PV Module Monitoring Equipment with Optimized Sampling, Filtering, and Time-Response Characteristics

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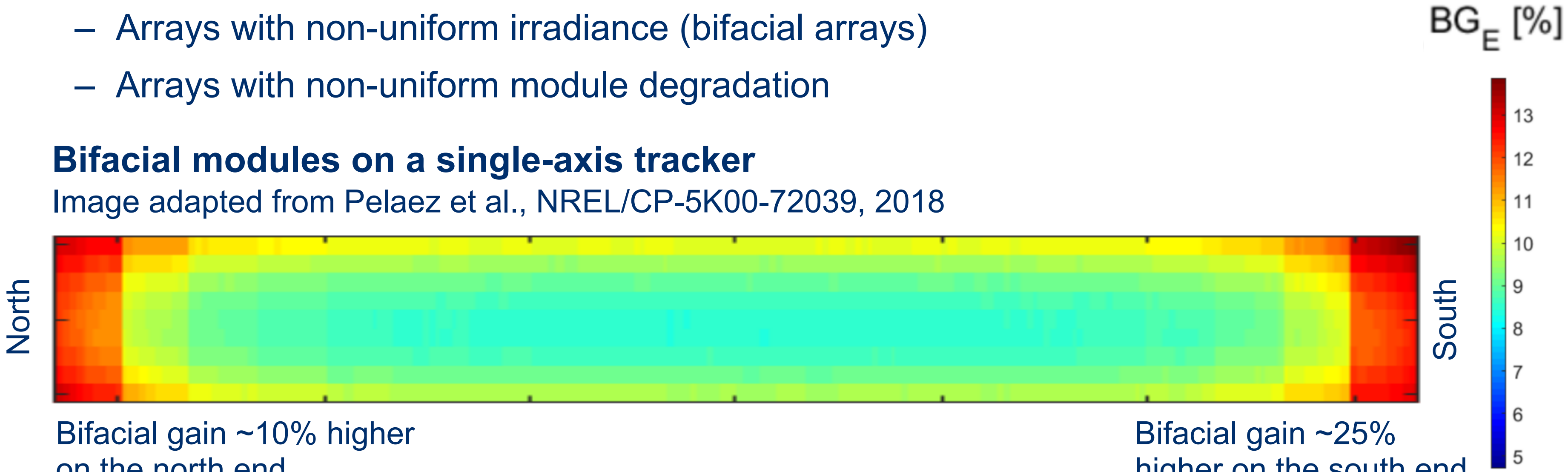
When Do You Need Module-Level Monitoring?

- It is helpful to have module-level monitoring when you have large module-to-module mismatch.
- Examples:
  - Arrays with non-uniform irradiance (bifacial arrays)
  - Arrays with non-uniform module degradation

Bifacial modules on a single-axis tracker

Image adapted from Pelaez et al., NREL/CP-5K00-72039, 2018



Bifacial gain ~10% higher on the north end

Bifacial gain ~25% higher on the south end

Existing Solutions for Module-Level Monitoring

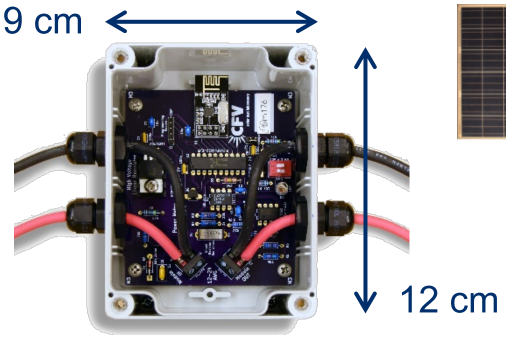
- Microinverters or DC optimizers
  - Microinverters: not compatible with 72-cell modules without clipping
  - Modules are MPP-tracked individually; Not suitable to study module-to-module mismatch effects in utility-scale scenarios
  - Sample rate and filtering are not under your control.
  - Products with lab-grade accuracy (< ± 0.5 %) are not currently available.
- Module-level I-V tracers
  - Expensive, especially if you want to monitor many modules
  - Many topics do not require full I-V curves; Imp and Vmp values are sufficient.

Developing Our Own Module Monitoring Device

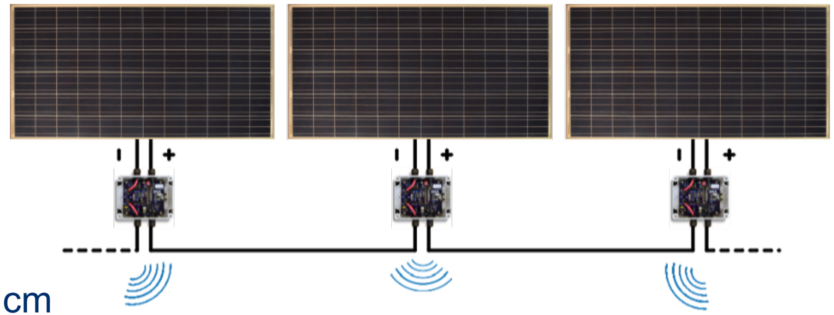
- None of the commercially available solutions met our needs. We decided to develop our own.
- Design challenges
  - Measuring the operating voltage of a module in a string requires measuring a relatively low differential voltage (~40 V) with a variable high offset from the earth ground (-1500 V to +1500 V).
  - Powering the devices while maintaining ease of installation and avoiding excessive wiring
  - Outdoor operation: Weatherproof enclosure, wide range of temperatures
  - Keeping the cost low

CFV’s Module Monitoring Device

- Powered directly from the PV module and communicates wirelessly;
  The monitoring device does not see the earth ground.
- Typical power consumption: 0.3 W;
  Max error: ± 0.1 % over 60 V / 16.6 A input range, in temperatures 0-85 °C
- Base station provides a bridge between datalogger and the monitoring devices.

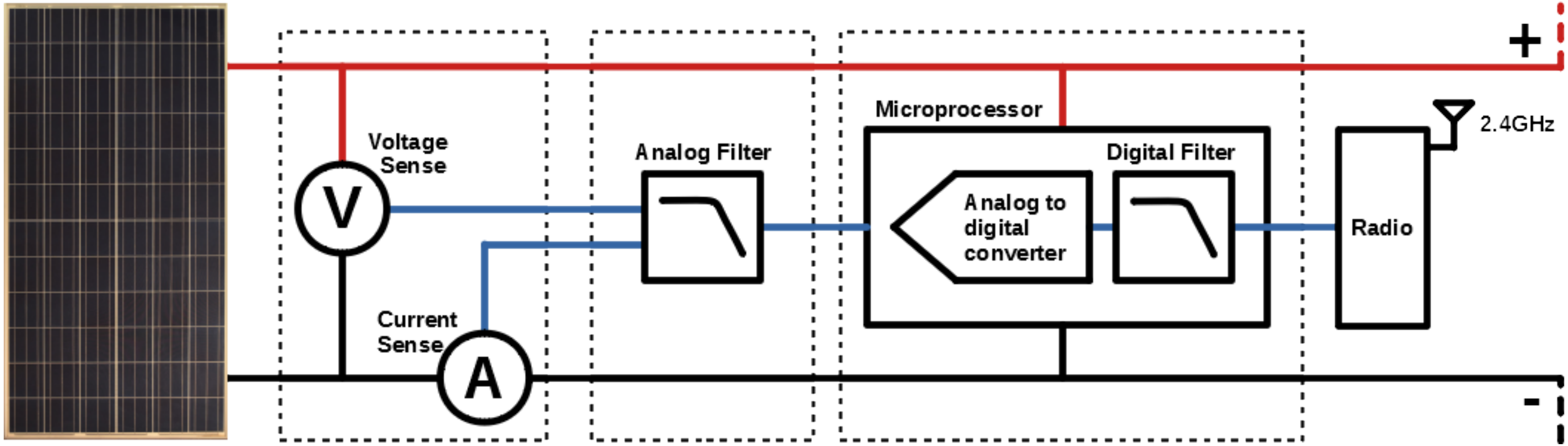


Module Monitoring Device



Base Station

Device-Level Signal Processing



Scale voltage and current

Remove line noise (MPPT, anti-islanding, etc.)

Digitize (200 Hz) and process signal to match time response of irradiance sensor

First Stage: Analog Filtering

- The DC lines contain high-frequency content due to line-frequency harmonics, perturbations from anti-islanding detection, MPPT searching action, etc.
- Based on the recommendations from a Sandia paper (figures shown below) we implemented an analog filter to remove high-frequency content.

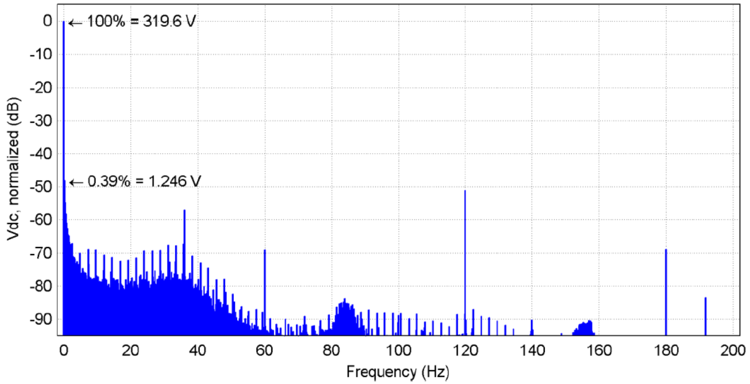


Figure 26 Average spectrum of the DC voltage signal under stable conditions

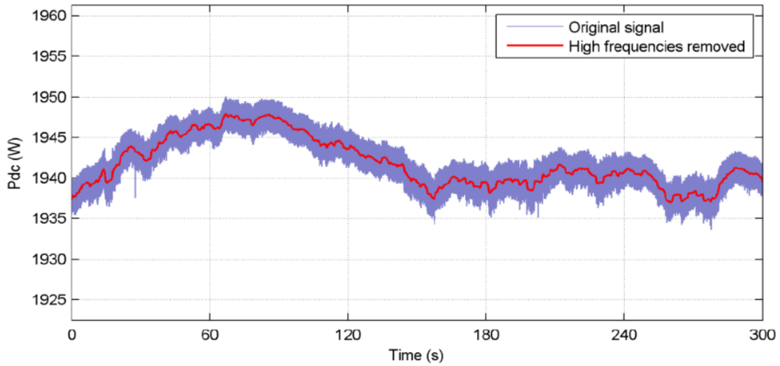


Figure 32 DC power signal with and without high-frequency content

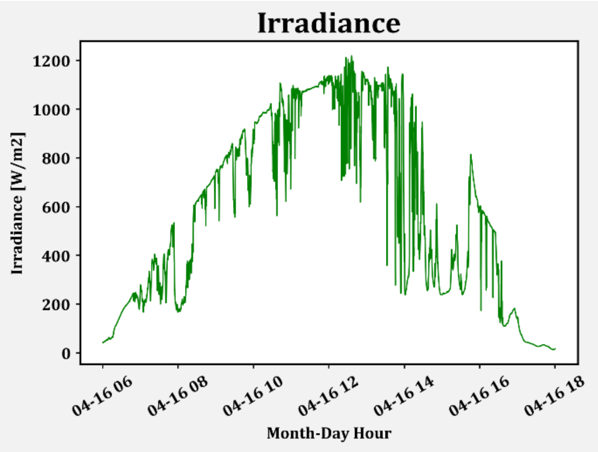
A. Driesse, J. S. Stein, D. Riley and C. Carmignani, "Sampling and Filtering in Photovoltaic System Performance Monitoring," SANDIA REPORT SAND2014-19137.

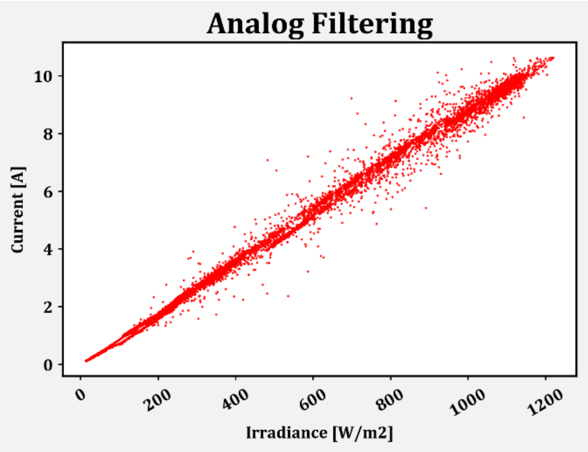
Second Stage: High-Speed Sampling and Digital Filtering

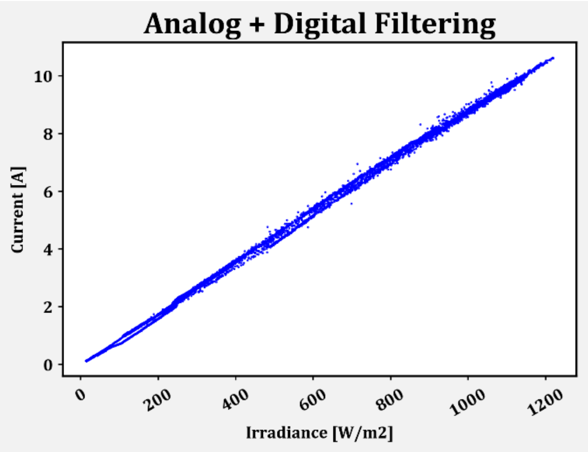
- Our device digitizes the signal at 200 Hz and processes it with a microprocessor.
- Current implementation: exponential filter. $y_k = \alpha y_{k-1} + (1-\alpha) x_k$
  - The microprocessor-computed output is polled by the datalogger at a lower frequency.
- Sampling and filtering at the device level simplifies the data collection and storage further down the pipeline.
  - You can scale up the number of devices without overcrowding the wireless network.
  - You are not overwhelmed with excessive data.
- The exponential filter was found effective at matching the time response of the device to an irradiance sensor.

Matching the Time Response to a Pyranometer

- The root cause of the difficulties in analyzing cloudy days is the difference in time response between the pyranometer (slow) and the PV modules (fast).
- Data analysis becomes more straightforward when you match the time response of the module’s output reading to the pyranometer (with the digital filter).



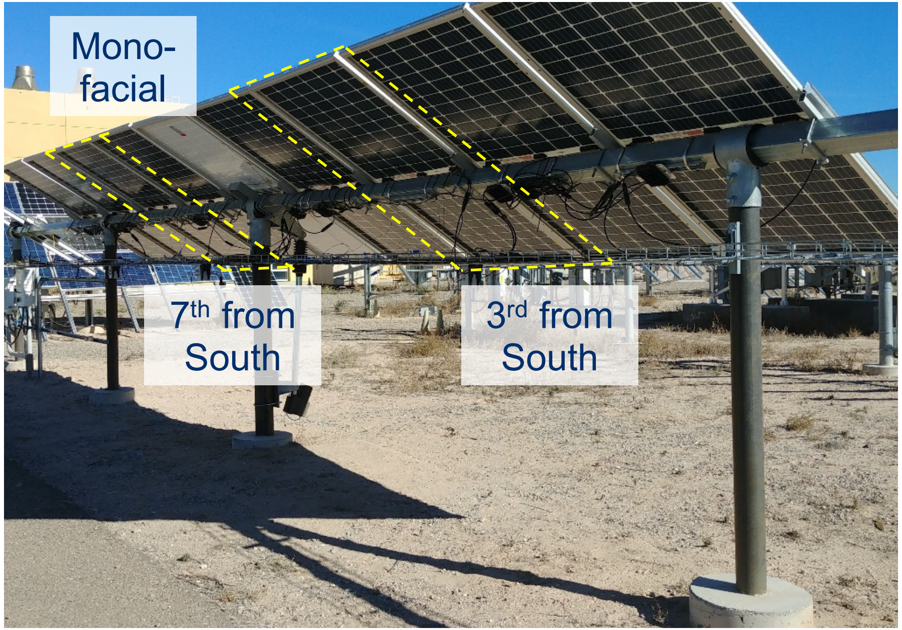




Uses in Highly Mismatched Scenarios

Bifacial Array Edge Brightening

- Bifacial array on a tracker, with a monofacial reference module in the middle
- Modules on DC optimizers + string inverter
- Power of indicated modules monitored with MMDs.



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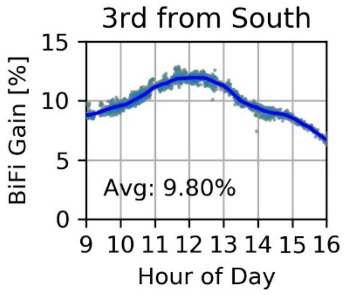
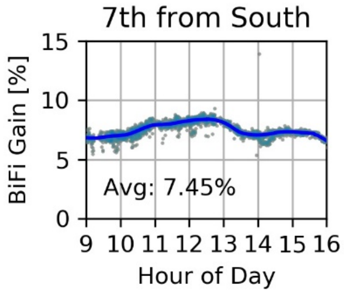


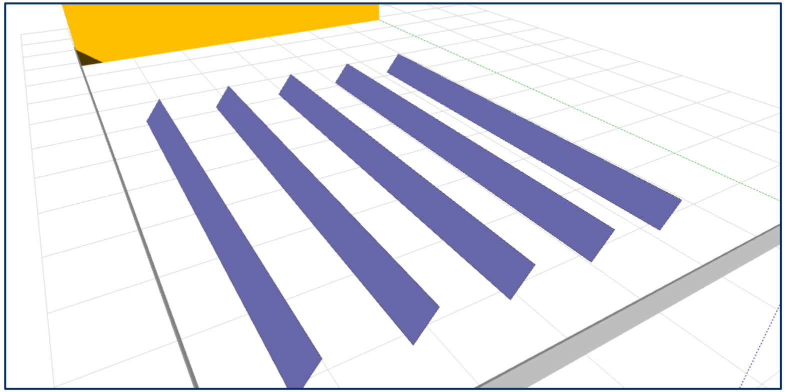


String Monitoring Device

- Works with higher voltages
  (600, 1000, and 1500 V versions available)
- Identical to module monitoring devices in terms of sampling and filtering functionality
- More accurate and higher resolution than string inverters
  - 150 mV / 5 mA resolution over 600 V / 18.5 A range for the 600 V model
  - Maximum error ± 0.13 %;
    (String inverters typically ± 3 % accurate)
- Power and communication lines galvanically isolated

CFV's Bifacial Test Yard

- Five single-axis trackers from Array Technologies Inc. (30 modules per row)
  - Three center rows to be used for testing and monitoring; 3 string inverters per row
  - Long rows allow measurements that minimize edge effects from light and wind.
  - Instrumentation per IEC 61724-1 + CFV's module/string monitors
- Currently under construction; Operation to start in June 2019



Summary

- Module-level monitoring devices can provide insight into highly mismatched scenarios, such as bifacial arrays.
- CFV developed its own module monitoring devices, with features optimized for PV monitoring:
  - Analog filtering to remove high-frequency noise specific to PV inverters
  - Digital filtering to match the time response to an irradiance sensor
- CFV's bifacial test yard with 5 industrial trackers will start operation in June 2019.
  - The test yard will be equipped with instrumentation per IEC 61724
  - Modules and arrays will be monitored with the module and string monitoring devices.

CSA Group