

CHAPTER 3

MEASUREMENT OF PRECIPITABLE WATER USING AN INFRARED SPECTRAL []

31 Introduction

The Intensity of the solar radiation received at the surface of the earth depends not only on the sun's elevation but on the varying constitution of the atmosphere, particularly its content of water vapour, dust and haze. Measurements of solar intensity at the surface of the earth can therefore be used to analyse to some extent the instantaneous composition of the atmosphere and its total water vapour content.

Because of the diurnal variation, simple measurements of intensity of solar radiation are comparable only when made at the same solar elevation and optical depth (path-length of the ray). The mean extinction coefficient would be a more comparable measure, but extinction varies rapidly with wavelength and the mean extinction coefficient is not completely independent of solar elevation.

The basic relation for the extinction of solar radiation may be written as follows:

$$I = \frac{1}{S} \int I_0(\lambda) e^{-A(\lambda)} d\lambda \quad (3.1)$$

where I is the radiation intensity measured at the

surface of the **earth**,

$I_0(\lambda)$ is the solar radiation intensity outside the atmosphere, at the mean sun-earth distance as a function of the wavelength.

$S = R^2/R_m^2$, the reduction factor for mean solar distance, R is the sun-earth distance corresponding to the date. R_m is the mean sun-earth distance, and $e^{-A(\lambda)}$ is the **transmission** of the whole atmosphere as a function of the wavelength. ?

The exponent $A(\lambda)$ is composed of three components depending on the wavelength.

$$A(\lambda) = A_R(\lambda) + A_D(\lambda) + A_W(\lambda) \quad (3.2)$$

where $A_R(\lambda)$ gives the extinction in clean dry air, according to **Rayleigh's** theory of scattering by air molecules. $A_D(\lambda)$ is the extinction due to atmospheric haze and $A_W(\lambda)$ the extinction due to absorption by water vapour.

$$A_R(\lambda) = m \cdot a_R(\lambda) \quad (3.3)$$

where m is the air mass and $a_R(\lambda)$ the extinction coefficient due to Rayleigh scattering.

$$A_D(\lambda) = m_h a_D(\lambda) \quad (3.4)$$

where m_h is the **relative** air mass, given by

$$m = 10^{-3} p \cdot m_h'$$

where p is the atmospheric pressure in **mb**, and a_D is the extinction coefficient due to atmospheric haze.

$$A_w(\lambda) = m_h \cdot a_w(\lambda) \quad (3.5)$$

where a_w is the coefficient of selective absorption by the water vapour contained in the atmosphere.

These form the basis of measurements of **precipitable** water in the atmosphere either from the **surface** of the earth or from satellites by remote sensing using infrared absorption techniques.

3.2 Water vapour measurement using infrared absorption techniques

3.2.1 Nature of water vapour absorption bands

The water vapour absorption bands are identified with the vibrational and rotational motions of the water vapour molecules. Ascribed to the three normal modes of vibration of these molecules are three intense bands (Fig 3.1) designated ν_1 , ν_2 , and ν_3 (Levine, 1975).

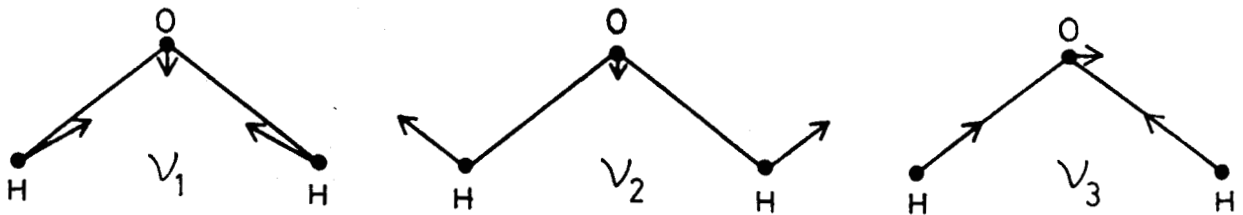


Fig.3 I Normal modes of vibration of water molecule
(Levine, 1975)

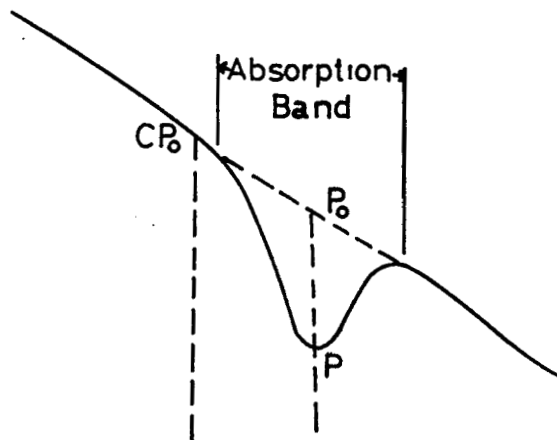


Fig 3.3 Absorption and reference bands in IRSH
(Foster, 1945)

The **vibrational** energies of a **molecule** are quantized and designated by a **vibrational** quantum number ν_k where $k = 1, 2, 3, \dots, 3N-6$ where N is the number of atoms in the **molecule**. For water, there are three such quantum numbers (ν_1, ν_2, ν_3). The ground **vibrational level** (000) is generally the most **populated level**. The most intense absorption transitions are those from the ground level (000) to the **fundamental levels** (100), (010) and (001) which correspond to **normal vibrations** ν_1, ν_2 , and ν_3 respectively, called **fundamental frequencies**. But **actually**, a rotation of the **molecule** can also occur **simultaneously** with the vibration, although with a **smaller frequency**. As a **result**, a band of **closely spaced lines** will be observed under high **resolution** instead of a sharp **line**. Hence, three **fundamental** vibration-rotation bands are observed in the case of water. These occur at wave numbers 1595, 3657, 3756 cm^{-1} (Levine, 1975) corresponding to **wavelengths** of 6.27 μ , 2.77 μ and 2.66 μ (Foster, et al, 1965). Of these three intense bands in the infrared, the last two overlap considerably, thereby forming a broad region of absorption often referred to as the 2.7 μ band. A number of other bands repre-

senting various multiples and combinations of the fundamental frequencies, occupy spectral positions from 31.7μ to 0.57μ . The more prominent bands of this group are centred in the near infrared at approximately 1.88μ , 1.38μ , 1.14μ and 0.93μ (Fig 3.2). A detailed description of the vibrational components of the water vapour spectrum is given by **Adel** and **Lampland** (1938).

As described above, rotational notions serve to shape the bands around the central **wavelengths** provided by the vibrational motions. Also contained in the water vapour **spectrum** is the strong and extensive band that lies in the far infrared beyond the so-called 10μ window. **This** band is attributed solely to the effects of rotation. Water vapour absorption bands generally diminish in strength gradually towards the shorter wavelength, with those in the visible region exhibiting relatively little absorption.

In a spectral region of continuous absorption, the relationship between the absorption and the absorbing mass can be expressed as a simple exponential function. However, such a **function** does not accurately describe

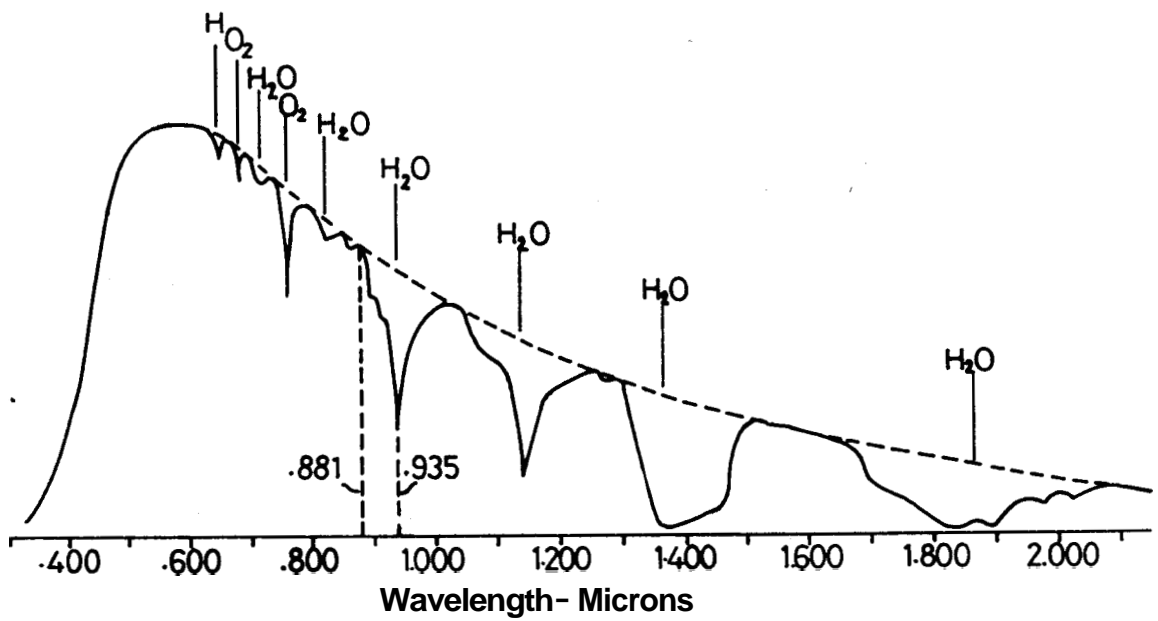


Fig. 3.2 Water vapour absorption bands in the visible and the infrared region of solar spectrum (Foster, 1945).

the absorption that occurs in the water vapour bands, as these are not of a continuous character. Actually these **bands** consist of numerous closely-spaced lines; the line patterns are also irregular in spacing and intensity. The absorption that occurs in bands having such irregularities is actually a complicated process, not precisely describable by a simple mathematical formula. The relation of absorption intensity to the absorbing water vapour mass cannot therefore be expressed by the usual exponential function (**Beer's law**) as in the case, where the region is one of continuous absorption. Nevertheless, a relationship between the absorption and the absorbing mass does exist, and the curve approximating this relationship in a particular band, or sub-interval thereof, can be established by empirical means. Furthermore, in most cases, a relatively simple square root expression closely describes this curve through a limited range of the fractional absorption.

Elsasser (1935, 1938, 1942, 1960) **formalised** the square-root absorption law, which relates specifically to sub-intervals within the infrared water vapour bands. The square root law states that the fractional absor-

ption A, which occurs in an atmospheric layer of finite thickness is directly proportional to the square root of the absorbing **mass** \bar{x} and the square root of the atmospheric pressure P and inversely proportional to the fourth root of the absolute temperature T .

$$A = K (\bar{x}P)^{1/2} T^{-1/4} \quad (3.6)$$

can be used as an expression of the square-root law. Here K is a dimensional constant that depends on the units in which the variables are expressed as well as the spectral characteristics of the particular sub-interval under consideration. Elsasser demonstrated that the square root law closely describes the actual absorption curve in the range of relatively small to intermediate values of the fractional absorption. For **strong** absorption the increase in absorption is less than the square root of the water mass.

The square-root law clearly indicates that the absorption spectra method suffers from a degree of uncertainty, due to the dependence of the absorption process on the pressures and temperatures through which the atmospheric water vapour is distributed. While the effect of temperature is a second-order one,

the effect of pressure **is** of **such** magnitude that it **must** be taken into account if observations are made at other elevations. The fact that the exact form of the **water-mass-absorption** function is not known, and probably cannot be expressed by a single equation, would appear to detract from the absorption-spectra method. This is not necessarily true since, despite the lack of information on the exact relationship between water vapour mass and absorption, an empirical relationship can be determined experimentally between absorption and absorbing mass. It is well established that within **limits**, the rate of change of absorption increases with a decrease of water vapour concentration in the optical path, leading to an increase of **sensitivity** in the infrared absorption hygrometer with a decrease in water vapour absorption.

The relative errors arising from distributional variations are also not significant, the absorption process being relatively insensitive to a) temperature, in the range of temperatures through which the bulk of atmospheric water is distributed, as the absorption varies only as the reciprocal of the fourth root of the absolute temperature, and to b) pressure, as the

bulk of the atmospheric water vapour normally appears in the lower troposphere. The vertical distribution of water vapour is weighted towards the higher pressures where the absorption process **is** relatively less affected by incremental pressure variations.

Howard **et al** (1955), in a comprehensive study of the absorption bands of water vapour and carbon dioxide, found that the empirical relation

$$A = C W^{1/2} (P + p)^K \quad (3.7)$$

fits experimental water vapour absorption data quite satisfactorily for weak absorptions. A is the total absorption, C is a constant depending on the spectral region of observation and other factors, K **is** a constant approximately equal to 0.3 and p is the partial pressure of water vapour. Other variables are as indicated for the equation proposed by **Elsasser**.

Foster **et al** (1965), considering the spacing and intensity of the **spectral** lines and hence also their degree of overlapping, concluded that the pressure dependence of the absorption region of the spectral hygrometer which monitors only a fraction of the **wavelengths** in the 0.93μ band follows a relationship somewhere between the square root and fourth root.

Howard **et al** (1955) also suggested that the effect of temperature might be smaller than that indicated in equation (3.6) . Considering that temperature as well as pressure decreases with altitude in normal atmospheric profiles and that absorption is opposingly affected by pressure and temperature when a vertical displacement of water vapour occurs, Foster **et al** (1965) concluded that an empirical calibration of the spectral hygrometer should follow closely, through a limited range of fractional absorption, the simple equation:

$$A = K^1 \cdot X^{1/2} \quad (3.8)$$

In the equation, the new constant K^1 incorporates fractions representing the integrated mean **effects** of temperature and **pressure**, as well as the fraction ascribed to the constant in equation (3.6) . The average effects of varying p and T with height are incorporated in the calibration of the spectral hygrometer, when radiosonde observations provide the comparative data for calibration. When the instrument is to be used over a wide range of pressure and temperature, the equation becomes (Foster and **Foskett**, 1945)

$$A = K \left(\frac{p}{p_0} \right)^{1/2} \cdot \left(\frac{T_0}{T} \right)^{1/4} \cdot X^{1/2} \quad (3.9)$$

where A is the fractional absorption, p_0 and T_0 are standard pressure and temperature respectively corresponding to the calibration, and p and T are the quantities corresponding to the site where A is measured. A correction has therefore to be applied to the estimated value of W , using a hygrometer calibrated as mentioned earlier. **This** can be avoided should the instrument be operated at an elevation close to that of the place where it was calibrated.

So, while the absorption spectral method can be expected to give fairly accurate relative measurements of total precipitable water, allowing for its dependence on pressure and temperature (i) the spectral hygrometer must be calibrated close to the locations and elevations where it will be operated. (ii) the instrument can be used only within a limited range of optical air mass values.

That the first of the limitations exists has been **confirmed** by King and Parry (1965). Since independent calibrations at different elevations show significant differences in the calibration curves, further work on the application of an empirical relationship such as this for general applications seems necessary. **Uncer-**

tainties due to the pressure effect resulting from widely varying quantities of the vertical water vapour content seem to be not important.

A third uncertainty arises at very low solar elevation angles primarily related to the effects of refraction and excessive scattering and to possible timing errors associated with the rapidly changing long optical paths.

3.2.2 Infrared absorption techniques

It was Fowle (1904, 1912) who originally suggested that measurements of radiation in two regions of the infrared spectrum, one in a water vapour sensitive absorption region and the other close by, where no water vapour absorption occurs, would enable the determination of the amount of water vapour in the path by spectrophotometric observations. This required the measurement in the laboratory of the absorption resulting from known amounts of water vapour at the wavelengths at as nearly as possible conditions of temperature, density and temperature as exist in the atmosphere. The laboratory source used by Fowle (1912) was a Nernst lamp, the wavelengths at which measurements were made being 11 3μ and 1.47μ , the determinations covering

quantities of water vapour up to 0.5 cm precipitable water over path lengths of more than **250** metres. From the absorption **vs** humidity data obtained with this instrument, he was able to transfer the calibrations to other spectrosopes used in solar observations and thus measured the total water in the earth's atmosphere (**Fowle, 1913**). Since **Fowle's** work, scientists in the field have developed infrared absorption hygrometers of varied design and operation, both for measuring ~~atmo-~~spheric total precipitable water overhead and for measuring water vapour at the **earth's surface** and in the atmosphere. (Hand, 1940; **Staats et al, 1965**; Tank and **Wergin, 1963**).

Wood (1958) used an infrared hygrometer with a **light** beam as the principal sensing element for the measurement of water vapour in the atmosphere. Composed of two narrow bands of infrared radiation, this beam traversed a 30 cm path through a sample atmosphere containing the humidity concentration to be measured. Wavelength isolation was by means of germanium coated narrow band-pass interference filters at two wavelengths, one at 2.60μ subject to attenuation by water vapour and the other at 2.45μ , free from absorption by water vapour. The ratio of the transmitted band energies is sensitive to the

concentration of water vapour in the path and is effectively maintained at unity by a servo-operated glass wedge which moves to compensate for energy imbalance caused by changes in absorbing vapour. The wedge position is read by an electrical transducer calibrated in terms of vapour density, g m^{-3} . He also showed that vapour concentration W , total pressure P and partial pressure p of water vapour may be related to fractional absorption A by the equation.

$$A = C \cdot W^{0.6} \cdot (P + p)^{0.23} \quad (3.10)$$

Prototype instruments employing interference band pass filters for isolating particular wavelengths of interest have been built by the U.S. Weather Bureau (Foskett and Foster, 1953; Wood *et al*, 1954). These instruments made use of the 1.38μ absorption band and utilized a reference wavelength of 1.24μ .

Foster and Foskett (1945) developed a **spectrophotometer** to determine the precipitable water in a vertical column of the atmosphere using the sun as a source.

A transmission grating was used to disperse the sunlight, and two exit slits were positioned where the radiation corresponding to absorption band (0.94μ) and reference band (1.01μ) came to focus. A phototube was used as a detector which received radiation alternately from the two exit slits. The output signals were amplified and the ratio **was** calculated. This is typical of the dispersive type of optical **system**. The instrument was calibrated by comparison with radiosonde observations.

Another approach is absorption spectra analysis using a **non-dispersive** optical system. In the instrument developed by the U.S. Weather Bureau described by **Foster, Volz** and Foskett (1965), the system was mounted on a **sun-tracking** arrangement. The two **bands** of radiation centred at 0.935μ and 0.881μ were obtained separately using narrow **bandpass** filters and received by two matched silicon solar cells. The instrument was **so** designed that the ratio of the photocurrents generated by the cells **is** proportional to the ratio of the **respective** transmitted radiation intensities. The ratio of currents is determined with the help of a **ratio-bridge** circuit. Calibration was done empirically **from** simultaneous values of total precipitable water calculated

from radiosonde observations.

In a similar instrument described by Kondratyev, **et al**, (1965) the two separate beams 0.935μ and 0.8804μ are incident on the two **havles** of a photo-element. These photocurrents are made equal by adjusting the width of the slit which allows the reference band. The reading of the micrometer screw which controls the slit width which is then proportional to the ratio of **fluxes**. This is an example of a null balancing method.. These two were also calibrated against radiosonde measurements.

To isolate the two bands of radiation, a rotating sector filter was used by Wood (1958) . Similar null balancing instruments are described by Hirst **et al** (1 970) and Siverstaen and Solheim (1975) . By means of rotating chopper discs, the two beams are allowed one after the other to fall on the detector and the intensities of the two bands of radiation are continuously compared electronically, and are made equal by introducing extra attenuation into the more intense beam. This is achieved by adjusting the angle between infrared polaroids kept in the path of the reference radiation beam. The angle between the polaroids is then the output which is an

indicator of water vapour absorption. In these instruments the same detector senses the radiation corresponding to the two spectral regions. This eliminates possible errors due to **differences** in the characteristics of two separate detectors used to receive the radiant fluxes.

Foskett **et al** (1953) have outlined basic advantages of the absorption spectra principle for water vapour measurements in the atmosphere. **i)** it provides instantaneous measurements of absolute humidity over path lengths from a few **mm** to **km**, as well as the integrated value over the whole atmosphere, if the **sun** is used as the source of radiation, **ii)** it provides precise measurements at very low vapour concentration, unlike other techniques which invariably fail at low temperatures and very low humidities, **iii)** the speed of response of the instrument is high, as it is controlled only by the speed of response of the associated electronic and servo systems and is **ideal** where rapid changes in humidity occur, **iv)** the method does not interfere with medium, by adding or subtracting water or **changing** its state, **v)** the **instrument** can be made light and portable, and is easy to operate and can

provide, quick, instantaneous measurements of precipitable water and continuous records, if it is mounted on a **suntracker**. A **single** beam filter-photometer with a relatively **simple** optical system, freedom from critical alignment problems and a minimum of auxiliary electronic equipment has obvious basic advantages, which are important in an instrument designed for general field use.

The disadvantages are that precipitable water measurements using the sun as a source can be carried out only during the day or when clouds do not obscure the sun or the region immediately surrounding it. **The** real problem, however, is its stability and the ability **to** obtain reproduceable data.

3.3 The infrared **spectral hygrometer**

3.3.1 Principle of measurement

The basic principle of the instrument is, as mentioned earlier, the measurement of the ratio of the intensity of solar radiation in two narrow regions of the solar spectrum, one lying in the water vapour absorption band and the other just outside it.

If P_0 is the radiant power from the sun falling on

top of the atmosphere within a narrow region in the water vapour absorption band, and P that received on the surface of the earth, the fractional absorptance A is given by:

$$A = \frac{P_0 - P}{P_0} = 1 - \frac{P}{P_0} \quad (3.11)$$

A is a function of the amount of absorbing material, namely the amount of precipitable water W . Therefore, $\frac{P}{P_0}$ is a function of W . The reference point chosen

lies just outside the absorption band (Fig 3.3)

(Foster and Foskett, 1945) and suffers no absorption due to water vapour in the atmosphere. The power

received in this narrow spectral region is proportional to P_0 , say $C P_0$. Therefore, the ratio $\frac{P}{C P_0}$ which is

proportional to $\frac{P}{P_0}$ is a measure of W in the path of

the solar radiation. That is, the ratio of flux

received in the two spectral regions is a function

of W . If the amount of water vapour changes, the

radiant energy in the absorption band changes while

the energy in the reference band remains the same, thus

giving a change in the ratio. However, if the flux

changes only because of haze, mist, smoke etc., the

energy ratio remains the same, unless there is a significant difference in scattering between the two spectral regions. By determining the value of the ratio of energies for different known amounts of W , a calibration can be obtained.

3.3.2 Selection of spectral region

Several important considerations go into the selection of the spectral bands. For example, there should not be atmospheric ingredients other than water vapour which absorb in the band chosen. Strong absorption bands by carbon dioxide do overlap water vapour absorption bands in the near infrared and the band used **must** therefore be so **situated** spectrally as to eliminate any effect of carbon dioxide. There **must** be no appreciable absorption by any of the optical parts of the system. The wavelengths chosen **should** be as close **as** possible to that of the maximum intensity in the solar spectrum. Also, **it** is important that the band corresponds to that of intermediate fractional absorption for the amount of water vapour content expected in the sensing path. If the absorption is too strong, total absorption may occur **when** the water vapour content is high. If the absorption is too weak, the change in

absorption for a given amount of W will be small, and the instrument will suffer from insensitivity and **instrumental** errors will tend to **mask** true values. The central region of the 0.935μ band gives a satisfactory range of fractional absorption for the amount of water vapour usually encountered in the path of normal incidence through the **earth's** atmosphere (Foster and Foskett, 1945). The 0.88μ band exhibits little or no absorption and therefore serves as an excellent region of reference (Fig 3.2). For a long optical path **and** high humidities, a band such **as** the 0.93μ is suitable, while for a short path length **and** low humidities a band such as 2.7μ **is** more desirable. Early work indicated that for best results, the maximum absorption should be kept to 40 per cent or less (Foskett et al, 1953).

3.4 Description of the infrared spectral hygrometer

3.4.1 System Description

The complete instrument on its stand is shown in **Fig** 3.4, while Fig 3.5 shows the instrument with its cover removed. The arrangement of the various optical **components** is shown in Fig 3.6. Two band pass filters F_1 and F_2 are mounted on either side

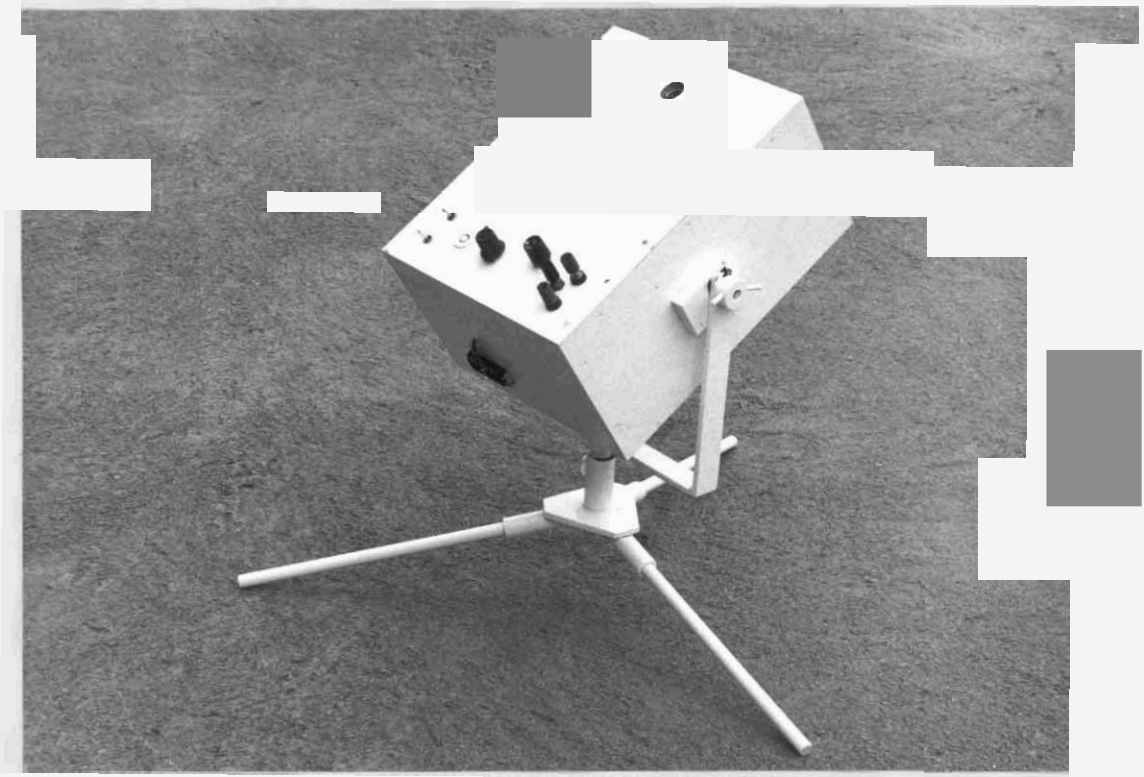


Fig 3.4: Infrared spectral hygrometer on stand

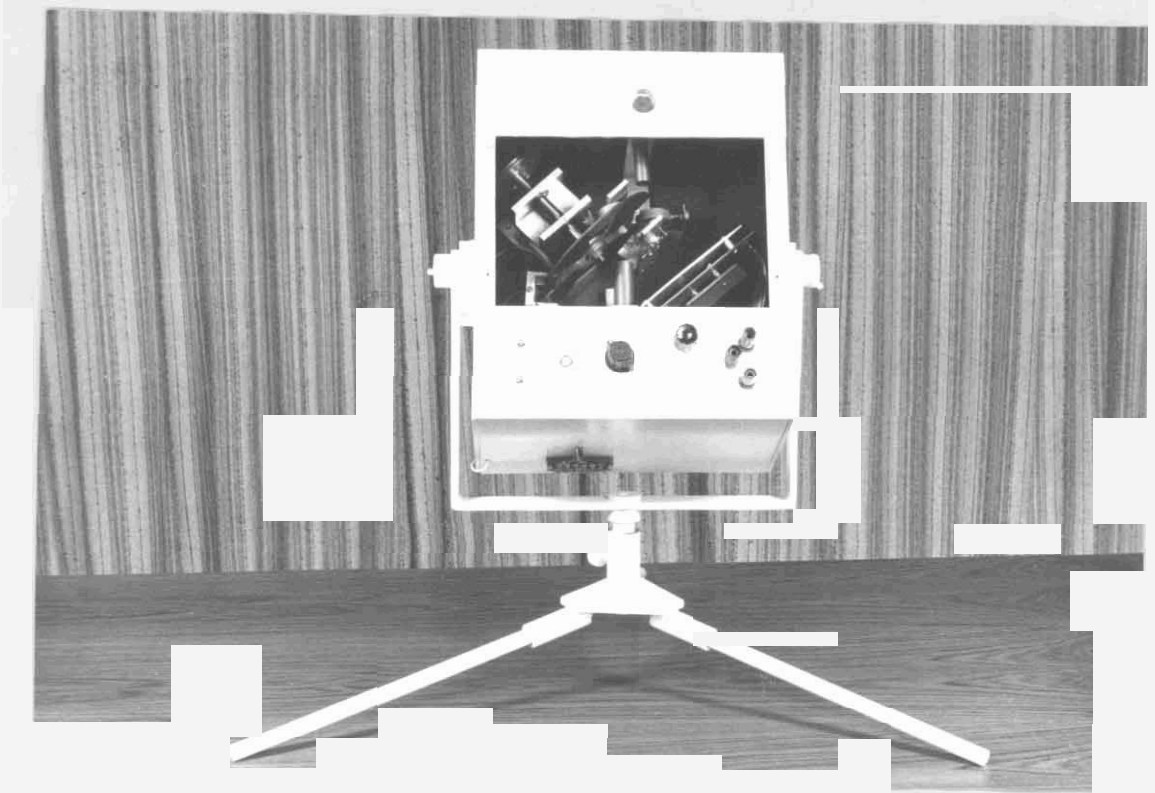


Fig 3.5: Infrared spectral hygrometer with cover removed

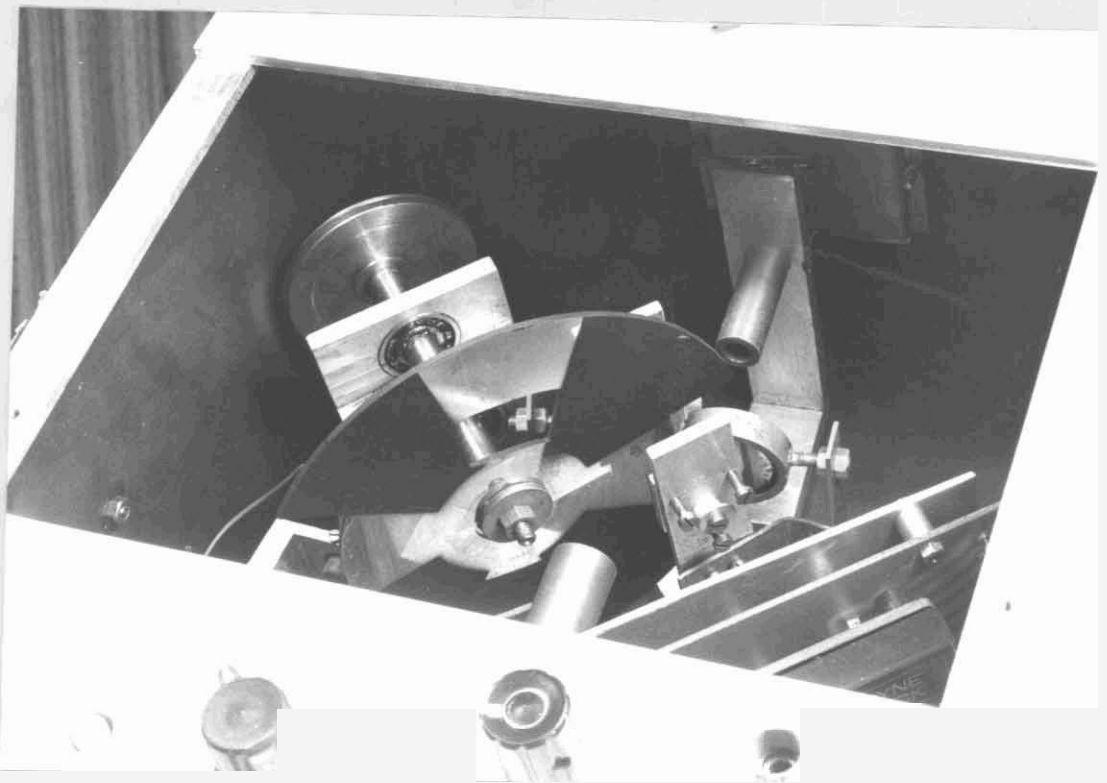
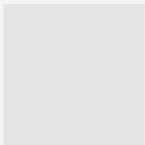


Fig 3.6: Infrared spectral hygrometer showing arrangement of various optical components.



of a rotating chopper disc M (Fig 3.7) and the incoming pencil of solar radiation SB is made to pass through the two infrared filters in a particular sequence by the chopper and the mirrors m_1 and m_2 . Radiation in the two spectral bands is received by the same infrared detector IRD one after the other, in a given sequence. The two signals are electronically amplified and detected synchronously. The A.C. amplifier gain is automatically adjusted to hold the output corresponding to the reference band channel at 1 volt. The actual output of the absorption band channel thus gives the ratio of the photocurrents generated in the detector.

3.4.2 Optical system (Fig 3.7)

The circular glass chopper disc M having a diameter of 12 cm used to isolate and separate the two bands is shown in Fig 3.8. The chopper was cut carefully to form sectors along two concentric tracks. The sectors marked TR are open and radiation passes through it. Those marked R were silvered and those marked BL were blackened on both sides. The chopper was fixed to a shaft mounted on ball bearings and was run smoothly

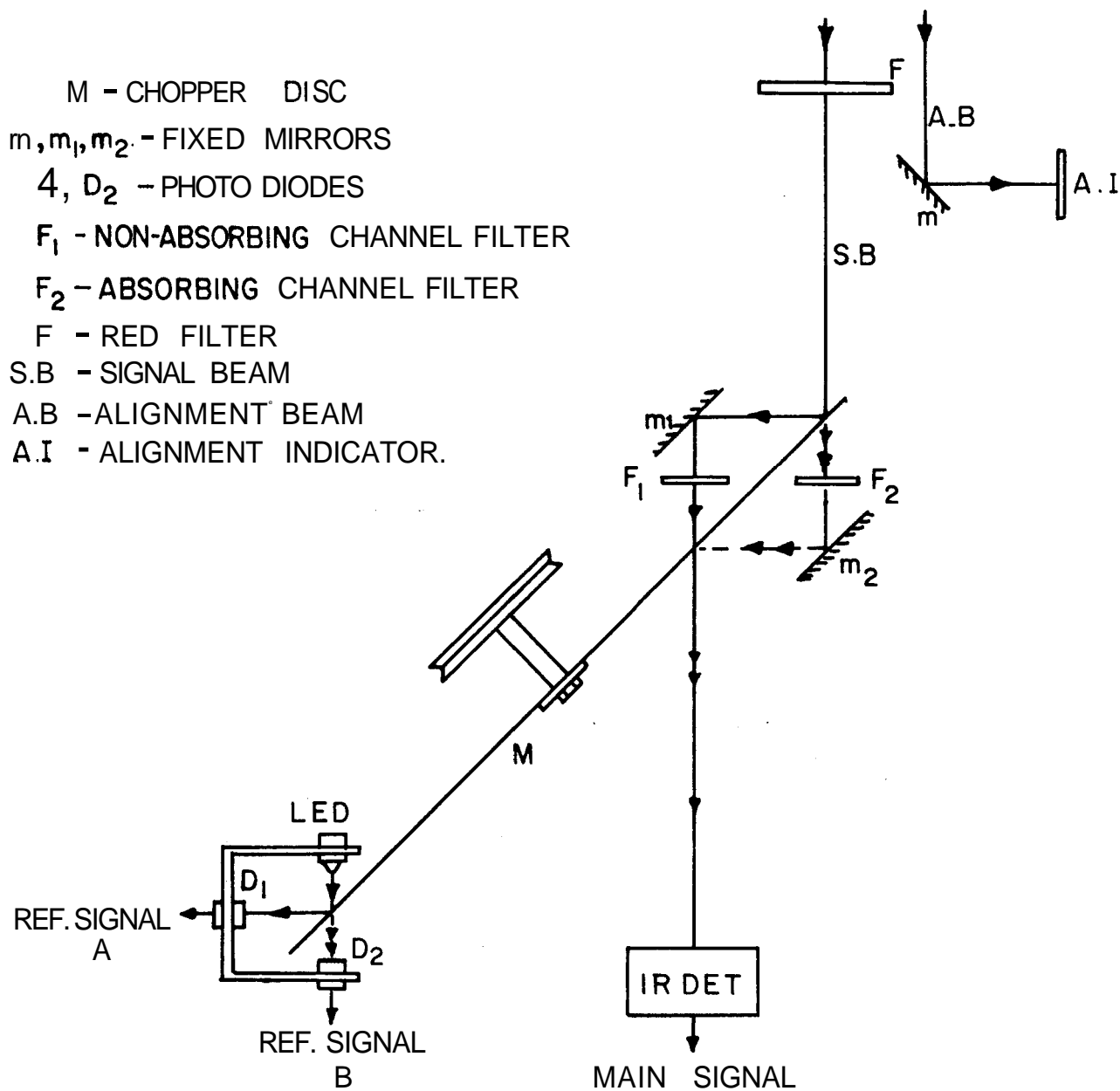


Fig. 3.7 Optical system of infrared spectral hygrometer

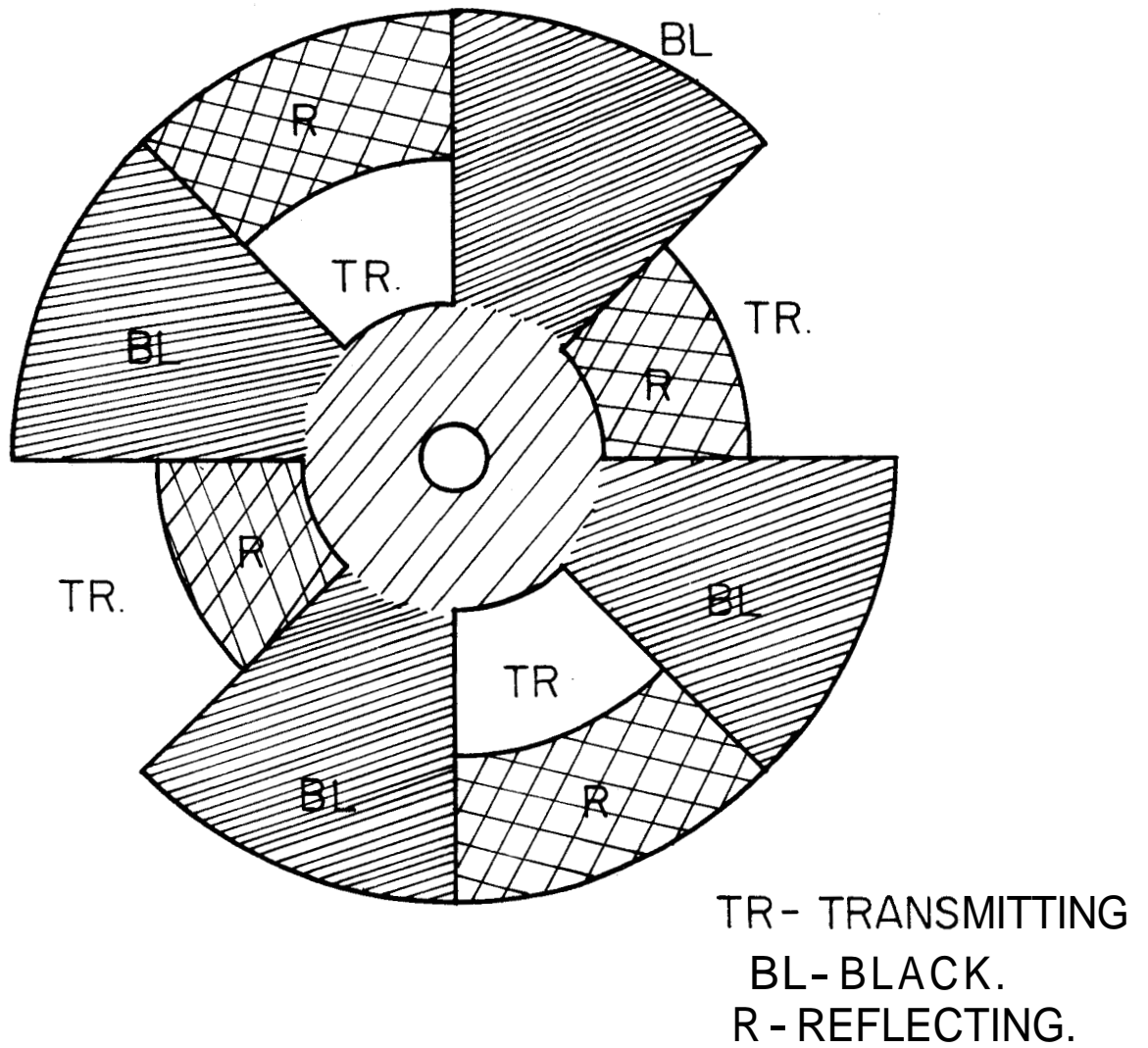


Fig.3.8 Chopper disc M

by a motor using a belt and wheel arrangement (Fig 3.7).

The sensor IR DET is a PbS photoconducting infrared detector biased by a d.c. supply through a load resistor, and with a response in the spectral range of interest. The two spectral regions isolated by narrow-bandpass interference filters F_1 and F_2 have the central wavelengths at 0.881μ and 0.935μ . The entrance aperture of the **instrument** is covered by a gelatine red filter with a cut-off wavelength at 0.75μ sandwiched between two thin glass plates. This prevents visible radiation wavelengths smaller than 0.75μ falling on the detector and eliminates the possibility of the **bandpass** filters transmitting higher orders of wavelengths.

Sunlight entering the instrument passes through a small collimator of diameter 8 mm and is led to the outer track of the chopper disc M, which is inclined at 45° to the front face of the instrument (Fig 3.7) . The frequency of rotation of the chopper disc is around 12 cycles per second. Fig 3.7 **shows** how the chopper disc M isolates the two bands. Two small mirror strips m_1 and m_2 are mounted parallel to M and positioned in such a way that they receive a ray **from/through** the

outer track of the chopper and reflect it through/from the inner track towards the IR detector when the instrument is aligned properly. In the two possible paths for the beam, the radiation will pass through one of two interference filters F_1 and F_2 before striking the **inner** track. The two bands do not enter the sensors immediately after one another; they are separated from each other by the BL sectors of the chopper, between the TR **and** R sectors.

The eight sectors of either track of the chopper are all equal, in width. The resulting output signal of the detector is shown in Fig 3.9. The heights of alternate signals are proportional to the **photocurrents**, which are proportional to the intensities of the two bands.

In the same horizontal plane containing the centre of the chopper and passing through the mirrors m_1 and m_2 are also mounted one red LED, and two photodiodes D_1 and D_2 as shown in Fig 3.7. Mirrors m_1 and m_2 , lie on one side of the centre of the chopper disc and the photodiodes and the LED on the other. When solar radiation falls on m_2 , D_2 receives light from the LED through the open space sector of the outer track. So

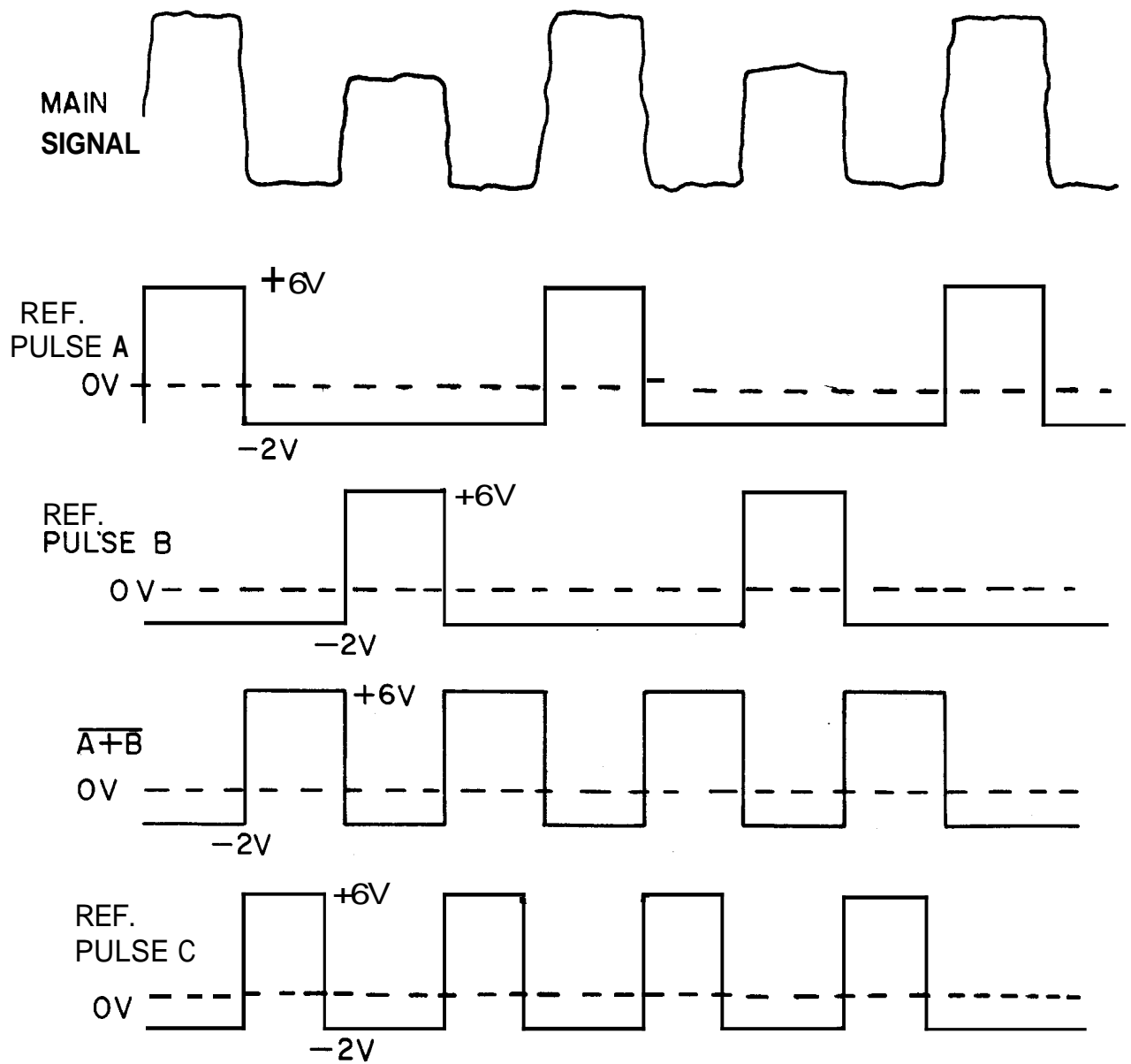


Fig 3.9 Timing diagram of reference pulse waveform and main signal

does D_1 after reflection from the reflecting sector of the outer track when m_1 , receives solar radiation. Thus D_1 provides a square wave (Reference A) in phase with the main signal corresponding to F_1 (0.881μ) the reference band and D_2 (Reference B) corresponding to the absorption band F_2 (0.935μ) (Fig 3.9). These reference pulses A and B enable the detection of the main signals corresponding to the two bands. The phase relation between the main signal and reference signals is also indicated in Fig 3.9.

It will be seen that the two beams traverse identical optical paths and suffer two identical reflections. The mirror strip m_2 is provided with aligning screws at the back so that its orientation can be adjusted to make the two beams travel practically along the same path before entering the IR detector. A high degree of symmetry is thus maintained. Right above the entrance aperture is an arrangement to form an image of the sun on a translucent glass plate fixed on the top cover. This is used as an indicator to align the instrument with the sun. All these optical components together with the preamplifier were housed in one compartment of an aluminium box 28 x 22 x 14 cm, the inside of which

was coated black and the outside painted white (Fig 3.6) .

3.4.3 Electronics

The functional block diagram is shown in Fig 3.10. The photocurrent in the IR detector is proportional to the radiant energy incident on it. Therefore the voltage developed across the load resistor is a measure of the **intensity** of incident radiation. The ratio of the voltages corresponding to the absorption band and reference band is determined electronically after amplifying the signal and is the ratio of the corresponding radiant fluxes $\frac{P}{CP_0}$, which depends on W . An AGC amplifier holds the output voltage of the reference channel (V_1) to 1 volt, so that the actual voltage of the absorption channel (V_2) as measured by a voltmeter is the ratio to be determined.

The IR detector output is fed to a low drift, low noise, high input impedance instrumentation amplifier which serves as a preamplifier (Fig 3.11). The next stage is the AGC amplifier (CA 3028A) whose control voltage is biased at around 5V. The amplifier has a linear response in this condition for an input in the range of 20 mV to 100 mV. The output is an AC coupled

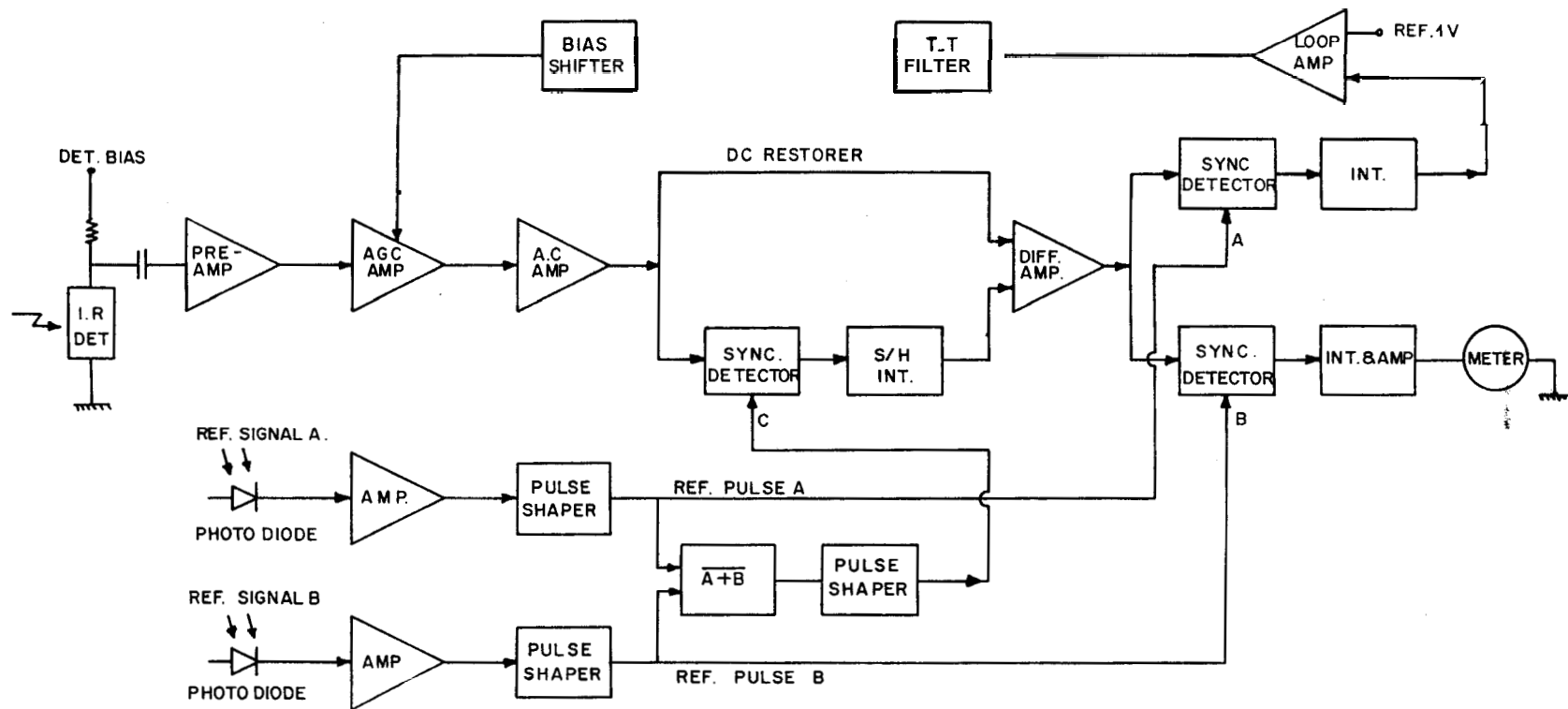


FIG.3.10 BLOCK DIAGRAM OF INFRARED SPECTRAL HYGROMETER

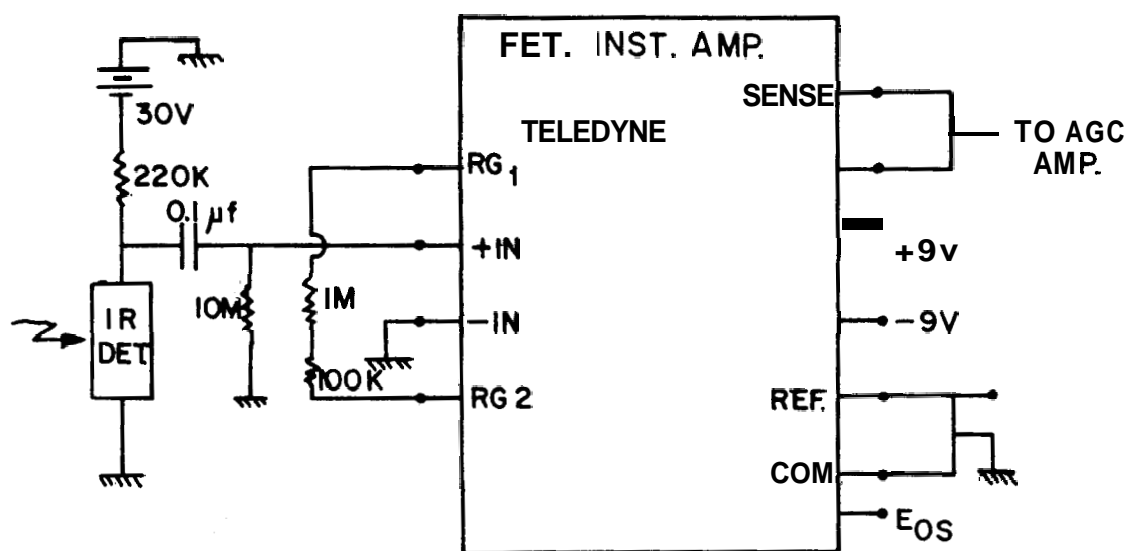


Fig 3.11 IR detector and preamplifier.

signal which is amplified by a **variable** gain-amplifier (Fig 3.12). The DC is then restored in the following way.

Two reference pulses (A, B) corresponding to the two signal **channel** are generated by the photodiodes D_1 and D_2 and are shaped using a non-inverting buffer IC (CD 4050), after amplification. A third train of reference pulses $\overline{A + B}$ is generated with a nor gate (CD 4001). The leading edge of this triggers a monostable **multivibrator** (CD 4047) with a time constant of ~ 10 ms. This square wave with a width of ~ 10 ms is the reference C pulse. Details are shown in Fig 3.13. Reference C is in phase with the portion of the output signal corresponding to the BL sector of the chopper disc (Fig 3.8). This portion of the signal is detected synchronously by one of the units of CMOS switch CD 4016, controlled by Reference C and fed to an S/H-integrator circuit and the output is taken as the reference voltage in the next differential amplifier to which the other input is the signal corresponding to the two chosen bands. The pulses in the output actually represent the magnitudes of the two signal voltages V_1 and V_2 . Fig 3.12 gives the details of the circuit.

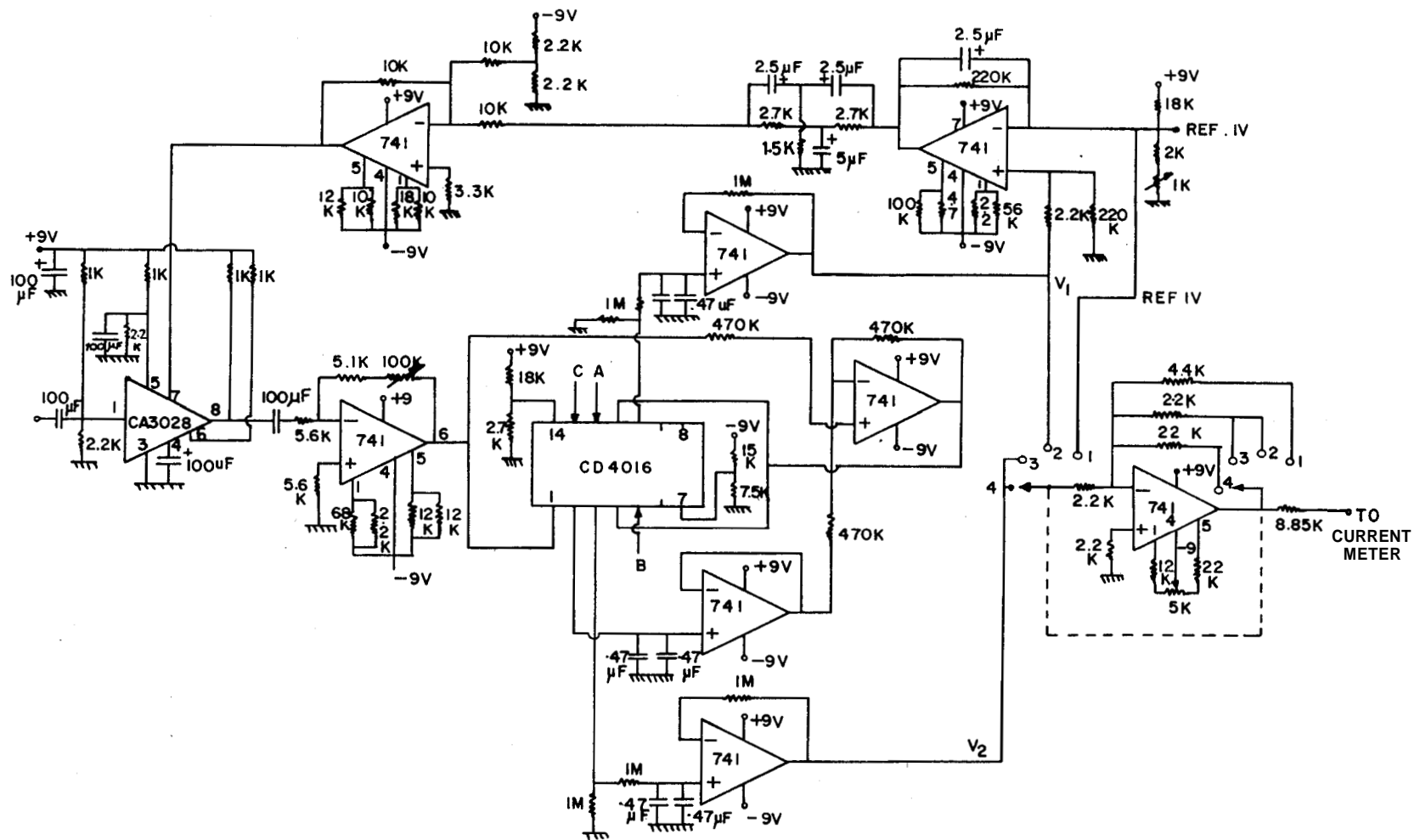


Fig 3.12 Circuit diagram of infrared spectral hygrometer

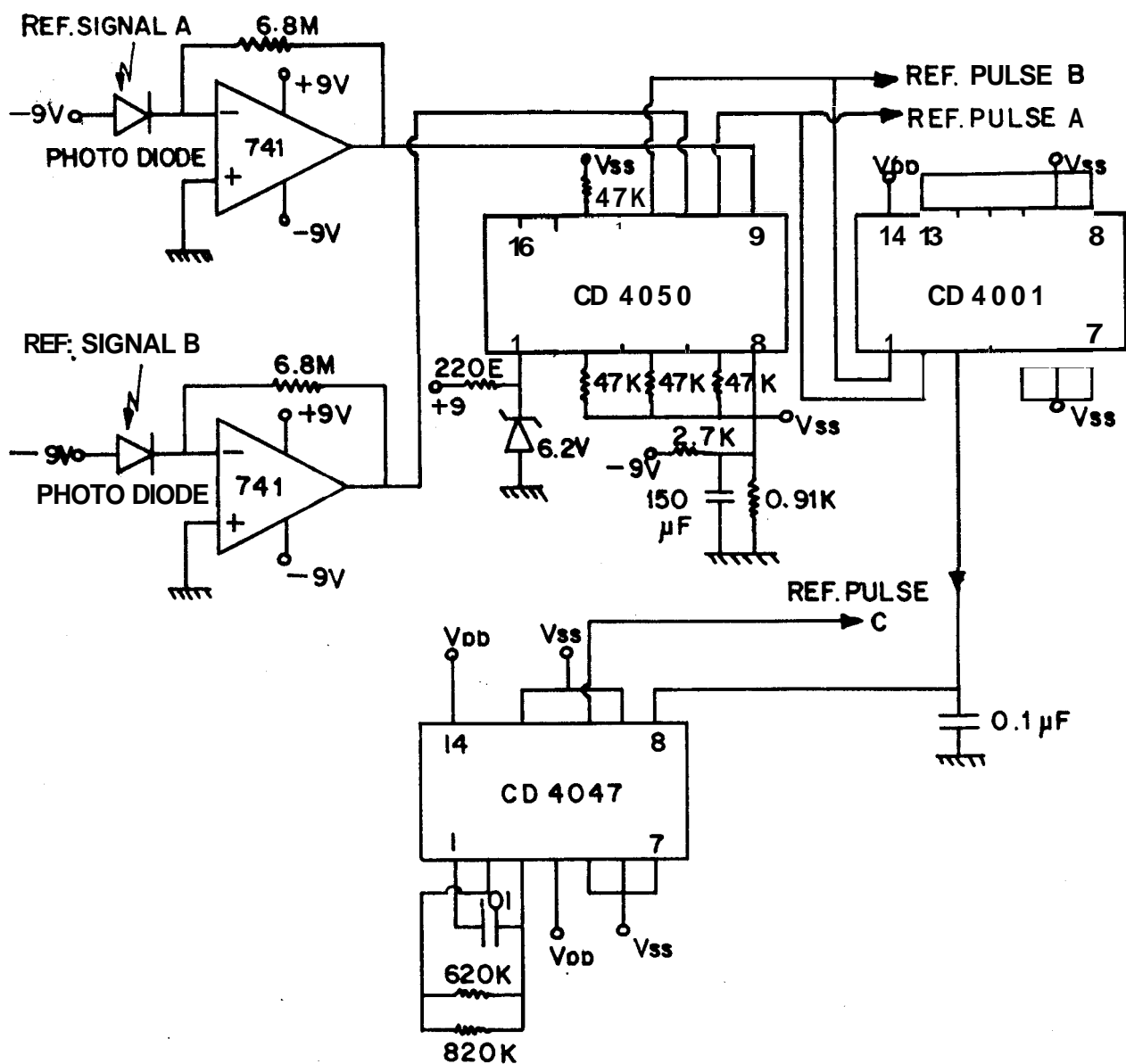


Fig.3.13 Reference signal (pulse) amplifier and shaper.

The output of the differential amplifier is detected synchronously by Reference A and Reference B pulses. Thus, reference band signal A and absorption band signal B are separated into two channels. The A channel signal **after** integration is sensed by the loop amplifier with reference to 1 volt and the difference is **amplified**. A twin-tee filter suppresses any 25 Hz oscillation leaking through the amplifier corresponding to the frequency of the reference pulse. A fixed **D.C.** (bias) voltage (4.5V) is added to this and fed back to the **AGC** amplifier to control its gain. **Thus**, the gain is automatically adjusted so that V_1 **is, always** maintained at 1V, and can be monitored using the selector **switch**. The B channel output is integrated and is **connected** to a voltmeter which gives a full scale deflection for 1V through an amplifier of unity gain.

3.5 Calibration of the Hygrometer

The calibration procedure consists of comparing the hygrometer ratios obtained from the instrument with concurrent or interpolated values of precipitable water computed from radiosonde data. This is necessary since the numerical ratio does not provide an absolute measure

of precipitable water in the path.

Calibration in the laboratory is not feasible because of the excessive path lengths required to duplicate the typical quantities of water vapour that exist in the atmospheric paths of the solar **beams**. Laboratory techniques also yield only constant pressure calibration data. Since theoretical and experimental knowledge of the pressure effect is still somewhat limited, adjustment of these data to the approximate average conditions prevailing in the solar-inclined atmospheric paths would only add to the uncertainties of calibration.

The calibration curve for the infrared spectral hygrometer based on a total of about 82 radiosonde ascents made at Bangalore and **Nandi** Hills is given in Fig 3.14, where line-of-sight values of **precipitable** water W in mm , are plotted against the values of ratio R from the infrared spectral hygrometer.

A least square fit line is shown. The regression coefficient is 0.74. The average **rms** difference between the fitted line and the precipitable water given by the radiosonde is about 3 mm .

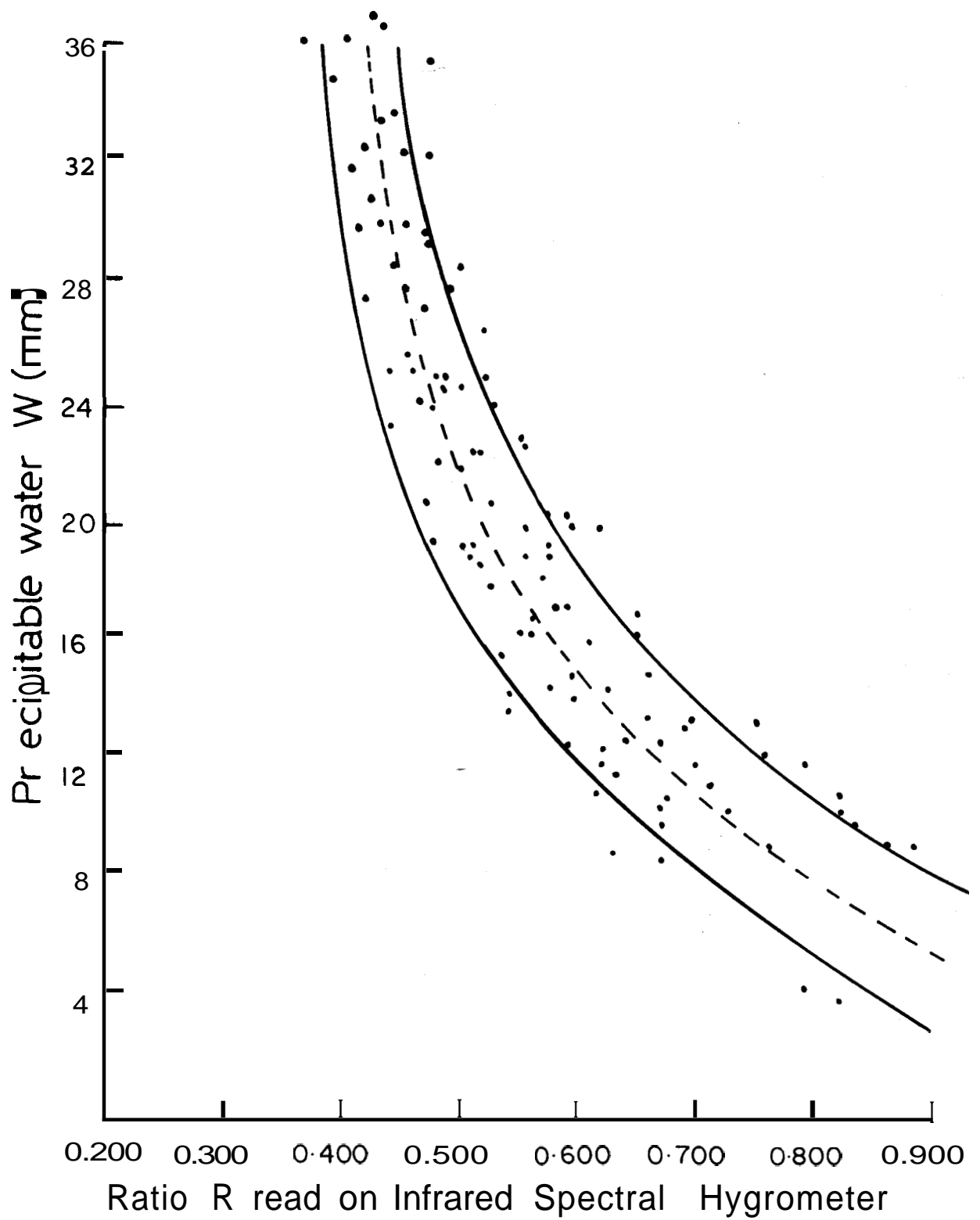


Fig. 3.14 Calibration curve of the Infrared Spectral Hygrometer

A statistical comparison between the precipitable water values obtained by King and Parry (1965) using the hygrometer and from radiosonde computations had shown that the two values fall within **0.13mm** of each other **65%** of the time and within 0.25 mm of each other 90% of the time. Differences have a Gaussian distribution around zero difference. The hygrometer was thus shown to be capable of measuring total precipitable water with as great reliability as the radiosonde. The considerable scatter observed was ascribed by them to

1) Imperfect humidity measurements by the radiosonde and errors in the computation of W, of the order of **\pm 20** per cent or more (See para 2.3.2.5) . The lithium chloride hygristor is particularly unreliable in the measurement of low humidities at all temperatures. At **-40°C** the typical lag of the radiosonde humidity sensor is about 10 minutes. Even under the most favourable circumstances, radiosonde humidity measurements **cannot** be more accurate than **\pm 10%** relative humidity. At relative humidities below 20 per cent, the sensor ceases to function and all water vapour below this level are thus omitted from the computation.

2) The hygrometer and the radiosonde measure total precipitable water along different paths and at different times, when there might be small scale variations in the moisture content. In actual practice, the balloon may drift with the wind as it ascends and the integrated water **vapour** content may then be measured over an area as large as 100 km in diameter. In any case, the calibration procedure requires that W be multiplied by a proportionality factor, the ratio of the length of the solar inclined atmospheric path to that of the zenith atmospheric path. This ratio in the optical air mass is approximated by $\text{cosec } \theta$, where θ is the elevation angle of the sun. The optical **airmass** is expressed more precisely by Bemporad's formula (Smithsonian Meteorological Tables, 1951) **particularly** for solar elevations below 20° .

3) Errors inherent in the spectrophotometric techniques. The effect of pressure and unwanted differential attenuation are the main causes.

4) **Instrumental** errors which might be of the order of a few percent. These are discussed in detail in para 3.4.5.

5) Random errors, which are, however, minimised by taking a large number of observations. Most of the calibration errors are largely compensating and the calibration curve despite its rather appreciable scatter appears to provide an adequate calibration of the instrument.

Daily mean values of W obtained with the spectral hygrometer at Bangalore during 1980-81 are plotted in Fig 3.15.

3.6. Sources of errors and **accuracy** of measurements

The most desirable characteristic of an instrument is accuracy and the ability of the instrument to maintain a known accuracy over a long period of time. Errors in measurement can be both systematic and random or accidental. In meteorological measurements, the problem of errors in measured values is complicated by the fact that measured quantities are themselves not constant but are subject to change on various space and time scales.

Field and laboratory tests carried out by various workers have shown that the infrared spectral hygrometer has, in principle, the necessary stability, linearity

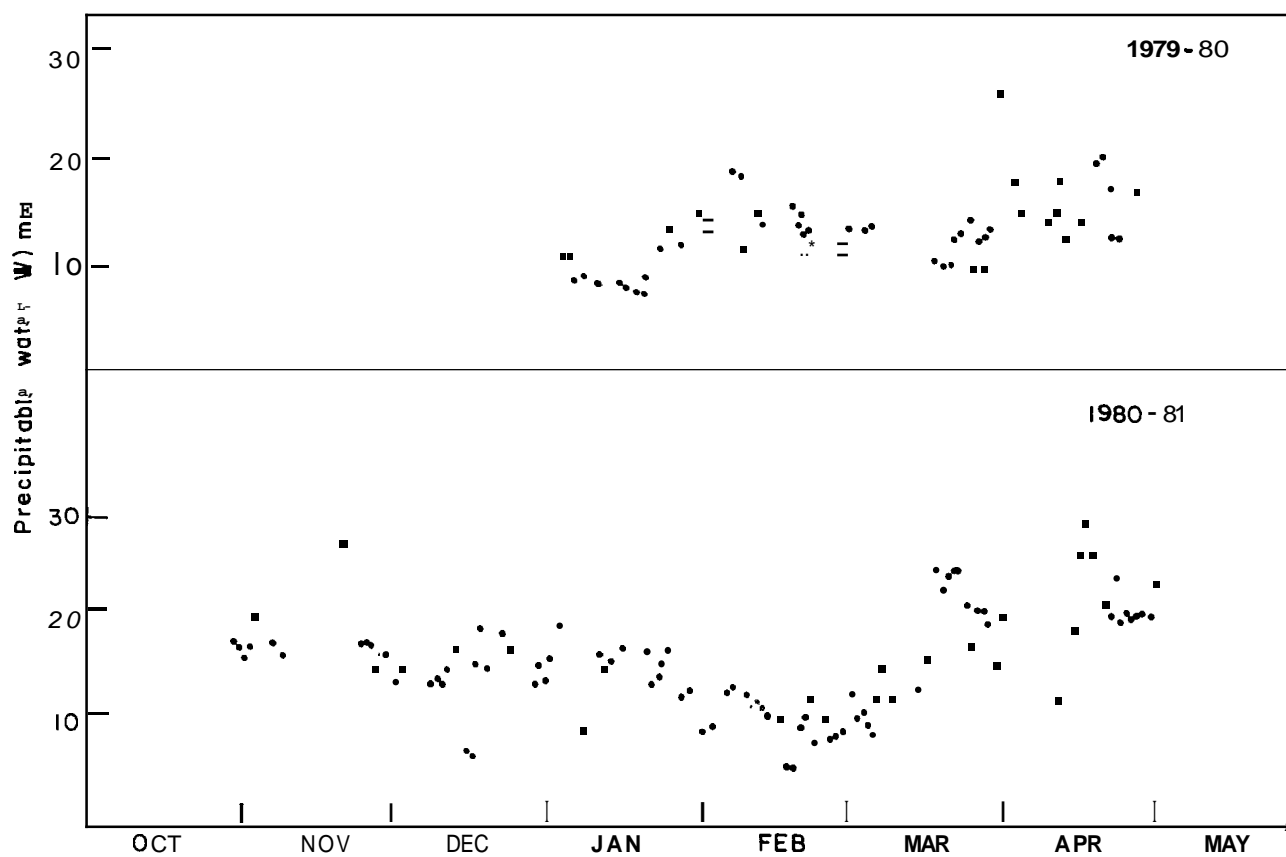


Fig 3.15 Daily mean values of W over Bangalore for 1980-81 obtained with the infrared spectral hygrometer

and reliability for routine precipitable water measurements. However, in actual practice, **instrumental**, observational and **calibration errors** can occur, **The** calibration curve itself of the hygrometer was found to change during the 3-year long period of observations and at **Bangalore** and Nandi Hills, therefore periodical calibration of the instrument had to be repeated and the latest calibration curves used in the evaluation of the data.

Instrumental errors can arise from various factors such **as** the incorrect optical **alignment** of the components of the **system** **and** the temperature dependence of optical components such as the broad band pass and interference filters. Scattered and reflected light within the instrument can also give rise to errors. Observational errors can arise from incorrect pointing of the instrument at the sun or by intensity fluctuations of the incident radiation during observations and personal errors. These are, however, small and typically of the order of 5%.

Ideally the IRSH should measure the ratio of true fluxes of the two spectral regions; but the measured ratio may be different from that of the true value

for the following reasons:

(i) The reflections undergone by the two beams at the chopper disc and at the mirrors m_1 and m_2 may not be identical.

(ii) If the filters are not held in the same orientation with respect to the corresponding beams, the absorptions and reflections if any at the surface, will be different.

(iii) There may be non-uniformity in the blackening or the sizes of the sectors of the chopper disc.

(iv) The two beams may not fall on the same spot on the IR detector.

(v) The spectral response of the IR detector may not be identical for the two wavelengths used.

If the above factors, even if present, remain unaltered during the calibration and measurement period, the calibration curve should take care of these errors.

Additional errors can be caused by:

i) The collection of dust or dirt within the instrument, resulting in differential absorption.

ii) Differential scattering in the atmosphere; this effect changes with the air mass and would be larger for greater air masses.

iii) Variations in supply voltages to the instrument. This possibility is, however, minimised by using a regulated power supply.

Any gain variations or effects of temperature variations on amplifiers are minimised, because the electronic system is switching system between the two spectral regions.

At very low values of W ($< 6\text{mm}$) even a slight error can vitiate the readings because of the inherent uncertainties involved in radiosonde measurements and also since the number of points in the calibration curve are few. For high values of ($> 25\text{mm}$) small errors in observation can lead to large uncertainties in W because of the nature of calibration curve.

Pressure induced uncertainties do not normally exceed 0.7 to 1.2 mm, although extreme variations have been **known** to cause occasional errors of 2.5 mm (Foster et al, 1963).

It can be said that in the intermediate range of W , the IRSH can give as accurate results as those given by radiosonde (within 5%). However, the systematic errors in radiosonde will be present. Therefore IRSH can be said to give W with an overall error typically of 25%.

3.7 Summary

An infrared spectral hygrometer designed and constructed by the author is described and the results of measurements made at Bangalore of the precipitable water in the atmosphere are presented. The various instrumental, calibration and observational errors are discussed. The most attractive feature of the instrument is its ability to measure precipitable water with virtually no **instrumental** lag and the freedom from effects of local smoke and pollution. The main drawback of the instrument is that measurements are limited to days when the sun and the immediate region of the sky around it is free from clouds.

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