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A LOW COST INSTRUMENT FOR MEASUREMENT OF PHOTOSYNTHETICALLY ACTIVE RADIATION IN FIELD CANOPIES

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ABSTRACT

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A robust, relatively low cost (parts $300 Aust., 1976) instrument suitable for field studies was constructed to give rapid estimates of photosynthetically active radiation, both absolute and as percentage transmission, within plant canopies. The instrument consists of 9 selenium photocells mounted in a probe and a single selenium cell as the reference sensor. The performance of the instrument was evaluated in both the laboratory and field.

INTRODUCTION

An instrument measuring the radiant flux density available for photosynthesis (Photosynthetically Active Radiation or P.A.R.) should have: (i) a quantum response in the 400—700 nm waveband (McCree, 1972); (ii) be linear over a wide range of irradiances; (iii) be independent of previous light history (fatigue); (iv) have a time constant sufficiently small to follow transient light fluctuations encountered in a canopy: (v) possess a small thermal coefficient of response; (vi) have long term stability; and (vii) have an acceptable cosine response. In addition, the sensor should be small thus creating minimal disturbance in canopies.

Silicon photovoltaic cells have successfully been used to record P.A.R. at relatively low cost (Norman et al., 1969; McPherson, 1969; Biggs et al. 1971), but their response in the near infra-red requires drastic spectral tailoring using filters. On the other hand, selenium photovoltaic cells, whilst still possessing the low-cost characteristics of the silicon photocells, have a sharp cut-off at 700 nm and an acceptable photon response in the 400—700 nm waveband (Federer and Tanner, 1966) when used with a Wratten 85 C filter.

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Light profiles of plant canopies quantitatively describe the distribution of P.A.R. within the canopy as a percentage of that incident on the canopy. This requires measurement of radiation both above the canopy and then at various levels within it. Sensors incorporating a single photocell are adequate for measurements of the first of these, but within the canopy at any horizontal level, irradiance varies from maximum outside values in sunflecks to deep shade. An obvious approach is to take many spot readings, but this time consuming operation may be impractical in many situations. The horizontal variability may be minimized by using a linear probe with a number of sensors mounted on it, all linked up to give an "average" value of P.A.R. at that level. This approach has been previously described by Daynard et al. (1969) who designed a space-integrating light meter employing 10 sensors connected in parallel to a meter.

The description of profiles in terms of percentage of incident radiation requires simultaneous readings both above and within the canopy. This may be achieved by taking successive readings, but considerable error is introduced when incident radiation is fluctuating under cloudy conditions. Alternatively, two separate instruments may be used, the sensor of one mounted permanently above the canopy and read simultaneously, but this is still relatively time consuming in that two readings must be recorded for each insertion of the probe. A refinement is to attach two sensors to the one instrument, into which is incorporated a ratio device, so that the output of one sensor is expressed as a percentage of the other giving a direct percent transmission readout. Miller (1951) developed an instrument employing two photocells connected to separate integrators. The outputs from the two photocells are integrated for a period of 1 min and their ratio obtained by adjusting a null-balance circuit. This method does not give continuous readings of percent transmission and requires high voltage batteries to power the valve integrators.

A linear probe incorporating 9 selenium cells was developed to measure average P.A.R. in plant canopies. Also a ratio device using reliable solid state electronics has been developed to give direct per cent transmission readings of P.A.R. in plant canopies.

DESIGN CONSIDERATIONS

Consideration must be given to three unfavourable characteristics of selenium photocells when using them to measure P.A.R. Firstly, they show considerable response below 400 nm. Secondly, at high irradiances, they saturate, thus giving non-linear responses to increasing irradiances. Thirdly, as with most photocells, they have poor cosine response characteristics. Federer and Tanner (1966) have shown that a Wratten 85 C filtered selenium cell gives a close approximation to the ideal photon response curve. This filter has a cut-off at 400 nm tailoring the cells response below this wavelength. An almost identical bandpass is displayed by the white Perspex diffusing head and a similar photon response curve would be shown by a sensor filtered by this material. Correction for cosine response errors is obtained by mounting an opaque Perspex diffusing head (Pleijel and Longmore, 1952) over the cell. This in conjunction with a neutral density filter limits the light level reaching the cell to values within its linear range of operation.

Measurement of absolute P.A.R. requires a system giving an average reading for the 9 selenium cells incorporated in the probe, independent of previous light history (fatigue). The photocurrents from the 9 selenium cells are summed at the input to an operational amplifier, whose feedback ensures short-circuit conditions at the input and an output voltage proportional to input current. This is known as a "current to voltage converter". Measurement of the cell photocurrent under short circuit load conditions minimizes fatigue (International Rectifier, 1972). Use of an amplifier also allows selection of a robust meter suitable for field measurements.

Direct percent transmission readout may be achieved by using a ratio circuit. Since readings ranging from 100% down to 1% transmission are of interest in crop-canopy studies, measurements must not be affected by a 10:1 change in irradiance which may occur under cloudy conditions. Logarithmic ratio circuits utilizing transistors as non-linear feedback elements (Dobkin, 1969) possess a wide dynamic range of operation (5 decades) and appear suitable for use in such a system.

The basic log ratio circuit (Fig.1) gives an output of the form:

$$e_0 = K \log \frac{i_{\text{probe}}}{i_{\text{ref.}}}$$

where K = slope factor of 1 V per decade; i_{probe} = probe photocurrent; i_{ref} = reference sensor photocurrent.

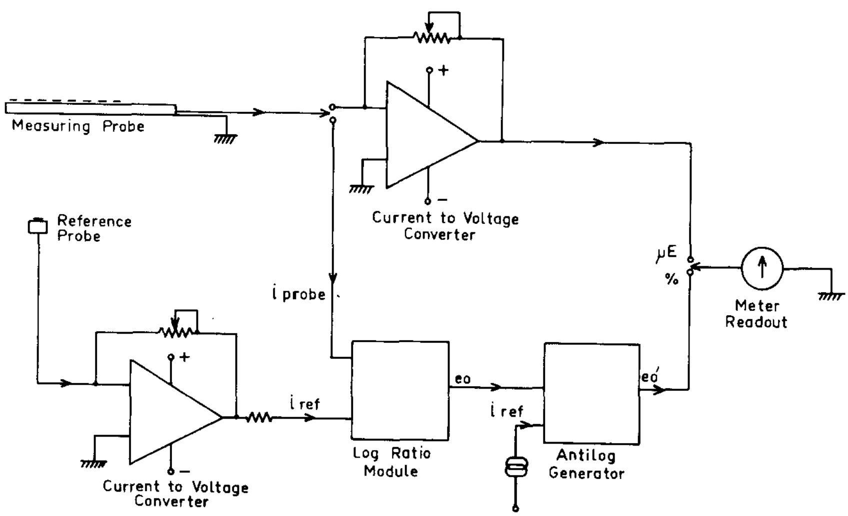

Fig.1. Electronic system of P.A.R. meter with percent readout facility.

When the probe and reference sensor are exposed to the same irradiance, the two photocurrents are adjusted to be equal and e_0 = 0.0 V. When the probe is receiving 10% of the irradiance received by the reference sensor, $e_0 = -1.0$ V. Thus the circuit provides an output which is the log of the ratio of the probe photocurrent to the reference sensor photocurrent with a slope factor of 1 V per decade, independent of the absolute values of the currents (and P.A.R.'s) involved.

A linear readout may be obtained by generating the antilog of the log ratio output. Such a circuit (Fig.1) gives an output of the form:

$$e'_0 = K\,10^{-|e_0|}$$

where K = slope factor of 1 V per decade; e_0 = output signal from log ratio circuit.

When the probe and reference sensor are exposed to the same irradiance (i.e., e_0 = 0 V), e'_0 = 1.0 V; whereas when the probe is receiving 10% of the irradiance received by the reference sensor (e_0 = 1.0 V), then e'_0 = 0.1 V.

Hence a meter calibrated for 1 V full scale would give a linear scale of 0 to 100% transmission.

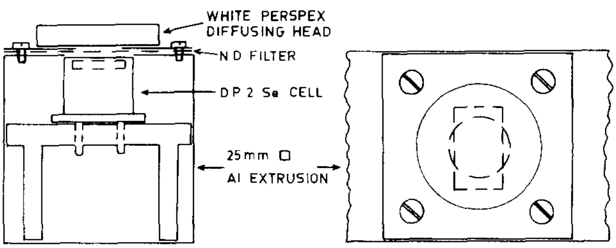

Fig.2. Mounting details of DP-2 selenium photovoltaic cells.

SENSOR CONSTRUCTION

The probe consists of 9 selenium cells (International Rectifier DP-2; Fig.2) mounted 100 mm apart on a strip of Perspex which fits neatly inside a 25 mm square section aluminium extrusion, into which corresponding windows 11 mm x 6 mm) are cut in the upper side to expose the active area of the cells. A 16 mm diameter disc of white Perspex 3 mm thick is polished to a matt finish on all surfaces with 400 mesh silicon carbide sanding paper. The disc is bonded (Plio Bond 20 Goodyear) to a 25 mm square of 22 gauge aluminium sheet predrilled with a 7 mm diameter hole, the disc is mounted concentrically over the hole. A 25 mm square of neutral density filter material (Kodak ND-0.9) is placed over the viewing window and the diffusing head screwed in place over it with four 8 BA screws. All dimensions are critical in determining the cosine response errors of the sensor. The average transmission of the diffusing head and filter is 2% in the 400—700 nm range. The reference sensor consists of a single selenium cell identically mounted in a 25 mm aluminium cube welded across the end of a length of 10 mm aluminium tube. Both the probe and reference sensor are fitted with a levelling device.

ELECTRONIC CIRCUIT DESIGN

The circuit (Fig.3, Board A) for absolute P.A.R. measurement comprises two operational amplifiers (LM 307 N National Semiconductor) mounted on a 50 mm x 60 mm section of 0.25 mm pitch veroboard. Two switched ranges of operation are provided (0—3000, and 0—300 μE m^{-2} sec^{-1}). The active leads from each of the 9 selenium cells are brought back to a common summing point on the board to ensure that all the cells operate under identical short circuit conditions.

The circuit (Fig.3, Board B) for direct percent transmission measurement is mounted on a separate board (96 mm x 115 mm). Temperature-compensated logarithmic modules (Philbrick Nexus Model 4358) containing matched transistor pairs comprise the non-linear feedback elements. The photocurrent from the reference sensor is amplified by a variable gain current to voltage converter to provide the reference current for the log ratio circuit. The reference current (100 μA) for the antilog generator is derived from a temperature-compensated reference diode (LM 113 National Semiconductor). A 100 μA F.S.D. meter calibrated for 1.0 and 0.2 V full scale provides ranges of 0—100% and 0—20% transmission.

Power for all the circuits is provided by two batteries (Eveready 216; 9 V), and in order to ensure long battery life, only that circuitry necessary for the required measurement is energized at any given time. Battery voltage variation had no effect on instrument accuracy over their normal useful life. To facilitate convenient multiple readings, the instrument has an output connection for an electronic recorder. The total cost of parts was $300 (Aust., 1976).

LABORATORY TESTING

Accuracy of the "percent transmission" scale was tested by feeding a known current into the i_{probe} input while maintaining a fixed input i_{ref} current. Readings of log ratio and antilog output voltage were taken over a 100:1 range of i_{probe} values using a digital voltmeter (Solartron LM 1426). Accuracy was within 1% in the range 100—10% transmission. Below this accuracy decreased gradually to a value of 10% at a level of 1% transmission (Table I). Errors due to changes in i_{ref} were assessed by feeding equal currents into the i_{probe} and i_{ref} inputs, and observing the change in log and antilog output voltages over a 20:1 change in current level. An error of less than 1% was observed (Table II).

Linearity of the current to voltage converter for absolute P.A.R. measurement was established by feeding a known current into the summing point,

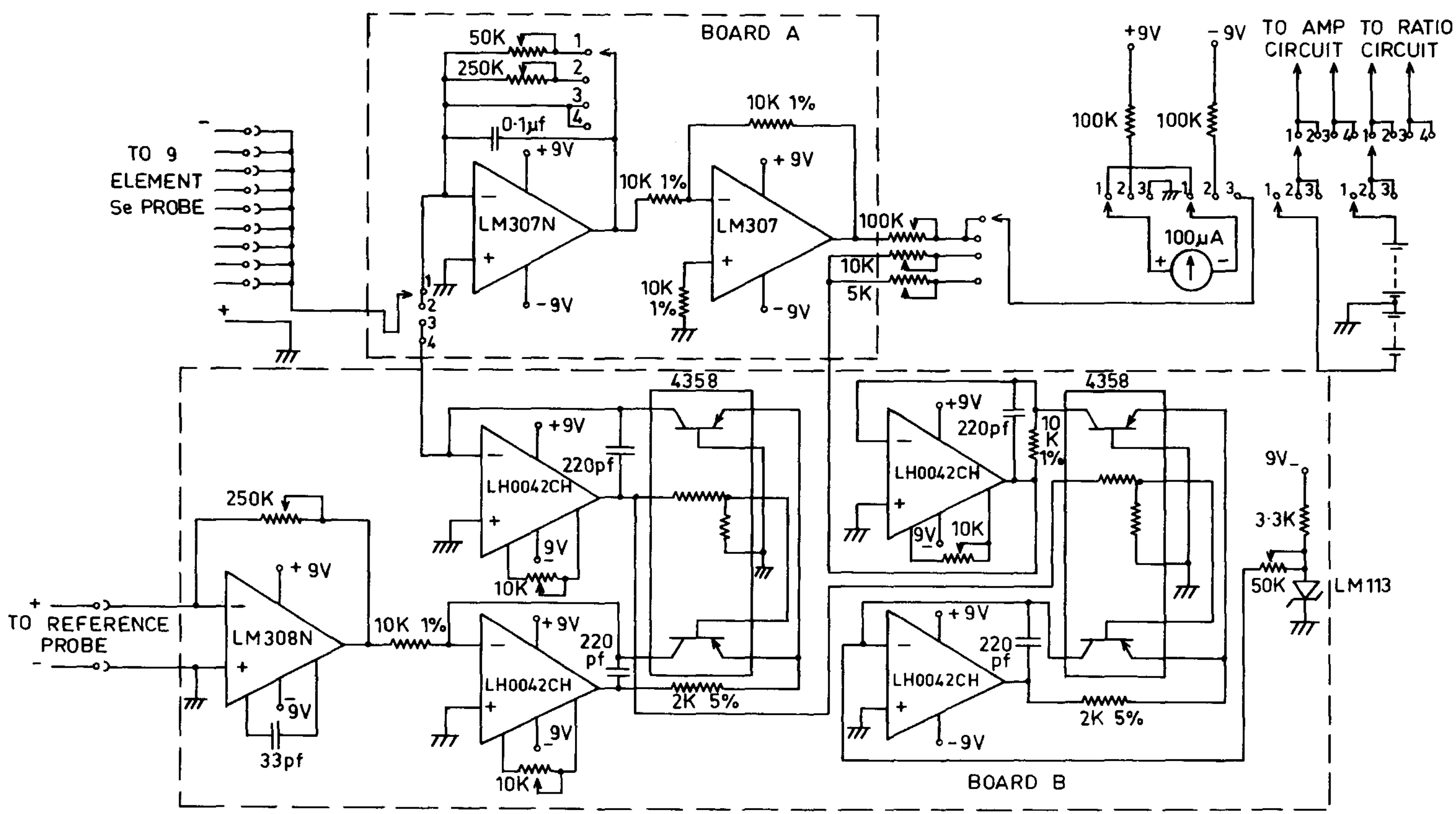

Fig.3. Electronic circuit of P.A.R. meter and percent transmission monitor.

TABLE I

Performance test of percent transmission circuitry using known input currents

i_{ref} (μA)	i_{probe} (μA)	$\frac{i_{probe}}{i_{ref}}$	Log output (V)	Antilog output (V)
200	200	1.0	0.008	0.998
200	150	0.75	0.135	0.747
200	100	0.50	0.313	0.498
200	50	0.25	0.619	0.247
200	40	0.20	0.715	0.199
200	20	0.10	1.015	0.099
200	15	0.075	1.142	0.075
200	10	0.05	1.321	0.049
200	5	0.025	1.636	0.024
200	4	0.02	1.732	0.019
200	2	0.01	2.028	0.009

TABLE II

Variation in 100% transmission reading over a 20:1 current range

i_{ref} (μA)	i_{probe} (μA)	Log output (V)	Antilog output (V)
200	200	0.008	0.998
100	100	0.007	0.999
50	50	0.004	1.005
20	20	0.007	0.996
10	10	0.005	1.001

and observing the change in output voltage with change in input current. A straight-line relationship with a high degree of correlation was obtained ($r^2 = 0.99$).

The temperature coefficient of the selenium cell was assessed by fixing a copper-constantan thermocouple to the side of the cell which was exposed to constant irradiance, and measuring the cell's short-circuit current. This test was performed at different sensor temperatures. The temperature coefficient was found to be small (of the order of $-0.075\%\,^{\circ}C^{-1}$) and not a source of significant error.

Cosine response errors were assessed using a procedure similar to that described by Briggs et al. (1971). A plot of percent of true response vs angle of incidence is given in Fig.4.

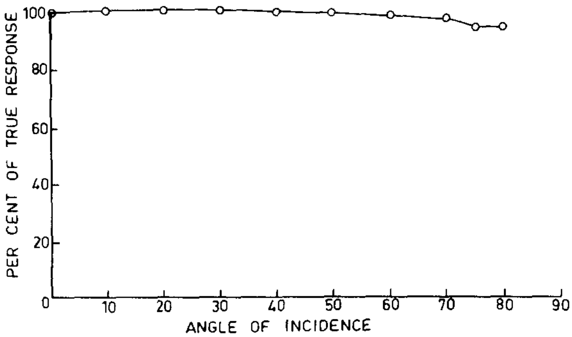

Fig.4. Cosine response of selenium sensor with Perspex diffusing head.

FIELD PERFORMANCE

Two field tests on the probe were conducted.

The probe was compared with a filtered silicon cell (Type LI-1905, Lambda Inst. Co., Inc.) known to have an almost ideal quantum response in the 400—700 nm waveband, and an acceptable cosine response. Simultaneous readings were taken from the horizontally oriented sensors in natural sunlight at approximately half-hourly intervals during the progress of a mid-summer day (latitude 27°S).

The relationship between values of P.A.R. obtained with the two instruments is shown in Fig.5. The regression line passes close to the origin, and the coefficient of determination (R^2 = 0.97) is highly significant.

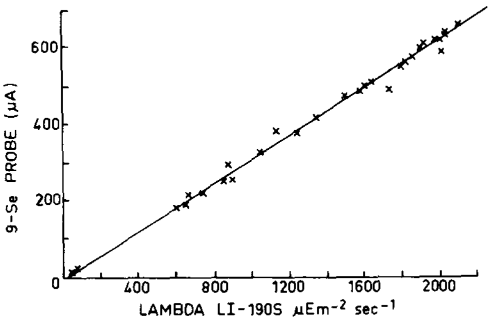

Fig.5. Relationship between P.A.R. readings taken with the probe and with a filtered silicon cell (Lambda LI-190S).

Both instruments were then compared by simultaneous recording of P.A.R. values under neutral shade cloths of three different light transmission ratings. Each shade cloth was placed over a frame 2 m square, 2.3 m high. On a clear day, 30 spot readings were taken under each shade with each instrument, and the values were expressed as a percentage of full sunlight (i.e., percent light transmission).

The results are shown in Table III. Analysis of variance showed no significant difference between recordings with each instrument for a given shade cloth.

TABLE III

Percent light transmission of 3 shade cloths as measured with the probe and the Lambda LI-190S instrument

Shade cloth	Percent light transmission	
	probe	Lambda LI-190S
A	46.2	47.6
B	61.7	62.3
C	59.6	59.4

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