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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 of a Pyranometer, or on the entrance window of a Pyrheliometer. Regular hand-cleaning, on a daily or weekly schedule, is generally necessary to maintain an accuracy of better than 2%.

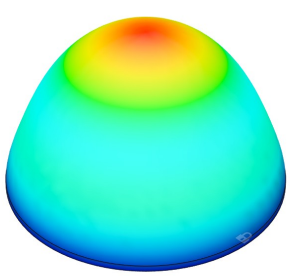
Manual cleaning is labour-intensive and expensive. Hands-free cleaning by water/air spray[1] has been investigated and reported on, as has mechanical cleaning by wiper/brush. These strategies have not been embraced because they require regular service & maintenance and do not eliminate the need for costly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

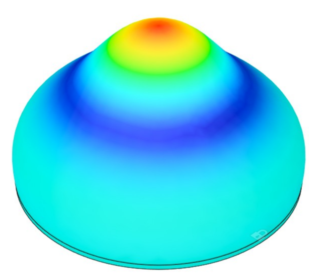
2. Computational Analysis

Finite Element Analysis of a typical Pyranometer outer glass dome, 50mm diameter x 2mm wall thickness, reveals >50 vibration mode shapes, of which only four are significant, and 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



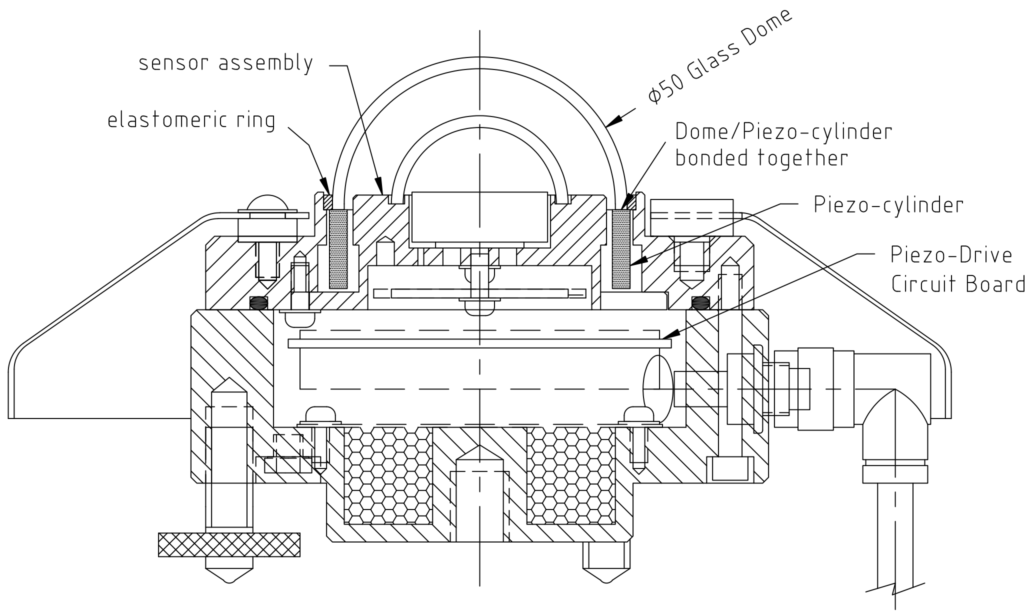
FEA image of mode #10

These two mode shapes in combination include 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.

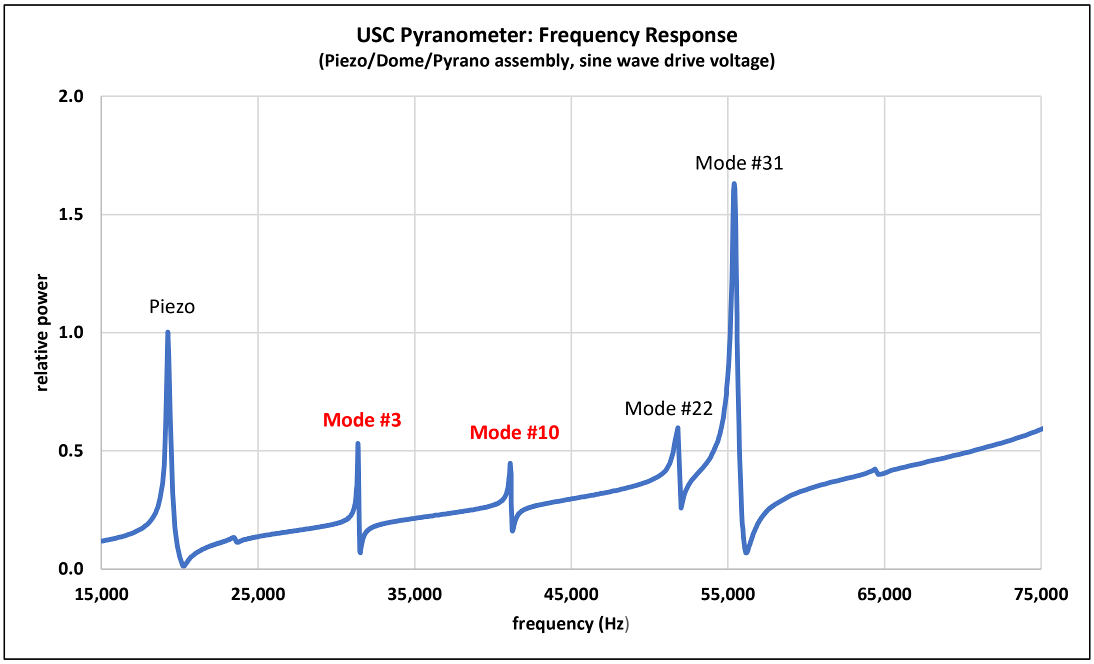


sectioned drawing of USC Pyranometer

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 selection of cleaning cycle programs can be switch-selected on the board, to repeat as necessary depending on the soiling profile at a specific site. Repeat can be every 30 minutes, or every hour, once a day, or some other period. Operation is fully automatic whenever power (nominal 12VDC) is connected to the Pyranometer. A ‘deactivate cleaning’ input is also provided.

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 resonance where their displacement is linear with frequency, but the glass dome resonance modes exceed 20KHz so the piezo-cylinder material must be optimized to remain effective well above the piezo resonant frequency.



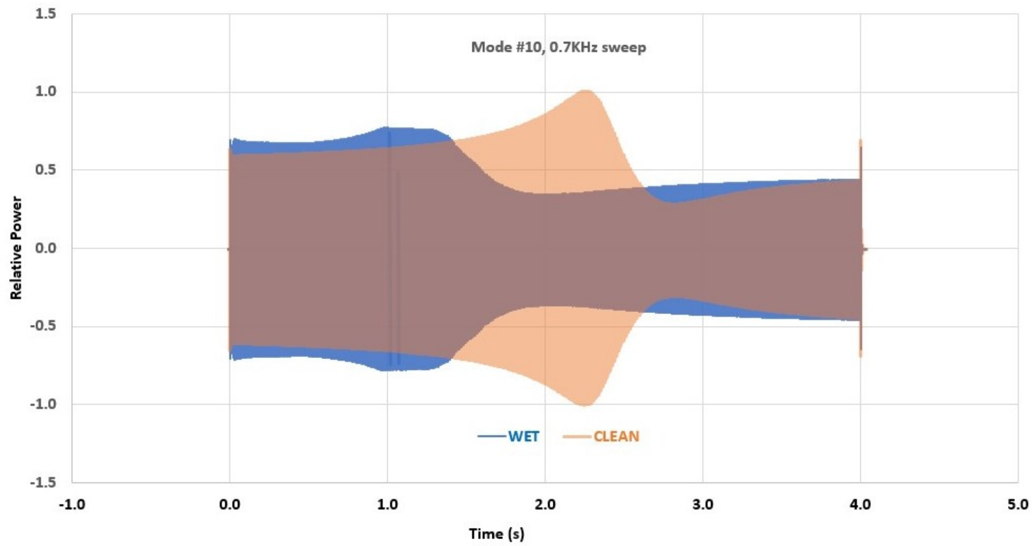
The piezo-cylinder is stimulated to vibrate radially by a modified square wave voltage (≈ 200Vpp) in frequency bursts that alternate between the two selected dome resonant frequencies. Dome resonance has a narrow effective bandwidth (≈ 50Hz), and changes frequency with temperature and soiling load, so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

Multiple bursts are used, each peaking at ≈ 15W supply power. No damage is caused to the glass dome as the Power Spectral Density is <1.5mW per Hz.

See Appendix A[2] for additional confidential information about the vibration protocol.

The surface acceleration of the dome reaches a peak at resonance, so dry matter such as dirt is readily ejected. Micro voids are created in water; the voids collapse violently (vacuum bubble cavitation) and cause the water to be ejected from the dome.

[2] Appendix A does not appear in open access versions of this document



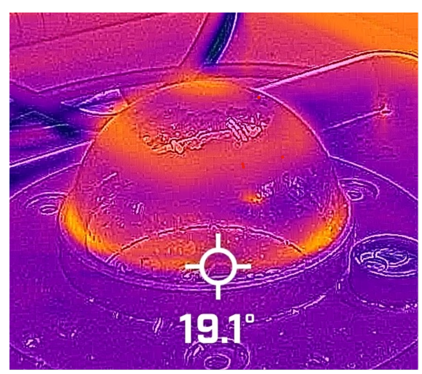
frequency shift of Mode #10 due to water load on dome

The power peaks at dome resonant frequency. 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.

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 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

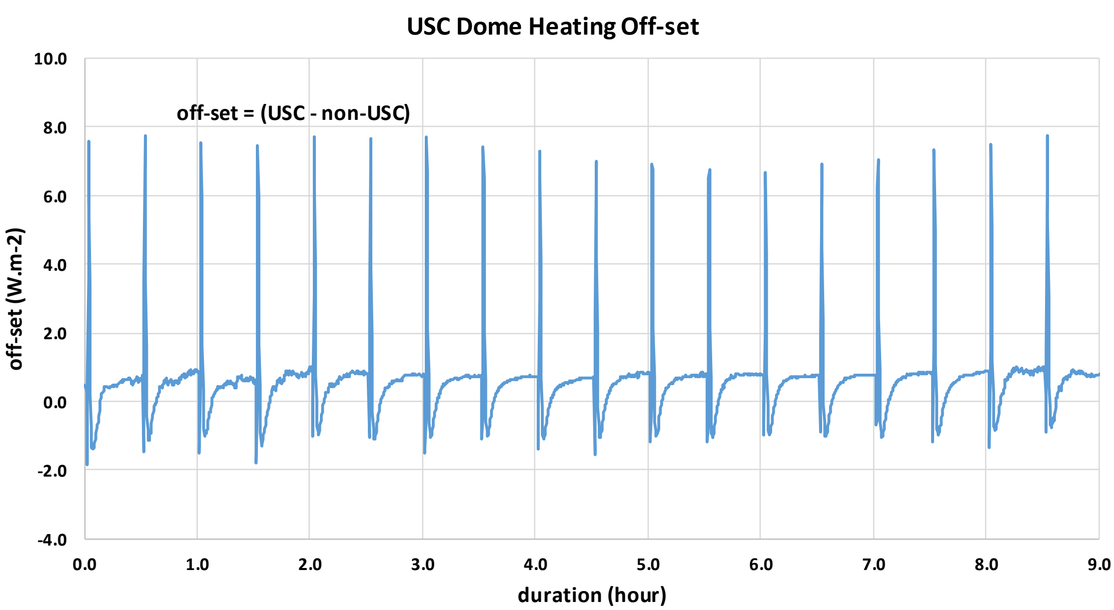
Left Photo: USC pyranometer outdoors on a rainy day, resonating at mode #10, clearly showing water mist shedding from the dome surface.

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

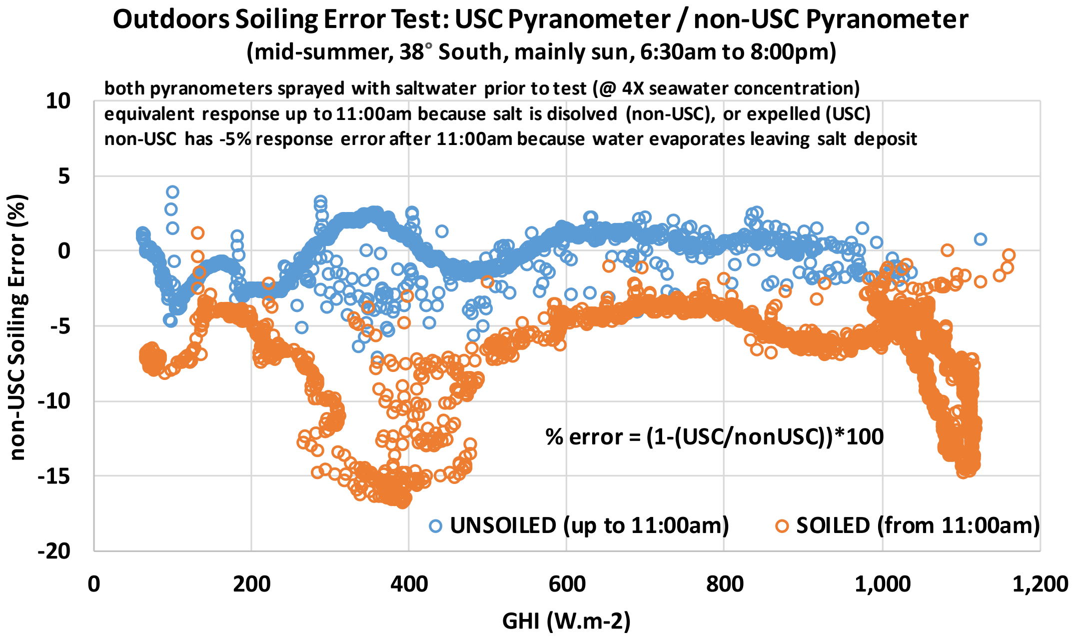
Ultrasonic self-cleaning is effective at removing water and particles, but not effective at removing material that has bonded to the surface of the glass dome.

Ultrasonic self-cleaning induces a momentary (≈10 sec) increase in the dome temperature resulting in ≈ 7.5 W.m-2 pyranometer response off-set spike due to IR radiation exchange, via the inner dome, with the exposed black sensor surface. This off-set is not evident in Fast-Response Pyranometers that use concealed sensor thermopiles.



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 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.

9. Development Timetable

Middleton Solar plans to provide sample units, to selected Users, for independent field evaluation in Q2 of 2025. Production release is anticipated for late 2025.

10. 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, Pyrheliometers, Sunphotometers, and Tracker Eyes.

11. 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

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Appendix A. CONFIDENTIAL

Vibration Protocol – Additional Information