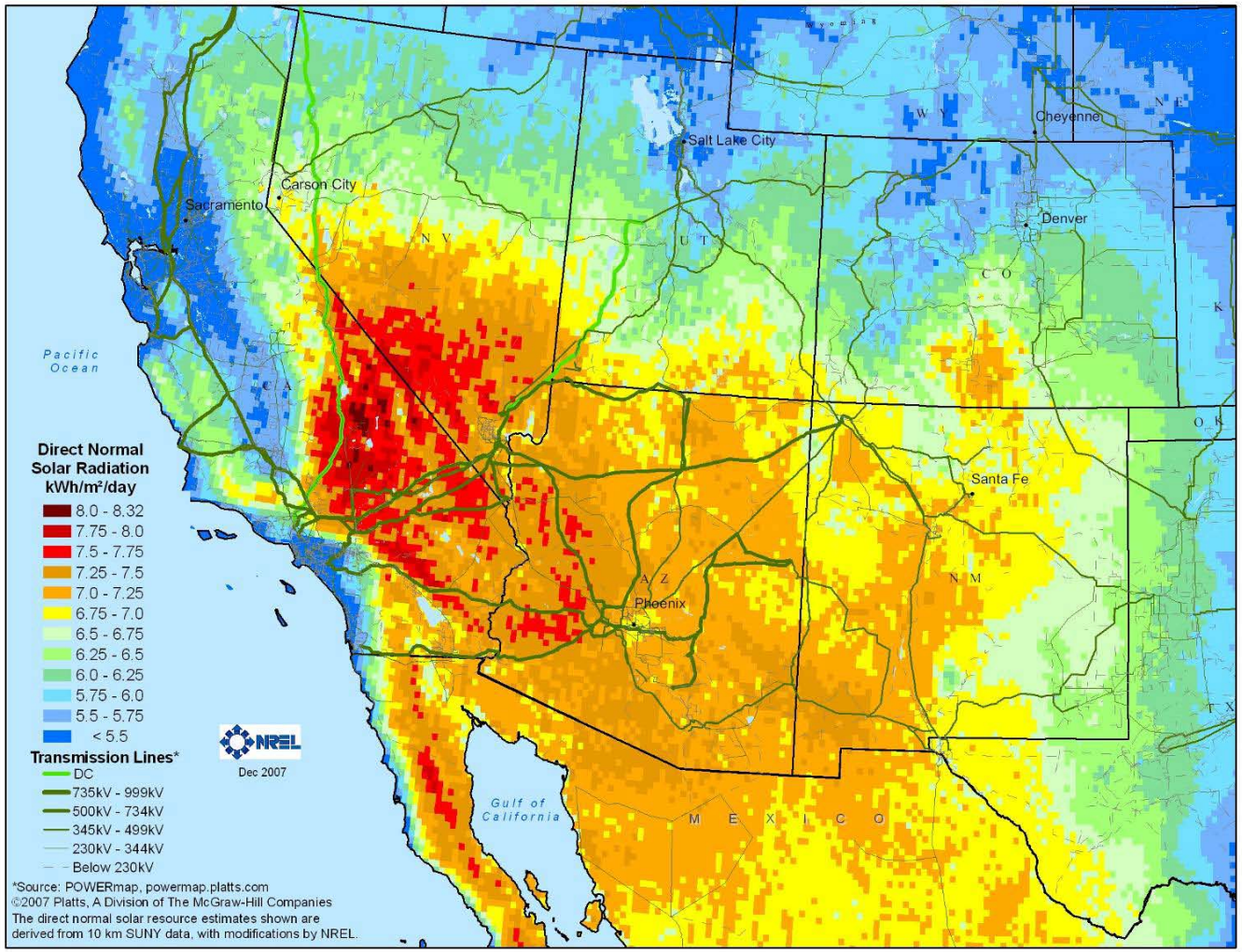
$f_K(\chi_k)$

BME estimate of *x*

68 % BME confidence interval

Southwest Solar Resources

This slide from Strategic Energy Analysis Center, NREL



Distributed Energy Interconnection Testing

This slide from Electric, Resources, Building Systems Integration Center, NREL

Distributed Energy Resources


Fuel Cell


PV


Microturbine


Wind


Energy Storage


PHEV - V2G


Generator

Interconnection Technologies

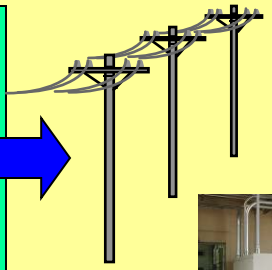

Inverter


Switchgear, Relays, & Controls

Functions

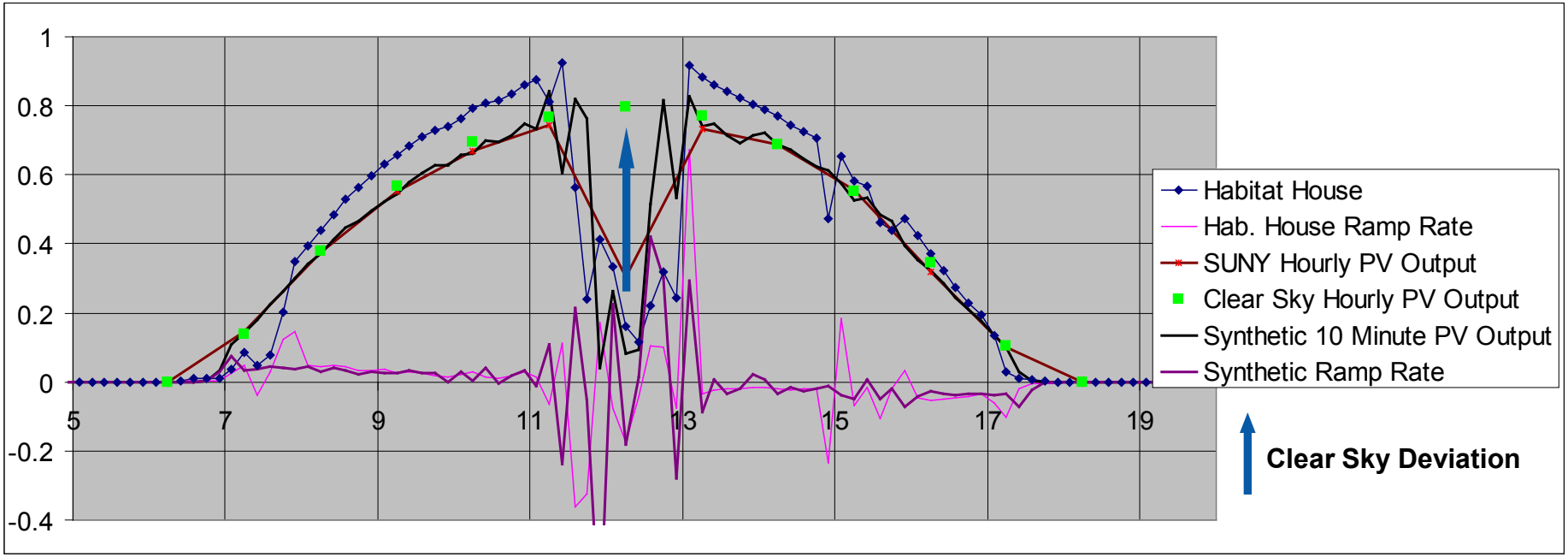
- Power Conversion
- Power Conditioning
- Power Quality
- Protection
- DER and Load Control
- Ancillary Services
- Communications
- Metering

Electric Power Systems



Loads

Cloud Effect on PV output



Data Available for PV Modeling

Solar radiation – satellite modeled – hourly “snapshots”

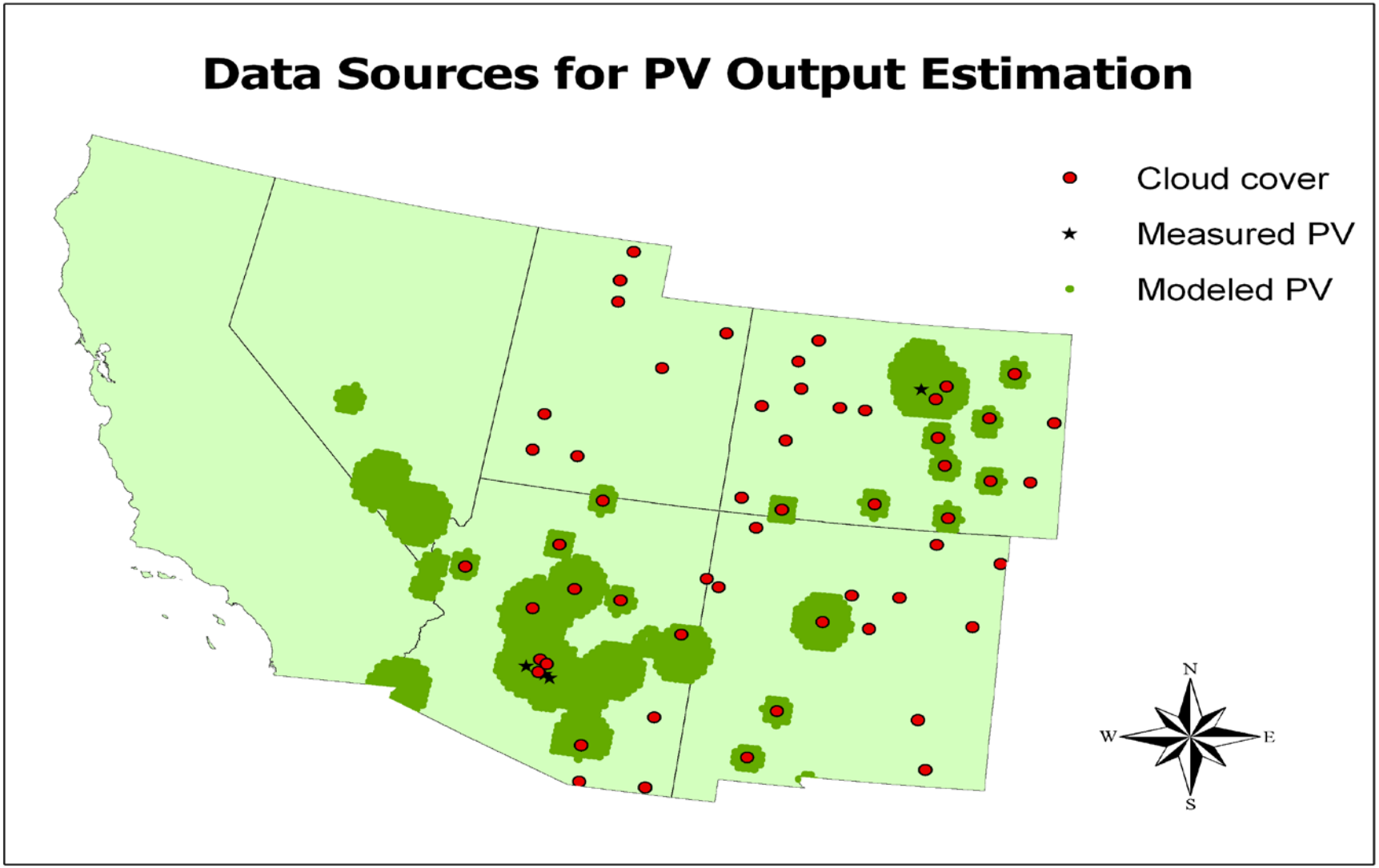
Cloud cover – 10 minute measured from Automated Surface Observing System

Modeled PV output – uses PVWatts (calculator for grid-connected PV systems) for any collector orientation → hourly PV output on 10 km solar grids

Measured PV Output – AC power, 1 minute or 10 minute averages → 10-minute PV output at 5 locations (4 in Arizona and 1 in Colorado)

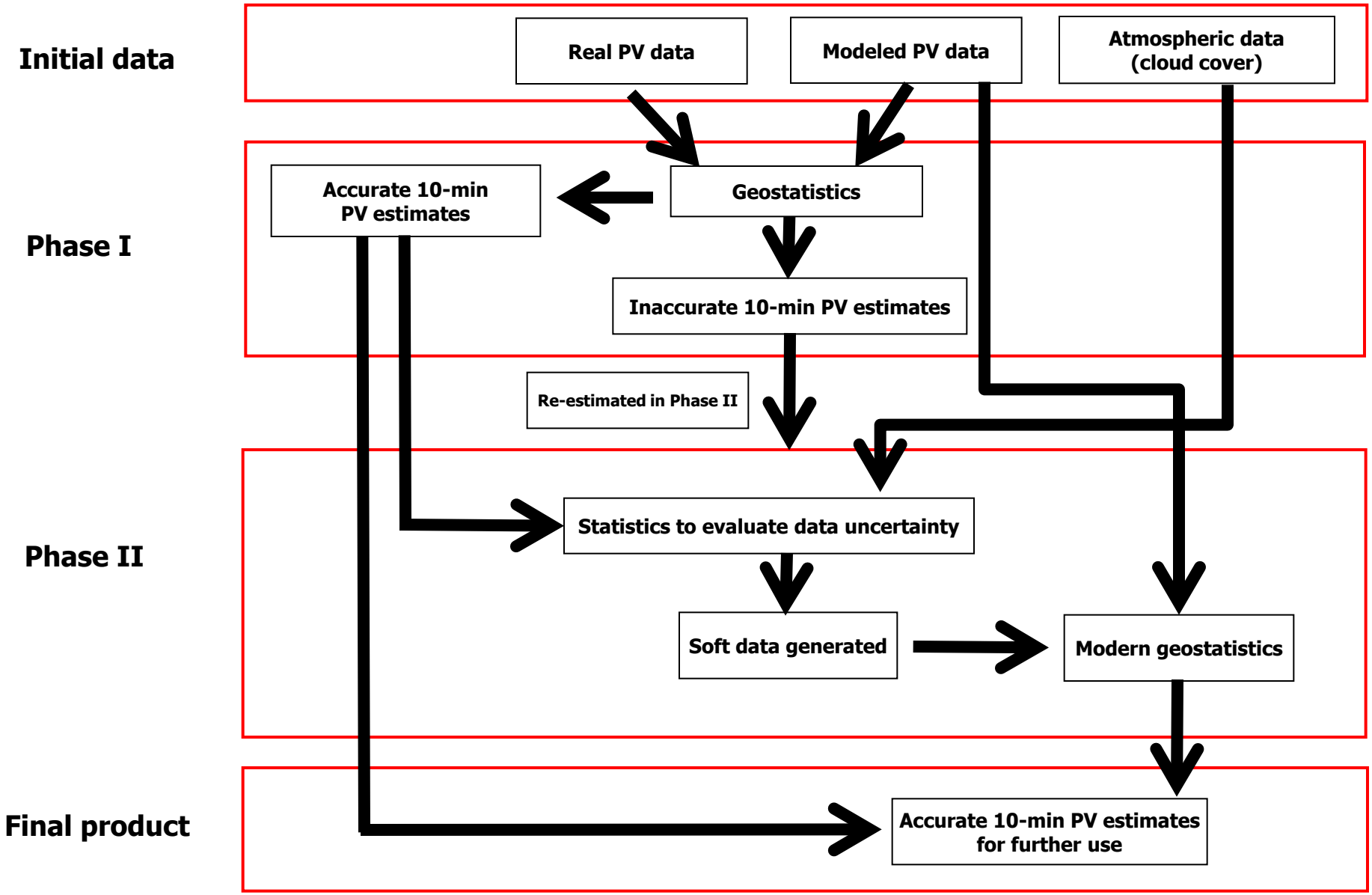
All PV outputs are normalized to the standard DC output of the PV panels.

Datasets We Used

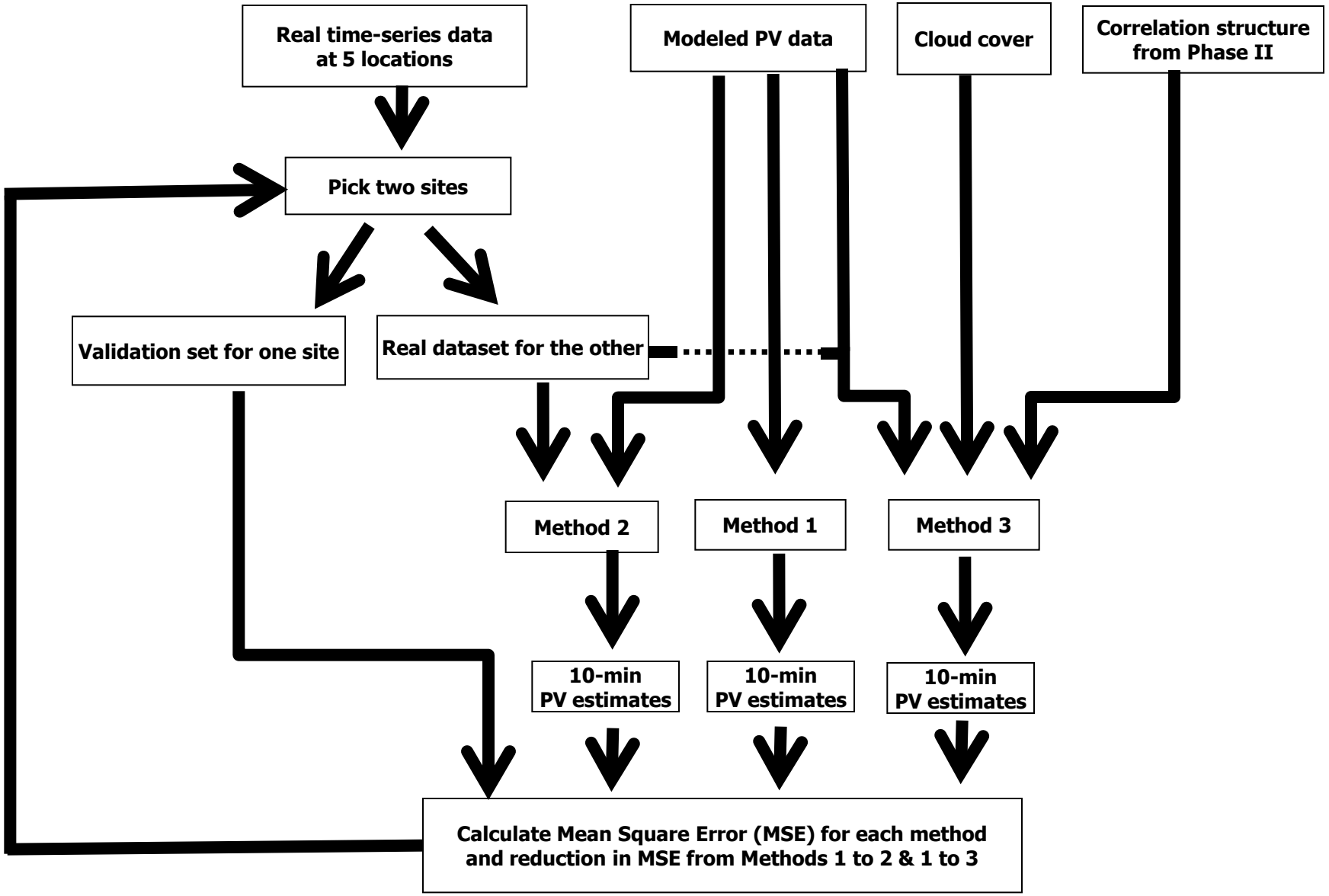


1-axis tracking Photovoltaic Plants over the Phoenix area

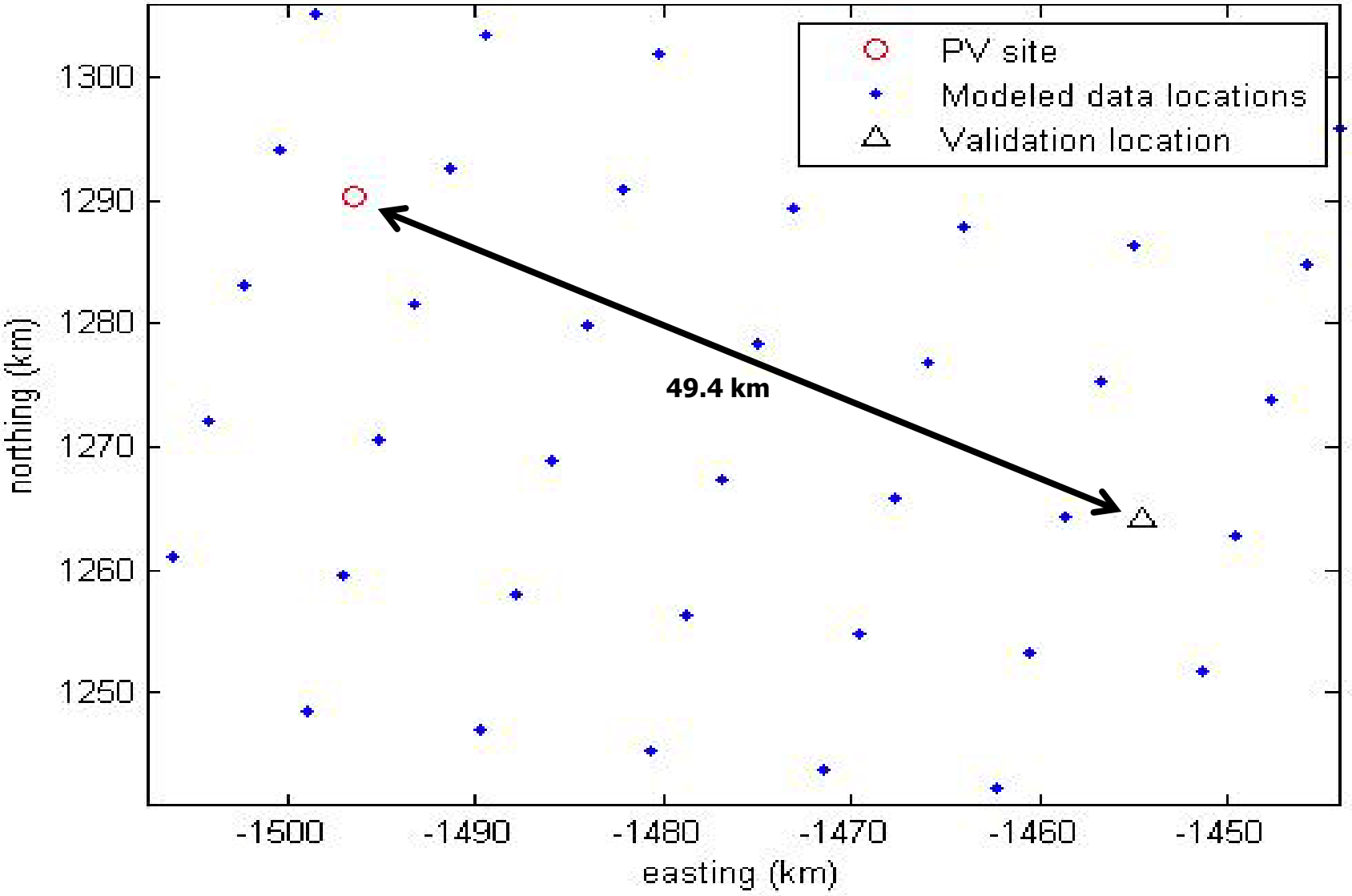
Project Procedure – Flow Chart



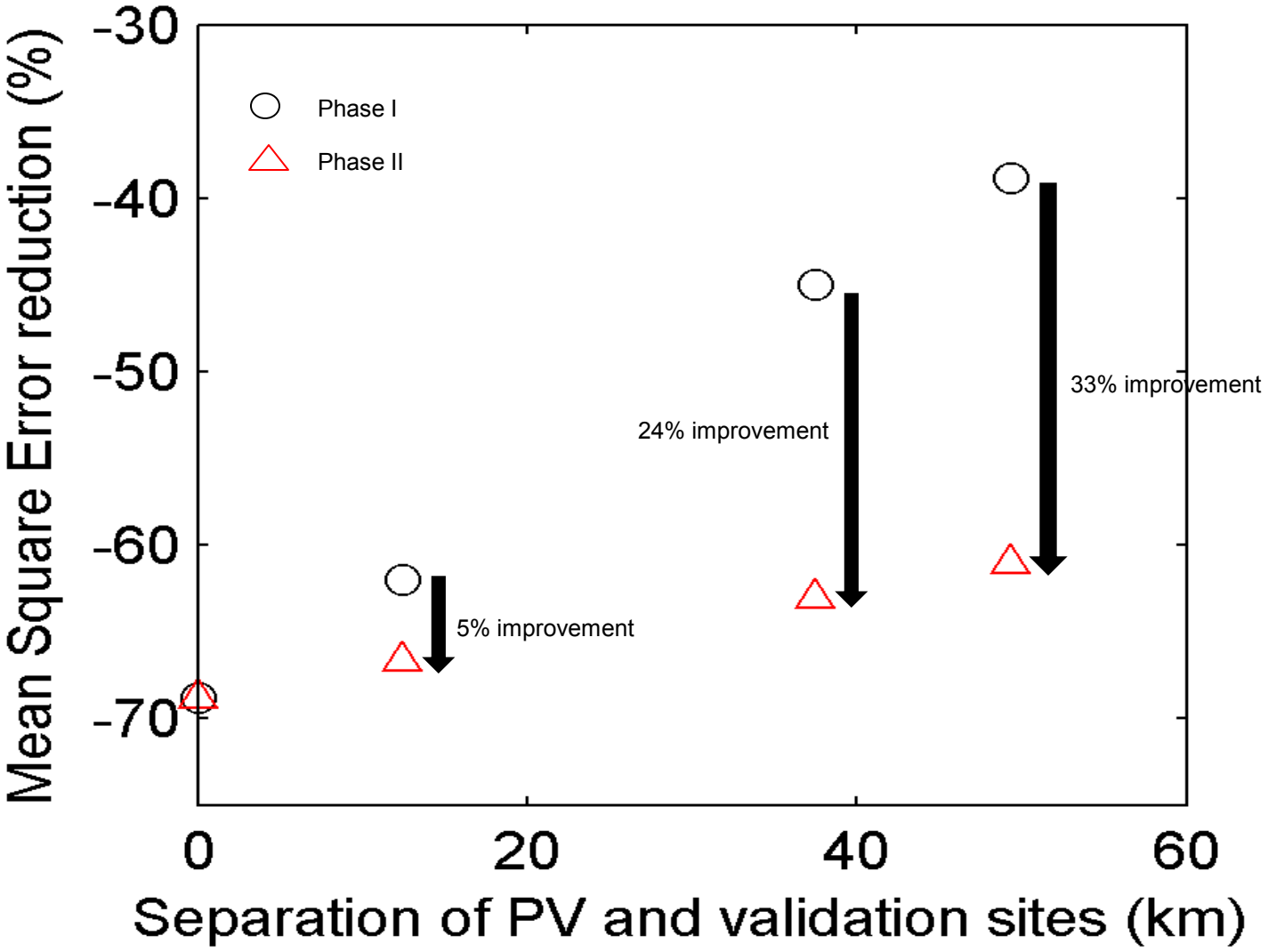
Validation Procedure



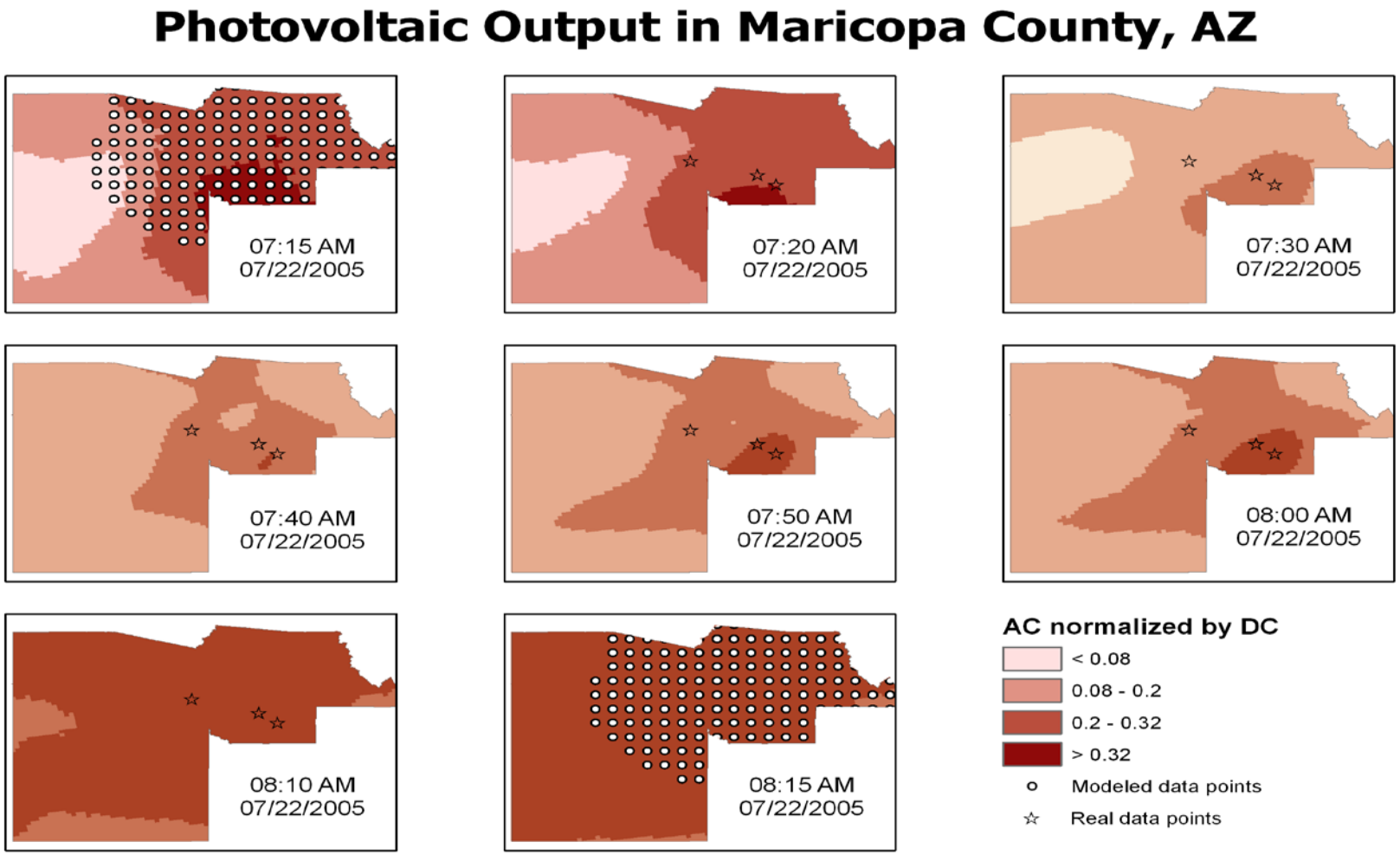
A Case of Validation (Case 1)



Validation Results



PV Output Estimation Maps



Conclusions

- The incorporation of real measurements into model-based PV estimates (Phase I) improves those estimates relative to model-only estimates within radii of approximately 15 km
- The accurate Phase I results can be extended spatially and temporally through the use of statistical models based on the correlation between Phase I results and atmospheric data (Phase II)
- Accounted for data uncertainty in PV model data that contain more biases than real measurements
- This technique can be used to quantify the value of measured data and provide guidance on the choice of new measurement sites
- This technique can be readily applied to wind and other RE resources (PV is actually a more difficult case than other RE resources because of fewer constraints on PV output and poorer data quality)