CARTER-SCOTT DESIGN
MIDDLETON SOLAR
Solar Measurement Specialists
Carter-Scott Manufacturing Pty. Ltd. A.B.N. 55 006 486 988
www.middletonsolar.com adm@middletonsolar.com

Unit 10, 9 Douro St.
North Geelong
Victoria 3215
Australia

T: +61-(0)438-030-502

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Ultrasonic Self-cleaning Pyranometer
Technical Description

1. Background

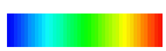
Solar resource appraisal is undertaken using Pyranometers and Pyrheliometers to precisely measure site-specific solar irradiance. Accuracy is degraded by the presence of water/ice/dust/mud on the glass dome/window. Typical soiling error is 1% to 10%/month. Regular cleaning is necessary to maintain an accuracy of better than 2%.

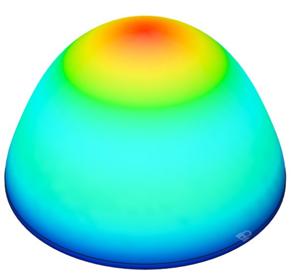
Manual cleaning is labour-intensive and expensive. Hands-free cleaning by water/air spray[1] has been investigated and reported on, as has mechanical cleaning by wiper/brush. These strategies have not been embraced because they require regular service & maintenance and do not eliminate the need for costly labour.

Middleton Solar has devised a fully-automatic self-cleaning technology for pyranometers using ultrasonic vibration of the protective glass dome at two resonant frequencies. The method was informed by the ‘Ultrasonic Lens Cleaning’ technique developed by Texas Instruments.

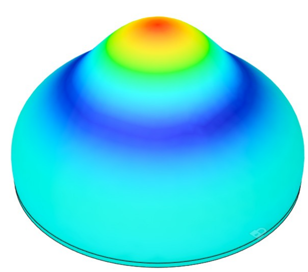
2. Computational Analysis

Finite Element Analysis of a typical Pyranometer outer glass dome, 50mm diameter x 2mm wall thickness, reveals multiple vibration mode shapes, of which four are significant, and only two are suitable for ultrasonic cleaning.
Mode #3 (≈ 31KHz) and mode #10 (≈ 41KHz) are the two natural frequencies that induce significant displacement of the dome.

relative displacement: 0  1



FEA image of mode #3



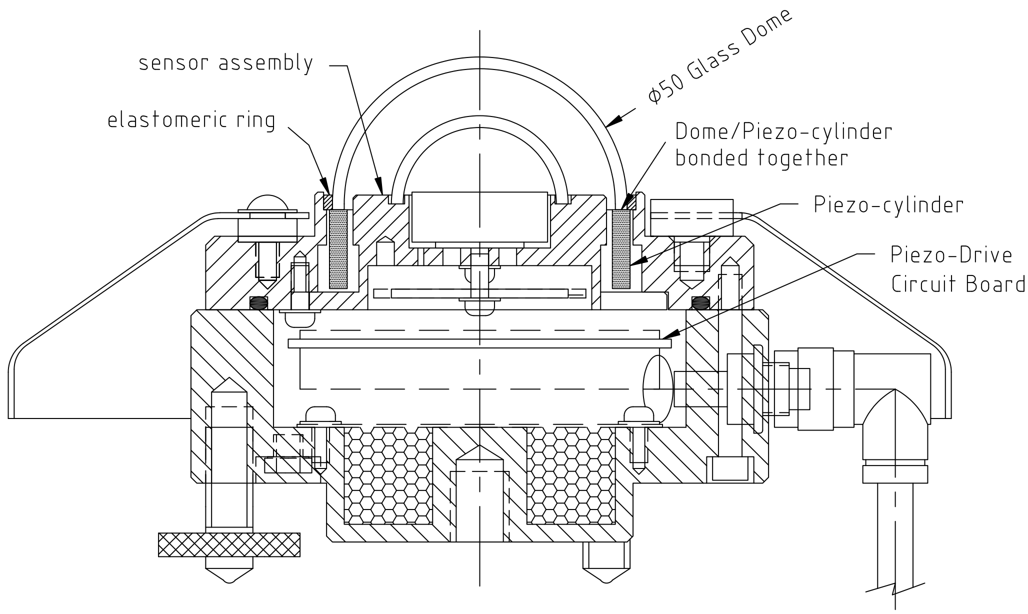
FEA image of mode #10

These two mode shapes in combination embrace most of the dome surface.

[1] US patent application number 62/180,452

3. Functional Description

The outer glass dome of a Pyranometer is bonded directly to one end of a piezoelectric cylinder of equivalent diameter and wall thickness. The dome/piezo-cylinder unit is joined to the Pyranometer body by a ring of elastomeric adhesive/sealant encircling the dome/piezo-cylinder joint. The elastomeric ring provides a hermetic seal and does not unduly damp ultrasonic vibrations.



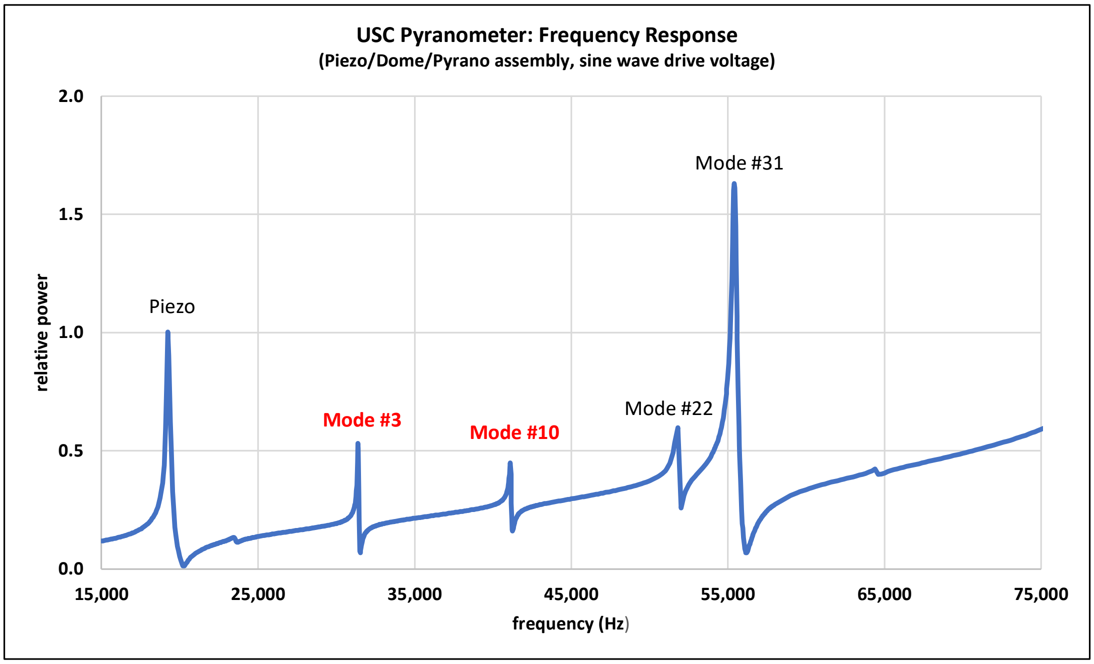
sectioned drawing of USC Pyranometer

A proprietary piezoelectric-drive Circuit Board is located inside the Pyranometer. It includes a 32-bit MCU running custom firmware to regulate the cleaning operation. A short or long cleaning cycle program can be switch-selected on the board, to repeat as necessary depending on the soiling profile at a specific site. Repeat can be set to every 30 minutes, every hour, or once a day.

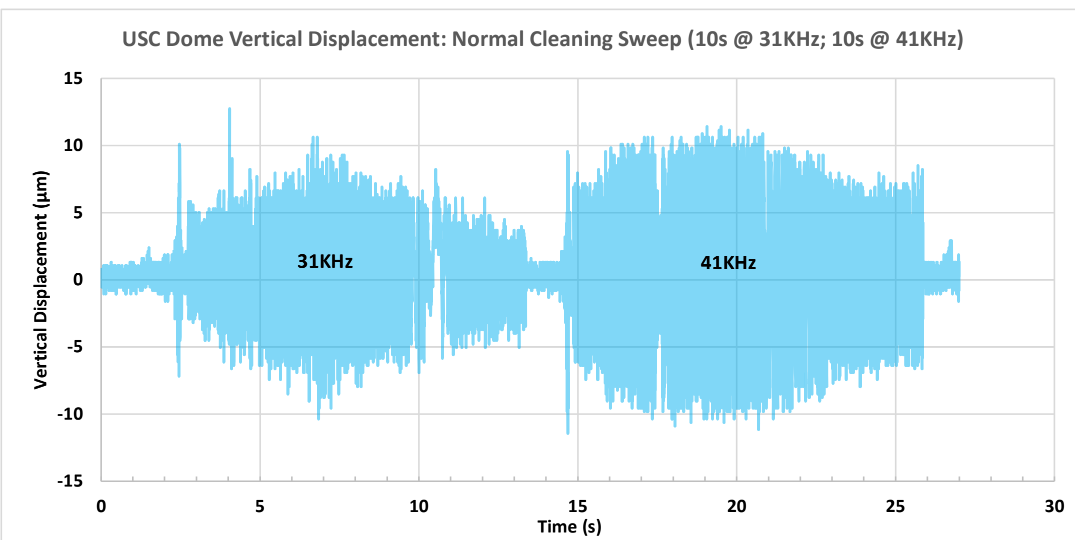
Operation is fully automatic whenever power (nominal 12VDC) is connected to the Pyranometer. A ‘deactivate cleaning’ input is provided whereby cleaning commences as soon as the ‘deactivate’ is removed. This input can be used to initiate or suppress cleaning events. A ‘piezo activity’ output is provided so that cleaning activity can be verified.

4. Vibration Protocol

The diameter & thickness of the piezo-cylinder is determined by the size of the 50mm glass dome. The radial resonant frequency of the piezo-cylinder (≈ 20KHz) is determined by its diameter, thickness, and elasticity. Piezo actuators are typically operated below self-resonance where their displacement is linear with frequency, but the glass dome resonance modes exceed 20KHz so the piezo-cylinder material must remain effective well above the piezo resonant frequency.

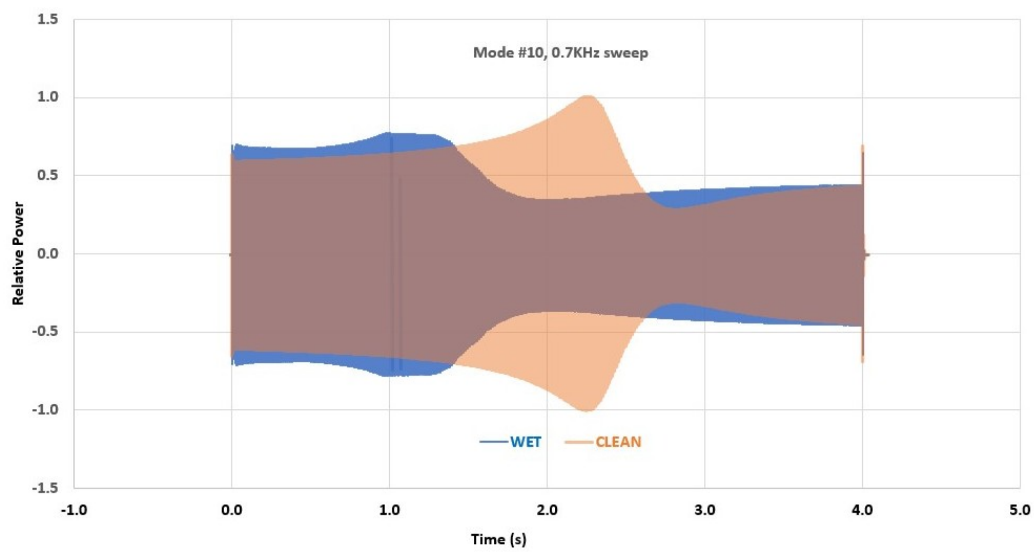


The piezo-cylinder is stimulated to vibrate radially by a modified square wave voltage (≈ 200 Vpp) in frequency bursts that alternate between the two selected dome resonant frequencies. Dome resonance has a narrow effective bandwidth (≈ 50Hz), and changes frequency with temperature and soiling load, so each cleaning burst is adjusted to track the shifting resonance.



Multiple bursts are used, each peaking at ≈15W supply power. An upper limit to power is determined by the stress-corrosion strength of optical glass. The maximum vertical displacement of the dome surface has an amplitude of ≈ 20μm, and the maximum surface velocity is ≈ 1.0m/s.

The surface movement of the dome reaches a peak at resonance, so dry matter such as dirt is readily ejected. At 41kHz, micro-bubbles in water will grow in size then collapse violently (inertial cavitation) and cause water and soil to be ejected from the dome.



frequency shift of Mode #10 due to water load on dome

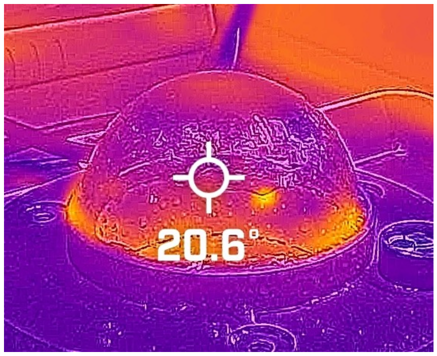
Two 4-second sweeps are overlaid to illustrate that the resonant frequency changes with water load on the dome. The wet-dome resonant frequency is displaced ≈ - 0.2KHz from when the dome is clean and dry.

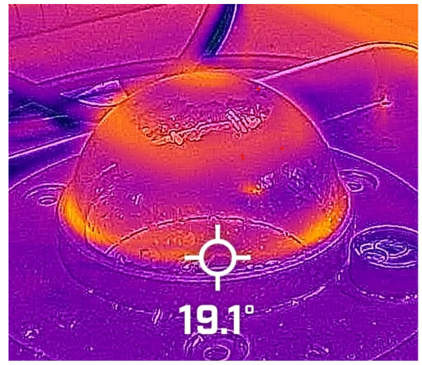
See Appendix A and Appendix B[2] for additional confidential Intellectual Property information about the operation of the USC pyranometer.

[2] Appendix A & B does not appear in Open Access versions of this document

5. Visualization of Dome Resonance

The glass dome wall exhibits small thermal gradients between regions of high and low displacement, at the resonant frequencies. Thermal imaging of a damp resonating dome reveals the mode shapes.





thermal image of mode #3 thermal image of mode #10

The two thermal images confirm that the actual mode shapes are consistent with the shapes anticipated by Computational Analysis (page 1), but also exhibit significant displacement where the dome base is attached to the piezo-cylinder.

6. Visualization of Ultrasonic Self-Cleaning

Left Photo: USC pyranometer outdoors on a rainy day, resonating at mode #10, clearly showing water mist shedding from the dome surface.

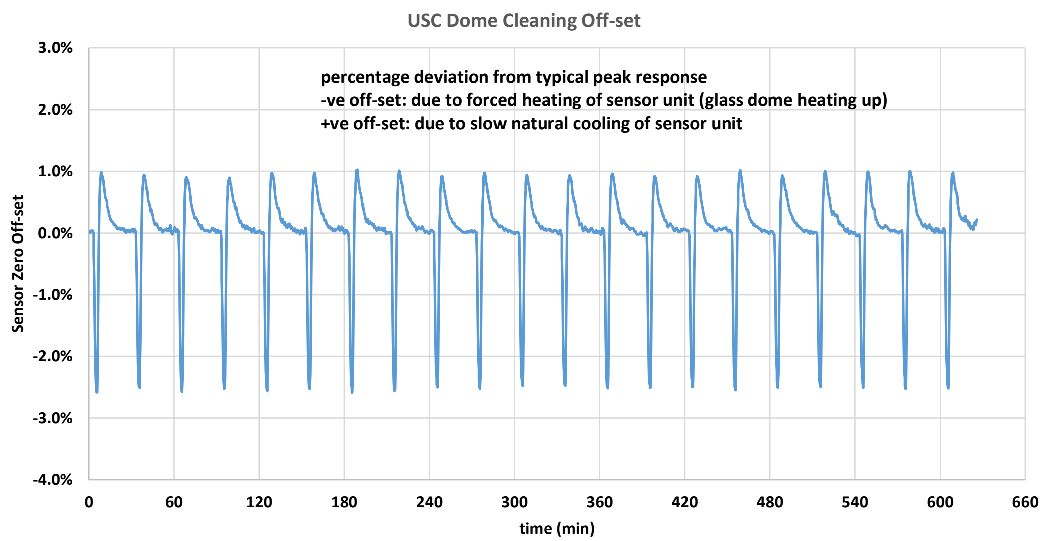
Right photo: a frame-grab from a slow-motion video of a wet glass dome indoors, resonating at mode #10, showing water being energetically expelled from the dome surface.

7. Self-Cleaning Limitations

Ultrasonic self-cleaning is effective at removing water and particles, but not effective at removing material that has bonded to the surface of the glass dome.

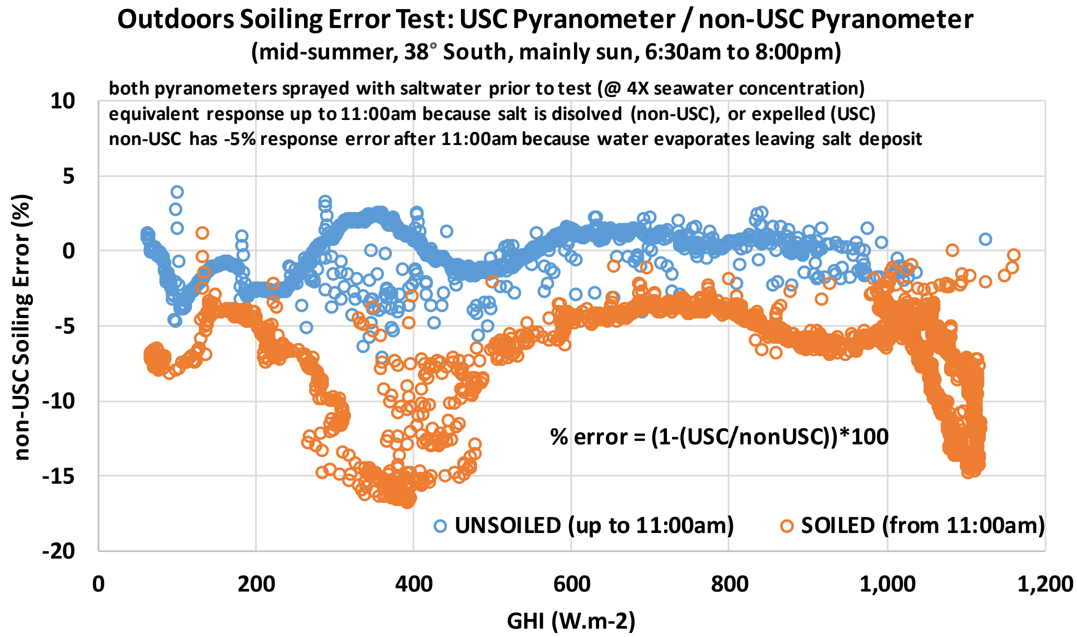
A thermal pyranometer will exhibit a Zero Off-set response proportional to the rate of temperature change (because the sensor time-constant produces a transient temperature difference across the sensor thermopile). The piezo-cylinder heats up when vibrating and some heat is transferred to the body of the pyranometer, resulting in a negative Off-set for warming up, and positive Off-set for cooling down.

The average Off-set is zero, over a typical cleaning event (30 min), because the negative and positive Off-sets cancel out. Ultrasonic cleaning will thus bias minute measurements, but not hourly or daily irradiance totals.



8. Self-Cleaning Validation

Middleton Solar has undertaken field testing of ultrasonic self-cleaning Class B Pyranometers.



The salt-soiling tests show that a non-USC pyranometer can exhibit significant daily soiling error, whereas a coextensive USC pyranometer remains error free.


non-USC: before test


non-USC: after test

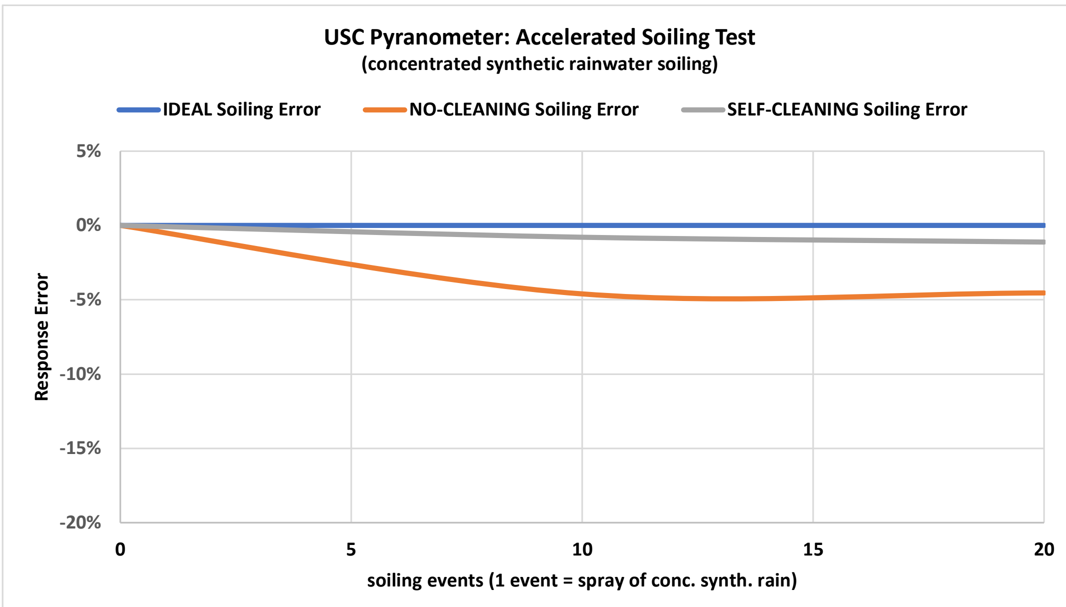

USC: before test


USC: after test

The photos above show that sea-salt soiling is effectively removed from the USC dome, but persists on the non-USC dome. The salt has been dissolved by dew during the test, and subsequently dried out, so the salt deposit pattern transforms.

The plot below shows the results of an Accelerated Cumulative Soiling test.

The test acceleration is achieved by frequent indoor rain-spray, using concentrated synthetic rainwater, to simulate long-term outdoor "cumulative soiling" exposure. Three equivalent pyranometers are used: the 'Ideal' pyranometer is maintained clean by hand; The 'No-Cleaning' unit is never cleaned; The 'Self-Cleaning' unit has the USC always active. The 'No-cleaning' and 'Self-Cleaning' units are equally exposed to the synthetic rainwater.

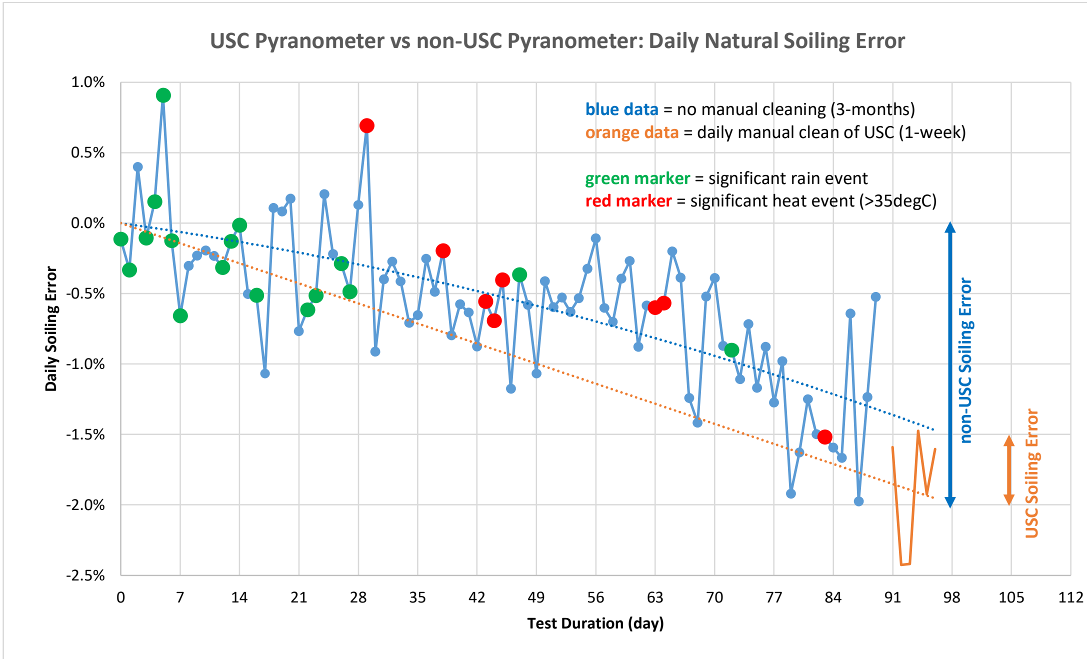


The No-Cleaning sample gives a long-term response error of -5%, whereas the equivalent USC Self-Cleaning error is -1%.

The plot below shows the results of a Natural Soiling test.

A self-cleaning USC pyranometer and an equivalent non-USC pyranometer were operated side-by-side outdoors in natural weather conditions of sun, cloud, rain, dew. The locale was residential/light-industrial with no nearby dirty industrial activity. The daily solar energy difference (USC vs non-USC) is an indicator of natural soiling accumulated by the non-USC instrument.

The soiling varies daily as wind and rain deliver natural cleaning events. However, there is a clear trend of soiling accumulation on the non-USC pyranometer. In contrast, the USC pyranometer exhibited 75% less soiling accumulation.



9. Life-Testing

Intensive ultrasonic vibrations may induce long-term damage to the glass dome or to the thermopile sensor. Accelerated life-testing is being undertaken to validate a service life of 10+ years. The test involves operating a USC pyranometer continuously 24/7/365, with no rest between ultra-sonic bursts, in a humid chamber (RH > 90%) under a light spray of 4X concentrated synthetic rainwater. 10-months of this testing is equivalent to 10 years normal use.

10. Development Timetable

Middleton Solar plans to provide sample units, to selected Users, for independent field evaluation in Q1/Q2 of 2026. Production release is anticipated for late 2026.

11. Other Solar Instrument Applications

Middleton Solar will over time apply ultrasonic self-cleaning to other solar instruments we manufacture such as Class A & Fast-Response Pyranometers, and Pyrheliometers.

12. Previous Public Release Versions of this Document

- R1.0, 31st Oct. 2023
- R1.1, 4th Dec. 2023
- R1.2, 18th Dec. 2023
- R1.3, 7th Mar. 2024
- R1.4, 13th Mar. 2025
- R1.5, 6th Oct. 2025

Author: A.D. Mathias, Middleton Solar.