PV Reference Cells for Outdoor Use: Stability Over Four Years of Deployment

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1 PV Performance Labs
2 National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

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Technical Report
NREL/TP-5D00-91994
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Suggested Citation
Driesse, Anton, Afshin Andreas, Aron Habte, Shawn Jaker, Manajit Sengupta, and Tao Song. 2025. *PV Reference Cells for Outdoor Use: Stability Over Four Years of Deployment*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-91994. https://www.nrel.gov/docs/fy25osti/91994.pdf.

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This work was authored in part by the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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List of Acronyms

ESTI	European Solar Test Installation
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
NREL	National Renewable Energy Laboratory
PV	photovoltaic
S40	fixed-tilt mount, 40° south
Si	silicon
SRRL	Solar Radiation Research Laboratory (at NREL)
TR1	single-axis tracker
TR2	dual-axis tracker
WPVS	World Photovoltaic Scale

Executive Summary

Photovoltaic (PV) reference cells are frequently used to evaluate the performance of PV power plants. They provide a measure of irradiance that strongly correlates with the electrical output of PV modules, which makes them very useful for detecting short-term anomalies or long-term degradation.

This study evaluates the stability of 22 commercial PV reference cells over four years at NREL's Solar Radiation Research Laboratory (SRRL). The study involved three mounting configurations: fixed tilt, single-axis tracking, and dual-axis tracking. While all products met the ISO 9060 Class A pyranometer stability requirement (±1.05%/a), three models (NES SOZ-03, IMT Si2, EETS RC01) exhibited exceptional stability within ±0.04%/a. To ensure reliable PV system performance monitoring, a stricter stability target for radiometers of ±0.1%/a is recommended.

Table of Contents

List of Figures

List of Tables

1 Introduction

Photovoltaic (PV) reference cells are frequently used to evaluate the performance of PV power plants. They provide a measure of irradiance that strongly correlates with the electrical output of PV modules, which makes them very useful for detecting short-term anomalies or long-term degradation in PV power plant output. With the advent of more complete standardization of PV reference cells (Driesse, Habte, and Sengupta 2023), the characteristics and quality of reference cells will receive more scrutiny. One very important characteristic is long-term stability.

In this report, we present observations about the stability of 22 commercial reference cells that have been in continuous operation for a period of four years at the Solar Radiation Research Laboratory (SRRL) site at the National Renewable Energy Laboratory (NREL).

Figure 1. Reference cells installed for field observations at the SRRL. *Photos by NREL*

One set is tilted at 40° south (left), and one set is on a dual-axis tracker (right). The third set is on a single-axis tracker (not shown, but it is similar to the dual-axis tracker).

The 22 reference cells at the SRRL represent 10 different models from 6 manufacturers. They are divided into three sets or groups: One set is mounted at a fixed 40° tilt facing south (S40), one set is mounted on a single-axis tracker (TR1), and the third set is mounted on a dual-axis tracker (TR2). Details are given in Table 1, and Figure 1 shows the physical arrangements.

When PV cells are used as irradiance sensors, their short-circuit current is measured. All products we tested have a built-in shunt resistor, and the voltage across that resistor, which is proportional to the short-circuit current, is the sensor's output signal. During calibration, the ratio between the output voltage and the incident irradiance is determined, which is called either the *sensitivity* or *responsivity*, and it has the units $\frac{V}{W \cdot m^{-2}}$. The term *calibration factor* is closely related and refers to the inverse of the sensitivity or responsivity. In this report, we use the term *responsivity*, and the results are mainly presented as relative changes from an initial responsivity.

Table 1. Products Under Evaluation at SRRL

Company	Model	Cell Type	Short ID	Fixed Tilt (S40)	Single Axis (TR1)	Dual Axis (TR2)
Atonometrics	810226-02	Mono	RC18	Yes	Yes	Yes
Atonometrics	810226-03	Mono (filtered)	RC18-F	Yes		Yes
EETS	RC01	Mono	RC01	Yes	Yes	Yes
Fraunhofer ISE	511311102	Mono	WPVS	Yes		Yes
IKS Photovoltaik	ISET	Mono	ISET	Yes	Yes	Yes
IKS Photovoltaik	ISET-poly	Poly	ISET-P	Yes		
IKS Photovoltaik	ISET-amorphous	Amorphous	ISET-A	Yes		
IMT	Si-mV-85-PT1000	Mono	Si2	Yes	Yes	Yes
NES	SOZ-03	Mono	SOZ-03	Yes	Yes	Yes
NES	SOZ-03-P	Poly	SOZ-03-P	Yes		

2 Evaluation Strategy

The NREL Cell Lab is capable of very accurate secondary calibrations with an uncertainty approximately of ±0.8%, k=2 (±0.9%, k=2 in 2019); however, changes in reference cell responsivity per year are ideally much smaller than the uncertainty of these calibrations. For this reason, the project plan called for several cells of known and trusted stability to be deployed together with the collection of newly acquired commercial reference cells. This would allow small changes in responsivity to be detected by comparing the continuously collected time-series data from all the products with the stable references. The NREL Cell Lab calibrations of selected units would be used to confirm or disprove potentially larger anomalies and confirm the stability of the references.

Two Fraunhofer World Photovoltaic Scale (WPVS) reference cells were purchased to fill the role of the trusted stable sensors. Unfortunately, calibration checks at the NREL Cell Lab after approximately one year of deployment indicated a drop in responsivity of approximately 1%, and further reductions were observed in subsequent years. This means that the WPVS cells cannot be used to assess the stability of the other products as planned.

Fortunately, the time-series analysis shows that three other products (NES SOZ-03, IMT Si2, EETS RC01) remain very closely aligned with each other in all three test groups (S40, TR1, TR2). This could mean that all their responsivities increased or decreased at the same rate, or that none of them changed very much. Because the products were made by different manufacturers using different materials, it is much more likely that they were all quite stable. Indeed, recalibrations in the NREL Cell Lab after three and/or four years do not show significant responsivity changes. (See Section 4: Comparison of Laboratory Calibrations.) Therefore, we conclude that this subset of three products is suitably stable in both relative and absolute terms and can take the place of the WPVS cells as trusted stable references. To compose a single reference signal, we use the mean value of these three products. Similar reasoning is used regarding the stability of the WPVS reference cell set maintained at the European Solar Test Installation (ESTI) (Müllejans, Zaaiman, and Dunlop 2015).

The next section explains the time-series comparison in more detail and discusses the differences between products.

3 Time-Series Analysis of Field Measurements

In a previous report (Driesse, Gotseff, and Sengupta 2022), we carried out a relative field calibration using a small number of measured points occurring at conditions that satisfy International Electrotechnical Commission (IEC) 60904-2 Ed.3 and/or ASTM E1362-15. Applying these strict data point filtering requirements to the full four-year time series of measurements produced a rather sparse and irregular set of points for comparison; therefore, another approach was sought to incorporate more data points into the analysis.

The purpose of the strict filtering is, of course, to avoid the influence of secondary characteristics, such as spectral and directional response—and ideally also temperature response, for which the correction is imperfect. Differences in these characteristics between two products produce systematic diurnal and seasonal cycles, driven both directly and indirectly by the sun position. This pattern is superimposed on any gradual change in responsivity that needs to be identified.

The approach proposed here is to model the daily average responsivity *r* of each product as a function of time that incorporates seasonal cycles with periods of 12 and 6 months:

$$r(t) = R_0 + dR * t + a_1 \sin(\omega) + b_1 \cos(\omega) + a_2 \sin(2\omega) + b_2 \cos(2\omega)\,, \omega = 2\pi t$$

where *t* is the elapsed time in years. The six model parameters are: R_0, the initial responsivity; dR, the linear rate of change of responsivity; and a_1, b_1, a_2, b_2, the parameters defining the seasonal pattern. These six parameters are easily determined through robust linear regression which, minimizes the impact of outliers. Incorporating the periodic functions in the model leads to much smaller residuals and a tighter confidence interval for the only parameter that really matters here: dR. For display purposes, responsivity values are scaled so that $R_0 = 1.0\ (100\%)$ for all sensors.

Figure 2, Figure 3, and Figure 4 show how responsivities of the three most stable products evolve over the four-year period of observation on the fixed-tilt mount. Despite some differences in seasonality, the long-term trends agree to within 0.04%/a (per year). Figure 5 shows the WPVS cell at fixed tilt, which appears to be trending steadily downward at −0.26%/a.

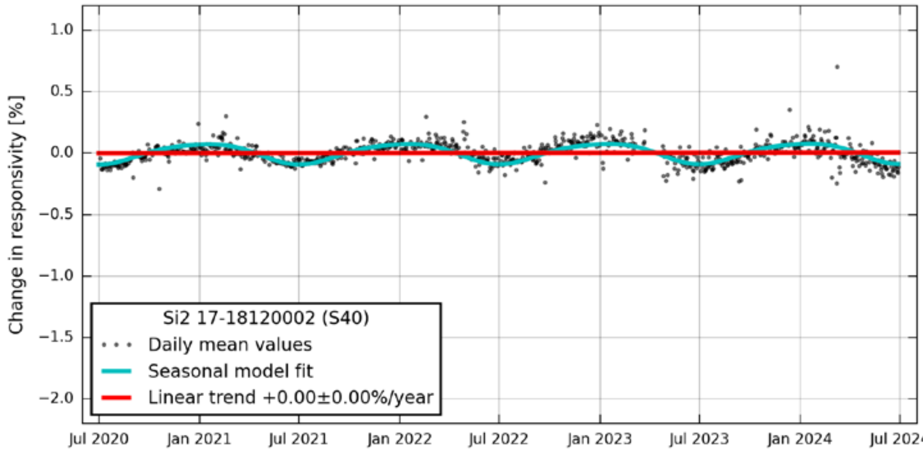

Figure 2. Seasonal model fit and linear trend for one IMT Si2

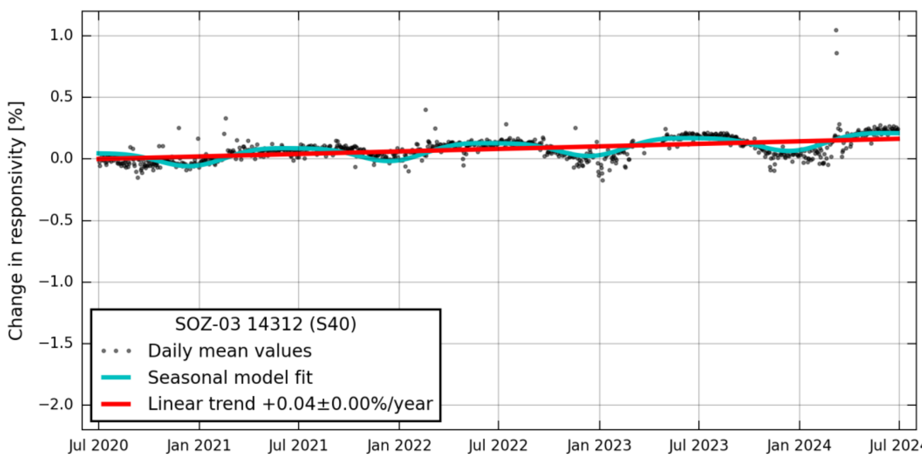

Figure 3. Seasonal model fit and linear trend for one NES SOZ-03

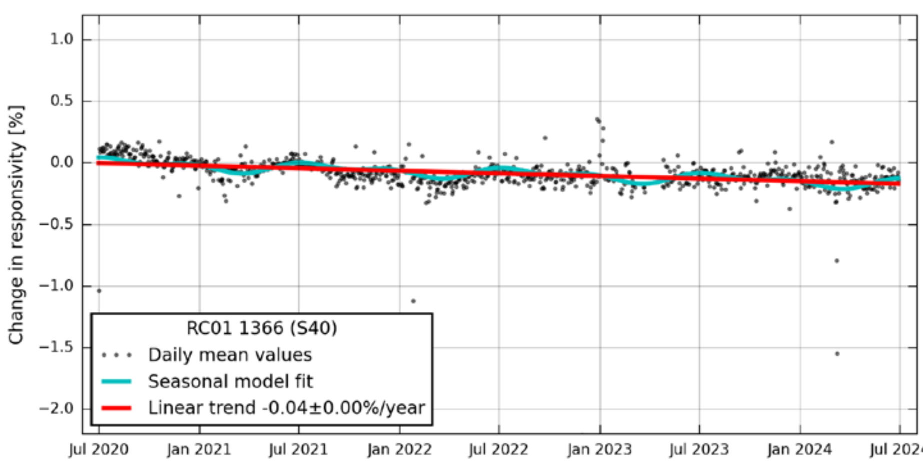

Figure 4. Seasonal model fit and linear trend for one EETS RC01

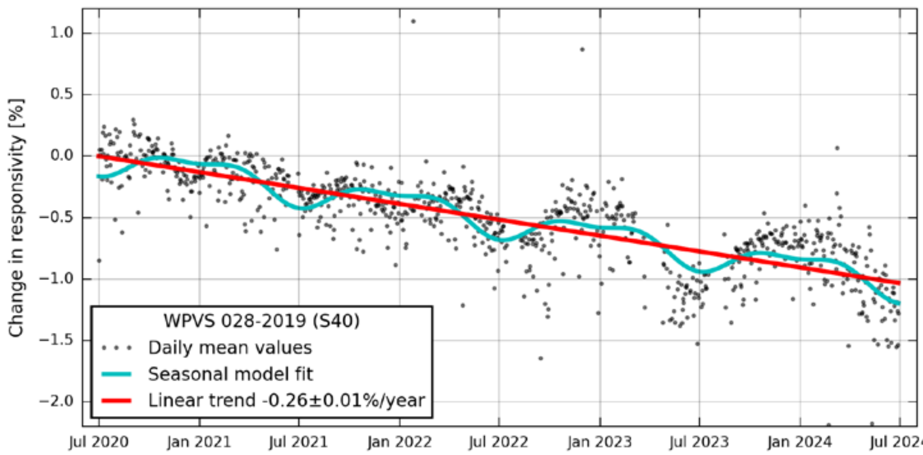

Figure 5. Seasonal model fit and linear trend for one WPVS

The one-minute data that are used to calculate daily means are also filtered in order to exclude periods of higher uncertainty at shallow sun angles or low irradiance, and when measurements are inconsistent with each other. For this purpose the following filtering criteria are applied:

- Air mass between 1 and 3 (solar zenith angle <70.7°)
- Total irradiance >800 W/m² and <1100 W/m²
- Irradiance difference between reference sensor and test sensor <5%.

After these filters, daily mean values are calculated for the ratio of test sensor to reference sensor. Weekend values are discarded because sensors were only cleaned on regular working days.

Linear rates of change for all sensors are listed in Table 2, and charts of all the model fits are included in Appendix A. Statistical 95% confidence intervals for the rate-of-change model parameter are ±0.01% or better for the monocrystalline and polycrystalline products, and ±0.04−0.05% for the amorphous silicon and filtered products.

Table 2. Observed Rates of Change in Responsivity

	SRRL S40	SRRL TR1	SRRL TR2
SOZ-03	+0.04	+0.01	+0.02
Si2	0.00	-0.01	-0.02
RC01	-0.04	-0.01	0.00
ISET-P	-0.10		
ISET	-0.13	-0.10	-0.11
SOZ-03-P	-0.14		
ISET-A	-0.16		
WPVS	-0.26		-0.30
RC18-F	-0.29		-0.28
RC18	-0.41	-0.36	-0.16

Note that the RC-18 product differs from the others in that it contains digital electronics to measure the analog voltage on the shunt resistor. The output is available as a digital Modbus signal and as a reconverted analog signal (either current or irradiance). The comparison between the digital and analog signals over a two-year period showed that the analog and digital outputs exhibit equal degradation rates.

We make the following observations based on these results:

- Because three products of ten agree to within ±0.04%/a, a value of ±0.10%/a could be a realistic target for high-quality PV reference cell products. This level of stability is also appropriate for evaluating whether long-term PV module performance guarantees are met. Such guarantees frequently allow for degradation rates on the order of −0.5%/a.
- All products satisfy the long-term stability requirement for Class A pyranometers of ±0.8%/a (or ±1.05%/a including the guard band of 0.25%/a). Many Class A pyranometer products specification sheets list the value ±0.5%/a, which is also achieved by all the tested devices.
- Because the ranking of products is nearly the same in each of the three test groups, stability appears to result from overall product designs and material properties; but one cannot assume that a product will be stable just because it uses a monocrystalline cell.
- The amorphous silicon specimen exhibited a degradation rate of −0.16%/a, which is better than some monocrystalline silicon products. This is somewhat surprising because amorphous silicon modules are generally less stable than their crystalline silicon counterparts. But there were large seasonal fluctuations, which might have been caused in part by metastabilities.

4 Comparison of Laboratory Calibrations

In this section, we present the responsivities determined by the NREL Cell Lab. We do so in a manner similar to the outdoor test results, by normalizing to 1.0 at the first calibration so that relative changes can be easily compared. All products were calibrated once before deployment, but only selected products were recalibrated after periods of one, two, three, and/or four years. The results are grouped by product for presentation.

Comparisons of calibrations carried out years apart must consider the uncertainty of those calibrations (Osterwald et al. 2023). The uncertainty of the initial calibrations was given as ±0.9% (k=2); therefore, the figures in this section show a gray band around the initial value of 1.0 to draw attention to it. If any responsivity deviates from the initial responsivity by more than 0.9%, it seems likely that the change is real and significant; however, the uncertainty of the second calibration should also be considered, which widens the range of values subject to doubt.

A formal comparison using *En* numbers could be carried out to determine the significance of the observed changes in responsivity, but such a comparison would be undermined by the fact that there is considerable uncertainty *about* the uncertainties. Due to the wide variety of designs and materials, the ability to control and measure cell temperature varied substantially by product, and it is unclear to what extent this influenced measurements. On the other hand, because we are making a comparison, some components of the absolute uncertainty cancel out, which should improve the ability to detect small changes. All things considered, there is no clear threshold for the detection of significant changes.

Despite the foregoing, the NREL Cell Lab measurements permit us to do what we need: to confirm the excellent stability of our nine best cells. Figure 6, Figure 7, and Figure 8 show the evolution of the responsivities for the three most stable products in our test. The furthest deviation from the initial responsivity is approximately equal to the uncertainty of the initial calibration, which is a plausible result for a stable cell.

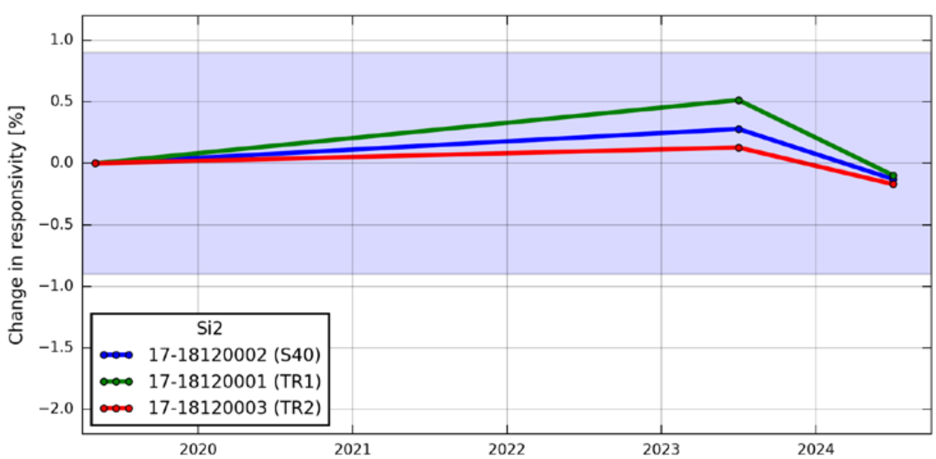

Figure 6. Evolution of responsivities measured by the NREL Cell Lab for IMT Si2

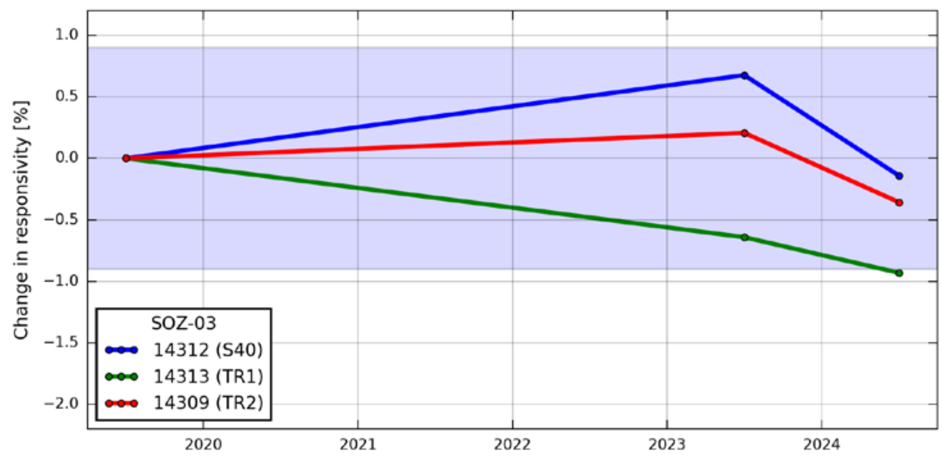

Figure 7. Evolution of responsivities measured by the NREL Cell Lab for NES SOZ-03

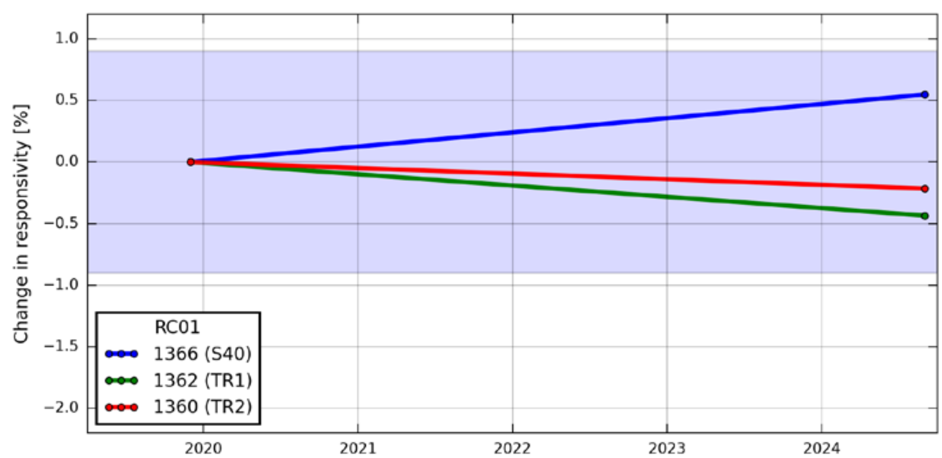

Figure 8. Evolution of responsivities measured by the NREL Cell Lab for EETS RC01

As in Section 3, we again take a closer look at the Fraunhofer WPVS cells (Figure 9), which were calibrated more often than the others. (Note that cell 029-2019 was replaced by 070-2019 in August 2019; we focus on the latter here.) The two final responsivities are ~1.6% below the initial values, which is well below the uncertainty band of the initial calibration, and the intermediate calibrations provide supporting evidence for the overall downward trend of approximately −0.4%/a on average. This rate is somewhat steeper than the rates derived from the time-series measurements (−0.26%/a and −0.30%/a), but it corroborates the conclusion that the WPVS cells are among the least stable in our collection.

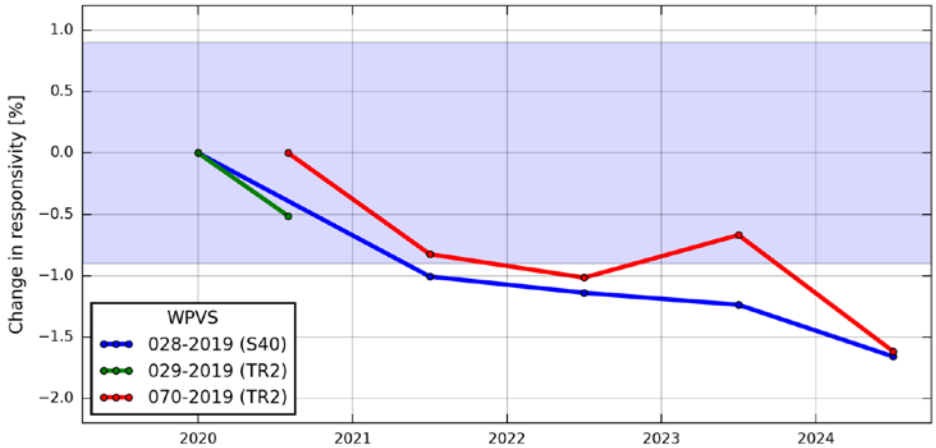

Figure 9. Evolution of responsivities measured by the NREL Cell Lab for Fraunhofer WPVS

Appendix B contains charts for all cells that were calibrated more than once in the NREL Cell Lab. None of the NREL Cell Lab measurements contradict the rates of change found using the time-series analysis.

5 Summary and Conclusions

The 22 reference cells deployed at NREL exhibited varying degrees of stability over four years of continuous observation. Differences in stability were not random; rather, they were clearly associated with different products and manufacturers. The three units of the three most stable products drifted apart by no more than ±0.04%/a over the four-year period, whereas the least stable unit degraded by more than −0.4%/a.

Despite the clearly noticeable differences between products, all units meet the requirements of the International Organization for Standardization (ISO) 9060 Class A pyranometers of ±1.05%/a (with guard band); however, PV module manufacturers provide performance guarantees with allowable degradation on the order of 0.5%/a. For early detection of such degradation, therefore, irradiance sensors must be much more stable than the ISO 9060 Class A requirement (whether they are pyranometers or reference cells). Based on this need, and based on the excellent stability seen in multiple commercial reference cell products, we recommend that a stability requirement of ±0.1%/a be adopted for future reference cell accuracy classifications.

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Appendix A. Time-Series Analysis Results

This appendix is a visual catalogue of the individual time-series analysis results for all 22 reference cells deployed at NREL. Multiple units of the same model are grouped on the same page. Numerical values of the estimated linear degradation rates are given in the figure legends. See Section 4 for more information.

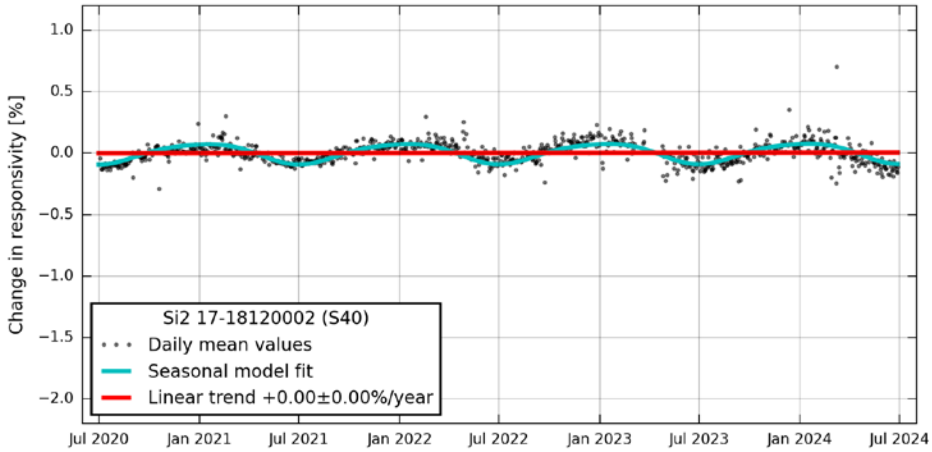

Figure 10. Seasonal model fit and linear trend for IMT Si2 on S40

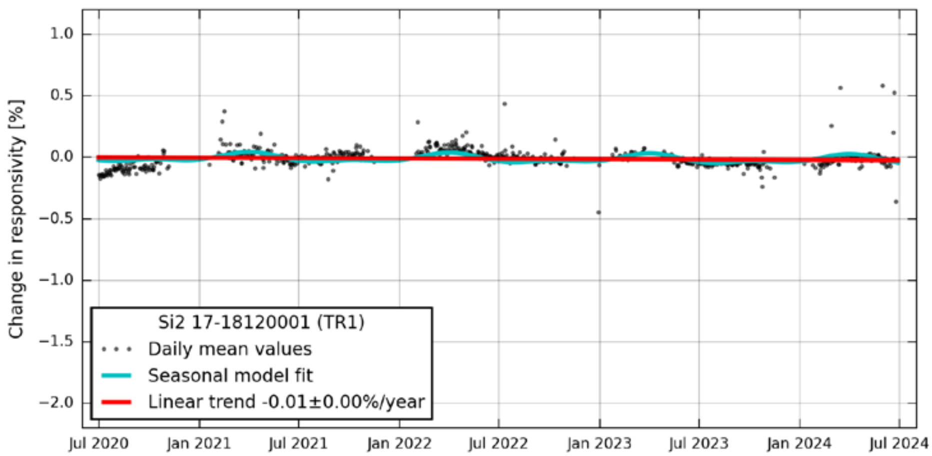

Figure 11. Seasonal model fit and linear trend for IMT Si2 on TR1

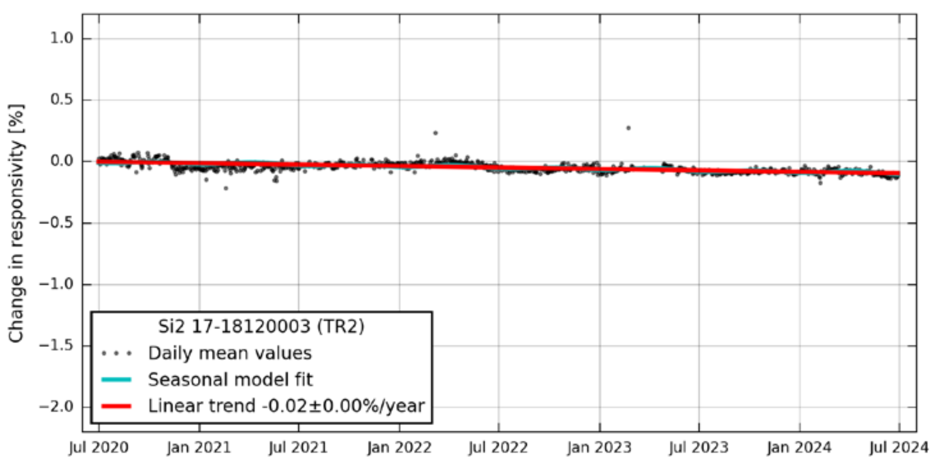

Figure 12. Seasonal model fit and linear trend for IMT Si2 on TR2

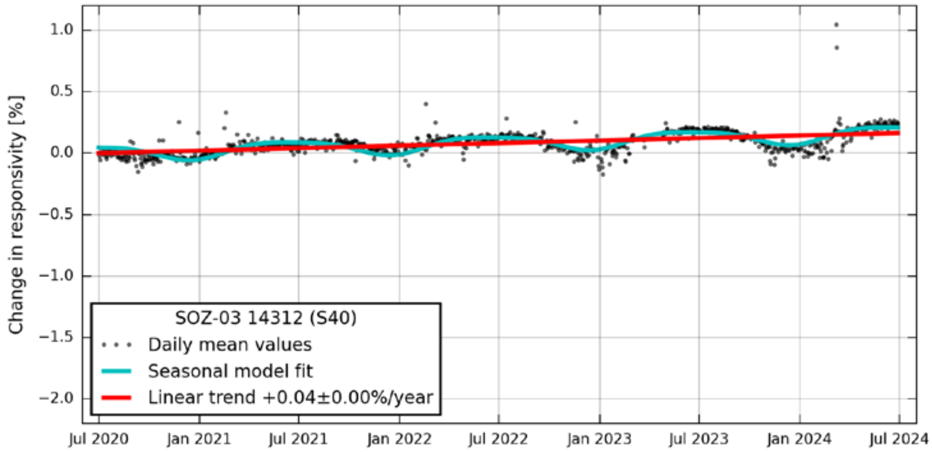

Figure 13. Seasonal model fit and linear trend for NES SOZ-03 on S40

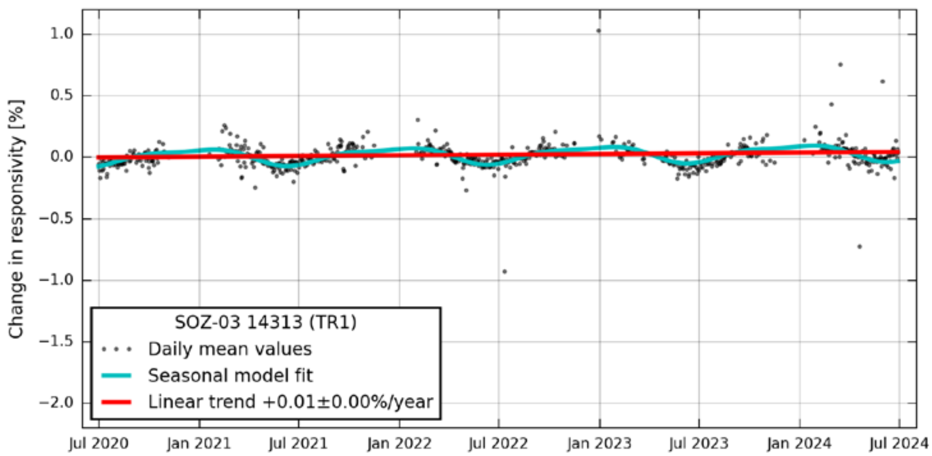

Figure 14. Seasonal model fit and linear trend for NES SOZ-03 on TR1

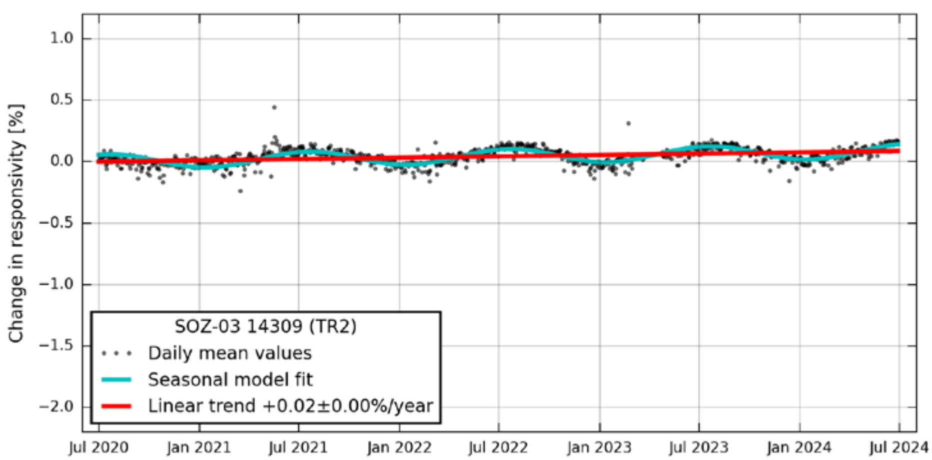

Figure 15. Seasonal model fit and linear trend for NES SOZ-03 on TR2

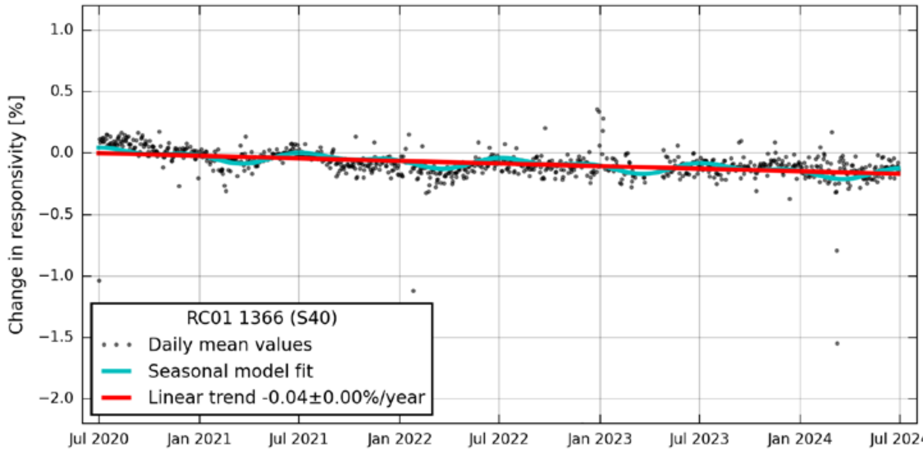

Figure 16. Seasonal model fit and linear trend for EETS RC01 on S40

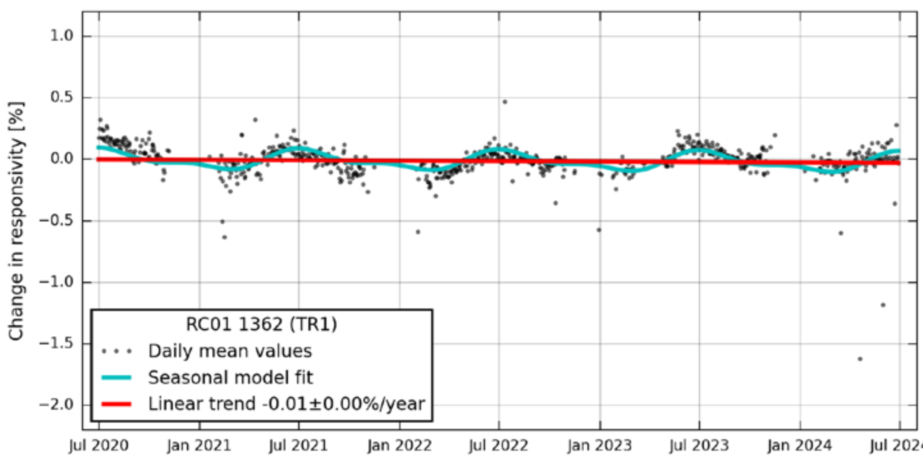

Figure 17. Seasonal model fit and linear trend for EETS RC01 on TR1

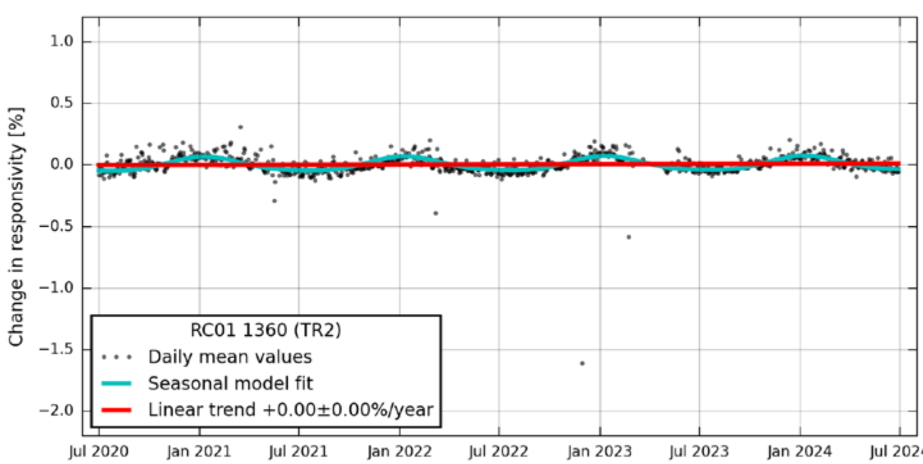

Figure 18. Seasonal model fit and linear trend for EETS RC01 on TR2

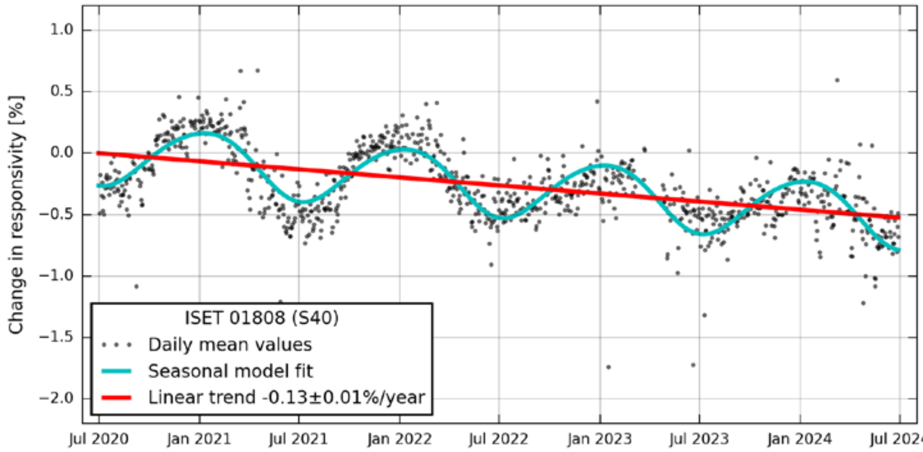

Figure 19. Seasonal model fit and linear trend for IKS ISET on S40

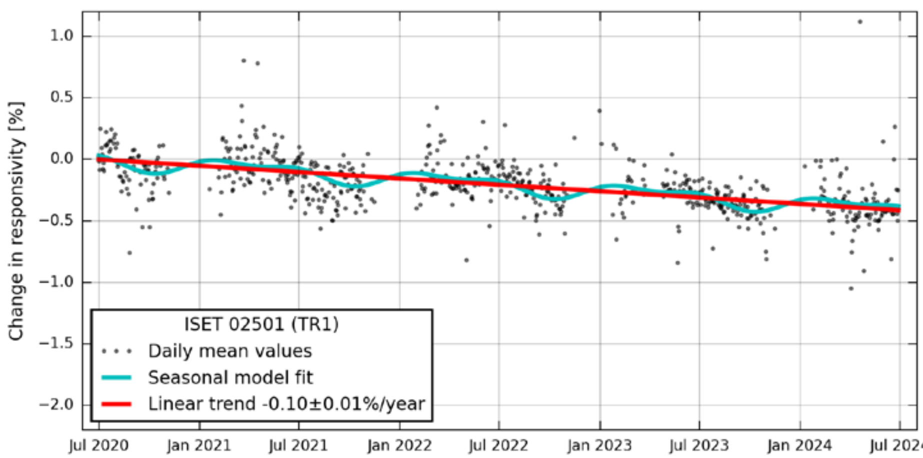

Figure 20. Seasonal model fit and linear trend for IKS ISET on TR1

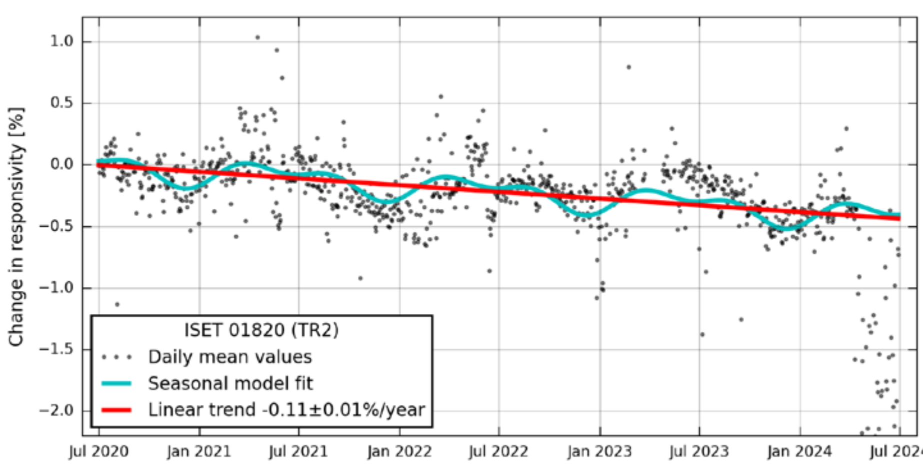

Figure 21. Seasonal model fit and linear trend for IKS ISET on TR2

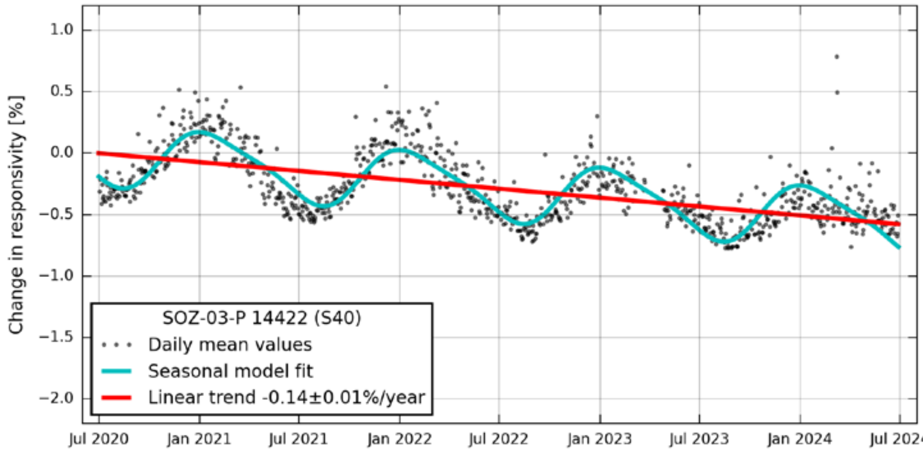

Figure 22. Seasonal model fit and linear trend for NES SOZ-03-P on S40

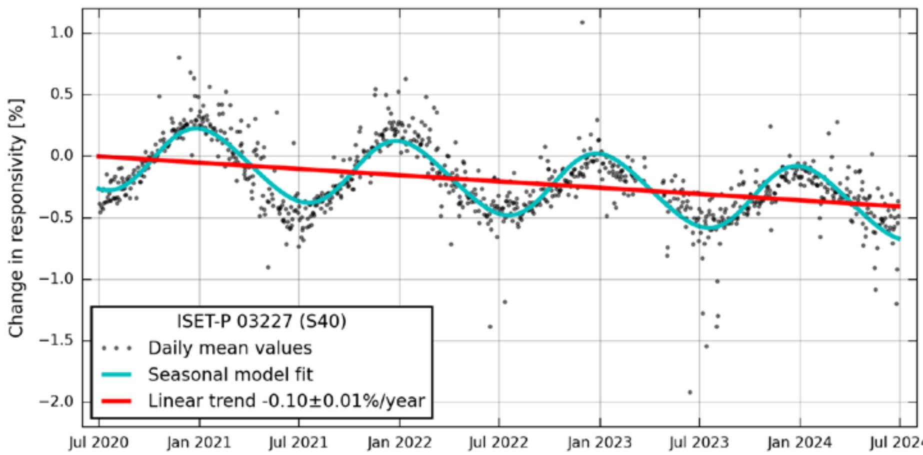

Figure 23. Seasonal model fit and linear trend for IKS ISET-P on S40

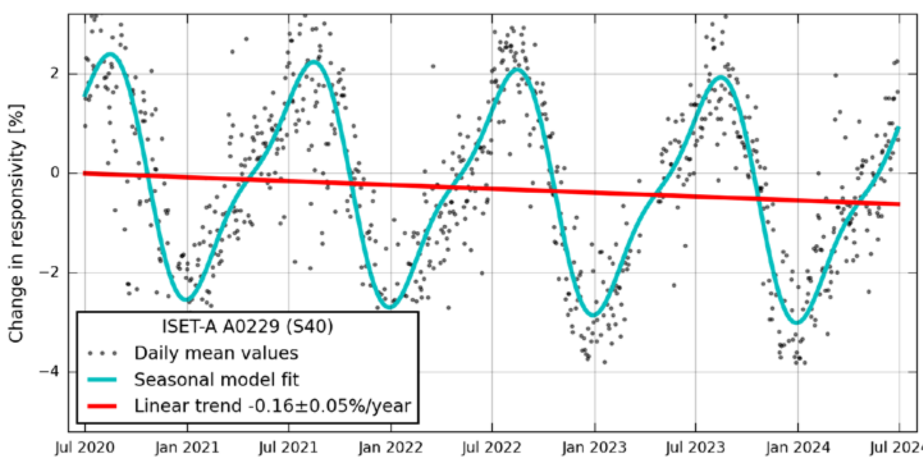

Figure 24. Seasonal model fit and linear trend for IKS ISET-A on S40

(Note the expanded vertical scale.)

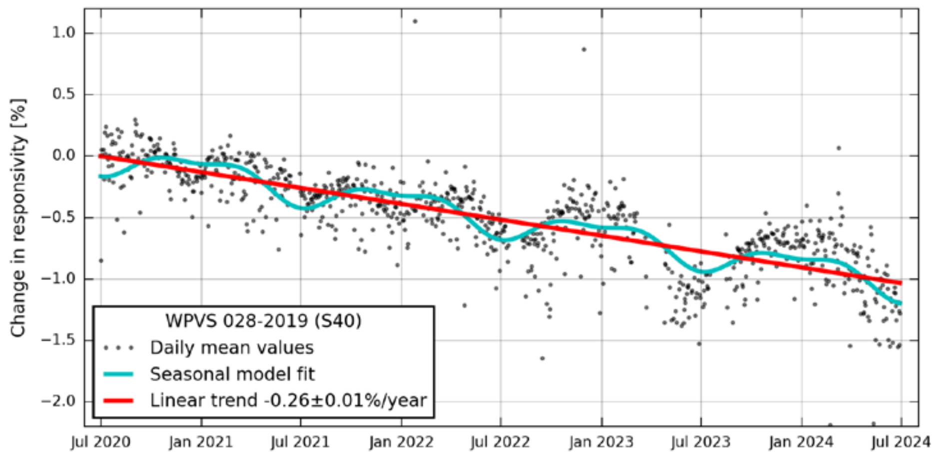

Figure 25. Seasonal model fit and linear trend for Fraunhofer WPVS on S40

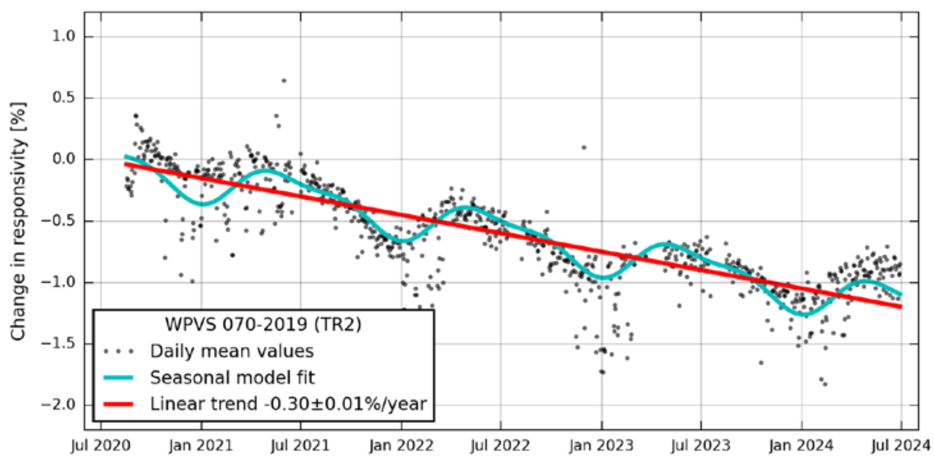

Figure 26. Seasonal model fit and linear trend for Fraunhofer WPVS on TR2

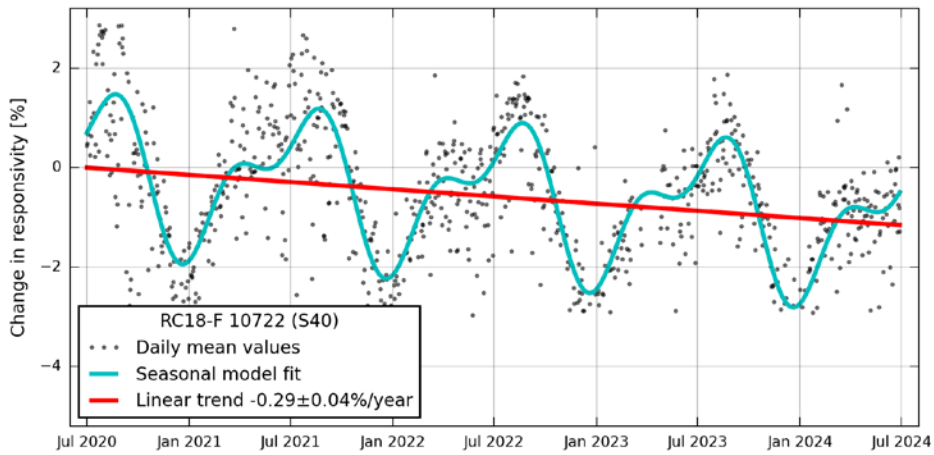

Figure 27. Seasonal model fit and linear trend for Atonometrics RC18-F on S40

(Note the expanded vertical scale.)

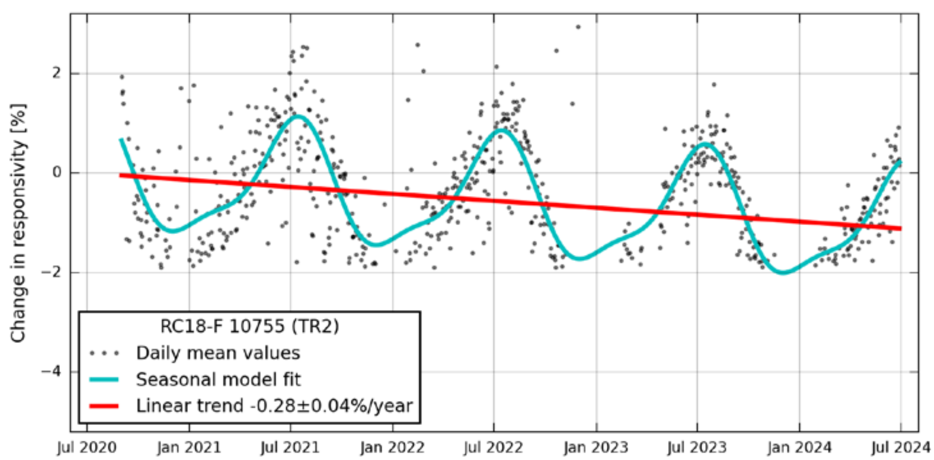

Figure 28. Seasonal model fit and linear trend for Atonometrics RC-18-F on TR2

(Note the expanded vertical scale.)

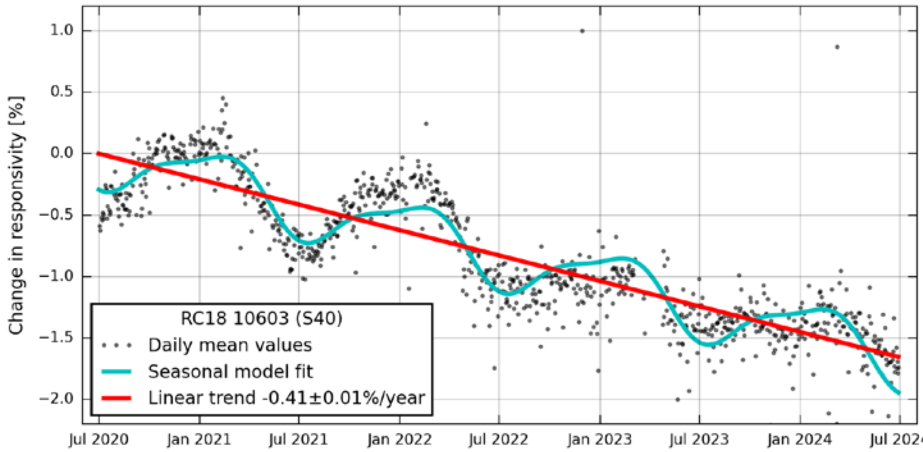

Figure 29. Seasonal model fit and linear trend for Atonometrics RC18 on S40

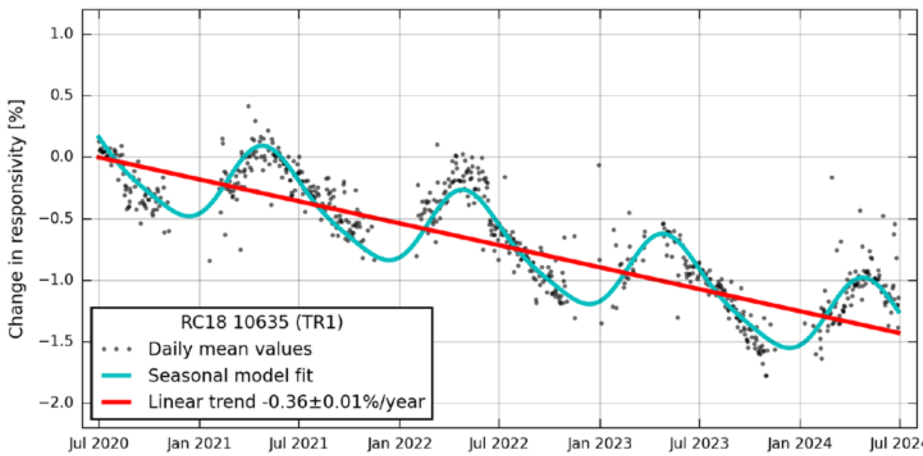

Figure 30. Seasonal model fit and linear trend for Atonometrics RC18 on TR1

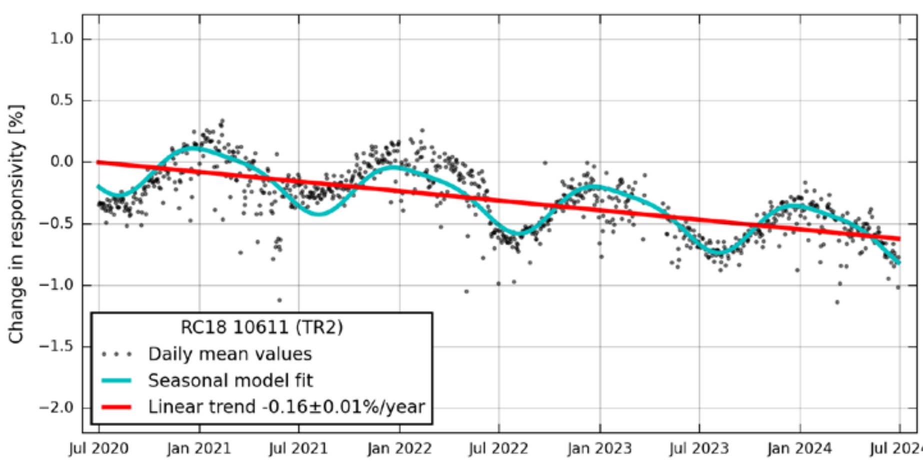

Figure 31. Seasonal model fit and linear trend for Atonometrics RC18 on TR2

Appendix B. Cell Lab Calibrations

This appendix is a visual catalogue of the NREL Cell Lab calibrations for selected reference cells. Multiple units of the same type are grouped together on the same chart. The dark band between ±0.9% indicates the expanded uncertainty of the initial calibration. See Section 5 for more information.

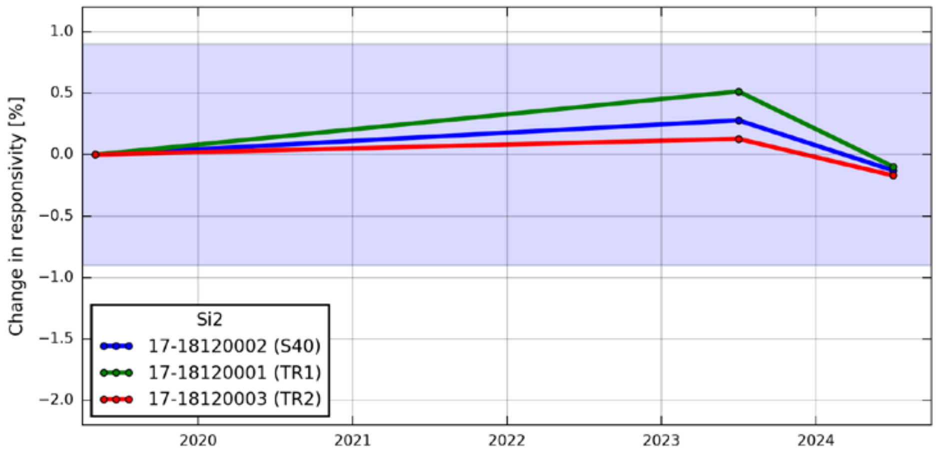

Figure 32. Evolution of responsivities measured by the NREL Cell Lab for IMT Si2

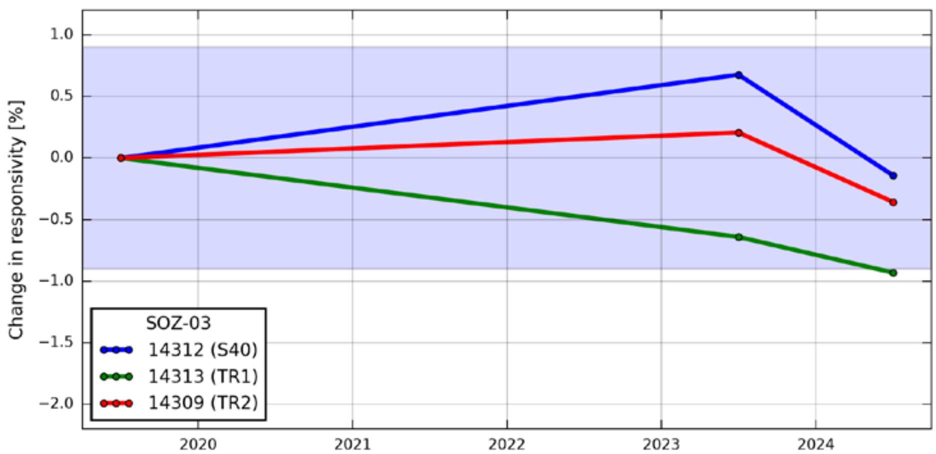

Figure 33. Evolution of responsivities measured by the NREL Cell Lab for NES SOZ-03

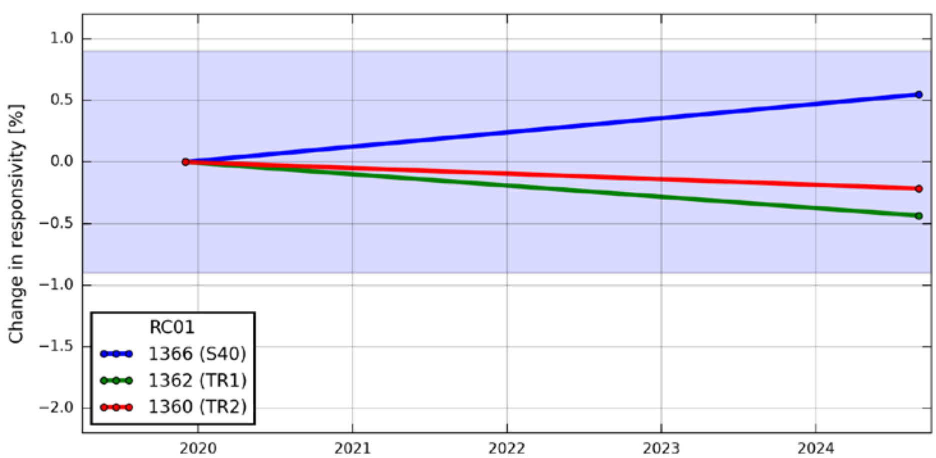

Figure 34. Evolution of responsivities measured by the NREL Cell Lab for EETS RC01

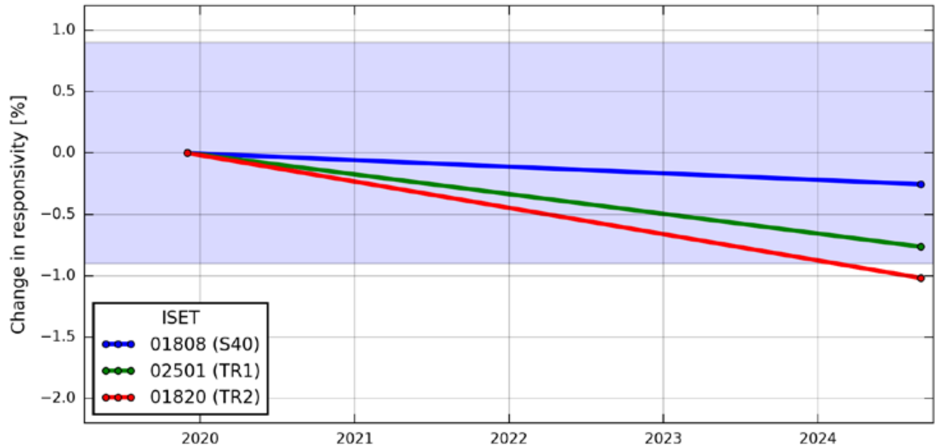

Figure 35. Evolution of responsivities measured by NREL Cell Lab for IKS ISET

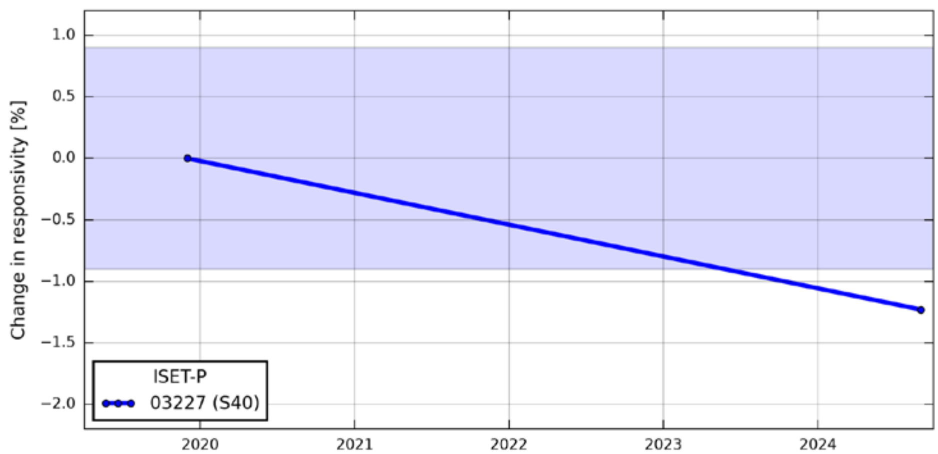

Figure 36. Evolution of responsivities measured by the NREL Cell Lab for IKS ISET-P

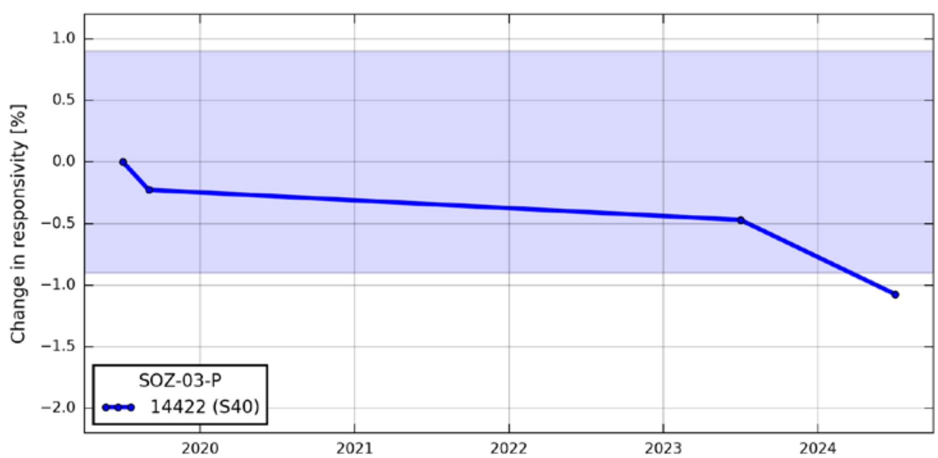

Figure 37. Evolution of responsivities measured by NREL Cell Lab for NES SOZ-03-P

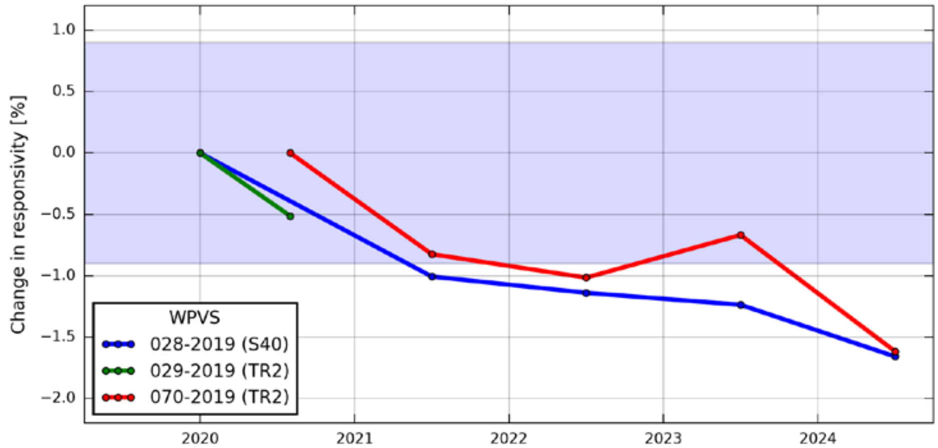

Figure 38. Evolution of responsivities measured by the NREL Cell Lab for Fraunhofer WPVS

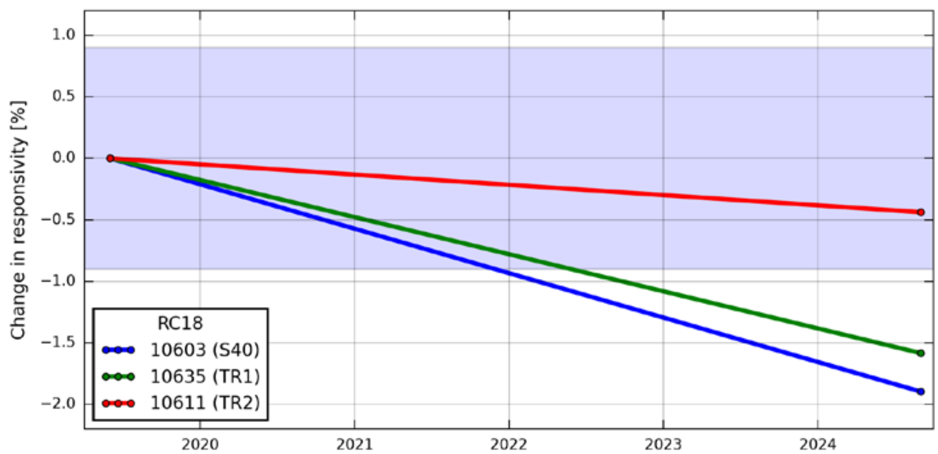

Figure 39. Evolution of responsivities measured by the NREL Cell Lab for Atonometrics RC18