INFRARED DEVICE FOR MEASUREMENT OF CARBON DIOXIDE FLUCTUATIONS UNDER FIELD CONDITIONS

I. Single Beam System

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INTRODUCTION

The atmospheric flux of carbon dioxide above vegetation is a governing factor in the CO_2 balance of vegetation. The CO_2 flux is usually estimated by the aerodynamic method (Inoue et al. 1957) or the heat balance method (Monteith and Szeicz 1960). Inoue (1964) suggested the feasibility of the eddy correlation technique. This technique involves measurement of turbulent fluctuations in CO_2 concentration. Among available methods of CO_2 measurement, the technique based on the CO_2 absorption in the infrared is considered as the most promising one for the present purpose. The conventional infrared gas analyser is not constructed for measurement of fluctuations, though its response characteristics can be improved by contriving the sampling system (Desjardins and Lemon 1974). A fast response device with open sensing path, such as realized by Elagina (1962) for water vapor fluctuations, needs to be developed. We begin by constructing a single beam system to examine the practicability of the open path measurement under field conditions.

CONSTRUCTION AND PERFORMANCE

4.3 micron absorption band of carbon dioxide In the intermediate infrared region the absorption bands of CO_2 are found at 2.0, 2.7, 4.3 and 15 μm. The 2.0 μm band is weak in intensity; 2.7 and 15 μm bands are overlapped by water vapor bands. The 4.3 μm band, which is quite strong and well removed from water vapor bands, is the only practicable selection for CO_2 measurement.

The 4.3 μm absorption band extends from 2280 cm^{-1} to 2380 cm^{-1} under normal conditions of CO_2 concentration and pressure in the atmosphere. The mean spectral absorption is calculated from the empirical formula given by Burch et al. (1962)

$$\bar{A}=15.0\ (w\cdot P^{0.75})^{0.54}/(\nu_2-\nu_1),$$

where $\bar{A}$ is the mean absorption over the range bounded by wave number ν_1 and ν_2, w is the absorber (CO_2) concentration in atmos-cm, and P is the total pressure in mmHg. The results are listed in Table 1 for

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the relevant range of concentration and a fixed path length of 50 cm. P is taken as 760 mmHg.

TABLE 1.

Mean spectral absorption of 4.3 μm CO_2 band calculated from the empirical formula given by Burch et al. (1962).

CO_2 concentration ppm	50	100	150	200	250	300	350	400	450	500
mean absorption	0.087	0.126	0.157	0.183	0.207	0.228	0.248	0.266	0.284	0.300

Optical system The configuration of the device is shown in Fig. 1. The optical arrangement is schematically shown in Fig. 2.

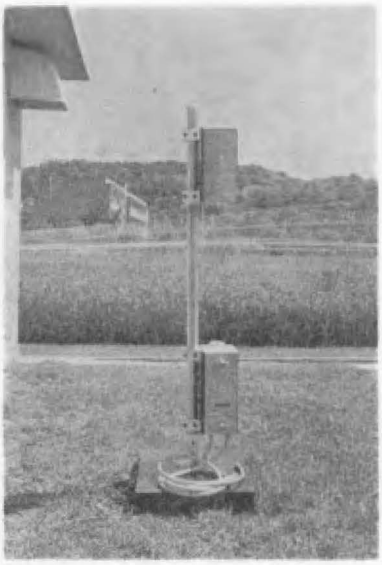

Fig. 1. Photograph of the single beam device for measurement of CO_2 fluctuations. Path length 50 cm.

The beam from the source H is focused by a mirror $M1$ at a chopper C and then collimated by a lens $L1$. After traversing the sensing path $L1$-$L2$ of 50 cm in length, the beam is focused by a lens $L2$ at a filter F and finally the image of the source is formed by a spherical mirror $M2$ at a detector D. The two blade disk of the chopper rotated by a d.c. motor M modulates the beam at frequency of 10 Hz. The modulation frequency has been selected in view of the time constant of the detector.

The radiant source H (Watlow Firerod Cartridge Heater) is a nickel-

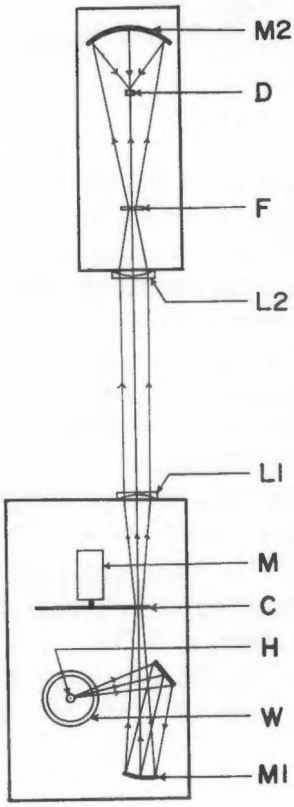

Fig. 2. Optical arrangement of the single beam device.

H=infrared source
W=cooling water jacket
*M*1 and *M*2=reflecting mirror
C=chopper disk
M=d. c. motor
*L*1 and *L*2=CaF_2 lens
F=narrow band interference filter
D=infrared detector

wire heater wound on an insulating core; the heater is positioned by magnesium oxide within an inconell metal tube of 25.4 mm in length and 6.25 mm in outside diameter. This rod source is housed in an enclosure of fire brick surrounded by water jacket *W*. The source is heated by a stabilized d. c. current to an operating temperature of about 1000°K. The emissivity is about 0.5 at 4.3 μm region (Carlon 1966).

The filter *F* is a 4.3 μm band-pass filter with half-width of 0.1 μm and peak transmittance of 70 per cent. The lenses *L*1 and *L*2 are made of calcium fluoride.

The detector *D* (Thermofilm LP-11) is a thermal detector. Typical values of characteristic parameters are as follows:

responsivity = 0.15 mV/mW
resistance = 15 kΩ
time constant = 20 msec
diameter of sensitive area = 1 mmϕ

The detector is mounted on a heat sink of copper rod.

The irradiance $H\lambda$ at the detector is estimated by a design equation (Hutchinson and Jarratt 1971).

$$H\lambda = \phi\lambda \cdot W\lambda \cdot \Delta\lambda \cdot (1-\bar{A})/4F^2,$$

where $\phi\lambda$ is the efficiency of the optical system, $W\lambda$ the black-body radiance of the source, $\Delta\lambda$ the spectral bandwidth specified by the filter, $\bar{A}$ the mean spectral absorption of CO_2, and F the f-number of the optical system. $\bar{A}$ is taken as 0.2 (cf. Table 1). For the operating temperature of 1000°K of the source $W\lambda$ is approximately 1 W cm^{-2} μm^{-1} at $\lambda=$ 4.3 μm. $\phi\lambda$ is estimated at 0.15 from optical losses at mirror, lens and filter, and emissivity of the source. $\Delta\lambda$ is taken as 0.1 μm, a half-width of the filter. The f-number of the present optical system is estimated as 3. Substituting these values in the above equation, we have $H\lambda = 3.3 \times 10^{-4}$ W cm^{-2}. Taking account of the detector area and responsivity, the corresponding signal level of the detector is estimated as 4×10^{-7} V.

Electronic circuit A block diagram of the electronic assembly is given in Fig. 3. The detector signal is amplified by a tuned amplifier with center frequency of 10 Hz and band-width of 1 Hz. The output of the tuned amplifier is rectified by an AC-DC converter and then passed through a low-pass filter with a time constant of 0.5 sec to

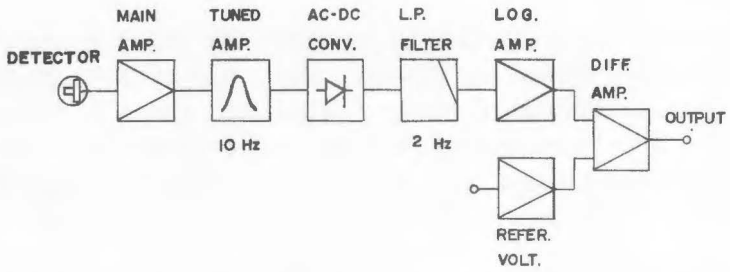

Fig. 3. Block diagram of electronic assembly for the single beam device.

improve the S/N ratio. At the following stage the signal is made approximately linear with the CO_2 variation by a log amplifier and then is fed to one terminal of a differential amplifier. A reference voltage regulated by a Zener diode is supplied to the differential amplifier to suppress the zero level of the signal voltage. The overall gain of the amplifiers is 3.5×10^6.

Calibration The calibration is made as follows. The sensing path is closed by a hollow cylinder. The cylinder is fitted by connecting rings to the rims of the apertures of the housings. This calibration cell is flushed by standard gas of known CO_2 concentration.

The calibration curve is illustrated in Fig. 4. The zero is established by flushing N_2 gas. It is found that the output voltage varies as a power function of CO_2 concentration. Over a range between 200 ppm and 400 ppm a linear relation can be assumed within an error of 1 %.

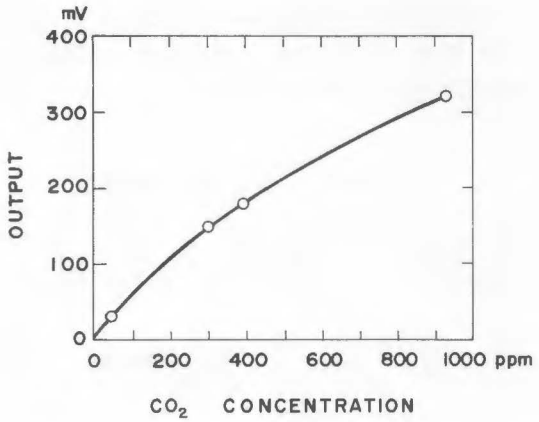

Fig. 4. Output voltage of the single beam device versus CO_2 concentration of standard gas.

Noise The total electronic noise is estimated at 1.8 mV from the standard deviation of the output voltage recorded in passing a CO_2 gas of 395 ppm through the calibration cell. This noise voltage is equivalent to the CO_2 fluctuation of about 3.5 ppm which indicates the limit of the resolution with the present device.

In the course of laboratory test erratic zero drift appeared in the instrument indication. For the operating duration of the order of 10 min this difficulty was practically resolved by purging the housings with constant flow of N_2 gas. The adequate longer-term stability was difficult to achieve with the single beam system.

PRELIMINARY FIELD TEST

A comparison test between the new instrument and IRGA URAS-2 was conducted over a short grass in the evening on 22 May 1975. The total record length is 14 min (19h46m-20h00m). In this test the instrument was used in the horizontal position. Its sensing path was 10 cm above the grass surface.

The gas intake of URAS-2 was an aluminium pipe 80 cm long and 10 mm in diameter with small holes punched on it. The pipe was located close to the sensing path. Sample air was drawn by a pump

through PVC tubing of about 10 m in length and 4 mm in inside diameter. It was desiccated by a thermoelectric cooler. The standard gas of 300 ppm was passed through the reference cell during the measurement.

Fig. 5 shows a sample record on a recording potentiometer of time constant of about 1 sec. The upper curve represents the data obtained from the present instrument and the lower one is the data of URAS-2. It is evident that these two time variations are strongly correlated with each other and that the new instrument responds more rapidly to fluctuations than URAS-2. The correlation coefficient is found to be 0.75. It is noted that the noise of the new instrument appears in the record as minor fluctuations with frequencies of the order of 1 Hz.

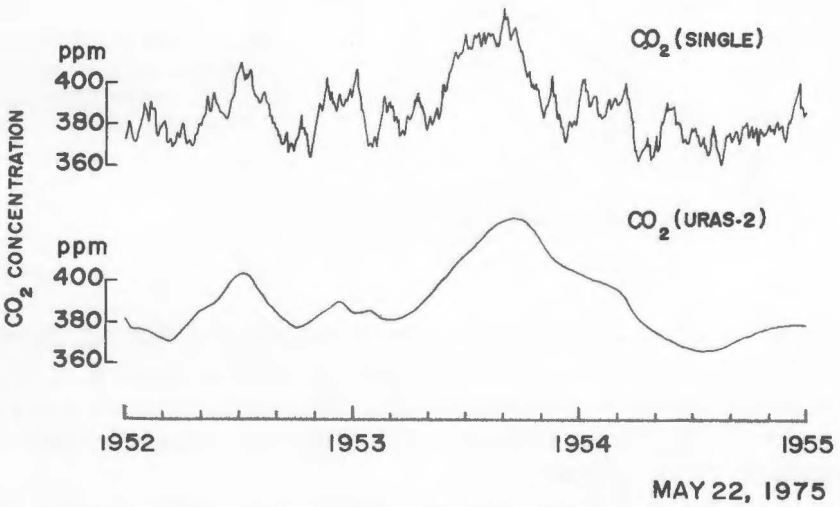

Fig. 5. Sample traces of CO_2 concentration with the single beam device and URAS-2.

The frequency response of the new instrument was compared with that of URAS-2 through spectral analysis. The 14 min record was digitized at every second and the computation was made by the use of Hanning's lag window. Fig. 6 shows the normalized power spectra of CO_2 fluctuations from the new infrared device and URAS-2. It is seen that both spectra agree well at lower frequencies below 0.02 Hz. At higher frequencies the spectral density from the new instrument decreases broadly with -5/3 power of frequency, while the spectral density from URAS-2 decreases more steeply as is expected from its slower response. The coherency* between the signal of the new instrument and that of URAS-2 is shown in Fig. 7. The coherency is better than

* Coherency=(coherence)$^{1/2}$.

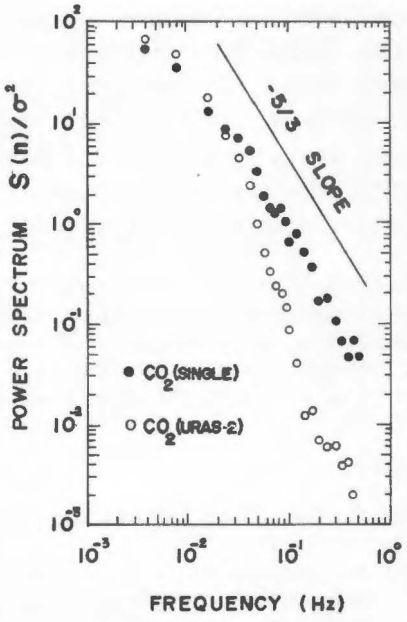

Fig. 6. Normalized power spectral densities of CO_2 fluctuation obtained by the single beam device and URAS-2.

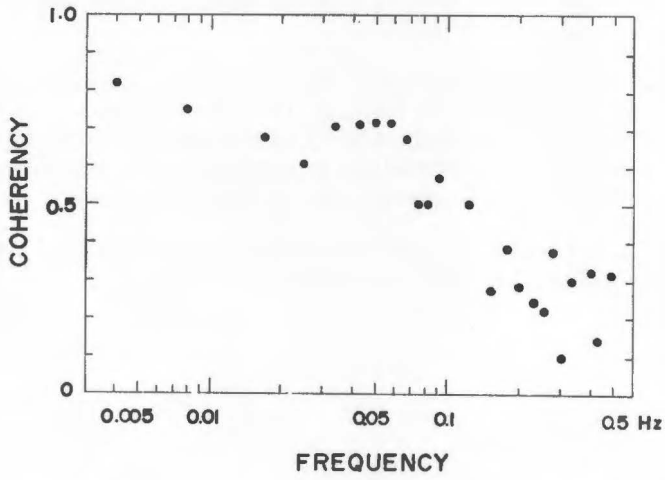

Fig. 7. Coherence between CO_2 fluctuations with the single beam device and those with URAS-2.

0.7 at lower frequencies up to 0.07 Hz; it drops gradually above 0.07 Hz.

CONCLUSIONS

The results of the performance test show that the new infrared device is feasible for measurement of CO_2 fluctuations under field con-

ditions. However, the present single beam instrument suffers from several limitations: (1) relatively high noise level equivalent to the fluctuation of 3.5 ppm in CO_2 concentration; (2) frequency response limited by cutoff frequency 2 Hz of the LP filter; (3) inadequate stability and reproducibility inherent in the single beam system. It will be shown in the succeeding report that these difficulties are well overcome by the use of double beam system equipped with a detector of higher detectivity.

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REFERENCES

1. Burch, D. E., Gryvnak, D. A. and Williams, D. 1962. Total absorptance of carbon dioxide in the infrared. Applied Optics. 1: 759-765.
2. Carlon, H. R. 1966. A useful infrared source. Applied Optics. 5: 1281-1283.
3. Desjardins, R. L. and Lemon, E. R. 1974. Limitations of an eddy-correlation technique for the determination of the carbon dioxide and sensible heat fluxes. Boundary-Layer Meteorol. 5: 475-488.
4. Elagina, L. G. 1962. Optical device for measuring the turbulent pulsations of humidity. Izv., Geophys. Ser. 1100-1107.
5. Hutchinson, R. J. and Jarratt, T. 1971. Infrared gas analysis. In: F. A. Sowan, Applications of Infrared Detectors. Mullard Limited, London. 129-142.
6. Inoue, E., Tani, N., Imai, K. and Isobe, S. 1957. The aerodynamic measurement of photosynthesis over the wheat field. J. Agr. Meteorol. (Japan) 13: 121-125.
7. Inoue, E. 1964. Turbulent fluctuations in atmospheric CO_2 concentration over the vegetated fields. In: K. Yoshida, Studies on Oceanography. Univ. of Tokyo Press. 232-237.
8. Monteith, J. L. and Szeicz, G. 1960. The carbon dioxide flux over a field of sugar beet. Quart. Jour. Roy. Met. Soc. 86: 205-214.