Compact Spectral Radiometer for In Situ Solar Flux Measurements

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Introduction

We describe here the breadboard version of a lightweight, compact radiometer, which uses microthermopile detectors for hemispheric measurements of broadband and spectral downwelling solar irradiance. The instrument has undergone initial operability tests, and some limited field characterization has been performed against an Eppley Precision Spectral Pyranometer (PSP).

The radiometer has a unique combination of characteristics that allow it to provide scientific data not easily available with any other technique. These characteristics include:

1. **Fast response**. The devices will stabilize to within 1% of final value after 250 ms if operated under vacuum, and after 75 ms, if operated in air. This stabilization time is five times the 1/e detector response time. In comparison, the industry standard Eppley pyranometer stabilizes in 5 s to 10 s. Fast response allows more accurate measurements from airplanes, particularly in partly cloudy conditions. For example, research airplanes typically travel at 100 m/s, so the Jet Propulsion Laboratory (JPL) radiometer will stabilize within a distance of 25 m, while the Eppley radiometer travels at least 500 m before stabilizing.

2. **Broadband (200 nm to 2700 nm) simultaneous with spectral energy distribution (out to 2000 nm)**. The central thermopile detector measures total energy in the range 200 nm to 2700 nm, limited by the dome transmission. Standard pyranometers detect either broadband radiation or a single spectral band. Spectral instruments typically use silicon detectors, which are sensitive only up to 1100 nm and cannot accurately measure broadband incident power. The JPL instrument has passbands from 350 nm to 2000 nm. The simultaneous precise measurement of broadband radiation and spectral radiation distribution will provide deeper understanding of atmospheric absorption processes.

3. **Compact size and lightweight**. The radiometer is light enough to allow flights aboard Unmanned Aerospace Vehicles (UAVs) and small meteorological balloon platforms (with total payload weight limited by the Federal Aviation Administration to about 1.5 kg). The current breadboard weighs less than 1 kg and is about 9 cm in diameter. The size and weight could easily be reduced by decreasing the radiometer body size and wall thickness.

Radiometer Assembly

A photograph of the instrument is shown in Figure 1. In the radiometer head are seven broadband thermopile detectors, each having a 1-mm^2 detection area on a 5-mm silicon substrate. The central detector receives unfiltered light. Six detectors spaced at 60° intervals around the central detector are covered by a segmented, donut-shaped filter on a fused quartz substrate. One filter segment is uncoated, while the other segments have interference coatings covering the spectral bands 350 to 450 nm, 450 to 600 nm, 600 to 820 nm, 820 to 1200 nm, and 1200 to 2000 nm. Over the detector/filter assembly are two concentric glass domes. The radiometer body houses a preamplifier assembly as well as thermistors for monitoring of instrument temperature. A pump-out valve allows evacuation of the detector area. The current radiometer body is much larger than needed for the enclosed electronics, so the mass and volume could be substantially reduced.

Figure 1. Assembled radiometer without spectral filters.

Detector Responsivity

Typical sensitivity and response (1/e) time for the micromachined thermopile detectors is 15 $\mu V/(Wm^{-2})$ and 15 ms in air. In comparison, the thermopile detectors used in the industry standard Eppley PSP have a 1-cm^2 area, a sensitivity in air of 9 $\mu V/(Wm^{-2})$ and a response (1/e) time of 1 s. The microthermopile detectors consist of a suspended silicon nitride membrane approximately 1 mm across and 1 µm thick supported by a silicon substrate on all sides. A soot black optical absorber coats the membrane. There are 124 constantan/chomel thin film thermocouples connected in series that run from the central membrane area to the silicon substrate, thus sensing the temperature rise of the membrane above that of the substrate.

Thermopile linearity was tested in air by comparison to a silicon photodiode. Less than 1% deviation from linearity was seen for incident energies from 2 μW to 3 mW, corresponding to about 2 Wm^{-2} to 3000 Wm^{-2}. The experimental setup used does not allow measurements outside this range with high precision.

Temperature dependence of thermopile response was measured both in air and in vacuum. The total deviation in response over the temperature range -50 °C to 50 °C is 6% in air and 4% in vacuum. For accurate radiometric calibration, the temperature dependence of each channel is measured, as it is in other types of radiometers.

If the detectors are used in air rather than vacuum, it is important that their sensitivity be stable as a function of pressure for the altitude range of interest. The pressure dependence of sensitivity for a micromachined thermopile detector varied less than 1% from 1 atmosphere down to 200 mbar, which is more than adequate for tropospheric measurements.

Filter Transmission

The approximate in-band transmission and total direct sunlight transmitted for each filter segment is listed in Table 1. The calculated value assumes that the sun is an ideal 5900 K blackbody with 1000 W/m^2 incident on the radiometer. The observations were obtained in the sun with ~970 W/m^2 incident on the radiometer. Because the filters are flat interference filters, the transmission bands will shift with increasing zenith angle. The geometry of the filters and detectors limits light detected by the filtered detectors to zenith angles of 50° or less. Therefore, the spectral channels will be most useful for high solar angles.

Table 1. In-band transmission and total direct sunlight transmitted for each filter segment.

Spectral Bandpass (nm)	% Transmission in Bandpass	% Sunlight Transmitted	
		Calculated	Observed
350-450	55	6.5	9.0
450-600	70	14.0	18.0
600-820	60	13.0	16.0
820-1200	55	11.0	10.0
1200-2000	70	9.0	9.0

Cosine Response

The cosine response of the test instrument normalized to an Eppley PSP is shown in Table 2. The test was carried out on March 18, 1999, at the Jet Propulsion Laboratory. The radiometer and Eppley instrument were mounted on a common plate, with a sun tracking apparatus. Conditions on this day were hazy, with occasional streaks of thin, visible cirrus.

Table 2. Test results for the detector located on the outer detector ring under blank filter substrate. Data was obtained at five tilt angles from direct incidence for each of four azimuth angles.

	Tilt Angle					
Azimuth Angle	**0°**	**10°**	**20°**	**30°**	**40°**	**50°**
25°	0.974	0.978	1.00	0.964	0.980	0.967
115°	0.989	0.990	1.00	0.996	0.999	0.998
205°	0.947	0.964	0.985	0.979	0.997	1.00
295°	0.879	0.907	0.925	0.947	1.00	0.980

Summary

An instrument, which can measure simultaneously broadband, hemispheric solar irradiance, and five spectral sub-regions has been evaluated. The housing and dome design are similar to a commercial Eppley pyranometer. The fast response of the instrument (75 ms) has virtually no lag. The scientific value of this instrument is in improving aircraft and balloon-based observations of downwelling solar flux in cloudy atmospheres.