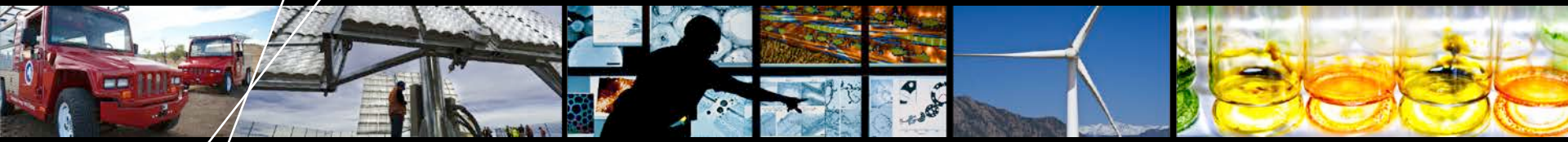
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Downscaling Solar Power Output to 4-Seconds for Use in Integration Studies



Marissa Hummon

3rd International Solar Power Integration Workshop

October 20-22, 2013
London, UK

NREL/PR-6A20-60336

Executive Summary

High penetration renewable integration studies require solar power data with high spatial and temporal accuracy to quantify the impact of high frequency solar power ramps on the operation of the system. Our previous work concentrated on downscaling solar power from one hour to one minute by simulation. This method used clearness classifications to categorize temporal and spatial variability, and iterative methods to simulate intra-hour clearness variability. We determined that solar power ramp correlations between sites decrease with distance and the duration of the ramp, starting at around 0.6 for 30-minute ramps between sites that are less than 20 km apart. The sub-hour irradiance algorithm we developed has a noise floor that causes the correlations to approach ~0.005. Below one minute, the majority of the correlations of solar power ramps between sites less than 20 km apart are zero, and thus a new method to simulate intra-minute variability is needed.

These intra-minute solar power ramps can be simulated using several methods, three of which we evaluate: a cubic spline fit to the one-minute solar power data; projection of the power spectral density toward the higher frequency domain; and average high frequency power spectral density from measured data. Each of these methods either under- or over-estimates the variability of intra-minute solar power ramps. We show that an optimized weighted linear sum of methods, dependent on the classification of temporal variability of the segment of one-minute solar power data, yields time series and ramp distributions similar to measured high-resolution solar irradiance data.

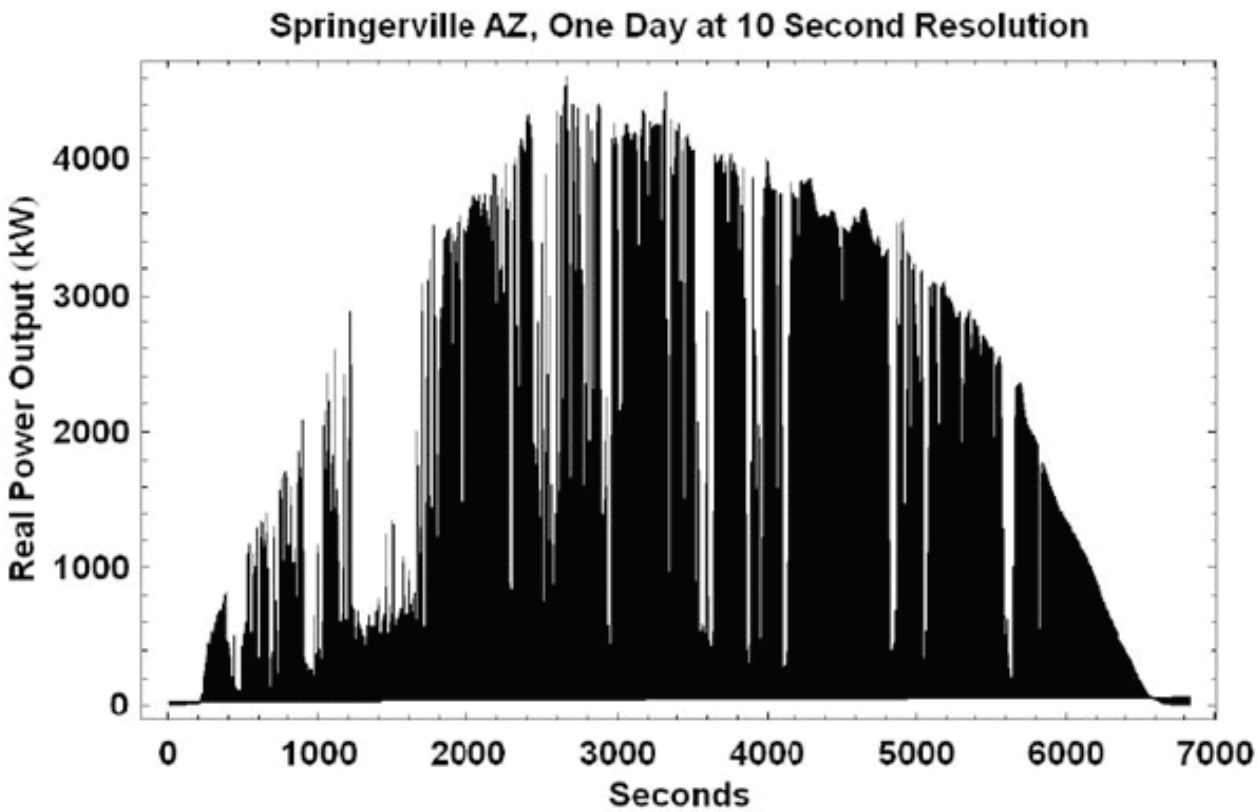
Corresponding paper:
Hummon, M., Weekley, A., Searight, K., and Clark, K., "Downscaling Solar Power Output to 4-Seconds for Use in Integration Studies", 3rd International Solar Power Integration Workshop, London, UK, October 20-22, 2013. (NREL CP-6A20-60335).

A most significant figure…

The lack of availability of sub-hour solar data impedes the study and adoption of high penetration solar energy.

Planners turn to "worse case scenario" data: single measurement site scaled to desired penetration.

Result:
Extremely large reserves requirements; solar integration costs are inflated.



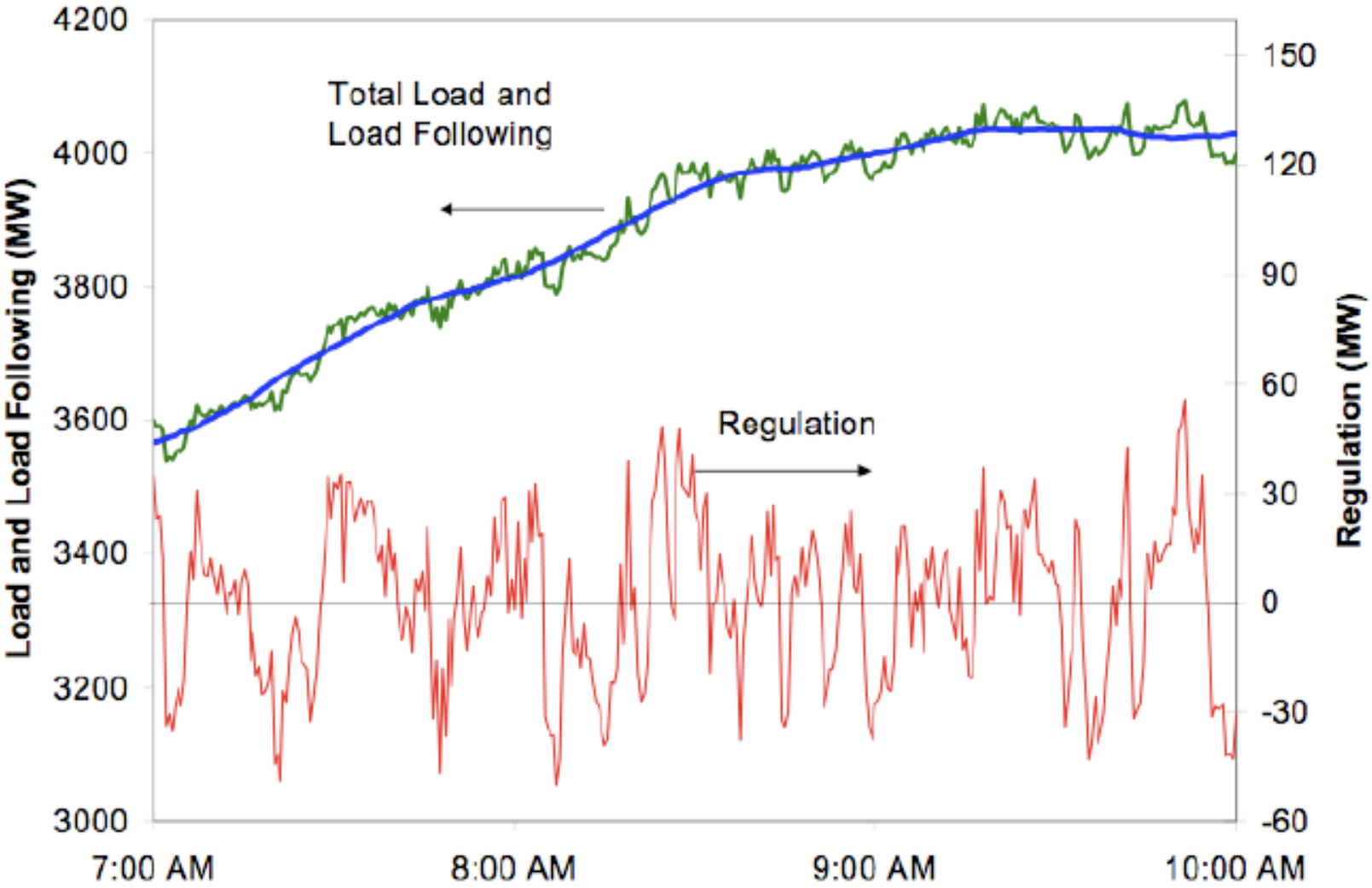
greentech media cites this as one of the "most notorious and historically significant slides in our industry" and "have served as change agents in greentech circles"

Solar Integration Studies

Solar Integration Study Phase	Impact	Solar data requirements*		
		Time (span, resolution)	Space (span, resolution)	Other
Site Selection	Site selection is a balancing act between resource quality, access to transmission, and coincidence of solar resource availability and system demand	10+ years, 1-hour	Nationwide, ~county/zip code	Capacity factor and variability weighting
Operating reserves	Carry too much operating reserves increases integration costs; carry too little operating reserves decreases system reliability, which in turn increases integration costs	2-3 years, 1-minute	Study region (e.g. Eastern Interconnect), <10 km	Clear sky solar data for all location/time periods
Unit commitment modeling	Economics of system operation; Curtailment of solar energy; Changes in emissions, conventional fleet operation.	1 year, 1-hour	Study region (e.g. Eastern Interconnect), <10 km	Requires forecast data: day-ahead, 4-hour ahead
Economic dispatch modeling	Economics of 5-minute operation including deplyment of flexibility reserves for intra-hour changes in solar, wind, and load	1 year, 5-minute	Study region (e.g. Eastern Interconnect), <10 km	
Reserves adequacy/ reliability analysis	System reliability (measuring CPS-2 violations) with increasing renewable penetration; mitigation options (DR, storage)	1 year, 4-second	Study region (e.g. Eastern Interconnect), <10 km	

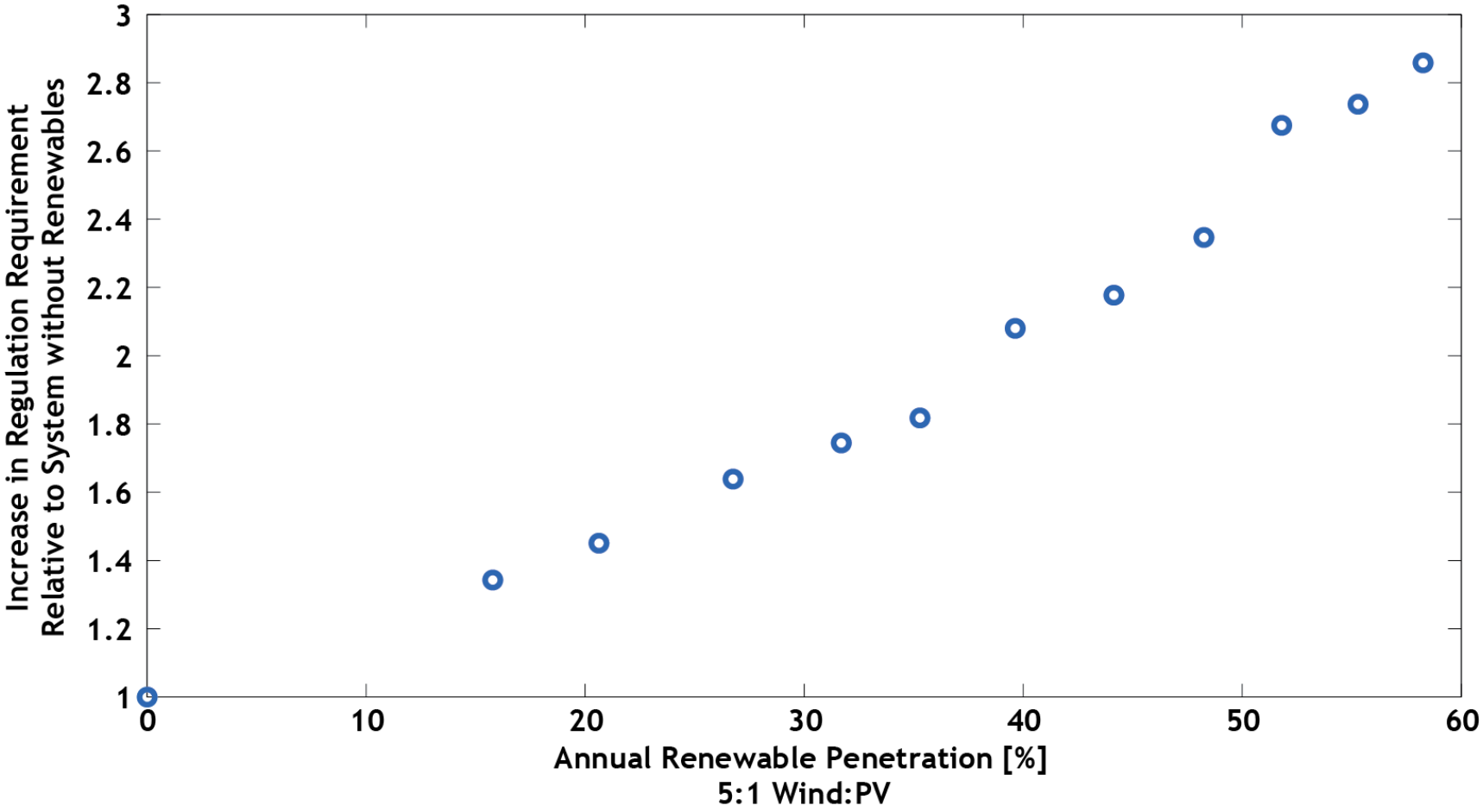
* Validated with ground measurements (of the appropriate temporal resolution)

Frequency Regulation Requirements



System load following and regulation. Regulation (red) is the fast fluctuating component of total load (green) while load following (blue) is the slower trend

Frequency Regulation and Solar Power

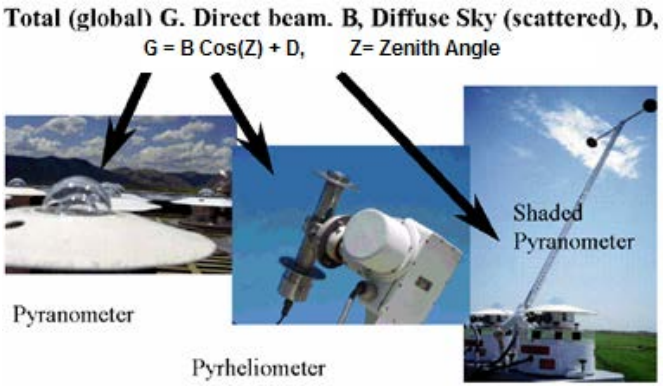


How do we measure/model solar radiation?

- **Ground Measurements:**

Pyranometers, Pyrheliometers, etc.

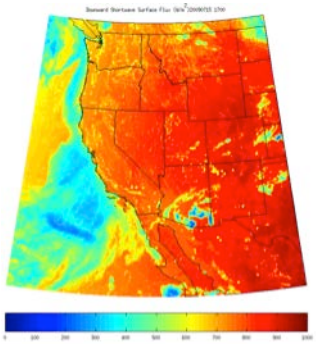
  - **Advantages**: accurate, high temporal resolution.
  - **Disadvantages**: local coverage, regular maintenance and calibration.



- **Satellite derived estimates:**

Physical (e.g. GSIP), empirical (e.g. SUNY), etc.

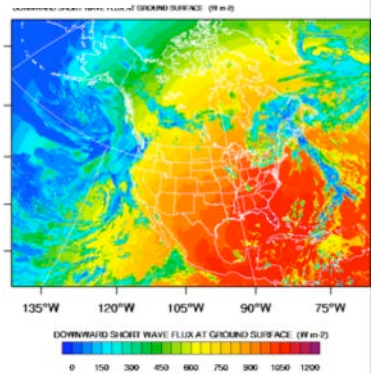
  - **Advantages**: global coverage, reasonably long time ser
  - **Disadvantages**: spatial and temporal resolution, complicated retrieval process, accuracy depends on information content of satellite channels.



- **Numerical Weather Prediction based estimates**

NAM, GFS, ECMWF

  - **Advantages**: global coverage, long time series (reanalysis data), increasing computing capability results in increasing resolution.
  - **Disadvantages**: level of accuracy especially in cloud formation and dissipation (initialization and model physics issues).



4-second Solar Power Data Algorithm

Andy Carter, View of clouds from above, South Africa.

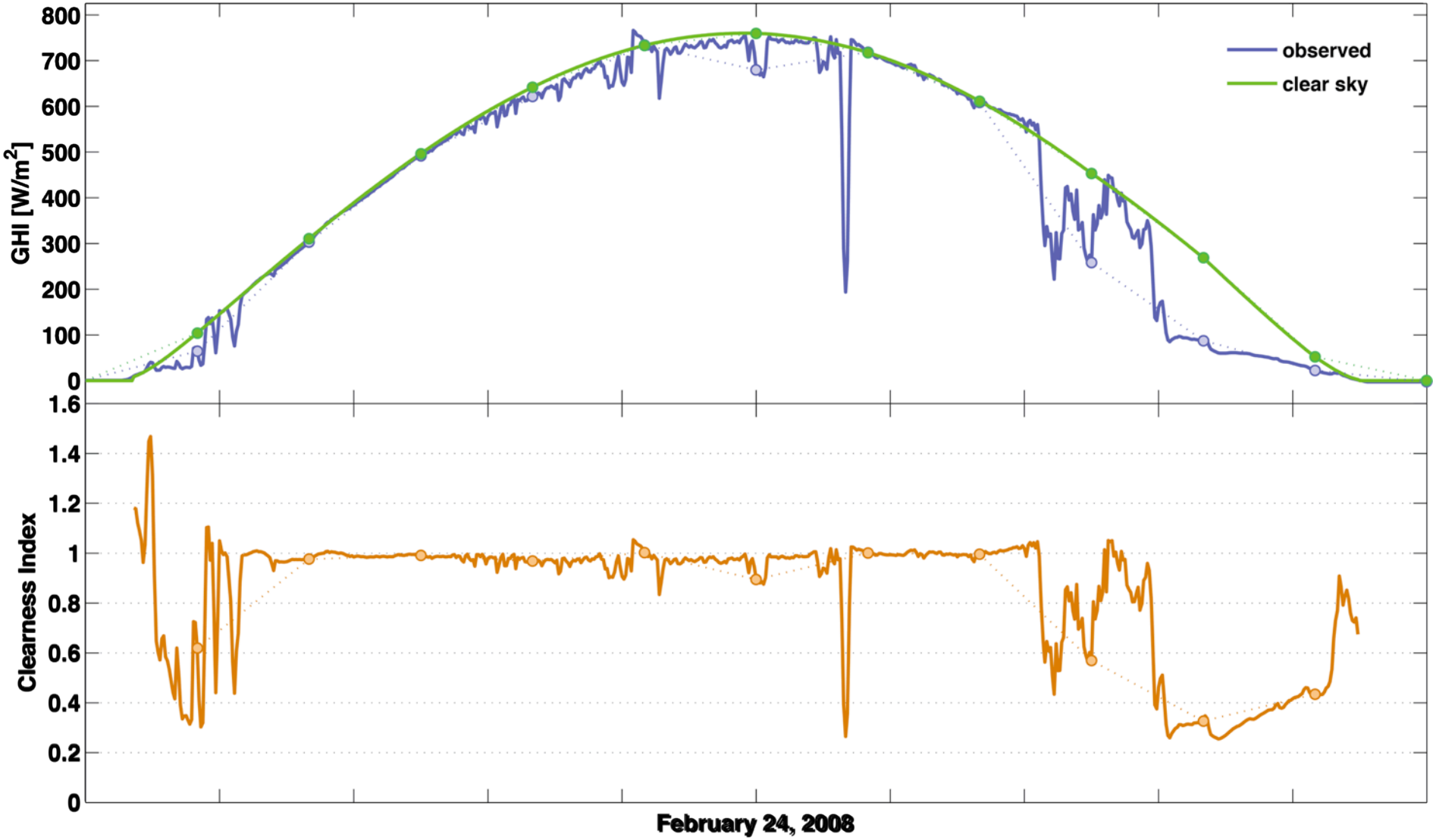
4-second Solar Power Data Algorithm

Analytical Approach:

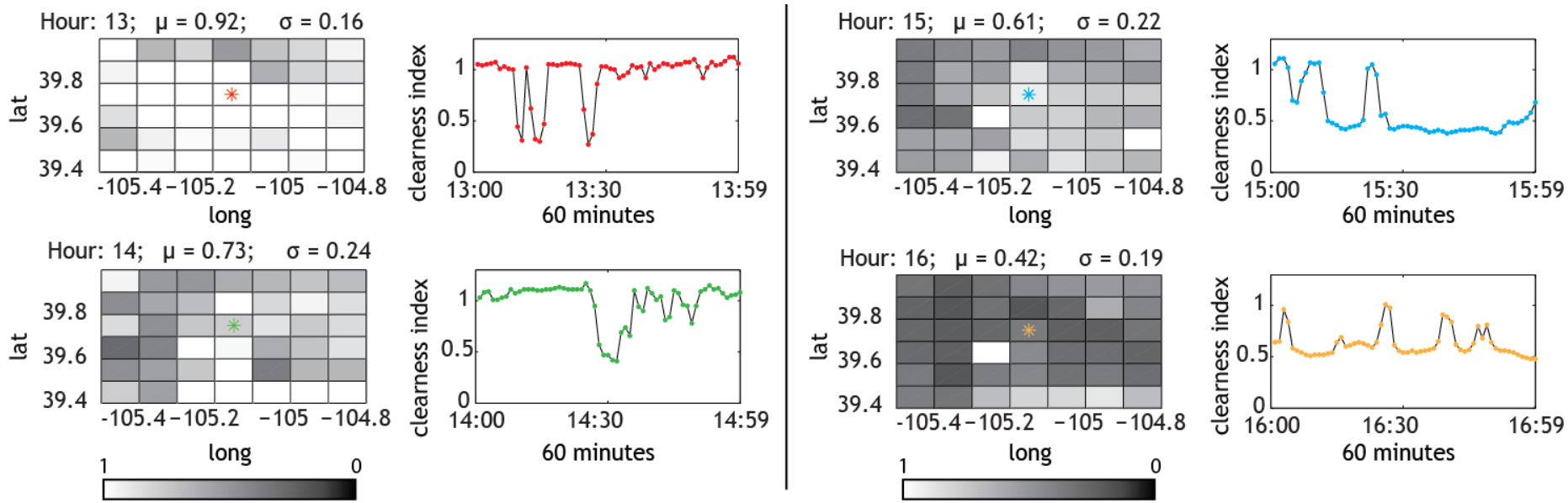
- 4-s Algorithm based on post processing on 1-minute solar power data
- Assumptions:
  - 4-second ramp distribution to be related to the 1-minute ramp distribution, e.g.
  - Expect no correlation in 4-second ramps between sites

Andy Carter, View of clouds from above, South Africa.

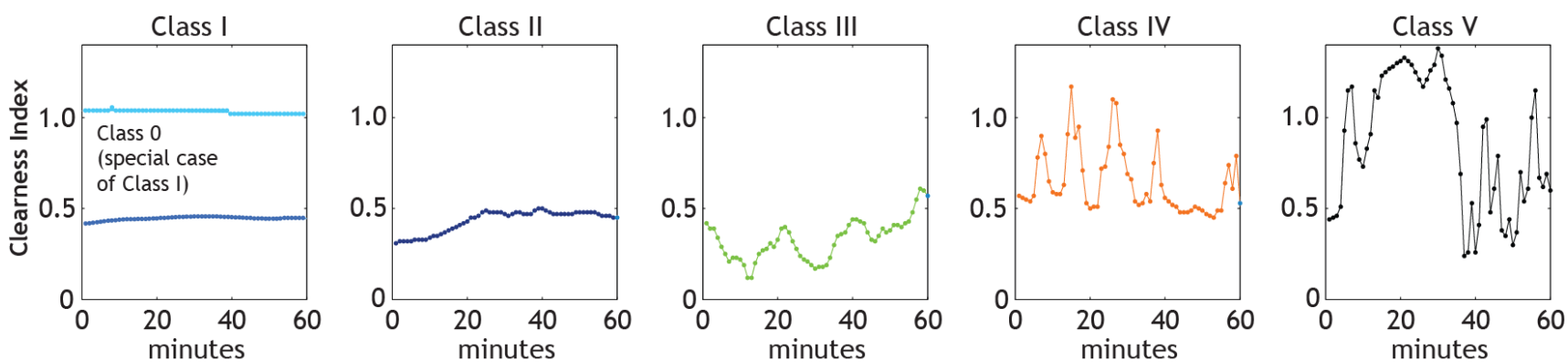
Clearness Index



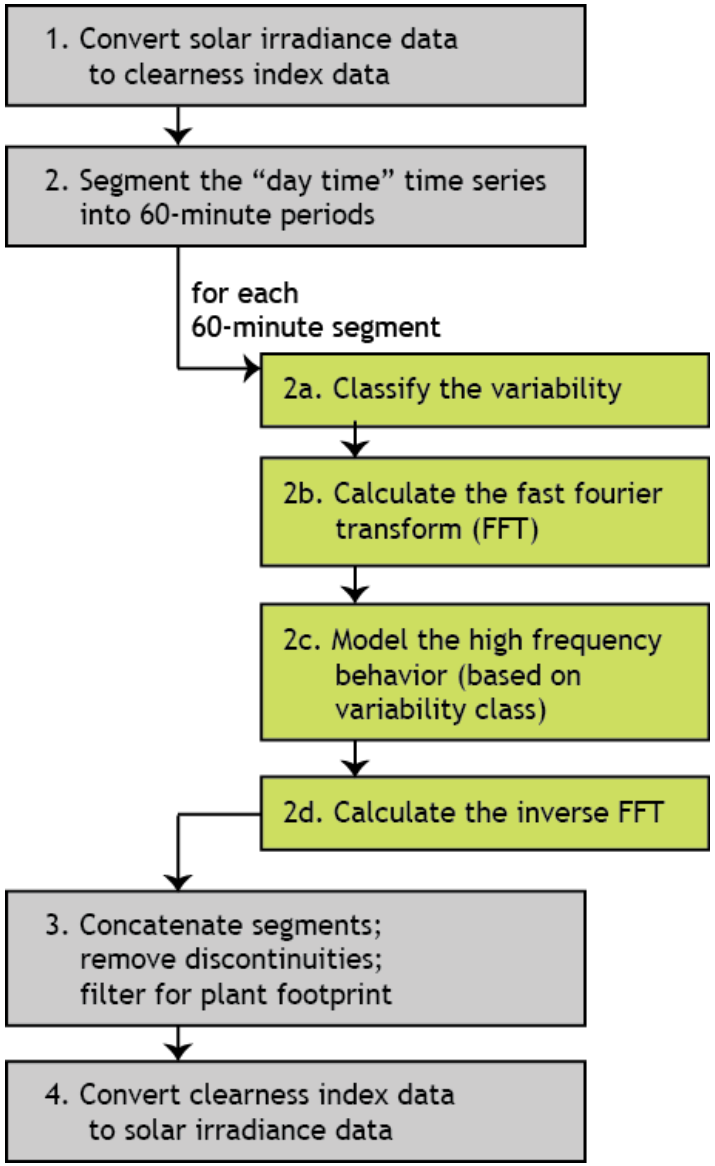
Down scaling to one minute…



We used spatial variability to determine the most likely temporal variability. The overlapping spatial data results in the temporal data having a higher correlation with nearby sites than with sites far away.



4-s Algorithm

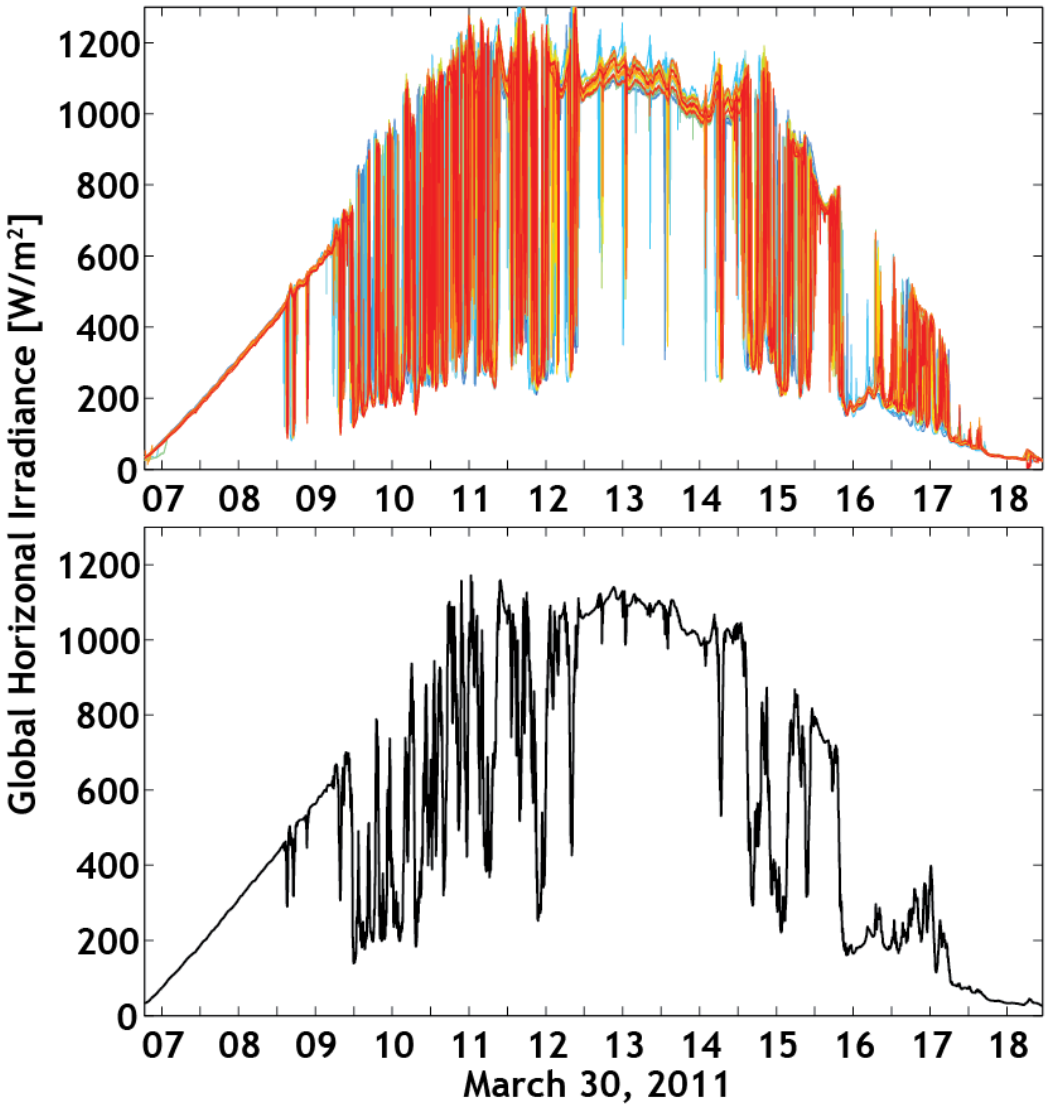


- High frequency behavior can be estimated in frequency space using several methods.
- Some of the methods are better suited to particular variability classes than others.
- This step includes an optimal linear combination of the different downscaling methods for each variability class.

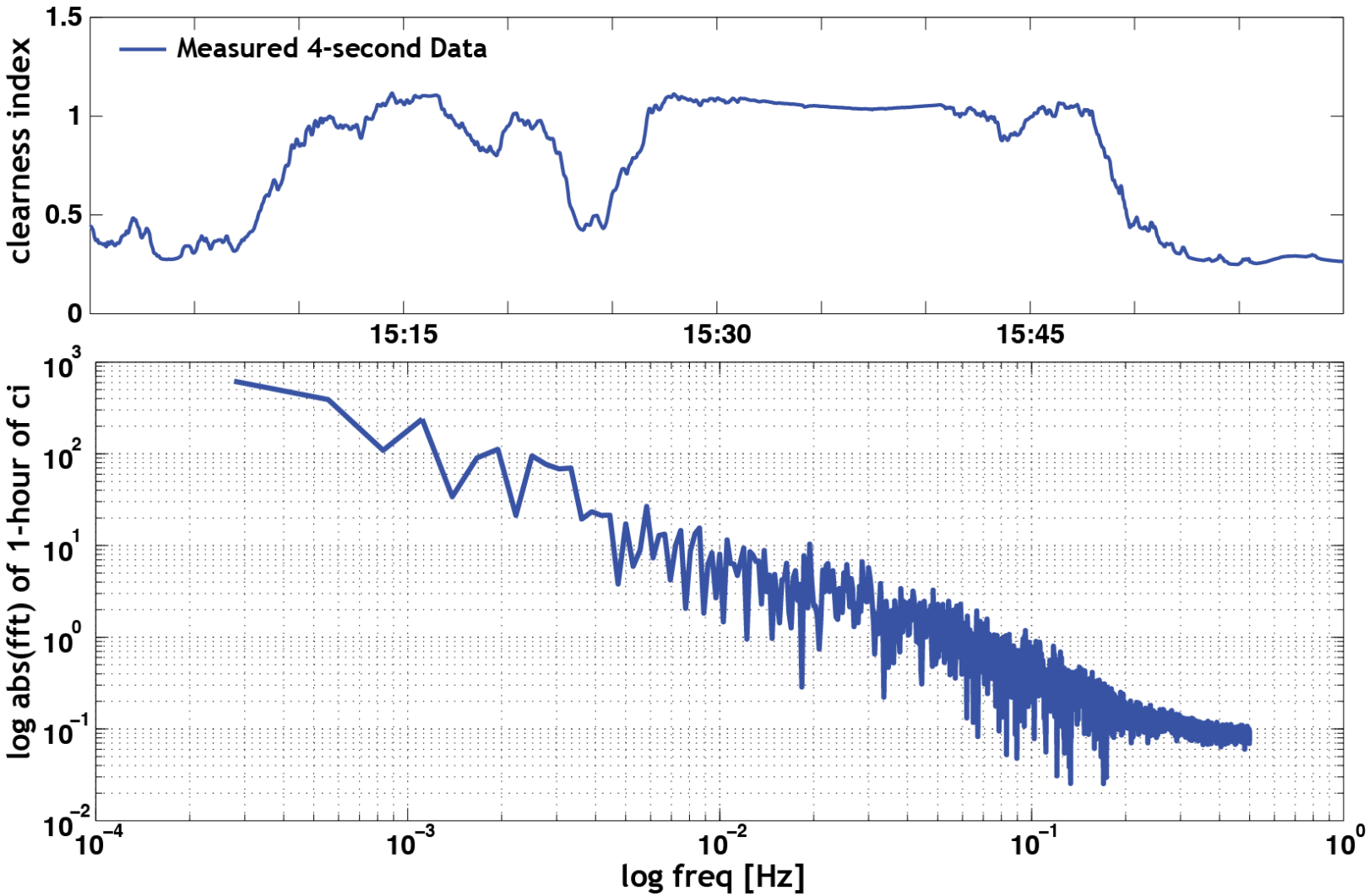
Measured data sources

Oahu, Hawaii Irradiance Sensor Network

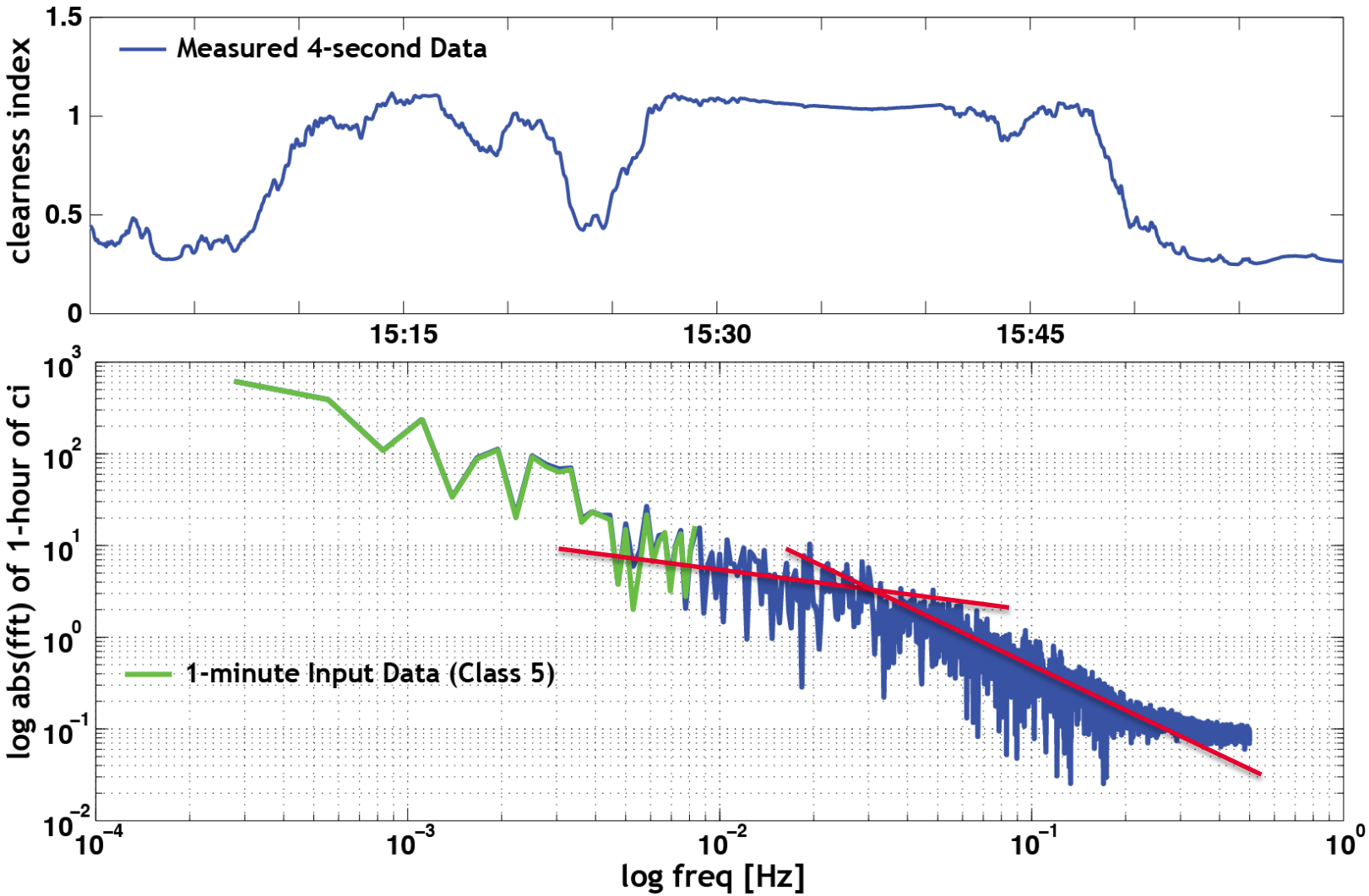
NREL campus Irradiance Sensor Network



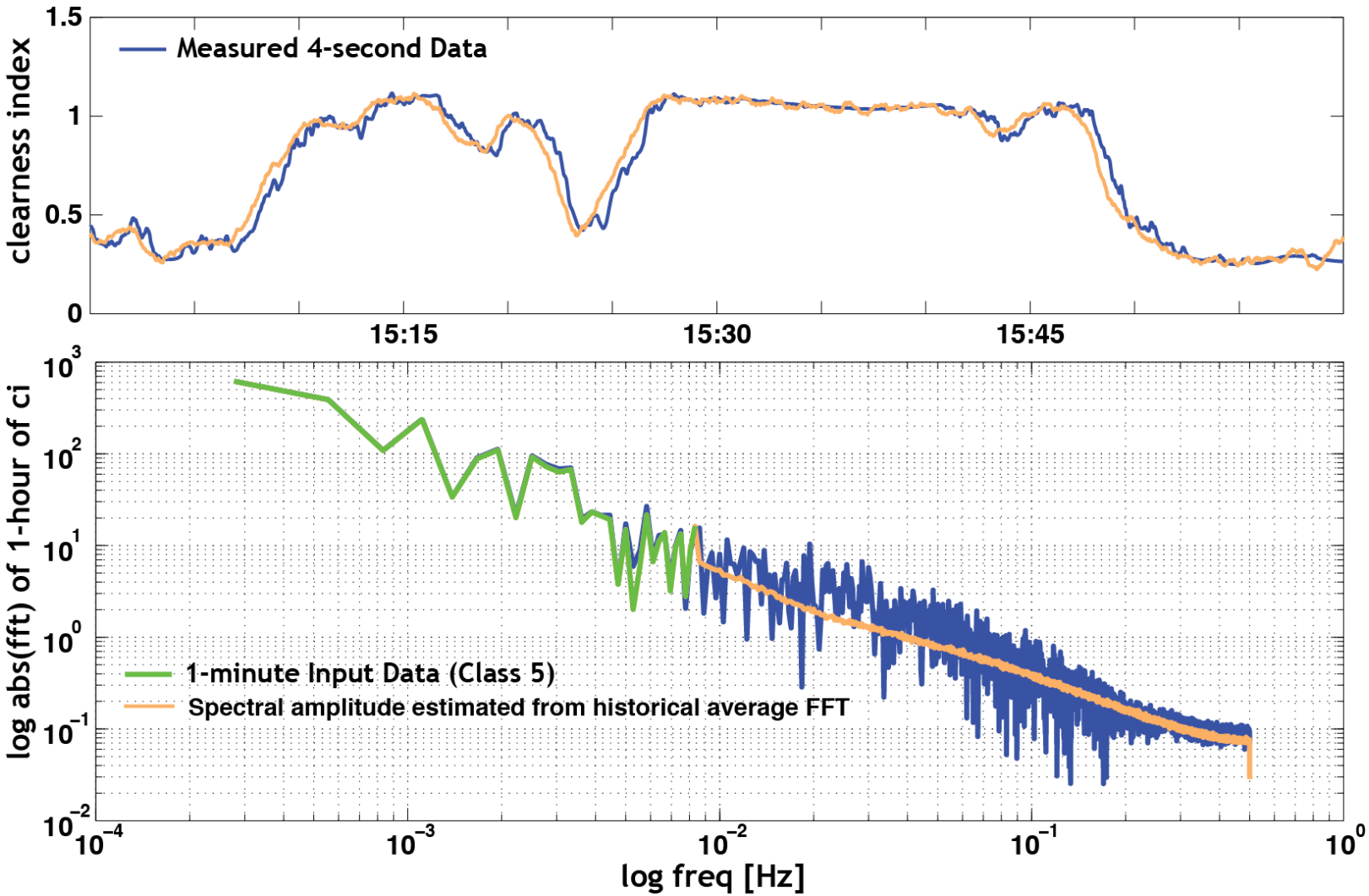
Downscaling to 4-s in frequency space



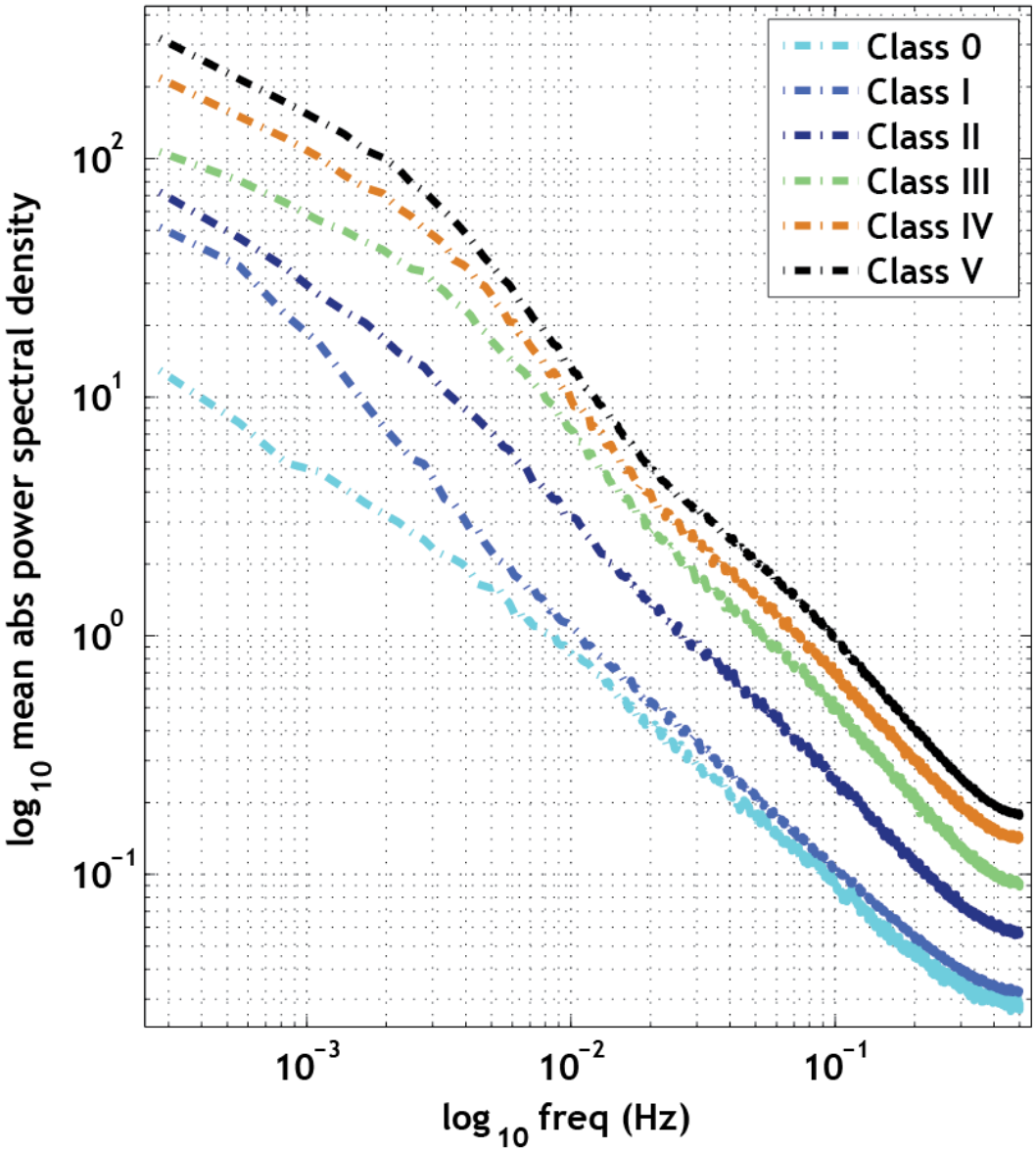
Downscaling to 4-s in frequency space



Downscaling to 4-s in frequency space

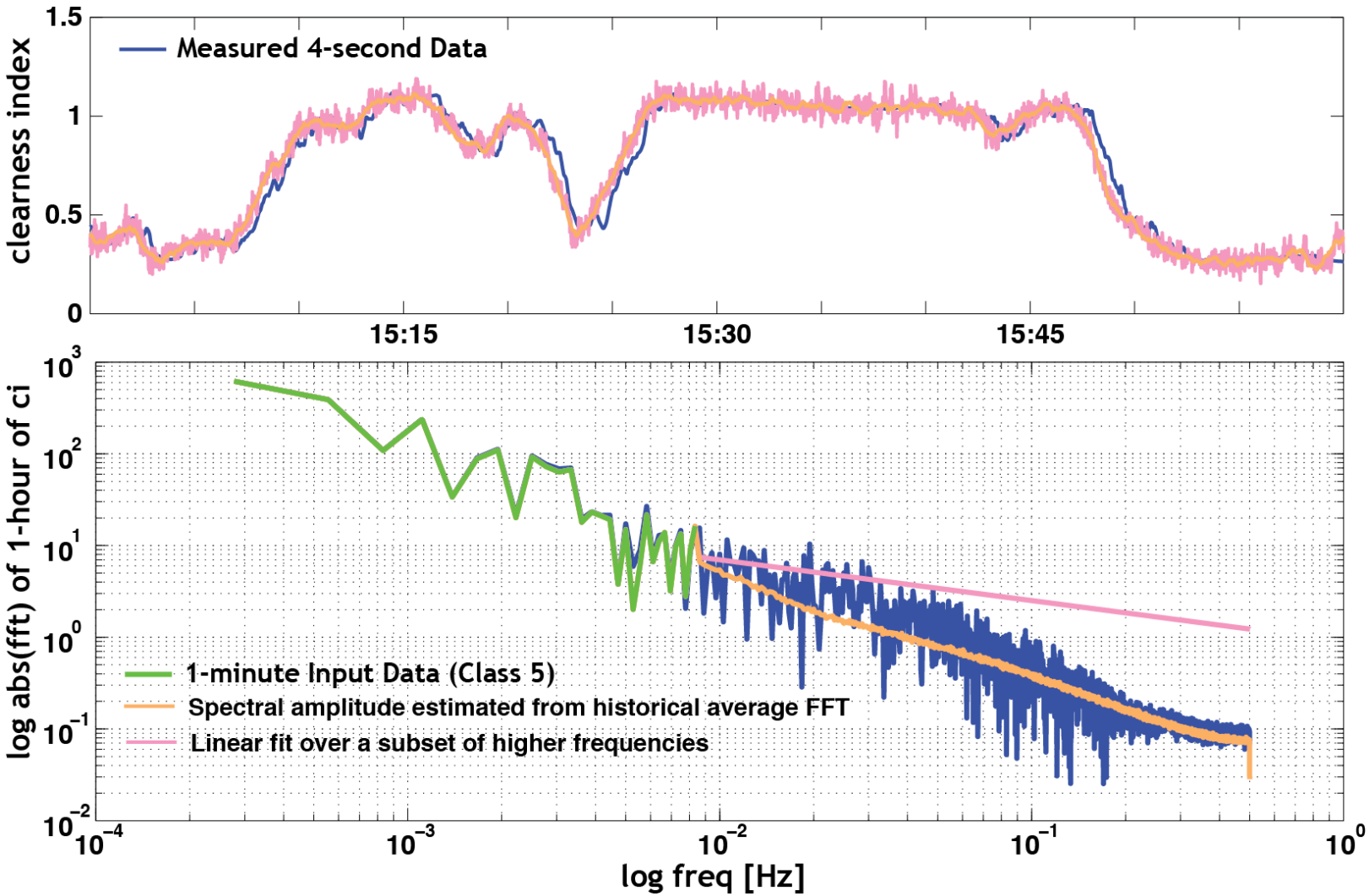


Spectral amplitude from historic data

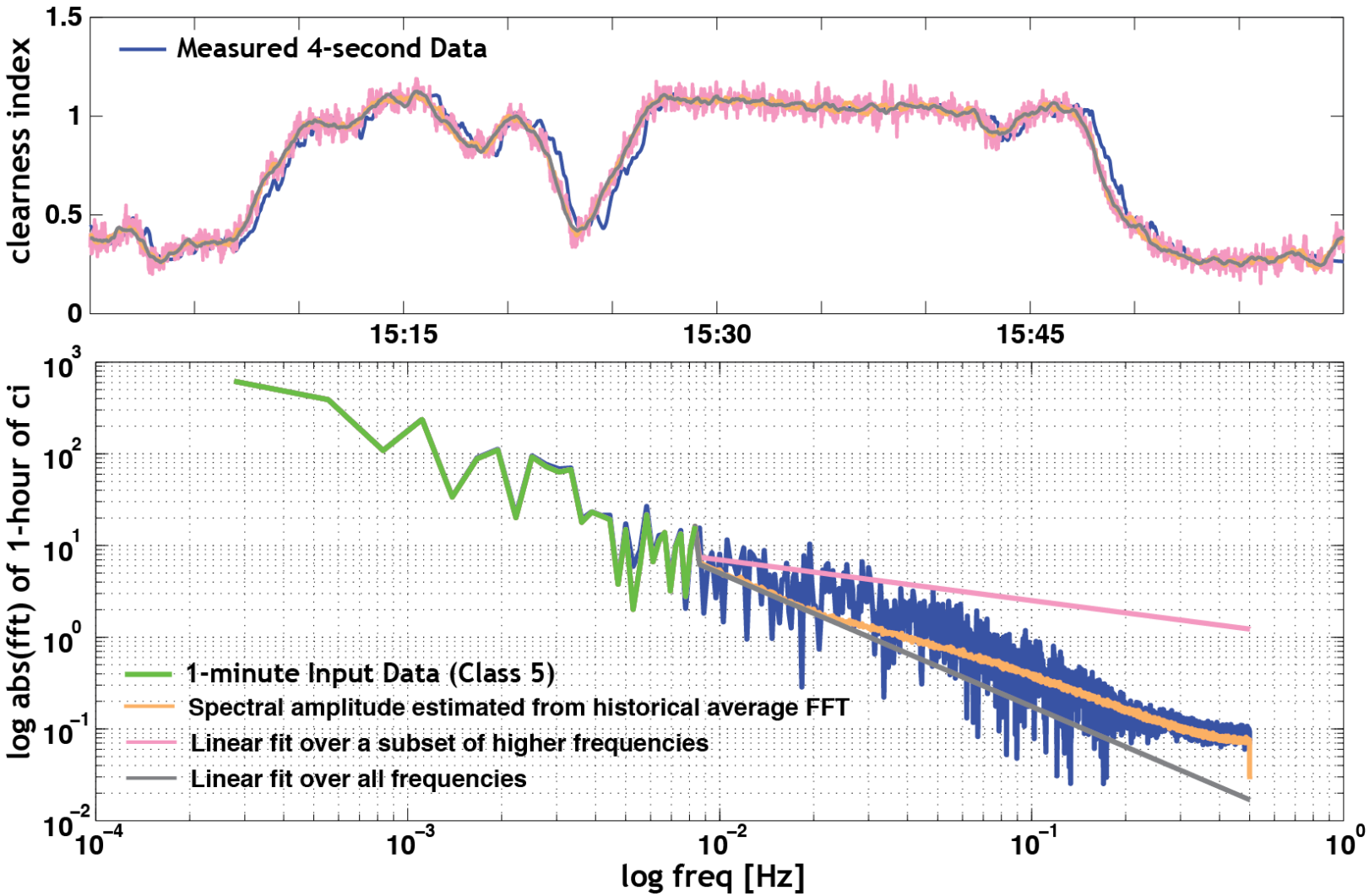


Spectral average from historic data shows distinct PSD for each class of temporal data.

Downscaling to 4-s in frequency space



Downscaling to 4-s in frequency space



Solution

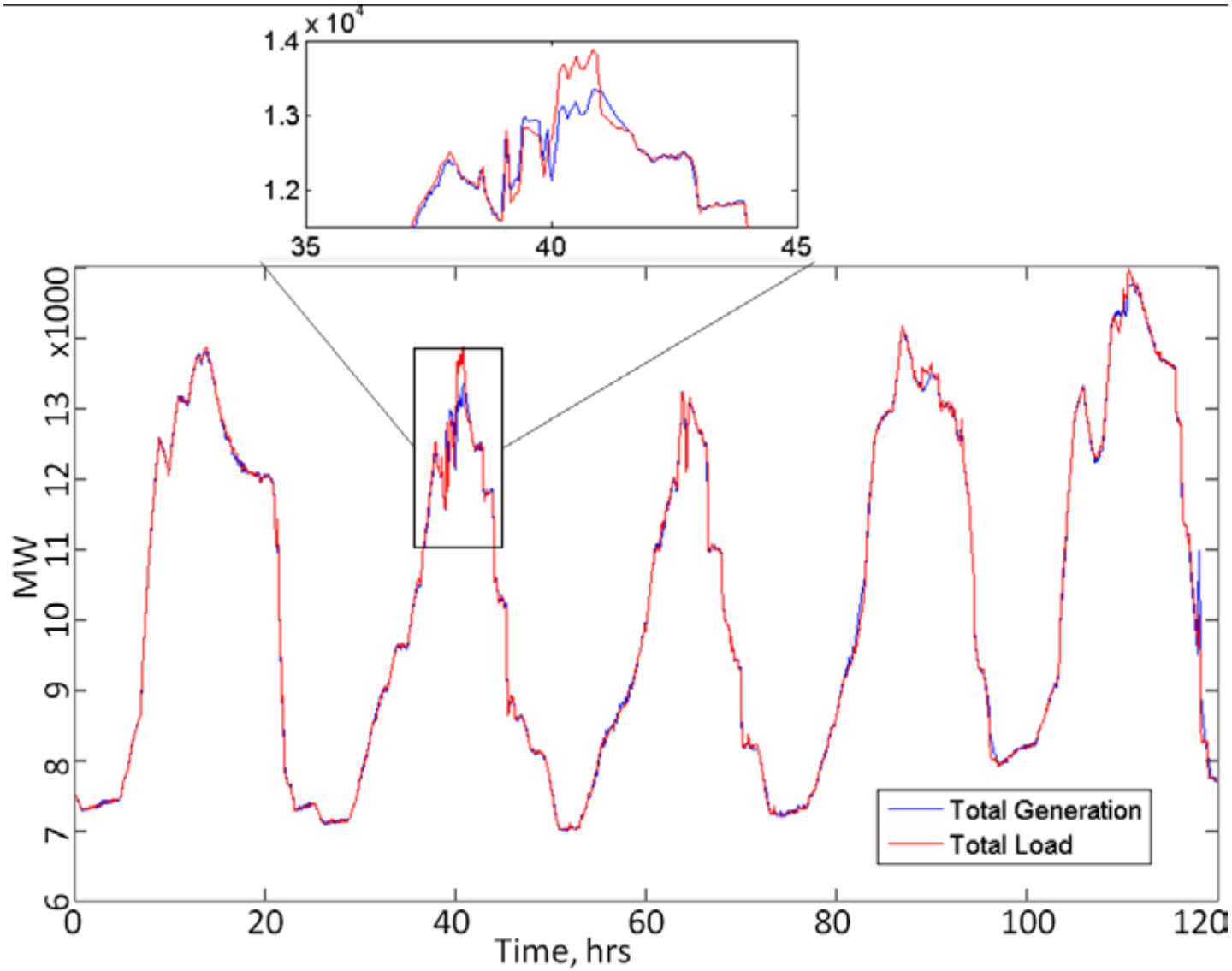
Concluded: Different methods for different classes

Developed: Optimal weighting of methods for each class

Weighting Downscaling Methods by Temporal Class

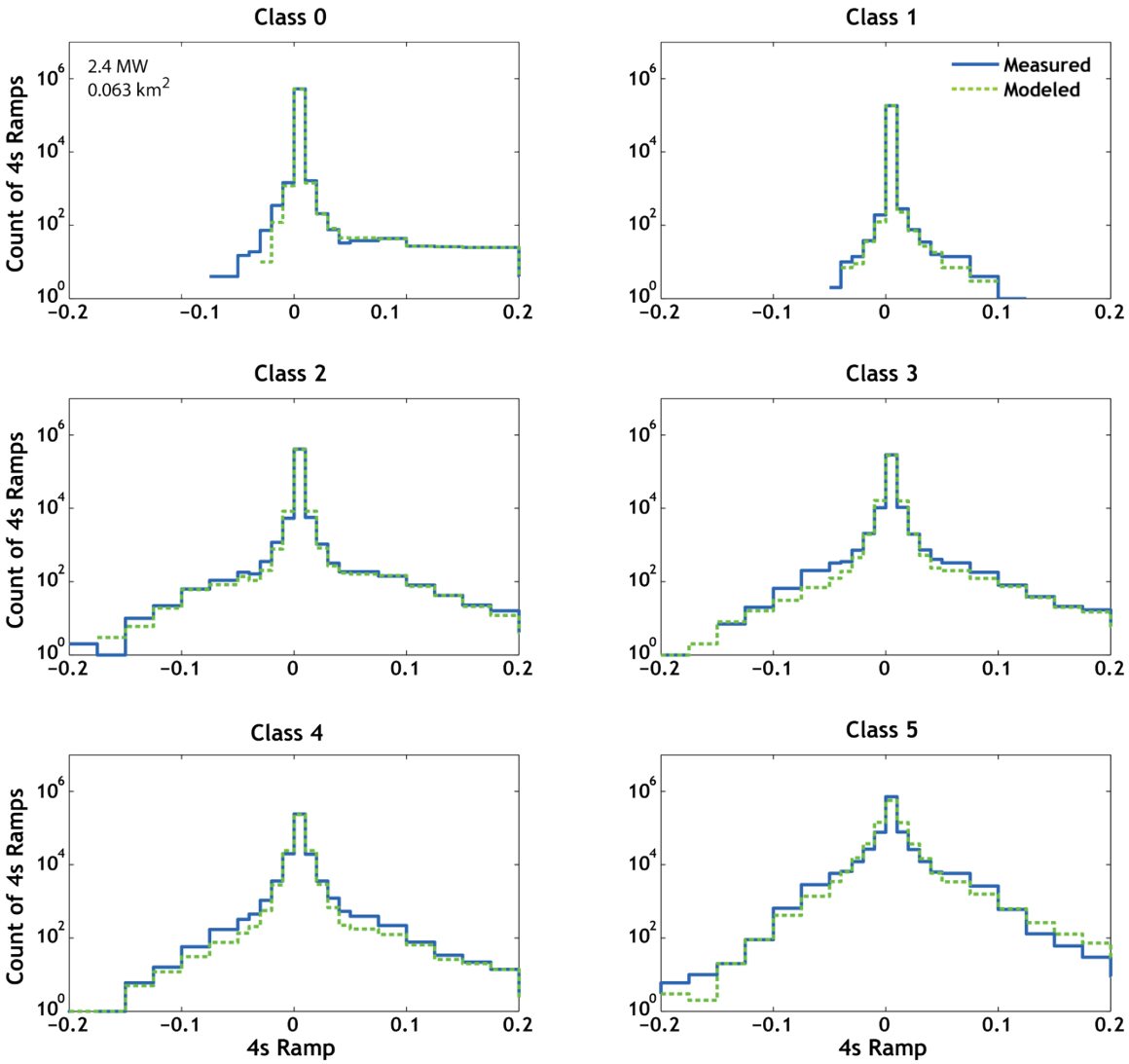
		Class of Temporal Variability (from 1-minute input data)					
		0	**I**	**II**	**III**	**IV**	**V**
Downscaling method	**Spline**	0.47	0.71	0.44	0.47	0.31	0.32
	Linear fit over all frequencies	0.27	0.01	0.28	0.35	0.36	0.22
	Linear fit over a subset of higher frequencies	0.11	0	0.11	0.1	0.16	0.45
	Spectral amplitude estimated from historical average FFT	0.15	0.15	0.16	0.08	0.17	0.01
Error (MSE)	**CI Time series**	9.2E-05	6.3E-06	5.2E-04	1.8E-03	1.9E-03	1.6E-02
	CI 4-s ramp distributions	6.6E-07	8.8E-11	3.6E-06	9.1E-06	1.0E-05	4.9E-06

Application of 4-s Solar Power Data



Results

E. Ela evaluated FERC Order 755 (the regulation market "pay for performance" order) in SMUD using the 4s solar data and fast response storage.



Conclusions

- **Presented a method of downscaling 1-minute solar data to 4-seconds by optimizing the linear combination of four methods for extending the PSD from f = 1/120 to 1/2 Hz (from 2-minutes to 2-seconds). The optimized weights vary by classification of the 1-minute temporal variability.**
- **Demonstrated the quality of the fit by observing the mean squared error of the modelled data.**
- **Modelled data performs very well in comparing the distributions of ramps, which makes this dataset ideal for use in integration studies concerned with the rapid change in solar power output.**
- **Four-second solar power data enables researchers to investigate new methods of balancing the system under high penetrations of solar power.**

Thank You

Questions?

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