Solar Resource Measurements and Site Adaptation

PVPMC 2026

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Site-Adaptation (aka Tuning, MCP, Bias Correction)

Short Term (1-2 yrs) high quality ground measurements
Long-term (20+ yrs) modeled resource data (satellite-based)

Use relationship between measured and satellite in the the concurrent period to adjust the full period of satellite data

Goals of Adaptation:
1. More Accurate Data – Reduce Error – Reduce EYA Bias
2. More certainty that the result is likely to be accurate – Reduce Uncertainty

This Session:
Test and compare methods
Test against data from GroundWork campaigns
Note: One-year tuning periods for this research

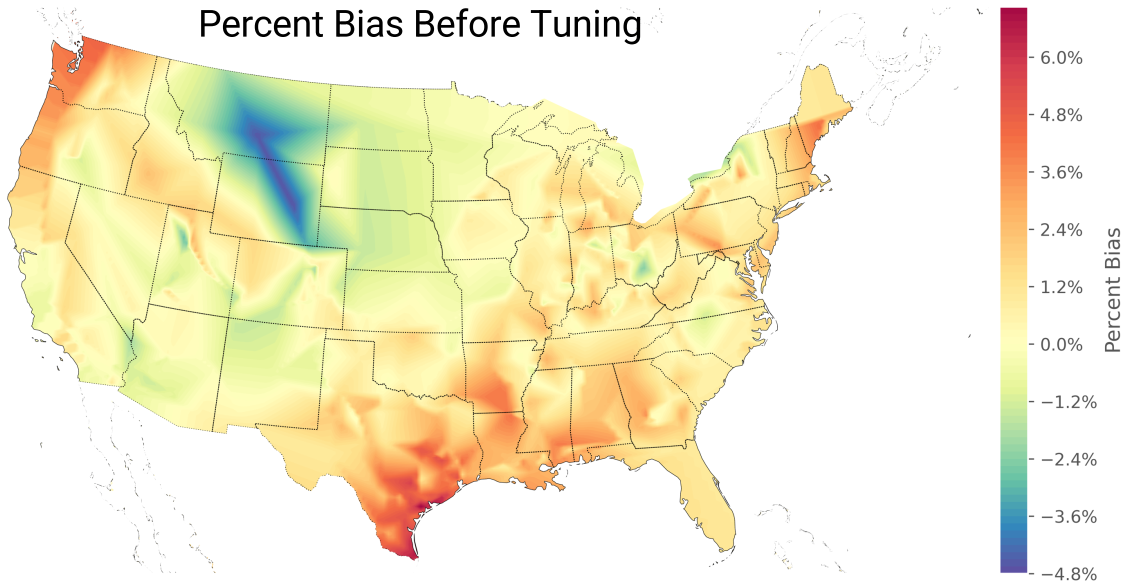
GroundWork Measured Data

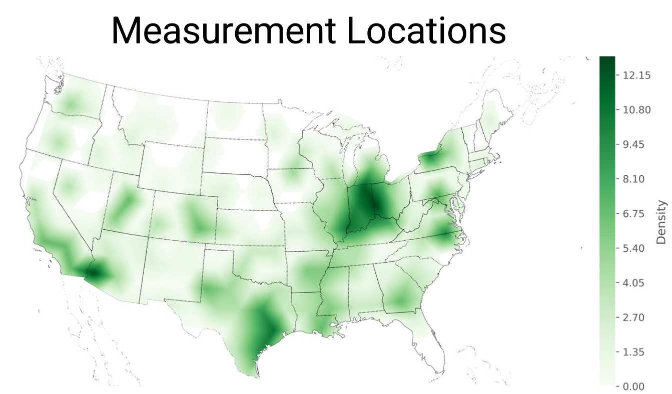
Dual Co-located GHI Class A Pyranometers
Weekly maintenance
Extensive QC process

515 locations with more than 1 year of measurements
87 locations with more than 2 years of measurements

Data is from before 2025 and only accessed for this research use

Modeled Data has Error





515 Measurement Locations
1-year+ campaign length

NSRDB PSM v4
CONUS Range: -4.8% to +7.3%

Site-Adaptation Method Examples

Ratio Style Methods	Example
Linear / Regression Ratio (no intercept)	$Measured = m * Satellite$
Linear / Regression Slope and Intercept	$Measured = m * Satellite + b$
Sinusodial	$Error = Asin\left({}^{2\pi}/_{365.25}\,(Dayofyear + B) + C\right) + D$

Parameter Style Methods	Example
Model Output Statistics ("MOS")	$Error = a_0 Predictor_1 + a_1 Predictor_2$
Polynomial	$Measured = p_1 Sat^3 + p_2 Sat^2 + p_3 Sat$

CDF Style Method	Example
Cumulative Distribution Function*	$Error \sim CDF_M / CDF_S$

* CDF can be used in combination with other methods

Option: Split into groups and do unique adjustments to each. E.g. Clearsky/Non-Clearsky, Seasonal

Full List of Tested Combinations:
All_Ratio
Clearsky_Ratio
Seasonal_Ratio
CS/Seas_Ratio
All_Poly
Clearsky_Poly
Seasonal_Poly
CS/Seas_Poly
All_MOS
Clearsky_MOS
Seasonal_MOS
CS/Seas_MOS
Daily_Ratio w/Int
Ratio w/Int
Clearsky_Ratio w/Int
Seasonal_Ratio w/Int
CS/Seas_Ratio w/Int
Seasonal_Sine
CS/Seas_Sine
All_CDF
Clearsky_CDF
Seasonal_CDF
CS_Seas_CDF
CS/Seas_Ratio+CDF
CS/Seas_Sine+CDF
CS/Seas_Poly+CDF
All_MOS+CDF
CS/Seas_MOS+CDF

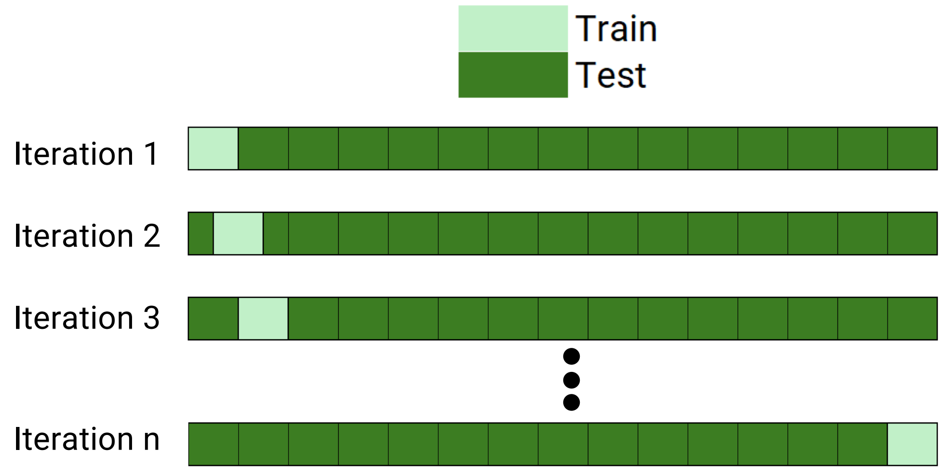
Testing Method

Long data sets (~2000-present) of measured data
NSRDB PSM v4 Satellite-based data

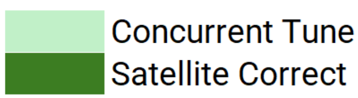
Train on 1 year, Test against rest of dataset
Iterate through multiple options for the test year

Outputs
Resulting Bias of Tuned data vs the Measured Data
Spread of possible outcomes of the method (Uncertainty)

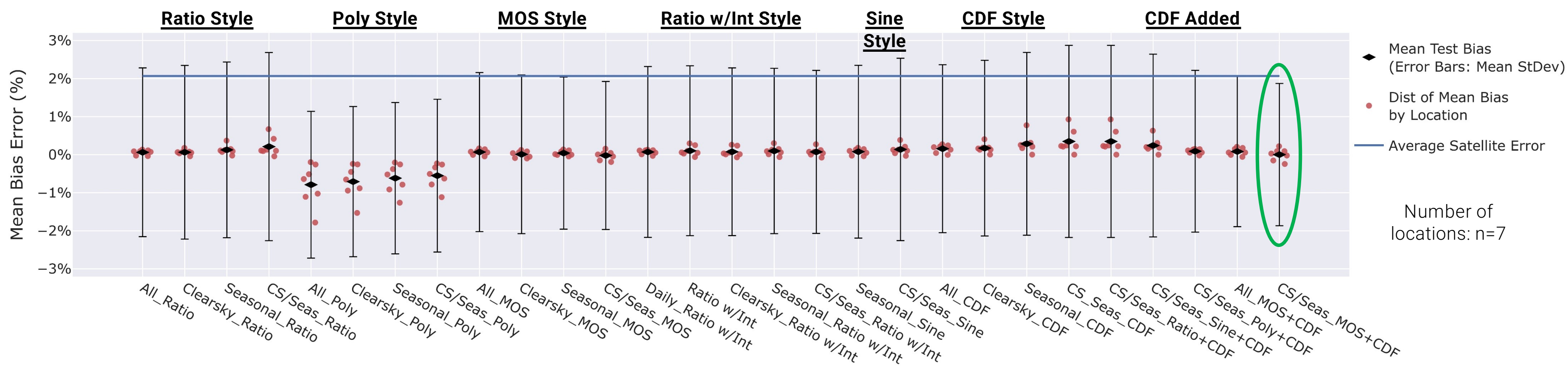
Allows a direct comparison of methods



Approximates a tuning scenario with 1 year of measurements



Full Period SURFRAD Data Test Results



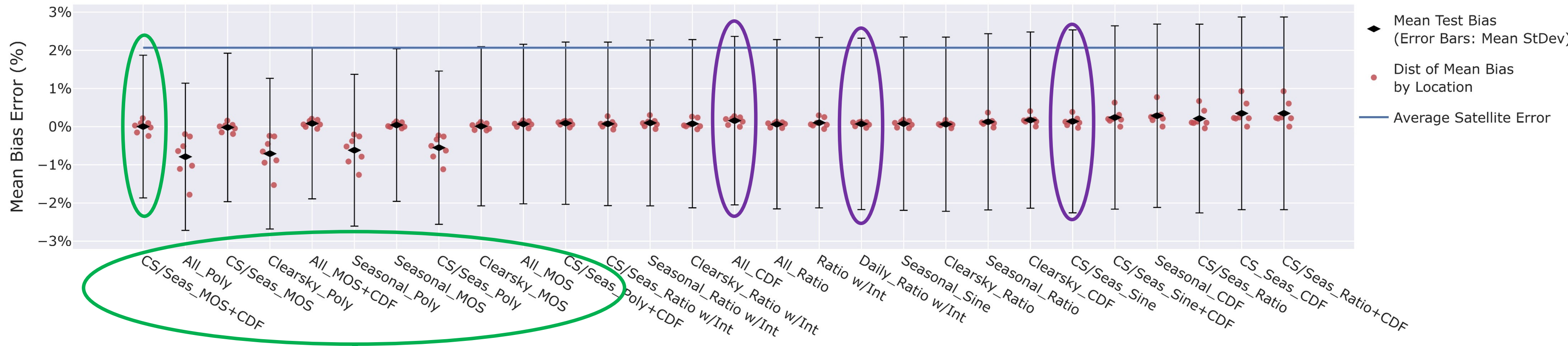
7 SURFRAD locations vs NSRDB PSM v4 Markers: Mean Bias Error of tests Error Bars: Standard Deviation of tests

Average Satellite error is ~+2%
All methods correct that error on average
Most, but not all, get close to 0% bias on average
Mean standard deviation of tests is about 2%

One method has lowest uncertainty across all locations and very low bias:
Clearsky, Seasonal, Model Output Statistics (MOS), plus CDF correction

Full Period SURFRAD Data Tests Lowest Variability

Sorted By Mean Standard Deviation – Lowest On Left



Parameter Style Methods

Parameter Style Methods	Example
Model Output Statistics ("MOS")	$Error = a_0 Predictor_1 + a_1 Predictor_2$
Polynomial	$Measured = p_1 Sat^3 + p_2 Sat^2 + p_3 Sat$

Parameter methods have lower variability

One method has lowest uncertainty across all locations and very low bias: **Clearsky, Seasonal, MOS, plus CDF correction**

Model Output Statistics

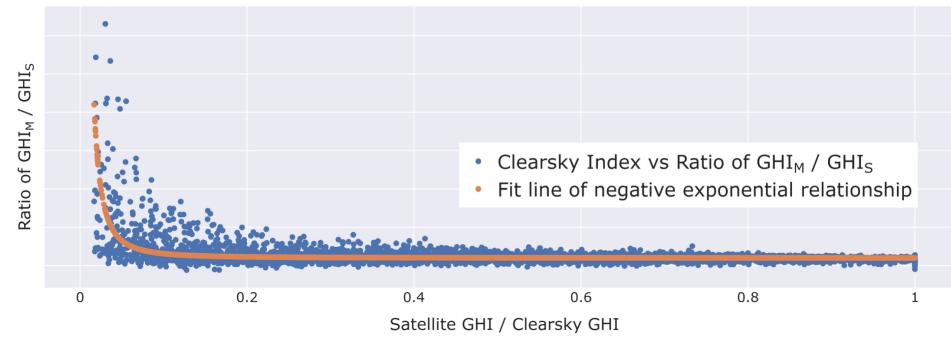
MOS is based on the relationship of error

In our version:
We identified a negative exponential relationship
Ratio of Measured GHI / Satellite GHI ~ Clearsky Index^{-2}

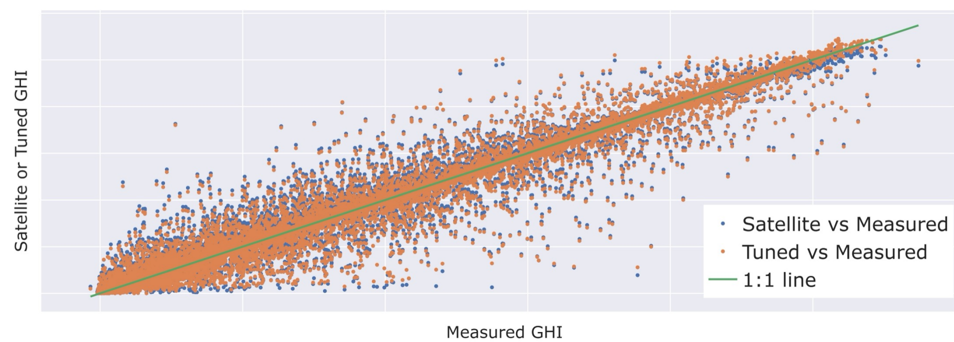
$$\frac{GHI_M}{GHI_S} = a_0 CI^{-2} + a_1 GHI_S$$

Plus a CDF correction to reshape the final adjusted data

Error vs Clearsky Index with fitted relationship

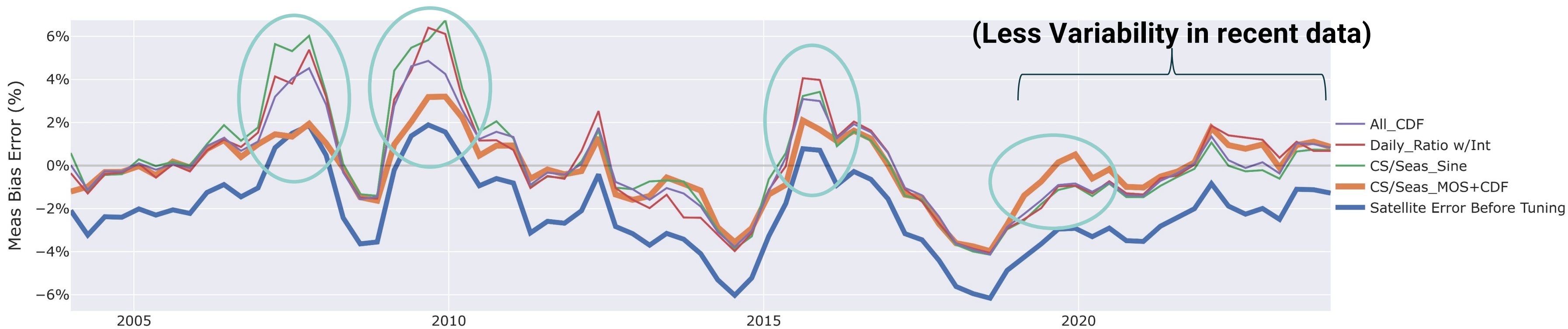


Satellite and Tuned Data vs Measured



Results of One Location Across Time for MOS, CDF, Ratio, and Sinusoidal

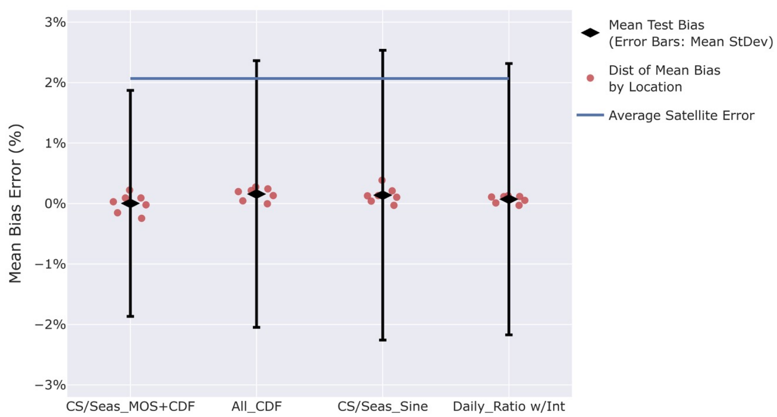
The tuning methods are subject to error in the training period *relative* to the error in the rest of the data
The MOS method shows some robustness to atypically high errors, and does not carry the full error through



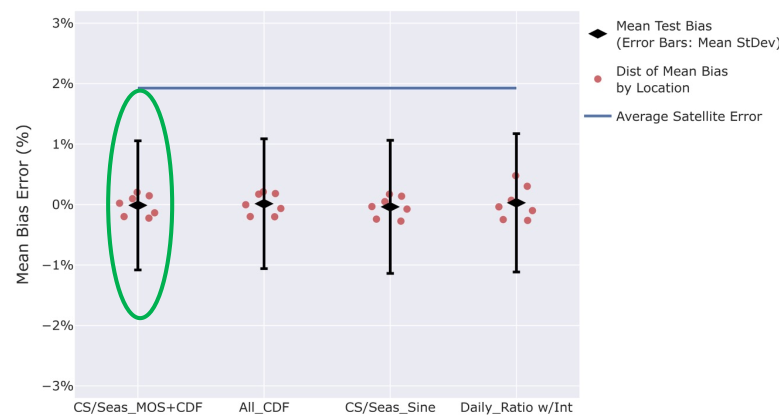
These days we are only tuning on recent data, testing recent data is what should be relevant to our tuning outcomes

Comparison of Full Period Results with Results after 2018

Full Period



Tuning after 2018



Standard Deviation is approximately half using more recent data

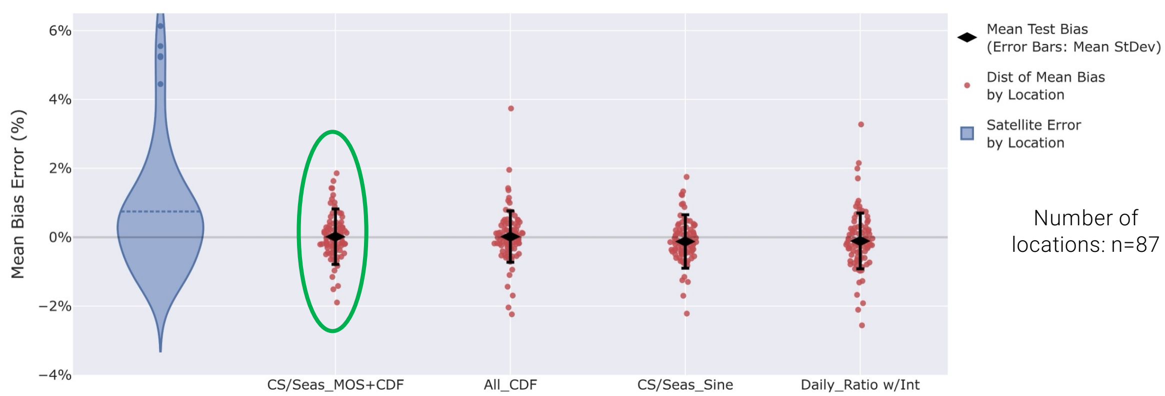
MOS statistics from tests:

- **Mean standard deviation (across tests, temporal): 1.1%**
- **Standard deviation of means (across locations, spatial): 0.2%**

Measured Data from Ground Stations

87 Locations with 2+ years of data

Satellite Errors shown with test results from
Model Output Statistics (MOS)
Cumulative Distribution Function (CDF)
Sinusoidal
Daily Ratio with Intercept



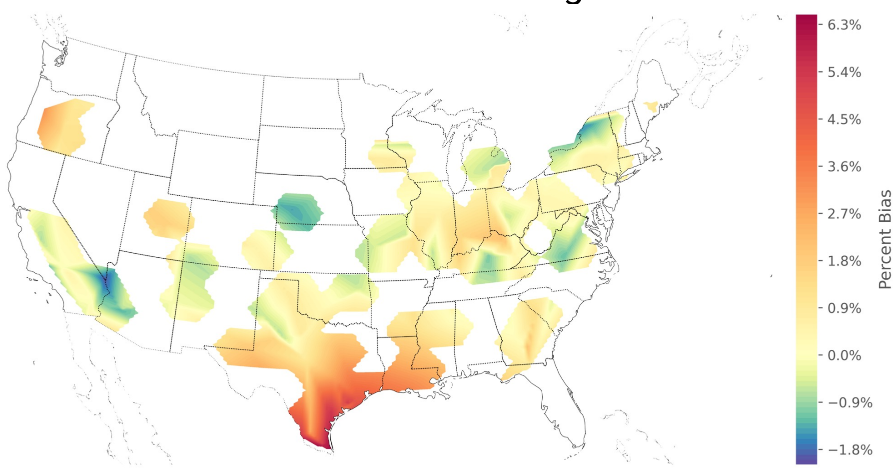
Number of locations: n=87

MOS method is among the best performers:
- **Near 0 bias (6th lowest)**
- **Low standard deviation**

MOS statistics from tests:
- **Mean standard deviation (across tests, temporal): 0.8%**
- **Standard deviation of means (across locations, spatial): 0.7%**

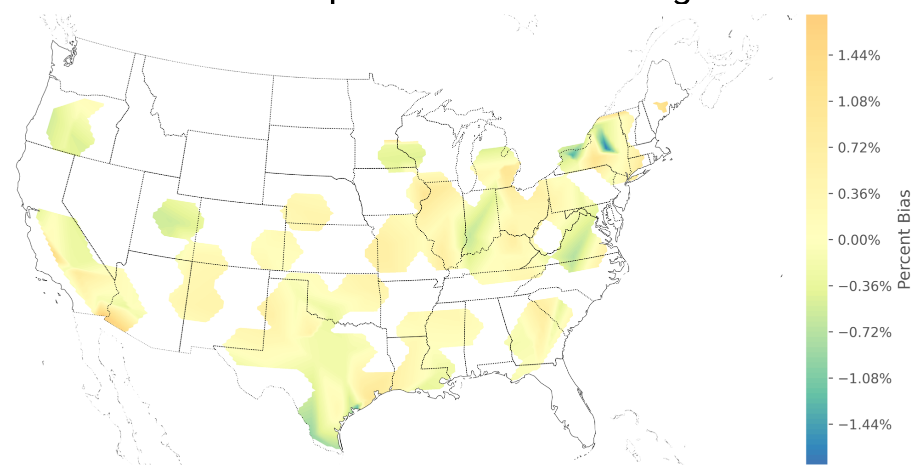
Comparison of Before and After Tuning with MOS by Location

Satellite Bias Before Tuning



NSRDB PSM v4
CONUS Range: -2.02% to +6.58%

Site-Adapted Bias After Tuning

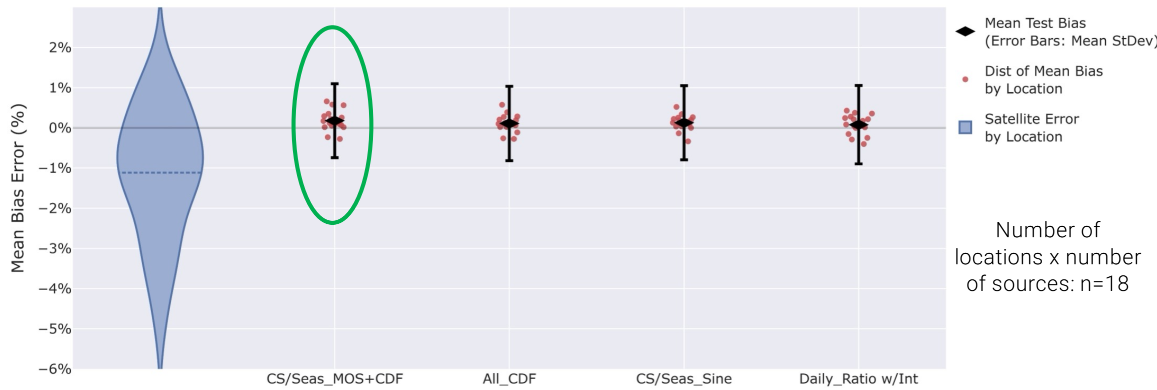


Adapted with CS/Seas MOS + CDF
CONUS Range: -1.89% to +1.85%

Does it work with the paid sources?

3 paid providers
6 GroundWork station locations
24.5 years of measured data (within the last 3-7 years)

Satellite Errors shown with test results from
Model Output Statistics (MOS)
Cumulative Distribution Function (CDF)
Sinusoidal
Daily Ratio with Intercept



Number of locations x number of sources: n=18

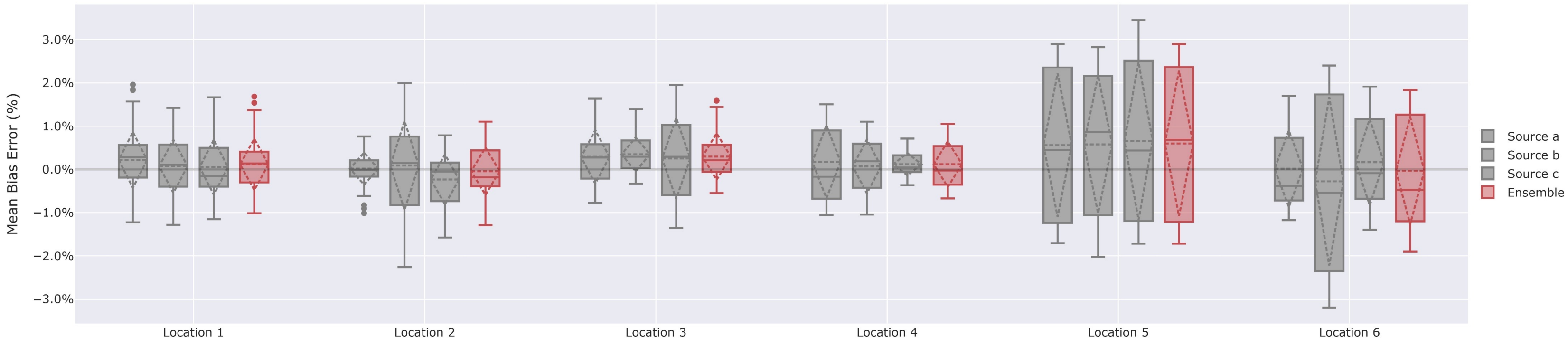
All methods achieve near 0% mean bias and mean standard deviation of about 0.9%

MOS statistics from tests:

- **Mean standard deviation (across tests, temporal): 0.9%**
- **Standard deviation of means (across locations and sources): 0.3%**

How Else Can We Improve Results – Ensemble Approach

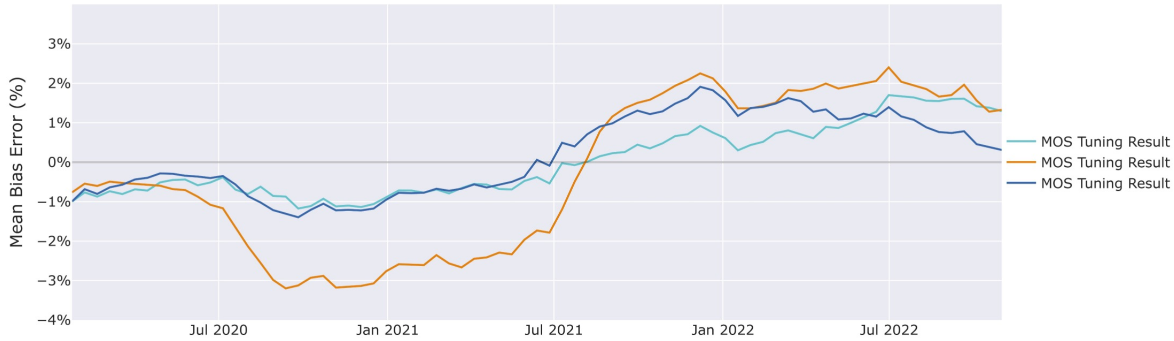
Any one source can have error at times
We can mitigate that by tuning and merging multiple sources into the final target



Uncertainty of individual tests: 0.95%
Uncertainty of Avg of tests: 0.88%

1. Tune All, find annual average GHI
2. Create a Typical "Tuned" Year (TTY?) using one complete dataset that targets the average GHI
3. Resulting P50 GHI with low uncertainty

Ensemble Tuning Example



Shows the tuning result in the train periods

Three Different Sources

Same Tuning Method: CS/Seas MOS +CDF

Taking the average of tunings results in less variability in the outcome

Uncertainty of GHI Values and Conclusions

Estimated Uncertainties of GHI, MOS Tuning Method (k=1)

SURFRAD Tune Full Period with NSRDB (7 Locations, ~25 years): 1.87%

SURFRAD Tune since 2018 with NSRDB (7 Locations, ~25 years): 1.08%

GR Stations with NSRDB (87 locations, ~2 - 7 years): 1.03%

GR Stations with Paid Sources (6 locations, ~3.5 - 7 years): 0.95%

GR Stations with Paid Sources, Ensemble (6 locations, ~3.5 - 7 years): 0.88%

Relevant statistics with large samples:
Across Years, Temporal Variability
(Mean standard deviation, SURFRAD tests)
1.1%

Across Locations, Spatial Variability
(Standard deviation of means, GroundWork Stations)
0.7%

Model Output Statistics ("MOS") is a viable site adaptation method for low uncertainty and low bias error

Site-Adaptation works with about 1% - 1.25% uncertainty

Combining multiple sources in tuning reduces uncertainty

References

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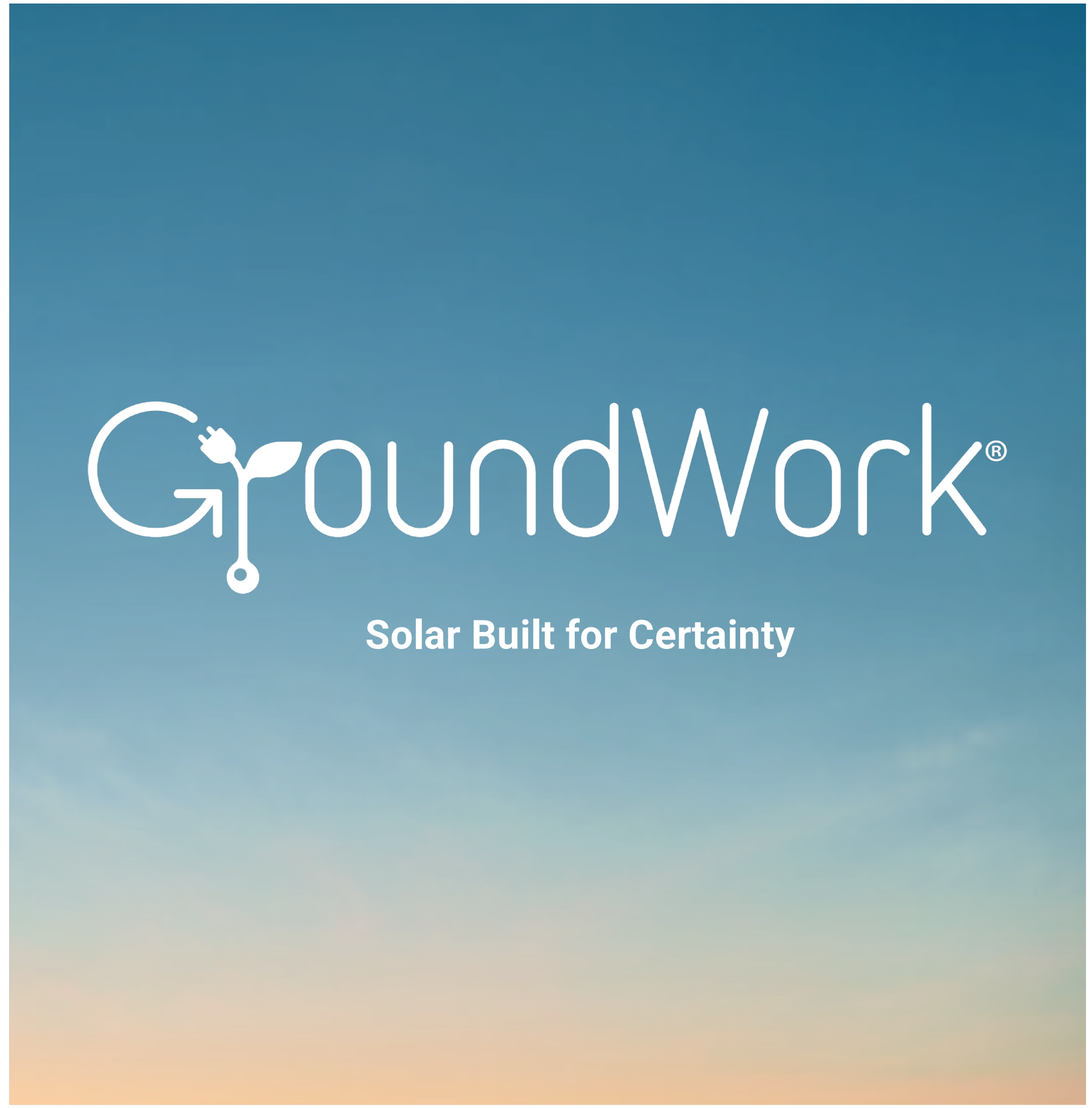

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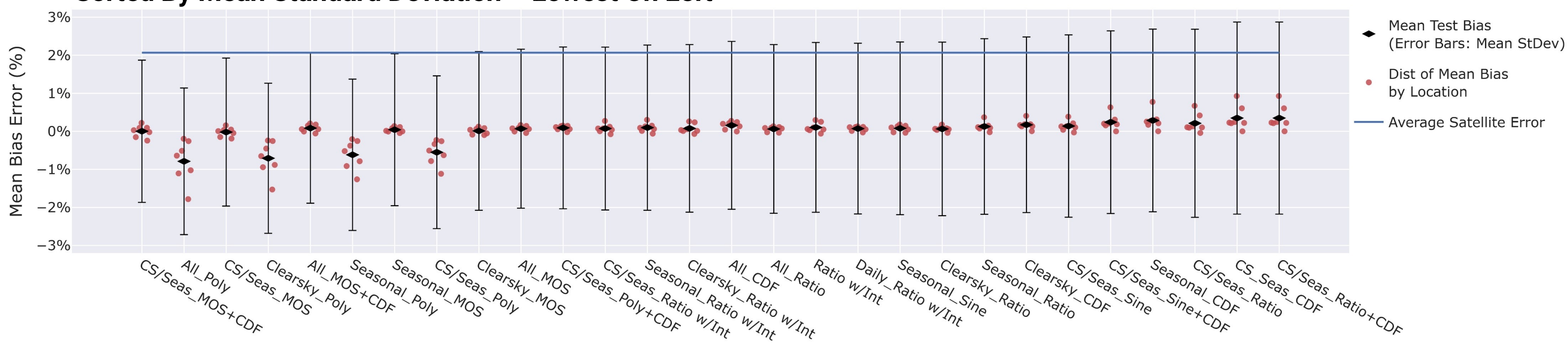
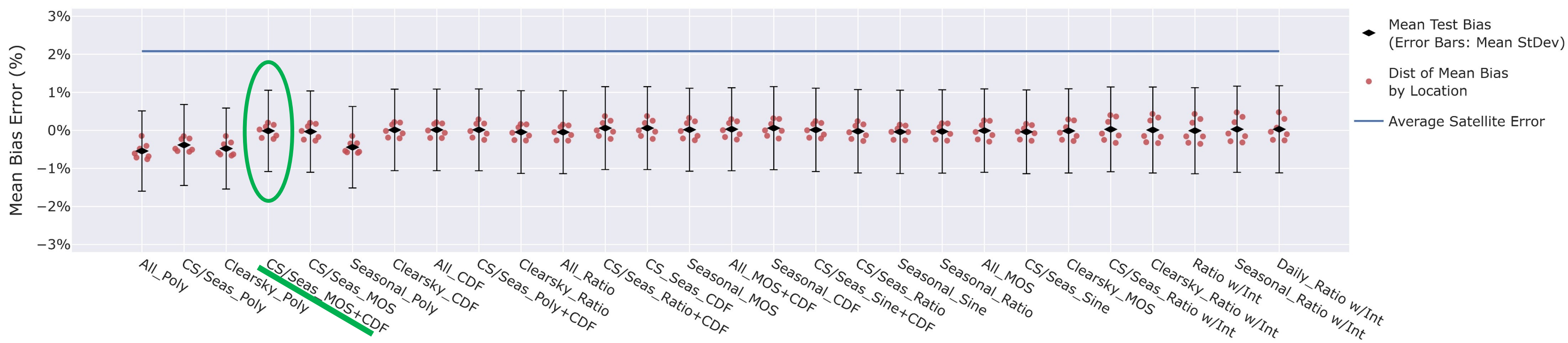


Tuning after 2018



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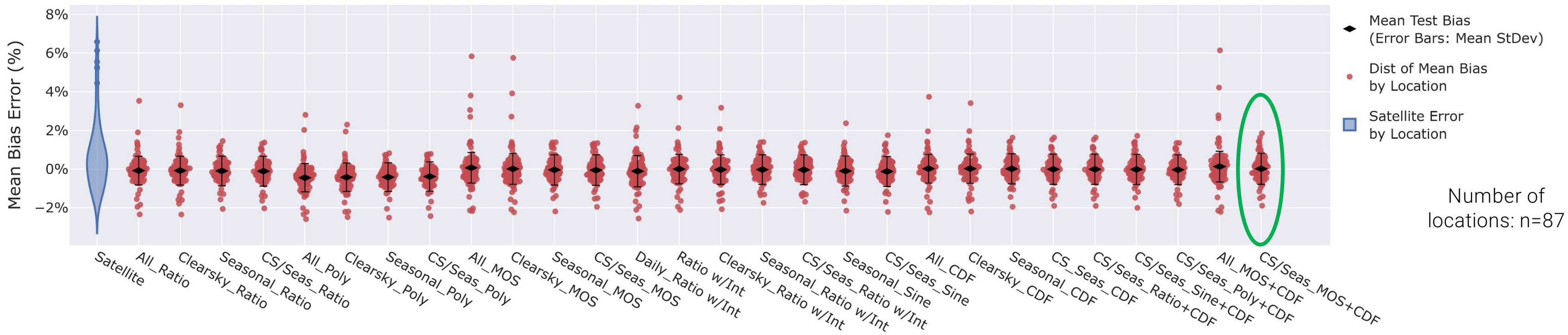

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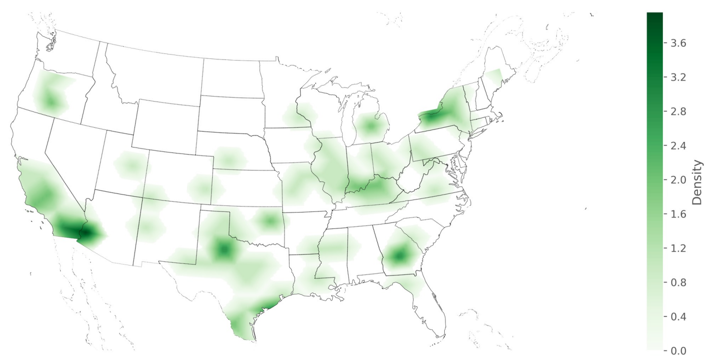

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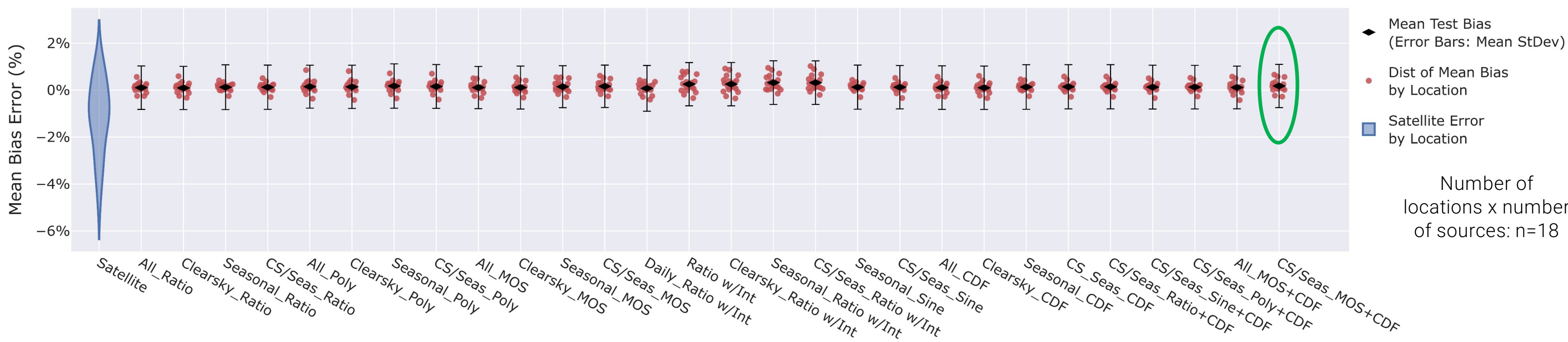

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