# A Single-Beam Infrared Hygrometer for Evaporation Measurement

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ABSTRACT

Two instruments are described which serve as humidity sensors in conjunction with existing eddy correlation techniques. The first instrument is an infrared absorption device, with a 40 cm path length, operating in a water vapor vibrational band at 6.3 μm. The second instrument is a development of this, operating at 2.7 μm with a 20 cm path length. Both devices have been successfully field-tested in a latent heat flux format, using a propeller anemometer as a vertical velocity sensor. Satisfactory energy balances at the surface have been obtained. In the case of the 2.7 μm instrument, a specific advantage is its lack of sensitivity to ambient humidity levels, while both instruments are insensitive to slow variations of optical and electronic performance.

## 1. Introduction

Development of a water vapor sensor suitable for use in eddy correlation applications near the surface has been a considerable problem confronting experimental micrometeorologists. Early equipment [such as the "Evapotron," described by Dyer and Maher (1964)] used fine wire wet-bulb thermometers to give the total turbulent sensible and latent heat transport, $H+LE$. These devices were unsatisfactory in several respects. They were, for example, susceptible to contamination and it was difficult to maintain their elements in an optimally wet condition.

More recently, alternative methods have been employed. Examples include instruments which rely upon variations in the refractive index of air [such as the microwave refractometer reported by Hay *et al.* (1961)] and instruments which depend upon surface film effects [such as the sensitized quartz crystal hygrometer reported by Hicks and Goodman (1971)].

Experiments gained from recent field trials conducted using CSIRO eddy correlation equipment suggest that neither approach is completely satisfactory. The refractometer requires an electronic package of a complexity which is not desirable in many field applications, while the quartz crystal hygrometer proved to be as susceptible to contamination as conventional wet bulbs, and is further complicated by its sensitivity to relative humidity rather than water vapor concentration.

The method reported here relies upon the absorption of radiation in one of the many water vapor absorption bands. This approach offers several distinct advantages, while not suffering from the disadvantages of the methods mentioned above. The calibration in this case is essentially a function of the optical filter characteristics, which are invariant with time, so that calibration changes are eliminated. Furthermore, the associated electronics is uncomplicated and can therefore be made very reliable.

## 2. Design criteria

For eddy correlation application, an instrument should be capable of sensing all eddies in the frequency range of 0.01 to 2 Hz, the range of relevant frequencies normally encountered in the height range of 2 to 20 m. It should cause little obstruction to the flow of air, in order to avoid distortion of the flow and consequent decoupling of the humidity and vertical velocity fluctuations. Furthermore, it is desirable that the instrument be mechanically rugged and light in weight, and the associated electronics simple, with low power consumption.

The present paper is concerned with the design, construction and field testing of two devices intended to meet these criteria, one operating at a wavelength of 6.3 μm (with a 40 cm path length) and the second operating at 2.7 μm (20 cm path length). The latter instrument is used at present in CSIRO eddy correlation studies.

### *a. The 6.3 μm sensor*

Fig. 1 shows the mechanical layout of this instrument. Two housings, containing respectively a Nernst

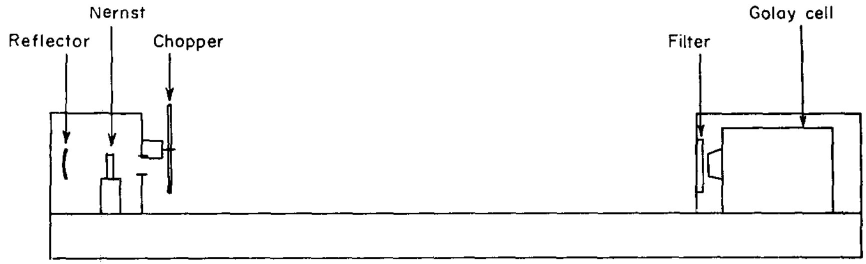


FIG. 1. Schematic arrangement of the 6.3 $\mu$m instrument.

filament with a small spherical reflector and a Golay cell fitted with a 6.3 $\mu$m narrow band filter, are mounted some 40 cm apart on a rigid frame. Each housing is thermally insulated. A chopper disc is fixed to the shaft of a small dc motor, supported by a cradle attached to the Nernst filament housing. The field of view of the Golay is about 5°.

The beam is chopped at 14 Hz, this being an optimum value for the Golay cell while being adequate for the required 2 Hz maximum frequency response. In field use, the Nernst filament is usually mounted vertically above the Golay cell.

Fig. 2 is a block diagram of the electronic package. The output from the Golay cell is amplified and rectified. After smoothing with a time constant of 0.5 s, the rectified signal forms the denominator in an analog divider circuit, and the fluctuating component (after dc blocking with a time constant of 100 s) forms the numerator. The quotient, together with an analog signal proportional to the vertical velocity obtained from an anemometer, is fed to eddy-correlation equipment designed to compute the required covariance $\overline{w'q'}$ (in conventional notation). The time constant of the $w'$ system is typically about 0.5 s.

Power requirements are 20W for the Golay cell and 25W for the Nernst filament.

The filter pass band of the 6.3 $\mu$m interference filter falls entirely within the water vapor absorption band, thus optimizing the sensitivity. The measured transmission of the infrared beam plotted against specific humidity is shown in Fig. 3, and may be represented by

$$\tau = \exp(-a\rho_w^{\,b}), \qquad (1)$$

where $b=0.65$, $\rho_w$ is the density of water vapor, and $a$ is a constant.

Now the output of the instrument is a measure of the ratio $\tau'/\tau$, where the prime indicates a small departure from the mean value. From (1) we obtain by differentiation

$$\frac{\tau'}{\tau} \approx -ab\rho_w^{\,(b-1)}\rho_w'. \qquad (2)$$

Since $\rho_w = [q/(1-q)]\,\rho_a \approx q\rho_a$, where $\rho_a$ is the density of air and $q$ is the specific humidity, we have

$$\frac{\tau'}{\tau} \approx -abq^{(b-1)}\rho_a^{\,b}q'. \qquad (3)$$

As short-term variations are less than 1%, the term containing $\rho_a'$ can be omitted. Under average conditions ($T=290$ K, $p=1000$ mb), and taking into account the divider output, we have for a change of 1 g kg$^{-1}$ in specific humidity,

$$\frac{\tau'}{\tau} = -348q^{-0.35}\ [\mathrm{mV}]. \qquad (4)$$

The factor 348 includes $\rho_a^{\,b}$ which may exhibit a day-to-day variation of up to 6%. Using a measurement of $q$ obtained by some other method, this value, combined with the appropriate vertical wind speed calibration

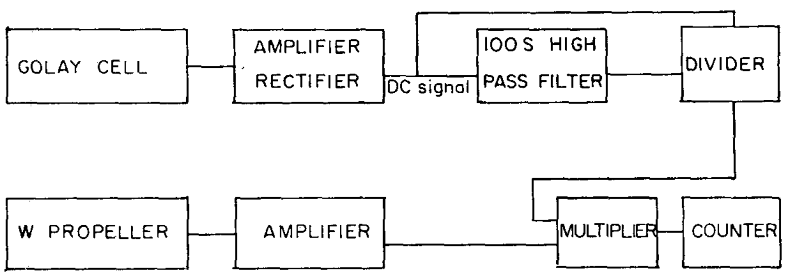


FIG. 2. Electrical layout common to both sensors.

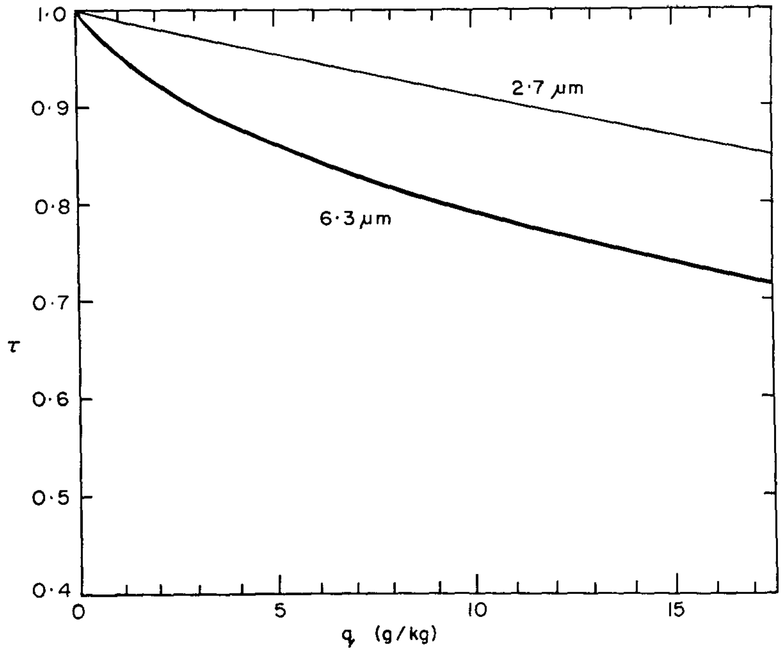


FIG. 3. Transmission $\tau$ in the 6.3 $\mu$m water vapor band over a 40 cm path length vs specific humidity $q$ (g kg$^{-1}$), and transmission in the 2.7 $\mu$m band over a 20 cm path.

(mV per m s$^{-1}$) and that of the associated covariance instrumentation, provides the calibration for the evaporative flux. However since the absorption is slightly temperature-dependent, a correction may be required in the case of large Bowen ratios (see Appendix).

*b. Description of the 2.7 μm instrument*

For general field use, it is desirable that the active components of any water vapor sensor be sealed from the environment. While the optical properties of glass do not allow it to be used in conjunction with the 6.3 $\mu$m instrument, it is quite suitable for use in designs operating at near-visible wavelengths. The 2.7 $\mu$m water vapor band, although less absorptive than the 6.3 $\mu$m band, is sufficiently strong to be employed. Adoption of this wavelength allows replacement of the Golay cell by a cheaper, more rugged and faster response light-dependent resistor (LDR), and the Nernst filament with its high current drain can be replaced by a simple light bulb.

The 2.7 $\mu$m instrument is much lighter, smaller and cheaper than its 6.3 $\mu$m counterpart, but operates along identical lines. The LDR is a Mullard type 61 SV, and a 6 V globe with a reflector serves as the light source. A four-blade chopper provides a chopping rate of 800 Hz. Overall power consumption is less than 200 mW. The smoothing filter and dc blocking filter here have time constants of 0.04 and 300 s respectively. For reasons of compactness, simplicity of

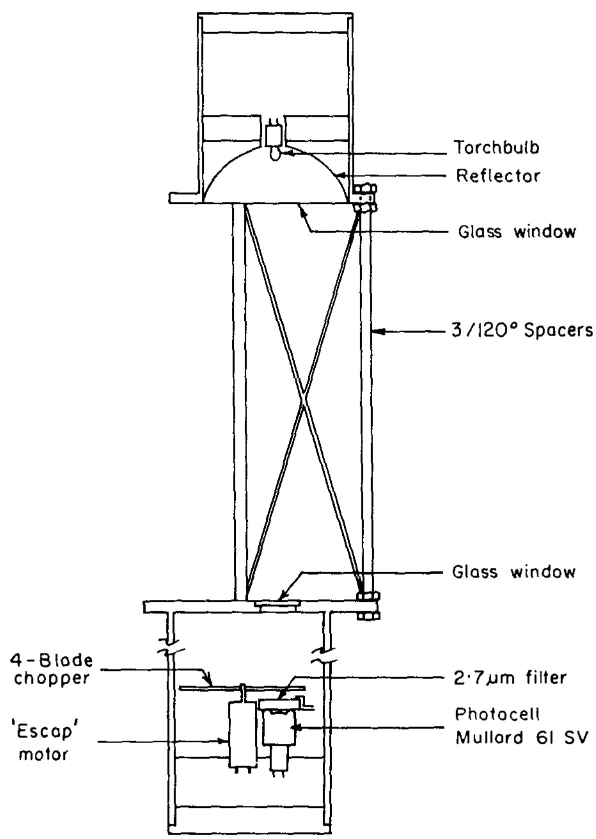


FIG. 4. Schematic arrangement of the 2.7 $\mu$m instrument.

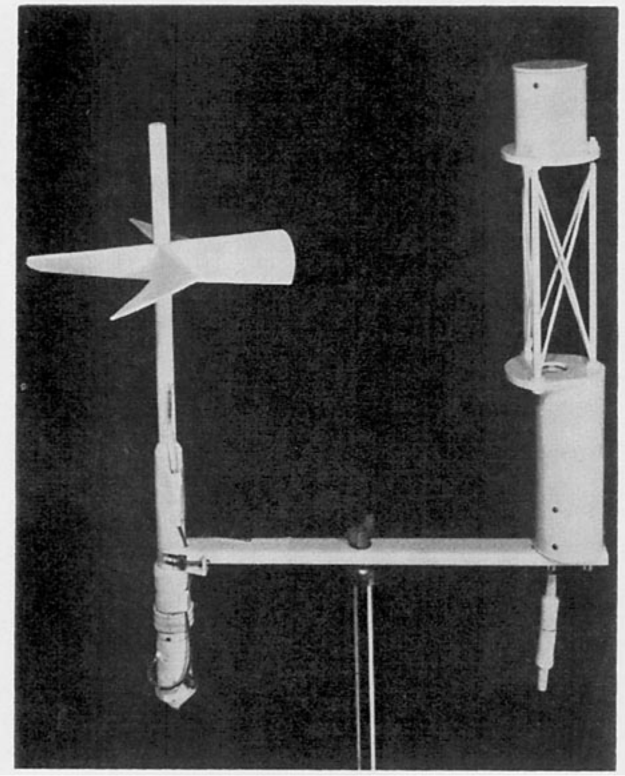

FIG. 5. Photograph of the 2.7 $\mu$m instrument and $w$ sensor.

calibration (see below), and response to higher frequencies, the pathlength chosen here is 20 cm.

In this instrument the transmission (Fig. 3) is a simple exponential [$b=1$ in Eq. (1)], due to the shorter pathlength and the weaker absorption band, which makes the calibration independent of the specific humidity. Following the same procedure as above, we have

$$\frac{\tau'}{\tau} \approx aq' \text{ [mV]}, \quad (5)$$

giving an output of 95 mV, with $q' \approx 1$ g kg$^{-1}$. However, as previously, a small temperature influence has been neglected, and an appropriate correction should be applied.

Fig. 4 is a schematic diagram of the instrument, and Fig. 5 shows the instrument together with the vertical velocity sensor for the eddy correlation studies reported below.

## 3. Instrumental noise

Tests have been conducted with the 6.3 $\mu$m instrument in the open air, but with the optical path shielded from fluctuations in wind, temperature and humidity by a tube between the infrared source and detector. The total electronic noise detected in these tests corresponds to water vapor fluctuations with a standard deviation of 0.095 g kg$^{-1}$. In the case of the 2.7 $\mu$m instrument, total noise is equivalent to a 0.18 g kg$^{-1}$ fluctuation in humidity. In both cases such electronic noise is random, and hence not correlated with fluctuations in the vertical velocity and the level is tolerable in eddy-correlation applications, where integration times of 30 min are typical.

Laboratory tests have shown that neither instrument is sensitive to wind speed or temperature variations, provided the wind is not directed into the aperture of the Nernst filament housing of the 6.3 $\mu$m instrument. To minimize the effects of wind, the 6.3 $\mu$m instrument is generally mounted vertically.

## 4. Frequency response

Both instruments contain two RC filters—one to smooth the ripple due to the chopping signal after rectification, and the other to block the dc component. These two circuits limit the use of the 6.3 $\mu$m instrument to the frequency interval between 0.005 and 0.5 Hz. The 2.7 $\mu$m device has a broader response, from 0.002 to 6 Hz. In practice, the upper frequency limit of the latter instrument is determined more by the optical beam length, the wind speed, and its orientation than by electronic noise.

## 5. Field trials

Verification of the water vapor eddy fluxes determined with the humidity sensors described here has been based on heat budget considerations. Over

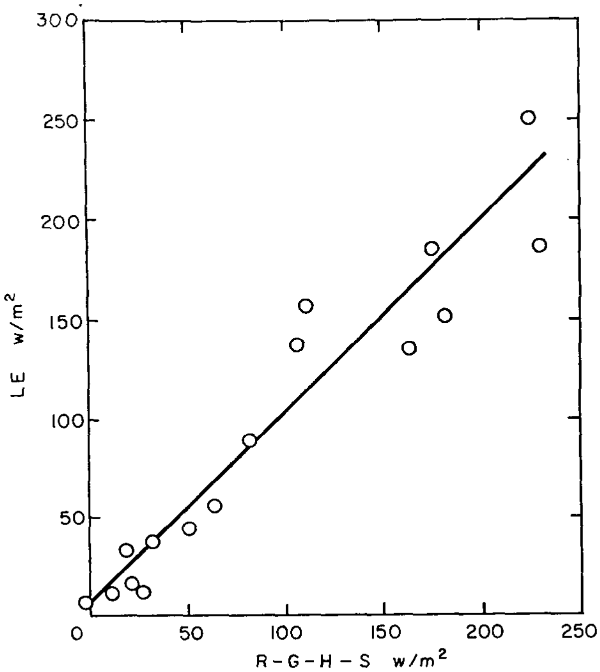


FIG. 6. $LE$ vs $R-G-H-S$ for 17 runs over grassland, $LE$ being measured with the 6.3 $\mu$m instrument.

large, uniform and flat terrain, the surface energy balance can be expressed (in steady-state conditions and neglecting photosynthesis) as

$$H+LE=R-G, \qquad (6)$$

where $H$ is the sensible heat flux, $LE$ the latent heat of evaporation, $R$ the net radiation, and $G$ the heat transfer into the ground. Using existing eddy correlation equipment to determine $H$ (Hicks, 1971), in conjunction with a conventional net radiometer and ground heat flux plates, the measurements of $LE$ using the hygrometers described here allow evaluation of the recovery ratio $r=(H+LE)/(R-G)$ and of the energy imbalance $Q=R-G-H-LE$.

The 6.3 μm instrument was tested over a grassland site neat Mt. Gambier, South Australia (Hicks *et al.*, 1975). Over 17 half-hour runs, the average values obtained were $r=1.01\pm0.06$ and $Q=-7$ W m$^{-2}$. In this experiment, the eddy correlation sensors were mounted at a height of 5 m and corrections for high-frequency loss of flux were applied, following Hicks (1972). The relation between $LE$ and $R-G-H-S$ is shown in Fig. 6.

The 2.7 μm instrument was deployed over a forest near Mt. Gambier, at a height of about 6 m above the zero plane. Fig. 7 is a plot of $LE$ vs $(R-H)$ for the period 4–6 October 1973. The data points are marked by numbers indicating the time of measurement (CST). The cluster of results near the origin represents nighttime data. A marked hysteresis effect is noticeable. Fig. 8 shows the averaged hourly values of $LE$, $R$ and $(R-H)$ over the period 1–9 October 1973, when the instrumentation operated continuously and unattended. The storage term $(R-H-LE)$ is clearly apparent. The mean discrepancy in the energy balance over a 24 h period is $R-H-LE=3$ W m$^{-2}$.

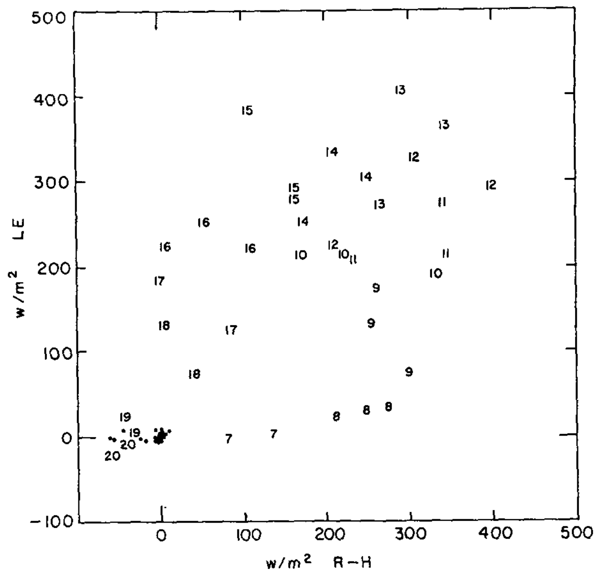


FIG. 7. $LE$ vs. $R-H$ for 3 days, as measured with the 2.7 μm instrument over a forest. Numbers indicate time (CST).

## 6. Discussion of the results

In both trials the heat flux was obtained with a thermistor to measure the fluctuations in temperature $T'$, and a propeller anemometer for the vertical wind speed $w'$. The same propeller measured $w'$ for the computation of the evaporation. This detracts from the independence of the parameters to which

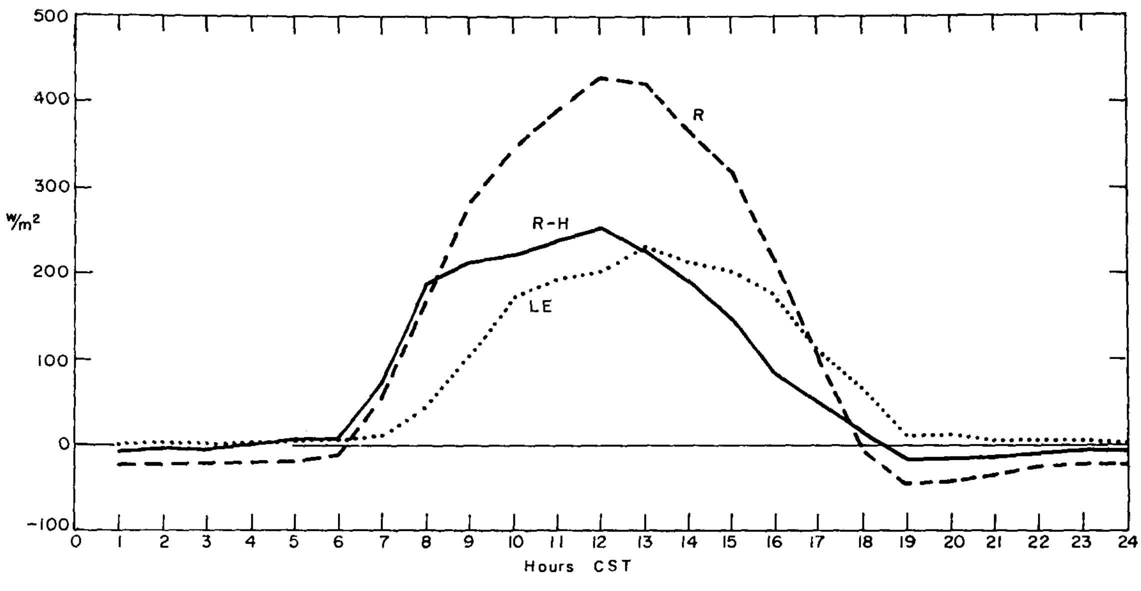


FIG. 8. Average value of $R$, $R-H$ and $LE$ plotted against local time over the period 1–9 October, 1973. $LE$ values were obtained with the 2.7 μm instrument mounted above a forest canopy. Time is Australian Central Standard.

$LE$ is compared, although an error in $w'$ would affect the comparison adversely; furthermore, the Bowen ratio was low in both trials (generally $H/LE<0.4$). The radiometer measurement which yields the larger component for comparison with $LE$ is, of course, completely independent.

It appears that the evaporation data supplied by the instruments quantitatively satisfy the energy balance requirements and that the evaporation cycle follows the energy input cycle in a realistic manner. The marked hysteresis effect shown in Figs. 7 and 8 indicates energy storage in the canopy and ground following sunrise, with release of stored energy in the afternoon, resulting in a very good 24 h budget.

## 7. Conclusions

The hygrometers described here are designed for use in conjunction with existing eddy correlation equipment. The technique used here of dividing an apparent $q'$ by the mean signal level allows the output to be independent of ambient humidity in one instrument (the 2.7 $\mu$m device) and only a slowly varying function of it in the other (6.3 $\mu$m). Also this method makes the data independent of slowly changing light source intensities or increasing dirt on the optical elements. From the eddy flux viewpoint, these features are most desirable, since they result in a simple and reliable instrument having few calibration parameters to concern the field experimenter.

The use of the present dividing technique involves, essentially, the adoption of a low-frequency cutoff in $q'$. In the present case, the limit is set at about 0.005 Hz, enabling the entire flux-carrying range of the $q'$ spectrum to be detected within reasonable heights of operation above the surface (2–20 m). The high-frequency response of the 2.7 $\mu$m instrument appears to make this model well suited to studies of the inertial subrange near the surface. This aspect is currently being evaluated.

Of the two instruments described, the second (2.7 $\mu$m) instrument is preferred. First, it operates at a wavelength where both the light source and the detector can be sealed from the external environment using glass. Second, the reduced water vapor absorptivity at this wavelength means that the calibration of the instrument is independent of the ambient humidity (cf. Eqs. 4 and 5), and nearly independent of ambient temperature, so that generally no supporting measurements of ambient parameters are required. Third, it requires considerably less power, and is lighter and easier to manipulate. Finally, it has the added advantage of a higher frequency response.

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## APPENDIX

### Correction for Temperature Fluctuations

The measured signal

$$S'=I_0\tau, \tag{1}$$

where $I_0$ is the source strength and $\tau$ is the transmission. Hence

$$S'=I_0\tau'. \tag{2}$$

The transmission, corrected for temperature and pressure is

$$\tau=\exp\left(-\alpha q\rho_a l\frac{p}{p_0}\frac{\sqrt{T_0}}{\sqrt{T}}\right), \tag{3}$$

where $\alpha$ is the absorption coefficient, $q$ the specific humidity, $\rho_a$ the density of air, $l$ the path length, $p$ the pressure, and $T$ the temperature. Thus

$$\frac{S'}{S}=\frac{\tau'}{\tau}=\left(\alpha l\rho_a\frac{p}{p_0}\frac{\sqrt{T_0}}{\sqrt{T}}\right)\left(-q'-q\frac{p'}{p}+\tfrac{1}{2}q\frac{T'}{T}\right). \tag{4}$$

We now let

$$\alpha l\rho_a\frac{p}{p_0}\frac{\sqrt{T}}{\sqrt{T_0}}=C. \tag{5}$$

The fluxatron is designed to multiply the vertical velocity $w'$ with the output from the hygrometer electronics $S'/S$. Thus the fluxatron output is

$$\overline{w'\frac{S'}{S}}=C\left[-\overline{w'q'}-q\frac{\overline{w'p'}}{p}+\tfrac{1}{2}q\frac{\overline{w'T'}}{T}\right], \tag{6}$$

where we may ignore the $\overline{w'p'}$ contribution. Now

$$H=\rho_a C_p\overline{w'T'}, \tag{7}$$

$$LE=\rho_a L\overline{w'q'}. \tag{8}$$

Hence

$$\overline{w'T'}=\frac{H}{LE}\frac{L}{C_p}\overline{w'q'}, \tag{9}$$

where $H$ is the heat flux, $LE$ the latent heat flux, $\rho_a$ the density of the air, $C_p$ the heat capacity of air at constant pressure, and $L$ the latent heat of evaporation.

Combining (6) and (9) yields

$$\overline{w'\frac{S'}{S}}=-C\overline{w'q'}\left[1-\frac{1}{2}\frac{q}{T}\frac{H}{LE}\frac{L}{C_p}\right]. \tag{10}$$

For $T=300$ this becomes

$$w'\frac{S'}{S}=-C\overline{w'q'}\left[1-4.1q\frac{H}{LE}\right], \tag{11}$$

so that for $q\approx 0.01$, the correction term is 4% of the Bowen ratio $H/LE$.

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