Methods for Analysis of Outdoor Performance Data

NREL

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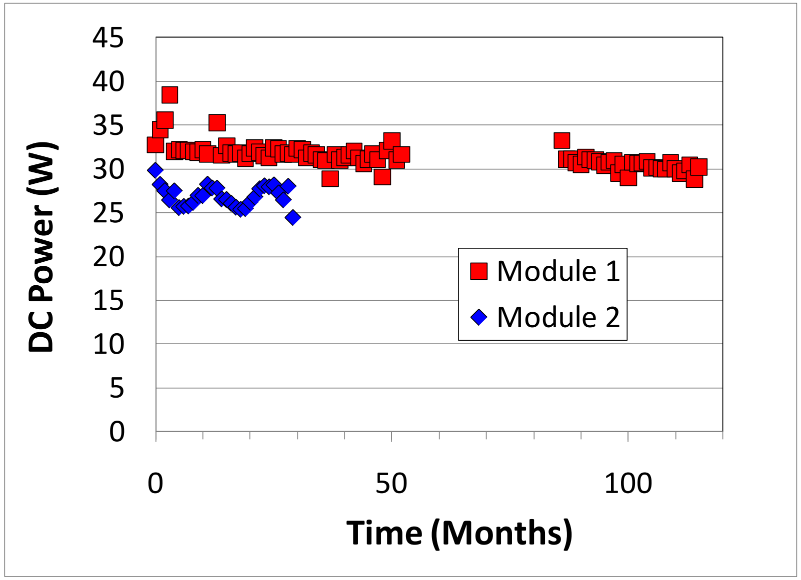
Outline

- Motivation: Impact of uncertainty in degradation rates (R_d)
- Methodologies
  1. IV data taken in discrete intervals
  2. Continuous data, PVUSA & Performance Ratio
  3. Additional methodologies for continuous data - Classical Decomposition, ARIMA
- Historical R_d and what we can learn from it.
  1. Methodologies
  2. Number of measurements
  3. Climate

Motivation

For solar industry to keep growing we need to accurately understand & predict how different technologies behave/change with weather, climate and time.

Change of power output with time is degradation rate (R_d)….uncertainty is very important too.



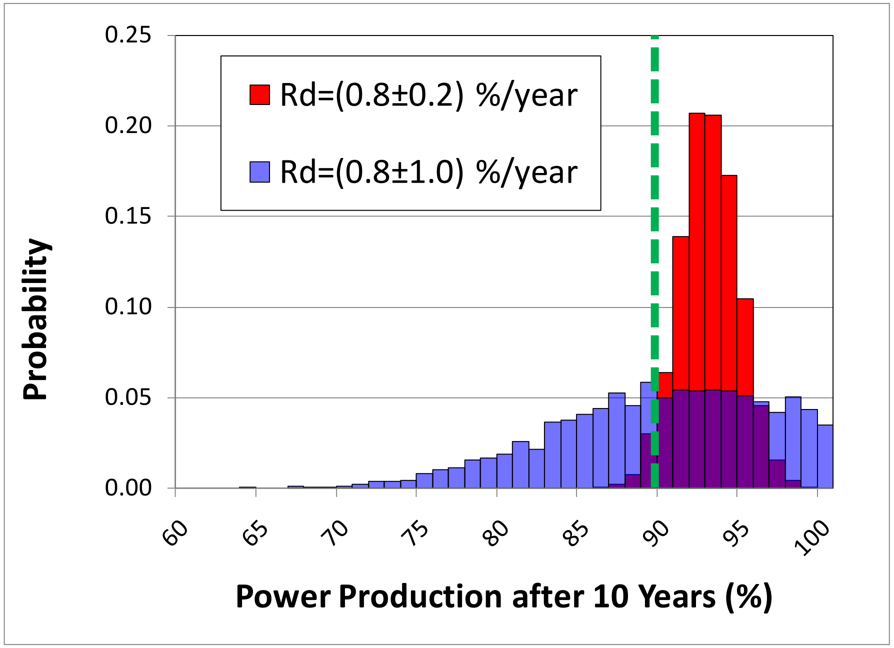
2 examples from NREL:
Different observation lengths, seasonality etc. → Leads to different uncertainties

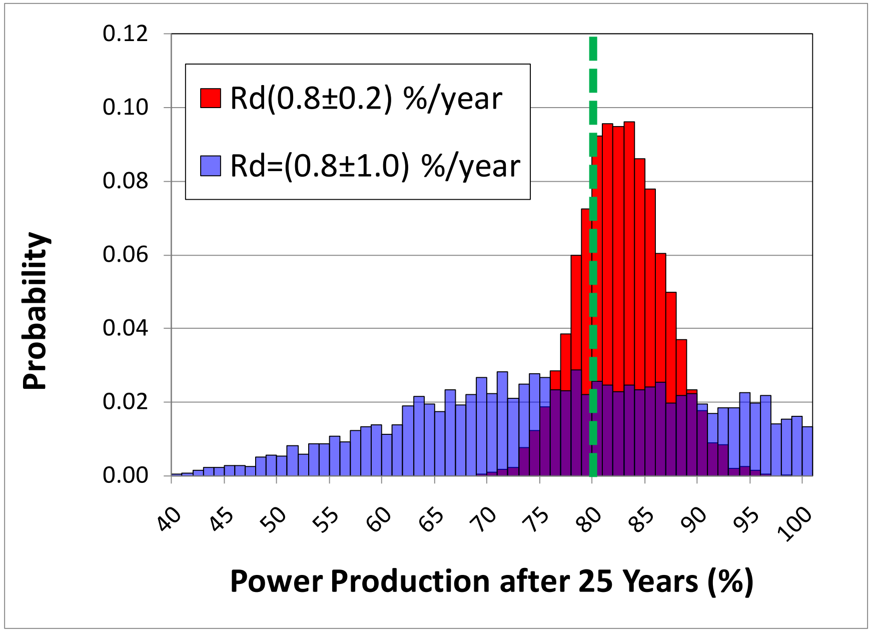
R_d (Module 1) = (0.8 ±0.2) %/year
R_d (Module 2) = (0.8 ±1.0) %/year

Same R_d but very different uncertainty

R_d Uncertainty Impact on Warranty

Manufacturer Warranty often twofold: 90% after 10 years, 80% after 25 years





Probability to default warranty:

1.0 %/year uncertainty = 46%
0.2 %/year uncertainty = 4%

$$Energy(Year_N) = \sum_{n=1}^{N} \frac{Energy(Year_1)\cdot(1-R_d)^n}{(1+r)^n}$$

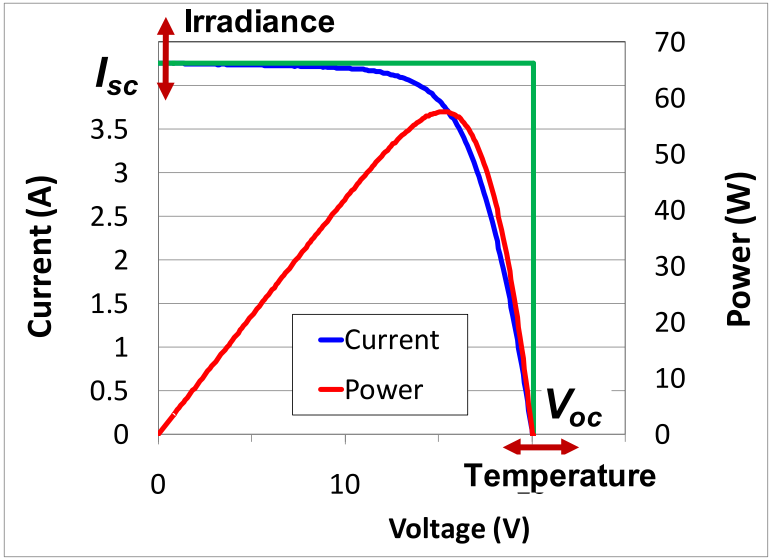
Probability to invoke warranty:

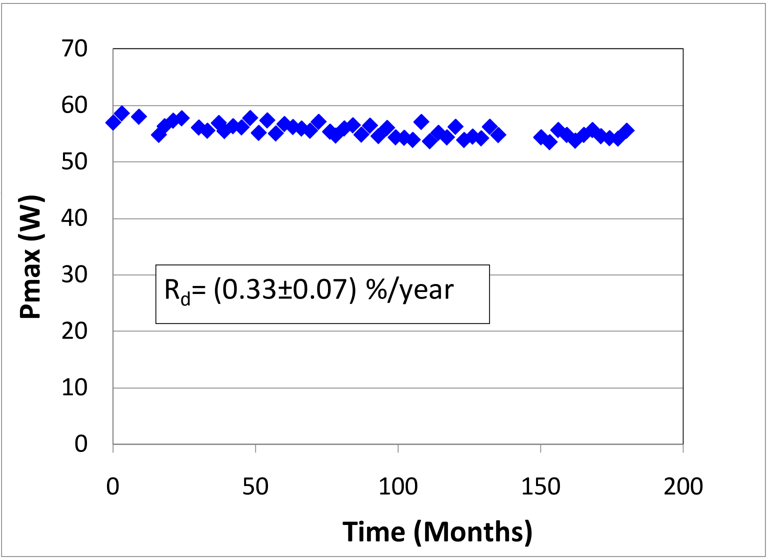
1.0 %/year uncertainty = 57%
0.2 %/year uncertainty = 24%

Higher R_d uncertainty significantly increases warranty risk

Degradation Rate (R_d)- Discrete Points

1. Translation to reference conditions (IEC60891)
2. Time series to determine degradation rate





$$FF = \frac{P_{\max}}{I_{sc} \cdot V_{oc}} = \frac{I_{\max} \cdot V_{\max}}{I_{sc} \cdot V_{oc}}$$

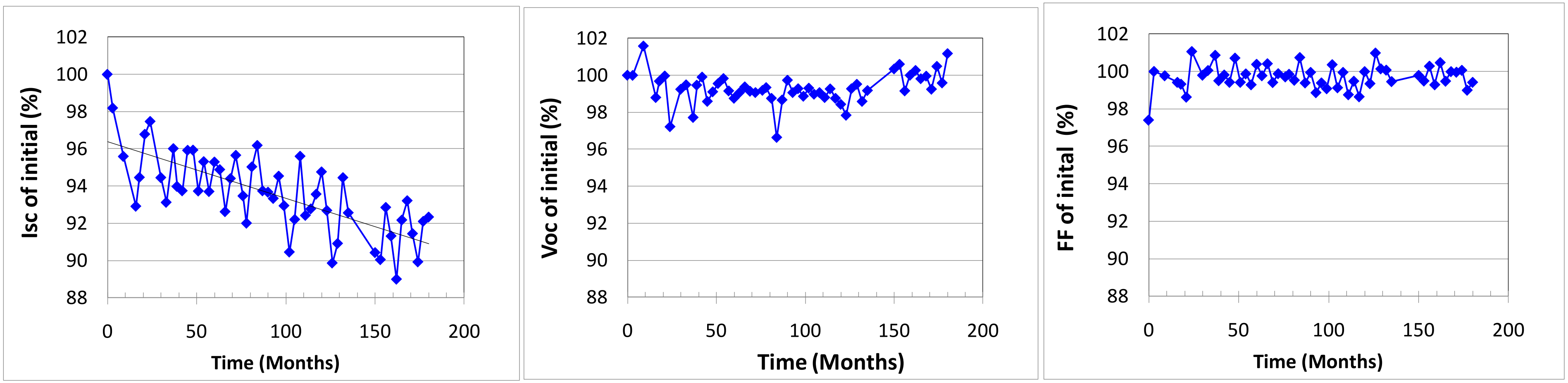
Quarterly taken I-V curves for degradation

Degradation Rate - Discrete Points

Short-circuit Current

Open-circuit Voltage

Fill Factor



Monocrystalline-Si

Degradation is due to decline in I_{sc}, (V_{oc} & FF are stable) → clues to degradation mechanism

Problem: 1. Labor-intensive, has to be clear sky
2. Large arrays → portable I-V tracer may not be available
3. Typically historical data not available

I-V curves provide clues to underlying failure mechanism

PV for Utility Scale Application (PVUSA)

The plant was originally constructed by the Atlantic Richfield oil company (ARCO) in 1983.

Provided electricity, data & experience in the 1980s and 1990s. Plant was dismantled in the late 1990s.

PVUSA Rating Methodology

Improved PVUSA models include Sandia & BEW model**

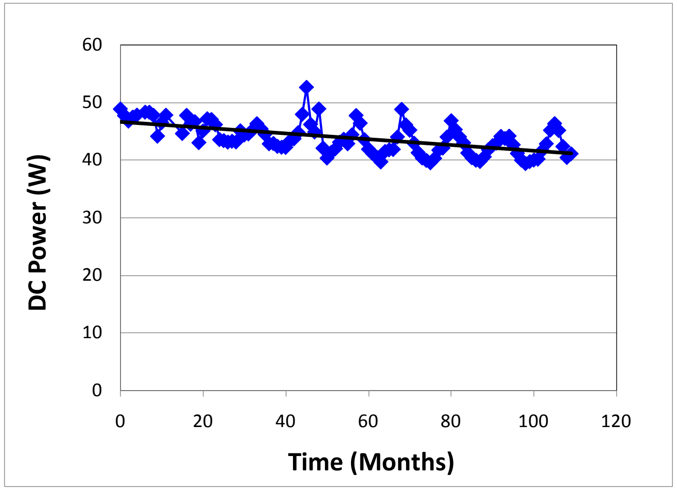
1. Step: Translation to reference conditions (use a multiple regression approach)

$$P = H \cdot \left(a_1 + a_2 \cdot H + a_3 \cdot T_{ambient} + a_4 \cdot ws\right)$$

H= Plane-of-array irradiance
$T_{ambient}$=ambient temperature
ws= wind speed
a_1, a_2, a_3, a_4= regression coefficients

Reference conditions:
PVUSA Test Conditions (PTC): E=1000 W/m^2, $T_{ambient}$=20ºC, wind speed=1 m/s

2. Step: Time series to determine degradation rate



Need basic weather station to collect $T_{ambient}$ and wind speed on top of irradiance

Seasonality leads to required observation times of 3-5 years* → long time in today's market

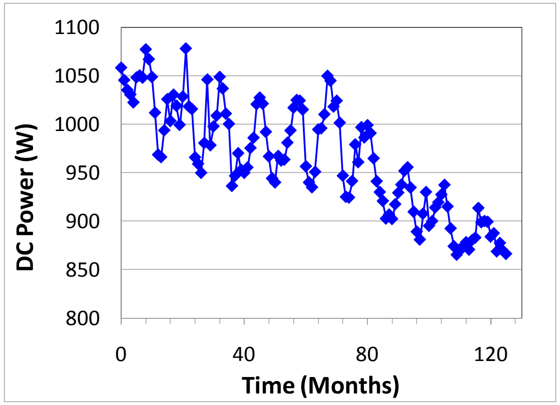
Long time required for accurate R_d

*Osterwald CR et al., Proc. of the 4th IEEE World Conference on Photovoltaic Energy Conversion, Hawaii, 2006.
**Kimber A. et al., Improved Test Method to Verify the Power Rating of a PV Project. Proceedings of the 34th PVSC, Philadelphia, 2009.

Classical Decomposition

Signal = Trend + Seasonality + Irregular

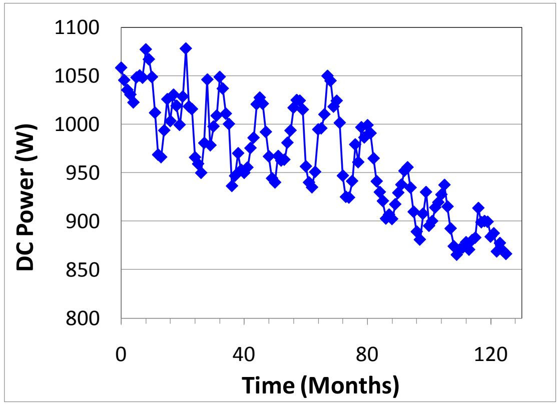
Original Data

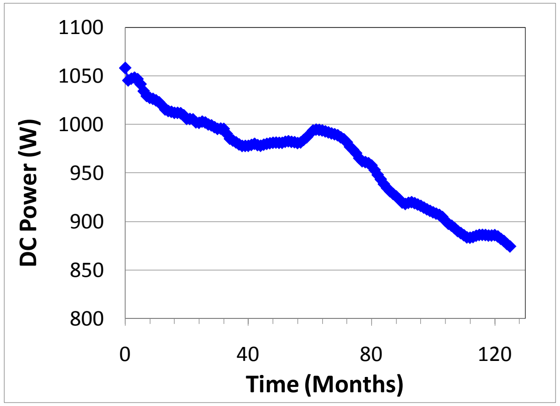


Classical Decomposition

Signal = Trend + Seasonality + Irregular

Original Data





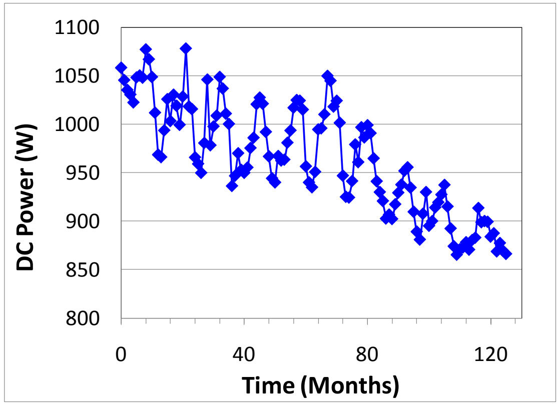
Trend

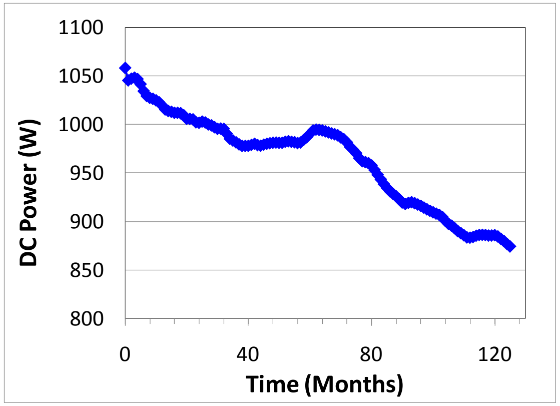
12-month centered-Moving Average

Classical Decomposition

Signal = Trend + Seasonality + Irregular

Original Data



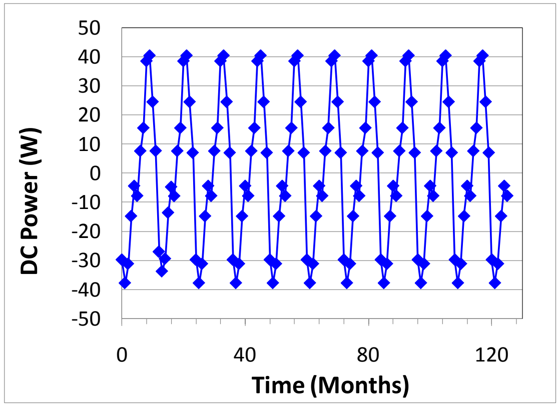


Trend

12-month centered-Moving Average

Seasonality

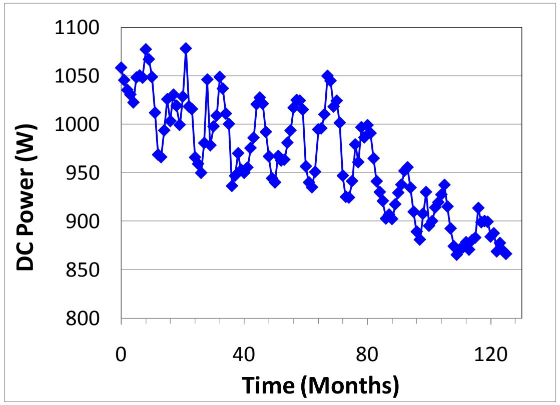
Average of each month for all years of observation



Classical Decomposition

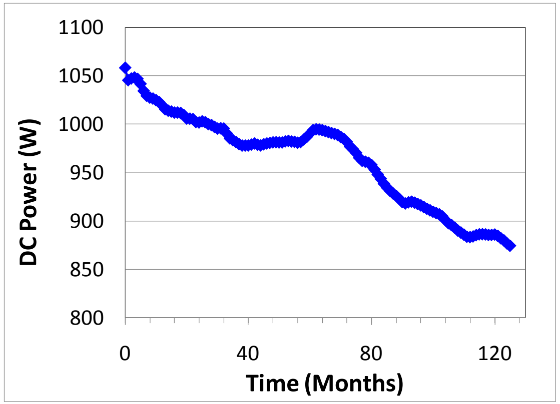
Signal = Trend + Seasonality + Irregular

Original Data



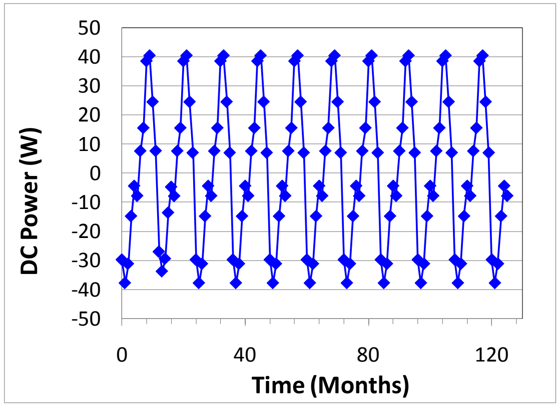
Trend

12-month centered-Moving Average

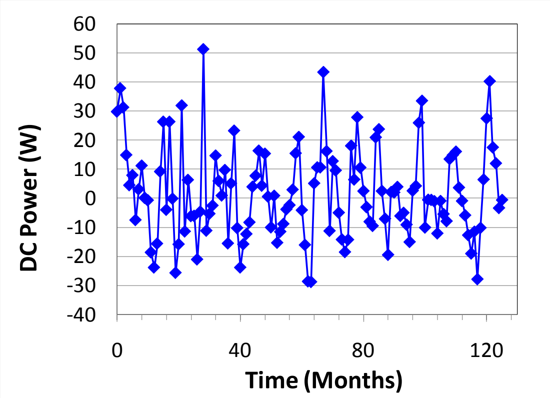


Seasonality

Average of each month for all years of observation



Irregular



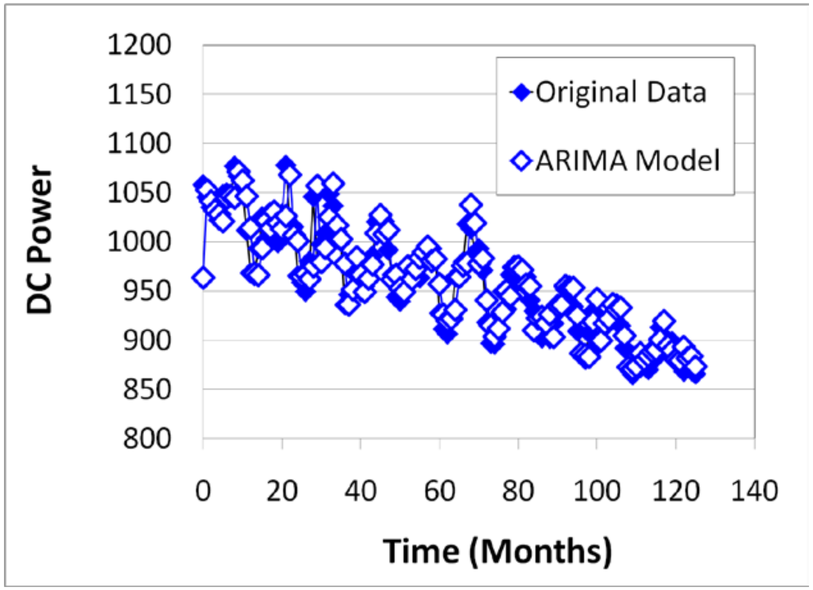
Determine R_d from Trend graph for higher accuracy

S.G. Makridakis et al., “Forecasting”, New York, John Wiley & Sons 1997.

ARIMA

Auto**R**egressive **I**ntegrated **M**oving **A**verage (ARIMA)

Model trend & seasonality component w/ Linear Combination of weighted differences & averages



$$P_t - P_{t-12} - \phi \cdot P_{t-1} + \phi \cdot P_{t-13} = \delta + \varepsilon_t - \theta \cdot \varepsilon_{t-12}$$

ARIMA(100)(011)

P=Power
c, δ, ϕ, θ =constant
ε=noise

1. Built several Models → minimize noise component
2. Chose parsimonious model w/ aid of several selection criteria

2 free software packages, US Census Bureau, Bank of Spain: plug & play, sensitive to outliers!

Many statistical software packages include time series analysis (JMP, Minitab, R etc)
Developed script to make model selection less sensitive to outliers.

Use ARIMA to model data, then decompose

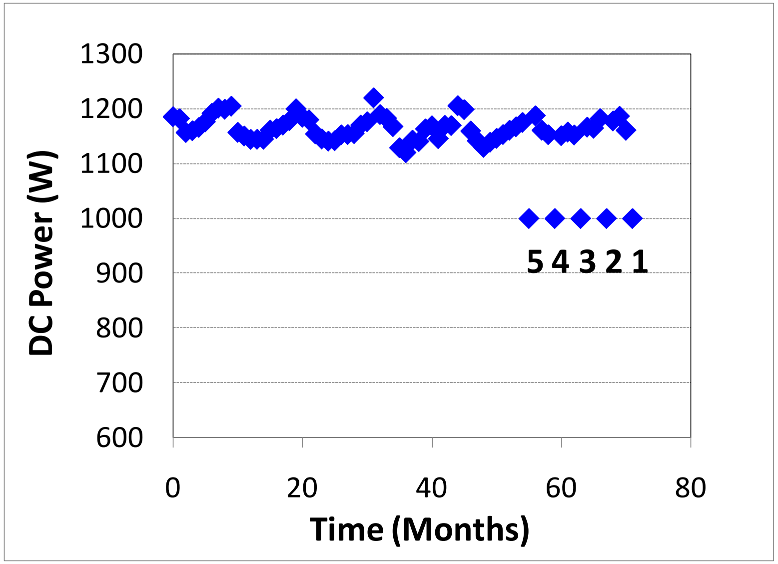
Box, GPP and Jenkins, G: Time series analysis: Forecasting and Control, San Francisco: Holden-Day, 1970.

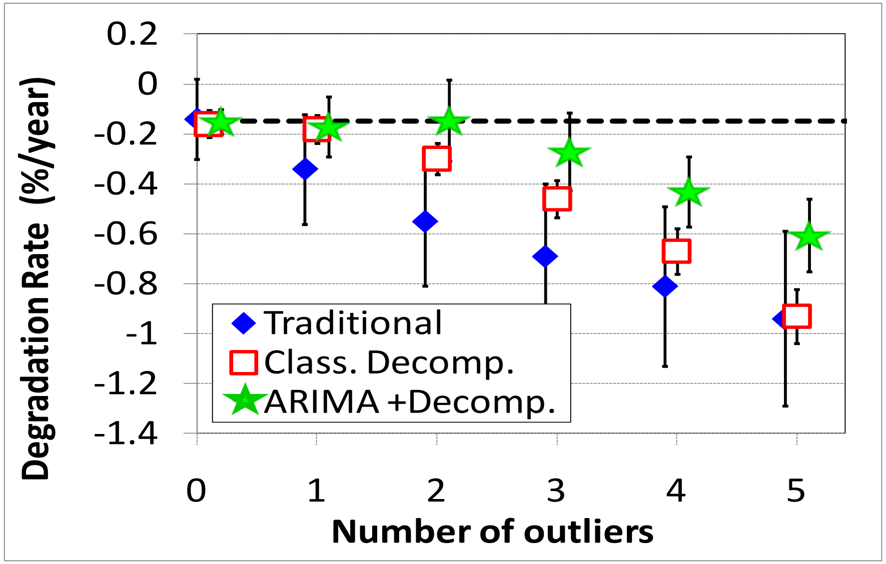
Outliers

Compare sensitivity of 3 methods to outliers

Procedure:

1. Dataset from NREL
2. Introduce outliers sequentially
3. Calculate R_d & study effect on all 3 methodologies





ARIMA most robust against outliers

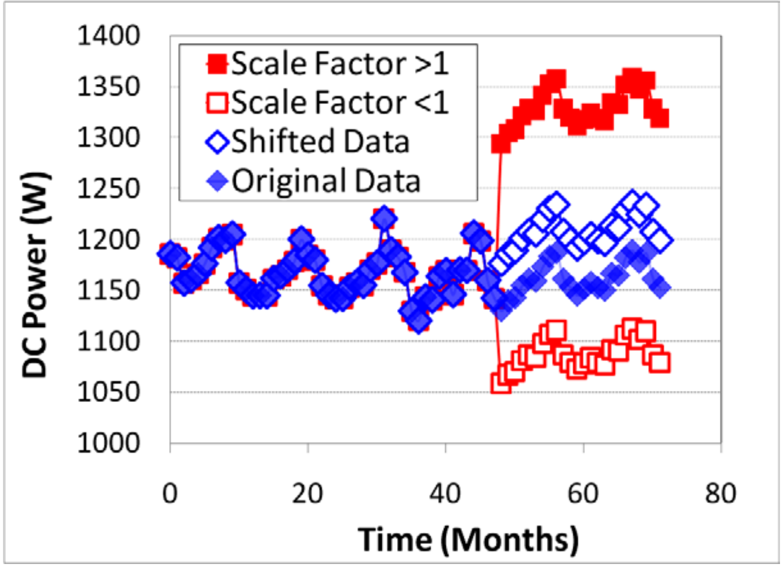
Data Shifts

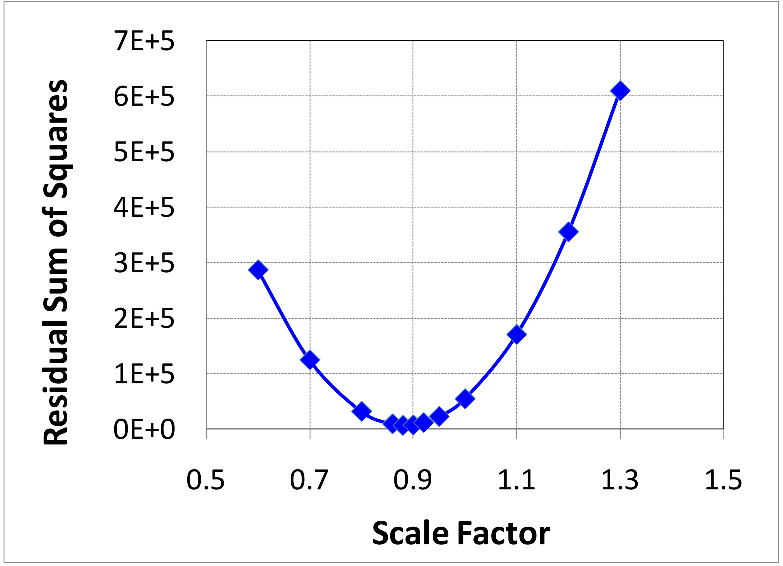
Compare sensitivity of 3 methods to data shifts

Example: inverter change

Procedure:

1. Dataset from NREL
2. Introduce a data shift deliberately
3. Multiply shifted section with a scaling factor
4. Calculate R_d & study effect on all 3 methodologies

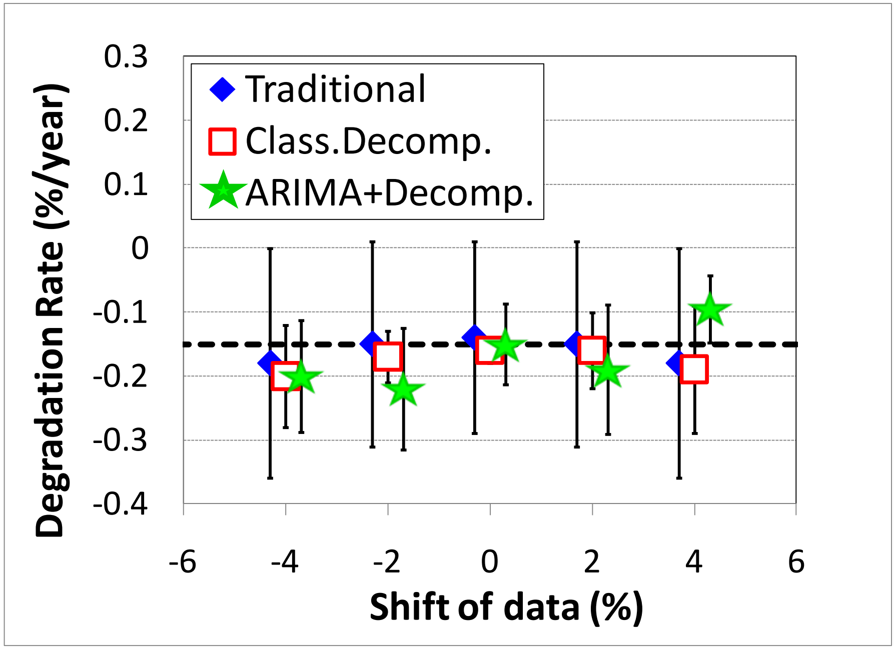




Correct data shifts by minimizing residual sum of squares

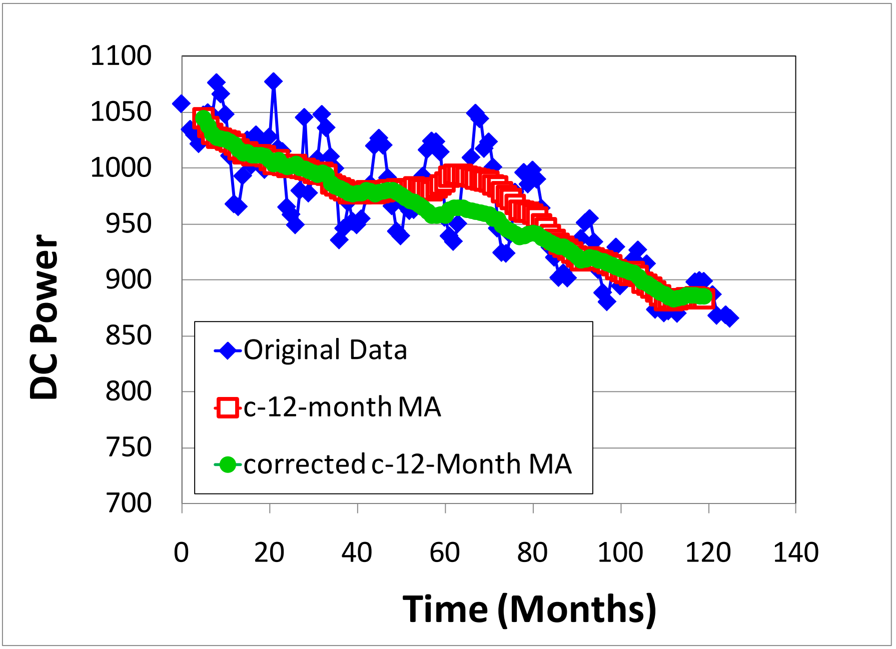
Data Shift Results

Results from induced shift



Data shift correction procedure is successful for all 3 approaches.

Real Shift – Blind test



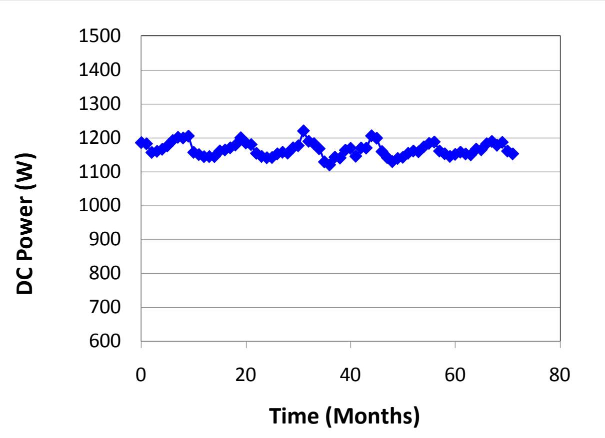
Data shift cause: Erratic ambient Temp sensor.
Misleading degradation rate if R_d calculated after shift.

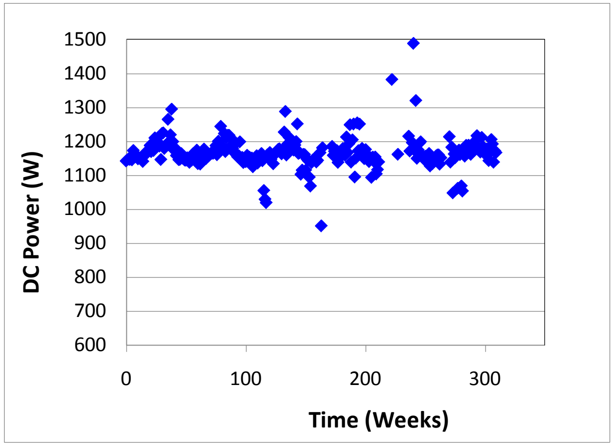
Residual minimization technique works on real shifts

PVUSA – Weekly Intervals

Multi-crystalline module

Monthly Intervals



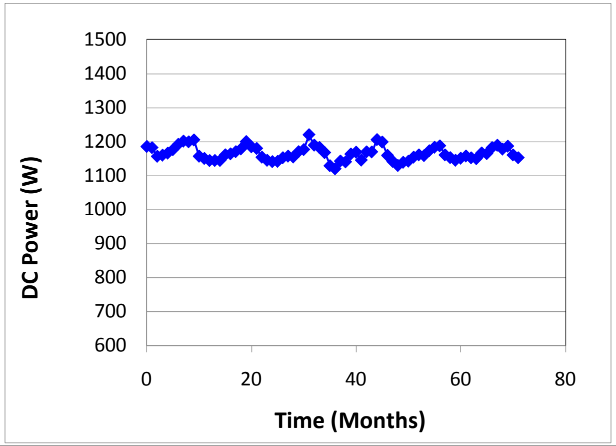


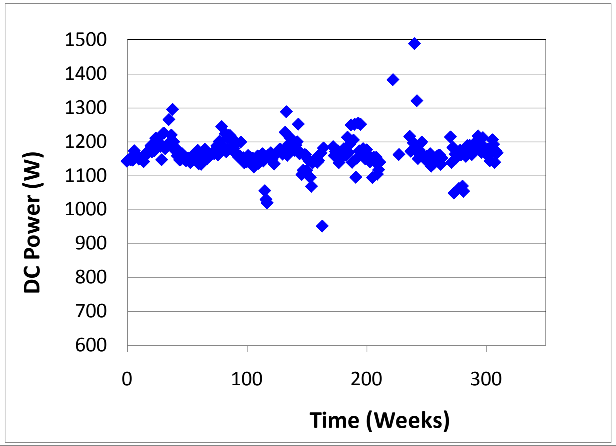
Weekly Intervals

PVUSA – Weekly Intervals

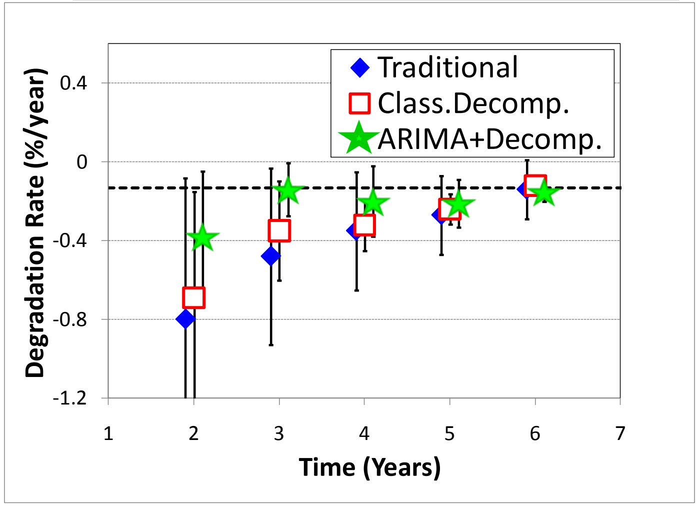
Multi-crystalline module

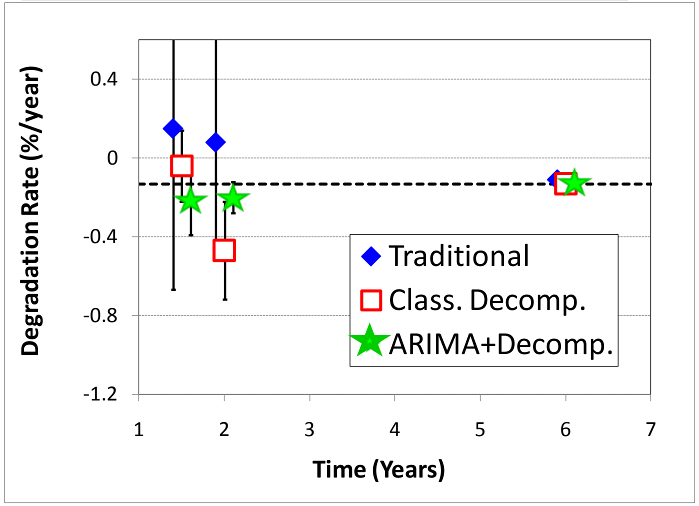
Monthly Intervals





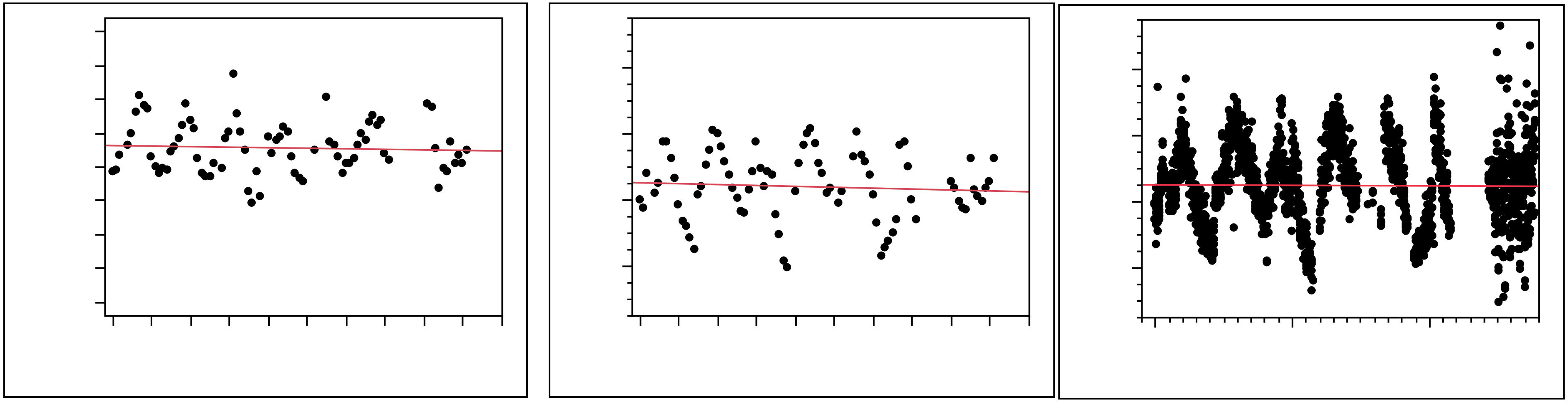
Weekly Intervals





Weekly intervals → converges in less time

Performance Ratio



PVUSA

Monthly PR

Daily PR

Multi-crystalline Si system

$$Y_f = \frac{E}{P_0}$$

Y_f=Final Yield
E=Net Energy output
P_0=Nameplate DC rating

$$Y_r = \frac{H}{G}$$

Y_r=ReferenceYield
H=In-plane Irradiance
G=Reference Irradiation

$$PR = \frac{Y_f^{*}}{Y_r}$$

Can apply same modeling approaches to minimize seasonality

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*B.Marion et al., "Performance Parameters for Grid-Connected PV Systems", Proc. 31st PVSC, Orlando, FL 2005.

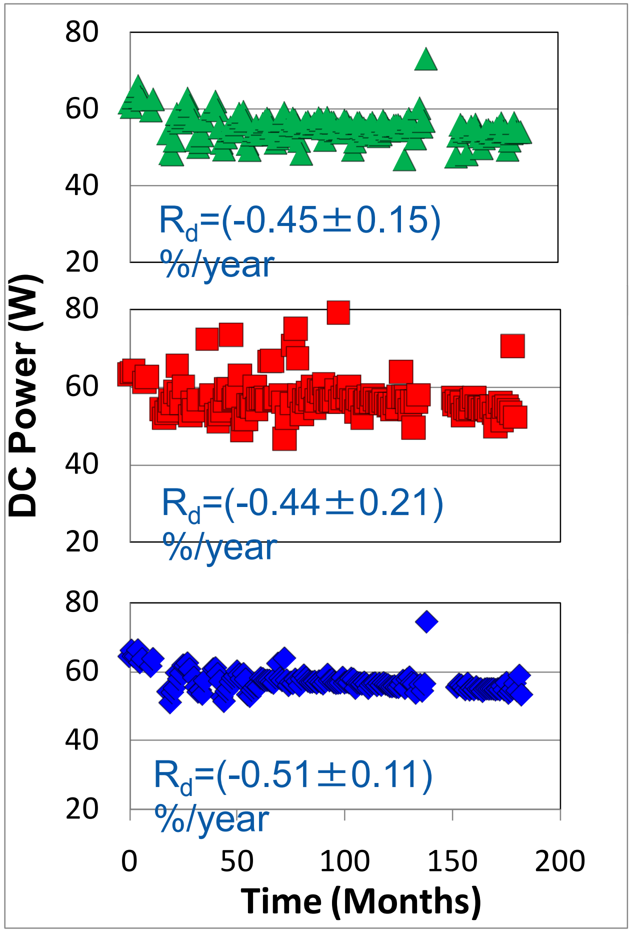
Data Filtering

Irradiance filtering interval

Too broad

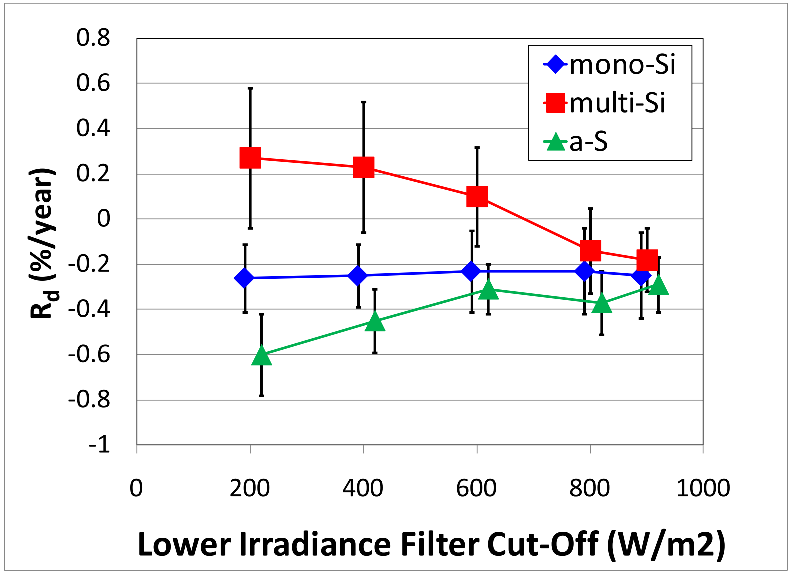
Too tight

best



mono-Si

PVUSA on 3 different modules



Example on how variable R_d may be depending irradiance filtering (may not be representative)

Filtering interval too tight or broad → R_d may be substantially different and uncertainty goes up

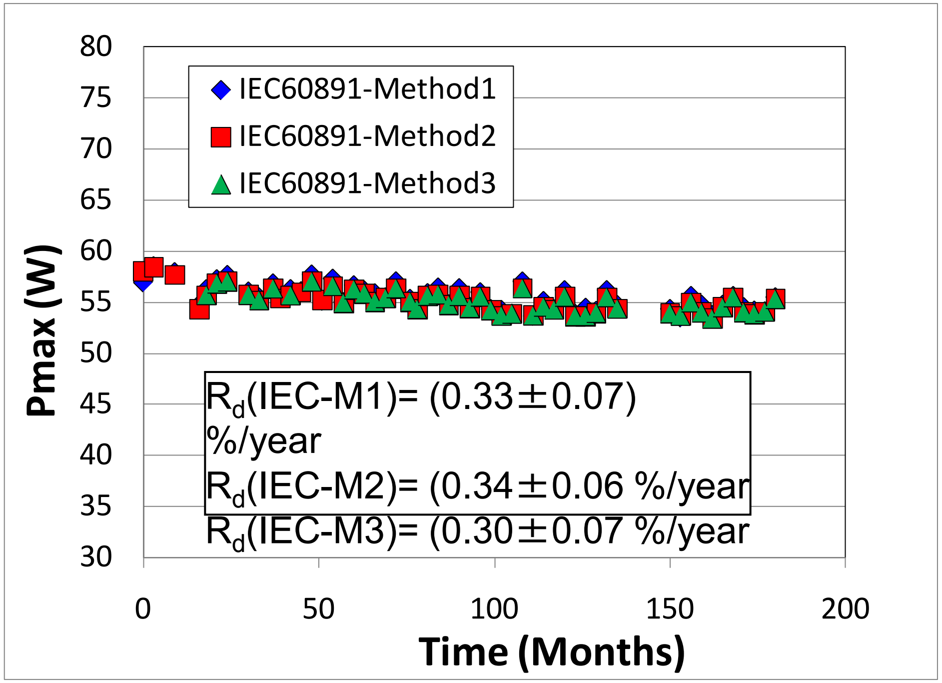
A. Kimber paper showed uncertainty may be reduced by using only sunny days

Data filtering has important impact on determined R_d

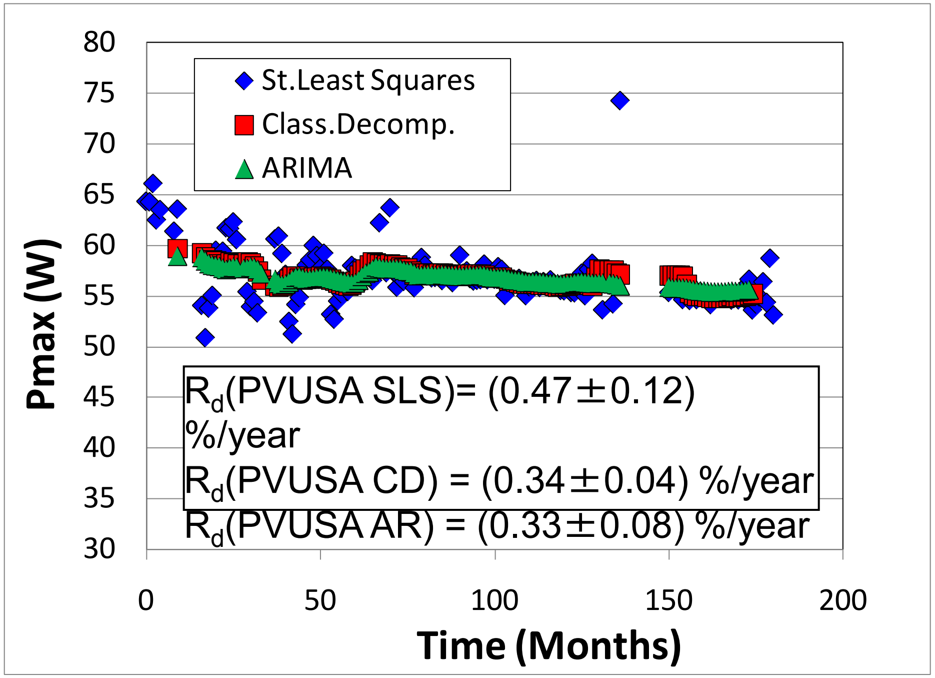
Kimber A. et al., Improved Test Method to Verify the Power Rating of a PV Project. Proceedings of the 34th IEEE PV Specialist Conference, Philadelphia, 2009.

Discrete vs. Continuous Data

IEC 60891



PVUSA



Quarterly taken IV + IEC translation less uncertainty than PVUSA

PVUSA + Modeling uncertainty is comparable to IEC method

Methodologies - Summary

	Time series	Data Type /# Data Pts.	Data Aqc.	Reference condition	Uncer-tainty	Outliers/ Dt.shifts sensitivity	Impleme ntation	Comments
PVUSA	**SLS**	continuous	DC, H, T, ws	PTC	ok?	high	easy	
	CD	"	"	"	good	medium	easy	
	ARIMA	"	"	"	best	low	difficult	Software & training required
PR	**SLS**	continuous	AC, H	----	ok?	high	easy	
	CD	"	"	"	good	medium	easy	
	ARIMA	"	"	"	best	low	difficult	Software & training required
IV-2	**SLS**	discrete, 2	I,V, H, T	STC, IEC60891	ok?	high	easy	difficult for larger arrays
IV-3+	**SLS**	Discrete, >2	"	"	best	low	easy	"

SLS: Standard Least Squares, CD: Classical Decomposition
H: in-plane irradiance, T: temperature, ws: wind speed

Contin. Data: Class.Decomp. may be good compromise

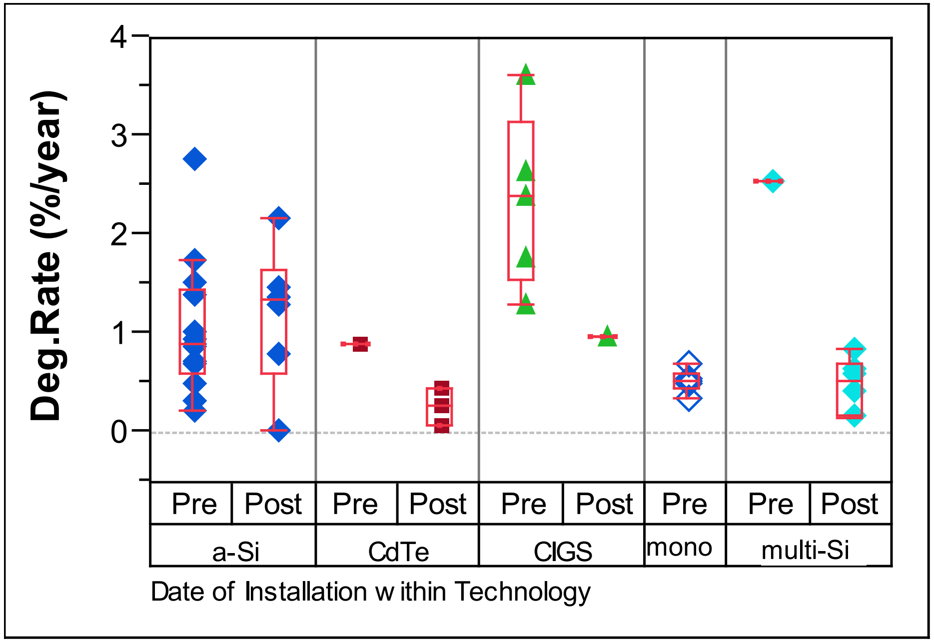
Discrete: Better take more than 2 measurements

PERT – Degradation Rates

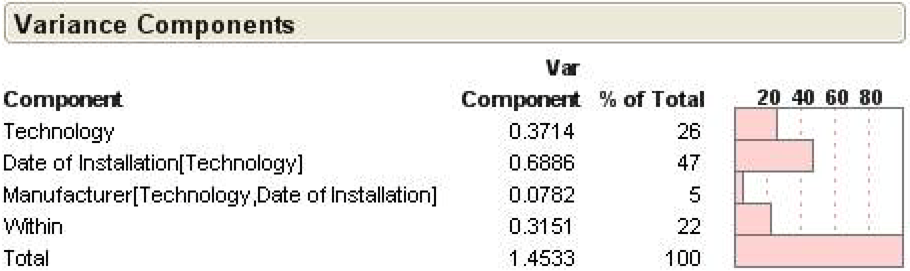
Performance Energy Rating Testbed = PERT

Photo credit: Warren Gretz, NREL PIX 03877.

More than 40 Modules,
> 10 manufacturers,
Monitoring time: 2 yrs-16 yrs



Pre: Installed before year 2000
Post: Installed after year 2000



Variance Components

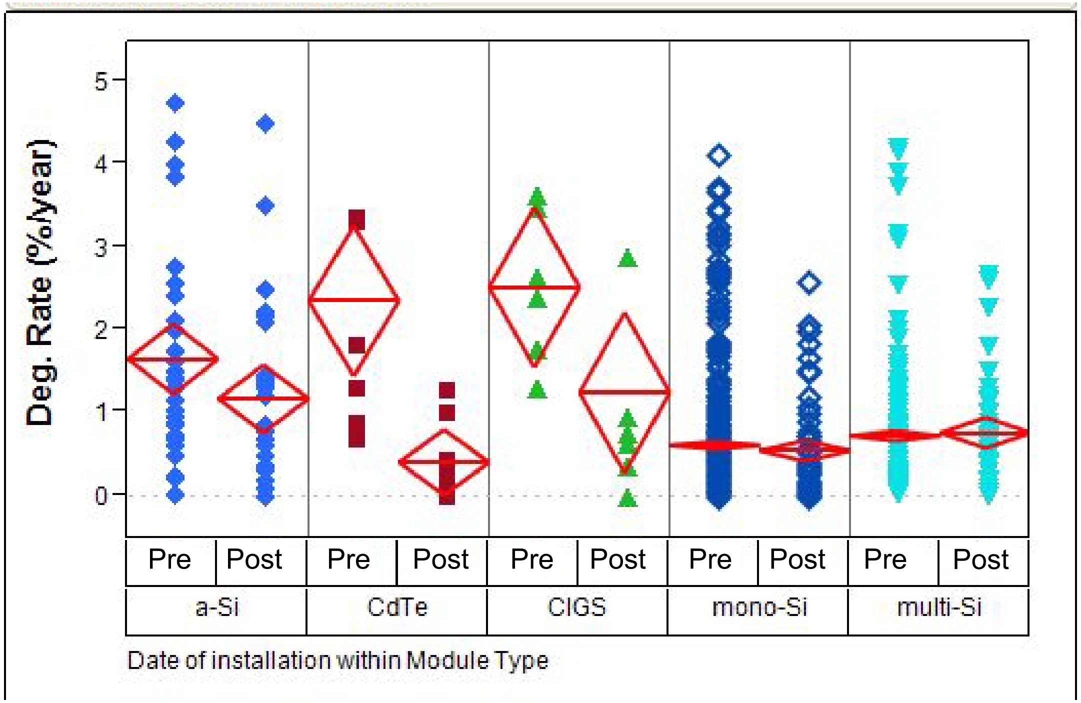
Component	Var Component	% of Total
Technology	0.3714	26
Date of Installation[Technology]	0.6886	47
Manufacturer[Technology,Date of Installation]	0.0782	5
Within	0.3151	22
Total	1.4533	100

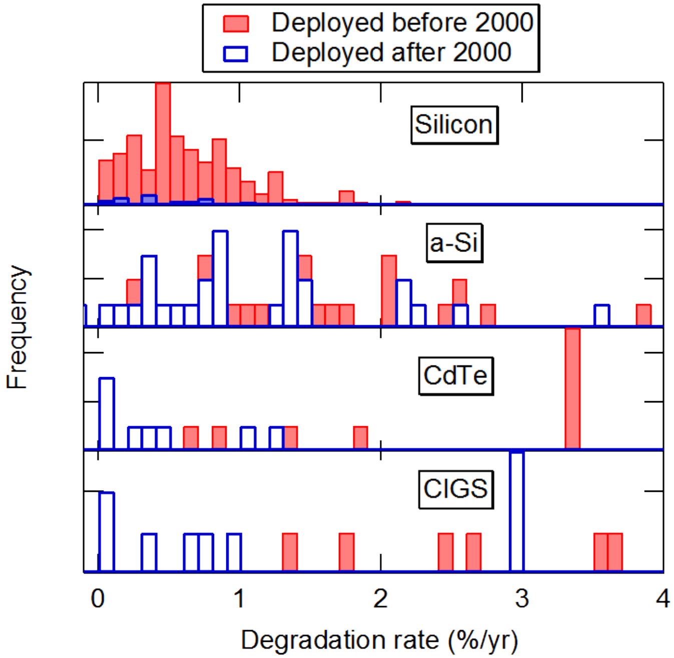
Appears that CdTe, CIGS & multi-Si improved

D.C. Jordan et al., Outdoor PV degradation comparison, Proc. IEEE PVSC, 2010, 2694.

Degradation Rates – Literature Survey

Number of R_d from literature: 1364 ca. 100 publications (see end)





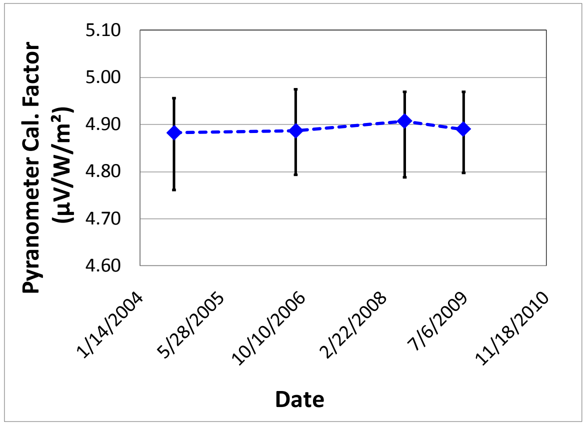
Partitioned by date of installation: Pre- & Post-2000
Red diamonds: mean & 95% confidence interval

Crystalline Si technologies appear to be the same

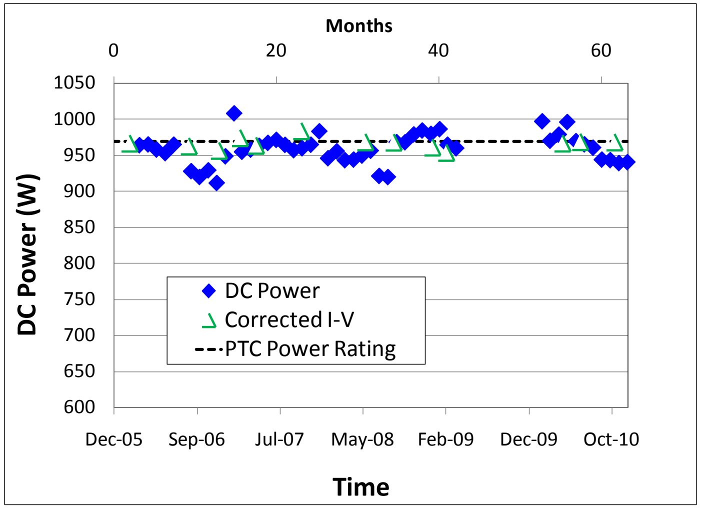
Thin-film technologies saw significant drop in R_d in last 10 years

NREL CIGS System

Shell Solar E80-C modules deployed at NREL. Photo credit: Harin Ullal, NREL PIX 14725



Pyranometer calibration



PVUSA + Field I-V data

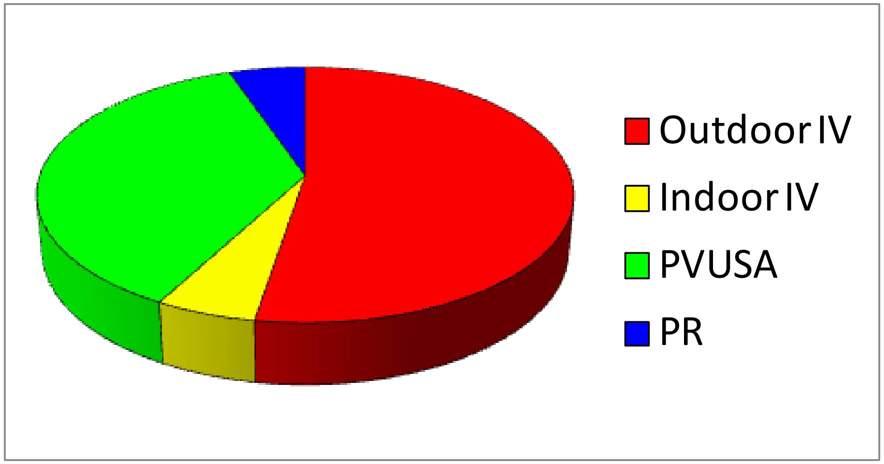
R_d	Statistical Uncertainty	Method	Interval
0.14	0.22	PVUSA Linear Fit	Monthly
0.57	0.21	PVUSA Cl.Decomp	Monthly
0.28	0.23	PVUSA ARIMA	Monthly
0.12	0.35	Performance Ratio Linear Fit	Monthly
0.61	0.10	PR Cl.Decomp	Monthly
0.47	0.13	PR ARIMA	Monthly
0.14	0.10	Performance Ratio Linear Fit	Daily
0.28	**0.22**	**Median ± pooled Standard deviation**	

Deployed in Golden ,CO
Jan-06

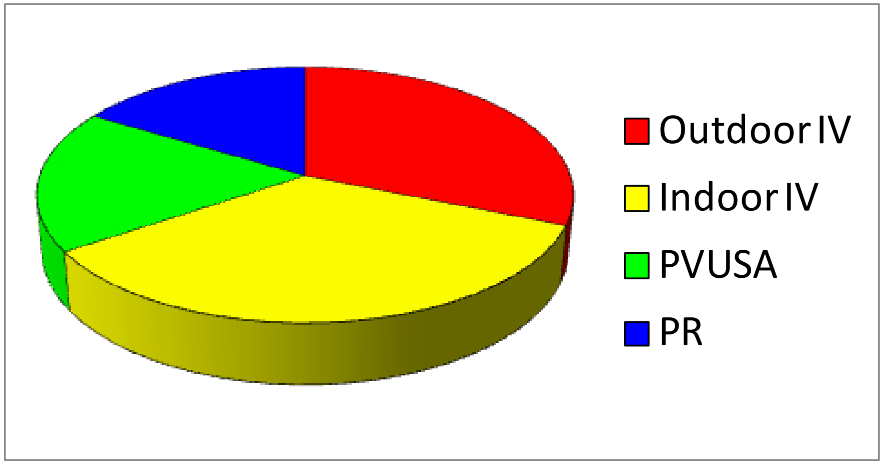
Results from this array appears to support findings from literature

Development of Methodologies

Pre 2000



Post 2000



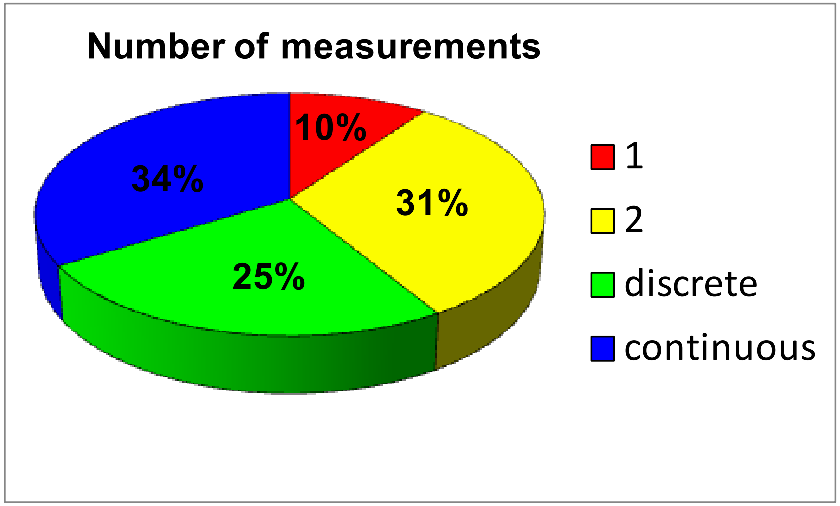
Percentage of Indoor IV has increased manifold → better tools

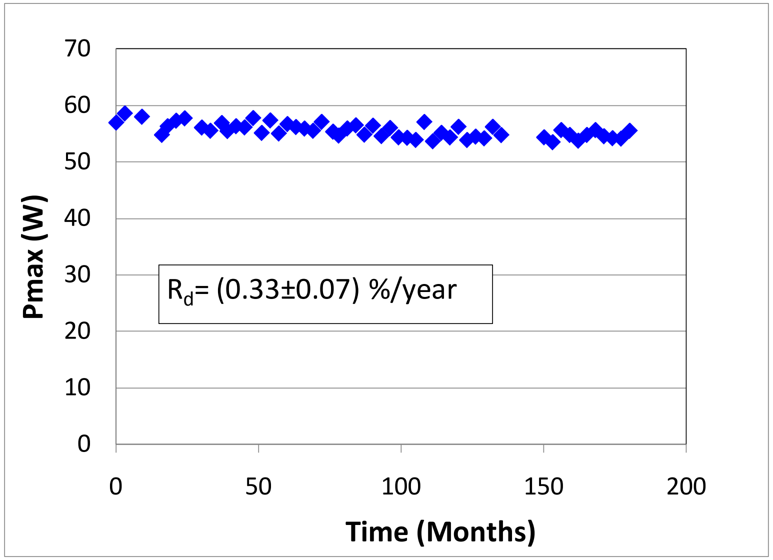
Percentage PR has increased → more installations, easy to collect AC data, don’t necessarily need an entire weather station

Percentage PVUSA decreased significantly → pronounced seasonality & sensitivity to outliers

PVUSA methodology use has significantly declined

R_d literature – Number of measurements





40% take only 1 or 2 measurements

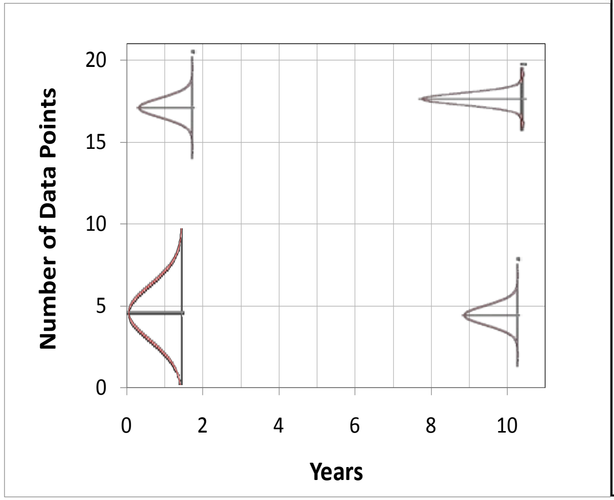
1 Measurement: baseline no longer available or were never taken → have to compare to nameplate rating

Procedure:

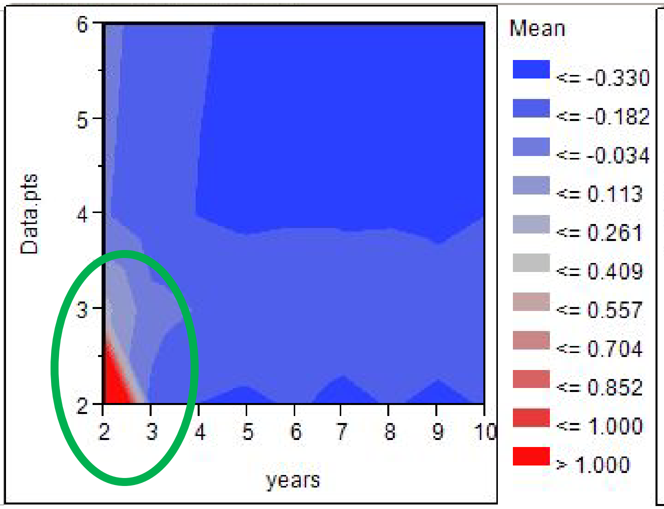
1. Take quarterly I-V data set
2. Randomly pick 2 data points & calculate Rd → repeat many times
3. Randomly pick 3 data points & calculate Rd → repeat many times
4. Rd will depend on # of data points & time span → can create 2D map

More than 40% of all R_d literature take only 1 or 2 measurements

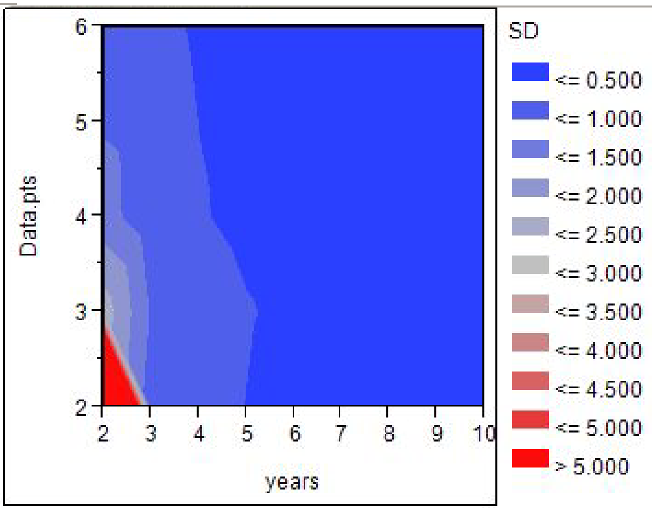
Effect of number of data points and years on R_d



Mean R_d



Standard Deviation



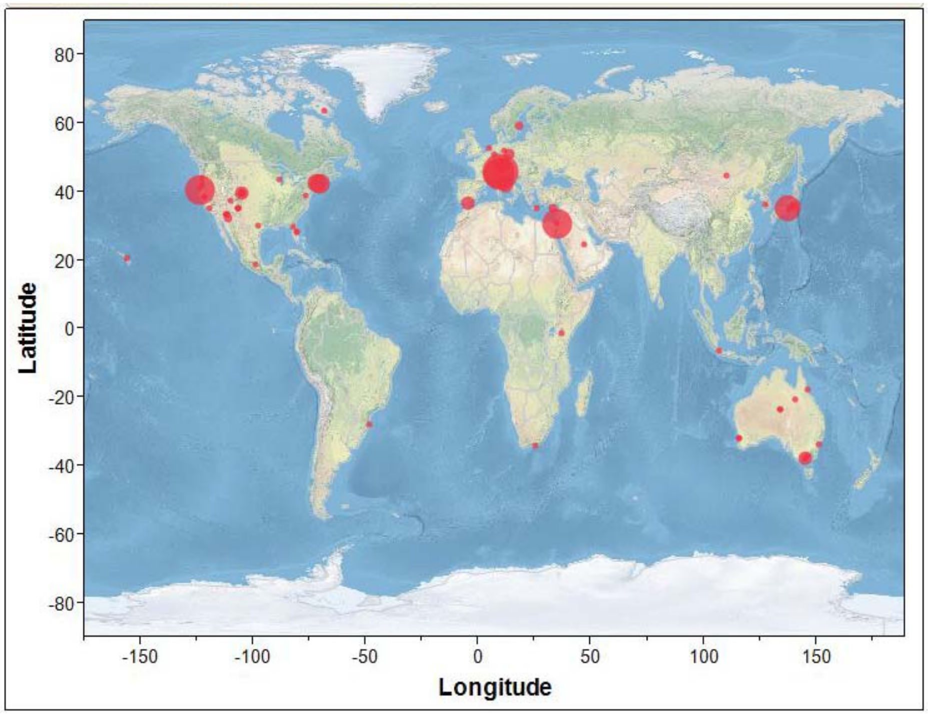
“True Rd”=-0.33 %/year (dark blue)

The curve is very steep for small data points and short time span

Even between 2-3 years can come close to “true Rd” simply by taken a few more data points

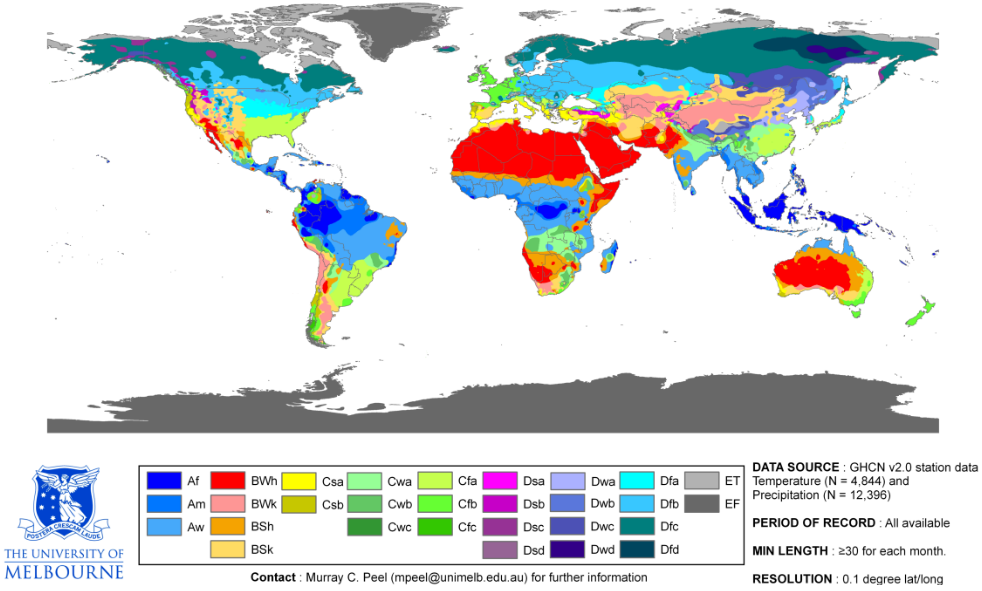
Would like to see more data points taken

Degradation Rates around the World



Size of circle: number of modules/systems tested

Köppen-Geiger climate map of the world (2007)



DATA SOURCE : GHCN v2.0 station data Temperature (N = 4,844) and Precipitation (N = 12,396)

PERIOD OF RECORD : All available

MIN LENGTH : ≥30 for each month.

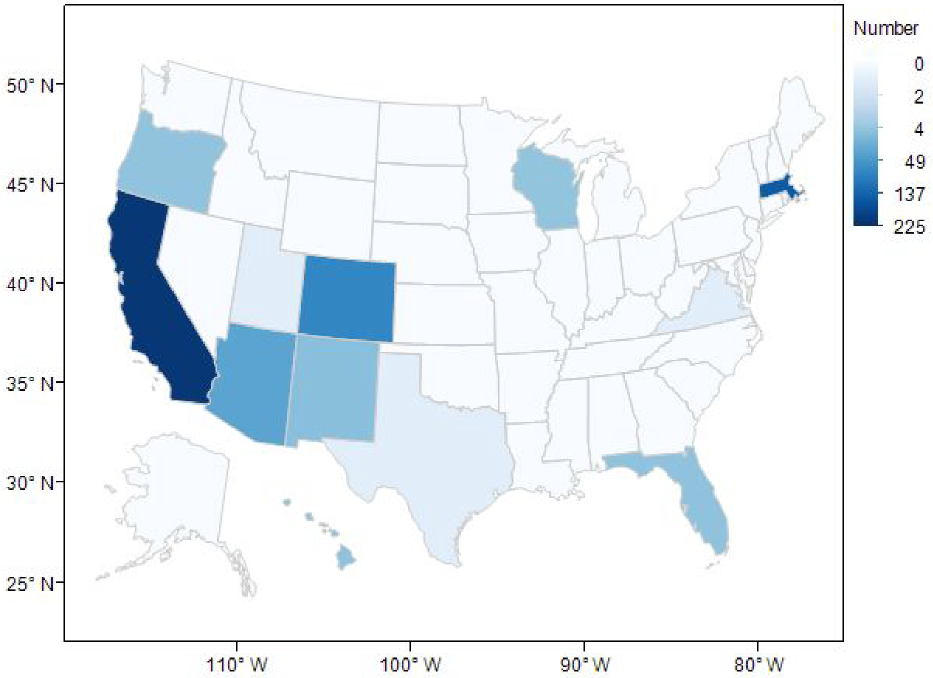
RESOLUTION : 0.1 degree lat/long

Contact : Murray C. Peel (mpeel@unimelb.edu.au) for further information

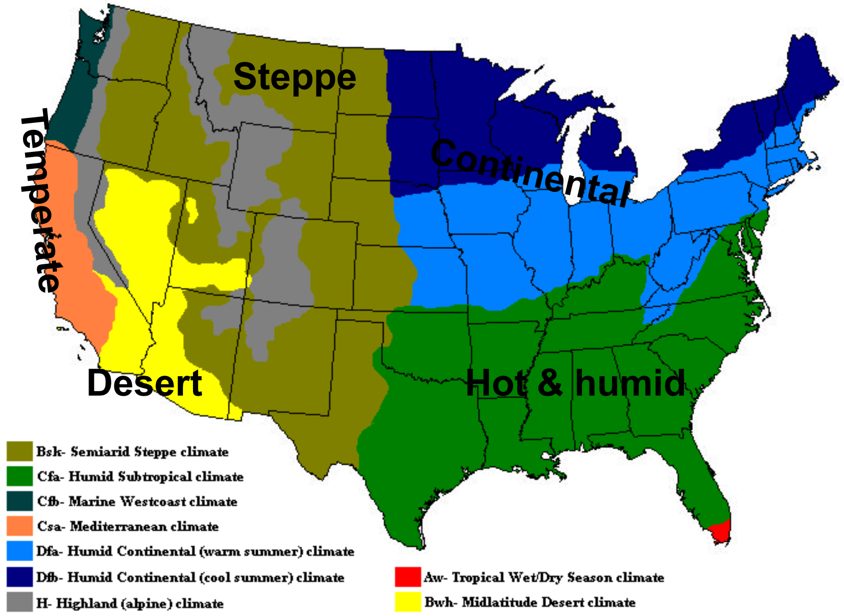
Main climates	Precipitation	Temperature	
A: equatorial	W: desert	h: hot arid	F: polar frost
B: arid	S: steppe	k: cold arid	T: polar tundra
C: warm temperate	f: fully humid	a: hot summer	
D: snow	s: summer dry	b: warm summer	
E: polar	w: winter dry	c: cool summer	
	m: monsoonal	d: extremely continental	

No reported degradation rates in many climate zones

Degradation Rates around the USA



Climate Zones of the USA

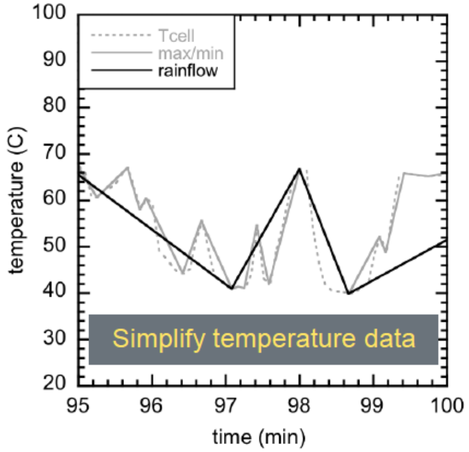


Similar picture as from around the world → some climate zones have not been investigated

No reported degradation rates in some climate zones

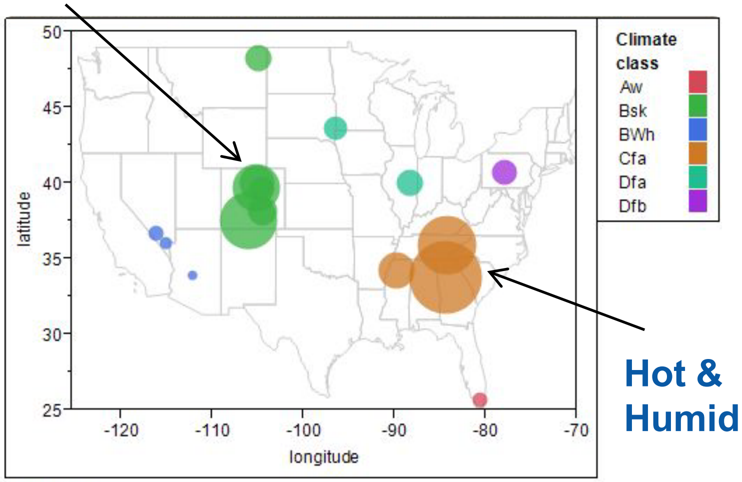
Rainflow Calculations

*

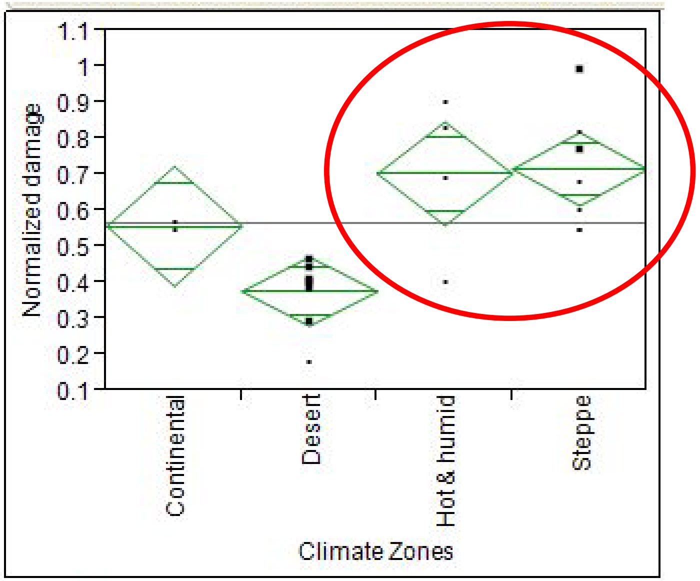


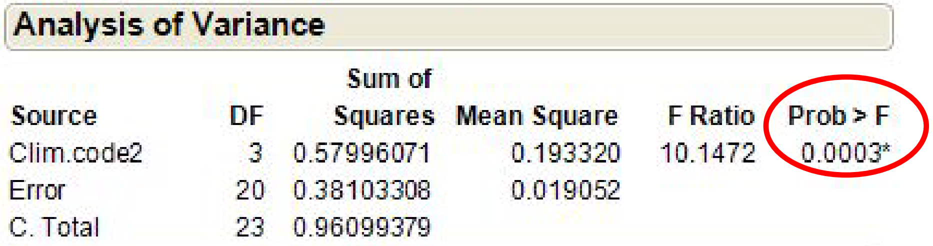
Simplify temperature data

Steppe



Hot & Humid





Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Clim.code2	3	0.57996071	0.193320	10.1472	0.0003*
Error	20	0.38103308	0.019052		
C. Total	23	0.96099379			

Steppe, Hot & humid show significantly higher damage than Desert & Continental climate.

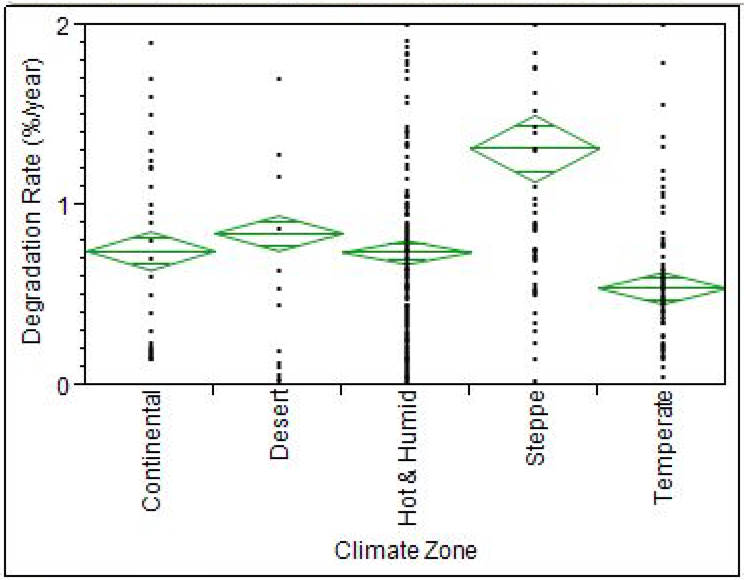
Steppe Climate has high damage due to thermal cycling

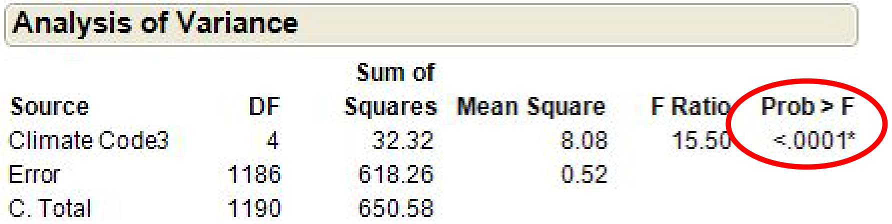
*Quantifying the Thermal Fatigue of CPV Modules_Bosco__NREL_International Conference on Concentrating Photovoltaics_2010

Analysis of all R_d by climate

All Technologies

Pre 2000



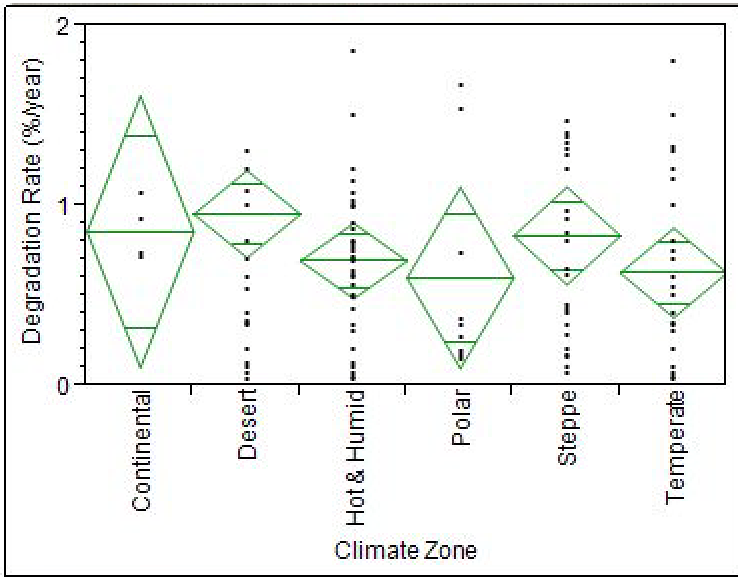


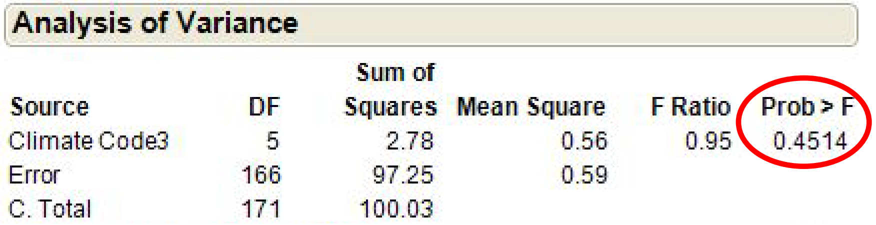
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Climate Code3	4	32.32	8.08	15.50	<.0001*
Error	1186	618.26	0.52		
C. Total	1190	650.58			

Steppe climate significantly higher.

Post 2000





Analysis of Variance

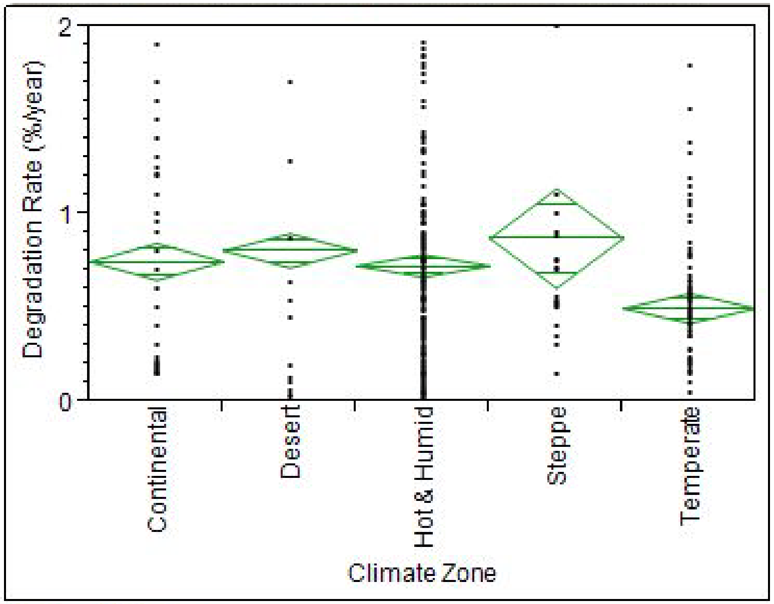
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Climate Code3	5	2.78	0.56	0.95	0.4514
Error	166	97.25	0.59		
C. Total	171	100.03			

No significant difference.

Steppe Climate shows significantly higher R_d before 2000

Analysis of R_d by climate – c-Si

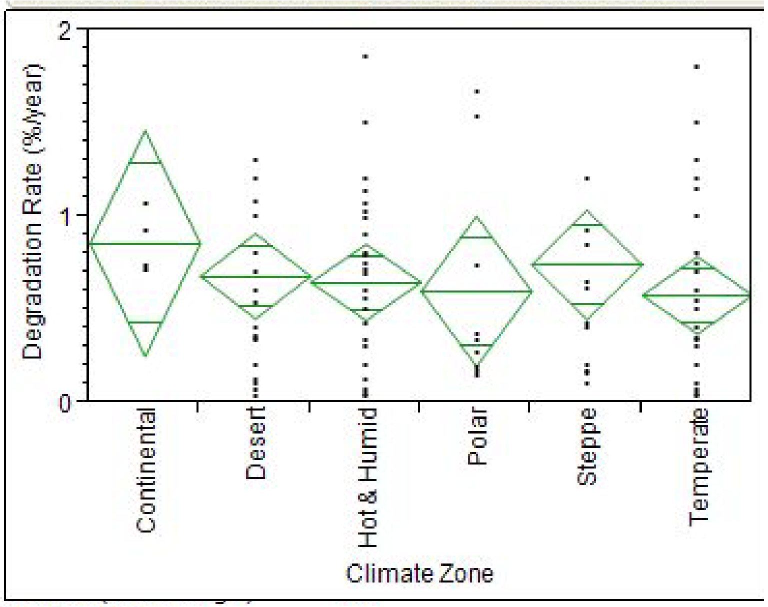
Pre 2000



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Climate Code3	4	14.53	3.63	8.28	<.0001*
Error	1138	499.39	0.44		
C. Total	1142	513.92			

Post 2000



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Climate Code3	5	0.53	0.11	0.29	0.9197
Error	121	45.15	0.37		
C. Total	126	45.69			

Similar but not as distinct trend for c-Si

Use of automated equipment, low stress ribbon effect visible…?

Steppe Climate shows significantly higher R_d before 2000

PVDAQ Project

PV Data Acquisition

The PVDAQ Project

The PVDAQ Project

PV performance in the United States.

Use data from government-funded and other projects

Performance data accessible on web page

Eliminate blank spots on the map

Conclusion

- Uncertainty can result in significant warranty risk
- Time series Modeling with continuous data (PVUSA, PR ..) can significantly reduce uncertainty
- Cont. Data: Class. Decomp. May be a good compromise between quality of results & ease of implementation.
- Discrete data: better practice to take more than 2 measurements.
- Analysis from literature and our own systems indicate that degradation rates have improved for installations after 2000.
- Have no data from many of the world’s climate zones

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- Have no data from many of the world’s climate zones

Need more data!

Acknowledgments

Thank you for your attention!

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Bill Marion
Bill Sekulic
Kent Terwilliger
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Eric Maass

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