Improving satellite-derived irradiance estimates using sparse rooftop solar data and optimal interpolation

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Summary

- **Idea:** Combine Satellite derived irradiance estimates with sparse ground irradiance measurements though optimal interpolation.
- **Motivation:** Accurate irradiance estimates are needed for resource assessment, realtime estimates of PV power generation, and forecasts of PV power generation.
- **Results:** Optimal interpolation reduces root mean square error (RMSE) by ~20% and mean bias error (MBE) by ~85% for cloudy images.

Essentials of optimal interpolation

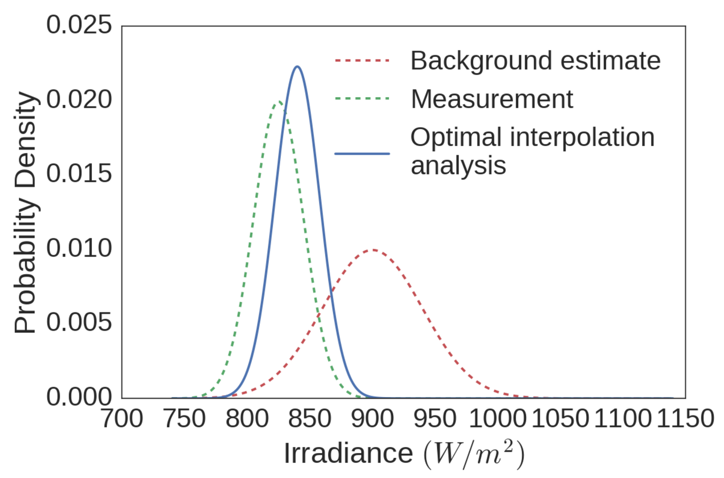
Suppose you estimate that irradiance outside is ~900 W/m² and a sensor measures the irradiance to be ~850 W/m². How can you optimally combine these two pieces of information?

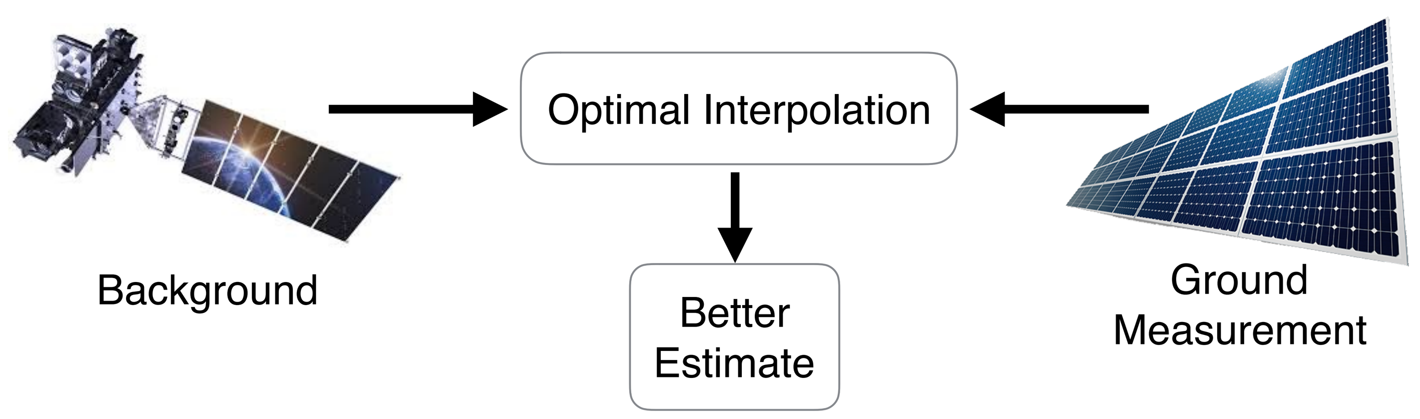
- Call your estimated value x_b and the measurement y.
- The error variances, $\sigma_b{}^2$ and $\sigma_y{}^2$, measure how large of an error you expect from each estimate.
- Optimal interpolation (equivalent to least squares) is the best, linear, unbiased estimate of the true value:

$$x = x_b + w(y - x_b)$$

where

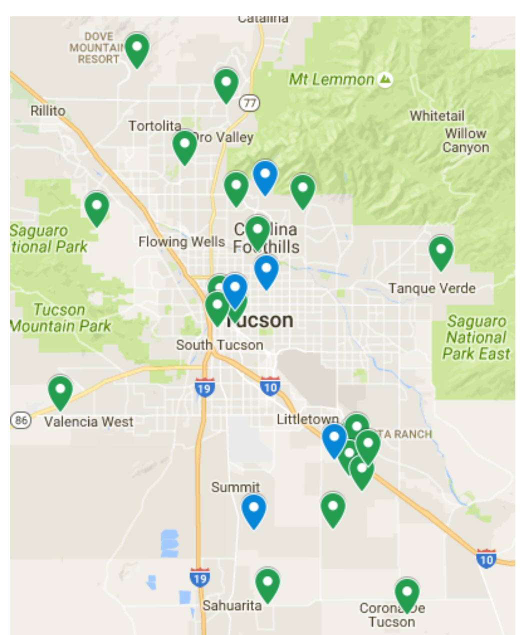
$$w = \sigma_b^2(\sigma_y^2 + \sigma_b^2)^{-1}$$





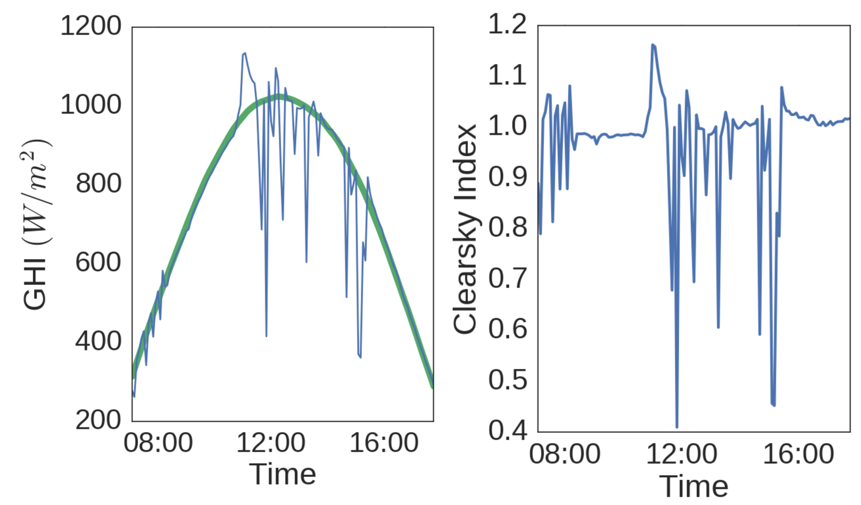
Satellite and ground data

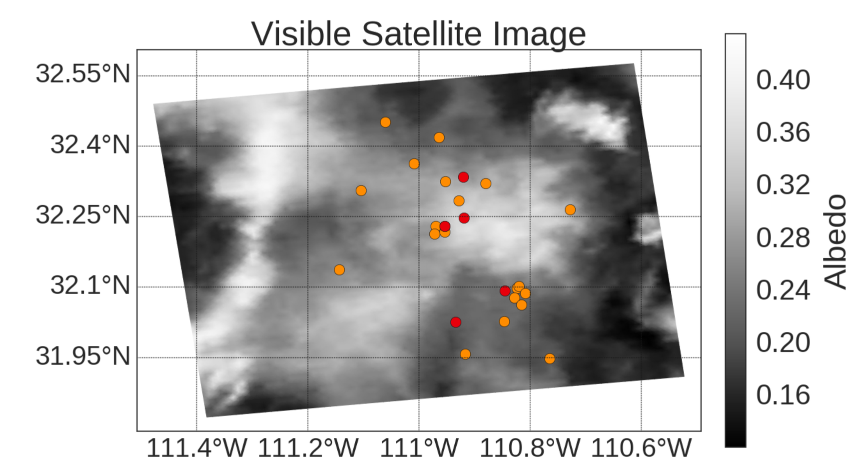
- Data are derived from two sources, geostationary satellite images and ground irradiance measurements from sensors and PV cells.
- Optimal interpolation enables sparse ground data to improve the irradiance estimate over a large area.



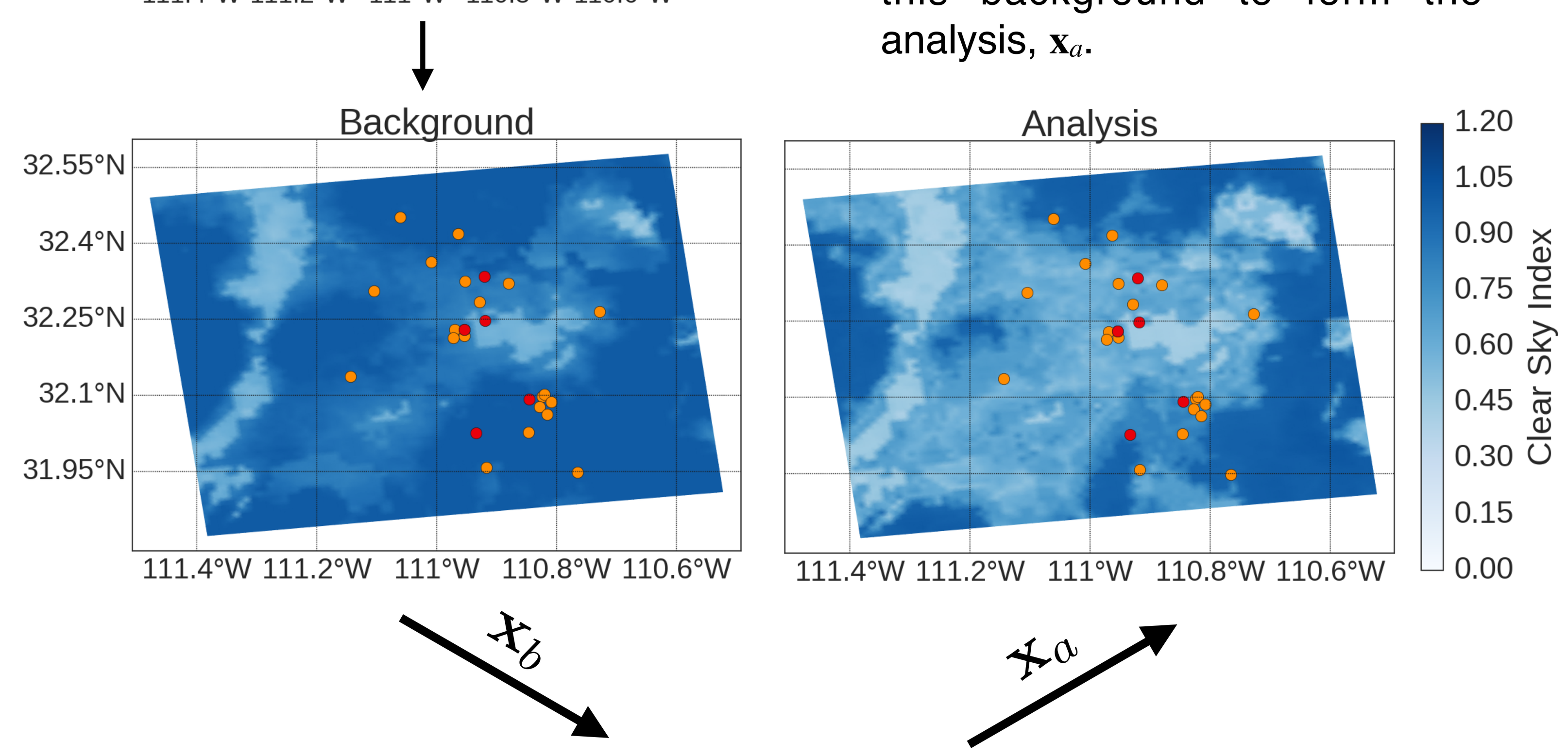
Optimal interpolation with satellite data

We remove the effects of time of day, time of year, and unit of measurement by converting sensor and PV data to a clear sky index. This is done by dividing the measured irradiance or power production by the irradiance or power production under a clear sky.





Visible satellite images are converted to a surface irradiance estimate using a radiative transfer model. The background, $\mathbf{x}_b$, is this surface irradiance divided by the clear sky expectation. Optimal interpolation combines measurements, $\mathbf{y}$, with this background to form the analysis, $\mathbf{x}_a$.



$$\mathbf{P} = \mathbf{D}^{1/2}\mathbf{C}\mathbf{D}^{1/2}$$

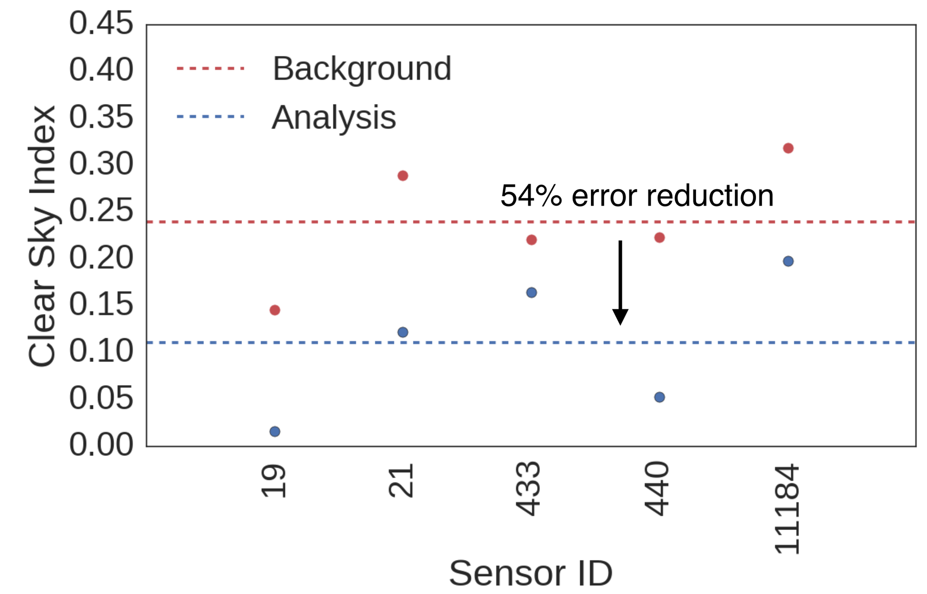
$$\mathbf{W} = \mathbf{P}\mathbf{H}^T(\mathbf{R} + \mathbf{H}\mathbf{P}\mathbf{H}^T)^{-1}$$

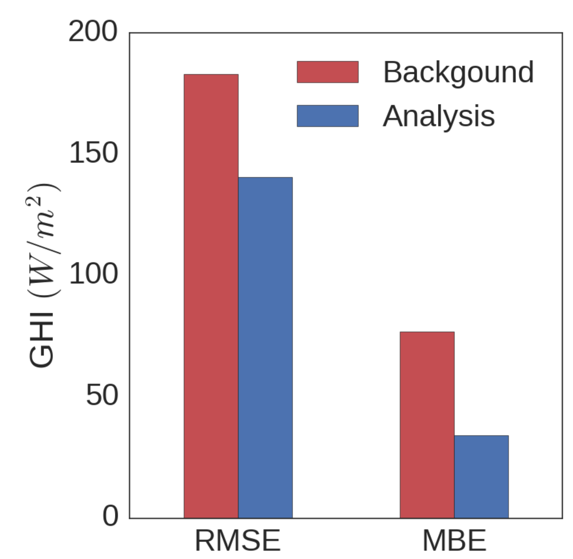
$$\mathbf{x}_a = \mathbf{x} + \mathbf{W}(\mathbf{y} - \mathbf{H}\mathbf{x}_b)$$

- $\mathbf{C}$ is the satellite correlation matrix. Points in the background are more correlated if they have similar cloud cover. For example, if two points in Arizona have a similar pixel value in the visible satellite image the clouds over the two points will likely have similar properties.
- $\mathbf{D}$ is the background error variance. It describes how far from the truth one can expect the background irradiance estimate to stray.
- $\mathbf{P}$ and $\mathbf{R}$ are the satellite and sensor error covariance matrices. If we know the error at one location this will tell us what to expect at others.
- $\mathbf{R}$ is a diagonal matrix because we expect the error correlation between sensors to be negligible.
- $\mathbf{H}$ maps points in the satellite image to sensors on the ground.
- $\mathbf{W}$ is the weight matrix. The larger the weight the more we trust our ground observations.

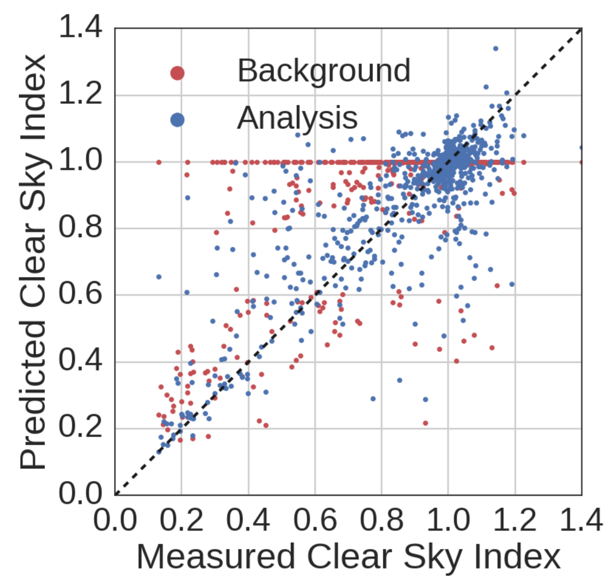
Results

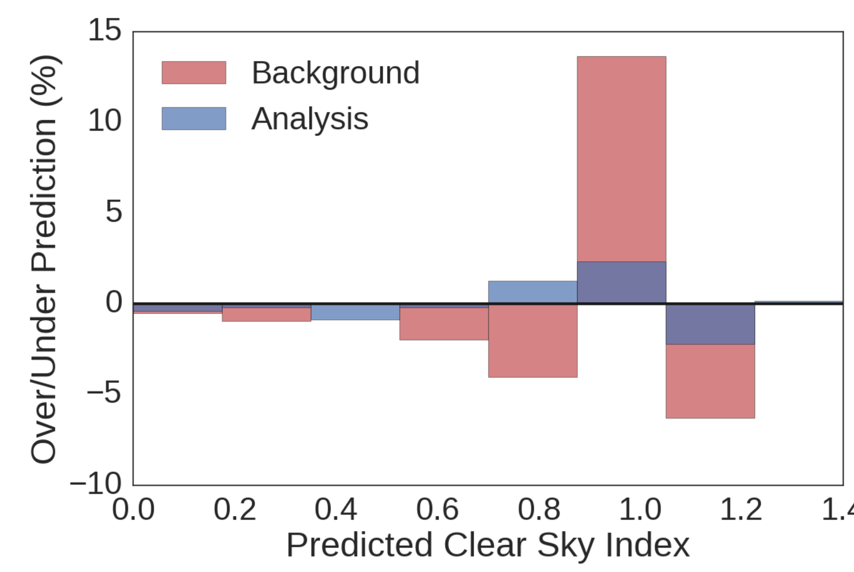
For the example shown in the center column, optimal interpolation reduces the error 54%. This is only for one image and others may have a lower or higher reduction. Errors are calculated using 5 test sensors which were not used for the interpolation process.





- For a calibrated GHI sensor in Tucson, RMSE is reduced by 23% and MBE is reduced by 55% for the 517 cloudy days in our data set.
- The distribution of values seen in the analysis more closely matched those observed.
- In the scatter plot, analysis points fall closer to the identity line. The analysis also predicts values between 0.6 and 0.8 while the background does not.





Future work

- Improve process by optimizing over parameters within satellite correlation matrix $\mathbf{P}$.
- Optimally combine correlation methods based on spatial distance and a cloudiness index.
- Combine 15 minute satellite images with a numerical cloud advection model and ground irradiance measurements using a Kalman filter in order to create forecasts.

References

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