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Validation of PV Performance Models Using Satellite-Based Irradiance Measurements: A Case Study

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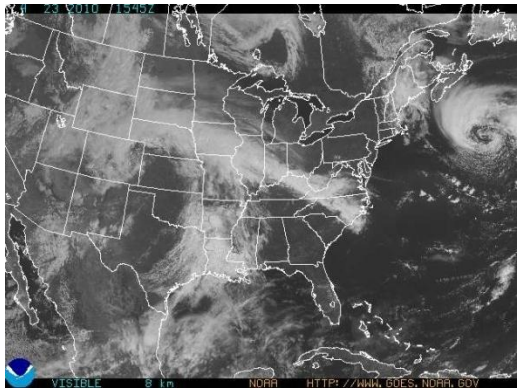
Introduction

- **PV performance models are used for:**
  1. **<u>Prediction</u> of expected energy production for project proposals**
     - **Evaluation of different designs (e.g., tracking vs. fixed, module technology, inverter, BOS) and locations.**
  2. **<u>Monitoring</u> of system performance**
- **Weather data is required for input to models**
  - **Typical Meteorological Year (e.g., TMY2 & TMY3)**
  - **Dedicated weather station at site**
  - **Satellite-based products**

Satellite-Based Irradiance and Weather



- Available nearly everywhere
  - Data from geostationary satellites
  - 2 to 10 km spatial resolution
- Availability
  - Raw imagery is available from NOAA (free)
  - SUNY Database (10 km)
    - Current data from Clean Power Research's SolarAnywhere (fee). Includes air temperature and wind speed.
    - NSRDB has data from 1991 – 2005 (free)
  - 3Tier offers ~3km data for 10-13 year period (fee)
  - Others…

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Problem Statement

- How accurate are system performance models based on satellite weather data?
- Which model applications are more sensitive to satellite-based weather errors?
- Do different performance models respond to weather uncertainties differently?

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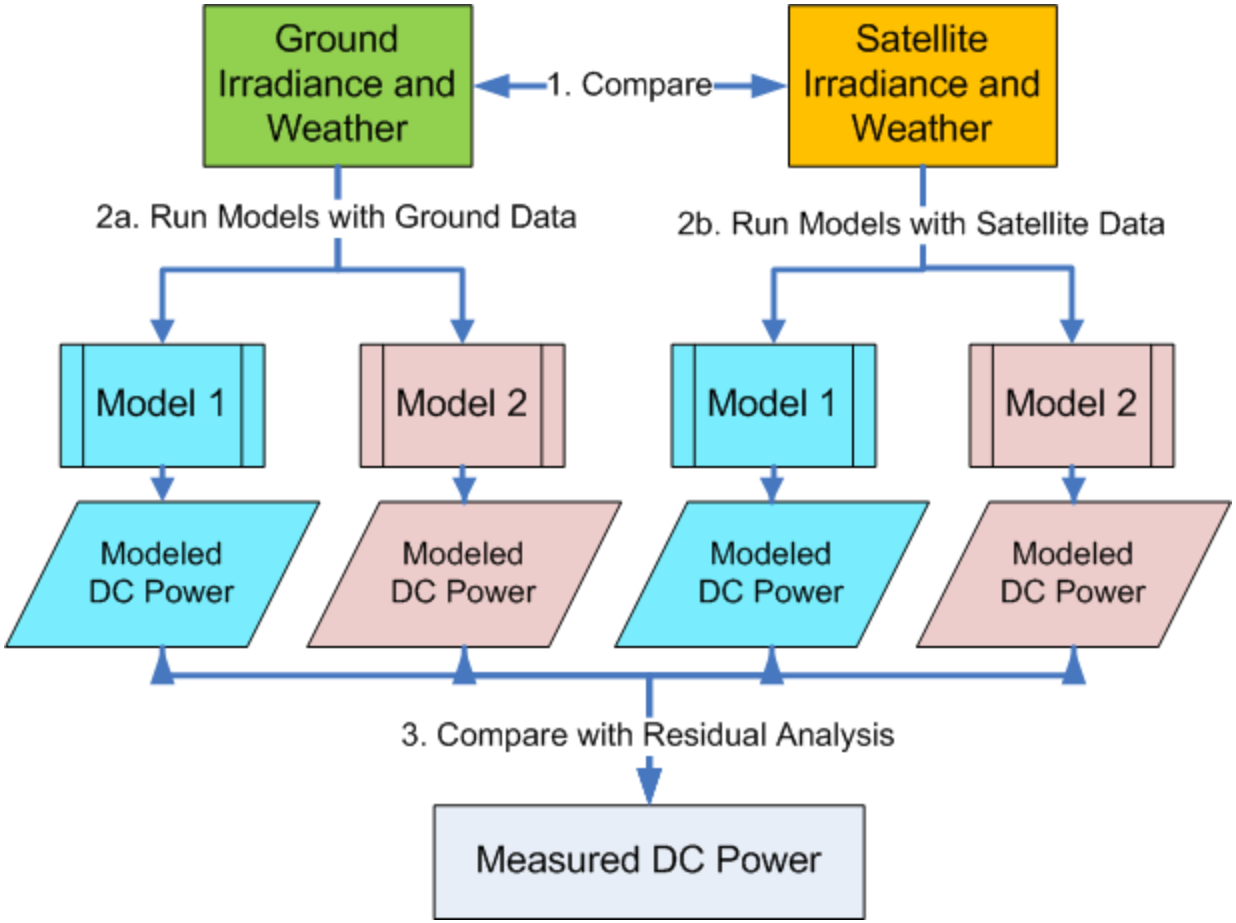
Analysis Methods



Data

- 1 kW DC, m-SI photovoltaic system in Albuquerque, NM
  - 1 year of hourly-averaged weather and performance data collected at site.
    - GHI, DNI, DHI, air temperature, wind speed
    - DC (and AC) current and voltage
  - 1 year of hourly satellite irradiance and weather data from Clean Power Research's SolarAnywhere database.
    - GHI, DNI, air temperature, wind speed
  - 1 year of performance data (DC and AC current, voltage, and power)

Array Configuration

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Inverter and DAS Configuration

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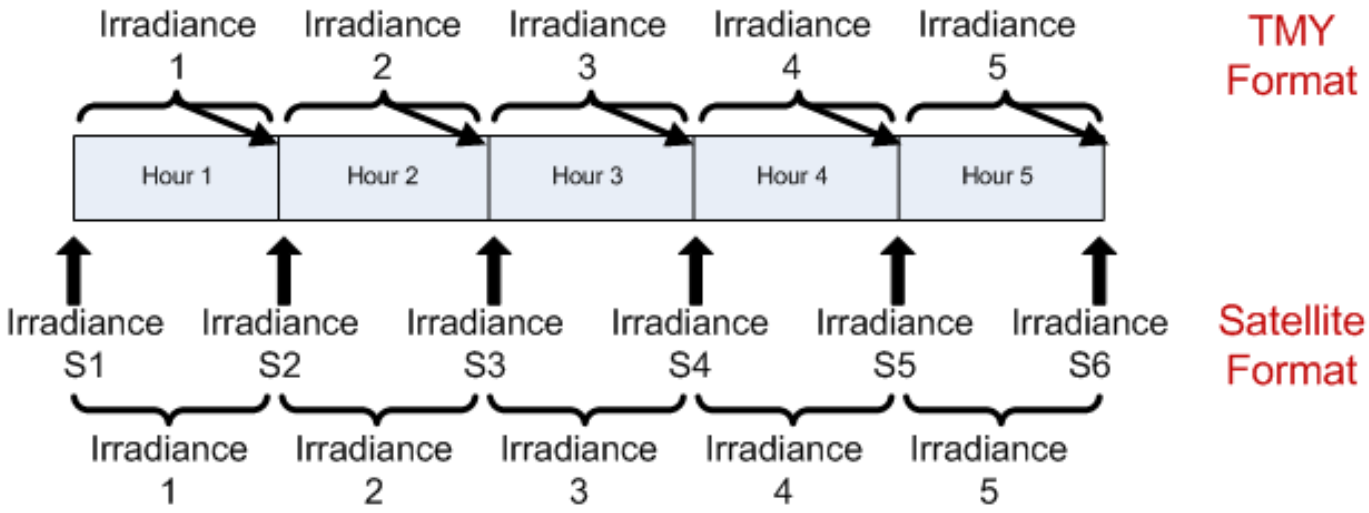
1. Compare Ground and Satellite Data

- **Data needs to be consistent before comparison.**
  - **TMY format data is hourly average over past hour.**
  - **Satellite irradiance is an instantaneous estimate on the hour.**
- **We have averaged satellite data to be consistent with TMY format.**



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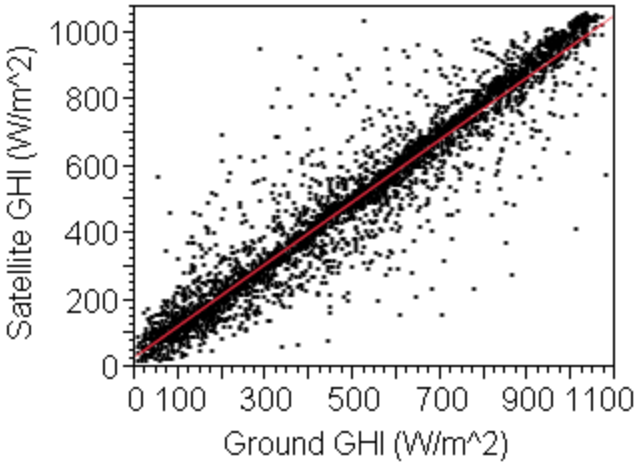
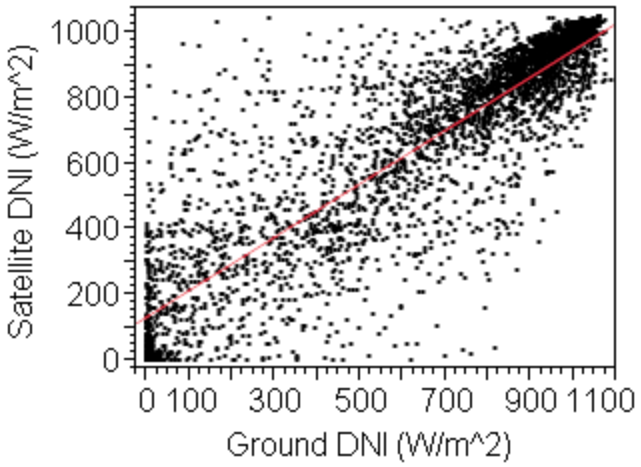
Irradiance Comparison

- **Satellite estimates of GHI are quite accurate especially for calculations of energy.**
  - **Mean residual is <1 W/m^2, Stdev = 83 W/m^2**
- **Satellite estimates of DNI are not as good.**
  - **Mean residual is 17 W/m^2, Stdev = 166 W/m^2**





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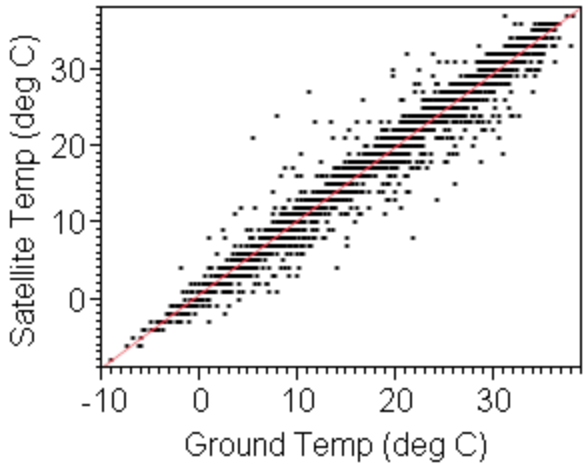
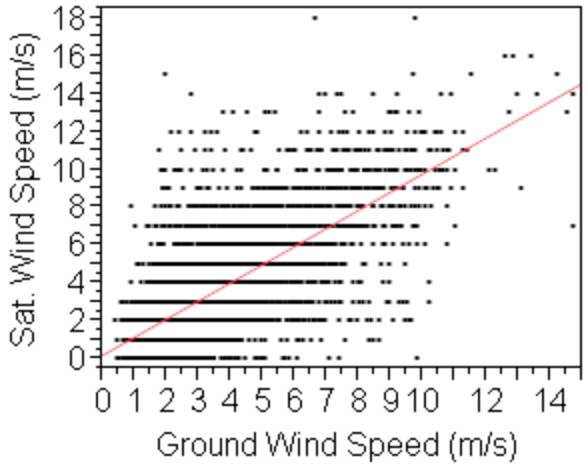
Temperature and Wind Speed Comparison

- **SolarAnywhere temperature and wind speed estimates come from the METAR network of ground stations across U.S.**
- **Estimates of temperature are better than for wind speed.**
- **The timing of fast changes are especially difficult to predict (residuals are correlated to derivatives)**





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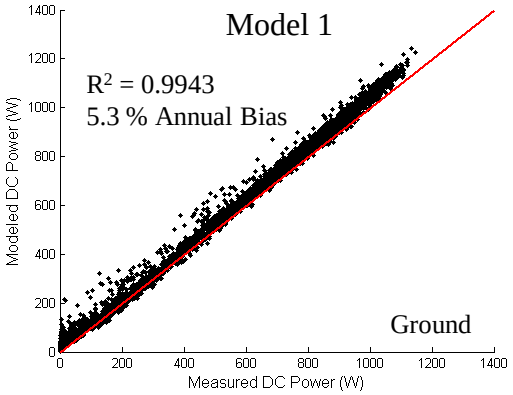
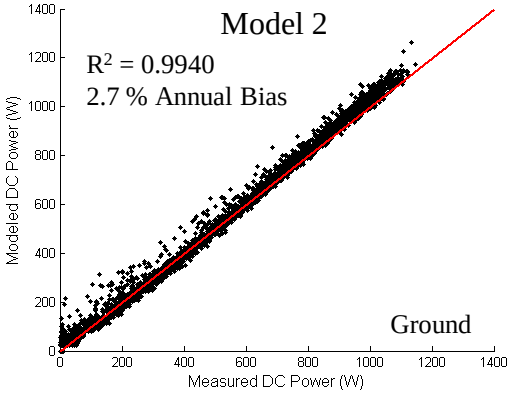
2a. Run Models with Ground Data

- **Derate factors are ignored in this study.**
- **Models 1 and 2 have nearly equal R^2 values but differ slightly in their bias errors.**
- **Models appear to have no systematic differences, or do they?**





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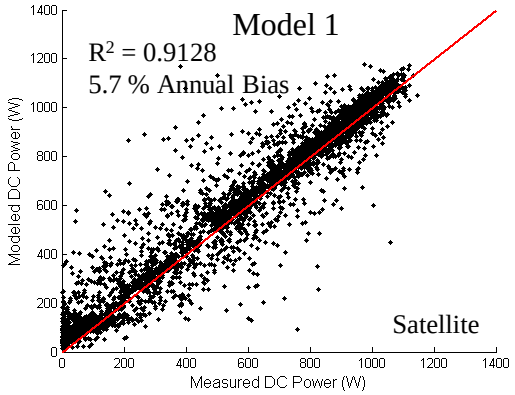
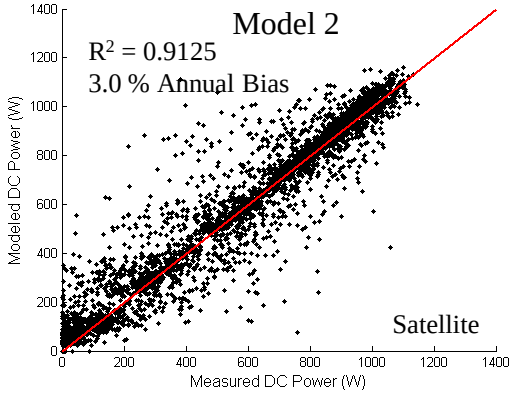
2b. Run Models with Satellite Data

- **Running models 1 and 2 with satellite data increases random error but does little to change bias errors.**
  - ***Stdev is 3-4 times greater***
  - ***Variance is 9-16 times greater***
- **Similar bias errors indicate that satellite data is quite accurate for estimating energy production over relatively long periods of time.**





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3. Residual Analysis

- **Residuals are differences (model – measured)**
- **Residuals from a 'Perfect' model will be randomly distributed and uncorrelated with input variables.**
- **Residual analysis identifies any correlations if they exist.**
  - **These represent potential 'flaws' in the model and/or parameters.**
- **Stepwise regression allows variables which affect residuals to be indentified and ranked.**

$$Y = b_0 + \sum_{j=1}^{P} b_j X_j$$

Y = dependent variables
X = P vectors of independent variables
b = linear regression coefficients

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Stepwise Results

Model 1 (Ground)			
Order	**Variable**	**R^2**	**Incremental R^2**
1	Temp	0.2302	0.2302
2	DNI	0.3143	0.0841
3	WS	0.3301	0.0158
4	AOI	0.3350	0.0049

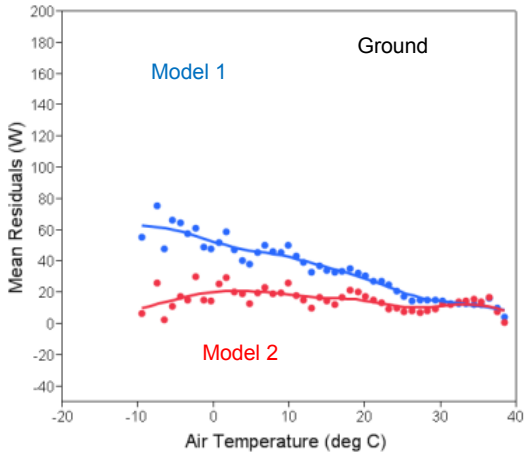
Model 2(Ground)			
Order	**Variable**	**R^2**	**Incremental R^2**
1	AOI	0.0886	0.0886
2	AMa	0.2115	0.1229
3	GHI	0.2575	0.0459
4	DHI	0.2646	0.0071

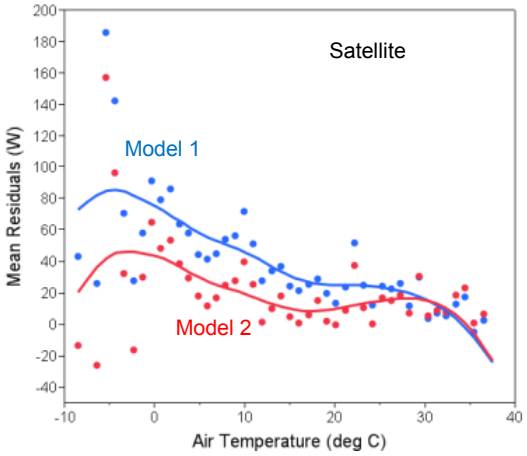
Model 1 (Satellite)			
Order	**Variable**	**R^2**	**Incremental R^2**
1	SA_Temp	0.0281	0.0281
2	SA_DNIa	0.0573	0.0292
3	AMa	0.0736	0.0163
4	SA_WS	0.0776	0.0040

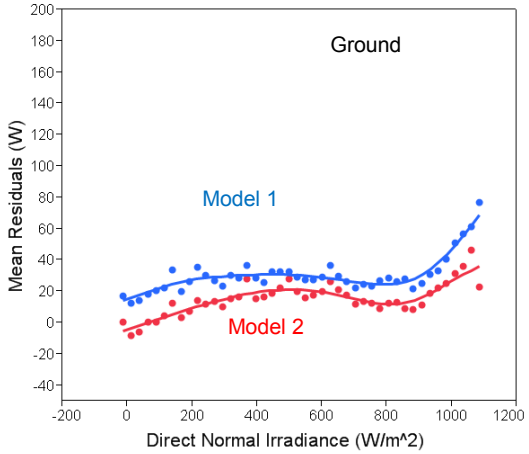
Model 2 (Satellite)			
Order	**Variable**	**R^2**	**Incremental R^2**
1	SA_DNIa	0.0288	0.0288
2	AMa	0.0655	0.0368
3	SA_GHIa	0.0753	0.0098
4	SA_Temp	0.0794	0.0041

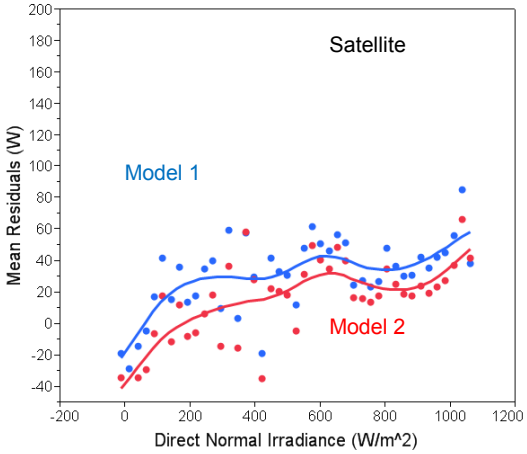
- Inc. R^2 values = fraction of the variance explained by identified correlations
- Model 1 residuals show a correlation with air temperature and DNI
- Model 2 residuals exhibit a different pattern with correlation to (AOI and AM) and DNI and GHI.

Residual Analysis









- Mean residuals calculated in bins of air temperature (top) and DNI (bottom).
- Sloped lines illustrate correlations.
- Model 1 residuals is negatively correlated with temperature. Model 2 is not.
- Both models show correlation with DNI

- Areas for model improvement?

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Summary

- Models based on satellite irradiance generated very accurate estimates of total annual energy production for Albuquerque.
  - Satellite irradiance should be considered for design calculations (available everywhere, multiple years)
- Hour to hour errors were significant, especially during partly cloudy periods.
  - Real-time monitoring might have to average satellite-based performance estimates over days in order to increase accuracy to the level needed to identify array problems.
- Residual analysis shows that two popular models exhibit different residual correlations but that the use of satellite irradiance does not appear to affect these sensitivities.
- Future work should replicate comparisons for a wider range of climates and geographical locations.

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