Evaluation of Irradiance Decomposition and Transposition Models at Locations Across the United States

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First Solar.

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NNSA National Nuclear Security Administration

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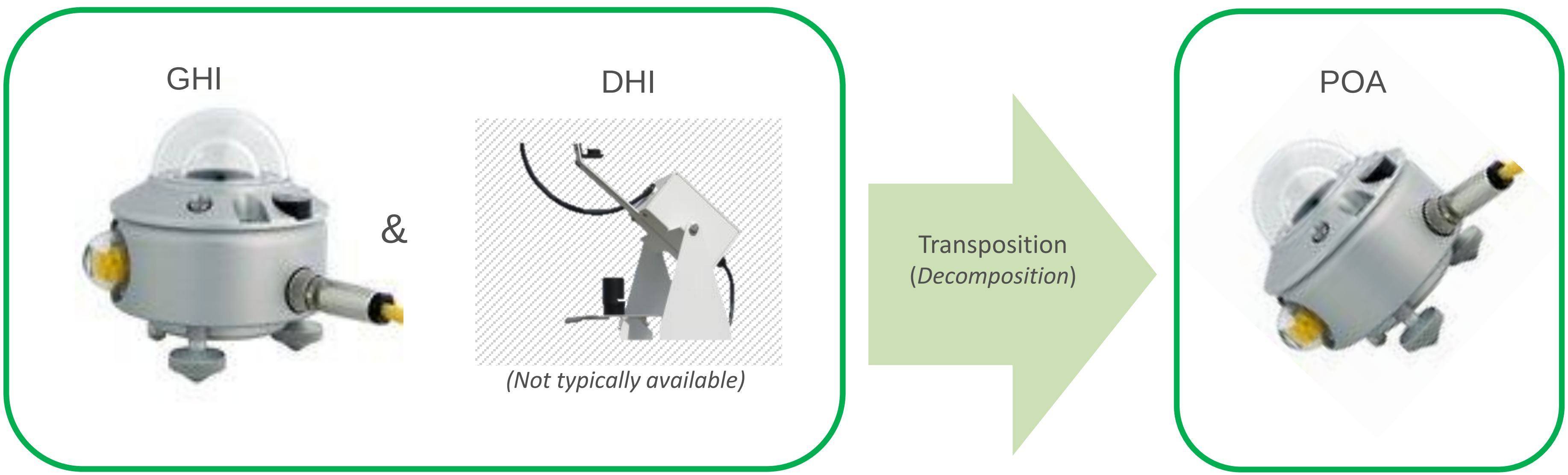
Summary

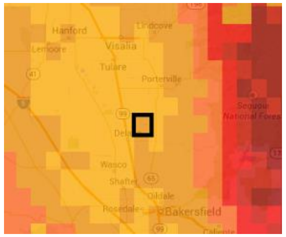
- Estimations of POA irradiance are evaluated for tilt angles/orientations that are relevant to fixed tilt PV systems covering different climates in North America.
- Estimating plane of array (POA) irradiance often requires a sequence of models:
  - Decomposition: GHI to direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI)
  - Transposition: GHI, DNI and DHI to total irradiance in POA
- Sandia and First Solar evaluated numerous models, individually and in combination, to develop an understanding of model accuracies and general shortcomings.



The problem

- The number of choices for transposition and decomposition models generates confusion and introduces risk in deployment of PV systems.
- For example, PVsyst provides two options which provide different estimates of POA irradiance (and consequently different estimates of AC energy)

EPC #1



Tilt	25°
Transposition	Perez

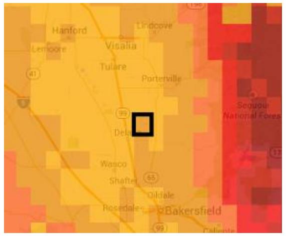
Identical design

Identical meteo

Different Model

Energy$_{\#1}$ ≠ Energy$_{\#2}$

EPC #2

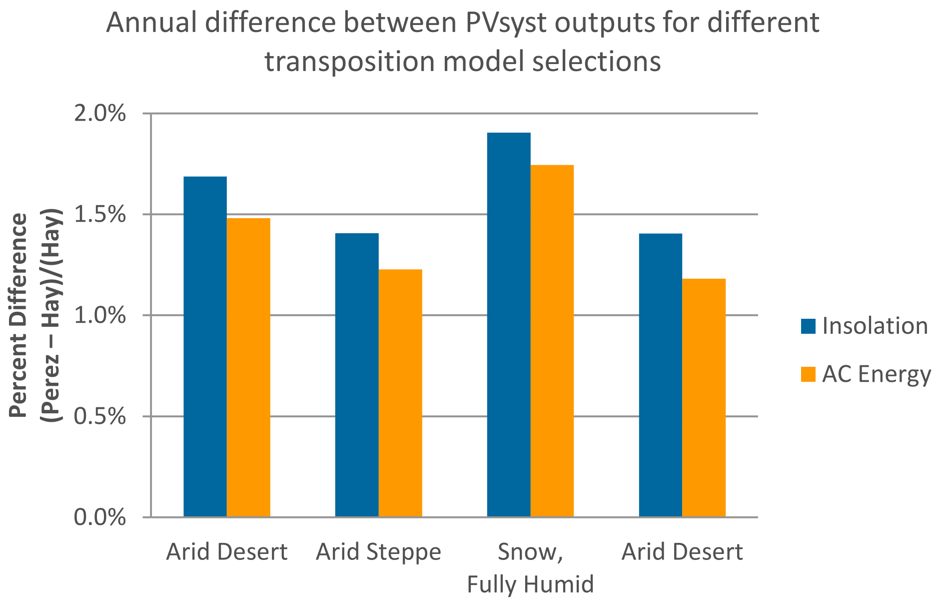


Tilt	25°
Transposition	Hay

*http://maps.nrel.gov/prospector

Differences in energy estimates and associated risks

- The modeling options available in PVsyst can produce energy estimates that are upwards of 1 % different on an annual basis.
- Depending on which estimate is more accurate the risk can be borne by either stakeholder:

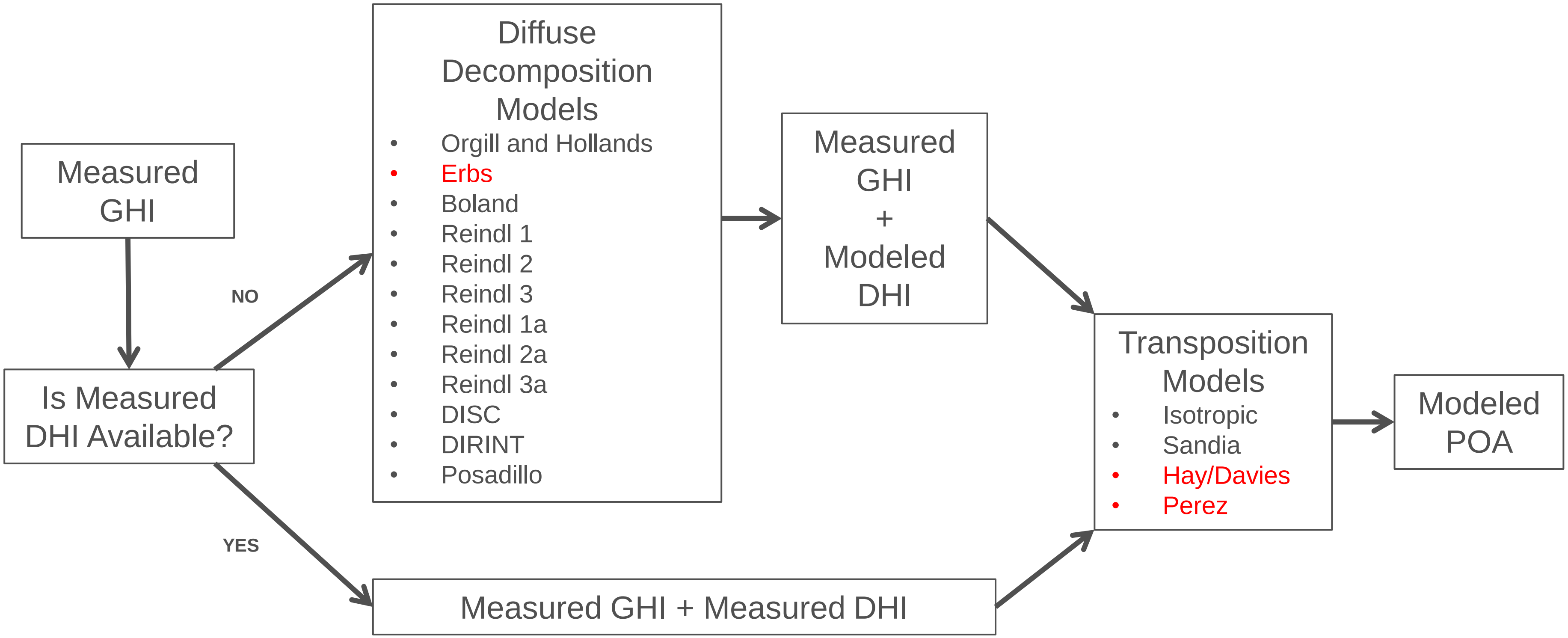


Stakeholder	Risk of underestimate	Risk of overestimate
Developer and/or EPC	Lose bid or undercapitalize on sale.	Fail performance guarantees.
Owner and/or Financer	May not be able to capitalize on additional energy generation (contract specific).	Financial return adversely affected. (Bear risk if a PR guarantee)

Transposition risk is transferred if a PR guarantee

Generic system design applied for all simulations: 1.25 DC/AC; 0.56 GCR; Fixed 25° Tilt; 0° Azimuth

Modeling Process and Models Considered



Models in red denote options in PVSyst.

Data/inputs required for models

Diffuse Decomposition Models

Model	Input variables
Orgill and Hollands	Kt, GHI
Erbs	Kt, GHI
Boland	Kt, GHI
Reindl 1	Kt, GHI
Reindl 1 adj	Kt, GHI
DISC	Kt, GHI, SunEl
DIRINT	Kt, GHI, SunEl
Reindl 2	Kt, GHI, SunEl
Reindl 2 adj	Kt, GHI, SunEl
Reindl 3	Kt, GHI, SunEl, AmbT, RH
Reindl 3 adj	Kt, GHI, SunEl, AmbT, RH
Posadillo	Kt, GHI, SunEl, MF

Transposition Models

Model	Input variables
Isotropic	DHI, SurfTilt
Sandia	DHI, SurfTilt, GHI, SunZen
Hay and Davies	DNI, DHI, HExtra, SunZen, SurfTilt, AOI
Perez	DNI, DHI, HExtra, SunZen, SurfTilt, AOI, AM

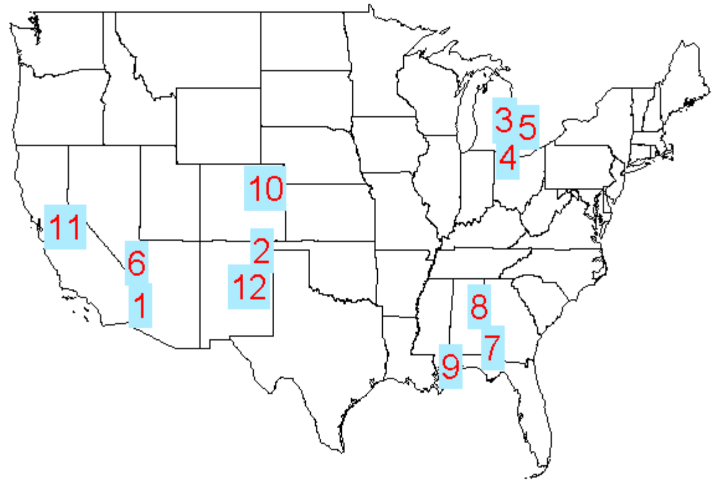
All models of either type are:

1. (stationary) empirical (piecewise) correlations;
2. between measured DHI/DNI or POA and input variables;
3. using some historical hourly data set.

Several previous evaluations have found that models perform similarly at shorter time intervals.

Data Used in This Evaluation

- Twelve locations representing a range of climates
- GHI, POA for a southward tilted instrument
  - CMP-11, CM22, Eppley PSP, some Licor-200
  - Multiple instruments at several locations
  - DHI (RSR) at several locations (single instrument)



Station	Location	Elevation [m]	Climate Zone	Measured Data	Time Period	SurfTilt	SurfAz
1	Southeast CA	120	Arid Desert Hot (BWh)	GHI, POA	12/2009 - 8/2013	25°	180°
2	Northeast NM	100	Arid Steppe Cold (BSk)	GHI, POA	12/2010 - 8/2013	25°	180°
3	East MI	188	Snow; Fully humid; Warm summer (Dfb)	GHI, DHI, POA	2/2012 - 7/2013	25°	180°
4	East MI	181	Dfb	GHI, DHI, POA	2/2012 - 7/2013	25°	180°
5	East MI	193	Dfb	GHI, POA	10/2010 - 9/2013	25°	180°
6	Southern NV	572	BWh	GHI, POA	1/2011 - 12/2012	25°	180°
7	Southeast AL	97	Warm temperate; Fully humid; Hot summer (Cfa)	GHI, POA	8/2013 - 11/2013	26°	180°
8	Central AL	226	Cfa	GHI, POA	7/2013 - 11/2013	40°	180°
9	Coastal MS	6	Cfa	GHI, POA	2/2013 - 11/2013	15°	180°
10	Central CO	1829	BSk	GHI, DHI, POA	1/2013 -12/2013	40°	180°
11	Central CA	200	Warm temperate; dry, hot summer (CSa)	GHI, DHI	1/2013 -12/2013	N/A	N/A
12	Central NM	1657	BSk	GHI, GHI, POA	1/2011 – 12/2011	35°	180°

Stations in red allowed for independent testing of diffuse decomposition and transposition models.

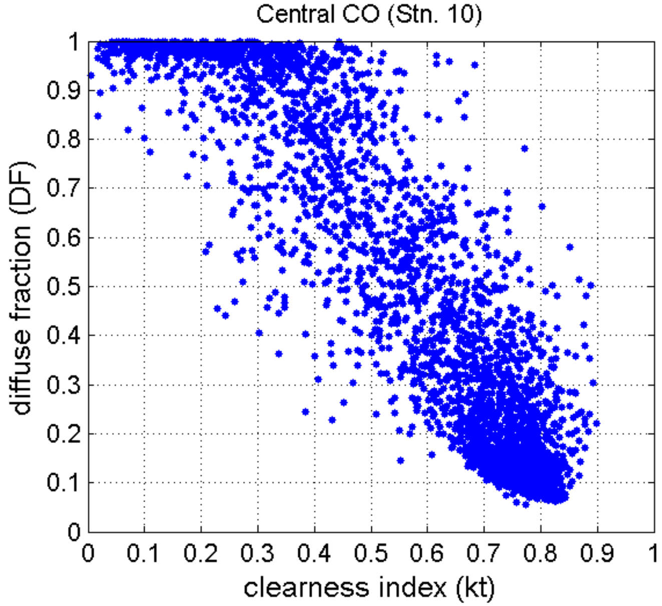
Diffuse Decompositions

Decomposition Models: How they work

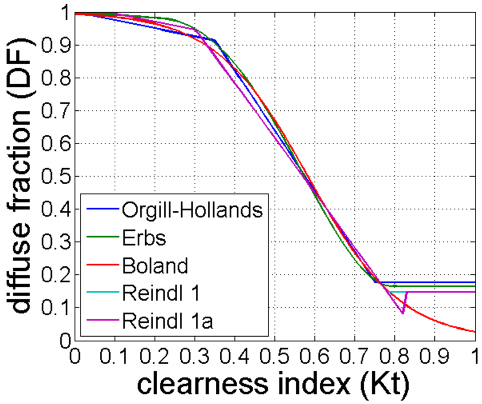
GHI -> DHI

(kt -> DF)

- measured diffuse fraction versus clearness index

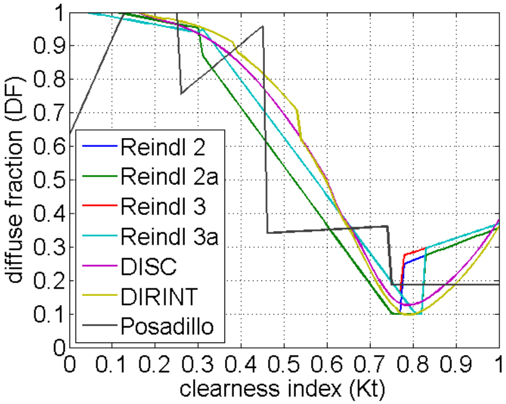


- "simple" decomposition models
  - diffuse fraction a function of clearness index



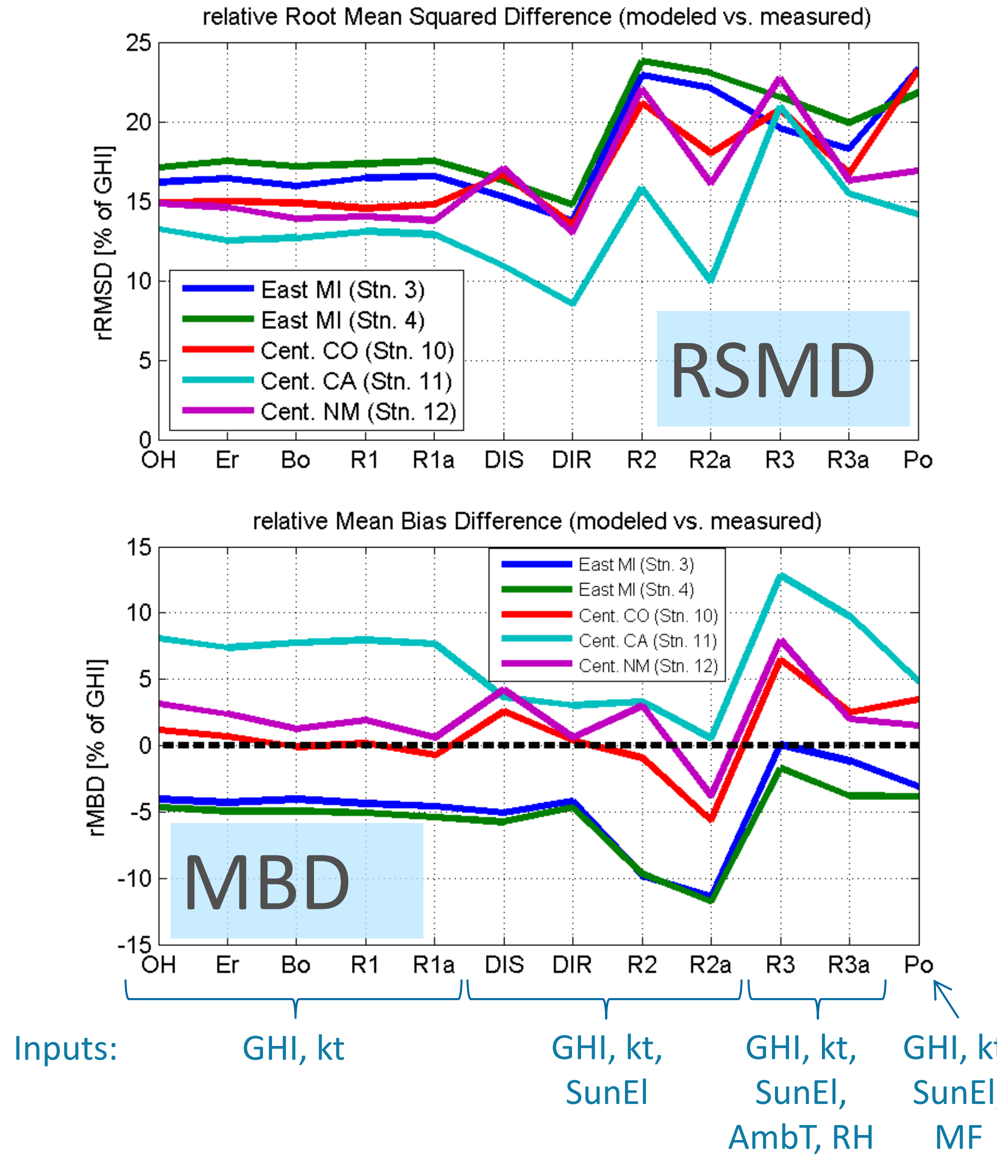
- "complex" decomposition models
  - add other variables attempting to better model variation in diffuse fraction

plotted for case when:
$SunEl = 45°$,
$AmbT = 25°C$,
$RH = 0.5$,
MF = 0.2.



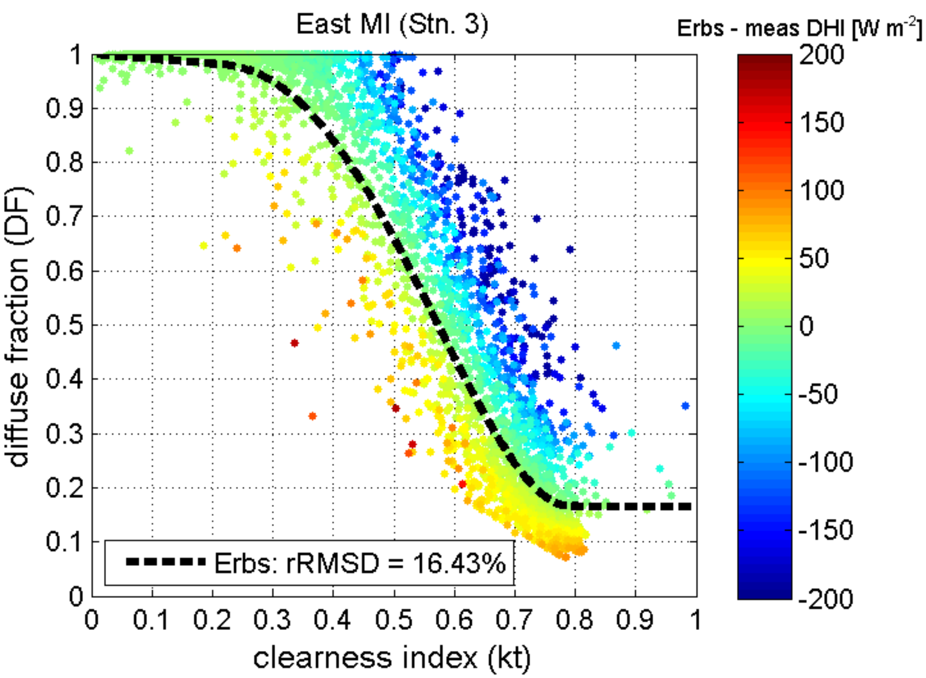
Findings: Decomposition Models

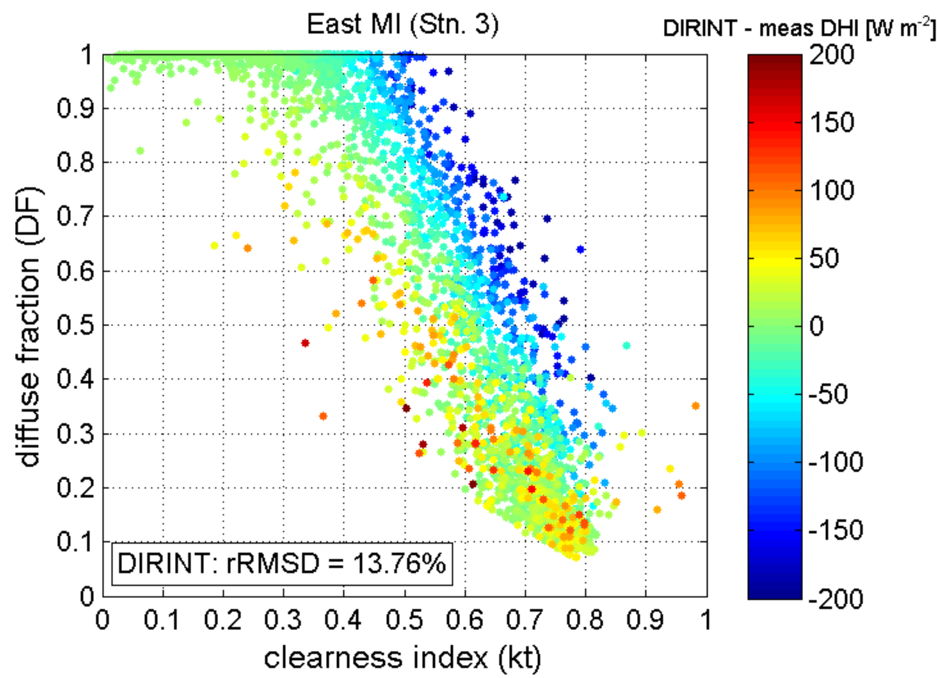
- Examined hourly data
- Two annual difference metrics (compare modeled vs. measured) :
  - RMSD : relates to hourly deviation
  - MBD : relates to annual energy
- DIRINT had lowest RMSD and MBD at all locations, but
- Not significantly less than other models
  - Simple models had similar performance
- Deviation in decomposition model depends on location



Breaking Down the Differences: Decomposition RMSDs

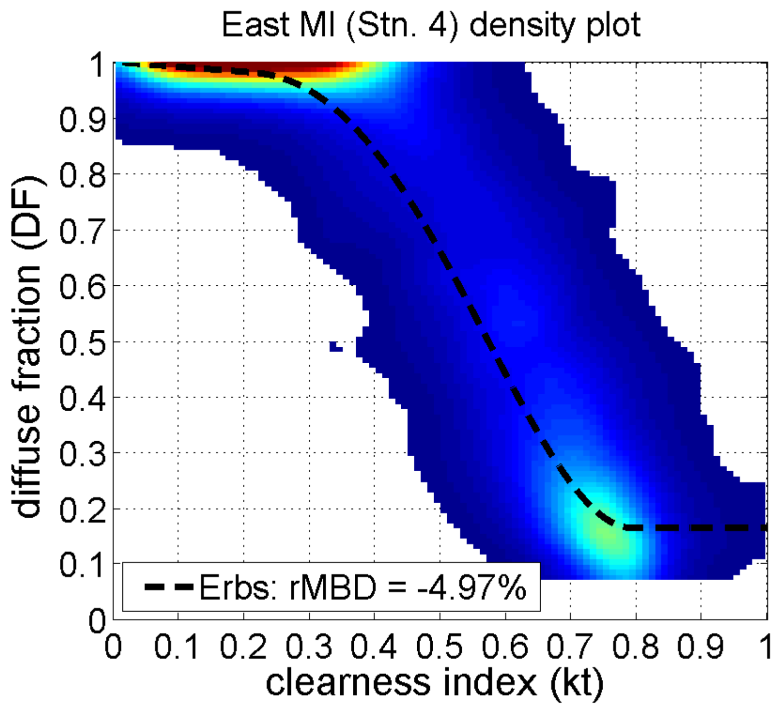
- For simple models (e.g., Erbs), any point above model curve means DHI was underestimated; any point below means DHI was overestimated.
  - RMSD describes spread of data around the model curve
- DIRINT is a slight improvement over Erbs
  - Lower RMSD, but still shows similar patterns (e.g., gradient from bottom left to top right).

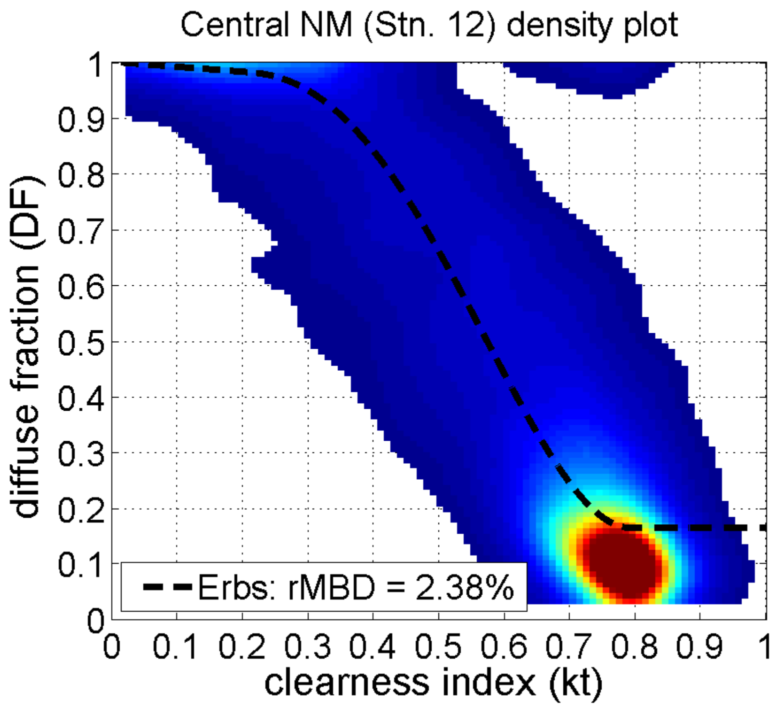




Breaking Down the Differences: Decomposition MBDs

- Climate Plays an important role in annual errors (MBDs)
  - East MI: cloudy days are common
    - more points are above the Erbs model, leading Erbs to have a negative MBD
  - Central NM: clear days are common
    - Clustering of clear-sky values (kt=0.8, DF=0.1) below Erbs model that contribute to positive MBD





First Solar

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Transposition Models using measured DHI

Transposition Models: How they work

GHI +DHI -> POA

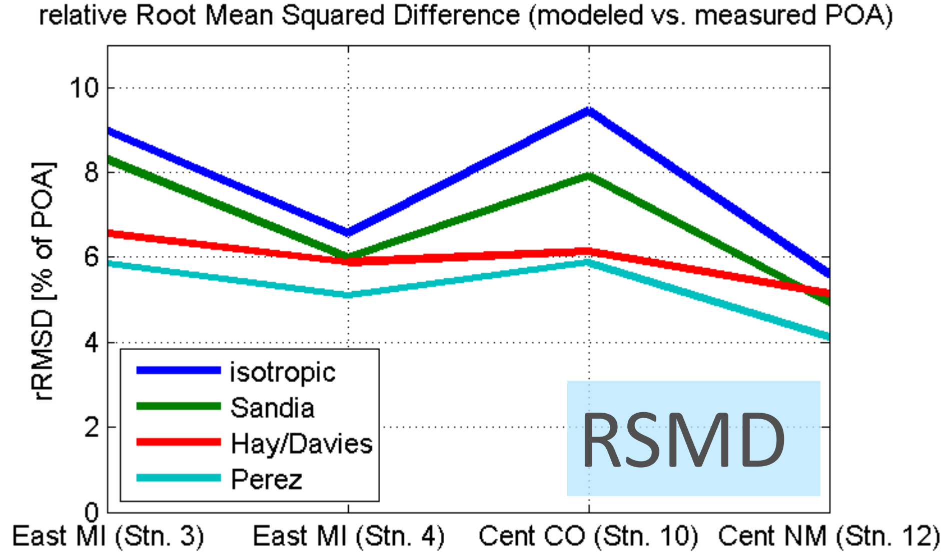
- POA has three components:

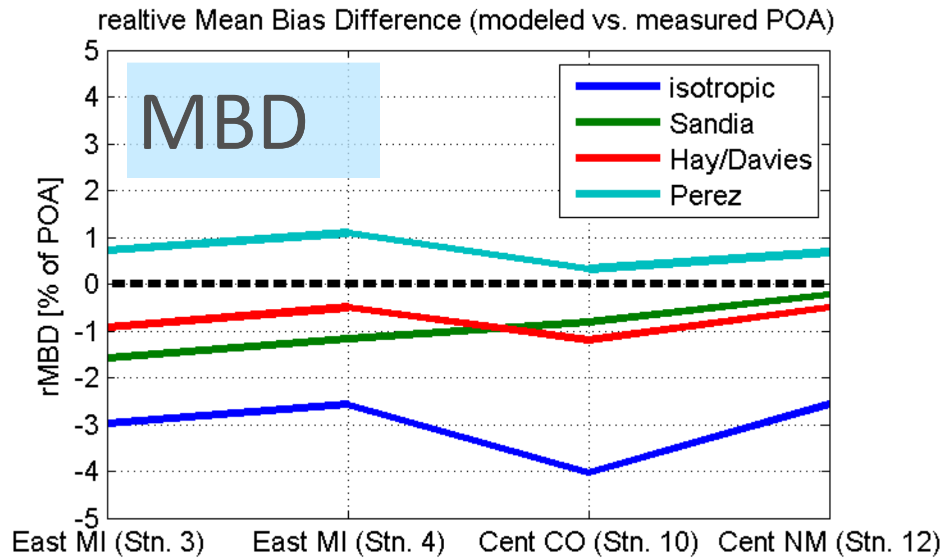
$$POA = POA_{direct} + POA_{diff,refl} + POA_{diff,sky}$$

  - POA_{direct} a function of GHI, DHI, and angle of incidence
    - Same for each model
  - $POA_{diff,refl}$ a function of GHI, tilt, and ground albedo
    - All models except for Sandia use $albedo = 0.2$
    - Sandia model uses empirical albedo derived for central NM
  - $POA_{diff,sky}$ varies from model to model
    - Isotropic, Sandia: sky diffuse only function of amount of sky seen
    - Hay/Davies, Perez: more diffuse irradiance in circumsolar region

Findings: Transposition Models

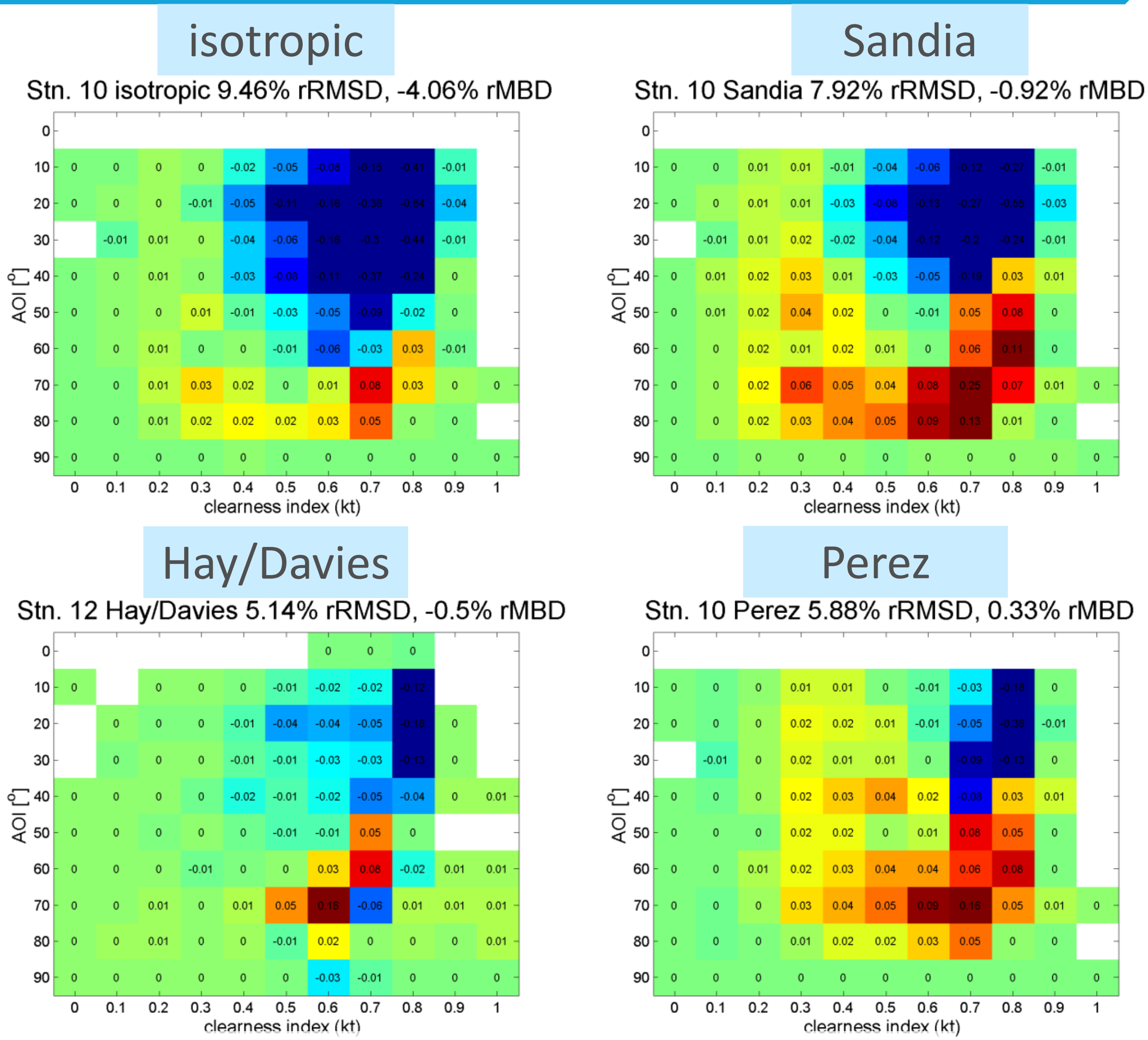
- Hay/Davies and Perez show lower RMSD than other models; similar to each other.
- Systematic difference in MAD: Perez > Hay/Davies
  - E.g., Hay/Davies MBD -1% at Stn. 3, while Perez +1%
- Little dependence on location
  Except for Sandia model, which was calibrated at Stn. 12





Breaking Down the Differences: Transposition Models in Circumsolar Region

- Isotropic model has large negative errors during clear-sky conditions (kt≈0.7) and low angles of incidence (AOI<40°), since it doesn't account for additional diffuse in the circumsolar region.
- Sandia model has similar behavior, but generally more positive values due tc enhanced albedo.
- Hay/Davies and Perez also have negative values in clear sky, low AOI conditions, but effect is smaller.



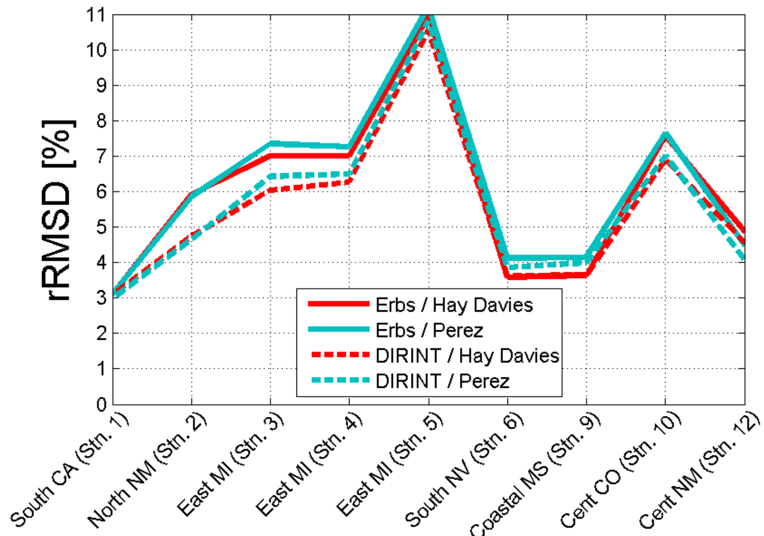
Colors and numbers in plots indicated contribution to MBD;
if all boxes were summed, the result would be the rMBD.

Combined Models:
Transposition Models with Diffuse Models

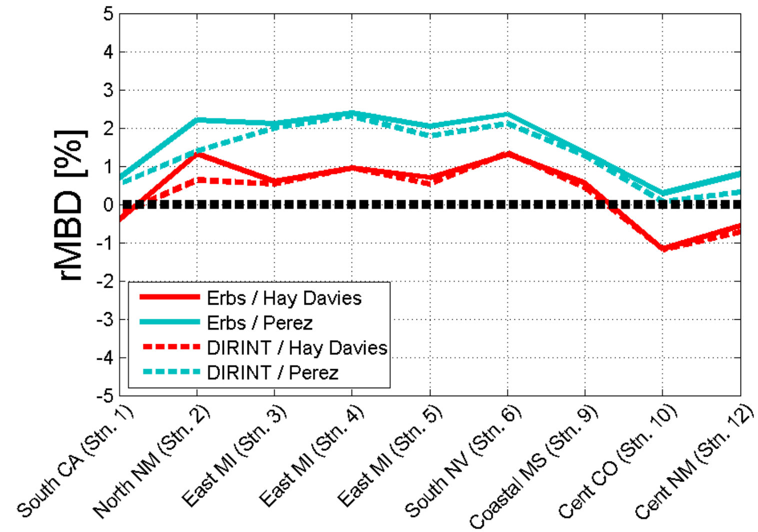
Findings: Combined Models

- Focused combined model evaluation on 2 decomposition and 2 transposition models
  - Decomposition: **DIRINT** (lowest deviation) and **Erbs** (default in PVsyst)
  - Transposition: **Hay/Davies** and **Perez** (best performing and both options in PVSyst)
- Combined model POA deviation is NOT the sum of deviation from individual models
  - Positive errors in DHI from decomposition models lead to negative errors in DNI
    - This may lead to underestimating POA
    - But this can also be offset by positive errors in the transposition models
- RMSD depends more on location than model combination

RSMD



MBD



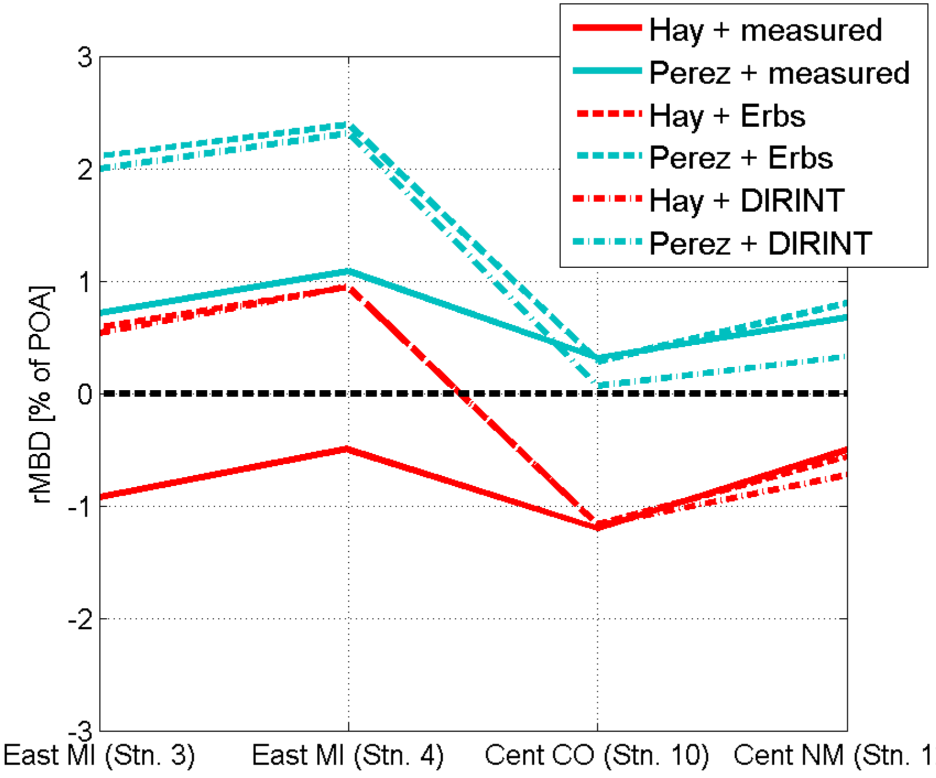
Modeled vs. Measured DHI

- Combined models tend to have higher POA estimates than transposition models with measured DHI
  - Large negative errors in decomposition models significantly increased MBD / POA annual energy
  - Small to moderate positive errors in decomposition models had little effect on MBD / POA annual energy

rMBE in DHI estimates

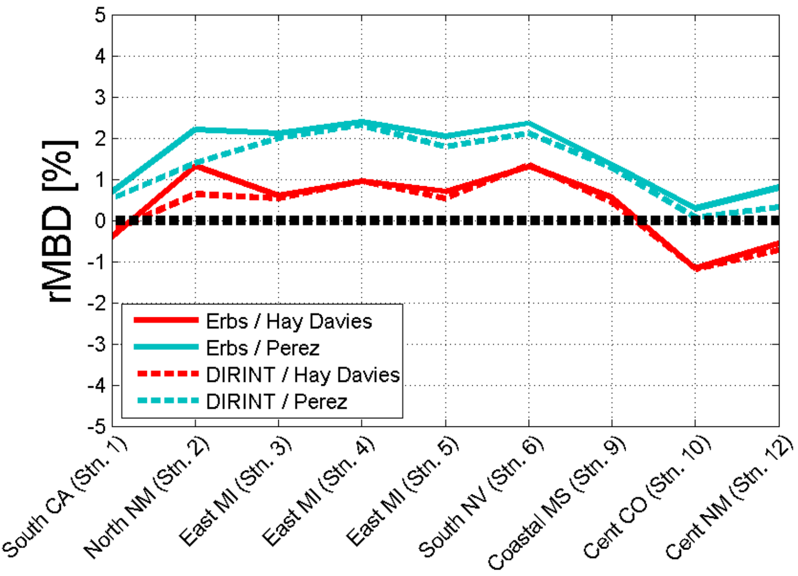
	Erbs	DIRINT
Stn. 3	-4.3%	-4.2%
Stn. 4	-5.0%	-4.7%
Stn. 10	0.7%	0.4%
Stn. 12	2.4%	0.6%

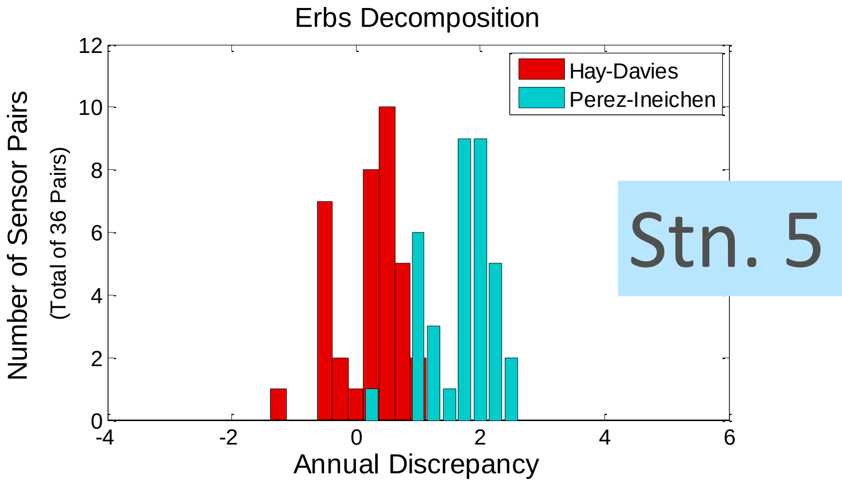
rMBE in POA estimates

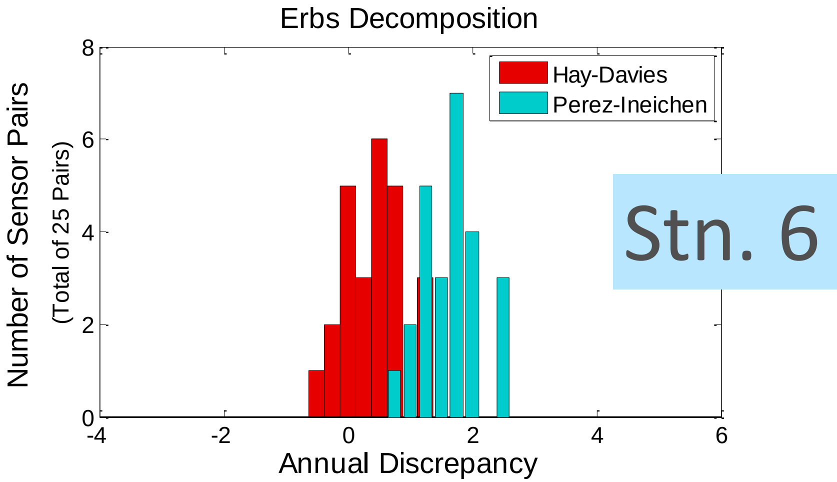


Addressing uncertainty

- Biases can be present in measurements, making it challenging to determine which model had the smallest annual bias error.
- Multiple sensors can be used to reduce the effect of measurement bias.

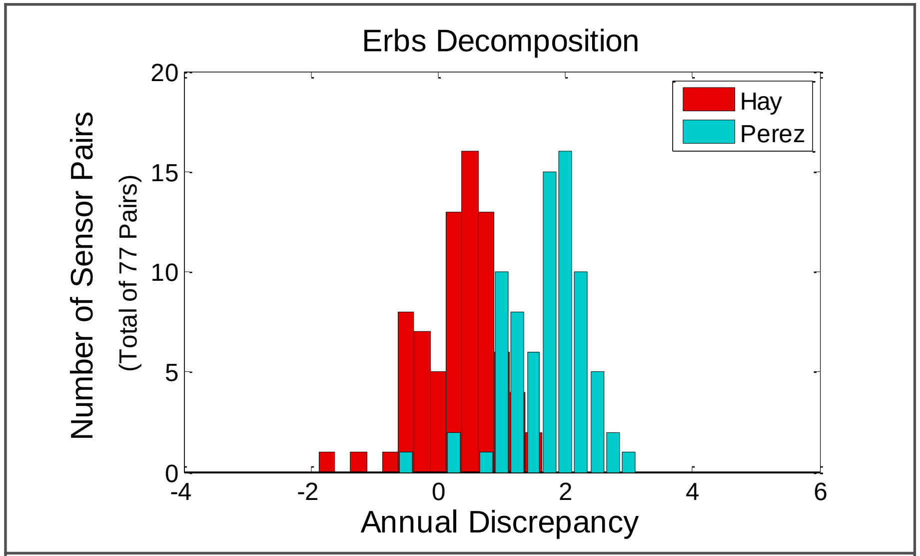


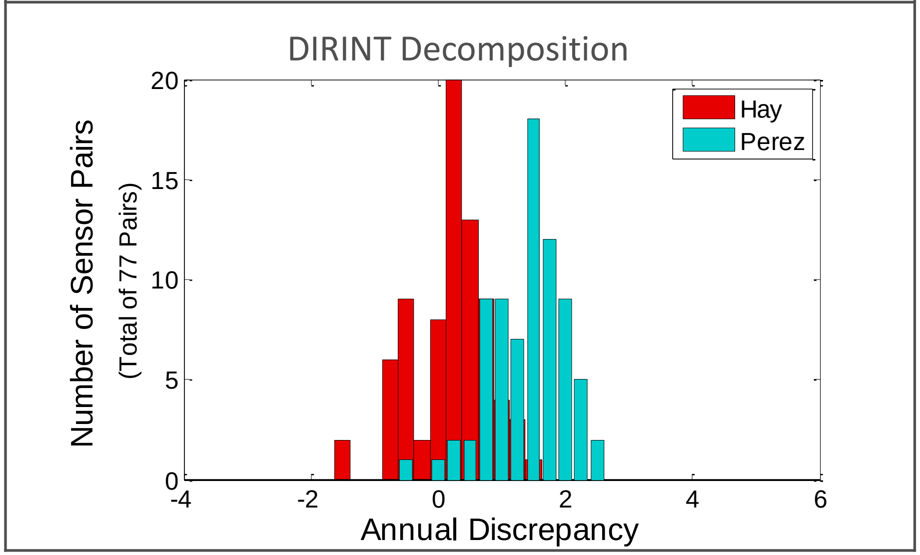




Distributions of Discrepancies

- Distributions of annual relative mean bias differences (discrepancy) were computed for all combinations of models.
- Results highlight a +/- 1% spread in discrepancy which represents the effect of sensor biases (in both GHI and POA).
- Bias discrepancies suggest that the Hay transposition model has a lower relative error compared to Perez when using modeled DHI as input.





Findings/Summary

- Diffuse decomposition model performance varies based on climate
  - In predominantly clear or cloudy climates, models may over or under estimate the amount of diffuse
  - Annual errors range from rMBD of ~-10% to +10% (of GHI) at locations studied.
  - Hourly errors in DHI are large (>10% rRMSD) at all locations

- Transposition model performance does not seem to vary much with climate
  - Transposition model rMBD ~-4% (isotropic) to ~+1% (Perez)
  - rRMSD (% of POA) <10%; smaller than decomposition model rRMSDs

- Combined models typically overestimated POA
  - Most sever for Perez transposition model where POA was already high
  - Hay/Davies transposition + modeled DHI found to have rMBD closer to zero than Perez transposition

Further Work Needed

- Improve decomposition and transposition models
  - Decomposition models which account for local climate (amount of clear-sky hours)
  - Transposition models which perform better during clear-skies and low AOIs
  - Combined models with low RMSD and MBDs.

- Evaluate transposition models for tracking systems (which experience more instances of low AOI).

- Validation at more locations to further derive the impact of climate, AOI, tilt angle, etc.

- Determine impact of high DC/AC ratios. Do clear-sky errors become less important due to clipping?