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Understanding Tracker Accuracy and its Effects on CPV

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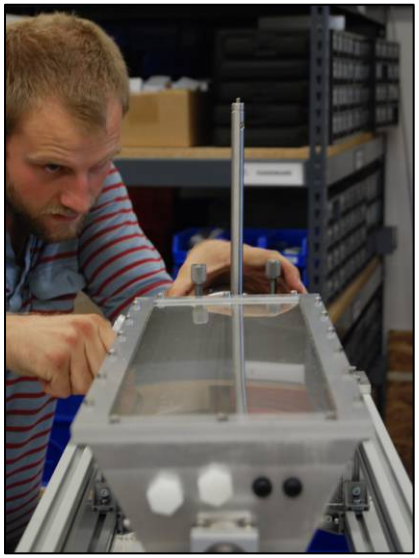
Engineers Dedicated to Cleantech™

Presentation Outline

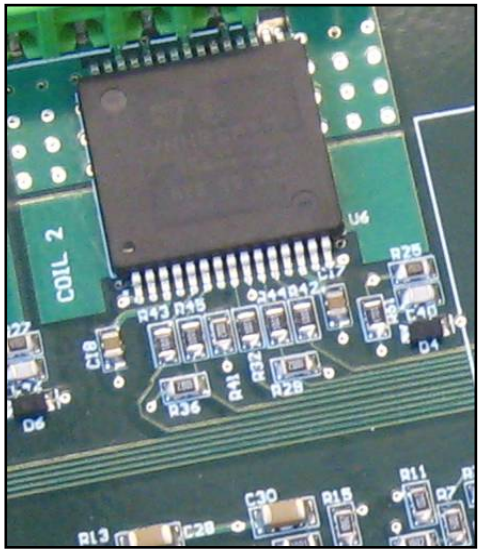
- Background
- Accuracy Measurement
- Accuracy Specs & Reporting
- Real-world Data

About GreenMountain Engineering

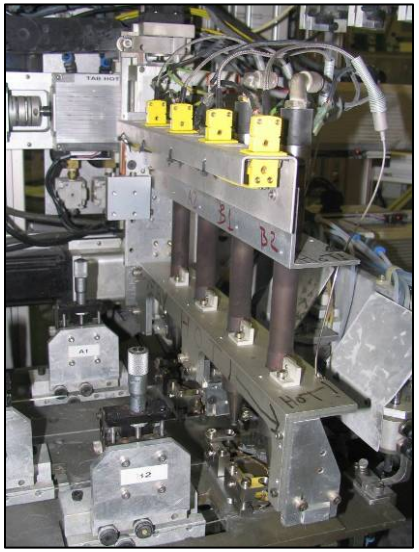
- Engineers dedicated to the advancement of cleantech
- Engineering design services and problem-solving, from R&D labs to commercial-scale manufacturing
- Since 2003, over 60 client projects in PV, 30 in CPV



Modules & Receivers



Trackers & Controllers



Manufacturing Tools

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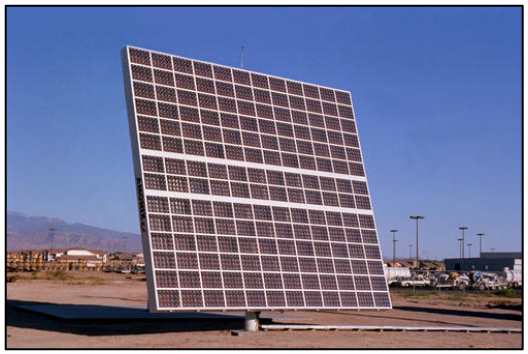
(Most) CPV Requires Tracking



There is no single solution that has been proven best for all applications– there is still room for innovation in tracking.

Why “Understand Tracker Accuracy”?

There are two different reasons to have good methods of characterizing tracker accuracy:

- Technically relevant tracker accuracy metrics help predict system energy production and Levelized Cost of Energy (LCOE)*.

$$\text{Initial Investment} = \frac{\sum_{n=1}^{N} \frac{\text{Depreciation}^n}{(1+\text{Discount Rate})^n} \times (\text{Tax Rate}) + \sum_{n=1}^{N} \frac{\text{Annual Costs}^n}{(1+\text{Discount Rate})^n} \times (1-\text{Tax Rate}) - \frac{\text{Residual Value}}{(1+\text{Discount Rate})^n}}{\sum_{n=1}^{N} \frac{\text{Initial kWh/kWp} \times (1 - \text{System Degradation Rate})^n}{(1 + \text{Discount Rate})^n}}$$

- Standardized, repeatable, generalized methods of characterization allow side-by-side comparison between different tracker designs.

Trackers are a significant component of system cost– avoiding overdesign and allowing more assembly/installation variation can reduce cost.

* See, for example, M. Campbell et al., “The Drivers of the Levelized Cost of Electricity for Utility-Scale Photovoltaics”, SunPower Corp 2008

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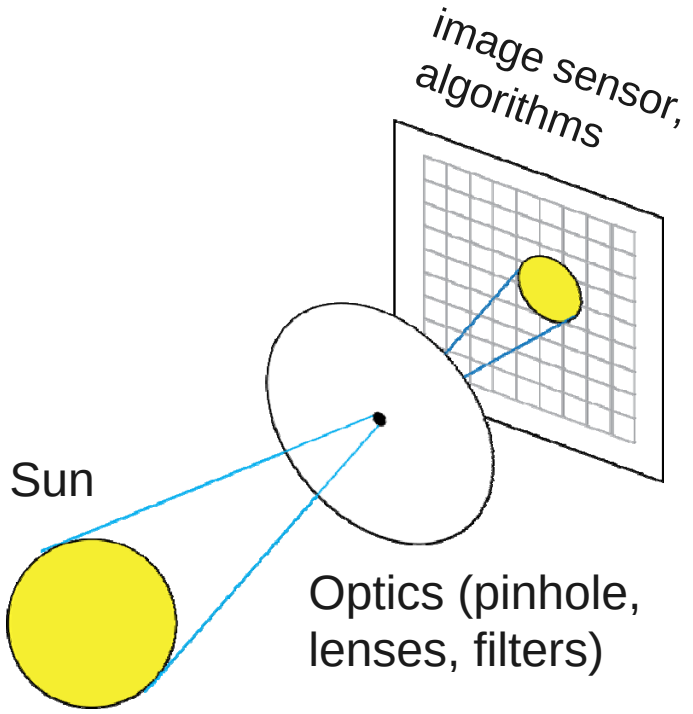
Tracking Accuracy Measurement

A variety of methods have been used to measure pointing accuracy. Many are essentially optical methods.

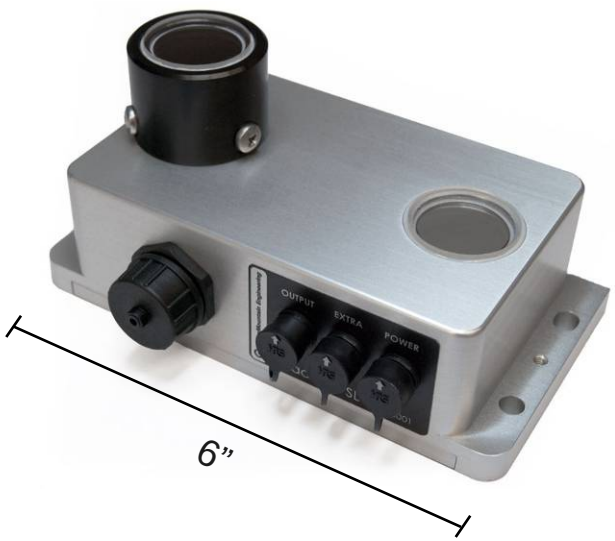
Calibration plays an important role in the accuracy of these methods.



For further discussion, see for example:

- I. Luque-Heredia, et al. “A Sun Tracking Error Monitor […]”, EUPVSEC 2005
- C. Cancro, et al. “Field Testing the PhoCUS Solar Tracker […]”, ICSC 2007
- M. Davis, et al. “Machine Vision […] for Characterizing Tracker Performance”, IEEE PVSC 2008

Measuring Tracker Accuracy Today

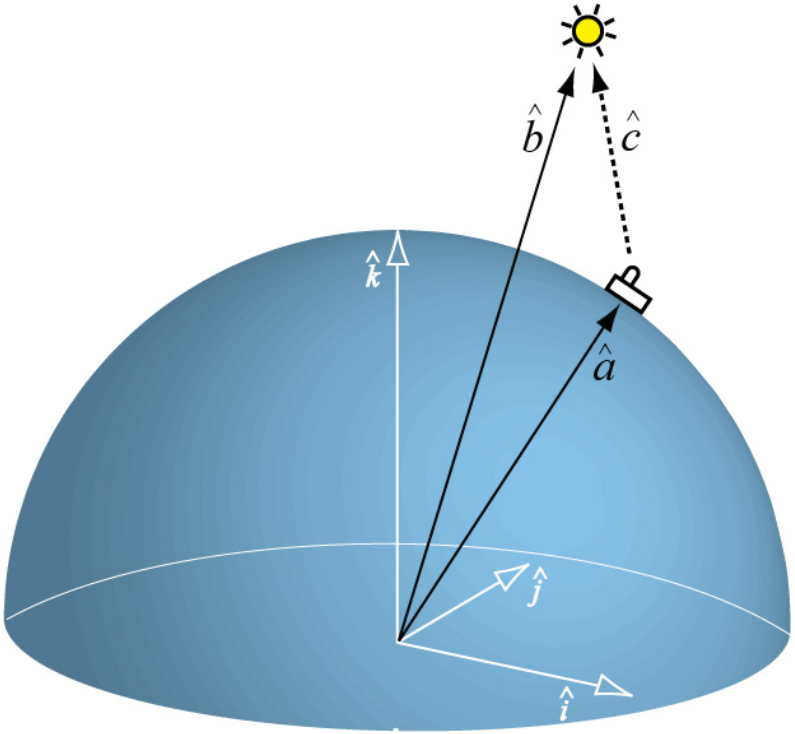


- Trac-Stat SL1
- A diagnostic instrument for measuring the performance of solar trackers
- 0.02° accuracy
- Datalogging capability

A Note on Reference Frames

Pointing errors reported in a sensor's reference frame are not the same as errors in the tracker's axes of motion or earth reference frame.

Vector transformations can be performed based on current tracker angle or even just time of day and location (via sun position calculations)



Transforming from sensor reference frame:

$$\hat{b} - \hat{a} = \hat{c}_{GND} - \hat{a} = (c_x - 1)\hat{a} + c_y(\hat{k} \times \hat{a}) + c_z(\hat{a} \times (\hat{k} \times \hat{a}))$$

(for certain assumptions about system rotation, otherwise there are multiple possible solutions)

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Accuracy Spec -- Metrics

Desirable in an accuracy spec:

- Correlates with system energy production
- Assesses full tracker performance (mechanical, controller, algorithms, calibration)
- Measureable, on-site, in real installations

Undesirable:

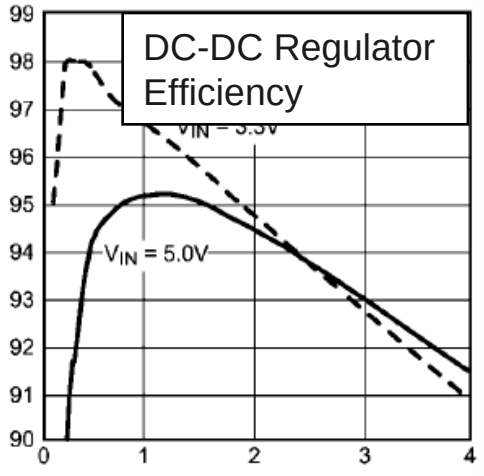
- Too conservative (promotes tracker overdesign)
- Too optimistic (based on a “perfect day”, etc)
- Arbitrarily penalizes certain tracker architectures in ways not related to real-world performance

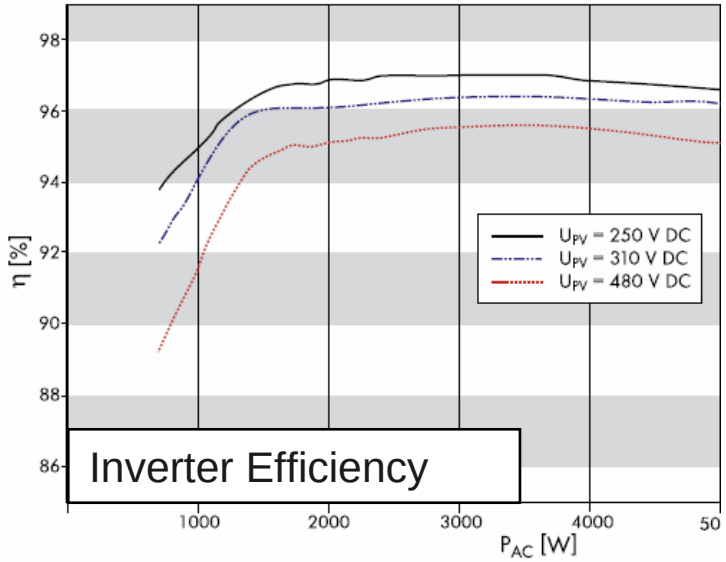
Accuracy – not a single number?

Having a single number for a spec (inverter efficiency, module watts, and so on) is simplest.

However, the goal of much of the PV and CPV industry is large-scale deployments.

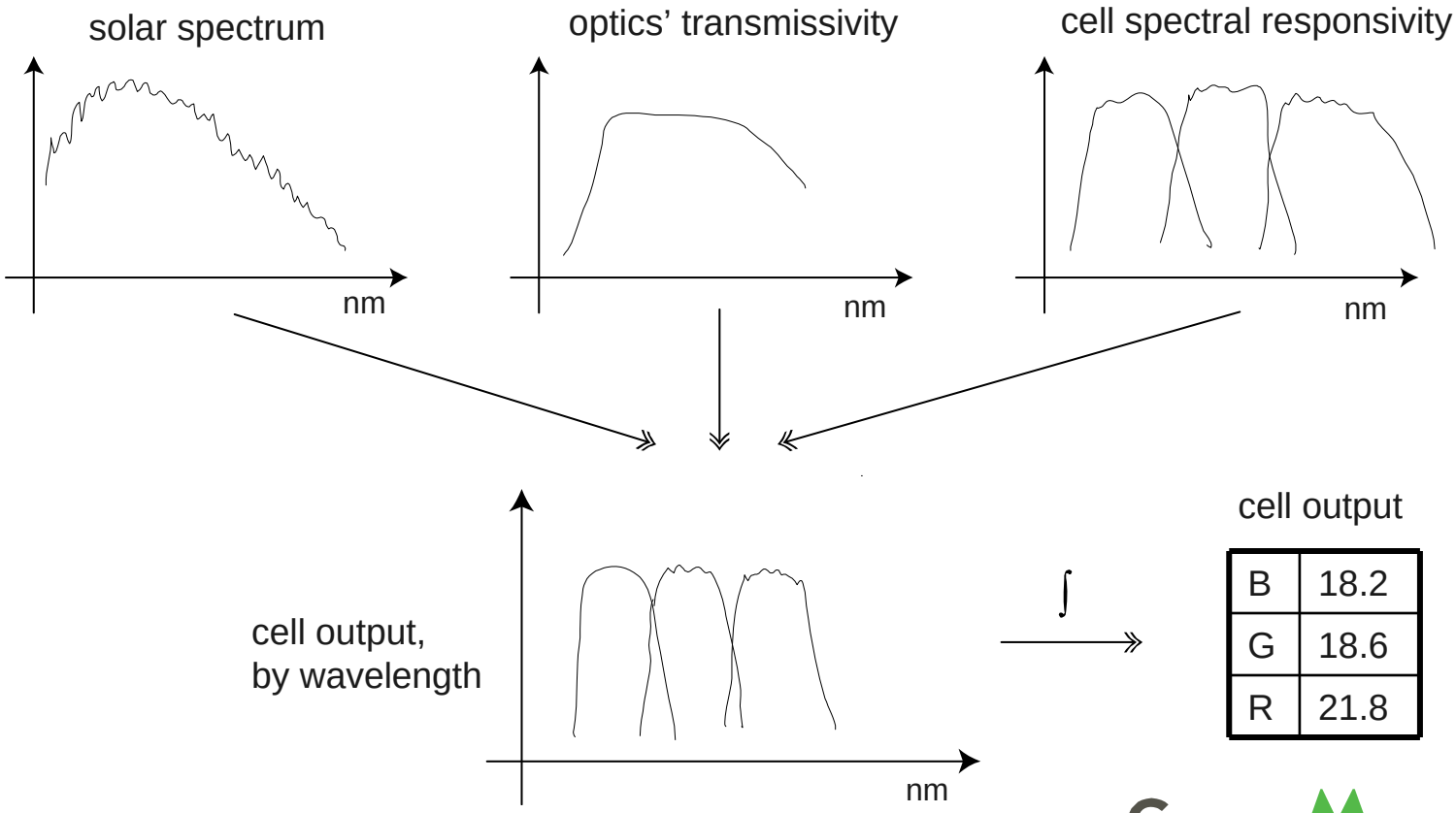
At this scale, it is reasonable to expect the purchaser to look at and interpret a more detailed set of specs.





A Side Note on Convolution

Various data sets with matching or nested dependent variables can be convolved or combined. For example, in the context of spectral performance:



Accuracy Specs Not to Use

type of tracking	1-axis	2-axis
type of control unit	sensors	program (PLC)
suitable for CPV modules	yes	yes
azimuth	150°	270°
elevation	–	0 ... 80°
drive unit	electrical	electrical

- Ephemeris calculation accuracy (<<0.01°, but this doesn't matter if there are other uncompensated errors)
- Motor encoder resolution – not really accuracy
- Worst-case accuracy (too conservative as an *only* spec)
- Simulated accuracy
- Mean pointing accuracy (skewed unfairly by horizon-pointing performance)

Accuracy Specs – Mixed Usefulness

- Mean pointing accuracy over the subset of a day for which the sun elevation is above (10°)
  - While this avoids penalizing a tracker for not being able to point directly at the horizon, this choice of 10 degrees is arbitrary and will penalize certain trackers disproportionately.

- Median pointing accuracy
  - While a median could be used to remove outliers, this is a roundabout way of doing it.

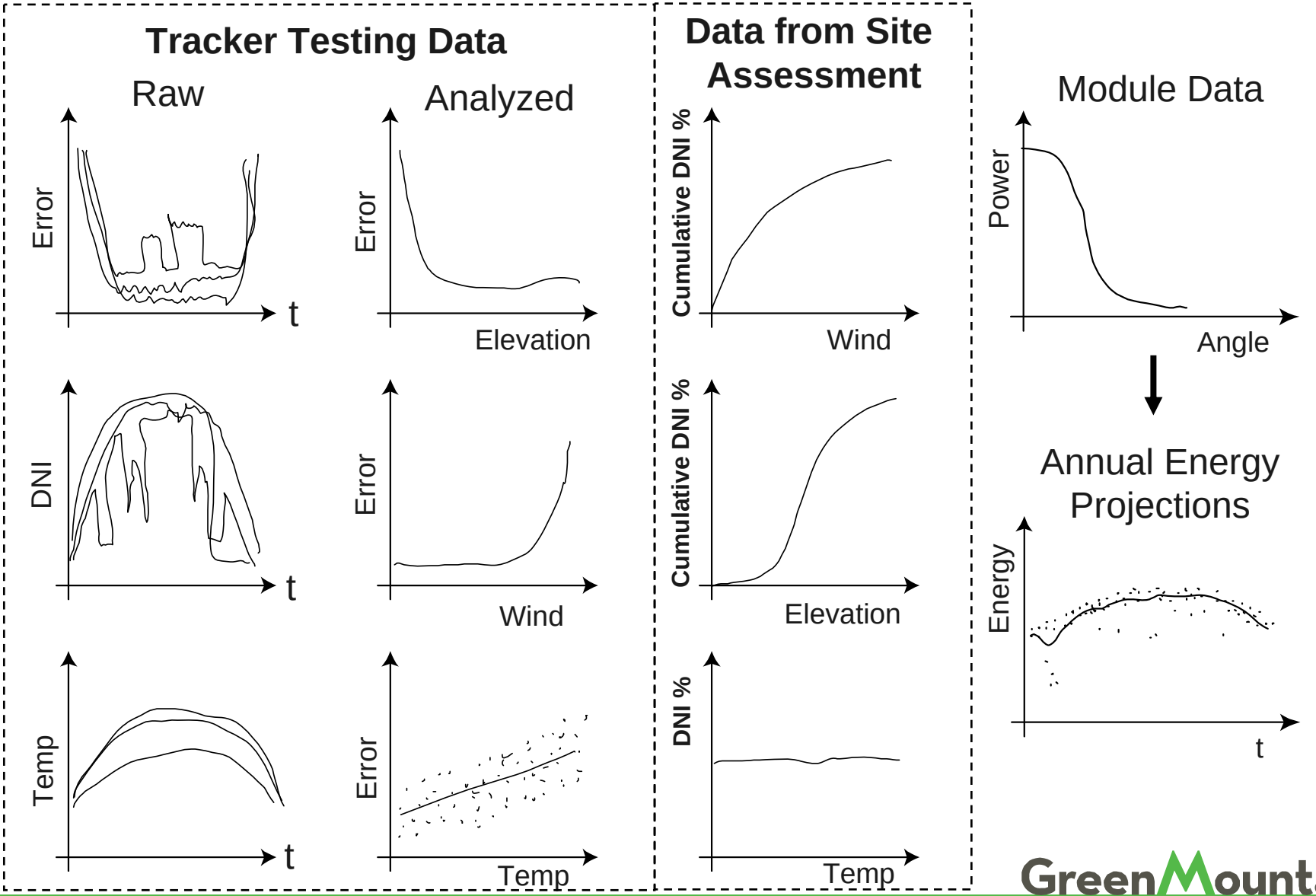
- 95th percentile accuracy (the pointing accuracy the tracker exceeds over 95% of sunrise-to-sunset hours)
  - This is another way to remove outliers from a data set, and has the advantage of being fairly simple to compute and explain, and fairly relevant, but is also somewhat arbitrary and not necessarily best-coupled to energy production.

Accuracy Specs – Potentially Useful?

- Graphs of tracking error as functions of
  - Sun elevation and azimuth (can be determined by time of day and location, without other sensors)
  - Tracker position (on local tracker axes)
  - Ambient temperature
  - Wind speed and direction
  - DNI, GNI
- These provide data sets that can potentially be combined with site assessment data collected at different sites (or from existing databases), where trackers have not yet been installed.

Sample High-Level Workflow

(this slide is just a conceptual example– the process itself is not easy and there are many difficult-to-measure variables to include)



Other Accuracy Concerns – Weight* & Wind**

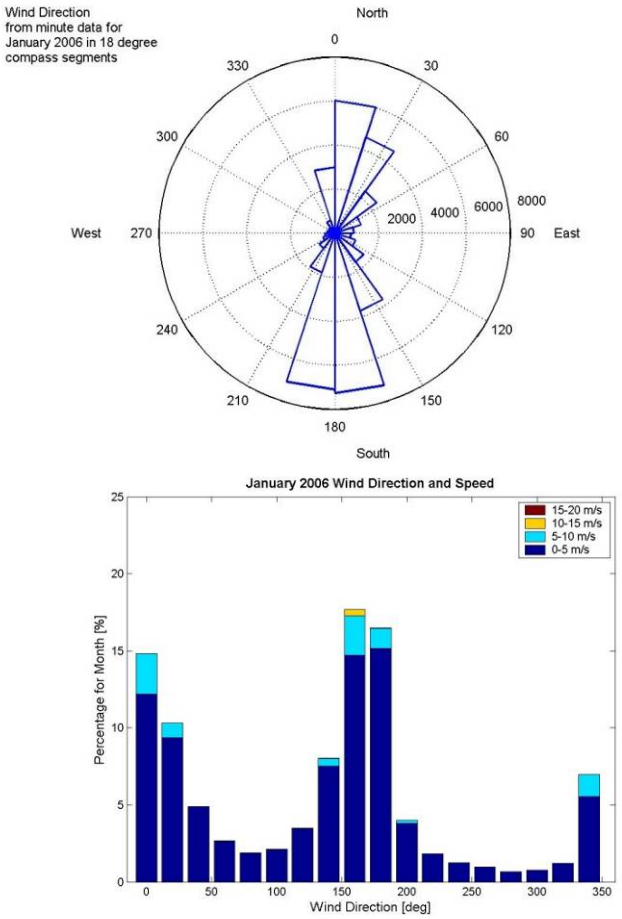


Image: SOLARGENIX

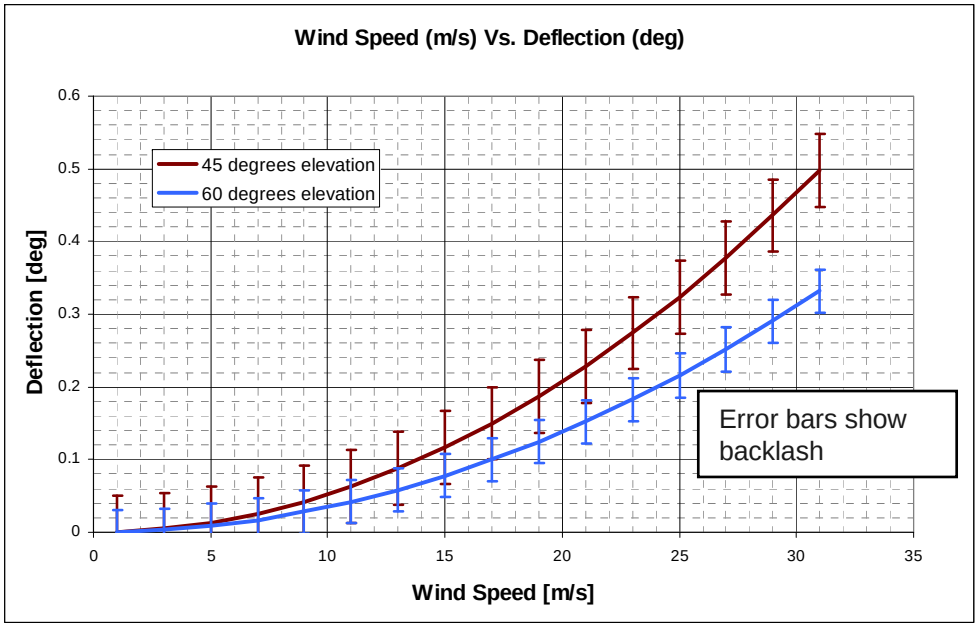


Image: GreenMountain Engineering

* For more information, see for example: A. Hakenjos, et al. “Field Performance FLATCON High Concentration PV Systems”, EUPVSEC 2007

** For more information, see for example I Luque-Heredia, et al. “CPV Tracking Systems: Performance Issues, Specifications & Design”, ICSC 2007

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Data Sources & Notes

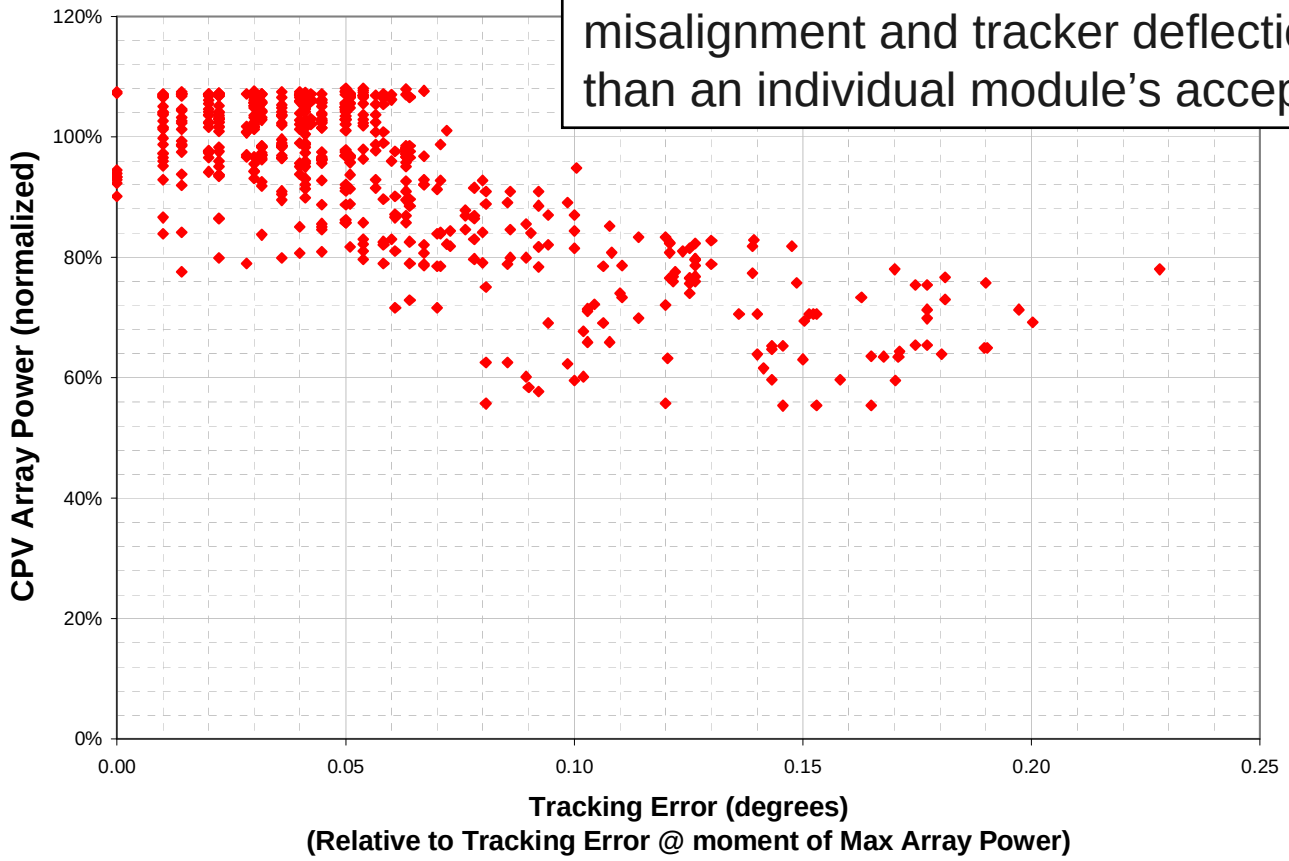
- ISFOC testing
- Several HCPV manufacturers who are SL1 customers provided data anonymously.
- GreenMountain testing

- Data taken between March ‘08 and November ‘08 (primarily Oct ‘08 and later)
- Not “champion data”– data from a range of conditions.
  - A few manufacturers included disclaimers such as: data was before optimal tracker alignment and calibration had been performed, or without the newest control algorithms.
- Very preliminary data/results– additional statistical analysis and interpretation will be performed in the future.

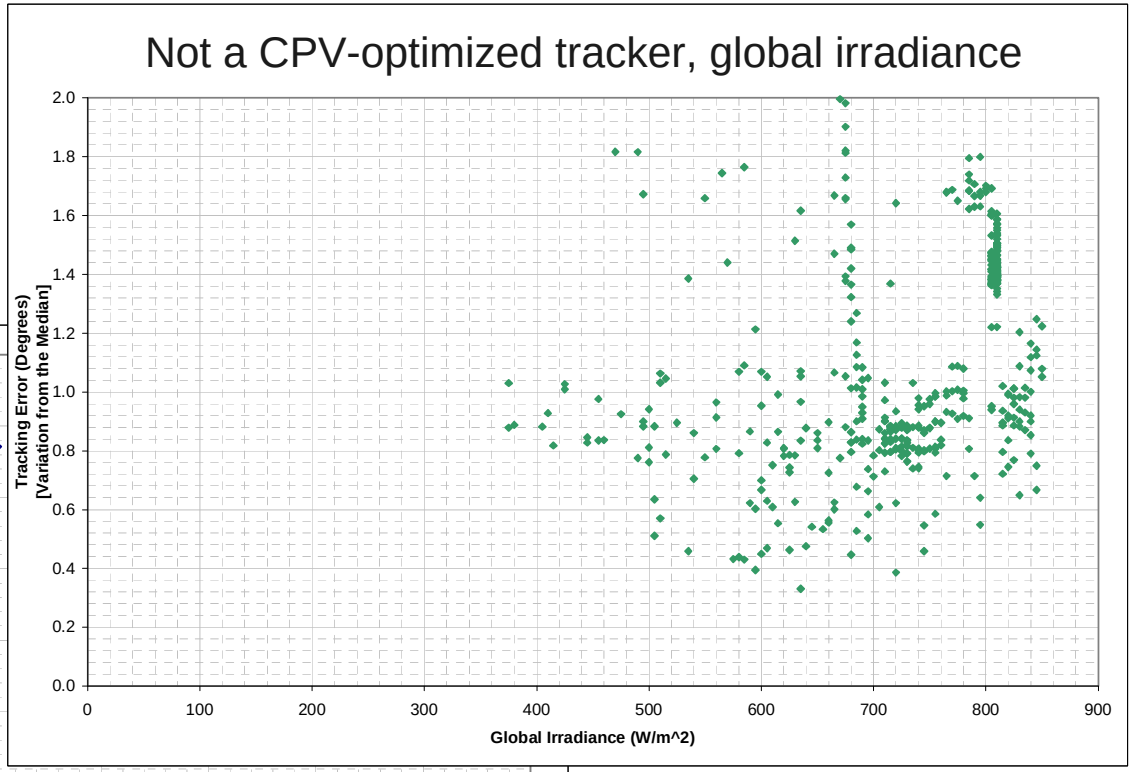
System Acceptance Angles

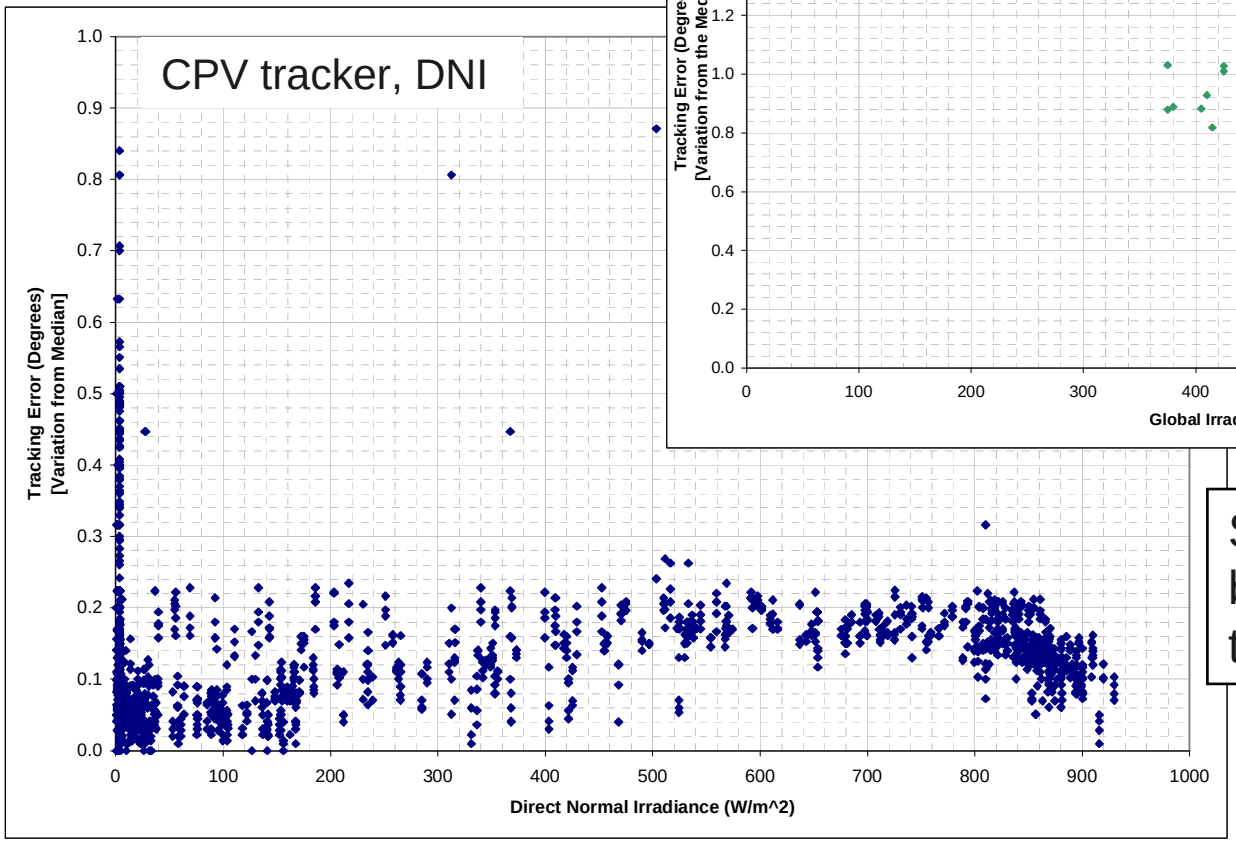
Correlation, though not necessarily causation.

Could indicate that the effective acceptance angle of the system (influenced by panel-to-panel misalignment and tracker deflection) is much tighter than an individual module's acceptance angle.



Tracking Error vs Irradiance





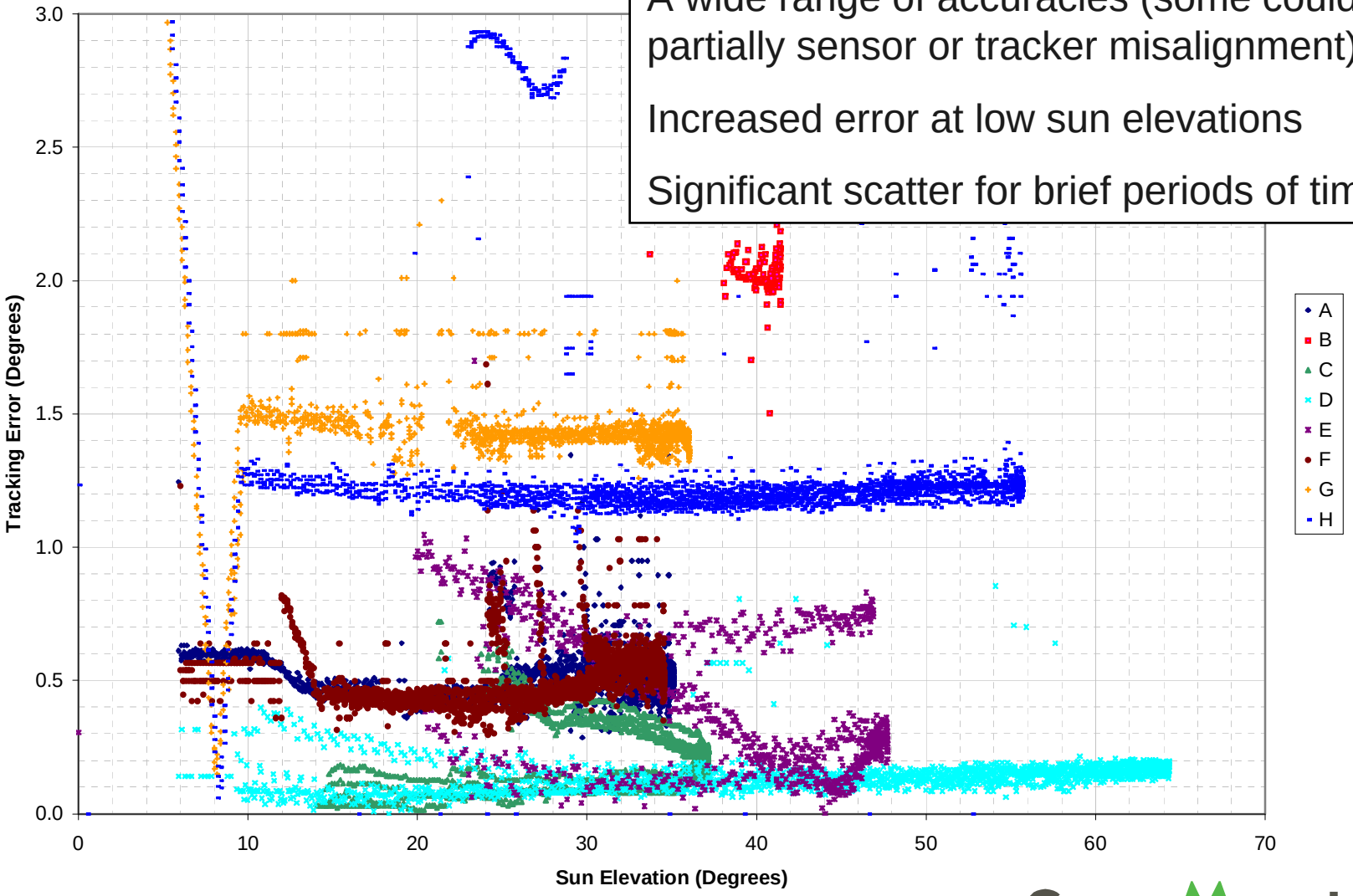
Slight correlation shown between irradiance and tracking accuracy.

Tracking Errors, Various Trackers

A wide range of accuracies (some could be partially sensor or tracker misalignment)

Increased error at low sun elevations

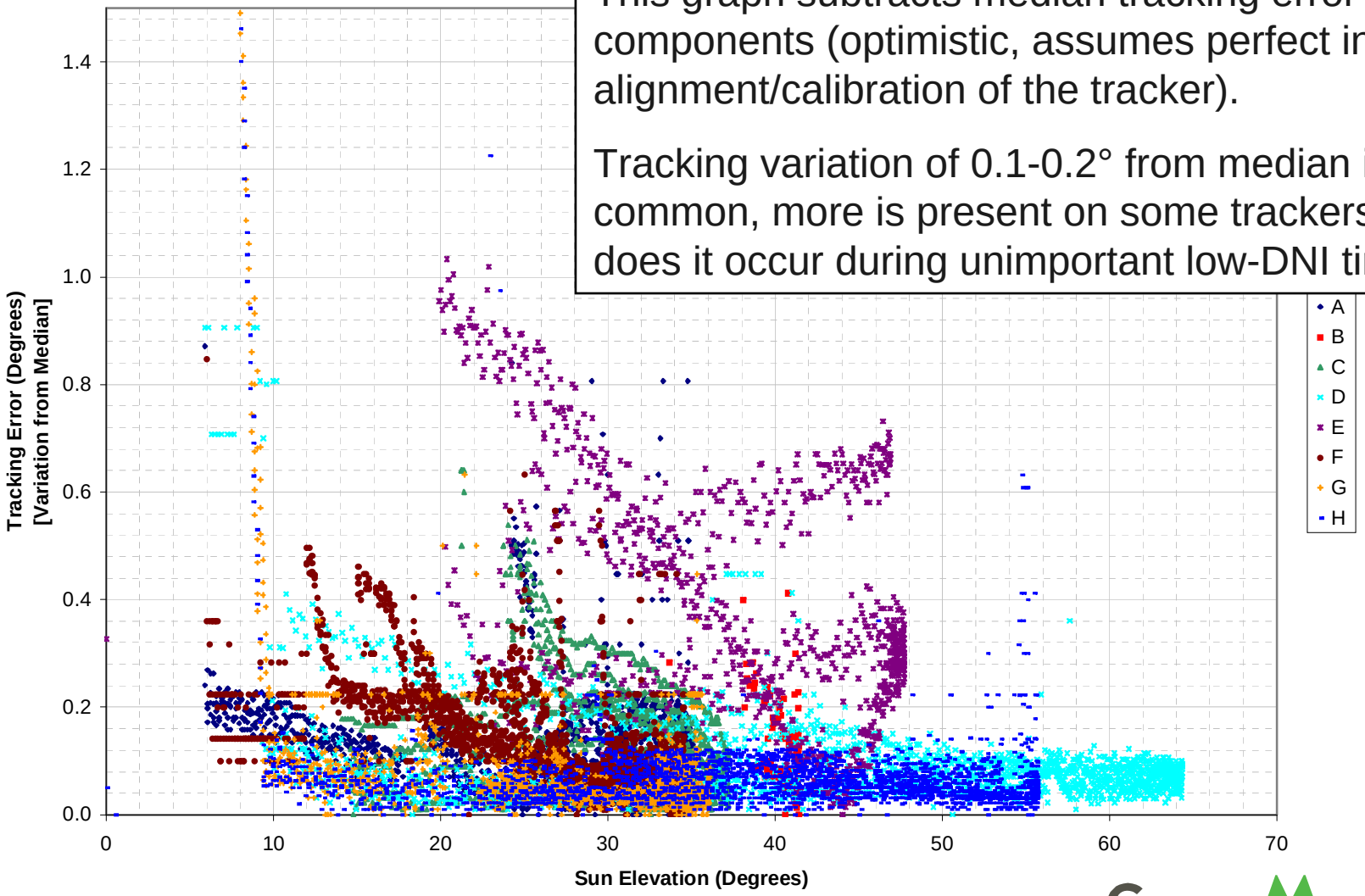
Significant scatter for brief periods of time



Tracking Errors, Various Trackers

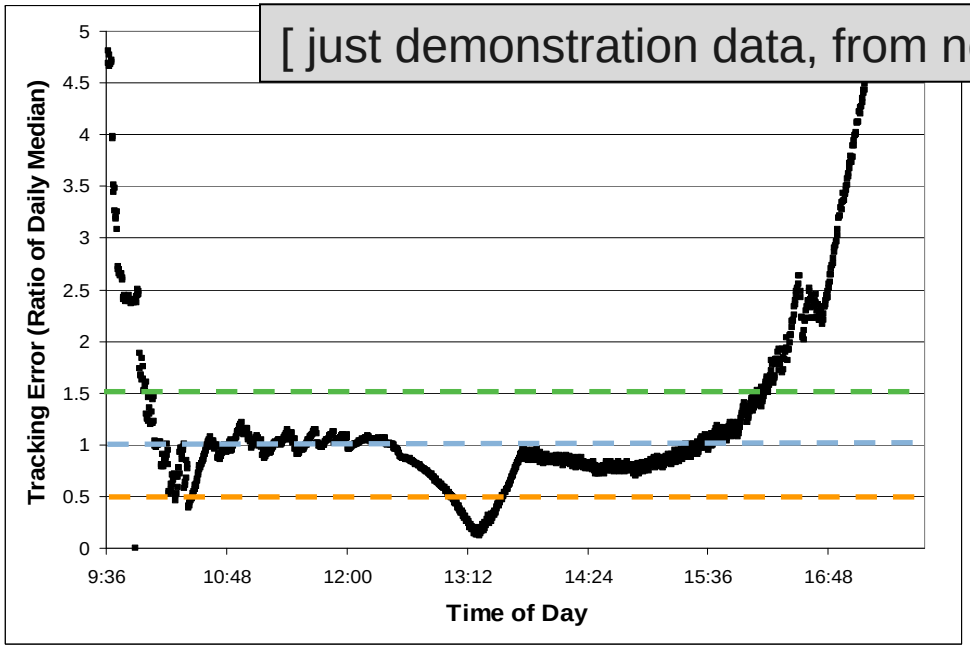
This graph subtracts median tracking error components (optimistic, assumes perfect initial alignment/calibration of the tracker).

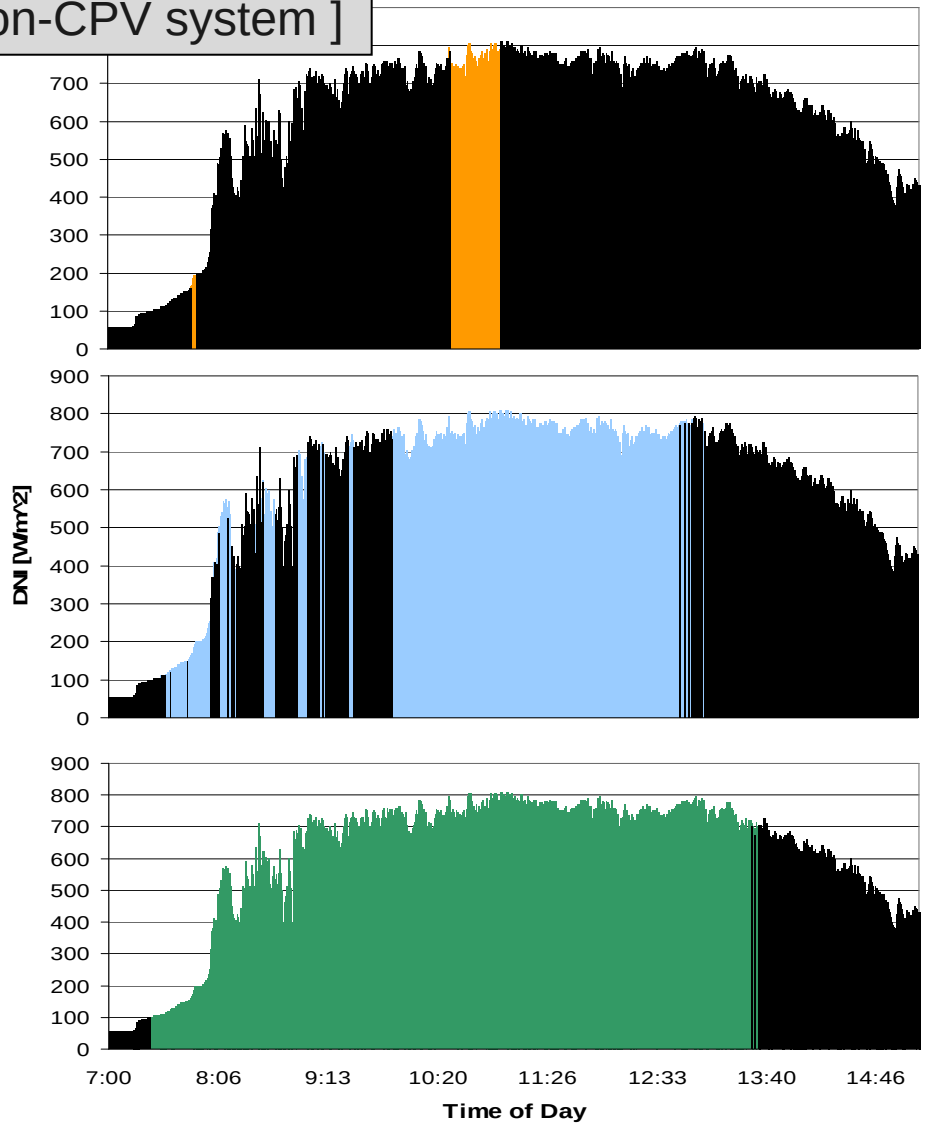
Tracking variation of 0.1-0.2° from median is common, more is present on some trackers (but does it occur during unimportant low-DNI times?).

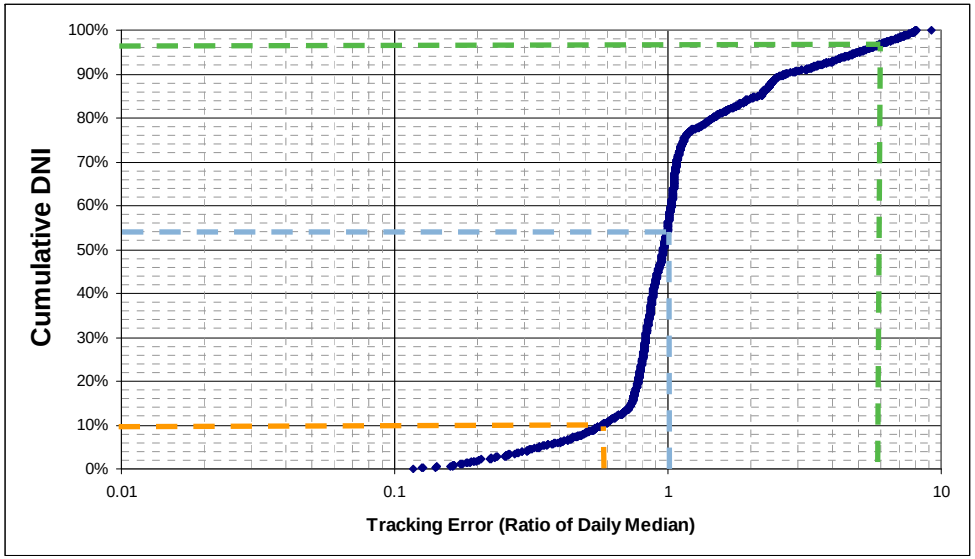


The P Plot Concept

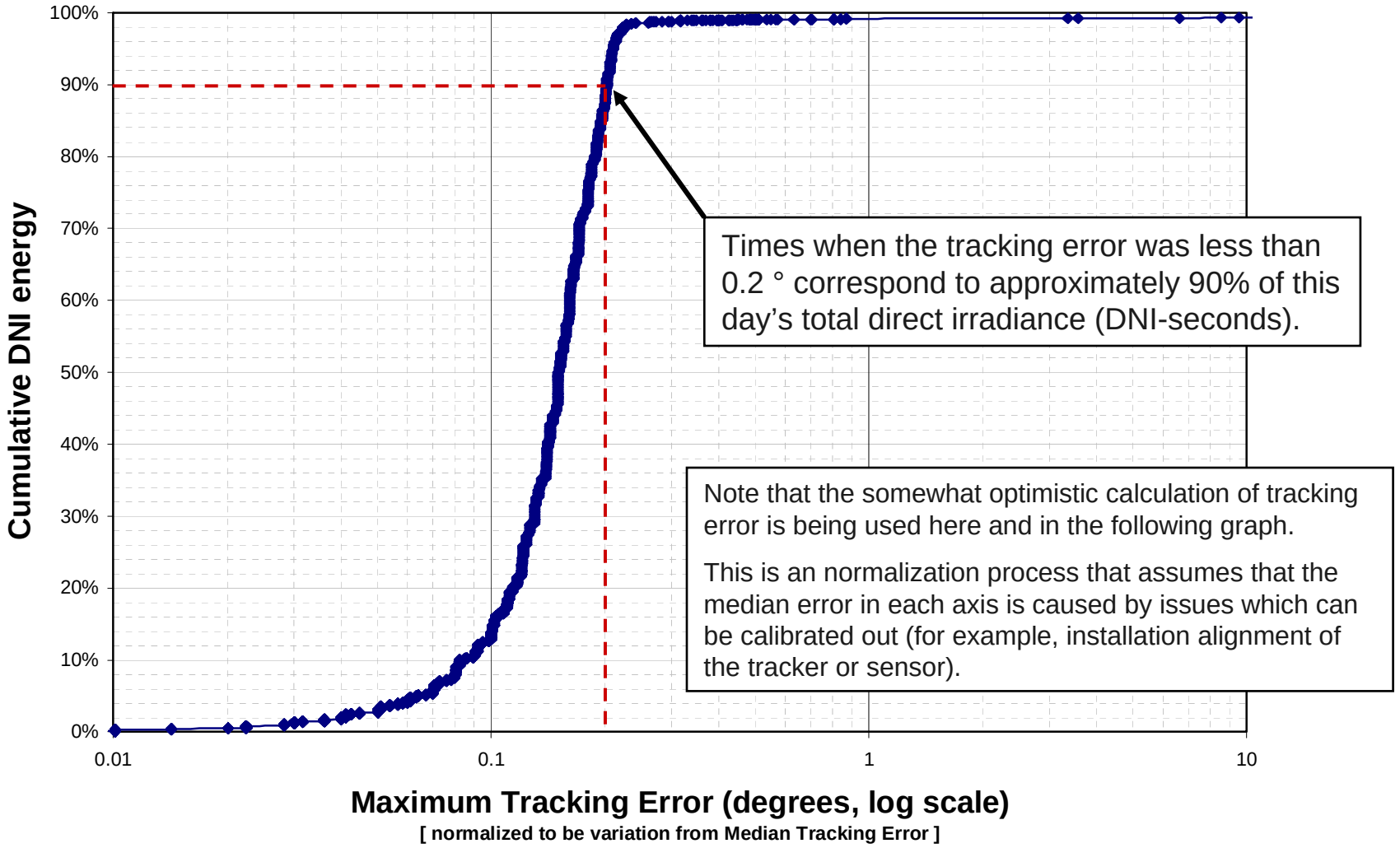
[just demonstration data, from non-CPV system]



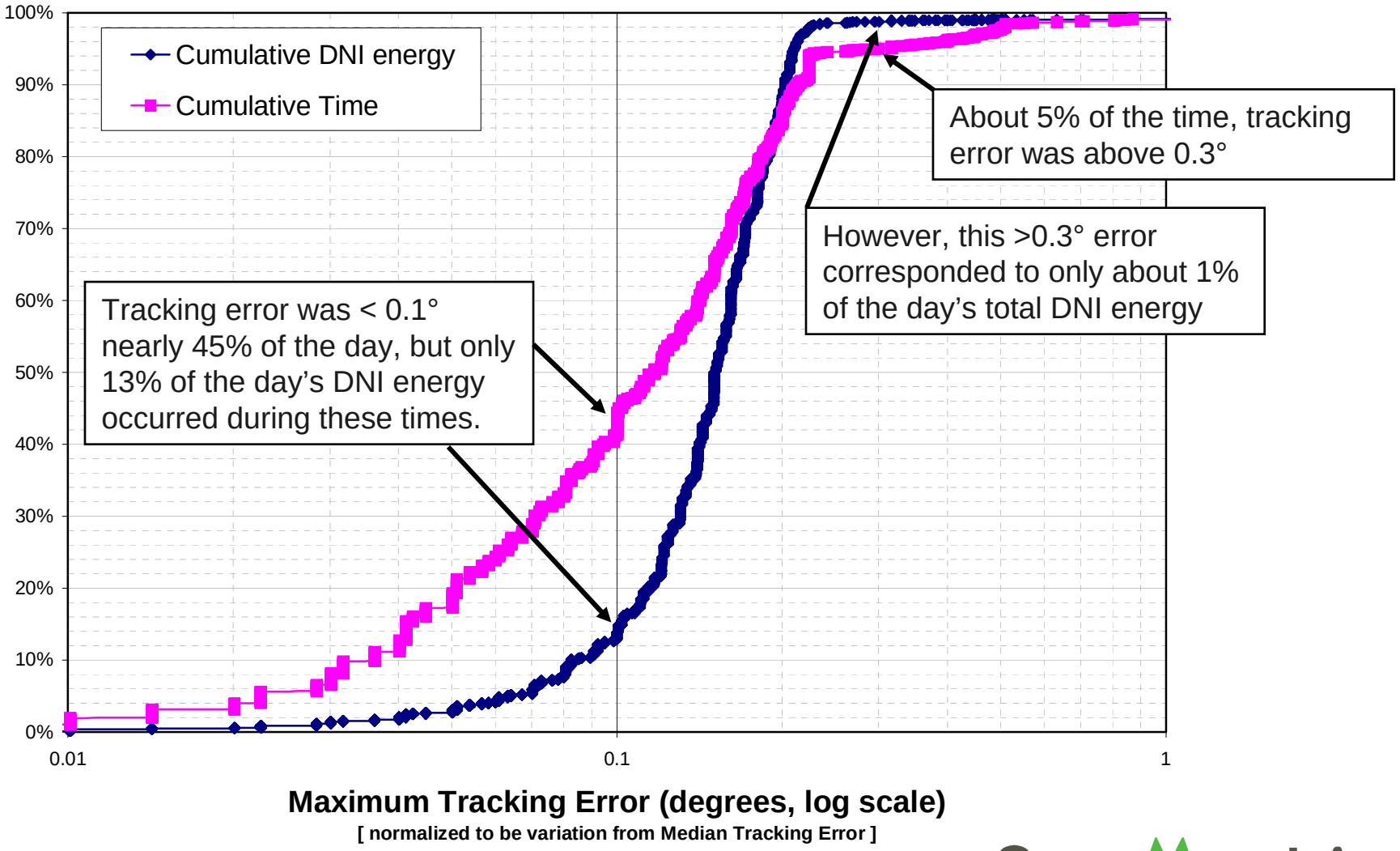




Cumulative DNI



DNI vs Time as weighting



Conclusions

- It is possible to measure tracking accuracy in the field.
- Examining and analyzing detailed data sets can provide more insight than a single numerical value.
- Without optimal alignment, tuning, and calibration, CPV tracking errors of 0.1° to 2.0° have been observed.
  - Tracking is not as trivial as “just calculate the sun ephemeris position”.
- The need for future tracker cost reduction can be assisted by a careful understanding of performance and design trade-offs.

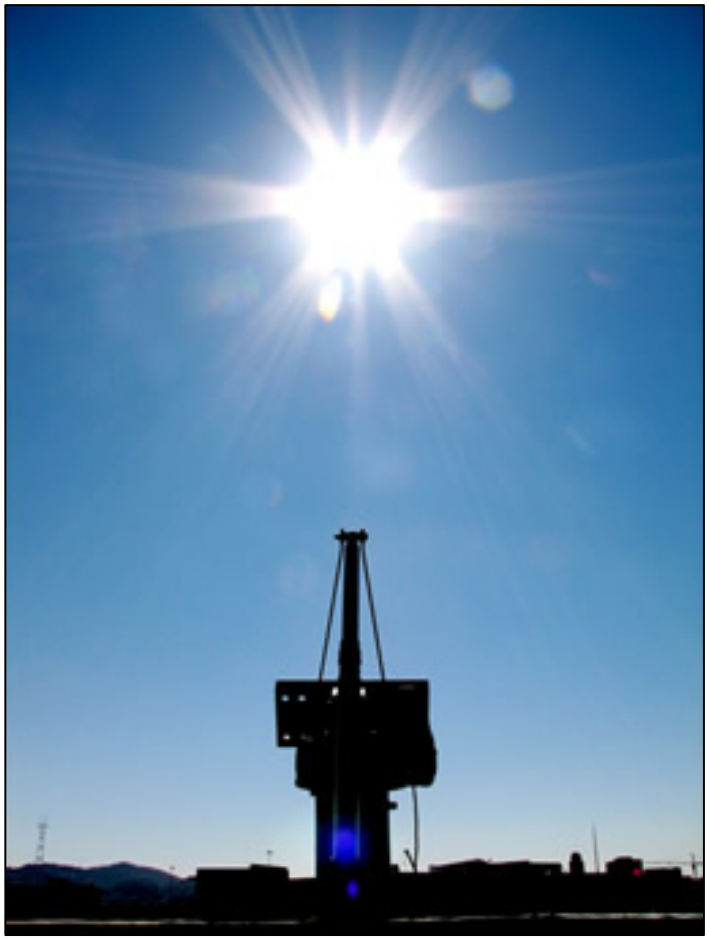


Image: GreenMountain Engineering

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Acknowledgments

- ISFOC, and especially María Martínez, for supporting us in this work.

- CPV manufacturers and Trac-Stat customers who were willing to anonymously share real field data.

- The ICSC-5 Conference Committee.

- All of the previous contributors to the shared body of CPV technical knowledge whose work we've drawn on.

[This document was originally presented with additional verbal commentary to explain particular slides. For further information or details, contact Max Davis at mdavis@greenmountainengineering.com]