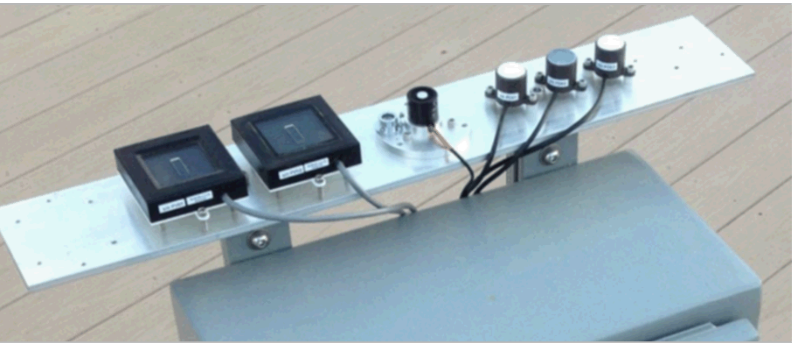
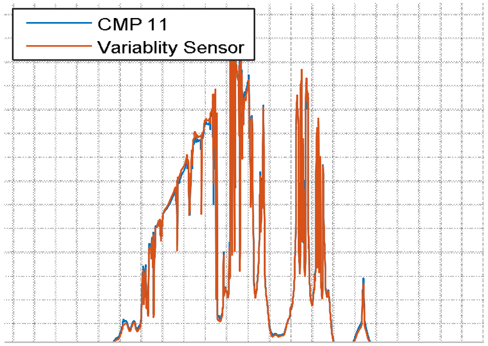
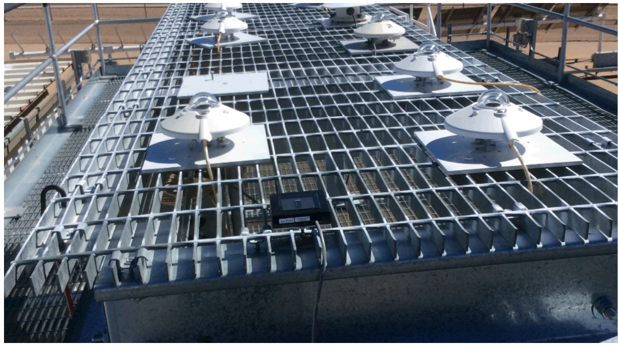
SAND2015-4747C

*Exceptional service in the national interest*

Sandia National Laboratories





# Low-cost Solar Variability Sensors for Ubiquitous Deployment


Matthew Lave[1], Matthew J. Reno[1], Joshua Stein[1], and Ryan Smith[2]

[1]Sandia National Laboratories

[2]Pordis, LLC.


U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration


Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

# Motivation for a Low-Cost Sensor

- Currently used solar irradiance sensors are expensive pyranometers with high accuracy (relevant for annual energy estimates).
- Low-cost sensors can have similar precision (relevant for solar variability measurements), even if they are not as accurate.

| Pyranometer Name | Pyranometer Class | Pyranometer Cost | Data Logger Name | Datalogger Cost | Pyranometer + Datalogger Cost |
|---|---|---|---|---|---|
| Apogee SP-110 | Second Class[1] | $195[2] | CR200X | $650[3] | $845 |
| | | | LI-1500G | $1750[4] | $1945 |
| Licor LI-200SL | First Class | $295[4] | CR200X | $650[3] | $945 |
| | | | LI-1500G | $1750[4] | $2045 |
| Eppley PSP | Secondary Standard | $1975[5] | CR200X | $650[3] | $2625 |
| | | | LI-1500G | $1750[4] | $3725 |

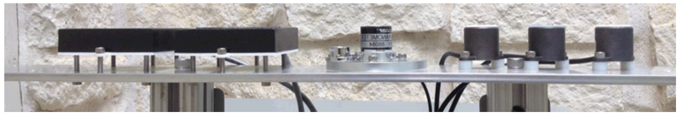
[1] The Apogee SP-110 is not rated on the ISO 9060 standard, but is expected to be similar to a "second class" instrument.
[2] Apogee Instruements: http://www.apogeeinstruments.com/pyranometer-sp-110/, accessed 8/28/2014
[3] Campbell Scientific 2010 price list, accessed at http://tge2008-2.wikispaces.com/file/view/March_2010-macs-Price.pdf on 8/28/2014.
[4] Price Quote from LI-COR Biosciences received Aug. 28, 2014.
[5] 1997 prices listed in Masters Thesis "An Improved Multipyranometer Array for the Measurement of Direct and Diffuse Solar Radiation" accessed at http://esl.tamu.edu/docs/publications/thesis_dissertations/ESL-TH-97-12-02.pdf on 8/28/2014.

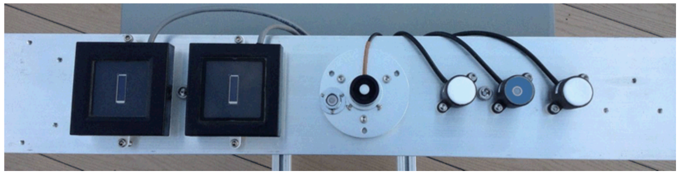
# Variability Sensor Requirements

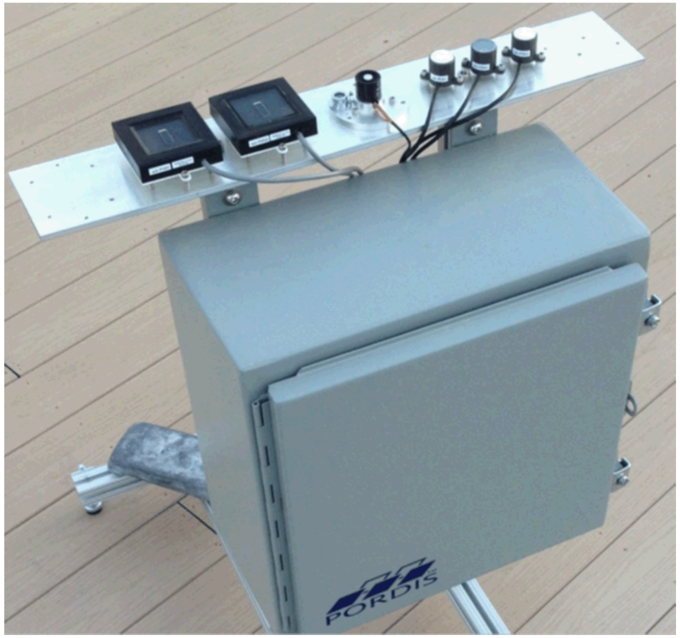
- Based on previous experience and literature review, Sandia established baseline hardware, operational, and data requirements for the variability sensor.
  - **Hardware Requirements (partial list)**
    - Low-cost components where practical (maintain solar variability measurements)
    - Irradiance sensitivity between 0-1400 $Wm^{-2}$
    - Detector response time  sufficient for 1-second measurements
    - Spectral response similar to silicon PV modules
    - Wide thermal operating range and weatherized casing
    - Battery Powered; GPS receiver for location and time synchronization
  - **Operational and Data Reporting Requirements (partial list)**
    - Measure only during daytime to conserve battery and data storage
    - Wireless (Wifi and/or cell modem) transmission of data
    - Store up to 30 days of time-stamped measurement data in case on communication failures.
- In summary, final device will be inexpensive, easy to install and network, and require no maintenance during operating year.

# Tested Components

- In initial testing, considered 5 basic designs based on either PV cells or photodiodes.
  - All PV cells/photodiodes cost <$15.
- Deployed all 5 test devices and a LICOR pyranometer for validation.



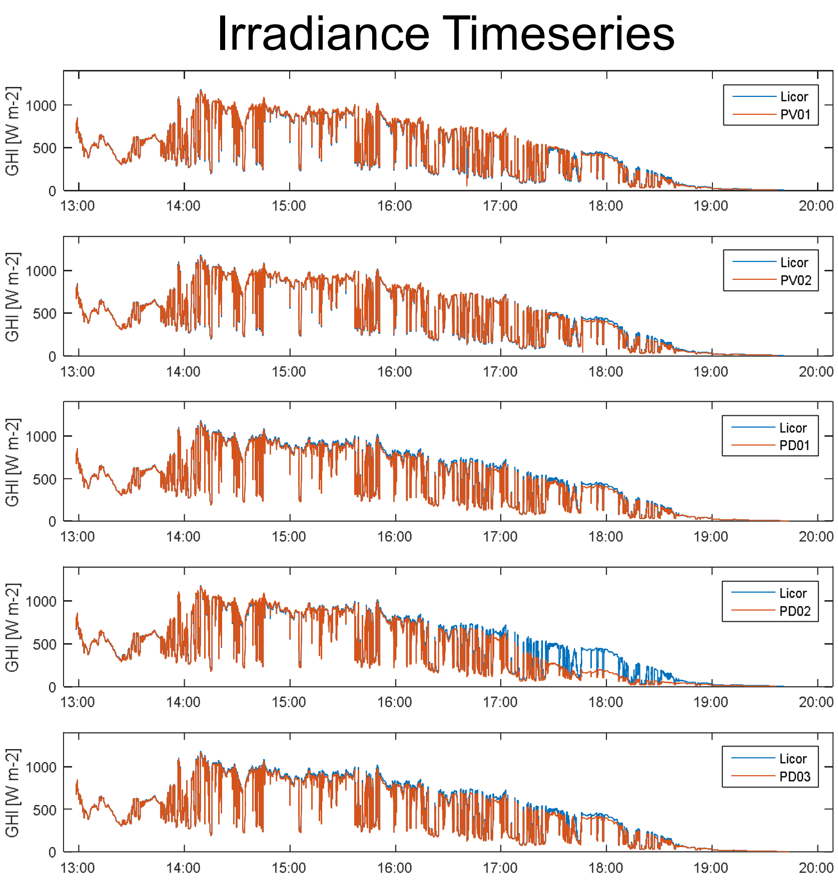


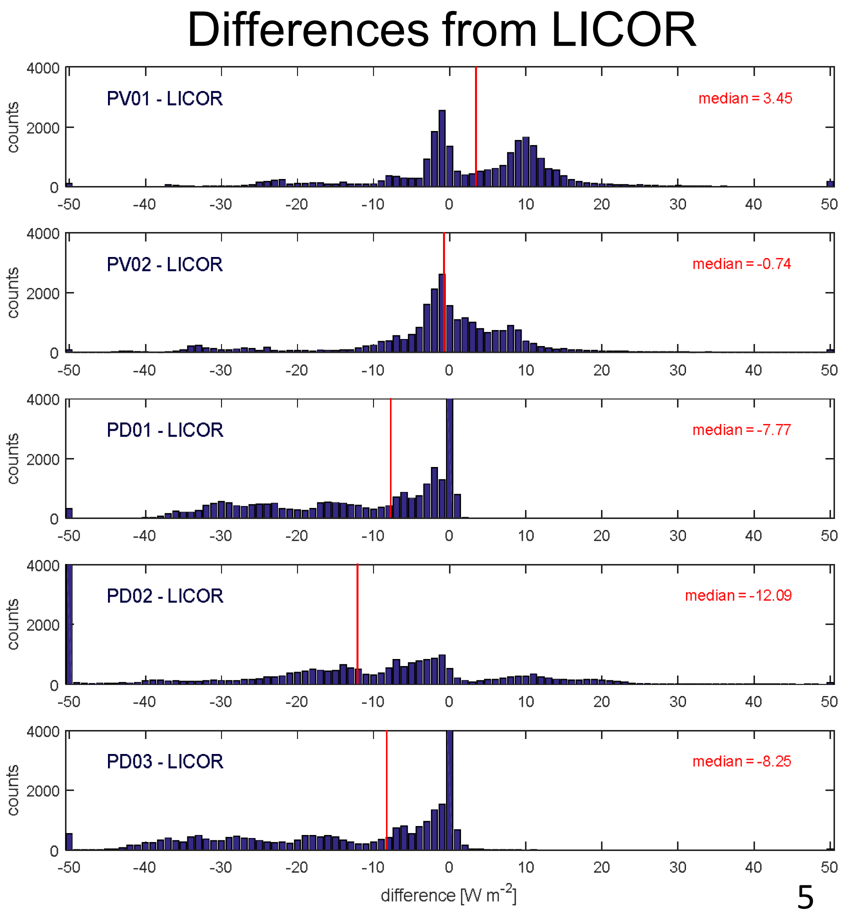



| Serial Number | Sensor type | Diffuser Material | Distance, PD -> Diffuser | Glass Window Mounting |
|---|---|---|---|---|
| **PV01** | PV cell (KXOB22-12X1L) | N/A | N/A | Inside |
| **PV02** | PV cell (KXOB22-12X1L) | N/A | N/A | Outside |
| **PD01** | Photodiode (Thorlabs FDS100) | Teflon | 4.13mm | N /A |
| **PD02** | Photodiode (Thorlabs FDS100) | FEP | 4.13mm | N/A |
| **PD03** | Photodiode (Thorlabs FDS100) | Teflon | 1.40mm | N/A |

# Comparison to LICOR: Irradiance

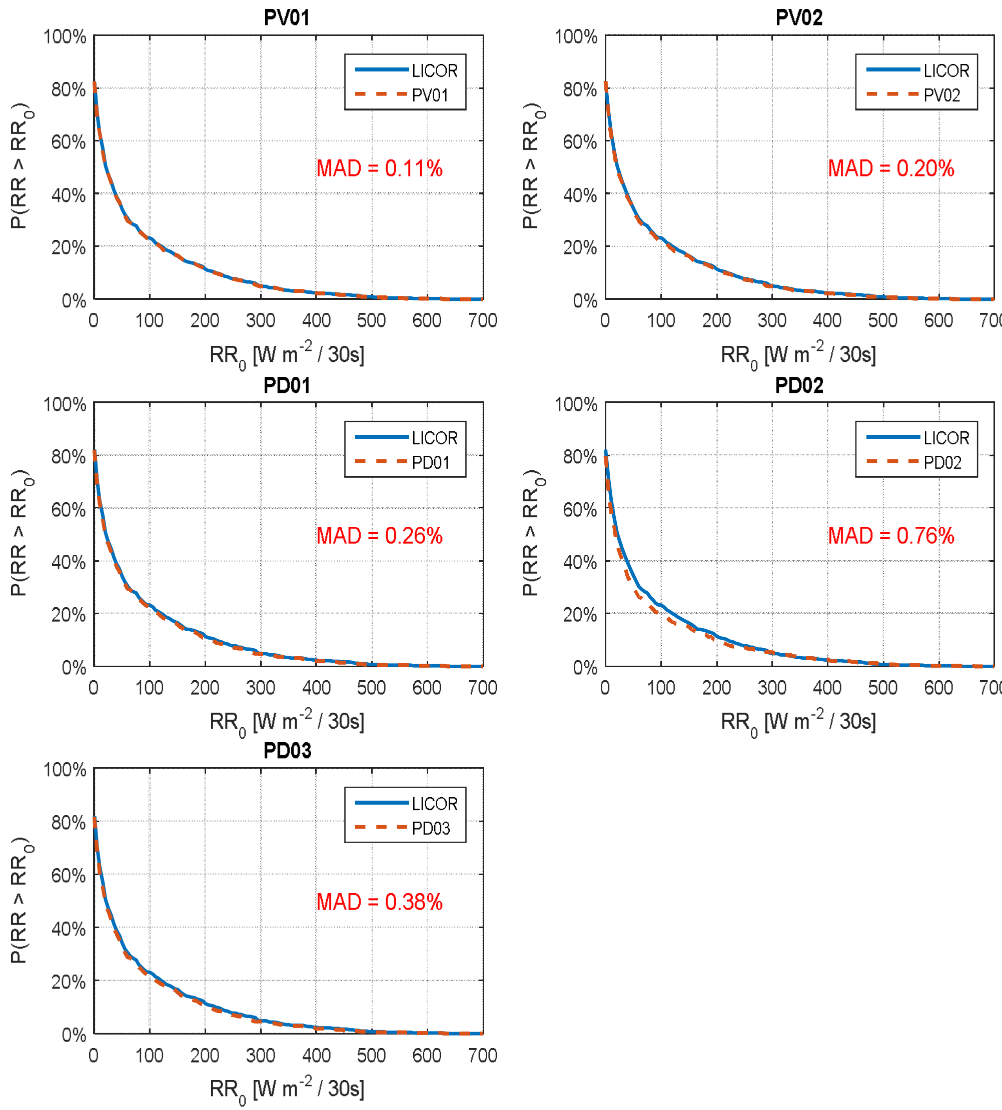
- Tested from 13:00 to 20:00 on a highly variable day in Austin, TX.
- Most deviation in the evening, especially for PD02.



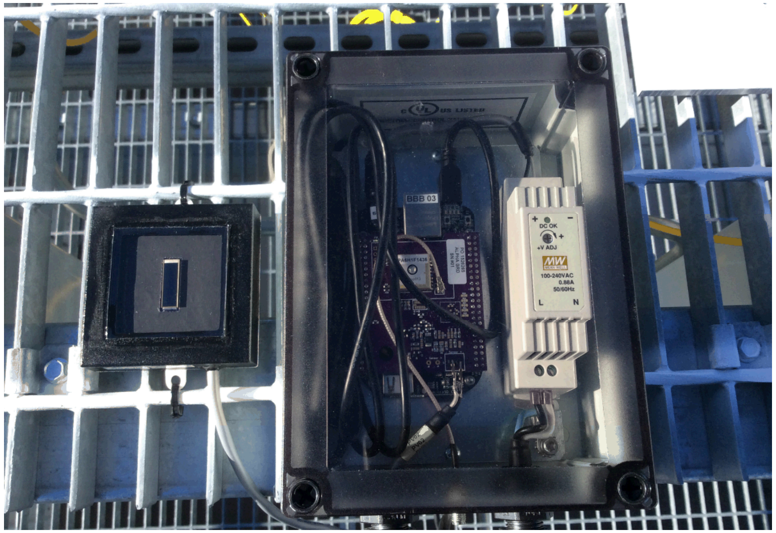
# Comparison to LICOR: Variability

- Irradiance comparisons are promising, but, we are developing a ***variability*** sensor.
- Comparisons of ramp rate distributions show good agreement (except for PD02).
- PV01 and PV02 have slightly better performance than PD01 and PD02, but differences are small for all.



# Alpha Prototype

- PV02 device was used as basis for alpha variability sensor prototype.
  - Good test performance vs. LICOR
  - Possibility for charging off of PV cell
- Alpha prototype was fast-tracked to allow for field testing of irradiance / variability measurements.
  - No battery power or wireless communications.
- Costs: PV cell $2.05, sensor casing ~$51, computer board TBD

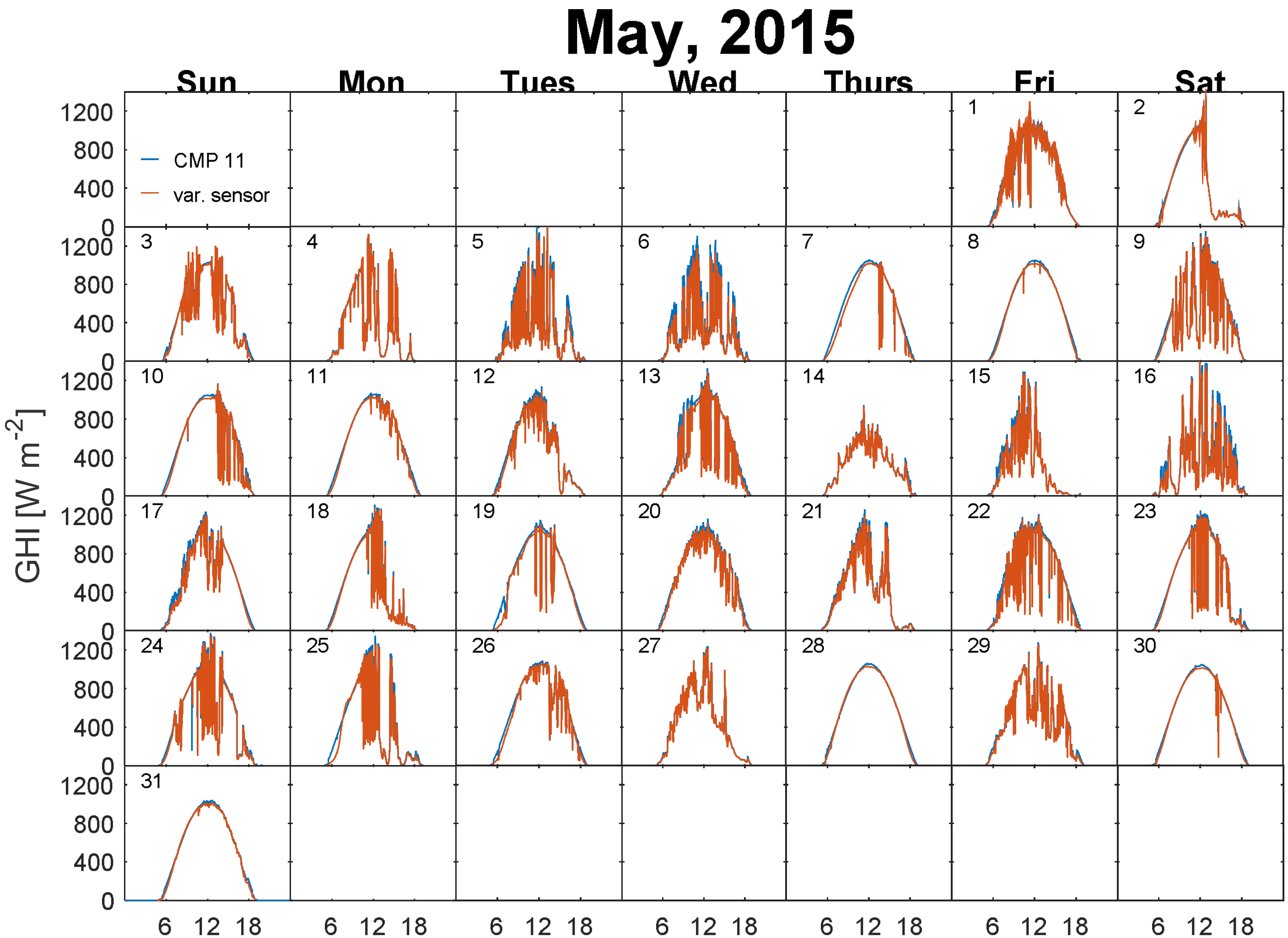


Alpha prototype showing (left) PV cell and casing and (right) computer board and power supply in box.

Alpha prototype deployed on test rack with PSPs undergoing calibration.

# Compare to CMP 11

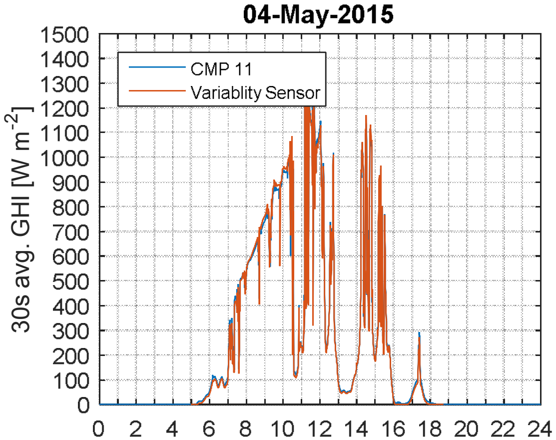
- Deployed at the Sandia's PSEL (Albuquerque, NM)
  - compared to CMP 11 (secondary standard) pyranometer at PSEL.

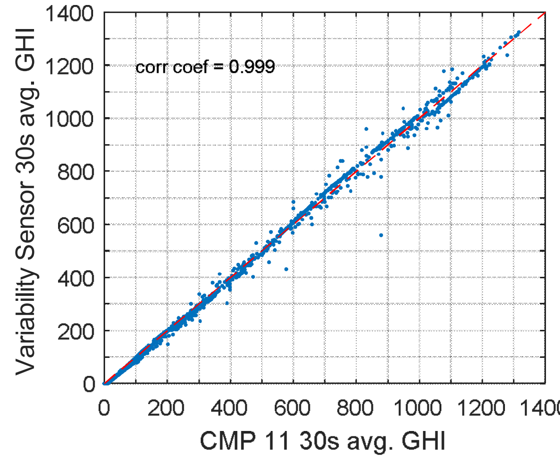


# May 4th, 2015

- Variability sensor matches CMP 11 well on highly variable day

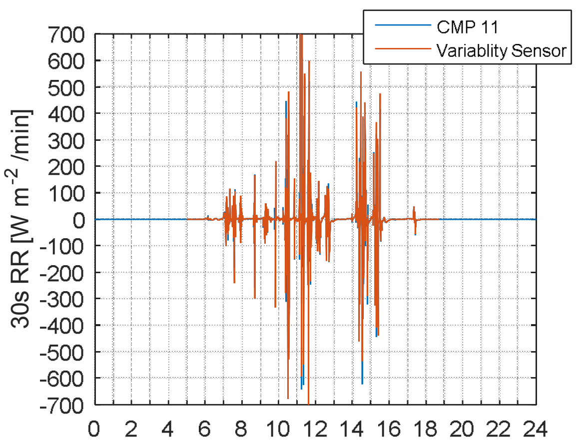
GHI timeseries

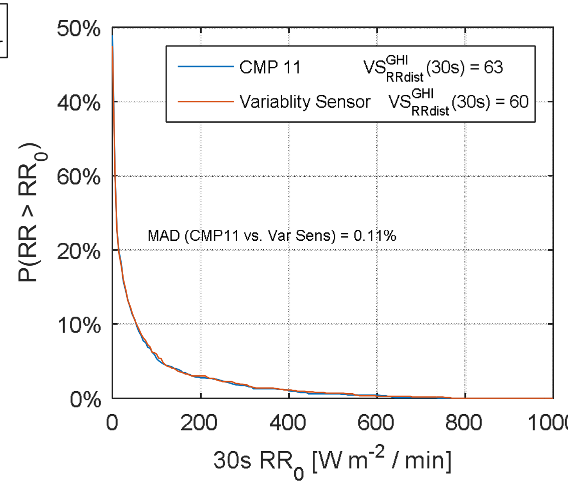



Scatter plot of variability sensor vs. CMP 11 GHI

30s ramp timeseries




30s ramp distributions and variability score (VS)[1]

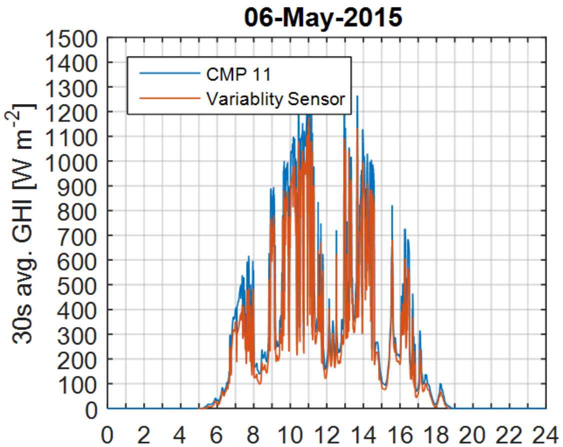
[1]see VS definition in M. Lave, M. J. Reno, and R. J. Broderick, "Characterizing local high-frequency solar variability and its impact to distribution studies," Solar Energy, vol. 118, no. 0, pp. 327 – 337, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0038092X15002881

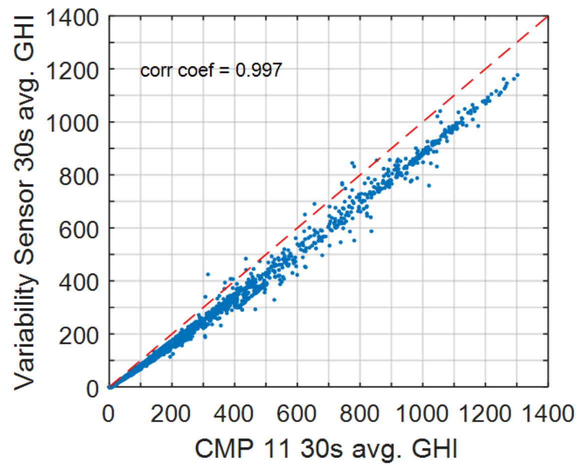
# May 4th, 2015

Sandia National Laboratories

- Variability sensor matches CMP 11 well on highly variable day

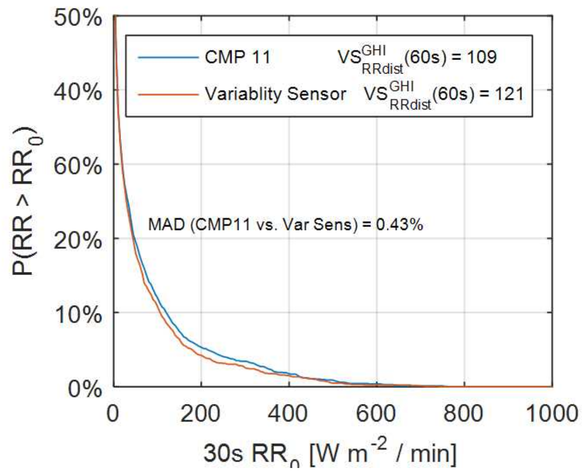
GHI timeseries




Scatter plot of variability sensor vs. CMP 11 GHI

Condensation on sensor

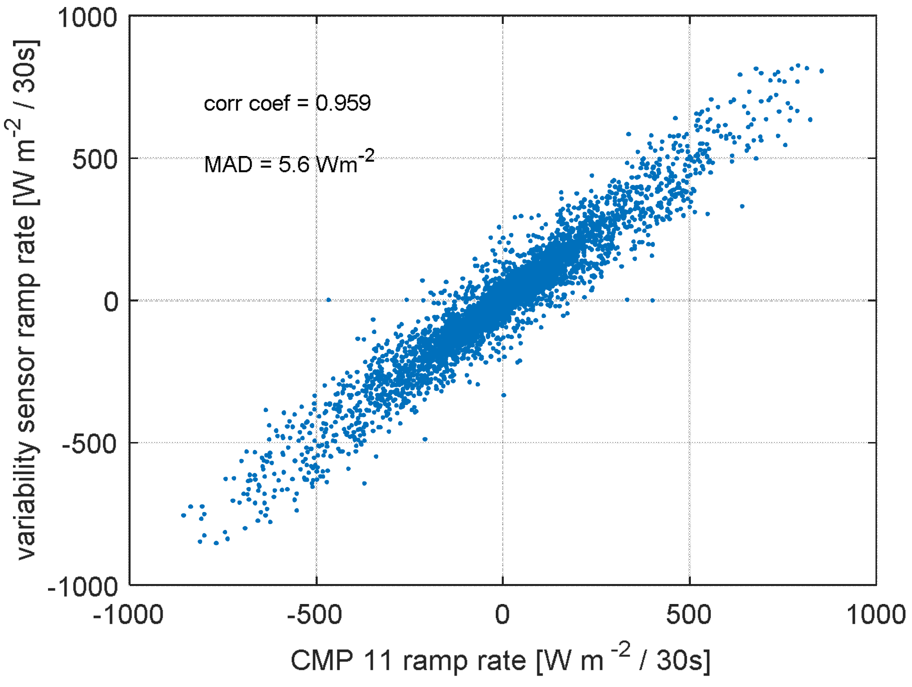



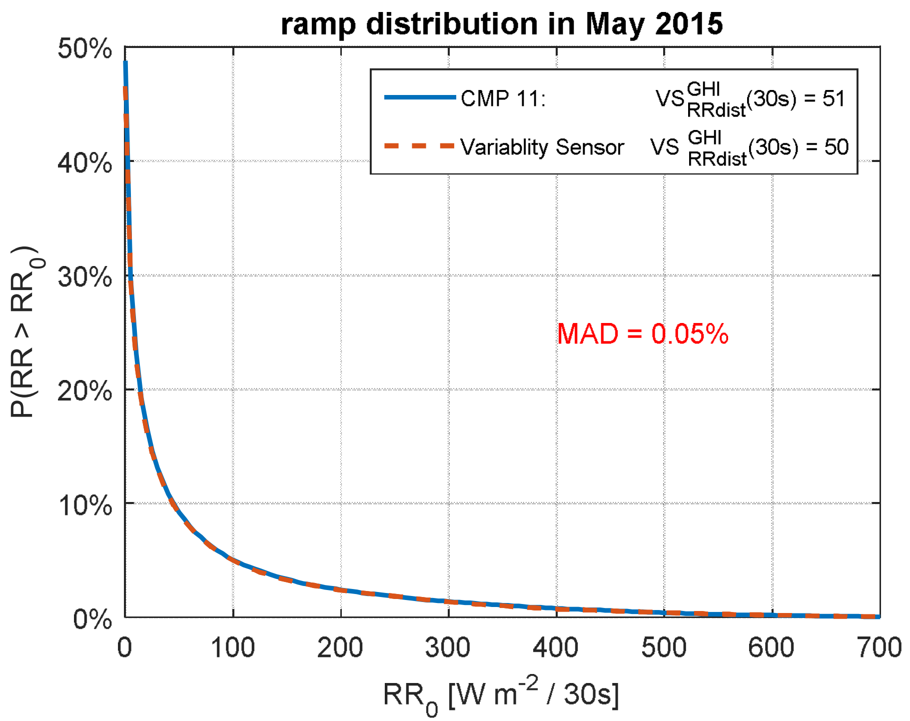

30s ramp distributions and variability score (VS)[1]

[1]see VS definition in M. Lave, M. J. Reno, and R. J. Broderick, “Characterizing local high-frequency solar variability and its impact to distribution studies,” Solar Energy, vol. 118, no. 0, pp. 327 – 337, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0038092X15002881

# May 2015

- Variability sensor matches distribution of 30s ramps in May 2015 very well.
  - Ramps are highly correlated.
  - MAD of 0.05% is much smaller than differences due to e.g., GHI vs. POA, differences by location, etc.



# Beta Prototype

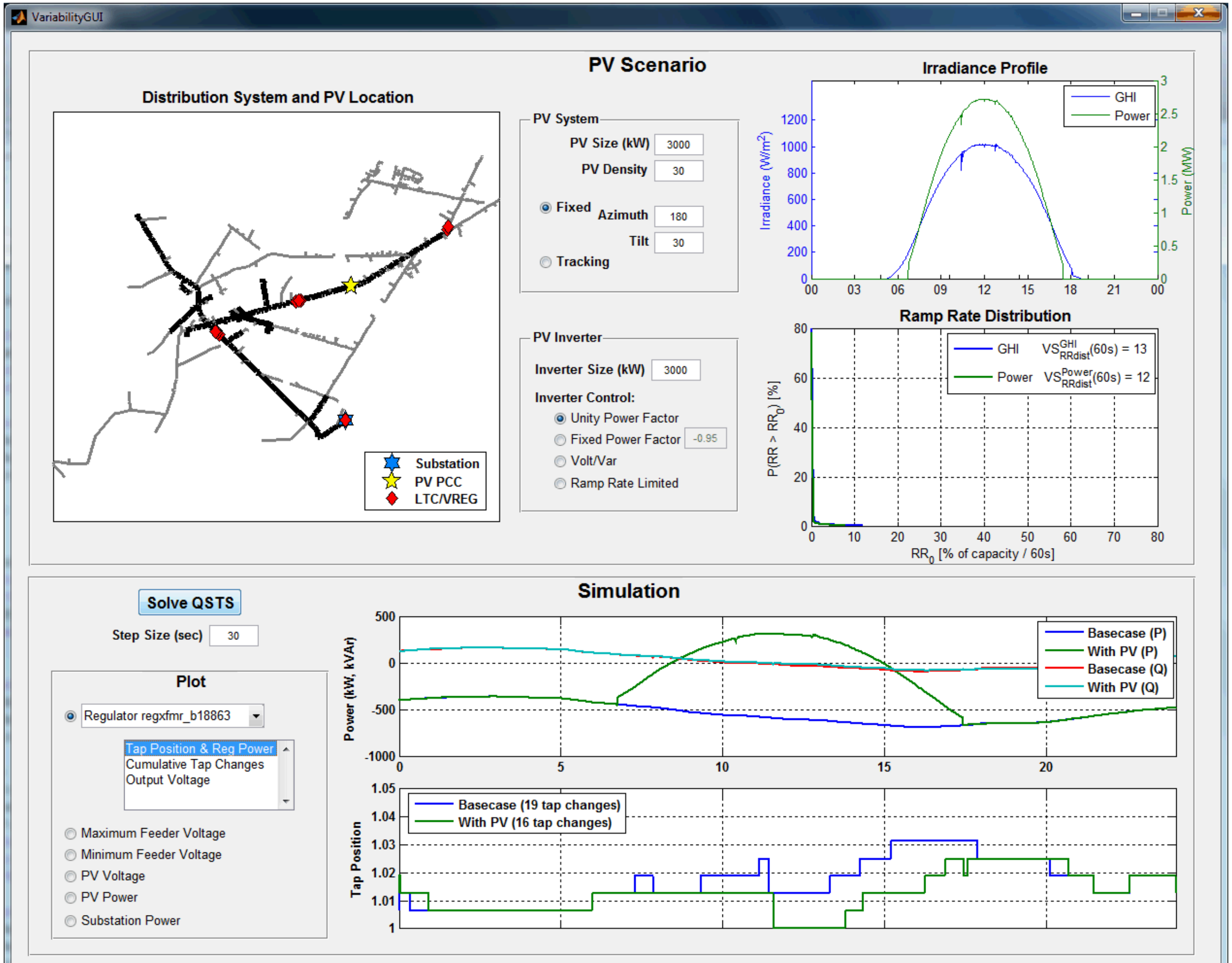
- Coming soon!
- Will have same or better variability measurement accuracy as alpha, but will incorporate features such as battery power, wireless data transmission, etc.
- One, self-contained device
- Sensor mounting cost expected to be similar to alpha (~$50), low-cost PC board used to minimize additional costs
- Will be deployed at 3+ locations
  - Continue to validate variability sensor measurements against commercial pyranometers
  - gain high-frequency variability measurements in locations of interest (e.g., Florida)

# Use for Grid Integration Studies

- Local measurements from a solar variably sensor can be used as inputs for accurate grid integration studies.
  - Other studies use proxy data (from a different location) or artificial ramps and may over or underestimate the impact of PV variability.
  - Up to 300% differences in the number of tap changes in a week found for different locational variability samples, showing importance of local data.
- To facilitate grid integration studies with variability sensor data, we have developed a GUI in data analysis program MATLAB.
  - User loads in variability sensor data and feeder layout (or default feeder).
  - User inputs PV tilt and azimuth (or tracking).
  - GUI uses GridPV toolbox to run distribution grid simulation.
  - Outputs include power through each voltage regulator, regulator tap position, cumulative number of tap changes, and minimum and maximum feeder voltage.

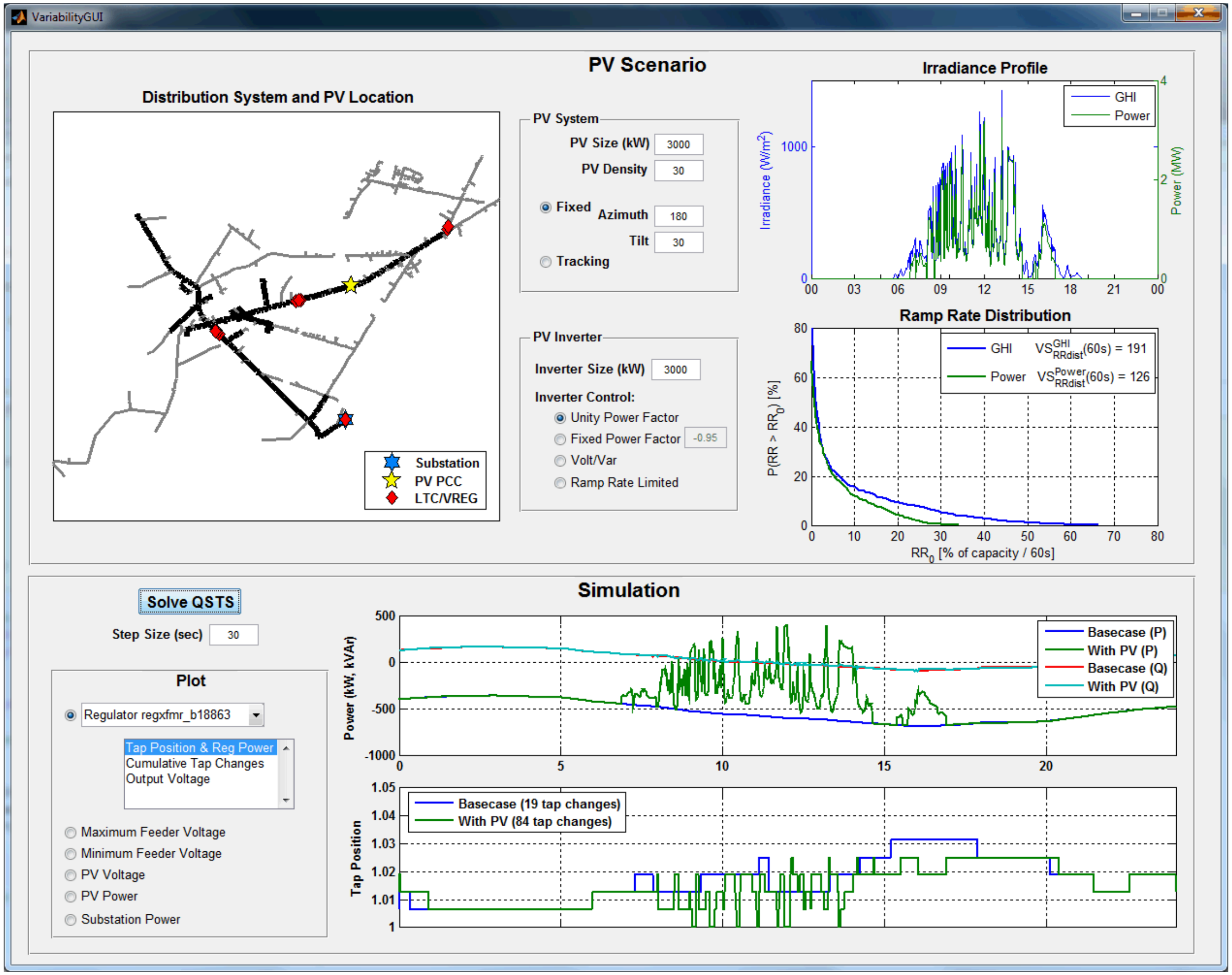
# GUI Example: Clear Day

- Tap change operations reduced when PV added to feeder!



# GUI Example: Cloudy Day

- Tap change operations significantly increased when PV added.



# Conclusion

- We are developing a low-cost solar variability sensor to encourage ubiquitous solar variability measurements for a better understanding of the impact of solar PV on the electric grid.
- PV cell and photodiode based sensor designs tested.
- Alpha prototype fabricated to test PV cell variability measurements.
- Variability measurements closely match secondary standard CMP 11 pyranometer, even with layer of condensation on window.
- Beta device will maintain variability measurement quality while incorporating wireless data transmission, battery power, etc.
- Value of data to grid integration studies easily determined through GUI tool.
- Overall, the variability sensor will reduce uncertainty about the impact of solar photovoltaic and so will encourage greater PV penetrations (where appropriate).