Validation of Volterra (now Maxim) Modules at the Regional Test Centers

Cooperative Research and Development Final Report

CRADA Number: CRD-13-00531

NREL Technical Contact: Christopher Deline

NREL is a national laboratory of the U.S. Department of Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5K00-78892
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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Cooperative Research and Development Final Report

Report Date: August 28, 2020

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement:

Volterra Semiconductor Corporation (now Maxim); Sandia National Laboratories

CRADA number: CRD-13-00531

CRADA Title: Validation of Volterra Modules at the Regional Test Centers

Responsible Technical Contact at Alliance/NREL:

Chris Deline | Chris.Deline@nrel.gov

Name and Email Address of POC at Company:

Bruce King | bhking@sandia.gov

Seth Kahn | skahn@volterra.com

Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office (SETO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$450,000.00
TOTALS	$450,000.00

Subject Inventions Listing:

None

ROI #:

None

Executive Summary of CRADA Work:

Volterra (now Maxim), Sandia National Laboratories, and the National Renewable Energy Laboratory are entering into a cooperative research and development agreement (CRADA) to perform validation testing of Volterra's PV modules through the DOE Regional Test Centers (RTCs).

Summary of Tasks and Research Results:

Regular CRADA-protected technical reports were prepared and provided as deliverables to Volterra detailing the performance of the systems. One publicly acceptable report is included below which details the project efforts by NREL for these 4 tasks.

Task 1: Design

Conventional modules were designed to be deployed in identical configuration with Volterra modules for the purpose of energy yield improvement for Volterral modules compared with conventional modules. Design was attentive to shading with several spacing distance options for optimization determination, as well as durability and wear-out mechanisms unique to this module design.

Task 2: Construction

The agreed upon design was followed to construct the racks and populate them with both Volterra and companion conventional modules and appropriate inverters and other components.

Task 3: Data Acquisition and Analysis

See the report included below for details.

Task 4: Prepare Final Report

A complete description of the research conducted with the data collected for the following tasks can be referenced in the public reports listed below and the included publicly acceptable report included below. Regular CRADA-protected technical reports were prepared and provided as deliverables to Volterra detailing the performance of the systems. One publicly acceptable report is included below which details the project efforts by NREL for these four tasks.

Public reports include:

- C. Deline et al., "Evaluation of Maxim Module Integrated Electronics at the DOE Regional Test Centers", 40th IEEE Photovoltaic Specialists Conference 2014 https://www.nrel.gov/docs/fy14osti/62024.pdf
- C. Deline, "Opportunities and Challenges in the Development of Smart PV Systems", 2015 https://www.nrel.gov/docs/fy15osti/64525.pdf

Private (CRADA-protected) internal reports include:

- C. Deline, Regional Test Center: Maxim/NREL Installation May 2014 Capacity Test Report**;** 7/22/2014.

- C. Deline, Regional Test Center: Maxim/NREL Installation 2014 Q4 Test Report**;** 1/8/2015.
- C. Deline, Regional Test Center: Maxim/NREL Installation 2015 Q1 Test Report**;** 4/20/2015.
- C. Deline, Regional Test Center: Maxim/FSEC Installation June 2015 Capacity Test Report; 8/20/2015.
- C. Deline, Regional Test Center: Maxim/FSEC Installation 2015 Q4 Test Report**;** 2/5/2016.
- C. Deline, Regional Test Center: Maxim/NREL Installation 2015 Annual Test Report; 3/31/2016.
- C. Deline, 2017. Regional Test Center: Maxim/FSEC Installation 2016 Annual Test Report; 3/27/2017.
- C. Deline, Regional Test Center: Maxim/NREL Installation 2014-2016 Final Test Report; 3/21/2017. The following is a publicly acceptable copy of this report.

Regional Test Center: Maxim/NREL Installation 2014-2016 Final Test Report

Chris Deline, 3/21/17

Executive Summary

The Regional Test Centers are conducting field trials to quantify the performance of Maxim's smart modules vs conventional panels. This report details the electricity generated by Maxim's system deployed at the NREL Regional Test Center site near Denver, CO. Based on two years of system performance (November 2014 - November 2016), the following characteristics stand out:

- The unshaded front-row Maxim string V1 and conventional string R1 performed comparably, within our 1.5% level of uncertainty. It is difficult to distinguish any yield differences between these two strings due to uncertainty in initial flash characterization of the modules. The second row at GCR = 0.45 was also comparable within uncertainty.

- For interior (shaded) rows, the Maxim panels outperformed their conventional peers. At a moderate ground coverage ratio (GCR), Maxim's yield was higher by an average 6.7% at GCR= 0.54. At the tightest GCR = 0.64, Maxim's yield was higher than the conventional string by 22% over two years of production.

- The conventional inter-row shading model included in SAM shows good agreement with these experimental results, within 1% absolute (i.e. predicting 7% shade loss where 8% loss was measured). The shade model in PVSyst was also able to predict Maxim's experimental results, within 2% absolute.

- The unshaded Maxim strings perform differently than the conventional strings under low and variable irradiance conditions. Maxim modules exhibit a slight performance loss at low irradiance (< 40 W/m^2), and improved performance under fast-changing irradiance conditions. These effects roughly balance out at the Colorado site, resulting in comparable front-row performance between Maxim and Conventional strings.

1. Maxim System Background

Figure 1: Maxim deployment at the NREL Solar TAC site

Maxim installation at NREL Regional Test Center sites

Maxim has developed a family of novel Integrated Circuits that enhance energy production of photovoltaic arrays by implementing maximum power point tracking (MPPT) at the sub-module level. Multiple circuits are laminated within the PV module, each providing MPP tracking on a small group of cells.

The Regional Test Centers are conducting field trials to compare the performance of Maxim's smart modules vs conventional panels. The test installation at NREL consists of five rows of modules, in single-module portrait configuration (Figure 1). A 30-degree fixed tilt along with different row pitches results in the following exposure conditions: an unshaded front row, followed by four partially shaded rows of ground coverage ratios (GCRs): 0.45, 0.54 and 0.64.

Each row contains conventional modules (labeled strings R1 through R4) and strings of Maxim modules (labeled strings V1 through V10). Each string of 10 modules is independently peak-power tracked by connection to one of seven multi-channel string inverters. This system configuration allows side-by-side comparison of Maxim panels vs. conventional panel performance at three different ground coverage ratios.

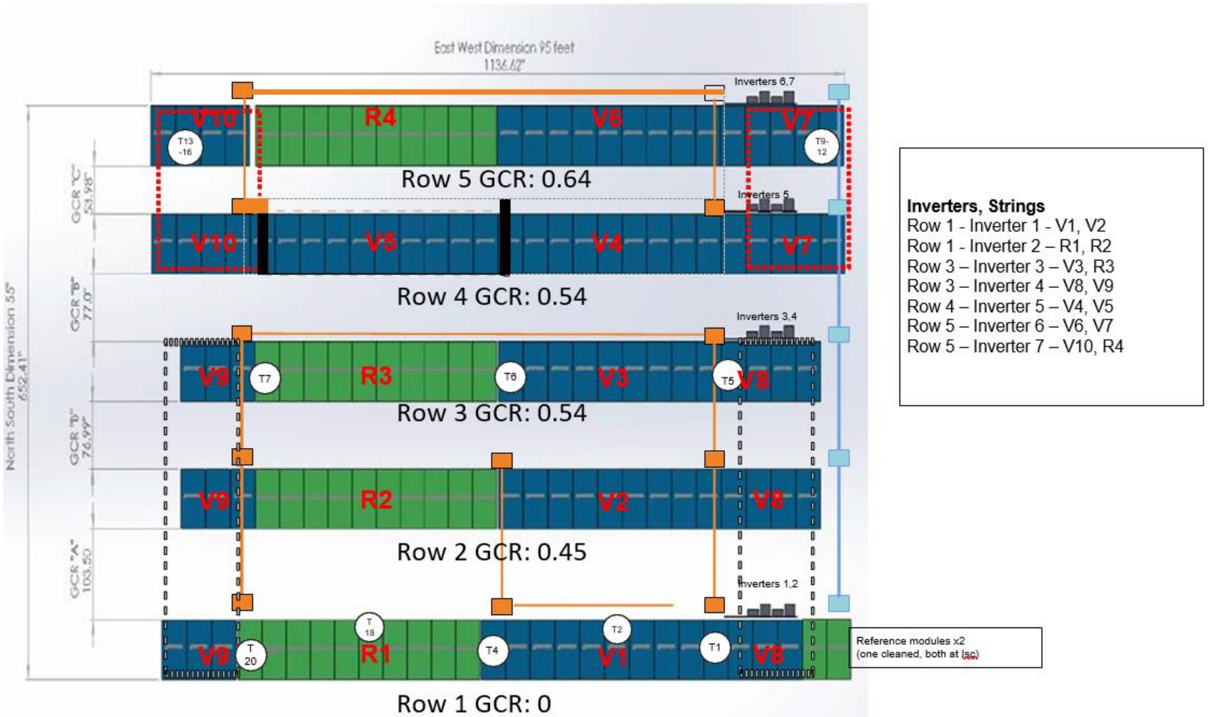

Figure 2: Maxim configuration from 6/18/14 onward. Maxim strings are noted in blue, while conventional strings are shown in green.

The overall system capacity is 40kW in ten Maxim strings and four Conventional strings. Following successful completion of the initial 2-year performance test, the system was decommissioned in December 2016. Two other Maxim RTC sites in Albuquerque, NM and Cocoa, FL are still in operation.

	Maxim	**Conventional**
Module type	Maxim VT8012 chip laminate-embedded in 300W Poly-Si	300W Poly-Si
Power rating	300 W, 72 Cell	300 W, 72 Cell
I-V parameters (typ)	Voc: 43V Isc: 9.5A Vmp: 34.5V Imp: 8.8A	Voc: 45V Isc: 8.7A Vmp: 36.5V Imp: 8.2A
Module dimension	1956mm x 1016mm	1956mm x 991mm
String size	10 modules, 3kW	10 modules, 3kW
GCR 0 string	V1	R1
GCR 0.45 string	V2	R2
GCR 0.54 string	V3, V4, V5	R3
GCR 0.64 string	V6	R4
'Dummy' strings	V7,V8,V9,V10 (8-9 modules ea)	N/A

Meteorological measurements are taken with a calibrated CMP-22 plane of array pyranometer as well as two calibrated reference modules held at Isc.

2. System Performance Methodology

System performance for each row is monitored by first excluding power data out of range (0W or below and above 5000W) which would indicate a monitoring malfunction. Data are also excluded for irradiance conditions less than 5 W/m^2. Each string's power is then summed per month, and as a cumulative total. Note that when data are rejected for one string, it is rejected for all strings, ensuring the cumulative total is consistent between strings.

Performance data are stated as a yield factor, defined as cumulative DC kWh production ΣP, divided by nameplate capacity P_0 :

$$Y_f = \sum P / P_0 \text{ (kWh / kW) or (hours)} \quad (0)$$

Here P_0 is determined for each string by a sum of the individual factory-measured module flash test measurements, which match within 1.6% of the NREL-measured flash test data.

Relative performance of the Maxim string vs. conventional string for e.g. Row 2 is accomplished by dividing the respective Yf values:

$$Y_f \, Ratio_{Row2} = Y_{f,V2} / Y_{f,R2} \quad (1)$$

A second yield comparison does not rely on nameplate capacity P_0. Instead this value is based on normalizing the performance of interior strings by the first row's performance (String V1 in the case of Maxim strings, R1 for conventional strings). This relative measurement assumes only that the modules are randomly distributed between rows. Therefore, the comparison of e.g. string V2 to R2 would be calculated by:

$$Ratio_{V2,rel} = \frac{\Sigma P_{V2}}{\Sigma P_{V1}} \Big/ \frac{\Sigma P_{R2}}{\Sigma P_{R1}} \quad (2)$$

where ΣP is the cumulative measured kWh for that string.

To be complete, we also define a reference yield Yr that represents the cumulative plane-of-array irradiance at the site:

$$Y_r = \sum G / G_0 \text{ (Whm}^{-2}\text{ /Wm}^{-2}\text{) or (hours)} \quad (1.b)$$

where G and G_0 are the measured plane-of-array irradiance, and standard 1000 W/m2 reference irradiance, respectively.

3. System Performance Nov 2014 – November 2016

Data outages

Occasionally due to inverter outages or data acquisition failure, performance data are removed from consideration. This ensures that each string is fully operational during the periods of comparison.

The following outages are noted during this period of comparison: (Additional detail provided in Appendix A)

1. Inverter 6 (String V6) malfunctioned from 11/14/14 – 12/15/14 and again 2/26/15 – 3/6/15. The inverter was power cycled and began to operate correctly.
2. String R2 data are invalid from 7/1/15 – 9/9/15 due to encroaching tumbleweed ground cover. (While this may represent a realistic performance loss condition, it causes differences in an otherwise identical side by side deployment.)
3. String R3 data are invalid from 7/22/15 – 9/9/15 due to a malfunctioning current measurement transducer.

Maxim vs Conventional

We can next plot Maxim performance data relative to the conventional panels at the same row spacing. Two methods of comparison are used. According to Equation (1), Y_f is dependent on the initial flash-test characterization of each PV module, which we have found to vary by 1.5% between the NREL and factory values. Equation (2) is independent of initial flash-test characterization of modules, but also assumes that modules are equally distributed between different strings. This assumption is correct within 0.7% for all strings. (Additional discussion of measurement uncertainty can be found in Appendix C).

Monthly yield ratios using Eq. 1 and annual cumulative total using both Eqs 1 and 2 are shown in Table 1. Figure 3 shows monthly yield ratios using Eq. 1.

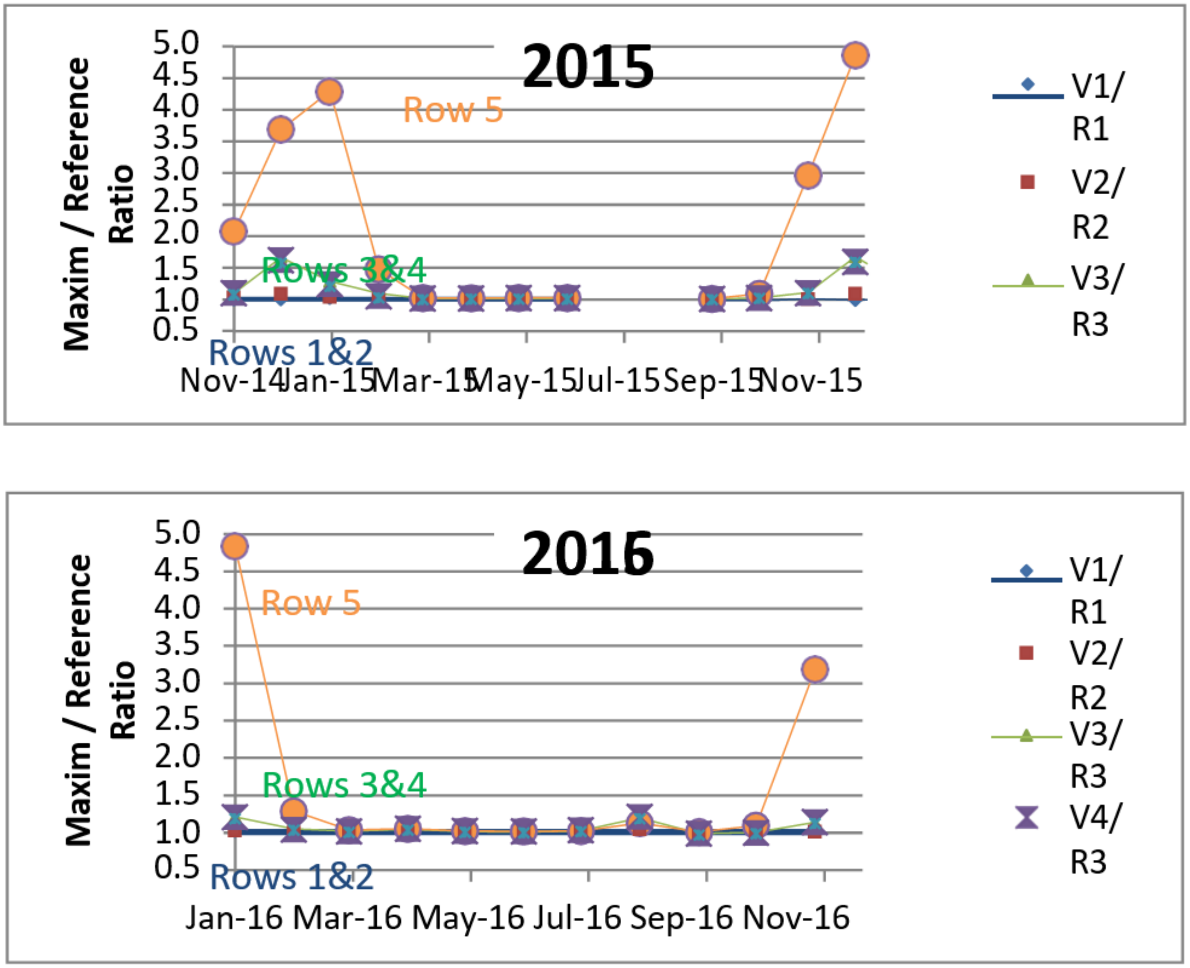

Figure 3: Ratio of monthly performance for Maxim strings V1-V6 based on Eq (1). Winter months display much greater performance benefit for Maxim's technology due to the extent of inter-row shade.

Table 1: Comparison of Maxim vs Conventional at same row spacing by month (Eq. 1).

Month of year	V1/R1	V2/R2	V3/R3	V4/R3	V5/R3	V6/R4
Nov-14	1.00	1.03	1.10	1.10	1.07	2.06
Dec-14	1.00	1.09	1.66	1.62	1.57	3.67
Jan-15	1.02	1.06	1.30	1.27	1.23	4.35
Feb-15	1.03	1.02	1.12	1.08	1.05	1.51
Mar-15	0.99	0.97	1.00	1.00	0.99	1.01
Apr-15	0.99	0.97	1.01	1.01	0.99	1.01
May-15	0.99	0.97	1.01	1.01	0.99	1.01
Jun-15	0.98	0.97	1.00	1.01	0.99	1.00
Jul-15	0.99	*	*	*	*	1.00
Aug-15	0.99	*	*	*	*	1.00
Sep-15	0.99	0.98	1.00	1.00	0.98	1.00
Oct-15	0.98	0.98	1.01	1.01	1.00	1.06
Nov-15	1.01	1.01	1.12	1.12	1.11	3.00
Dec-15	0.99	1.08	1.66	1.58	1.56	4.78
Jan-Dec 2015 Eq 1	0.99	0.99	1.07	1.06	1.05	1.17
Jan-Dec 2015 Eq 2	*	1.00	1.08	1.07	1.05	1.18
Jan-16	1.02	1.04	1.23	1.23	1.21	4.90
Feb-16	0.99	0.99	1.04	1.03	1.02	1.27
Mar-16	0.98	0.98	1.00	1.00	0.99	1.02
Apr-16	0.99	0.99	1.04	1.04	1.02	1.03
May-16	0.98	0.98	1.00	1.00	0.99	1.00
Jun-16	0.98	0.98	0.99	1.00	0.98	1.00
Jul-16	0.99	1.00	1.02	1.02	1.01	1.01
Aug-16	1.04	1.09	1.25	1.26	1.24	1.17
Sep-16	1.01	0.99	1.00	1.00	0.98	1.02
Oct-16	1.02	0.99	1.02	1.02	1.00	1.11
Nov-16	1.04	1.05	1.19	1.18	1.17	3.29
12/15-11/16 Eq 1	1.00	1.01	1.08	1.08	1.06	1.22
12/15-11/16 Eq 2	*	1.01	1.08	1.08	1.06	1.22
CUMULATIVE RESULTS						
12/14-11/16 Eq 1	1.000	1.003	1.075	1.071	1.054	1.216
12/14-11/16 Eq 2	*	1.003	1.076	1.071	1.054	1.221

Note that in Table 1, due to data acquisition outages in July and August 2015, no comparisons for strings R2 and R3 are possible. Also note that cumulative ratios calculated with Equation 2 are roughly equal to those calculated with Equation 1.

Table 1 shows that the highest monthly performance gain for Maxim modules comes in January 2016 when string V6 outperformed string R4 by 390%. On a cumulative basis, the outperformance of string V6 is reduced to a still-sizeable 22%.

Additional plots of raw Y_f values are shown in Figure 4.

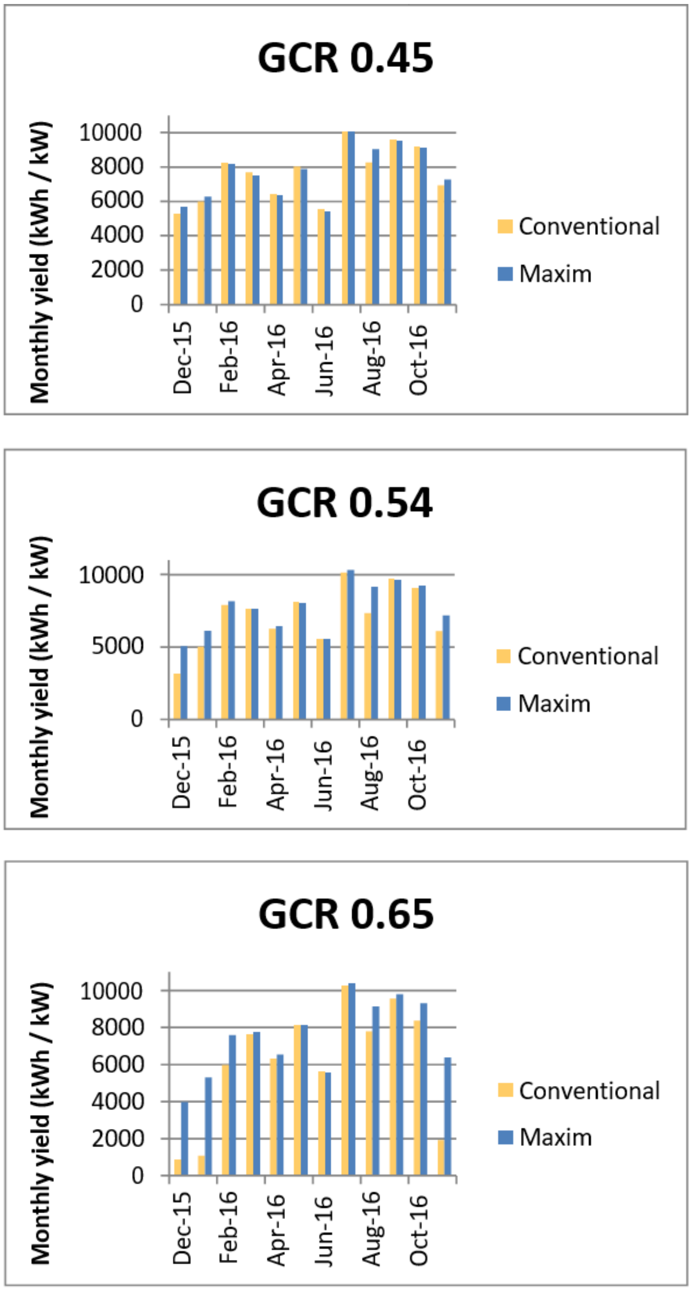

Figure 4: Monthly Y_f for three different ground coverage ratios (GCR) in 2016. Conventional string shade was extensive in the winter months, particularly at the highest GCR value.

Taken together, Table 1 and Figure 4 make it clear that performance is comparable between the Maxim and Conventional strings in the spring, summer and fall. The major performance difference is seen during the winter months November through February. During this time, performance is slightly improved for the smallest GCR value (0.45) but dramatically improved for tight row spacing (GCR 0.65). Overall annual benefit due to Maxim's technology is 0%-1% at GCR 0.45, 6%-8% at a typical GCR 0.54, and 18%-22% at a narrow GCR 0.65.

4. Comparison with performance models

Two simulated inter-row shade models were evaluated against the Maxim and Conventional field data: SAM and PVSyst. The SAM shade model has been validated previously[1], but is currently only configured to model conventional panels with regular inter-row shade.

PVSyst has previously been used to estimate field performance of both Maxim and conventional modules[2]. Inter-row shading is modeled in PVSyst by defining the 'electrical effect' of the module layout. If a single transverse string is assumed, this replicates the single-up portrait conditions of the Conventional modules. If 6 transverse strings are assumed, this attempts to replicate the 6 separate MPPT zones of the Maxim PV modules.

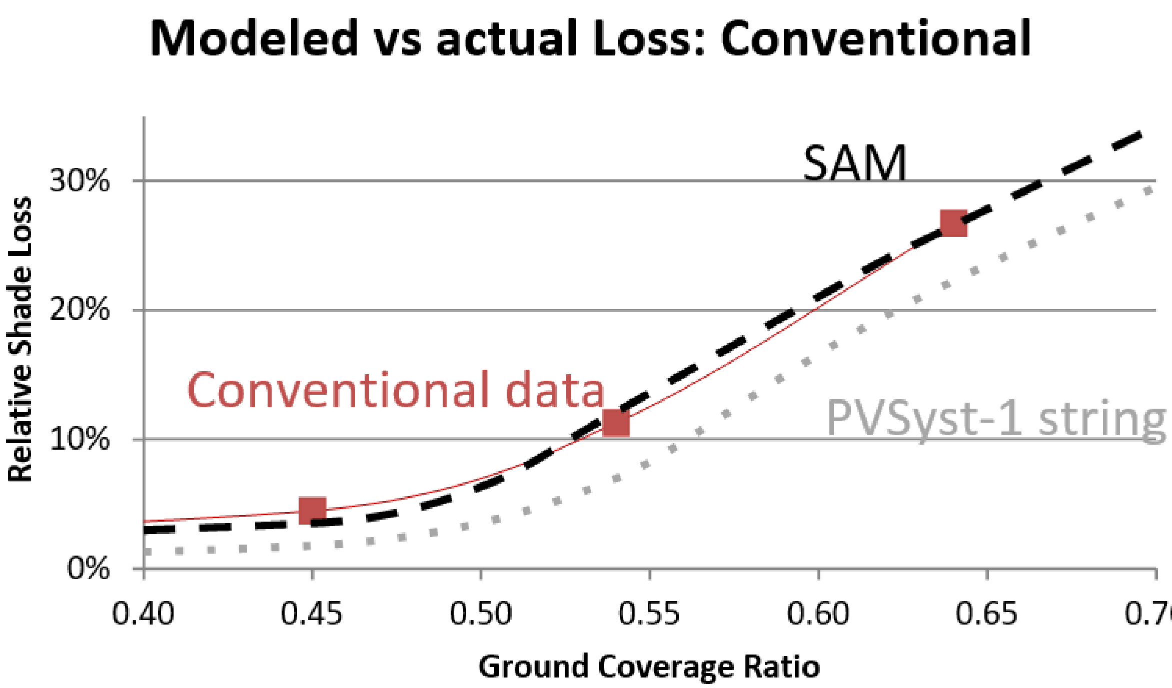

Figure 5: Annual shade loss for conventional modules in 2015. The SAM model compares quite well with the experimental data in this case. The PVSyst model assumes a single transverse string electrical model and slightly under-predicts shading losses in this case.

[1] C. Deline et al., "A simplified model of uniform shading in large photovoltaic arrays" Solar Energy 96 (2013) pp. 274–282

[2] C. Deline et al., "Evaluation of Maxim Module-Integrated Electronics at the DOE Regional Test Centers", IEEE PVSC, 2014

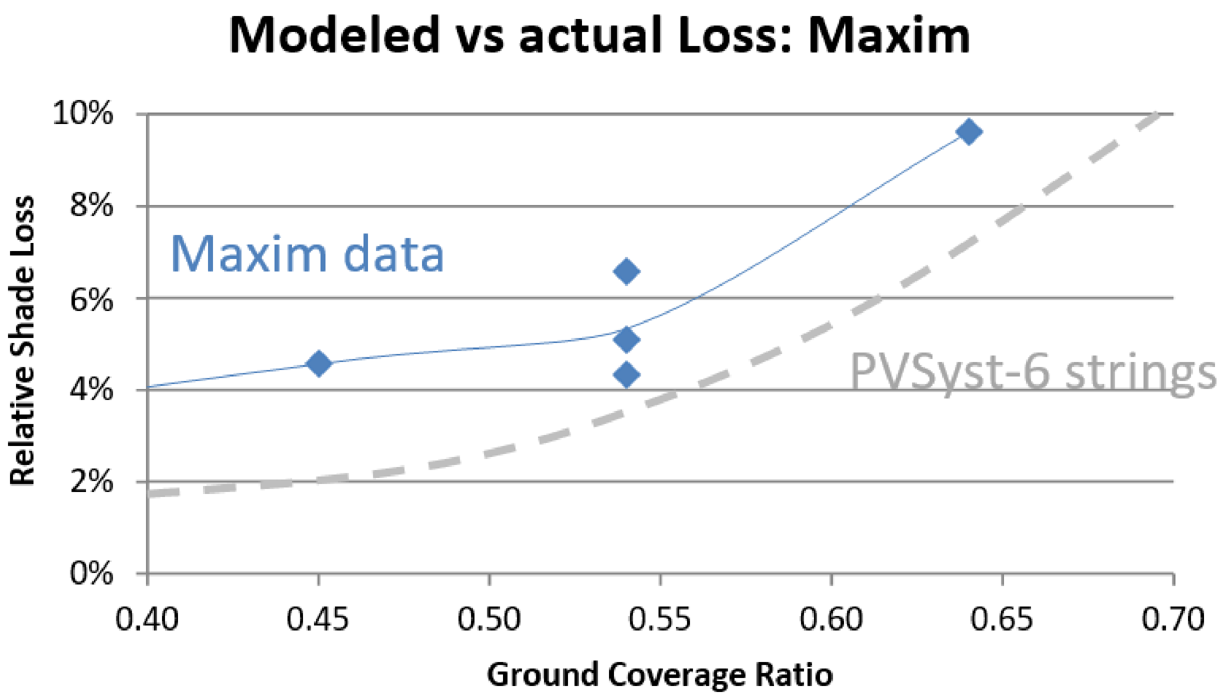

Figure 6: Annual shade loss for Maxim modules in 2015. The PVSyst model here assumes six transverse strings and has reasonable agreement. The SAM inter-row shade model cannot handle the Maxim sub-module MPPT simulations.

Figure 5 shows that the conventional modules are performing close to expectation. In particular the SAM inter-row shade model has a very close agreement with measured values, within 1%. The PVSyst model using 1-string in transverse doesn't come quite as close and under-predicts shading loss by a relatively constant 5% (absolute).

Figure 6 shows that the Maxim modules are also performing within 2% (absolute) of expected performance. This simulation is based on a PVSyst electrical simulation using 6 transverse strings.

The small apparent difference in performance may be due to multiple factors including measurement uncertainty and model inaccuracy. It's also possible that the Maxim product has small operating losses relative to ideal theory, but this is difficult to distinguish from other sources of uncertainty.

5. Additional Analysis

Low irradiance dependence

Specific analysis is conducted on Row 1 data for performance under low irradiance conditions. Figure 7 shows a plot of the ratio V1/R1 against irradiance. It is clear that below 40 W/m^2 the Maxim string begins under-performing compared to the conventional modules. The instantaneous V1/R1 ratio drops below 0.8 for irradiance below 15 W/m^2. By removing the low irradiance population below 100 W/m^2 from integrated system performance, the yield factor ratio $Y_{f,V1}/Y_{f,R1}$ increases from 1.000 to 1.002. Therefore, the modules may be losing about 0.2% performance due to the low irradiance response shown in Figure 5. However, the total energy at these low irradiances is small. Data below 100 W/m^2 contribute an integrated irradiance Y_r of only 2% of the total, indicating that these low irradiance conditions don't contribute much to the cumulative energy over the year.

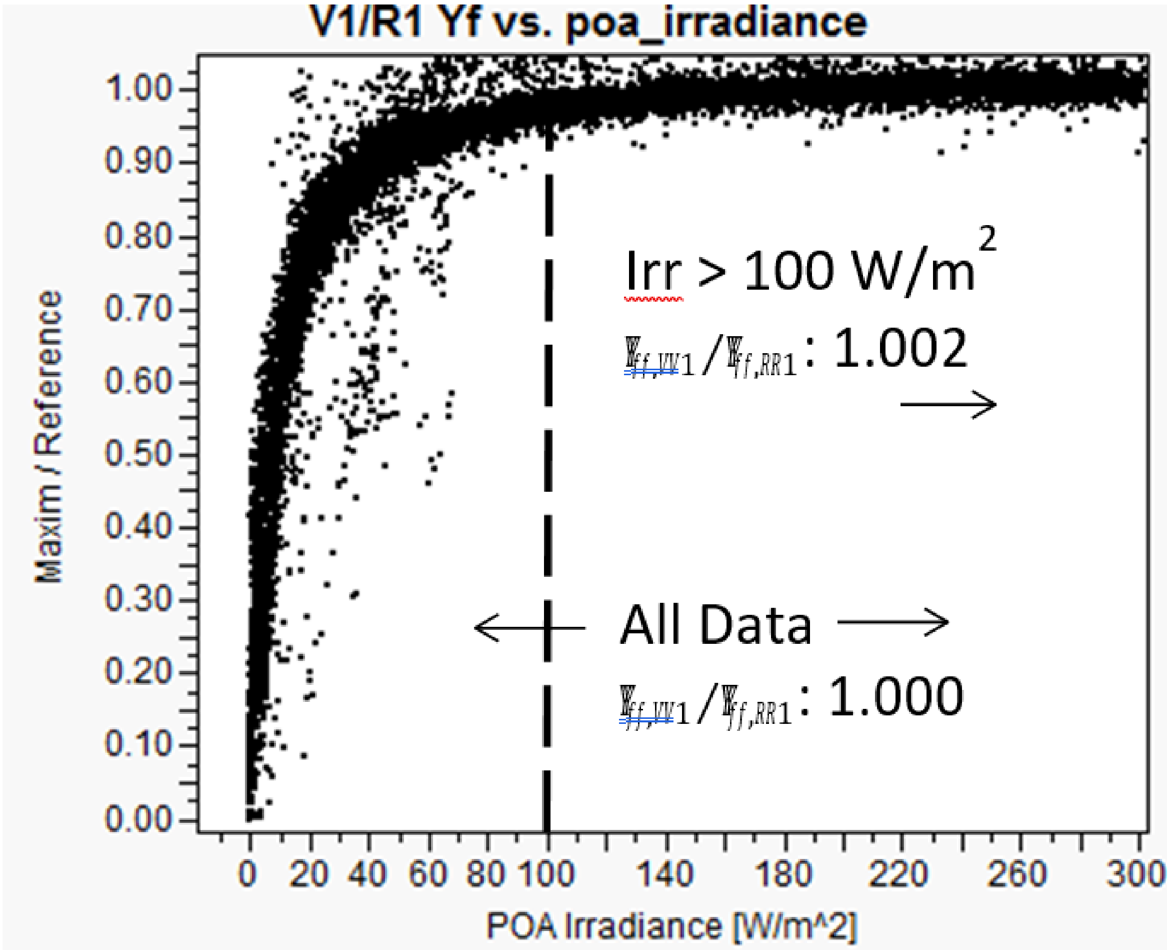

Figure 7: $Y_{f,V1}/Y_{f,R1}$ yield factor ratio plotted against irradiance. The low irradiance tail is responsible for Maxim performance loss around 0.2% annually.

Irradiance stability dependence

Another investigation of the unshaded first row involves Maxim's performance with respect to irradiance stability. It was previously discovered that quickly changing conditions could lead to differences in system performance. An irradiance stability condition was selected of $\Delta G < 10$ W/m^2 / minute to reject quickly moving clouds from the analysis. The resulting filter had a large impact on the dataset, reducing cumulative irradiance *Yr* by about half. The total integrated performance $Y_{f,V1}/Y_{f,R1}$ was reduced from 1.000 to 0.998. Conversely, if only *unstable* conditions are counted, $Y_{f,V1}/Y_{f,R1}$ increases from 1.000 to 1.002. This suggests that under variable irradiance conditions, which comprise about half of the operating conditions in this dataset, the Maxim string provides an additional performance benefit relative to the conventional string. The cause of this improved performance is probably due to faster peak-power tracking during dynamic irradiance changes. A comparison of performance data with the different irradiance stability conditions is shown in Figure 6.

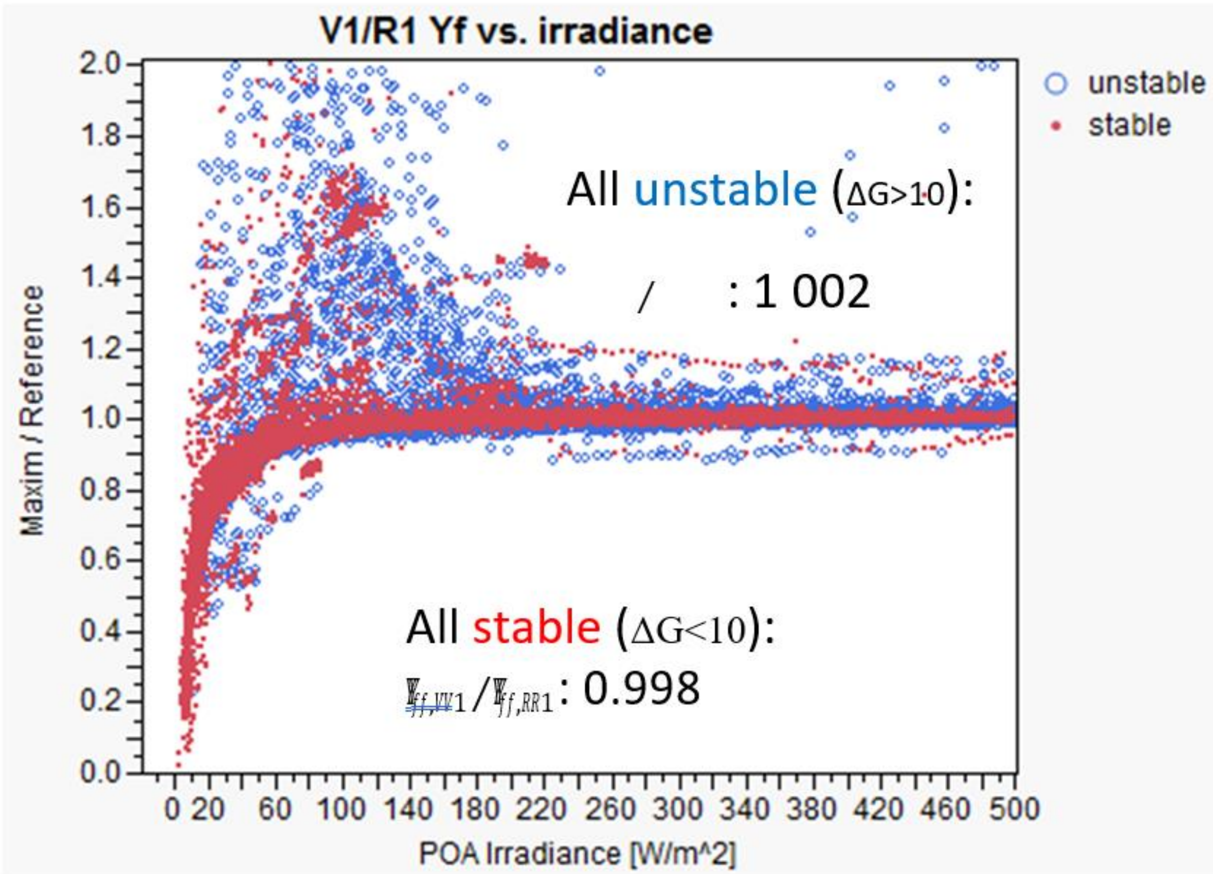

Figure 8: $Y_{f,V1}/Y_{f,R1}$ yield factor ratio plotted against irradiance. Unstable conditions have a change in irradiance ΔG > 10 W/m^2 per minute, and have a cumulative performance 0.4% greater than during stable conditions.

6. Conclusion

In conclusion, the system has performed well. Two years of performance data provide the opportunity to compare annual performance at three different inter-row spacing values.

Annual performance benefit of the Maxim system at the tightest row spacing (GCR = 0.64) was 22% cumulative, with a maximum monthly wintertime benefit of 390% during January 2016. (These details come from Table 1). The next tightest row spacing (GCR = 0.54) which is a more realistic spacing results in 7%-8% annual performance benefit. The widest row spacing (GCR = 0.45) has slight benefits, within 1.5% measurement uncertainty. Single-row (unshaded) deployment of the Maxim system was equivalent to the Conventional system within uncertainty.

The amount of shading loss in the system was modeled using PVSyst and NREL's SAM. The field performance was within 1%-2% of expectation from both the SAM model for conventional panels and the PVSyst model for Maxim's panels.

Appendix A: Maintenance Database Extract

sysname	starttime	endtime	category	event	notes
Volterra	2014-11-14 10:00:00	2014-11-14 11:30:00	MAINTENANCE	DAS Update/ Change	ICP-Das unit 7 was swapped out since it was sending spurious error messages. New logger code updated to reflect the ability to check for modbus errors (cdeline)
Volterra	2014-11-14 10:45:00	2014-12-05 14:30:00	DOCUMENTATION	System-Level	Inverter 6 (strings V6 and V7) was disabled with an 'arc fault' error. Inverter re-started on 12/5/14 by jrodrigu. Power on V6 is zero during this time. (cdeline)
Volterra	2015-01-08 11:10:00	2015-01-08 11:10:00	DOCUMENTATION	Report	2014 Q4 performance report, submitted to Maxim 1/8/15 (cdeline)
Volterra	2015-03-05 09:30:00	2015-03-05 09:45:00	MAINTENANCE	System was Offline	Inverter 6 had an error causing it to stay offline. Do not know what the error was, touched ESC button and inverter came online. (jrodrigu)
Volterra	2015-03-18 10:15:00	2015-03-18 10:20:00	MAINTENANCE	System Repairs	Heliovolt and Volterra/MaximMice chewed through the wiring to the field WIFI link. Jose and the IT folks patched up this morning. There will be some more work required to make this more rodent proof.-Bill (bsekulic)
Volterra	2015-04-30 08:00:00	2015-04-30 08:50:00	MAINTENANCE	DAS Update/ Change	Logger OS upgraded to v28.Jose reloaded logger files. Verified data and system is running. -Bill (bsekulic)
Volterra	2015-04-30 08:00:00	2015-04-30 09:10:00	MAINTENANCE	DAS Update/ Change	updated logger with new operating system v28 and reloaded associated files and program. (jrodrigu)
Volterra	2015-05-15 08:15:00	2015-05-15 10:40:00	MAINTENANCE	Other	Isolators with filters installed on current channesl for V7 and V10.filter on V7 - two 10 ohm resistors with parallel 1.0uF capacitorfilter on V10 - differential choke at ~1mH with parallel 1.5uF capacitor- Installed on signal line before Advantech Adam 3014 isolator.Code versioned to reflect new change and valid channels. (bsekulic)

Volterra	2015-05-15 09:00:00	2015-05-15 09:55:00	MAINTENANCE	System Repairs	Tightened terminal blocks from fuse to inverter input. There were numerous loose connections and a few browning terminals. Two terminal blocks replaced on V7 and V5. (bsekulic)
Volterra	2015-05-15 10:50:00	2015-05-15 12:00:00	DOCUMENTATION	System-Level	Updated logger code to allow the two additional ICP-Das channels to be measured. Note that isolators are still not installed on V7 and V10 voltage channels, just the current channels. (cdeline)
Volterra	2015-05-18 12:10:00	2015-05-18 12:10:00	DOCUMENTATION	System-Level	Updated the database import for V7 - V10 to upload the ICP-Das current and voltage data instead of the DC data measured by the inverter. (cdeline)
Volterra	2015-07-22 09:30:00	2015-07-23 13:30:00	MAINTENANCE	System Calibration	DC parameters calibrated. Filters installed on DC Voltage and Current lines. Bill and Jose performed calibrations.R3 - String 6 - was a fluctuating from valid current reading to full scale. V8, V9 need to have isolators installed. (bsekulic)
Volterra	2015-09-09 14:00:00	2015-09-09 14:30:00	MAINTENANCE	Other	Weeds found growing in front of R2, pulled and did some weeding over next two days. (bsekulic)
Volterra	2016-08-16 8:00:00	2016-08-19 13:40:00	MAINTENANCE	System Repairs	Weeds growing high among the PV modules. Jose knocked them down in rows 1 and 2 on 8/16 and rows 3, 4 5 on 8/19 by 13:40 MST. (cdeline)
Volterra	2016-12-01 12:00:00	2016-12-01 12:15:00	MAINTENANCE	Configuration Change	System taken off-line. Inverters switched off, modules removed (JA modules donated to Grid Alternatives, Maxim modules destroyed and landfilled). (cdeline)

Appendix B: Performance Data (Filtered Yield Factor)

Month	YfV1	YfV2	YfV3	YfV4	YfV5	YfV6	YfR1	YfR2	YfR3	YfR4	Yr
Nov-14	2390	2322	2239	2244	2190	2237	2397	2251	2043	1087	2770
Dec-14	4312	4185	3773	3679	3573	3035	4312	3836	2269	827	4854
Jan-15	5253	4993	4794	4651	4526	3898	5163	4727	3675	896	5803
Feb-15	5483	5273	5299	5095	4987	4786	5344	5170	4731	3175	6349
Mar-15	8375	7989	8176	8166	8040	8115	8476	8241	8139	8060	9394
Apr-15	7123	6818	6949	6962	6838	6845	7191	7026	6902	6811	8053
May-15	7573	7225	7388	7419	7262	7199	7676	7475	7334	7153	8456
Jun-15	9851	9476	9672	9699	9505	9538	10008	9779	9637	9519	11720
Jul-15*	7788					7428	7901			7416	9333
Aug-15*	10030					9762	10167			9808	12054
Sep-15	7122	6817	6925	6927	6841	6967	7207	6958	6955	6997	8489
Oct-15	8494	8111	8201	8212	8122	8177	8640	8288	8144	7689	9675
Nov-15	6447	6180	6114	6085	6056	5464	6360	6089	5439	1823	7216
Dec-15	6138	5694	5239	4981	4949	3966	6218	5284	3163	829	6665
Jan-16	6742	6273	6181	6140	6059	5288	6632	6004	5009	1080	7246
Feb-16	8656	8166	8242	8149	8094	7591	8752	8247	7909	5973	9526
Mar-16	7912	7510	7659	7628	7562	7722	8041	7696	7627	7600	8804
Apr-16	6715	6353	6484	6496	6398	6542	6792	6417	6256	6322	7553
May-16	8301	7877	8070	8101	7959	8119	8449	8031	8076	8118	9556
Jun-16	5664	5417	5553	5577	5485	5569	5753	5525	5583	5596	6780
Jul-16	10562	10078	10331	10377	10217	10356	10653	10081	10144	10238	12955
Aug-16	9490	9036	9194	9258	9072	9124	9123	8276	7342	7791	11545
Sep-16	9967	9525	9736	9707	9529	9781	9831	9591	9701	9569	11933
Oct-16	9596	9130	9300	9258	9108	9289	9454	9184	9109	8379	11162
Nov-16	7772	7273	7234	7213	7111	6366	7484	6939	6102	1933	8822

*Data outage of R2 and R3 during July – August 2015 results in lack of performance data for these strings and related Maxim strings V2, V3, V4 and V5.

Appendix C: Measurement uncertainty estimation

Equation 1 IV curve uncertainty:

The inherent uncertainty in the nameplate rating of each module will directly affect the uncertainty when comparing performance of one string against another. Factory IV data indicate that the V1 Maxim modules have a nameplate performance 2.7% above the R1 conventional modules. At NREL, the difference in nameplate performance was only measured to be 1.1%. Therefore, a discrepancy of 1.6% exists in the nameplate rating of the modules simply from uncertainty in the flash simulator measurements.

Equation 2 random distribution uncertainty:

Equation 2 assumes that modules are distributed randomly between the various strings. This is approximately valid for this experiment. Based on factory flash data, the highest power rated string (V6: 3085 W) is only 0.4% above the lowest strings (V2,V3,V5: 3074 W). For the NREL Maxim installation, Equation 2 assessment can be expected to be more accurate than Equation 1 assessment.

Calibration of data monitoring equipment

The plot in Figure 1 is dominated by the large winter-time performance advantage of the Maxim technology at close row spacing. It is interesting to note the performance difference during the unshaded summer months as well. Figure C1 shows a zoomed-in performance plot specifically looking at March – October unshaded performance in 2015.

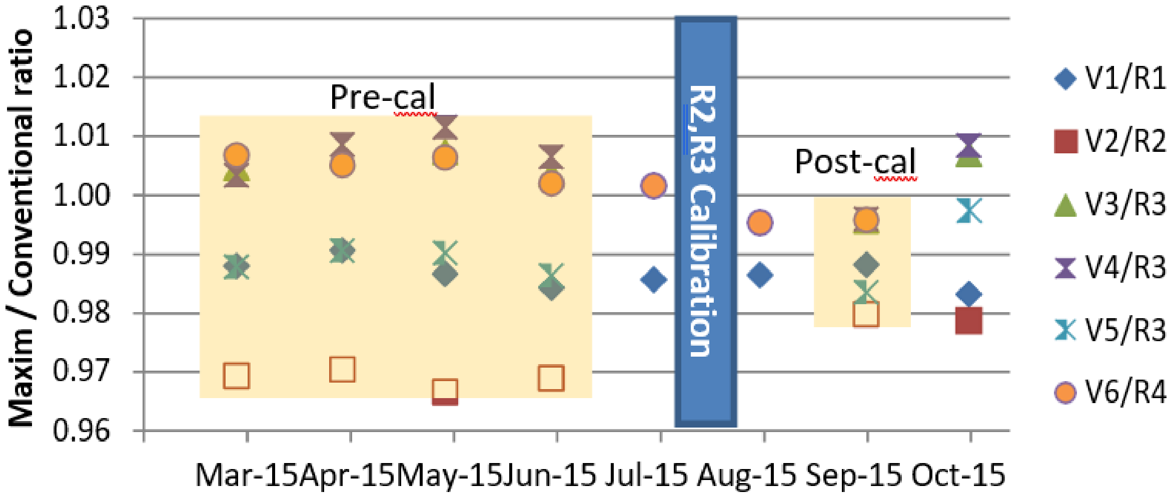

Figure C1: *Yf* ratio for Maxim strings V1-V6 based on Eq (1) focused on unshaded summer performance. Note that following the July 22 re-calibration of R2 and R3, unshaded *Yf* accuracy seems to improve (closer to 1.0). By October, inter-row shading conditions return to the experiment.

From this tight plot, it is clear that small changes in data acquisition calibration can dominate the system's performance, particularly for the very small differences in performance for rows 1 and 2. In particular, during unshaded months there is no reason why V2 and V5 should have any lower Yf ratio than V1. It is likely that the +/- 2% performance spread seen from March 2015 through June 2015 is due to inaccuracy in current sensing.

On 7/22/15, because of this widespread in performance and apparent under-performance of string V2, current sensors were re-calibrated and defective current transducers on strings R2 and R3 were replaced. The result was an improvement in measurement uncertainty, and a particularimprovement in the V2/R2 ratio. Judging from Figure C1, the post-cal spread in measurement (+/- 1%) is now tighter than the pre-cal measurement spread of +/- 2%.

It is possible that the performance reported in this report for the first half of 2015 was based on lower accuracy R2 and R3 measurements. Measurements in 2016 did show an improved performance for the Maxim systems at these two ground coverage ratios.

The total uncertainty of this analysis depends on the time of year and the comparison method used. Assuming the 0.4% uncertainty of Eq. 2, and a data acquisition uncertainty of 1.5% on average (2% pre-calibration, 1% post-calibration), total uncertainty of annual yield ratio comparisons using Equation 2 (e.g. $Y_{f,V2}/Y_{f,R2}$) is roughly 1.5%.