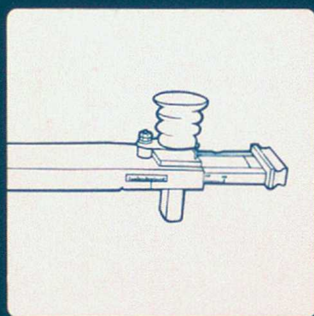
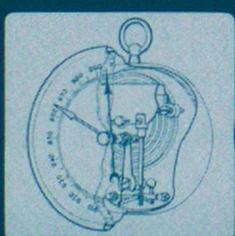
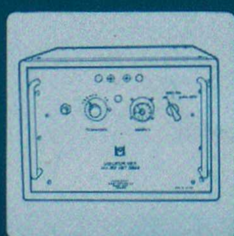
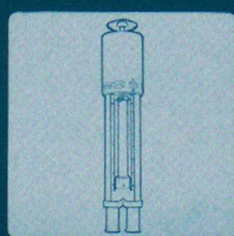
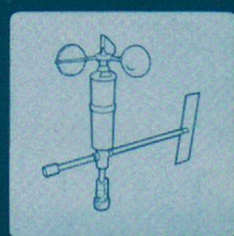
Meteorological Office

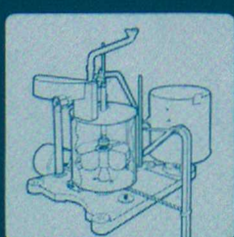
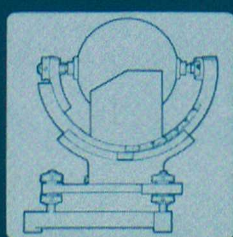
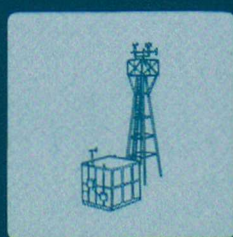
Handbook of Meteorological Instruments

Second Edition

7 Measurement of Visibility and Cloud Height



HMSO

Met.O. 919g

METEOROLOGICAL OFFICE

HANDBOOK OF METEOROLOGICAL INSTRUMENTS

SECOND EDITION

VOLUME 7

MEASUREMENT OF VISIBILITY AND CLOUD HEIGHT

LONDON
HER MAJESTY'S STATIONERY OFFICE

UDC 551.508(02)

First published 1956
Second edition 1982

HER MAJESTY'S STATIONERY OFFICE
Government Bookshops
49 High Holborn, London WC1V 6HB
13a Castle Street, Edinburgh EH2 3AR
41 The Hayes, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
Southey House, Wine Street, Bristol BS1 2BQ
258 Broad Street, Birmingham B1 2HE
80 Chichester Street, Belfast BT1 4JY
Government publications are also available through booksellers

ISBN 0 11 400338 6

INTRODUCTION

The first edition of the *Handbook of meteorological instruments* was prepared by the Instruments Division of the Meteorological Office in 1953, to provide a comprehensive source of information on the design, installation, operation and maintenance of all instruments then in use at Meteorological Office stations. Since then numerous improvements have been made to existing instruments, and new instruments and instrument systems introduced into service. This revised edition, whilst retaining some of the original material, gives information on the more recently developed instruments, and records the modifications made to some of the instruments previously described. In general, only instruments currently in use are included and if information is required on older, obsolete, types reference should be made to the previous edition.

Initially, eight separate volumes, each dealing with a specific aspect of meteorological instrumentation for surface observations, are being presented as follows:

Volume 1 Measurement of Atmospheric Pressure
Volume 2 Measurement of Temperature
Volume 3 Measurement of Humidity
Volume 4 Measurement of Surface Wind
Volume 5 Measurement of Precipitation and Evaporation
Volume 6 Measurement of Sunshine and Solar and Terrestrial Radiation
Volume 7 Measurement of Visibility and Cloud Height
Volume 8 General Observational Systems

When complete, the set can be bound to form one book.

Although this handbook is intended primarily to provide information for Meteorological Office personnel about the instruments used at official stations, particulars of some other types are included to illustrate different principles. Where these other types are not described in detail, sources of fuller information are given. It is hoped that the book will also be helpful to users of meteorological instruments outside the Meteorological Office. These readers should, however, understand that certain instructions on procedures are for the guidance of Meteorological Office personnel.

In addition to giving, where applicable, instructions for the installation, operation, and maintenance of Meteorological Office pattern instruments, this handbook deals with accuracy and sources of error.

The general requirements of meteorological instruments, both indicating and recording, are:

(a) Accuracy
(b) Reliability
(c) Ease of reading and manipulation
(d) Robustness and durability
(e) Low cost of ownership.

Most meteorological instruments have to be maintained in continuous operation and many are partially or wholly exposed to the weather. These restrictions call for especially high standards of design and manufacture. The need for uniformity is one of the most important requirements for meteorological measurements. The decisions and recommendations of the World Meteorological Organization, which affect instrument practice, have therefore been followed as closely as possible.

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VOLUME 7
MEASUREMENT OF VISIBILITY AND CLOUD HEIGHT

1 MEASUREMENT OF VISIBILITY — GENERAL

1.1 Definition

Visibility is defined as the greatest distance at which an object can be seen and recognized in daylight, or at night the distance at which an object could be seen and identified were the general illumination raised to a daylight level. The criterion of recognizing the object, i.e. of perceiving its shape and nature, is emphasized.

The commonest method of determining the visibility is direct estimation by observation of suitable objects by day and lights at night. It is unlikely, in the forseeable future, that these methods will be entirely superseded by instrumentation, but the availability and continued development of suitable instruments will no doubt accelerate the trend in the use of automatic instrumentation. Although estimation is not measurement, it is included in this volume because of its importance amongst the current methods for determining visibility.

To improve the scientific basis of visibility measurements, in 1957 the World Meteorological Organization (WMO 1971) recommended the adoption of a new measure of the optical state of the atmosphere — the Meteorological Optical Range (MOR). The MOR is defined as the length of a path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp at a colour temperature of 2700 K to 0.05 of its original value. Although meteorologists are primarily interested in the MOR and their observations of visibility are aimed at measuring MOR, the term 'visibility' is still used almost universally instead of MOR and this practice will be followed in this handbook.

1.2 Quantities and fundamental units

Light may be defined as electromagnetic radiation capable of inducing a visual sensation through the eye. Because visibility has historically been evaluated mainly by visual estimation, it has been appropriate to discuss the theory by using the concepts of photometry, which are defined in relation to the response characteristics of the human eye, rather than by using the concepts of the physics of radiant energy (see, for example, Middleton 1952). However, modern instrumentation for visibility measurement is not confined to the use of 'visual' radiation but may make use of, for example, infra-red wavelengths. It is therefore now more appropriate to develop the theory in terms of the fundamental physics of radiant energy. The relationship between the various quantities used in the case of radiant energy and their equivalents in photometry is simply a numerical parameter, the luminous efficiency, sometimes called the visibility factor. This parameter depends upon the wavelength of interest; the absolute value is of little consequence but its relative magnitudes across the visible spectrum are of importance in relating instrumental measurements of radiant energy of selective wavelength to the equivalent visibility. The various quantities required to develop an elementary theory of visibility are given in Table I in which the equivalent photometric quantities are given in parentheses.

1.3 Theory

The radiant flux of a beam passing through the atmosphere is reduced by scattering and absorption. The combination of these effects is generally referred to as the extinction coefficient and is defined in terms of the exponent in Bouguer's law:

$$\Phi = \Phi_0 e^{-\sigma x}, \qquad \ldots (1)$$

where Φ is the radiant flux remaining in a beam of initial radiant flux Φ_0 after traversing a distance x through a medium with extinction coefficient σ. The extinction coefficient can be expressed as the sum of an absorption coefficient a and a scattering coefficient b:

$$\sigma = a + b. \qquad \ldots (2)$$

For pure dry air the absorption is negligible compared to the scattering and this condition is generally maintained in the atmosphere even in very poor visibility.

Table I. *Quantities and units of radiant energy*

Quantity	Definition	Unit	Symbol
Radiant flux	Power emitted or received in the form of electromagnetic radiation	watt	Φ_e
(Luminous flux)	(Power emitted or received in the form of light)	(lumen)	(Φ_v)
Intensity	Radiant flux emitted per unit solid angle	watt steradian^{-1}	I_e
(Luminous intensity)	(Luminous flux emitted per unit solid angle)	(lumen steradian^{-1} or candela)	(I_v)
Radiance	Intensity per unit surface area of an extended source for a surface perpendicular to a specified direction	watt steradian^{-1} metre^{-2}	L_e
(Luminance)	(Luminous intensity per unit surface area of an extended surface for a surface perpendicular to a specified direction)	(lumen steradian^{-1} metre^{-2} or candela metre^{-2})	(L_v)
(Illumination)	(The luminous flux received on unit area of a surface)	(lux = lumen metre^{-2})	(E)

In the following sections radiation quantities are used in connection with instrumentation and photometric quantities where the human element is involved.

An alternative characteristic of the atmosphere, which describes the manner in which radiation is attenuated as it passes through the atmosphere, is the transmission coefficient τ, which is defined as the fraction of the initial radiant flux which remains in the beam after passage along a path of unit length. Thus,

$$\tau = e^{-\sigma}.$$

The transmittance T of a path of length x through the atmosphere is then defined as

$$T = \tau^x = e^{-\sigma x}. \quad \ldots (3)$$

The MOR, M, can therefore be obtained, by definition, from

$$T = 0.05 = e^{-\sigma M},$$

$$\text{or } M = \frac{-\ln 0.05}{\sigma} = \frac{2.9957}{\sigma} \quad \ldots (4)$$

Consider a small volume dv of the atmosphere illuminated by a parallel beam and suppose a portion $d\Phi$ of the incident radiant flux Φ is lost from the beam through interaction with the particles present in dv. At a distance large compared to the linear dimensions of dv the small volume may be regarded as a point source. If $I(\phi)$ is the intensity of dv, considered as a point source, in the direction ϕ with respect to the incident beam, then we define the scattering function for the scatterers within dv as $\beta(\phi)$ in the equation

$$I(\phi) = d\Phi\beta(\phi).$$

To totalize the radiant flux scattered from dv we integrate with respect to solid angle (ω) completely from 0 to 4π steradians, i.e. $\int_0^{4\pi} I(\phi)\, d\omega$, and this, in the absence of absorption which we regard as negligible, must be equal to $d\Phi$. Thus,

$$\int_0^{4\pi} d\Phi\beta(\phi)\, d\omega = d\Phi.$$

From the geometry of the spherical polar co-ordinate system we have the standard result that

$$d\omega = \sin\phi\, d\phi\, d\Theta,$$

where Θ is the declination angle. Thus,

$$\int_0^{4\pi} d\Phi\, \beta(\phi)\, d\omega = \int_0^{2\pi}\int_0^{\pi} d\Phi\, \beta(\phi) \sin\phi\, d\phi\, d\Theta$$
$$= 2\pi \int_0^{\pi} d\Phi\, \beta(\phi) \sin\phi\, d\phi,$$

but $d\Phi$ is independent of ϕ so that

$$2\pi \int_0^{\pi} \beta(\phi) \sin\phi\, d\phi = 1. \quad \ldots (5)$$

It is convenient to define a function $\beta'(\phi)$ called the volume scattering function. Suppose a collimated beam of radiant flux Φ to be incident upon a lamina of the atmosphere of thickness dx. Consider a volume of unit cross-sectional area viewed from a sufficient distance to be considered a point source. We may define a volume scattering function $\beta'(\phi)$ such that, viewed in direction ϕ with respect to the incident beam, the scattered intensity from unit volume of the atmosphere is

$$I'(\phi) = \Phi\beta'(\phi).$$

If we assume that the scattering characteristics of the particles within the volume are not a function of the volume itself we may write $I(\phi)$ the scattered intensity in direction ϕ from any volume dv, small enough to be considered a point source, as

$$I(\phi) = \Phi\beta'(\phi)\, dv.$$

Since we are considering a volume of unit cross-sectional area, $dv = dx$ and the total amount of radiant energy lost from the beam is

$$\int_0^{4\pi} I(\phi)\, d\omega = \int_0^{4\pi} \Phi\beta'(\phi)\, dx\, d\omega.$$

However, provided absorption is negligible, the total energy lost from an elemental path dx, of unit cross-sectional area, is, from Bouguer's law,

$$d\Phi = -b\Phi dx.$$

Thus, substituting for $d\omega$ and integrating we have

$$2\pi \int_0^{\pi} \beta'(\phi) \sin\phi\, d\phi = b. \quad \ldots (6)$$

In addition to the optical properties of the atmosphere, the determination of visibility by estimation involves the characteristics of the human eye. The response of the eye to light is limited to wavelengths in the range 0.4 μm to 0.7 μm and is defined, for light of wavelength λ, as the ratio of the luminous intensity at wavelength 0.550 μm, where the response of the eye is greatest, to the luminous intensity at wavelength λ required to produce equal impressions of luminance. Green light with a certain luminous intensity will therefore appear much brighter to the eye than red or violet light with the same luminous intensity. The question of colour does not normally arise when viewing distant objects as all objects tend to appear grey when nearing the limit of visual range.

An object will only remain visible so long as there is contrast between it and its background. If the luminance of the object is L and the luminance of the background is L', the contrast C is defined by

$$C = \frac{L - L'}{L'} \quad \ldots (7)$$

and in theory may range in value from −1 to infinity. In practice, very large, but not infinite, values of C may occur when considering lights at night, but in the daytime the value of C seldom exceeds 10.

As the value of L approaches that of L' a value of C is reached at which the eye can no longer distinguish between the object and the background; this value of C is called the threshold of contrast ϵ.

The luminous intensity of the light which is reflected from an object and received by the eye is affected by the atmosphere in two ways:

(a) by diminution, in accordance with equation (3), and

(b) by light reflected from other sources, e.g. the sun, sky or earth, also reaching the eye.

The luminances of the object and the background are both modified by the factor $e^{-\sigma x}$ so that, assuming σ to be constant over the optical path, there will be no alteration in contrast due to the first effect. The second effect, however, causes equal increases in the luminances of the object and the background, with a consequent change in contrast.

Suppose an object and its background have luminances L_0 and L'_0 respectively when viewed close at hand, and L_R and L'_R when viewed from a distance R, then,

$$L_R - L'_R = (L_0 - L'_0)\,e^{-\sigma R}. \qquad \ldots (8)$$

Using equation (7) the 'inherent' contrast may be written

$$C_0 = \frac{L_0 - L'_0}{L'_0}$$

and the 'apparent' contrast may be written

$$C_R = \frac{L_R - L'_R}{L'_R}.$$

Following the theories of Koschmieder (1926), equation (8) may then be written

$$C_R = C_0(L'_0/L'_R)\,e^{-\sigma R}. \qquad \ldots (9)$$

The simplest situation to visualize is an object viewed against an unchanging background, i.e. the horizon, when $L'_0 = L'_R$, so that equation (9) becomes

$$C_R = C_0\,e^{-\sigma R}. \qquad \ldots (10)$$

As the object distance increases, C_R decreases according to equation (10) until at some value of R, $C_R = \epsilon$ and the object would no longer be distinguishable, i.e. the object would be at the visual range V. Hence

$$\epsilon = C_0\,e^{-\sigma V}. \qquad \ldots (11)$$

For a black object, which has zero luminance, $C_0 = -1$ and equation (11) becomes

$$\epsilon = -e^{-\sigma V},$$

or $$V = \frac{-\ln \epsilon}{\sigma}$$

The value of ϵ recommended by WMO is 0.05. This equation can therefore be written,

$$V = \frac{-\ln 0.05}{\sigma}, \qquad \ldots (12)$$

following the theories of Koschmieder (1926), and has equality with equation (4). Thus if σ is measured, the MOR, which is equivalent to the daylight visibility, can be obtained approximately from equation (4).

If dark-coloured objects are not used or the objects are viewed against a terrestrial background, the observed value of V will, in general, be less than that given by equation (12). If, however, the terrestrial background distance is at least 1.5 times the object distance, the error due to having a terrestrial background is negligible.

1.4 Visibility objects

The assessment of the visibility in daylight is generally based on the observation of suitable objects at known distances. The principles involved in the selection of the objects are: (a) the objects should be black or very dark-coloured and should stand above the horizon when viewed from the normal observing point, and (b) the objects should subtend an angle of at least 0.5° in width and elevation to the observer but not more than 5° in width. This upper limit can easily be exceeded with near objects unless care is taken. The angle of 0.5° may be estimated by making a hole 7.5 mm in diameter in a card. When the card is held at arm's length the hole will subtend the specified angle at the observer's eye. As a guide to size, an angle of rather more than 0.5° is subtended by an object 1 m wide at 100 m, 10 m wide at 1000 m, and so on in proportion. It may be necessary to select smaller objects if the above specification cannot be complied with.

If an object with a terrestrial background has to be selected, the distance between the object and the background should be at least half the distance between the object and the observing point. A tree at the edge of a wood, for example, would not be suitable for visibility observations. A white house would also be unsuitable, particularly when the sun is shining on it, but a group of dark trees would be satisfactory except when brightly illuminated by sunlight.

At distances beyond 1000 m where there is a choice of objects, the larger object should be selected. For distances beyond a few kilometres it is usually necessary to select topographical features such as ridges or hill tops, though these are not ideal objects because they may be hidden at times by low cloud, or their luminance may be modified by seasonal features, e.g. a covering of snow.

1.5 Determination of visibility at night using lights

Visibility reports at night should indicate the same degree of atmospheric transparency as they would by day; the change from daylight to night-time does not in itself alter the visibility. The most suitable objects for determining the visibility at night are unfocused lights of moderate luminous intensity at known distances and the silhouettes of topographical features against the sky.

The distance at which a light can be seen at night depends mainly on the following factors:

(a) the luminous intensity of the light,

(b) the sensitivity of the observer's eyes,

(c) the presence or absence of other bright lights in the field of view,

(d) the general level of illumination, and

(e) the transparency of the atmosphere.

In determining the visibility from the observation of fixed lights the effects of the first four factors should be reduced as far as possible. After leaving a lit room the observer should allow at least two minutes to elapse in order that his eyes may adapt to the dark.

Luminous intensity and colour of selected lights. Each selected light should be of constant and known rating and luminous intensity which should not vary greatly with the direction from which the light is viewed. Lights fitted with lenses or mirrors to direct the light in preferred directions should not be used. Flashing lights may be used provided that the duration of each flash is at least one second.

The atmosphere transmits different colours unequally. Therefore coloured lights should not be used at distances greater than 100 m, otherwise appreciable errors may be introduced. In addition, the absorptive properties of any covering on a lamp, such as on an aerodrome red obstruction light, will result in a luminous intensity very much less than that of the lamp alone.

The luminous intensity of a light, where unknown, may be determined by measurement using a visibility meter (see page 7–8) on a night of good visibility, i.e. 15 km or more. The observer should stand at a carefully measured distance from the light, between 10 m and 100 m depending on its luminous intensity, and should adjust the visibility meter until the light is only just visible through it. This should be completed within three minutes of leaving a lit room. If the meter reading is N and the distance from the light is D, the luminous intensity I of the light is given by,

$$\lg I = 0.03N + 2 \lg D - K,$$

where K has the value 6 during twilight, 6.7 in moonlight and 7.5 in complete darkness.

The illumination produced at the eye by a light so faint that it can only just be seen is termed the visual threshold; it varies somewhat from one observer to another and for the same observer at different times. For practical purposes average values have been assumed in Figure 1 corresponding to (a) twilight or when there is appreciable light from artificial sources, (b) moonlight or when it is not quite dark, and (c) complete darkness or with no light other than starlight.

With the exception of red light, the visual threshold of the eye for indirect vision, i.e. looking a little to one side of the light, is greater than for direct vision after a few minutes have been spent in the dark. The visual threshold of the eye for indirect vision, again except for red light, continues to increase for an hour or more after the observer has gone from a lit room into weak illumination or darkness, whereas for direct vision the eye adapts completely to the dark in about two minutes. Indirect vision should not be used for visibility observations and a light should only be regarded as visible if it can be seen when looking at it directly.

Use of nomograms to determine visibility. The relationship between daylight visibility and the distance at which a light is just visible at night is shown graphically in Figure 1. Each nomogram shows the distance at which lights of various luminous intensities, from 1 to 10^6 candelas, are just visible when the equivalent daylight visibility has any value between 10 m and 10 km. The horizontal line corresponding to the distance of the light from the observer should be followed until it meets the curve corresponding to its luminous intensity, interpolating if necessary. The abscissa of this point gives the equivalent daylight visibility, and this value should be inserted in the list referred to on page 7–12. It is essential that the appropriate nomogram is used and that three lists are made for the specified conditions.

When very powerful lights are observed in poor visibility they may make the background so bright as to raise the observer's visual threshold. This effect is too variable to be compensated for easily, and the use of such lights for visibility observations should be avoided.

The nomograms in Figure 1 are based on the equation for the diminution of light, from a point source, in the atmosphere (Allard's law):

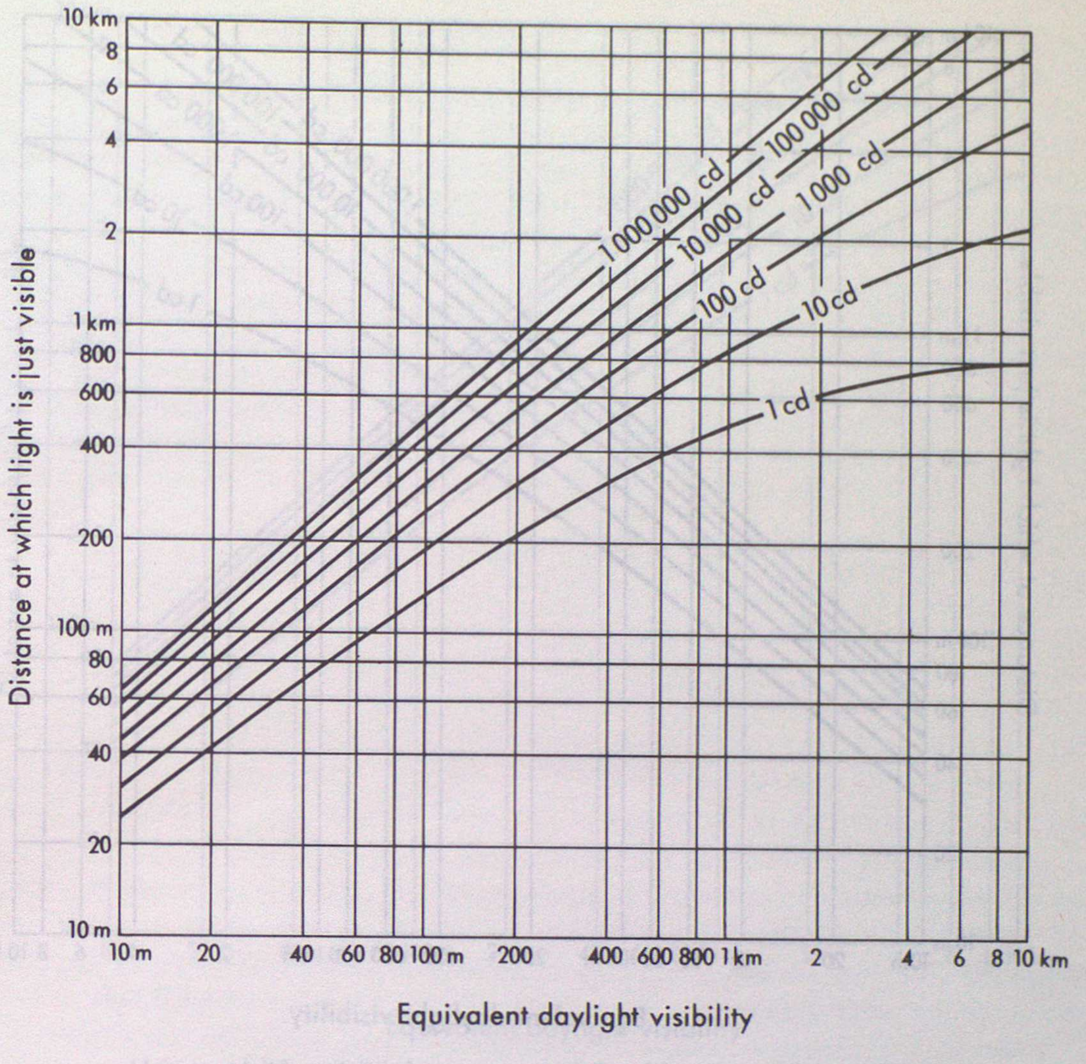


Figure 1 (a). Twilight nomogram of visibility of lights at night.

$$E_t = \frac{I}{d^2} e^{-\sigma d}, \qquad \ldots (13)$$

where E_t = the threshold of illumination of the eye for a point source at night,
I = the luminous intensity of the light, and
d = the distance in metres at which the light can just be seen, and on equation (12)

whence

$$V = \frac{2.9957}{\sigma}. \qquad \ldots (14)$$

It is assumed that $E_t = 10^{-6}$, $10^{-6.7}$ and $10^{-7.5}$ lux for twilight, moonlight and darkness respectively. These values are recommended by WMO.

It is obvious from the nomogram how misleading visibility observations can be if they are based simply on the distance at which ordinary lights are visible, without allowance being made for the luminous intensity of the light.

2 MEASUREMENT OF VISIBILITY USING INSTRUMENTS

2.1 General

Estimation of the visibility in daytime by an observer may be considered accurate enough for most purposes provided that a suitable set of visibility objects is available. The use of instrumentation to measure visibility used to be confined either to sites where the above condition could not be satisfied or to night observations. The development of

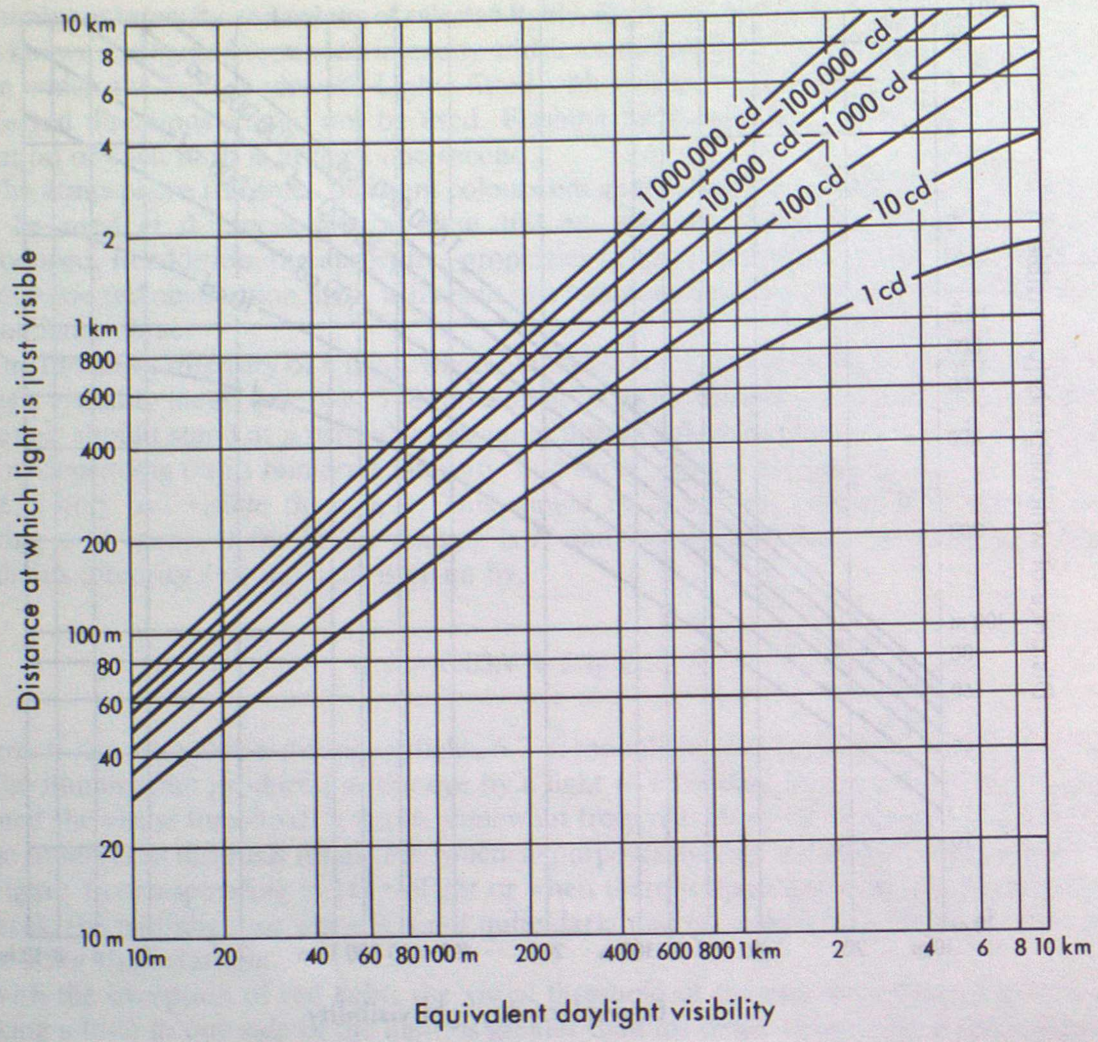


Figure 1 (b). Moonlight nomogram of visibility of lights at night.

suitable automatic devices has led to an increasing use of instrumentation both by day and by night, especially at unattended sites or where early warning of poor visibility is required, e.g. on motorways or at airports.

A distinction may be made between manually operated instruments, such as the Meteorological Office visibility meter, and automatic recording instruments.

2.2 Meteorological Office visibility meter Mk 2

This instrument, based on a visibility meter designed by Gold (1939), is a simple photometer used to measure the visibility at night by observing the apparent luminance of a distant light.

A variable density filter, A in Plate I, cemented between two glass plates, approximately 200 mm × 40 mm in size, is mounted in a frame which can slide in the main frame. The filter has the following main properties:

(a) It transmits light of all wavelengths equally.

(b) It is almost transparent at one end, while at the other end it transmits only about 2.5 × 10^{-4} of the incident light.

(c) The variation of density along the filter is uniform in the sense that if the fraction of light transmitted is measured at a number of equidistant points along the filter, the figures for adjacent points will always be in the same ratio.

Two small neutral filters, B, about 20 mm square, are mounted close to the open end of the main frame. These filters have the same uniform graduation of density as the main filter but are fixed so that the change in density is in the opposite direction. The superposition of

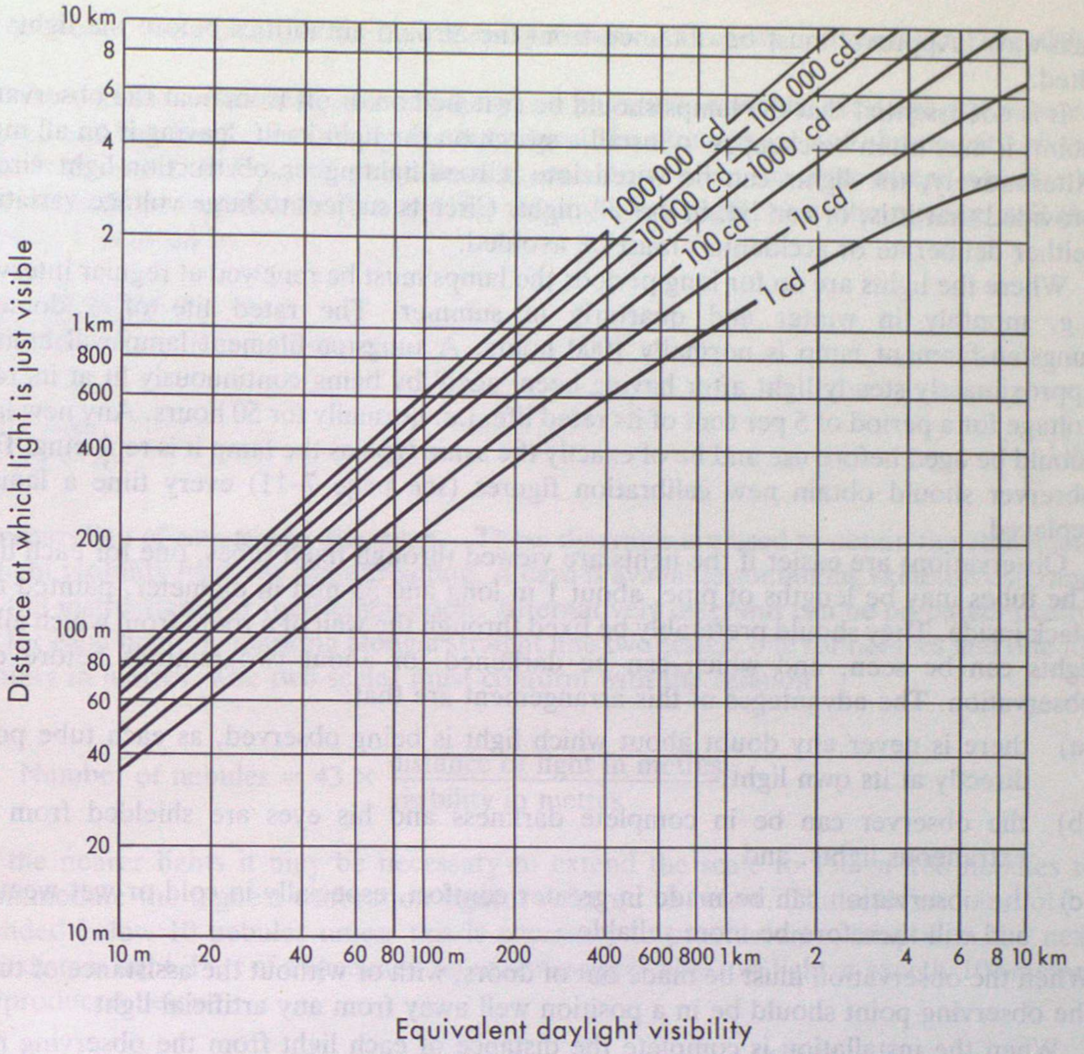


Figure 1 (c). Darkness nomogram of visibility of lights at night.

one of the small filters over any part of the main filter thus results in a uniform density over the area of the small filter. One of the small filters is nearly transparent; the other transmits only about 0.001 of the incident light. These filters are mounted side-by-side so that parts of the main filter which they cover have the same density and a movable eyepiece C enables the observer to look entirely through one filter or the other. The proportion of incident light transmitted by the combination of filters varies from about 0.4 to 2.5 × 10^{-4} if the clearer of the small filters is used, and between 4 × 10^{-4} and 2.5 × 10^{-7} if the denser filter is used; the actual value depends on the position of the main filter in relation to the small filter. Two scales, one on each side of the movable frame carrying the main filter, enable the total opacity of any filter combination to be obtained. The scales are graduated in terms of a special unit called the nebule (see page 7–10), and the scale on the same side as the small filter being used should be read. To reduce the glare from any other lights, a metal shield can be attached to the main frame on the opposite side to the eyepiece.

Visibility lights. Fixed lights of constant luminous intensity must be used and it is best to have at least three lights arranged at distances of approximately 100 m, 450 m and 1350 m from the observer. The lights should be mounted from 2 to 3 m above the ground and should have some form of hood to protect them from the weather; the hood should be removable so that the lamps can be cleaned or replaced when necessary. The hood should be black inside and no lens or focusing mirror should be used. A 15 W lamp is preferable at 100 m, a 100 W lamp at 450 m and a 100 W (or greater) at 1350 m.

On an airfield the lights should be visible only from near the observation point, should not shine along any runway and should not cause an obstruction to the runway or taxi-ways. Approval must be obtained from the airfield authorities before the lights are sited.

It is not essential that the lamps should be switched on or off from near the observation point; it may often be cheaper to install a switch on the light itself, leaving it on all night. Alternatively, the lights can be wired into a road-lighting or obstruction-light circuit, provided that it is, or can be, in use all night. Circuits subject to large voltage variations (either deliberate or accidental) must be avoided.

Where the lights are on for long periods the lamps must be renewed at regular intervals, e.g. monthly in winter and quarterly in summer. The rated life of a domestic tungsten-filament lamp is normally 1000 hours. A tungsten-filament lamp will emit an approximately steady light after having been 'aged' by being continuously lit at its rated voltage for a period of 5 per cent of its rated life, i.e. normally for 50 hours. Any new lamp should be aged before use and be of exactly the same type as the lamp it is replacing. Each observer should obtain new calibration figures (see page 7–11) every time a lamp is replaced.

Observations are easier if the lights are viewed through fixed tubes, one for each light. The tubes may be lengths of pipe, about 1 m long and 35 mm in diameter, painted matt black inside. They should preferably be fixed through the wall of a room from which all the lights can be seen, and which can be darkened for about two minutes before each observation. The advantages of this arrangement are that:

(a) there is never any doubt about which light is being observed, as each tube points directly at its own light,

(b) the observer can be in complete darkness and his eyes are shielded from any extraneous lights, and

(c) the observation can be made in greater comfort, especially in cold or wet weather, and will therefore be more reliable.

When the observation must be made out of doors, with or without the assistance of tubes, the observing point should be in a position well away from any artificial light.

When the installation is complete the distance of each light from the observing point should be carefully measured.

Theory of the instrument. Suppose that a screen with a transmittance T is interposed in the path of a beam of light with a luminous flux Φ. The luminous flux of the beam will be reduced to ΦT and if n similar screens are interposed in the beam the final luminous flux will be ΦT^n. If the value of T is chosen so that when $n = 100$, $T^n = 0.001$, the unit screen is said to have an opacity of 1 nebule and 100 screens have an opacity of 100 nebules. Therefore,

$$T^{100} = 0.001$$

$$\text{and} \quad T = 0.933.$$

Any length of the atmosphere acts in the same way as a number of screens and may be said to have an opacity of a certain number of nebules. If a beam of light traverses a length d of the atmosphere having an opacity of n nebules per unit distance, the transmittance of this layer will be T^{nd}.

Expressing this in terms of the extinction coefficient,

$$T^{nd} = e^{-\sigma d}$$

and therefore $e^{-\sigma} = T^n$.

Taking logarithms,

$$\sigma = n \ln 1/T,$$

$$\sigma = 0.0691n. \qquad \ldots (15)$$

An opacity of one nebule per metre is thus equivalent to an extinction coefficient of 0.0691 m^{-1}.

Every time an observation is made using one particular lamp the total opacity between the eye and the lamp, comprising the opacity of the atmosphere and the opacity of the filter, is the same. If R_0 is the meter reading on a night when the atmosphere is perfectly clear, then from equations (13) and (15), on any other night when the reading is R the visibility V is given by

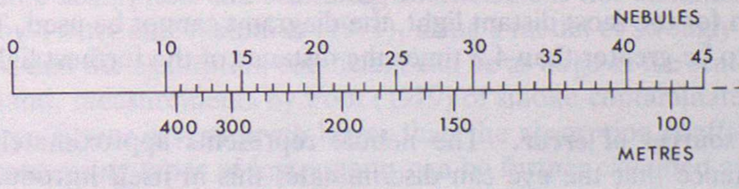
$$V = \frac{2.9957d}{0.0691(R_0 - R)}$$

$$= \frac{43d}{R_0 - R}. \qquad \ldots (16)$$

Preparation of conversion diagrams. These diagrams are used to obtain the equivalent daylight visibility from the meter reading. A card is available containing skeleton diagrams and full instructions for their completion. Alternatively diagrams can be prepared locally, one for each light, by marking along a straight line two scales, one for nebules and one for visibility in metres. The two scales must conform with the relation:

$$\text{Number of nebules} = 43 \times \frac{\text{distance of light in metres}}{\text{visibility in metres}}.$$

For the nearer lights it may be necessary to extend the scale to 150 or 180 nebules to accommodate the highest calibration figures referred to below. The scale should not be extended below 10 nebules unless this is necessary to provide an overlap with the next more distant light. Part of a specimen set of scales applicable to a light at exactly 100 metres is reproduced below.



Individual calibration figures. In 1.5 above, it is noted that the sensitivity of the observer's eyes is a factor which determines the distance at which a light can be seen at night. Thus, before the meter can be brought into use, each observer must determine his individual calibration figure for each light and for each meter when more than one is available. Because the sensitivity of the observer's eyes may change the calibration should be checked on suitable occasions. The calibration, which is the meter reading obtained when the atmosphere is perfectly transparent, should be done immediately after dark on an evening when the visibility observed during the preceding daylight hours was not less than 12 times the distance of the particular light from the observer and when the visibility is not expected to change much, e.g. when there is a cloudy sky, a fresh wind and humidity ≤95 per cent. The procedure described on page 7–12 for making an observation should be carefully followed. Only one light should be observed during a session, as a lengthy observation period would permit the eye to adapt to the dark and thus produce non-representative readings.

An observer having taken a meter reading, R_0, obtains from it his personal calibration figure for the particular light from the following expression:

$$\text{Calibration figure} = R_0 + 0.043 \times \frac{\text{distance of light in metres}}{\text{visibility in kilometres}}.$$

A calibration book should be kept, with a page for each observer, showing the calibration figure for each light and the date when it was determined. New figures should be determined on every convenient occasion; comparisons with earlier figures will give the best average figure for future use. A recalibration should always be made whenever a lamp is changed.

Method of use. The procedure for making an observation with the meter is:

(a) Ensure that the glass surfaces of the meter are clean; if necessary, clean them with a lint-free cloth. When the meter and the cloth are not in use keep them in a closed box.
(b) Allow about two minutes for the eyes to become accommodated to the darkness before beginning to make an observation.
(c) Observe the most distant light which is visible through the visibility meter and adjust the sliding filter until the light is only just visible. This is done by pulling out the slide until the light just disappears, then slowly pushing it in until the light just reappears. Always begin with the eyeshield over the clearer small filter, but if the light is still visible with the slide pulled right out, move the eyeshield to the dark filter. Look directly at the light during the observation because the sensitivity of the eye is more constant for direct vision. Do not spend a long time making an observation because the eye slowly adapts to the dark and this will invalidate the current calibration figure for an individual. Always attempt to complete the observation within three minutes of leaving a well-lit room. If spectacles are worn for distant vision wear them whilst making observations, but ensure that they are clean and free from condensation or rain (this also applies to the meter).
(d) When the sliding filter is correctly adjusted note the scale reading, taking care to avoid moving the slide before the reading is taken. The reading is taken from the scale on the side on which the eyeshield has been used.
(e) Subtract the reading from the calibration figure for that particular light; the resulting figure is then used, in conjunction with the appropriate conversion diagram, to obtain the visibility.
(f) If the difference between the calibration figure and the observed reading is less than 10 nebules, even for the most distant light, the diagrams cannot be used. The visibility is then known to be greater than 4.3 times the distance of the furthest light and must be estimated.

Accuracy and sources of error. The nebule represents approximately the smallest change in illuminance that the eye can discriminate; this in itself introduces a probable observational error of ± 1 nebule. Also the sensitivity of the eye may vary on different occasions and the possible error from this source has been estimated as ± 5 nebules (Bibby 1947). Finally there may be random fluctuations in the luminances of the lamps producing an error of ± 3 nebules. Gradual changes in the luminances due to deterioration of the lamps may be allowed for by regular checking of individual calibration figures. These errors can be combined in an overall error of about ± 6 nebules, which corresponds to an error in $R_0 - R$ in equation (16) of 14 per cent when $V = d$, 28 per cent when $V = 2d$ and 70 per cent when $V = 5d$. It is clear, therefore, that the furthest lamp that can be seen should be used for an observation.

The visibility meter requires more care in its use than the majority of meteorological instruments. Lack of care, for instance in varying the length of time for the eyes to adapt to the dark, can lead to considerable errors.

2.3 Runway visual range

The runway visual range (RVR) is defined as 'the maximum distance in the direction of take-off or landing at which the runway, or specified lights or markers delineating it, can be seen from a position above a specified point on its centre line, at a height corresponding to the average eye-level of pilots at touch-down'. A height of 5 metres above the ground level is regarded as corresponding to the average eye-level of pilots at touch-down.

An observer RVR system is in operation at some civil airports and Royal Air Force airfields in the United Kingdom and overseas, whereby an observer, at a known fixed position as close to the touch-down zone as safety permits, can count the number of designated RVR reference lights visible. Knowing this count, and by means of a calibration table, the air traffic controller can obtain the RVR applicable to the touch-down zone of the designated runway. The calibration tables are based on equation (13), i.e.

$$E_t = \frac{I}{d^2}\, e^{-\sigma d},$$

where, in this case, d is the RVR.

At some civil airports an instrumented RVR system is used. At present the most usual system uses several short baseline transmissometers which provide input to a minicomputer system from which the RVR is obtained.

3 AUTOMATIC INSTRUMENTS

3.1 General

Instruments for the automatic recording of visibility may be categorized according to their principle of operation:

(a) Transmissometers.
(b) Forward-scatter instruments.
(c) Back-scatter instruments.
(d) Integrating nephelometers.

As suggested by the name, instruments of type (a) measure the transmissivity of the atmosphere, i.e. the attenuation due to absorption and scattering. The remaining types in general exclude attenuation due to absorption. Unfortunately, agreement on the relative magnitudes of the absorption and scattering coefficients is not unanimous. For example, investigations by Twitty and Weinman (1971), using a model of strongly absorbing carbon aerosol, suggest that the absorption coefficient can be as large as the scattering coefficient. On the other hand, measurements by Foot (1979) of smoke-contaminated air suggest that the scattering coefficient is very much larger than the absorption coefficient.

The scatter-measuring types of instruments can be further classified as those measuring the scattering function at a specific angle, types (b) and (c), and those which integrate the scattering function and provide a quantity proportional to the scattering coefficient, type (d).

3.2 Transmissometers

A transmissometer measures the transmittance of the atmosphere along a fixed baseline, the transmittance being related to the extinction coefficient by

$$\sigma = 1/x \ln(1/T), \qquad \ldots (17)$$

where x is the length of the baseline. Substituting in equation (14),

$$V = \frac{2.9957x}{\ln(1/T)}. \qquad \ldots (18)$$

This can be expressed in the more practical form,

$$V = \frac{2.9957x}{\ln\{(V' - V_0)/(V_T - V_0)\}}, \qquad \ldots (19)$$

where V' = the output voltage when $\Phi = \Phi_0$,
V_0 = the output voltage when $\Phi = 0$, and
V_T = the output voltage at an intermediate value of Φ.

Meteorological Office transmissometer Mk 4. The transmissometer Mk 4 comprises essentially two units:

Projector unit. The projector unit consists of a square-section lamp housing, A in Figure 2, fitted to a tube 750 mm long and 150 mm in diameter. The lamp housing contains a lamp holder, a lead-backed parabolic mirror and a heat-resistant glass 'window'; the light source is a 200 W tungsten-halogen lamp, B. The tube is hinged at the point of attachment to the lamp housing to permit access to the glass for cleaning. The projector unit, Plate II(a), is mounted upon a base plate which is designed to be mounted, in turn, upon a tower. The unit may be adjusted in both vertical and horizontal planes. A lamp failure module, contained in a polyester box, is mounted under the projector base plate. The module contains a light-activated switch which controls the operation of a solid-state relay. When the lamp is functioning a length of fibre light-guide transfers light to the light-activated switch and the relay contacts remain open. When the lamp is extinguished the relay contacts close; the closure of the relay contacts may be used to operate a warning lamp or buzzer.

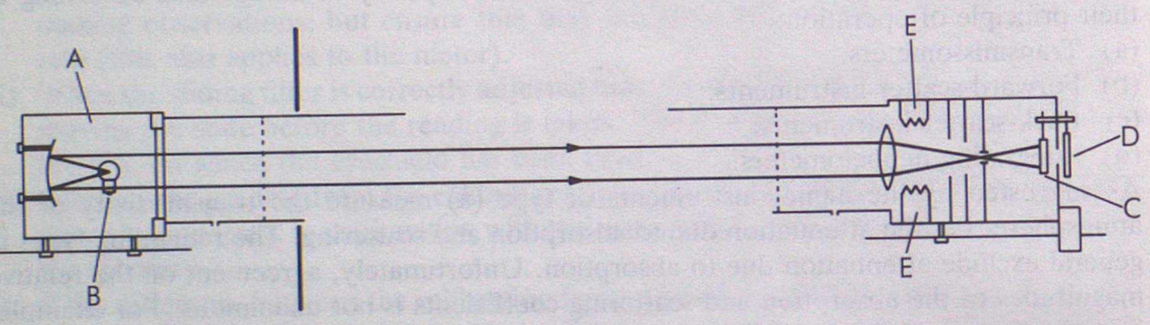


Figure 2. Optical system of the Meteorological Office transmissometer Mk 4.

Receiver unit. The receiver unit, Plate II(b), consists of a tube, 1.83 m long and 150 mm in diameter, which houses a lens, an iris and a photoelectric cell. The tube, which is in two parts, is hinged at approximately half-way along its length to facilitate cleaning of the lens which is mounted in the fixed section of the tube. The photoelectric cell, C in Figure 2, is mounted at the rear of the fixed section of the tube on a detachable plate which is keyed to an external handle D. The cell may thus be swung out of position to reveal a sighting hole used for visual alignment of the receiver unit. A low-voltage 15 W heater in the form of parallel-connected resistors E is mounted at the inner side of the lens to prevent condensation within the closed unit. A series of diaphragms in the tube between the lens and the iris exclude strong light. The receiver is mounted on a base plate, suitable for bolting to a tower, and is adjustable for elevation and azimuth.

The output from the photoelectric cell varies within the range 0 mV–15 mV as the transmittance of the atmosphere between the projector and receiver units varies between 0 and 100 per cent. The light entering the receiver is filtered so that the photoelectric cell/filter combination has a response similar to that of the human eye. This output is fed, via a receiver junction box, to an amplifier where it is amplified to a level compatible with the telemetry system. An electronic time-averaging device is incorporated in the recorder to provide a continuously smoothed output, filtering out unwanted electronic 'noise' present in the telemetry together with short-period fluctuations of the photoelectric cell output caused by small-scale changes in the transmittance. The time-averaging circuits may be switched out of circuit when the equipment is being calibrated. Depending on the type of recorder used, the output from the photoelectric cell may be either sampled and recorded every 10 or 20 seconds or recorded continuously.

The time-constant of the transmissometer is a function of the prevailing wind flow. The time-averaging circuits impose an additional equivalent time-constant of approximately one minute.

Siting. The projector and receiver units are mounted, on identical towers, 200 m apart and approximately 3 m above ground level. The system should be sited away from any local sources of pollution, e.g. aircraft run-up areas. A north–south baseline is to be preferred with the receiver unit at the northern end of the baseline so that it is least affected by sunlight incident on the background within its field of view. Reflecting surfaces within 5° of the baseline should be avoided and a terrestrial background, viewed from the receiver unit, is preferable to the sky as a background.

Accuracy and sources of error. The transmissometer measures the transmittance of the atmosphere between the projector and the receiver. Any error in this measured quantity will therefore produce a corresponding error in the derived visibility. Differentiating equation (18),

$$\frac{dV}{V} = \frac{1}{T} / (\ln \frac{1}{T})\, dT.$$

Figure 3 shows the percentage error dV/V in visibility as a function of the measured transmittance. It is seen that for a finite error in T the consequent error in visibility will be least for values of T between about 0.03 and 0.9; with a baseline of 200 m these values of T correspond to visibilities between about 170 m and 6 km respectively. If the transmittance can be measured with an uncertainty of no more than 1 per cent the error in the visibility should be less than 10 per cent over the above range.

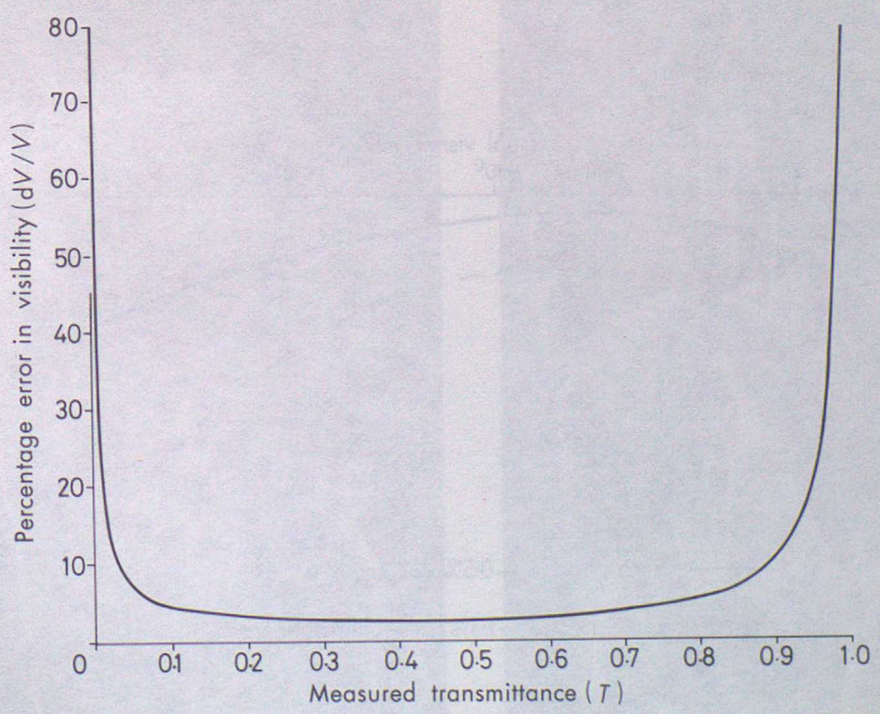


Figure 3. Percentage error in visibility as a function of the measured transmittance.

Figure 4(a) taken from Bond *et al.* (1981), shows the error in measured visibility caused by a calibration error, i.e. a change in the value of V' in equation (19). The most likely reasons for such an error are contamination of the optical surfaces or an uncorrected change in the intensity of the light source. Figure 4(b) illustrates the effect of a change in the instrument zero, i.e. a change in V_0 in equation (19). This can be caused by either a high background illumination or a drift in the instrument electronics. Early versions of the

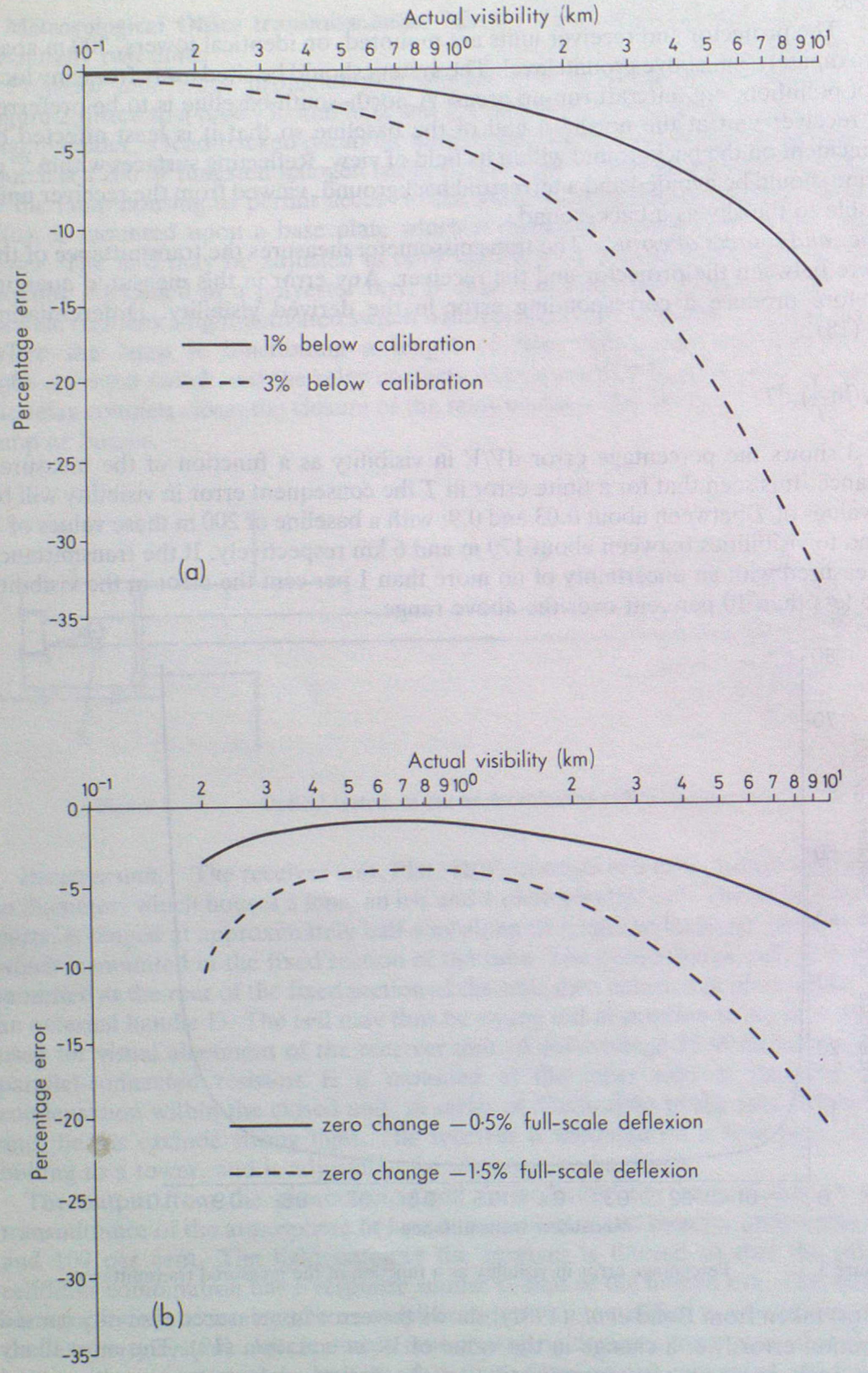


Figure 4. Error in the visibility recorded by a transmissometer Mk 4 due to (a) a calibration error, and (b) a zero error.

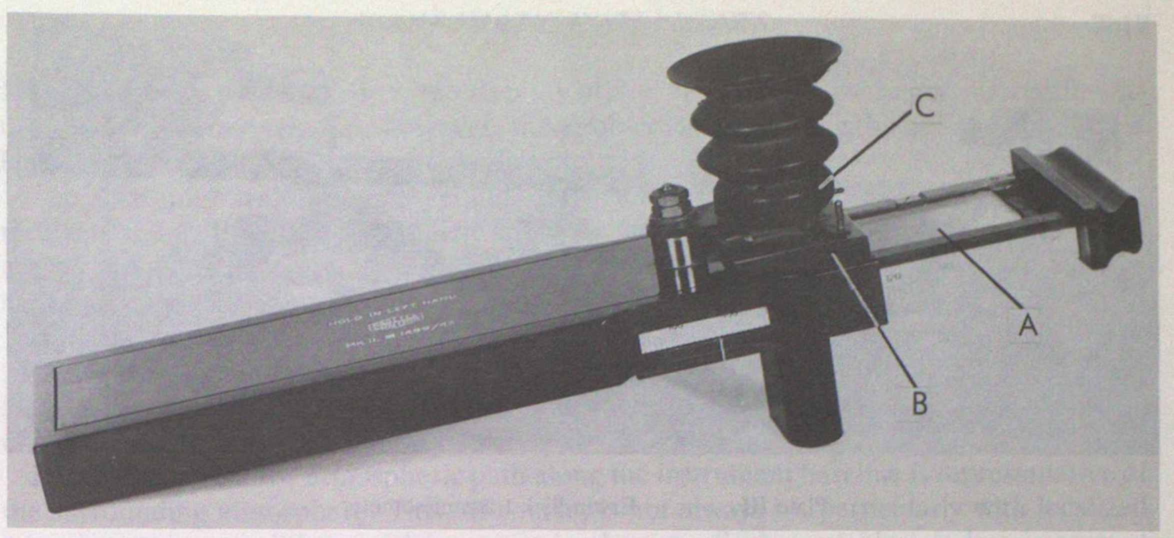
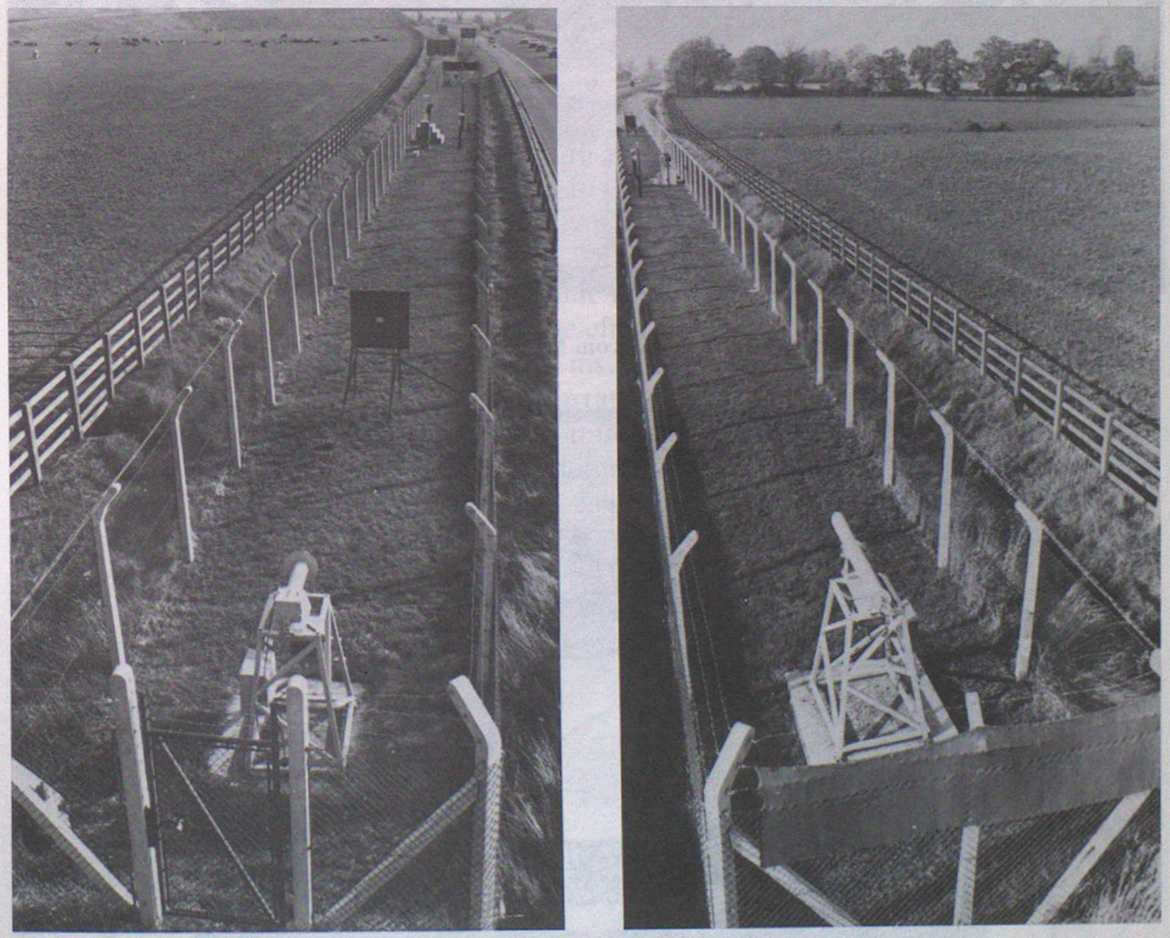


Plate I. Meteorological Office visibility meter Mk 2.



(a) Projector unit. (b) Receiver unit.

Plate II. Meteorological Office transmissometer Mk 4.

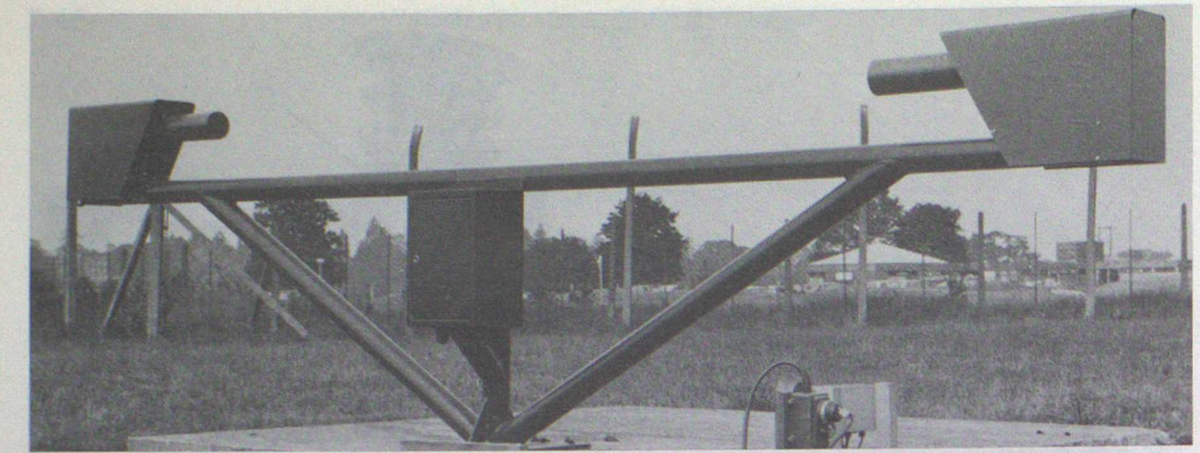


Plate III. Erwin-Sick transmissometer.

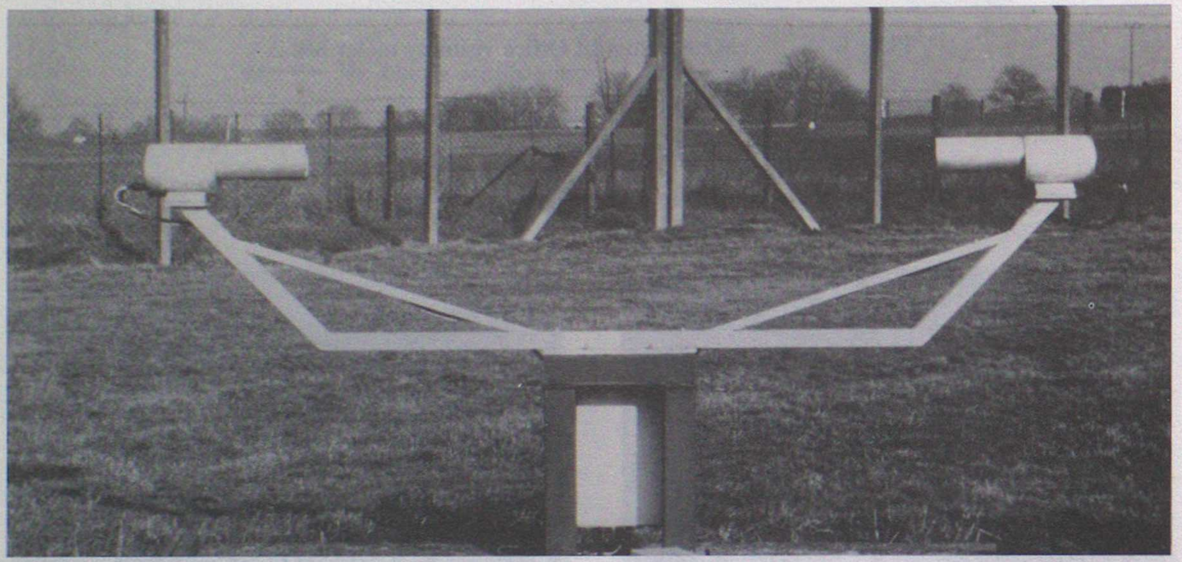


Plate IV. Marconi MET 1 transmissometer.

Plate V. Plessey point visibility meter.

Mk 4 transmissometer relied on the stability of d.c. circuitry and were very susceptible to drift errors. In later versions, however, this problem is reduced by the use of a modulated light source and phase-sensitive detection methods.

The measured transmittance should be a function of the direct light reaching the receiver. Errors due to scattered light entering the receiver are minimized by making the acceptance angle of the receiver as small as is practicable and by including diaphragms in the receiver unit.

At the lower limit of the visibility range the radiant flux received from the projector is small and adequate discrimination is difficult to achieve. At the upper limit of the visibility range dV/dT is large, so any change in lamp brightness or alignment can produce large errors.

It is assumed that the atmospheric path along the instrument baseline is representative of the surrounding atmosphere. This, of course, is not always so, particularly with localized inhomogeneous conditions such as occur in showers. Such a problem is less important where the instrument is used to measure 'local' visibility, e.g. adjacent to runways.

Erwin–Sick transmissometer. The Erwin–Sick transmissometer, Plate III, has a baseline of 3 m, with the transmitter and receiver mounted alongside each other at the ends of optical baffle tubes (A in Figure 5) 105 mm in diameter, and with a combined length of 1.5 m. A single-corner cube reflector B at the far end of the optical path and a multi-corner reflector C at the opposite end fold the light beam, as shown in Figure 5, so that the total geometrical length of the light path is about 18 m; this improves the sensitivity and discrimination of the instrument. The optical surfaces are heated to prevent condensation. The output from a quartz–halogen light source is mechanically modulated by a rotating chopper D and the use of phase-sensitive detection methods helps to reduce the effects of extraneous light and amplifier drift. A second rotating chopper E with a single reflecting segment is mounted so that the light is returned directly to a second detector F at regular intervals. The signal thus generated is used to check the radiant flux of the source and the detector sensitivity, which are automatically adjusted if they have changed. A reference mirror G is automatically interposed in the light path about once an hour and returns the light beam through the lens system without any significant atmospheric traverse. The resulting signal is used to compensate for the effects of contamination on the lens surfaces.

Marconi MET 1 transmissometer. This instrument, Plate IV, is also a retroreflecting, folded-beam transmissometer. The optical arrangement is shown in Figure 6. The concepts are very similar to those of the Erwin–Sick transmissometer, with an optical baffle system and a modulated light source. The main differences are that the light beam makes only two passes and has a total geometrical path length of 5.2 m, the light source A is an electronically modulated light-emitting diode (LED) emitting in the visible red spectrum and the signal is processed digitally.

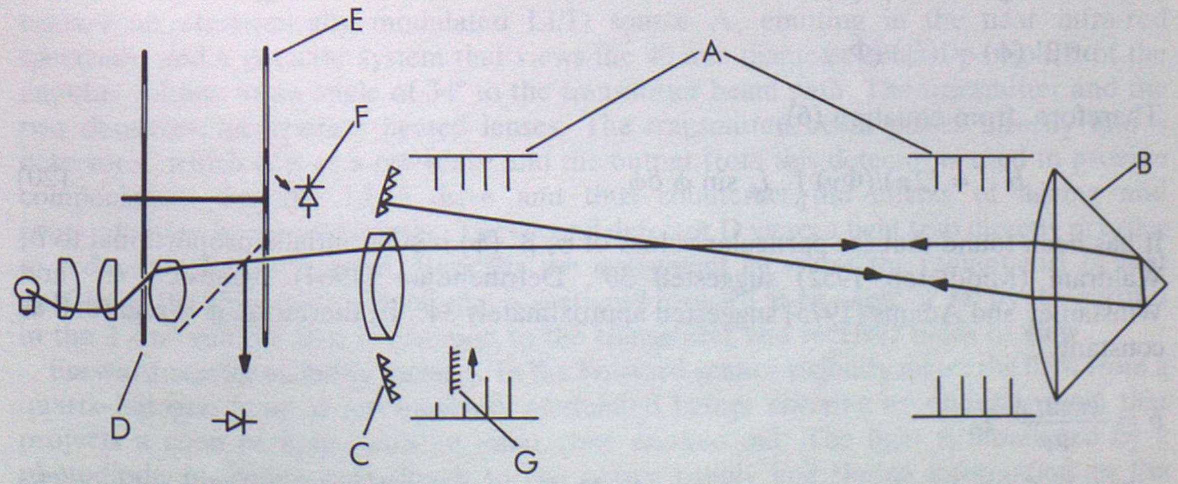


Figure 5. Optical system of the Erwin-Sick transmissometer.

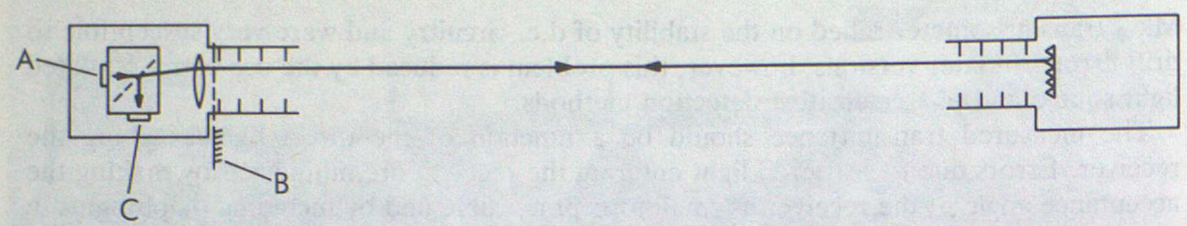


Figure 6. Optical system of the Marconi MET 1 transmissometer.

The output signal is digitized into 1024 bits so that 1 bit represents a change in transmittance of approximately 0.1 per cent. At about 10-minute intervals a reference mirror B is automatically interposed in the light path and reflects the light directly back to the detector C. Variations in the radiant flux of the reflected light cause changes to be made automatically in the gain of the analogue-to-digital converter, thus compensating for the effects of ageing of the LED and contamination of the lens surface. The measured transmittance (V_T in equation (19)) is assumed to accumulate an error of −1 bit every three days owing to contamination on the retroreflector. A correction of +1 bit is therefore applied to V_T every third day. If at any time V_T is greater than V, then single bits are subtracted from V_T until $V_T = V$; this system of compensation assumes that the visibility is never low for long periods of time. If the instrument was installed at a site where the visibility never exceeded, say, 5 km the instrument would set itself so that 5 km was indicated as 14 km (effectively infinity), equivalent to the least significant bit. The instrument is provided with three status flags which indicate that the instrument is operating in calibration mode, that the battery support for the calibration memory is satisfactory and that the calibration compensation has not reached the limit of its dynamic range.

3.3 Instruments measuring the scattering function

The scattering function may either be measured at one or more particular angles or integrated over an angular range. Various studies have been made of the volume scattering function and measurements from one such study by Foitzik and Zschaeck for a range of visibilities (1953) are shown graphically in Figure 7, where $\phi = 0°$ corresponds to forward scatter and $\phi = 180°$ corresponds to back scatter. The preponderance of forward scatter, particularly with decreasing visibility, is evident.

Forward-scatter instruments. Consider a volume v of the atmosphere illuminated by a beam of radiant flux Φ, then the intensity in direction ϕ relative to the incident direction is

$$I_\phi = \Phi v . \beta'(\phi),$$

$$\text{or } \beta'(\phi) = (I_\phi)/(\Phi v).$$

Therefore, from equation (6),

$$b = (2\pi)/(\Phi v) \int_0^\pi I_\phi \sin\phi \, d\phi. \qquad \ldots (20)$$

It has been found that for particular values of ϕ, $\beta'(\phi)$ is substantially proportional to b; Waldram (Middleton 1952) suggested 30°, Deirmendjan (1964) suggested 45° and Winstanley and Adams (1975) suggested approximately 34°. If, therefore, ϕ is regarded as constant,

$$b = \frac{2\pi \sin\phi}{\Phi v} I_\phi.$$

This is the basis of instruments such as the Plessey point visibility meter (see below). The Forward-scatter meter described on page 7–19, however, measures the scatter between ϕ

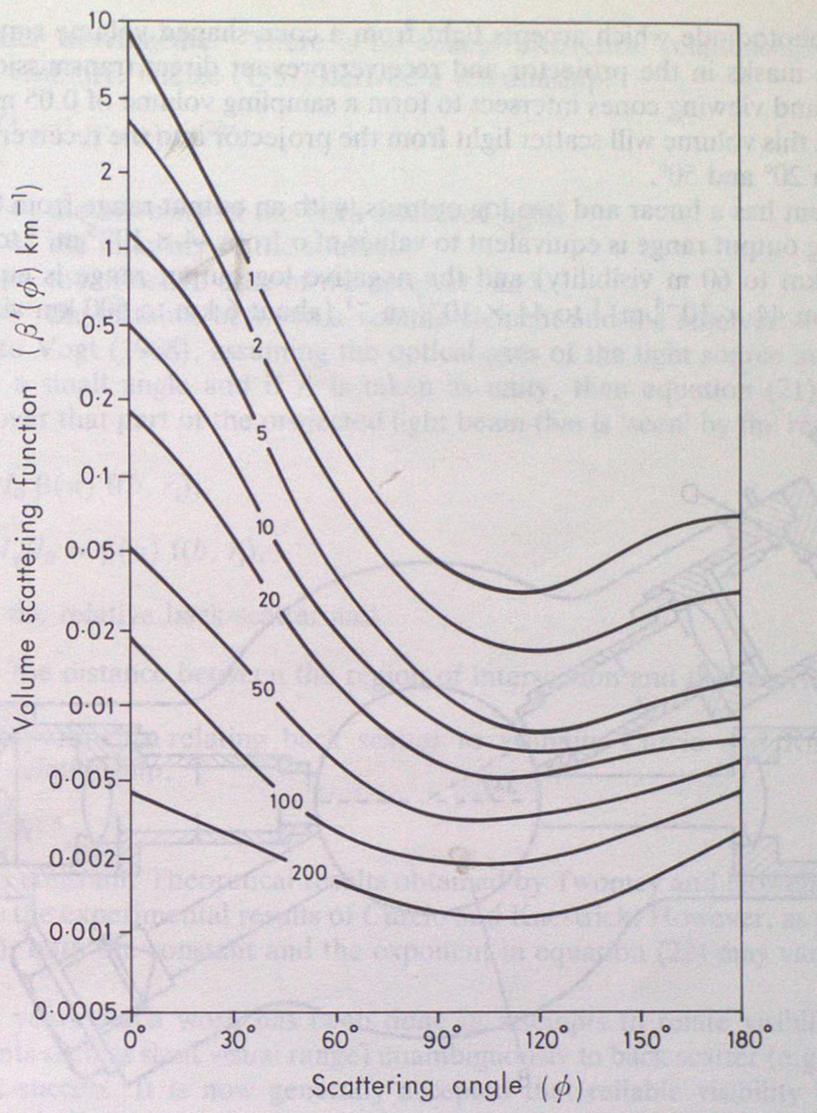


Figure 7. Relation between the scattering angle and the volume scattering function for various visibilities (km).

= 20° and $\phi = 50°$, which encompasses both Waldram's and Deirmendjan's suggested values for ϕ, and equation (20) becomes applicable. In either case the visibility is obtained from equation (14), assuming $\sigma = b$.

Plessey point visibility meter. The Plessey point visibility meter, Plate V, is shown schematically in Figure 8. It consists of an annular case 290 mm in diameter in which are housed an electronically modulated LED source A, emitting in the near infra-red spectrum, and a detector system that views the 40 mm diameter central portion B of the annulus volume at an angle of 34° to the transmitter beam path. The transmitter and the two detectors incorporate heated lenses. The transmitted beam passes directly into a detector C which acts as a reference and the output from this detector is used to provide compensation for the LED drive and thus counteract the effects of ageing and contamination in the transmitter. The second detector D views a light trap directly in order to reduce background noise. Basically the instrument measures the radiant flux of that portion of the transmitted beam that is scattered forward at an angle of 34° by the aerosol in the 2 cm^3 volume that is common to the transmitter and receiver fields of view.

Forward-scatter visibility meter. In the Forward-scatter visibility meter the light from a quartz–halogen lamp is mechanically modulated before entering an optical system that projects a cone of light, with an inner cone masked out. The light is monitored by a photodiode providing a feedback to the power supply and timing information to the receiver circuitry. The receiver, A in Figure 9, positioned about 1.2 m from the projector, B, contains a photodiode which accepts light from a cone-shaped volume similar to that projected. The masks in the projector and receiver prevent direct transmission of light. The projected and viewing cones intersect to form a sampling volume of 0.05 m^3. Aerosol particles within this volume will scatter light from the projector into the receiver at forward angles between 20° and 50°.

The instrument has a linear and two log outputs, with an output range from 0 V to 5 V. The positive log output range is equivalent to values of σ from $44 \times 10^{-5}\ m^{-1}$ to $44 \times 10^{-3}\ m^{-1}$ (about 6 km to 60 m visibility) and the negative log output range is equivalent to values of σ from $44 \times 10^{-5}\ m^{-1}$ to $44 \times 10^{-7}\ m^{-1}$ (about 6 km to 600 km visibility).

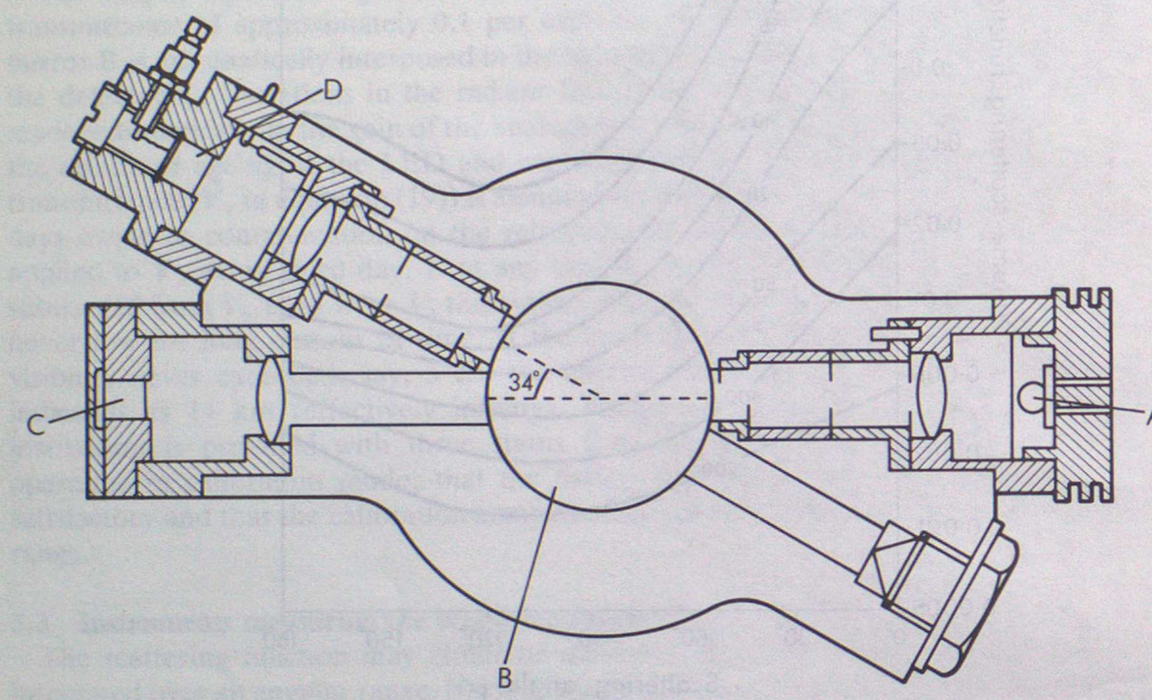


Figure 8. Optical system of the Plessey point visibility meter.

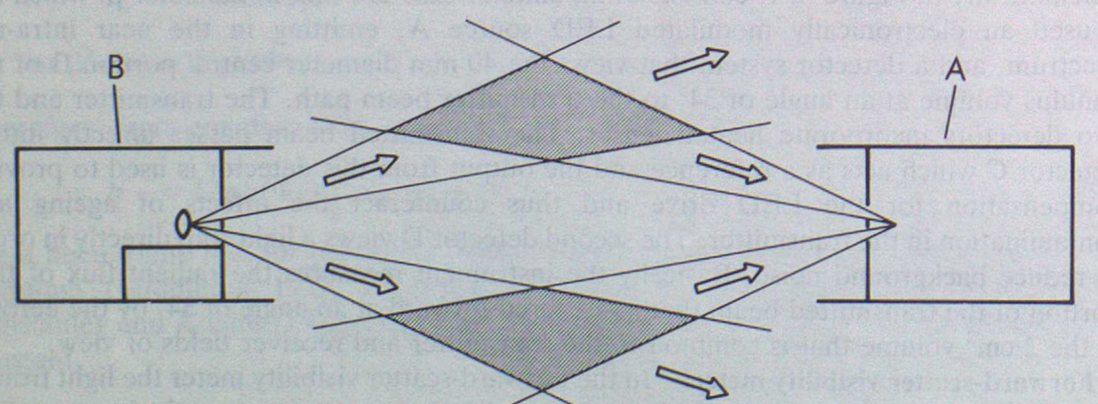


Figure 9. Optical system of the Forward-scatter visibility meter.

Back-scatter instruments. There is no simple theoretical relationship between back scatter and visibility. Dietze (1957) derived a relationship:

$$I_\pi = AI_0 \int_{r_0}^{r_1} r^{-2}\, \beta'(\pi)\, e^{-2br}, \qquad \ldots (21)$$

where I_π = the intensity of the back-scattered light,
I_0 = the intensity of the source,
A = the effective area of the receiver, and
r = the distance between a volume element and the receiver.

According to Vogt (1968), assuming the optical axes of the light source and the receiver intersect at a small angle and if A is taken as unity, then equation (21) need only be integrated over that part of the projected light beam that is 'seen' by the receiver. Hence,

$$I_\pi = I_0\, \beta(\pi)\, f(b, r_i),$$

$$\text{or } R = I_\pi / I_0 = \beta(\pi)\, f(b, r_i),$$

where R = the relative back-scatter and

r_i = the distance between the region of intersection and the receiver.

From the experiments relating back scatter to visibility Curcio and Knestrick (1958) derived the relationship,

$$V = K/R^{1\cdot5}, \qquad \ldots (22)$$

where K is a constant. Theoretical results obtained by Twomey and Howell (1965) largely substantiate the experimental results of Curcio and Knestrick. However, as pointed out by Fenn (1966), both the constant and the exponent in equation (22) may vary in abnormal weather.

In recent years much work has been done in attempts to relate visibility (or similar measurements such as slant visual range) unambiguously to back scatter (e.g. Lifsitz 1974), but without success. It is now generally accepted that reliable visibility measurements cannot be made in this way.

Videograph. The Videograph is a back-scatter measuring instrument designed by Früngel (1969). It consists of a projector and a receiver mounted in a common housing fitted with internal optical shielding to screen the projector and receiver from each other. The light source, A in Figure 10, is a xenon flash lamp, powered from a solid-state voltage regulator, which maintains a constant flash rate of 3 Hz; the flash duration is about 1 μs. The projector and receiver are each fitted with a heated glass cover to protect them from ice and condensation.

The projector is inclined upward at an angle of about 3° so that the light beam intersects the optical axis of the detector at a distance of about 5 m in front of the detector. The scattering volume extends from about 3 m to 250 m ahead of the instrument, but the greatest contribution comes from particles scattering the light beam backwards from distances between 3 m and 8 m.

The back-scattered light passes to the detector B, a solid-state photodiode, through a honeycomb baffle and quartz lens system. The instrument monitors its own stability by periodically diverting a small amount of the light from the projector through a fibre-optics light guide to the receiver.

AGA fog detector. In this instrument the projector, A in Figure 11, and receiver, B, are mounted side-by-side, in a single unit, in a horizontal plane with their optical axes parallel. The scattering volume, contained in the overlapping fields of view, extends from 10 m to 200 m in front of the receiver. The light from the projector lamp C is mechanically modulated at 750 Hz by a perforated disc chopper D, and projected via an infra-red filter E and a collimating lens.

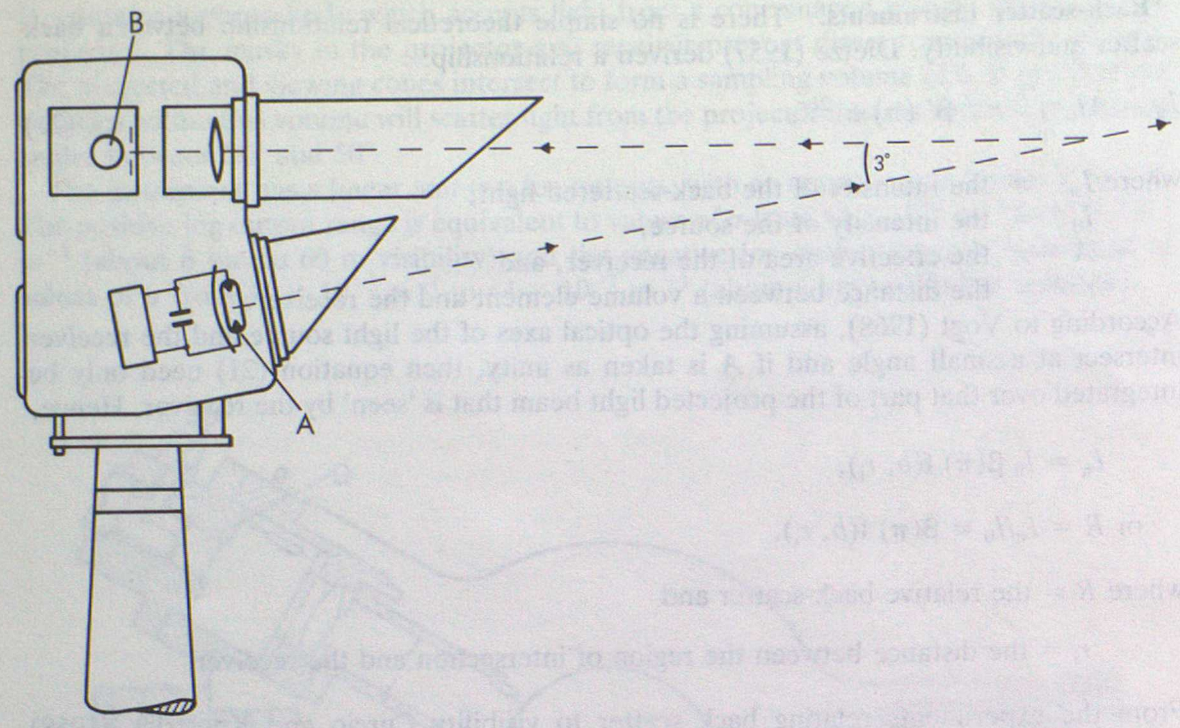


Figure 10. Optical system of the Videograph.

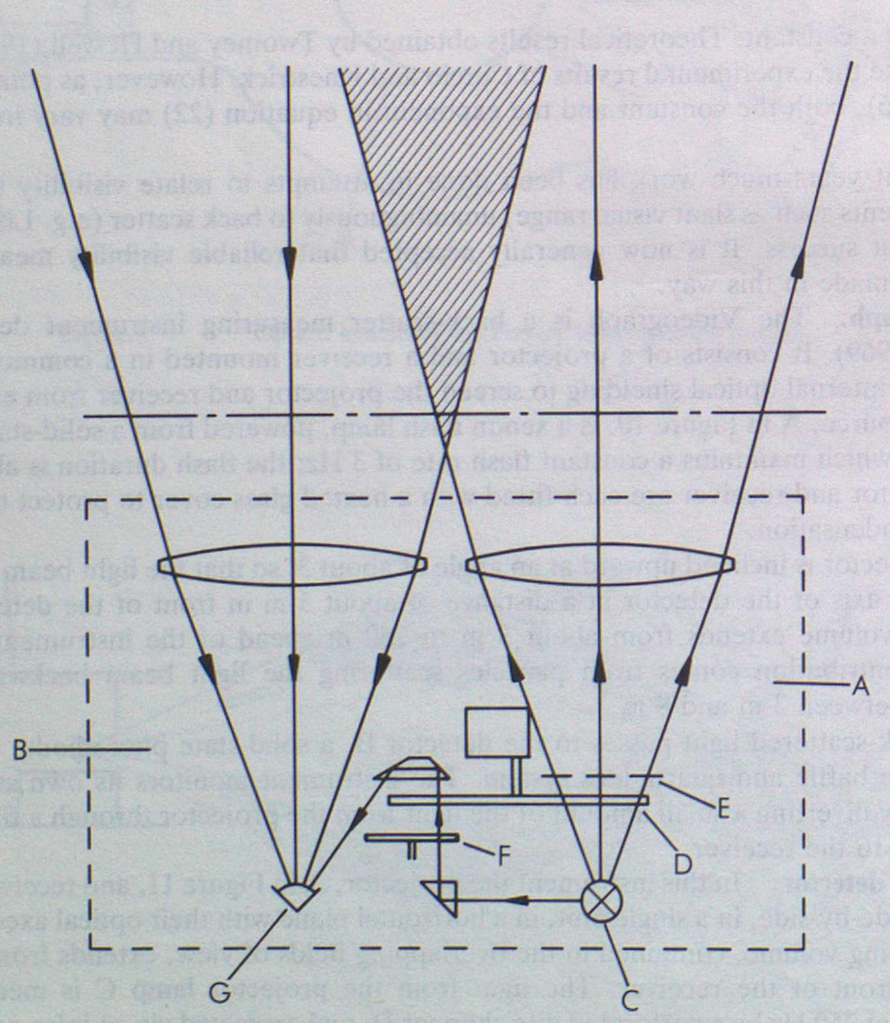


Figure 11. Optical system of the AGA fog detector.

A reference beam of light, modulated at the same frequency but 180° out of phase with the main beam, is directed via internal optics through a grey scale filter F and on to the detector G. The scale is rotated mechanically until the measured and reference signals balance and the output is determined by the position of the grey scale at balance.

Integrating nephelometers. In an integrating nephelometer a receiver views a volume of air, either enclosed or open to the atmosphere, which is illuminated from a direction perpendicular to the receiver path. Ideally the instrument should measure the light scattered over an angular range from 0° to 180°, but usually the angular span is restricted to less than 180° because of the constructional details of the instrument. The first instrument design to incorporate this concept was that due to Beuttel and Brewer (1949); the concept was later adopted by other designers (Crosby and Koerber 1963, Ruppersberg 1964, Ahlquist and Charlson 1967, 1968, and Garland and Rae 1970).

The equation forming the theoretical basis of the instrument is

$$\Phi = (I_e \omega s)/h \int_0^{\pi} \beta'(\phi) \sin \phi \, d\phi, \qquad \ldots (23)$$

where Φ = the total radiant flux at the detector due to scattered light,
I_e = the intensity of the light source, and
h = the perpendicular distance from the light source to the axis of the viewing cone,
ω = the solid angle of the viewing cone, and
s = the area of the detector.

The scattering coefficient, as given by equation (6), is

$$b = 2\pi \int_0^{\pi} \beta'(\phi) \sin \phi \, d\phi.$$

Equation (23) can therefore be written,

$$\Phi = \frac{I_e \omega s}{2\pi h} b,$$

$$\text{or } b = \frac{2\pi h \Phi}{I_e \omega s}.$$

M.R.I. fog visiometer. The M.R.I. fog visiometer, Plate VI, is an integrating device which detects the light scattered by atmospheric aerosol between 7° and 170° to the forward direction of the light beam. The optical assembly consists of two sets of diaphragms installed in two 100 mm diameter tubes which are permanently aligned facing each other. The detector, A in Figure 12, is a photomultiplier tube located in one end of the assembly and 'looks' through the open central section into a light trap B at the other end of the assembly. The light source is a xenon flashlamp which illuminates the atmosphere in the open section through an opal diffusion glass C, The sampling volume of approximately 100 cm^3 is defined by the diaphragm and the location of the opal glass. The light trap and all other internal surfaces in the optical system are coated with an optical black, non-reflective finish.

The light entering the optical system is limited mostly to the visual spectrum by a filter mounted on the face of the photomultiplier tube. An automatic gain control circuit requires direct observation of the flash and this is facilitated by a reference photodiode mounted in a collimating tube in the optical assembly. An air pump, mounted in a box at the light trap end, filters and heats ambient air and then pumps it through an insulated hose to the photomultiplier optical assembly. Thus the optical assembly is continuously flushed with clean warm air which prevents condensation and reduces the deposition of dust.

The opal glass is inclined towards the detector at an angle α to compensate for forward light losses in the instrument. Most of the diffracted light, which is concentrated in the small forward angles and which is very dependent on particle size, is thus excluded whilst the detection of reflected and refracted light, which is found in the forward angles between 7° and 90° and which is less dependent on particle size, is enhanced.

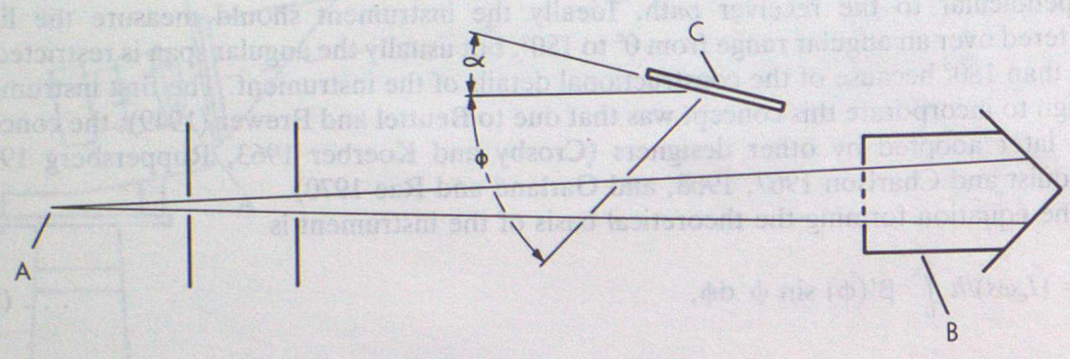


Figure 12. Optical system of the M.R.I. fog visiometer.

The instrument can be calibrated in all visibility conditions by the use of an internal system. The calibration system consists of two solenoid-actuated assemblies, one for setting the system zero and the other for setting a predetermined level of scattering. The zero calibrator is a black shutter which covers the hole in one of the collimating diaphragms so that scattered light from the flash is prevented from reaching the photomultiplier tube. This no-scattering condition simulates the conditions encountered in clean air when the scattering from the atmosphere is very small. The other calibrator consists of a set of diffuse reflecting surfaces which can be positioned in front of a collimating diaphragm in such a way as to receive light directly from the flash and to scatter a portion of this light towards the photomultiplier tube. These reflectors, which are coated with a high-stability white material, are calibrated by the manufacturer, Meteorology Research Inc., California. When in use, the second calibrator also excludes any scattered atmospheric light so that its operation is independent of the ambient visibility.

There is a small effect due to the scattering of light in bright fog, but the error introduced by ignoring this effect is small and within the accuracy of the instrument.

3.4 Comparison of the various types of instruments

The transmissometer is frequently used as a standard instrument for comparison purposes and, marginally, may be considered as more accurate than most other types. The use of a long baseline reduces the uncertainty due to spatial and temporal variations in the visibility but does necessitate a relatively large area of land on which to site the instrument; the deep foundations required for the mountings to obviate the effects of 'frost heave' are costly. Folded-beam transmissometers avoid this latter problem though at a cost of some loss in sensitivity. A decrease in the length of the baseline also increases the effect of any calibration error.

Most instruments can be made to provide good discrimination at low visibilities but only with a consequent decrease in discrimination elsewhere in the visibility range. A compromise is therefore usually necessary, providing sensible discrimination for visibilities up to about 5 km. For a given accuracy and visibility, the calibration figures of scattering instruments often depend on the prevailing weather (Chisholm and Jacobs 1975). For these devices a compromise is normally made between a single calibration figure, which is desirable for ease of use, and an acceptable accuracy. Transmissometers are much less susceptible to this problem and can be made to operate reliably with a single calibration figure for most weathers.

The size of the scattering volume in scattering instruments affects their response to spatial and temporal variations in the visibility, particularly if the volume is very small, though filtering and choice of suitable sample rate can help to smooth the response. An additional problem is that of evaporation or condensation occuring within the scattering volume owing to heat exchange between the instrument and the volume. This effect may give rise to significant errors during fog.

The limitation of the angular span of integrating nephelometers introduces an 'angular truncation error'. This is discussed in detail by Ensor and Waggoner (1970) and by Fitzgerald (1977). As the size and concentration of the scattering particles increase so does the amount of scattering, especially in small forward angles. The angular truncation error can, therefore, become significant for measurements made in fog.

A problem associated with most instruments, to a greater or lesser degree, is the accumulation of snow at the transmitter and receiver, often despite the presence of heaters. An additional problem for some scattering instruments is ice accretion within the scattering volume causing reflection and an enhancement of the return signal.

A comparative study of some of the particular instruments mentioned in this section has been made by Bond *et al.* (1981).

4 MEASUREMENT OF CLOUD HEIGHT

4.1 Introduction

The height of the cloud base over land is measured, or estimated, above the ground level in the vicinity of the observer. When the visibility is poor, because of haze or mist, the cloud base is often ill-defined and no rigid criterion can be laid down as to where the haze ends and the cloud begins. The cloud base is defined by the World Meteorological Organization (WMO 1971) as 'the lowest zone in which the type of obscuration perceptibly changes from that corresponding to clear air or haze to that corresponding to water droplets or ice crystals'. However, such a qualitative description is an unsuitable basis for the objective design of instruments if subsequently the instruments have to be 'adjusted' to conform to the estimates of the observers. In this connection it should be noted that cloud-base height measuring instruments can, currently, only be regarded as an aid to human observers and not as primary instruments.

At present, the two principal instrumental methods used for measuring the height of the cloud base are:

(a) Measuring from one end of a baseline the elevation of a spot of light produced on the base of the cloud by a beam of light from a projector at the other end of the baseline. Alternatively, the angle at which a beam of light is projected to produce a spot of light on the cloud base vertically above the other end of the baseline may be measured.

(b) Measuring the time taken for a pulse of light directed vertically upwards to reach the base of the cloud and be returned.

4.2 Searchlight methods

One of the most convenient methods of measuring the height of the cloud base is by means of a searchlight. A narrow parallel beam of light is projected, in a known direction, from a searchlight and the elevation of the spot of light produced on the base of the cloud is measured from the other end of a baseline (Figure 13). If h is the height of the cloud above the observer, E is the angle of elevation of the spot of light and L is the length of the baseline then, when the searchlight beam is projected vertically upwards,

$$h = L \tan E. \qquad \ldots (24)$$

An ordinary searchlight used in conjunction with a visual elevation indicator, called a clinometer or alidade, can only be used at night. Daytime as well as night-time measurements are, however, made possible with the use of a modulated light source and a photoelectric detector.

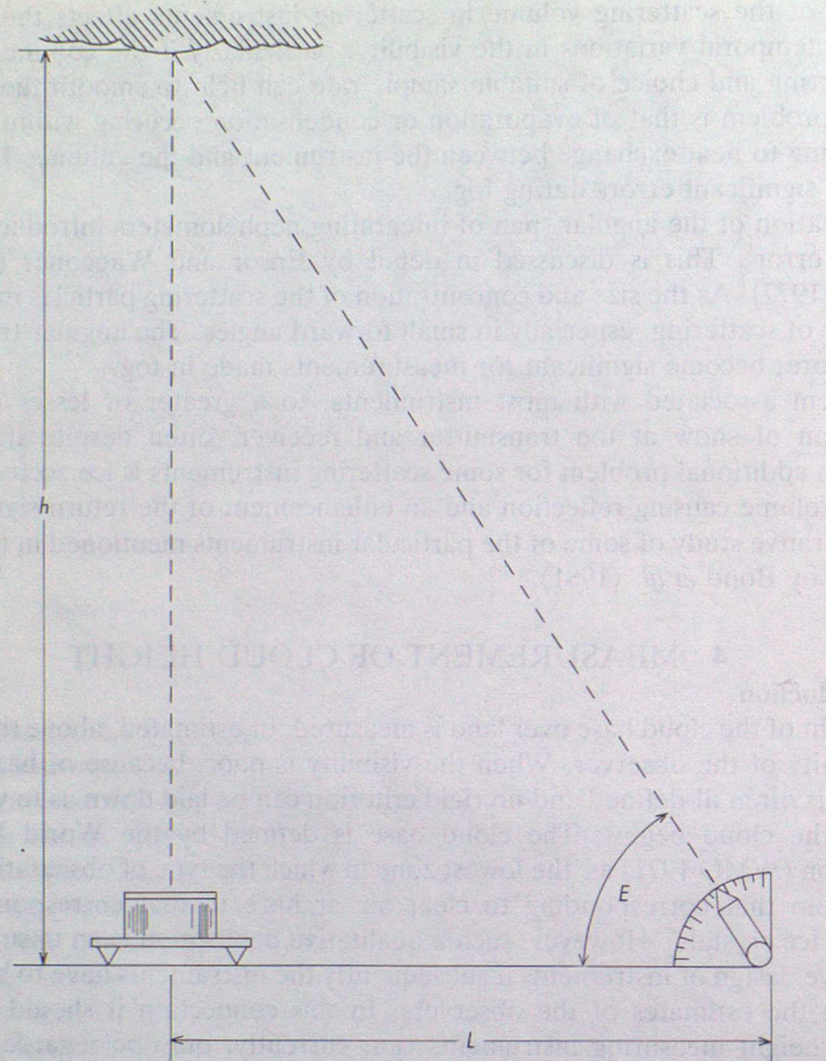


Figure 13. Principle of the cloud searchlight.

5 INSTRUMENTS FOR MEASURING CLOUD HEIGHT

5.1 Meteorological Office cloud searchlight

The standard Meteorological Office cloud searchlight, Plate VII, consists of a 406 mm diameter parabolic silvered glass mirror and a lamp mounted in a strong cylindrical case, the base of which has three adjustable feet for levelling purposes. The top of the case is sloped and is sealed by a glass window clamped between rubber and asbestos sealing rings. The metal ring which clamps the window in position is provided with a small hole at its lowest point to allow rainwater collected on the glass to drain away. The 24 V, 500 W lamp is overrun and consequently its average life is only about 100 hours; it is powered via a transformer having a 500 VA rating.

Installation. The baseline will usually be between 650 ft (180 m) and 2000 ft (600 m) in length, about 1000 ft (300 m) being the optimum length. In most installations there will be a difference, usually small, between the heights of the searchlight and the alidade. This difference can, however, be incorporated in the table mentioned on page 7–28.

Where the searchlight is to stand upon open ground, it should preferably be mounted on top of a brick-built plinth. Where there is a clear line of sight between the searchlight site and the alidade, the searchlight should be positioned with the sloping window towards the alidade so that if the searchlight is inadvertently left switched on during daylight the fact is more likely to be noticed from the alidade position. If a clear line of sight is not possible the

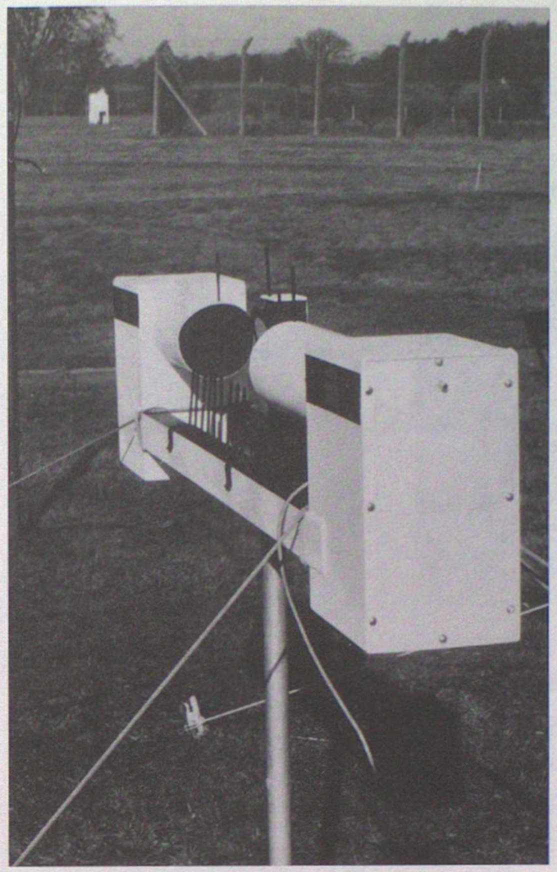


Plate VI. M.R.I. fog visiometer.

Plate VII. Meteorological Office cloud searchlight.

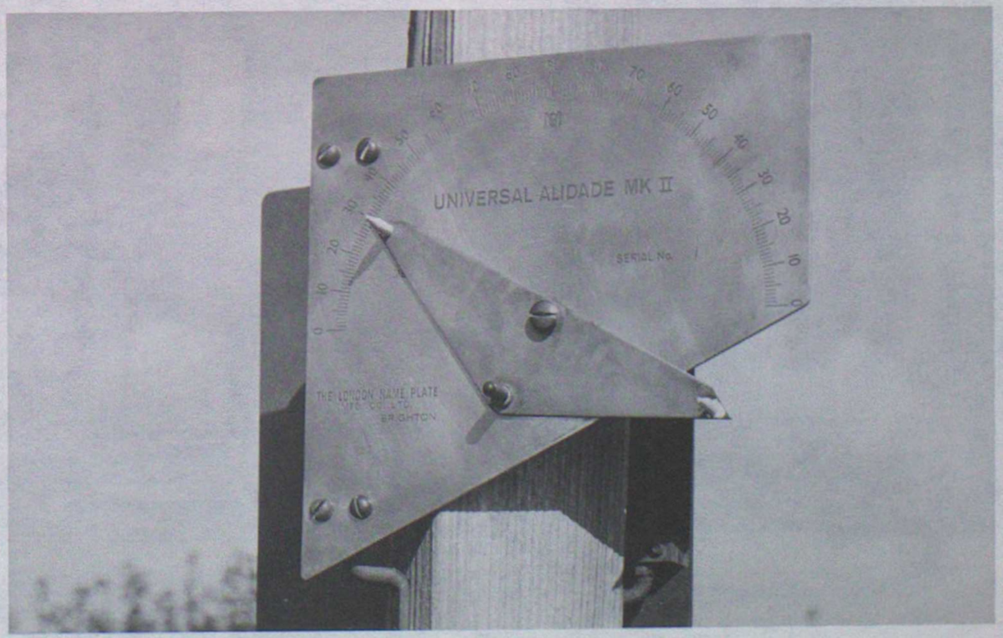


Plate VIII. Alidade.

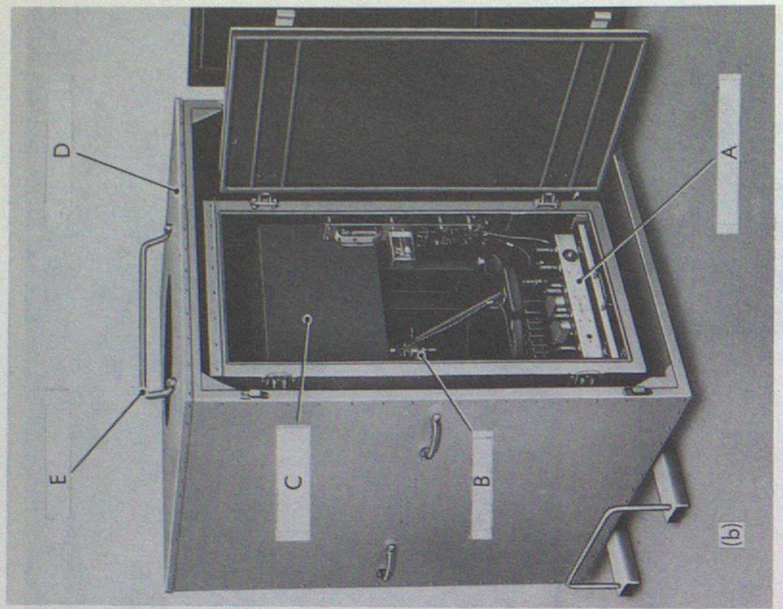
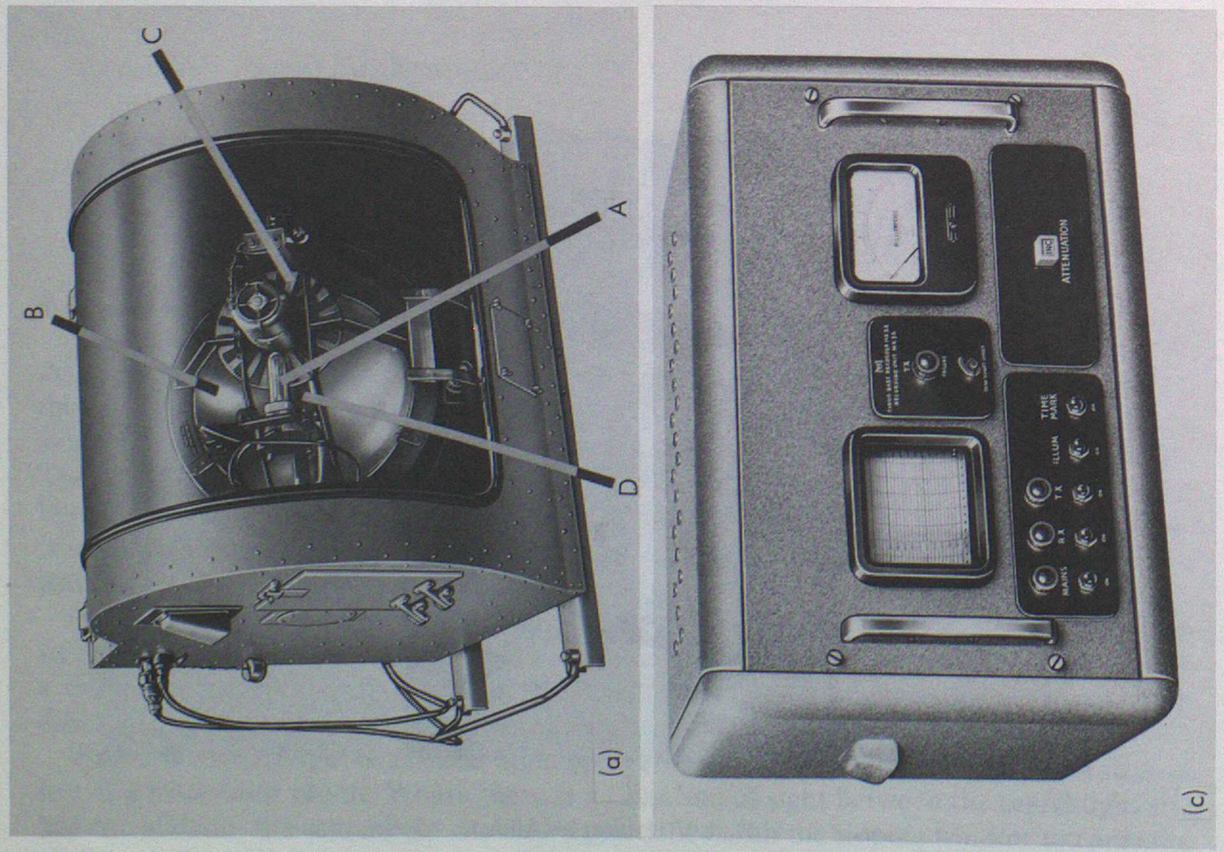


Plate IX. Meteorological Office cloud-base recorder Mk 3A.

(a) Transmitter unit. (b) Receiver unit. (c) Recording unit.



obscuration of the searchlight beam from the alidade position by intervening objects must not extend above 100 ft. Besides housing the necessary transformer the plinth may also house:

(a) a daylight switch to restrict operation of the searchlight to the hours of darkness, and

(b) a time switch to control the supply of power to the lamp at predetermined times.

Instead of the above switches a remote switch for the mains supply may be required in an office or at a position adjacent to the alidade.

The alidade, Plate VIII, must be mounted at eye level on a firm support in a position convenient to the observer. It must be in correct alignment with respect to the beam of the searchlight and should read 0° when the sights are horizontal. Before the instrument can be brought into use the distance between the alidade and the searchlight must be known to the nearest 10 ft (3 m).

Adjustment of the searchlight. The searchlight must be adjusted so that the beam is vertical and focused to produce a narrow nearly parallel beam. The necessary adjustments are as follows:

(a) Levelling to make the optical axis vertical.

(1) Level the base of the searchlight by adjusting the three external foot screws, A in Figure 14, until the bubble of the spirit-level, fixed to the base casting inside the casing, is in a central position.

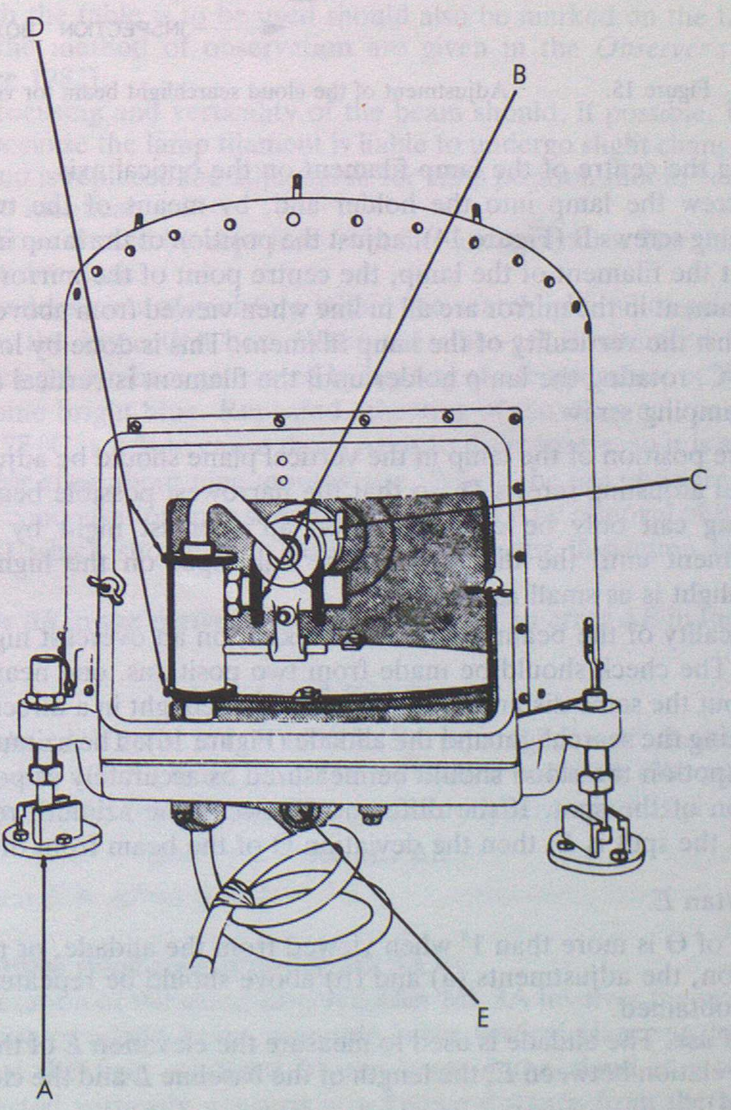


Figure 14. Meteorological Office cloud searchlight.

(2) Remove the two wing nuts securing the inspection box cover and remove the cover.

(3) Place a steel ball of about 20 mm diameter on the mirror adjacent to position A (Figure 15) and release it. If the ball does not oscillate across the centre point of the mirror the level requires adjustment. Slacken the lock-nut on the stud at either B or C and alter the position of the lower nut until the ball oscillates across the centre point. Repeat the process, releasing the ball from a direction at right angles to the first. The mounting at A is difficult to reach through the limited access provided by the inspection box entry but, as the mirror is spring-mounted, the level can be correctly adjusted by means of the mountings at B and C only.

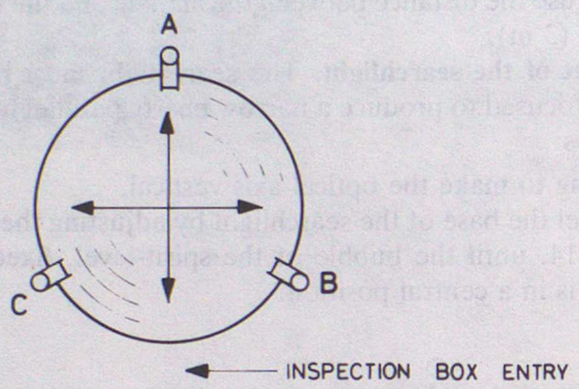


Figure 15. Adjustment of the cloud searchlight beam for verticality.

(b) Setting the centre of the lamp filament on the optical axis.

(1) Screw the lamp into the holder and, by means of the two sets of horizontal adjusting screws B (Figure 14), adjust the position of the lamp in the horizontal plane so that the filament of the lamp, the centre point of the mirror and the reflection of the filament in the mirror are all in line when viewed from above. It may be necessary to adjust the verticality of the lamp filament. This is done by loosening the clamping screw C, rotating the lamp holder until the filament is vertical and then retightening the clamping screw.

(2) The position of the lamp in the vertical plane should be adjusted by means of the vertical adjusting screws D, so that the narrowest possible beam is produced. Final focusing can only be carried out on an overcast night by altering the vertical adjustment until the diameter of the light spot on the highest cloud above the searchlight is as small as possible.

The verticality of the beam should be checked, on an overcast night, with the aid of a theodolite. The check should be made from two positions, one near the alidade and the other at about the same distance away from the searchlight in a direction at right angles to the line joining the searchlight and the alidade (Figure 16). The azimuths of the searchlight and of the spot on the cloud should be measured as accurately as possible, together with the elevation of the spot. If the difference between the azimuth readings is A and the elevation of the spot is E, then the deviation Θ of the beam from the vertical is given by

$$\Theta = A/\tan E.$$

If the value of Θ is more than 1° when viewed from the alidade, or more than 0.5° in the other position, the adjustments (a) and (b) above should be repeated until the necessary accuracy is obtained.

Method of use. The alidade is used to measure the elevation E of the spot of light on the cloud. The relation between E, the length of the baseline L and the cloud height is given in equation (24).

A table should be prepared, for each alidade in use at the station, giving the correct

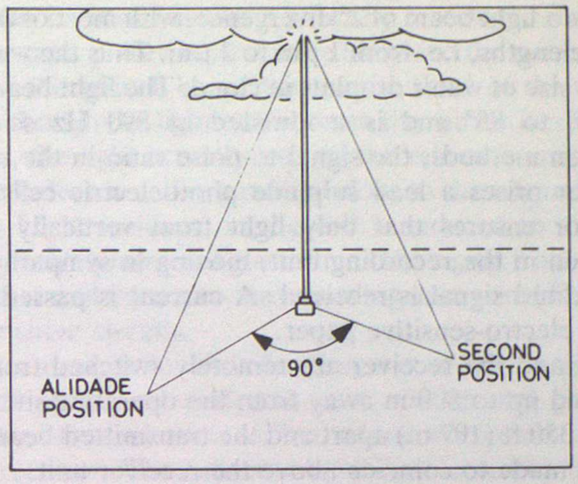


Figure 16. Checking the verticality of the searchlight beam with a theodolite.

cloud height for each degree of the alidade reading, incorporating any correction for the difference in heights of the searchlight and the alidade. The length of the baseline should be entered on the table and, if more than one alidade is in use at the station, the location of the alidade with which the table is to be used should also be marked on the table.

Details regarding the method of observation are given in the *Observer's handbook* (Meteorological Office 1982).

Maintenance. The focusing and verticality of the beam should, if possible, be checked about once a month because the lamp filament is liable to undergo slight changes in shape with time. When a lamp is replaced the adjustment for lamp position should be carried out since not all lamps are identical.

The window and mirror should be kept free from dirt and moisture. The mirror should be cleaned with a soft dry cloth.

To help prevent condensation of moisture within the searchlight, silica-gel desiccators may be placed within the inspection box. When the silica-gel is saturated the crystals become pink. The silica-gel can be regenerated by heating at a temperature of about 175 °C until the crystals become bright blue. Repeated reheating of the silica-gel, particularly at temperatures above 175 °C, tends to cause the crystals to disintegrate, so it is advisable to exchange the desiccator after about nine months' use. Where the use of desiccators is not practicable, excessive condensation may sometimes be reduced by removal of the drainage plug (E in Figure 14) which should then be placed inside the inspection box for safe keeping.

Accuracy. The error Δh in the derived cloud height due to an error ΔE in the measured elevation is given by

$$\Delta h = L \sec^2 E.\ \Delta E,$$

which is a minimum when E is zero. If $L = 1000$ ft (300 m) and $\Delta E = 1°$, then the value of Δh is 17 ft (6 m) when $h = 100$ ft (30 m), 35 ft (10 m) when $h = 1000$ ft (300 m) and about 450 ft (140 m) when $h = 5000$ ft (1500 m). The proportional error in h is given by

$$\Delta h/h = 2 \operatorname{cosec} 2E.\ \Delta E$$

and is a minimum when $E = 45°$ or $h = L$.

5.2 Meteorological Office cloud-base recorder Mk 3A

The principle of operation of the cloud-base recorder Mk 3A involves the measurement of the angle of elevation of a light beam, scanning in the vertical plane, at the instant at which a proportion of the light scattered by the base of the cloud is received by a photoelectric cell directed vertically upwards at a known distance from the light source (Figure 17). The equipment comprises a transmitter, a receiver and a recording unit.

The transmitter emits a light beam of 2° divergence, with most of the emitted radiation in the near infra-red wavelengths, i.e. from 1 μm to 3 μm. Thus the wavelength used is small in comparison with the size of water droplets in cloud. The light beam is swept in a vertical arc extending from 8° to 85° and is modulated at 890 Hz so that, by the use of phase-sensitive detection methods, the signal-to-noise ratio in the receiver is improved.

The receiver unit comprises a lead sulphide photoelectric cell and an angle-of-view restrictor; the restrictor ensures that only light from vertically above can reach the photoelectric cell. A pen in the recording unit, moving in sympathy with the transmitter beam, writes when a cloud signal is received. A current is passed through the pen tip, burning a trace on the electro-sensitive paper.

Both the transmitter and the receiver are remotely switched from the recording unit, which may be positioned up to 800 m away from the operating site. The transmitter and receiver are positioned 350 ft (107 m) apart and the transmitted-beam arc and the receiver cone of acceptance are made to coincide above the receiver unit.

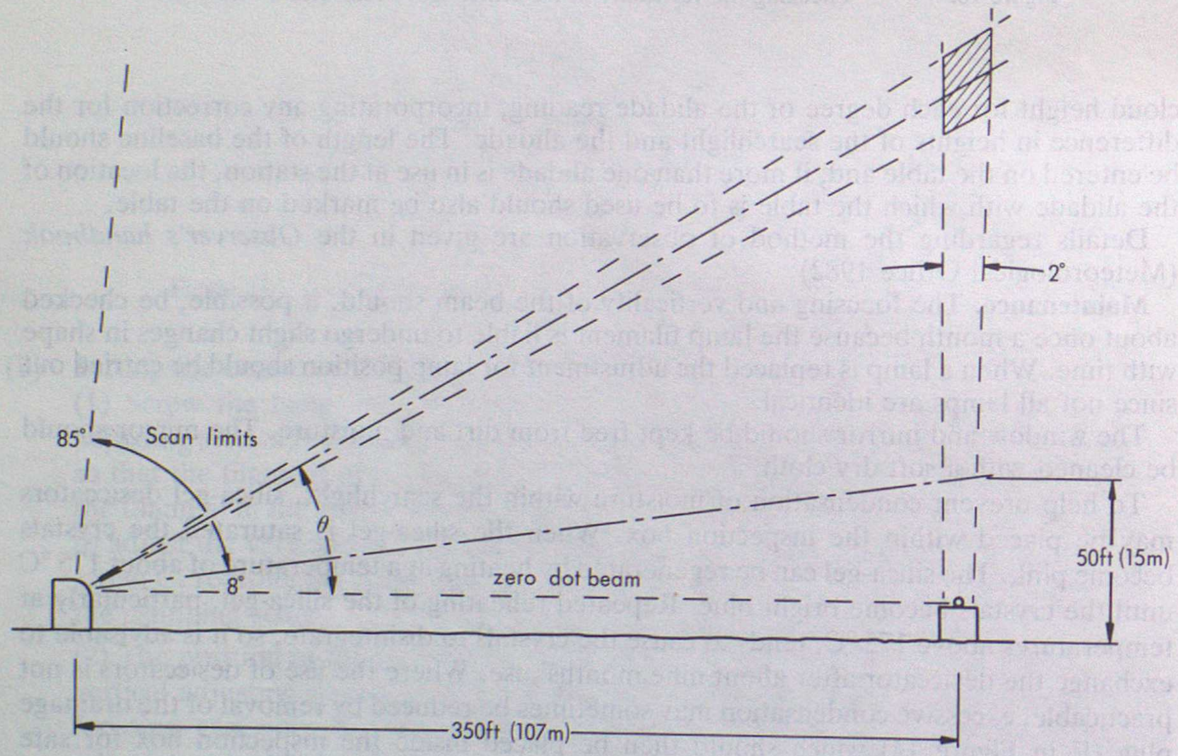


Figure 17. Principle of the Meteorological Office cloud-base recorder Mk 3A.

Transmitter. The transmitter unit, Plate IX(a), is enclosed in a weather-proof steel cabinet, which has an acrylic plastic window, and comprises a modulated light source and mirror, a mirror-scanning mechanism, a reference-signal system and a magslip transmitter. Partial air-conditioning is achieved by thermostatically controlled heaters and an air-extractor fan. The cabinet is mounted on a concrete plinth, the top surface of which is 150 mm above ground level. The light source A is a 24 V, 200 W quartz–iodine lamp mounted at the focus of a 406 mm diameter parabolic mirror B. The mirror is of polished glass with the front aluminized; the aluminized surface is quartz-flashed for protection. The whole mirror assembly is pivoted to enable the beam to scan in elevation, the scanning mechanism being driven by a single-phase motor coupled to the mirror axis by means of a heart-shaped cam and a cam follower. A complete scan from 8° to 85° and back to 8° takes one minute. The angular position of the mirror shaft is transmitted to the recording unit by a magslip system. Increased discrimination is obtained by driving a magslip transmitter from the mirror axis at a ratio of about 4 to 1.

The transmitted beam is modulated at 890 Hz by a sectored disc C, rotating at about 3000 revolutions per minute, placed between the lamp and the mirror. A metal disc D fixed between the lamp and the mirror keeps the middle third of the mirror permanently in shadow. In this way, although the light output from the mirror is restricted to two-thirds of the possible maximum, the light actually leaving the mirror is completely modulated.

A lead sulphide photoelectric cell is mounted close to the edge of the mirror to monitor the modulated beam. Light incident on the cell is reduced to a reasonable level by a cylindrical mask fitted with an infra-red glass filter. The signal from the cell is passed to the reference-signal amplifier and thence to the recording unit, providing a reference signal for the recorder phase-sensitive circuits.

When the transmitter is at its lowest elevation, i.e. 8°, the lower edge of the beam is intercepted by a small prism and deflected into a horizontal path. The beam is then reflected from the underside of a horizontal bar, of circular cross section, which is mounted across the top of the receiver. The reflected light is collected by the receiver mirror and focused on to the receiver photoelectric cell. The resulting output from the photoelectric cell is amplified and fed to the recording unit.

Receiver. The receiver, Plate IX(b), consists of a mirror–photoelectric cell assembly, a signal amplifier A, a power pack and a switching panel contained in a weather-proof cabinet. The cabinet is fitted with a sloping plastic window at the top and the complete assembly is enclosed in a radiation shield. A thermostatically controlled heater inside the cabinet ensures that the temperature inside the cabinet does not fall below 18 °C.

A 406 mm diameter parabolic mirror with a focal length of 201 mm is mounted in a metal frame. Attached to the frame is a tripod assembly which supports a photoelectric cell B at the focal point of the mirror; the cone of acceptance of the receiving system is 2°. The mirror is mounted facing vertically upward and adjusting screws are fitted to the mirror mount to permit accurate levelling of the mirror. Baffles, C, mounted above the mirror–photoelectric cell assembly minimize the ingress of stray light.

The purpose of the radiation shield D is to prevent the receiver from becoming overheated in direct sunlight. A hole, 464 mm in diameter, is provided in the top of the shield to enable the light reflected from the cloud to reach the mirror. A metal bar E, 6 mm in diameter, is mounted on top of the radiation shield in such a position that the horizontal beam from the transmitter is reflected into the mirror–photoelectric cell assembly.

Recording unit. The recording unit, Plate IX(c), contains a strip-chart mechanism driven through reduction gearing by a synchronous motor whose output shaft takes two hours to complete one revolution. The recording roll chart moves past the stylus at a rate of 76 mm per hour, and the take-up spool for the chart is driven from the chart roller by means of a slipping spring belt which maintains a constant tension on the chart and compensates for the increasing radius of the roll on the take-up spool.

The recording pen and its controlling magslip receiver are mounted on a sub-assembly frame which is attached to the main chassis. The pen is pivoted on the frame and is counterbalanced. The position of the stylus on the chart is determined by the angular position of a cam driven by the magslip receiver. As the transmitted light beam is swept between 8° and 85° a magslip link from the transmitter unit causes the rotor of the magslip receiver to turn through 308°. Rotation of the cam causes the stylus to be raised and lowered across the chart in synchronism with the transmitted light beam. The shape of the cam is such that the stylus moves over the chart at almost constant speed. The stylus can be lifted clear of the chart by operating a button on the front panel of the unit.

Provision is made for a fixed amount of attenuation to be applied in fog conditions. When the attenuation button is operated an event pen, attached to the front panel with its stylus permanently in contact with the chart, produces a horizontal trace.

The recorder receives, simultaneously, the main output signal from the receiver and the balanced output from the transmitter reference-signal amplifier. This latter output is fed to an amplitude limiter and differentiated; the voltage spikes resulting from the differentiation are used to operate a bistable circuit which supplies the gating wave-form to the

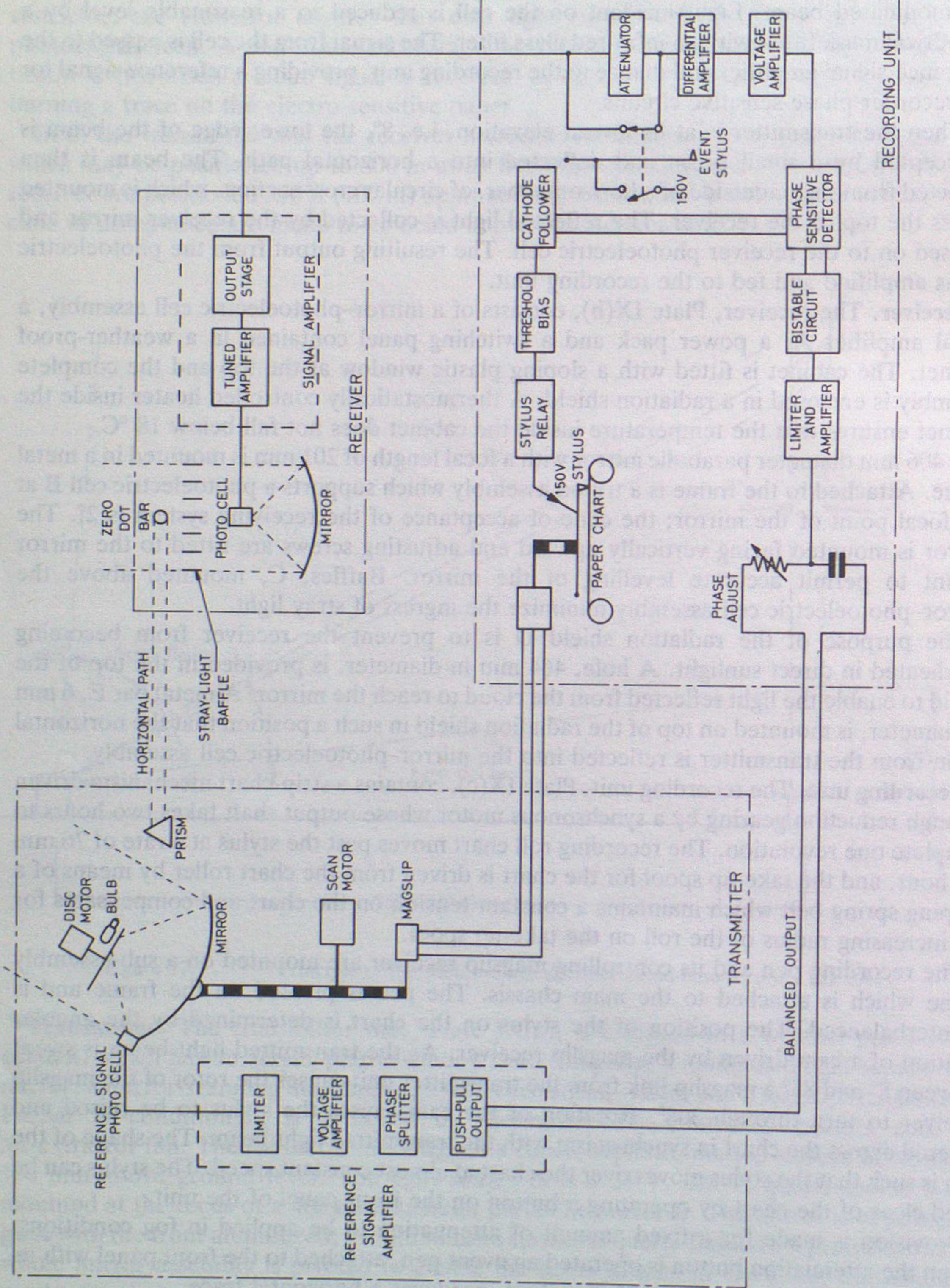


Figure 18. Block diagram of the Meteorological Office cloud-base recorder Mk 3A

phase-sensitive detector (Figure 18). If the receiver signal output coincides with the reference signal at the gating stage the signal is passed to the cathode follower output stage. If, then, the output from the cathode follower is sufficiently large to overcome the threshold bias, set by a Zener diode, the stylus relay operates. Operation of the relay applies a 150 V supply to the stylus, causing a trace to be burned on the chart.

The trace on the chart (Figure 19) appears as a 'ribbon' made up of parallel, vertical lines extending between two altitudes on the scale. The ribbon provides a picture of how the height of the cloud base vertically above the receiver changes with time. The lower of the two altitudes is the cloud base; the higher altitude may either be the top of the cloud layer or merely represent the distance to which the beam has penetrated the cloud.

By suitable shaping of the pen-arm drive cam the altitude scale is made linear up to 1000 ft and logarithmic from 1000 ft to 4000 ft.

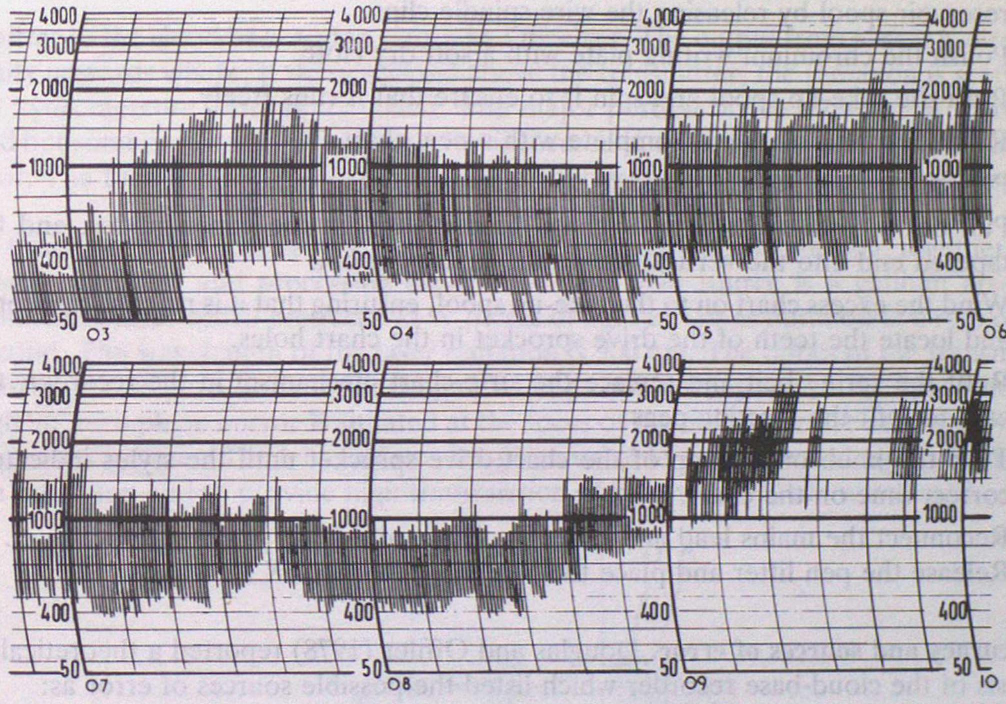


Figure 19. Cloud-base recorder chart. Upper part shows fog lifting into low stratus and lower part shows stratus lifting and dispersing.

The horizontal-path signal is ordinarily of sufficient amplitude to operate the stylus relay. Thus a dot is produced on the chart at the lowest position, i.e. 50 ft, once every scan. This dot is called the zero dot. On a clear day with no cloud to reflect the signal the zero dot is recorded and provides an indication that the equipment is operating. If neither a cloud trace nor a zero dot registers on the chart, the visibility is such that the horizontal beam and the scattered light from the main beam cannot reach the receiver. This normally occurs when the visibility is 80 m or less.

Installation. At the time of publication the Mk 3 cloud-base recorder was the Meteorological Office operational instrument for the automatic measurement of the height of the cloud base. This instrument will, however, eventually by superseded by the Laser cloud-base recorder (see page 7-34) and no further MK 3 cloud-base recorder installations are anticipated.

Maintenance. The only maintenance to be undertaken by the user involves cleaning the transmitter and receiver windows and changing the chart. At weekly intervals the outside of the plastic windows of the transmitter and receiver should be cleaned. A soft dry cloth should be used and care should be taken not to scratch the windows. At the same time the zero-dot reflector rod and the prism should be wiped clean.

Changing the chart. The procedure is:

(a) Place the TX and RX switches on the recorder unit to OFF.

(b) When the TX FAILURE lamp glows, place the MAINS switch on the recording unit to OFF.

(c) Operate the pen lifter.

(d) Undo the front panel retaining screws and pull the tray forward.

(e) Unscrew the mains connector on top of the strip chart mechanism and remove the mechanism from the tray, taking care not to touch the pen tips.

(f) Hold the pen arm firmly and carefully chip any 'coke' deposit from the pen tips with the tip of the blade of a small screwdriver.

(g) Remove the spring belt and the chart tensioning pillar near to the reservoir spool. Remove the take-up spool by lifting it 6 mm and sliding it to the rear and remove the reservoir spool by releasing the wire spindle clips.

(h) Polish the chromium writing plate with a soft dry cloth.

(i) Refit the take-up spool and spin it to ensure that it runs freely.

(j) Refit the reservoir spool complete with a new chart.

(k) Pull out 150 mm of chart and fit the chart tensioning pillar.

(l) Pull out a further 300 mm of chart, feed it through the paper guides, and fit the tapered end into the vertical slot in the take-up spool.

(m) Wind the excess chart on to the take-up spool, ensuring that it is running horizontally, and locate the teeth of the drive sprocket in the chart holes.

(n) Refit the spring belt and replace the strip-chart mechanism in the recorder, taking care to refit the locating pegs.

(o) Turn the knob on the top of the chart drive sprocket until the stylus indicates the correct time on the chart.

(p) Reconnect the mains lead and refit the chassis and front panel in the cabinet.

(q) Release the pen lifter and place the MAINS, RX and TX switches to ON.

Accuracy and sources of error. Douglas and Offiler (1978) reported a theoretical error analysis of the cloud-base recorder which listed the possible sources of error as:

(a) beamwidth,

(b) optical misalignment,

(c) magslip misalignment,

(d) function cam and baseline, and

(e) receiver electronics.

Beamwidth was considered as being probably the largest single source of error, such errors being expressed in Table II in the form of an expected true height for each selected indicated height. The standard deviations of the other errors are also given.

Experimental comparisons using heights obtained from cloud searchlight observations, pilot balloon ascents and aircraft reports substantiated the trend indicated by the theoretical treatment, though the errors found experimentally were numerically greater.

5.3 Meteorological Office cloud-base recorder Mk 3B

The cloud-base recorder Mk 3B is a telemetering version of the Mk 3A for use where the recording unit is housed more than 800 m from the transmitter–receiver site.

5.4 Laser cloud-base recorder

In the prototype Laser cloud-base recorder (LCBR) the height of the cloud base is determined by measuring the time taken for a pulse of coherent light to travel from a transmitter to the cloud base and to return to a receiver. The output from a laser is directed vertically upwards where, if there is cloud above the transmitter, the radiation is scattered by the hydrometeors forming the cloud. The major portion of the radiation is scattered upward but some is scattered downward and is focused in the receiver on to a photoelectric detector. The LCBR comprises two units, a transmitter–receiver assembly and a recording unit.

Table II. *Summary of the expected errors due to beamwidth and the standard deviation of the other errors for some selected indicated heights*

Indicated height	Expected height	Standard deviation of the expected height (due to errors other than beamwidth	Indicated height minus expected height
feet	*feet*	*feet*	*feet*
100	104	1.25	−4
250	257	1.9	−7
500	517	4	−17
1000	1059	11	−59
1500	1636	23	−136
2000	2253	39	−253
3000	3644	86	−644
4000	5332	150	−1332

The transmitter and receiver are mounted side by side in a single housing, together with the signal detection and processing electronics. The light source is a gallium arsenide semiconductor laser which produces 75 W pulses of light of 110 ns duration at a rate of 830 per second. The wavelength of the laser radiation is 900 nm. The optics of the transmitter are illustrated in Figure 20. After passing through a condenser system A the light is folded through 90° by a plane mirror B situated at the focus of the main aperture mirror C, which is 216 mm in diameter. The lens surfaces are given suitable quarter-wavelength coatings to reduce reflection and to provide high transmission of light with 900 nm wavelength, while

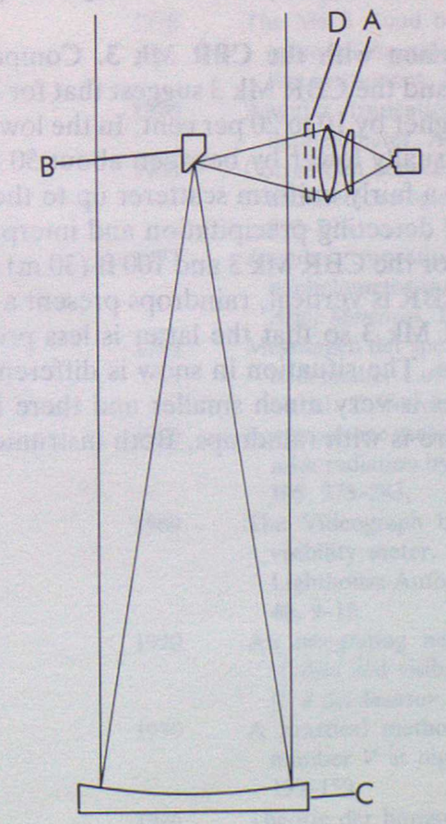


Figure 20. Optical system of the Laser cloud-base recorder.

the mirror reflecting surfaces are gold coated on a chromium base. The transmitter aperture is sealed by a glass window, which is anti-reflection coated on its inner surface, and angled at 20° to the horizontal so that rain will run off it.

The receiver is of similar construction to the transmitter except that the light source is replaced by a photodiode and a narrow-band optical filter D is incorporated between the condenser system and the plane mirror. The filter excludes most of the background diffuse solar radiation thus improving the detection of the scattered laser radiation by day.

The transmitter beam has a divergence of 7.5 minutes of arc and the receiver has a field of view of 13 minutes of arc. The transmitter and receiver are mounted side by side so that the transmitter beam and the receiver field of view begin to overlap at 5 m above the assembly and are fully overlapped at 280 m.

The housing is provided with thermostatically controlled heaters to prevent condensation on the optical surfaces and the humidity within the housing is reduced by the use of a desiccator. The top of the housing is fitted with a cover hood incorporating optical baffles which exclude direct sunlight.

The output from the detector is separated by an electronic processing unit into 96 sequential 100 ns range gates, each range gate representing a height increment of 50 ft (15 m). Each laser firing provides either a 'cloud' or a 'no-cloud' decision in each range gate; during one scan the laser is fired many times. A threshold is incorporated so that the probability of the instrument not 'seeing' cloud, or 'seeing' non-existent cloud, is remote. The radiant flux back-scattered to the receiver decreases with range according to an inverse-square law.

Within the recording unit the data are decoded and used to control the movement of a pen across a chart. The pen, at the beginning of each scan, is made to move vertically across the chart. When cloud is detected (i.e. a cloud signal in a particular range gate) the pen is lowered on to the chart and a trace is marked at the corresponding height. The length of the trace on the chart is equivalent to one height increment, i.e. 50 ft (15 m). When the scan is completed the pen is returned to the zero on the chart where it is made to mark the chart with a dot. The instrument has a height range from 100 ft (30 m) to 4850 ft (1455 m).

Accuracy and comparison with the CBR Mk 3. Comparison of indicated cloud-base heights from the LCBR and the CBR Mk 3 suggest that for heights above about 1000 ft the LCBR heights are the higher by 10 to 20 per cent. In the lowest few hundred feet, however, the LCBR heights are usually lower by between about 50 ft and 120 ft.

Precipitation provides a fairly uniform scatterer up to the cloud base. Both instruments are therefore capable of detecting precipitation and interpreting it as cloud at the lowest height, i.e. 50 ft (15 m) for the CBR Mk 3 and 100 ft (30 m) for the LCBR. However, since the light path for the LCBR is vertical, raindrops present a larger reflecting surface to the LCBR than to the CBR Mk 3 so that the latter is less prone to the above effect during periods of rain or drizzle. The situation in snow is different since the difference between reflecting crystal surfaces is very much smaller and there is no preferred orientation for falling snowflakes as there is with raindrops. Both instruments therefore behave similarly in snow.

References

Ahlquist, N. C. and Charlson, R. J.	1967	A new instrument for evaluating the visual quality of air. *J Air Pollut Control Assoc*, **17**, 467–469.
	1968	Measurement of the vertical and horizontal profile of aerosol concentration in urban air with the integrating nephelometer. *Environ Sci Tech*, **2**, 363–366.
Beuttel, R. G. and Brewer, A. W.	1949	Instruments for the measurement of the visual range. *J Sci Instrum*, **26**, 357–359.
Bibby, J. R.	1947	Gold visibility meter Mk II. *Meteorol Mag*, **76**, 130–133.
Bond, F. S., Foot, J. S. and Pettifer, R. E. W.	1981	A comparative study of some single-pole visibility sensors, the Meteorological Office Mk 4 transmissometer and estimates of visibility made by observers. *Sci Pap, Meteorol Off*, No. 39.
Bouguer, P.	1760	Traité d'optique sur la gradation de la lumière. Paris, H. L. Guerin et L. F. Delatour.
Chisholm, D. A. and Jacobs, L. P.	1975	An evaluation of scattering-type visibility instruments. Bedford, Mass., Air Force Cambridge Research Laboratories, AFCRL-TR-75-0411, *Instrum Pap*, No. 237.
Crosby, P. and Koerber, B. W.	1963	Scattering of light in the lower atmosphere. *J Opt Soc Am*, **53**, 358–361.
Curcio, J. A. and Knestrick, G. L.	1958	Correlation of atmospheric transmission with backscattering, *J Opt Soc Am*, **48**, 686–689.
Deirmendjan, D.	1964	Scattering and polarization properties of water clouds and hazes in the visible and infra-red. *Appl Opt*, **3**, 187–196.
Dietze, G.	1957	Einführung in die Optik der Atmosphäre. Leipzig, Akademische Verlagsgesellschaft Geest & Portig K.-G.
Douglas, H. A. and Offiler, D.	1978	The Mk 3 cloud base recorder — a report on some of the potential accuracy limitations of this instrument. *Meteorol Mag*, **107**, 23–32.
Ensor, D. S. and Waggoner, A. P.	1970	Angular truncation error in the integrating nephelometer. *Atmos Environ*, **4**, 481–487.
Fenn, R. W.	1966	Correlation between atmospheric backscattering and meteorological optical range. *Appl Opt*, **5**, 293–295.
Fitzgerald, J. W.	1977	Angular truncation error of the integrating nephelometer in the fog droplet size range. *J Appl Meteorol*, **16**, 198–204.
Foitzik, L. and Zschaeck, H.	1953	Messungen der spektralen Zerstreuungsfunktion bodennaher Luft bei guter Sicht, Dunst und Nebel. *Z Meteorol*, **7**, 1–19.
Foot, J. S.	1979	Spectrophone measurements of the absorption of solar radiation by aerosol. *Q J R Meteorol Soc*, **105**, 275–283.
Früngel, F.	1969	The Videograph backscatter fog detector and visibility meter. International Association of Lighthouse Authorities, *AISM-IALA Bulletin*, **40**, 9–16.
Garland, J. A. and Rae, J. B.	1970	An integrating nephelometer for atmospheric studies and visibility warning devices. *J Phys, E, J Sci Instrum*, **3**, 275–280.
Gold, E.	1939	A practical method of obtaining the visibility number *V* at night. *Q J R Meteorol Soc*, **65**, 139–159.
Koschmieder, H.	1926	Theorie der horizontalen Sichtweite. *Beitr Phys freien Atmos*, **12**, 33–55.

Lifsitz, J. R.	1974	The measurement of atmospheric visibility with lidar: TSC field test results. Washington, Federal Aviation Administration Systems Research and Development Service. Report No. FAA-RD-74-29, Final report.
Meteorological Office	1982	Observer's handbook, 4th edition. London, HMSO.
Middleton, W. E. K.	1952	Vision through the atmosphere. University of Toronto Press.
Ruppersberg, G. H.	1964	Registrierung der Sichtweite mit dem Streulichtschreiber. *Beitr Phys Atmos*, **37**, 252–263.
Twitty, J. T. and Weinman, J. A.	1971	Radiative properties of carbonaceous aerosols. *J Appl Meteorol*, **10**, 725–731.
Twomey, S. and Howell, H. B.	1965	The relative merit of white and monochromatic light for the determination of visibility by backscattering measurements. *Appl Opt*, **4**, 501–506.
Vogt, H.	1968	Visibility measurement using backscattered light. *J Atmos Sci*, **25**, 912–918.
Winstanley, J. V. and Adams, M. J.	1975	Point visibility meter: a forward scatter instrument for the measurement of aerosol extinction coefficient. *Appl Opt*, **14**, 2151–2157.
World Meteorological Organization	1971	Guide to meteorological instrument and observing practices. Geneva, WMO Publication No. 8 (TP 3).

APPENDIX 1

METEOROLOGICAL RECORDING INSTRUMENTS — GENERAL CONSIDERATIONS CONCERNING CONSTRUCTION, MAINTENANCE AND OPERATION

CONTENTS

LIST OF DIAGRAMS

LIST OF PLATES

APPENDIX 1

A.1 RECORDING METHODS

A.1.1 Introduction

The effect of friction on the accuracy of a recording instrument is generally larger and more serious than in a comparable indicating instrument, especially when a pen, writing continuously on paper, is used to record the results. The friction between the pen and the paper is usually much larger than the total amount of friction in the bearings of the instrument; the concept of adequate control thus arises.

The effect of friction is to impose a certain force on the indicating mechanism in the opposite direction to that in which the variable element is causing the mechanism to move. This force causes the reading of the instrument to be in error by a certain amount. The 'control' of the instrument may be defined as the force which must be applied to the indicating mechanism at the point where it is recording (e.g. at the pen) to keep the indication constant when the value of the element which is being recorded changes by one unit. This is equal to the force required to move the indicating mechanism over one unit of the scale provided the measured element remains constant. The greater the control the less will be the effect of friction and the more detailed will be the record. In any case the control should be such that the maximum effect of the friction on the reading should be less than the least change it is desired to record. If this is not so, the errors will be markedly different for rising and falling values of the element recorded and there will be 'lost motion' when the variable element reaches a maximum or minimum value.

A.1.2 Recording charts

There are several methods by which the indication of an instrument can be made to give a permanent record. In the majority of these the record is in the form of a line on a sheet of paper, and is measured by reference to the position of the line on the paper. The properties of the paper are thus of some importance.

Good chart paper is manufactured so that its fibres lie largely in one direction ('downboard'). These fibres are hygroscopic and swell slightly in a lateral direction when they absorb water. Thus it is found that an instrument chart changes its dimensions when it is soaked in water, or to a somewhat lesser extent when the humidity changes, and the magnitude of the change in any direction depends on the direction of the fibres. All Meteorological Office charts are cut with the time-scale 'downboard', and it is found that the change in length in this direction when the chart is immersed in water after being in a normal room atmosphere is about 0.2–0.3 per cent. On the other hand the change in length in a direction perpendicular to this is 2.5–3.0 per cent, i.e. 10 times as much. The chart will not of course become soaked in normal use, but experiments have shown that the changes in dimensions are very nearly as much when the charts are exposed in a humidity chamber and the relative humidity is altered from about 50 per cent to about 100 per cent. The change in length 'downboard' is 0.1–0.2 per cent, and the change in length in a perpendicular direction is 1.5–2 per cent.

In very accurate work it is thus necessary to have two datum lines drawn on the chart at fixed positions; these can be used as base lines to enable zero errors (due to chart slipping or being inserted wrongly) and changes in scale value (due to the chart altering in size before the record was made) to be measured and allowed for.

A.1.3 Pen recorders

In most meteorological instruments using pen recording the pen rests lightly on a chart wrapped around a vertical cylindrical drum. The drum is rotated at a constant speed, and as the element to be recorded varies the pen moves up and down the chart. To reduce friction, it is necessary to adjust the pressure of the pen on the chart to the minimum consistent with a clear record. This is achieved in many Meteorological Office instruments by means of the gate suspension (Figure A1). The pen arm is suspended in a small gate, A, so that it can rotate freely about the gate axis. The gate itself is fixed to a collar, B, and can be rotated about an axis parallel to the pen arm, i.e. its inclination to the vertical plane containing the pen arm can be varied. When the axis of the gate is in this vertical plane there is no tendency for the pen arm to move in one direction or the other, but when the gate is inclined to the vertical plane there is a component of the weight of the pen arm which exerts a moment about the gate axis and causes the pen either to press on the chart or to fall away from it. The pressure between the pen and the paper can thus be adjusted to a suitable value which remains practically independent of the position of the pen on the chart provided the pen arm is perpendicular to the pen-arm spindle. It is normally found that an inclination of the gate axis of about 10° to the vertical is quite sufficient.

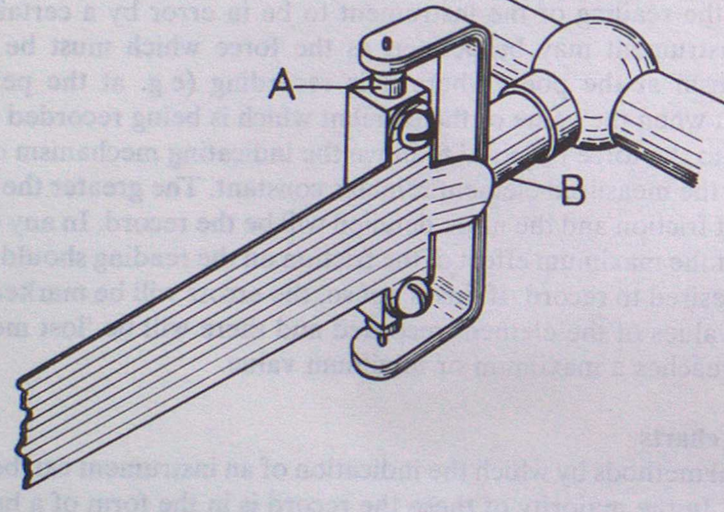


Figure A1. Gate suspension for pen arm.

There are two main ways in which the changes in the variable element being recorded are converted into changes of the position of the pen. In the first, the point of support of the pen arm is moved in a direction perpendicular to the time axis on the chart; the hour lines on the chart are straight lines and the length of the pen arm is immaterial. In the second, the changes in the variable element are converted into angular movements of a spindle on which the pen arm is mounted; the hour lines are approximately arcs of circles, with radii equal to the length of the pen arm (measured from the axis of the pen-arm spindle to the point of the pen) and with their centres on the plane through the pen-arm spindle parallel to the time axis. The true hour lines are not exactly arcs of circles because the pen writes on a cylinder and not on a plane surface.

It is necessary to ensure that the chart is printed for the correct pen-arm length and for the correct position of the pen-arm spindle. When replacing the pen on the pen arm, or fitting a new pen arm, every care must be taken to ensure that the effective pen-arm length is correct. The displacement of the pen at the end of the pen arm for a given angular movement is proportional to the length of the pen arm, so that an error of 8 mm in the length of a pen arm which should be 160 mm long will give an error of 5 per cent in the deflexion of the pen, and in the scale value on the chart at that point. The correct charts for all standard Meteorological Office instruments have identifying numbers, and these should always be quoted when

requesting stocks. If a non-standard chart has to be supplied specially, the data given should include the length of the pen arm and the position of the pen-arm axis, if the hour lines are not straight.

Pens. Various types of pen are used on the standard Meteorological Office instruments; the chief ones are illustrated in Figure A2. The type in normal use on the commoner instruments is shown at (a); it consists of a simple triangular reservoir attached to a short holder which can be slid over the end of the pen arm; it can hold more than sufficient ink for at least a normal week's record on any standard sized drum. Preferred alternatives for use on certain instruments are shown in (b) for the tilting-siphon rain-gauge, and in (c) for the thermograph and barograph. Both (b) and (c) are disposable items consisting of an ink reservoir fitted with a fibre nib; either pen will provide at least a year's normal record.

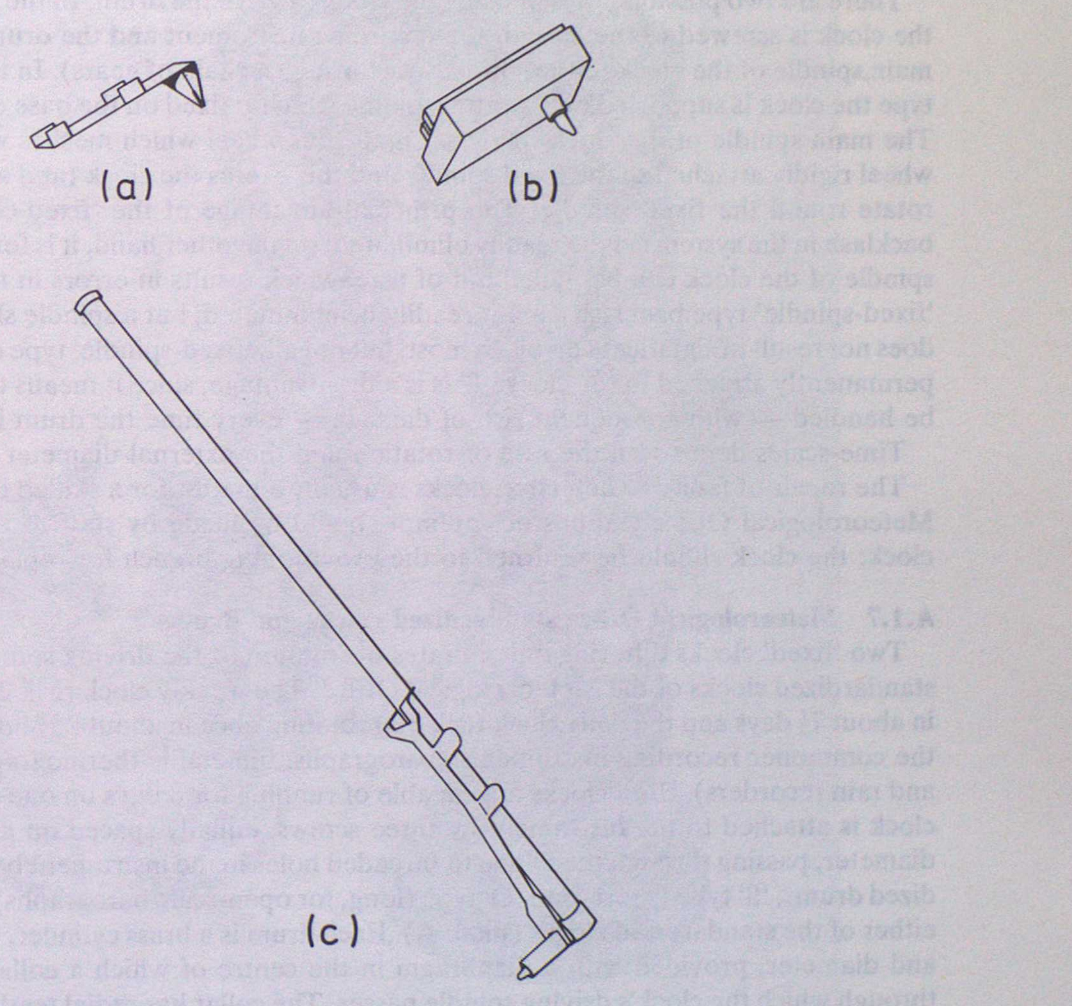


Figure A2. Instrument pens.

A.1.4 Electrosensitive paper

Recorders using various types of electrosensitive paper are also used. Paper is coated with zinc oxide so that when a small current passes from a stylus to the paper the zinc oxide coating is reduced to free zinc and a marking results. This process produces a fine, clean and dry trace resistant to smudging.

A.1.5 Electrical recorders

Devices for balancing potentiometric or bridge recorders have various forms, some manual, some self-balancing. Whatever the method used the principle is the same. A galvanometer, or an electronic circuit, is arranged to detect when the system is out of balance. Where a galvanometer is used, the position of the galvanometer pointer is detected either manually or electrically, and the slide-wire contact moved to the point of balance. Where an electronic circuit is used to detect the out-of-balance it is usual for the output of the detecting circuit to control the direction of rotation of a reversible motor which moves the slide-wire contact and positions the pen arm or pointer.

A.1.6 Clocks, drums and time-scales

Most meteorological recording instruments are fitted with 'daily' or 'weekly' clocks, i.e. clocks which cause the drum to rotate once in about 25½ hours and once in about 7⅓ days respectively. The overlap is necessary to allow some margin for the time of changing the chart, and to prevent the trace from crossing the join when the pen is near the top or bottom of the chart (on those instruments in which the hour lines are curved).

There are two possible ways of using the clock to drive the drum. In the 'fixed-clock' type the clock is screwed to the base of the recording instrument and the drum attached to the main spindle of the clock (either directly or through a chain of gears). In the 'fixed-spindle' type the clock is supported on a central spindle which is fixed on the base of the instrument. The main spindle of the clock carries a small gear wheel which meshes with another gear wheel rigidly attached to the fixed spindle and this causes the clock (and attached drum) to rotate round the fixed spindle. The principal advantage of the 'fixed-clock' type is that backlash in the system can be readily eliminated; on the other hand, it is found that the main spindle of the clock can be pulled out of true, which results in errors in the record. In the 'fixed-spindle' type backlash cannot readily be eliminated, but a spindle slightly out of true does not result in significant error. In most, but not all, 'fixed-spindle' type clocks the drum is permanently attached to the clock. This is a disadvantage, since it means that the clock will be handled — with consequent risk of damage — every time the drum is removed.

Time-scales depend on the rate of rotation and the external diameter of the drum.

The repair of faulty or defective clocks is usually a matter for a skilled clock repairer. At Meteorological Office stations no attempt should be made by staff to repair a defective clock; the clock should be returned to the provisioning branch for replacement.

A.1.7 Meteorological Office standardized clocks and drums

Two 'fixed' clocks differing only in rates of rotation of the driving spindles, serve as the standardized clocks of the Meteorological Office. The weekly clock (Mk 2A) rotating once in about 7⅓ days and the daily clock (Mk 2B) rotating once in about 25½ hours are used with the commoner recording instruments (barographs, bimetallic thermographs, hygrographs and rain recorders). Both clocks are capable of running for 8 days on one full winding. The clock is attached to the instrument by three screws, equally spaced on a circle of 89 mm diameter, passing through the flange to threaded holes in the instrument base. Two standardized drums, 'S' type (short) and 'O' type (long, for open-scale barographs), are for use with either of the standardized clocks (Plate A). Each drum is a brass cylinder, of defined height and diameter, provided with a diaphragm in the centre of which a collar is screwed and through which the clock's driving spindle passes. The collar has radial teeth on its underside which engage with similar teeth on a collar attached to a clutch drive on the driving spindle of the clock; a knurled nut secures the drum to the driving spindle of the clock. The object of the clutch drive is to facilitate the setting of the drum to its correct position when fitted to the clock. The drum is flanged around its base and the chart is held in position by two clips. In addition to the chart clips the 'O' type drum has two small pins screwed into its side, lying in the same line as the chart clips. These pins help to keep the chart in position where the two ends overlap. The 'S' type is 93 mm in diameter, so that it gives a time-scale of 11.4 mm h^{-1} with a daily clock. When used with a weekly clock Mk 2A the clock is adjusted to rotate once in 7 days 7.2 hours, giving a time-scale of 1.67 mm h^{-1}. The 'O' type drum is not normally used with a daily clock, but if it were the time-scale would be 17.2 mm h^{-1}. Used with a weekly clock Mk 2A, the clock is adjusted to rotate once in 7 days 8 hours, giving a time-scale of 2.5 mm h^{-1}. (The difference between a time of rotation of 7 days 8 hours and 7 days 7.2 hours is negligible for most purposes.) The standardized clocks and drums are completely

Plate A. Standard Meteorological Office clocks and drums.

interchangeable, i.e. any clock can be used with any drum. The weekly clocks can be regulated over a range of 2¼ hours in the 7 days and the daily clock over a range of 20 minutes in the 24 hours.

A.2 CORRECTION OF RECORDING INSTRUMENTS

It is important to ensure correct timing of any part of the recorded trace, and to be able to make an estimate of any errors in the record itself. There are three main causes of error that can affect the timing of the record:

(a) Backlash between the drum and the spindle on which it is mounted. This defect is not serious with clocks of the standard Meteorological Office pattern or similar types. It delays the starting of the record and causes a constant error once the record has started.

(b) An error in the clock rate (or the use of an unsuitable time-scale on the chart). If the difference is small the rate of revolution of the drum can be adjusted to the correct value (given by the time-scale on the chart) by means of the clock regulator. Small errors may occur, however, owing to the variability of the clock rate, e.g. with temperature changes.

(c) Errors due to the change in length of the chart with humidity variations (see page A–3). These are small in charts which are cut from the paper in the correct direction, but are serious if the chart is cut in the wrong direction.

In order that errors of this kind may be recognized it is essential to make accurate time marks on the records themselves. Although it is preferable that the time marks be made at about the same time each day, it is not essential provided the exact time at which the mark is made is known. The actual time (it suffices for most records if it is correct to the nearest minute) should be entered in the register. On weekly charts one time mark a day would suffice. On daily charts it is preferable to have more than one, the first being made at least half an hour but not more than 2 hours after starting the record, and another after about a further 8–12 hours. It is often convenient to make a time mark coincide with an hour mark and to note the timing error.

On most instruments a time mark may be made by depressing the pen between 3 mm and 6 mm and then releasing it. These limits should not be exceeded, as the careless depression of the pen can often disturb the calibration of the instrument or even strain some of the parts beyond their elastic limits.

On some instruments, e.g. barographs, a simple mechanical device is provided which enables time marks to be made without opening the case of the instrument. If a reading of the record has to be obtained at the same time as the time mark it should be made just before the time mark and not after it.

Recording instruments are generally less accurate than the comparable indicating instruments, and they cannot often be made absolute. It is therefore usual to compare their readings with those of an indicating instrument at several of the main observation hours throughout the day. In some recording instruments, e.g. the barograph, this will give immediately the error of the record or the necessary correction to the record, assuming that the indicating instrument is correct. It should be noted that the error is equal, but opposite in sign, to the correction. The mean correction for the day can therefore be ascertained and applied to any tabulated readings taken from the record.

No instrument responds immediately to changes in the element that is being measured, and different instruments respond at different rates. Comparisons should therefore be made only when the measured element is constant or changing very slowly, or mean values should be taken over a period in which any errors due to the different time-constants may be expected to cancel out.

Another possible procedure is to plot the readings of the recording and indicating instruments against one another; the points obtained should lie on or about a line at 45° to each axis passing through the origin. If the best-fitting straight line does not pass through the origin a zero error is indicated, and if the slope is not 45° there is an error in the scale value of one instrument, usually the recording instrument.

A.3. OPERATIONAL PROCEDURE

Some general instructions on the method of handling recording instruments are given below. These are supplementary to the more particular instructions given for each individual instrument.

A.3.1 Changing the chart

Remove the pen from the old chart, noting the correct time to the nearest minute (this serves as an extra time mark). Clean the pen if necessary and top with ink. See that the ink is flowing sufficiently freely to give a legible trace, but not so freely as to give a thick trace. It is rarely advisable to fill the reservoir completely. Remove the old chart and wrap the new chart round the drum so that it fulfils the following conditions (these are absolutely necessary if good and reliable records are to be obtained):

(a) The chart should fit tightly round the drum.

(b) The lines of equal scale value should be parallel to the flange at the bottom of the drum, i.e. corresponding lines on the beginning and end of the chart in the overlap portion should coincide.

(c) The bottom of the chart should be as close to the flange as possible and touching it in at least one place (if the chart is not cut quite correctly it may not be possible for it to touch the flange in all places and still comply with the other conditions cited).

(d) The end of the chart should overlap the beginning and not vice versa.

When the chart is fitted properly the spring clips should hold it in place. The clock can then be wound and the new record started. When setting the pen to the correct time the final adjustment should be made by moving the drum in the opposite direction to its normal motion to take up any backlash in the gear train, i.e. the drum should be moved from a time on the chart in advance of the actual time back to its correct position. Once they have been correctly set most recording instruments should not require readjustment more often than three or four times a year. If careful examination, extending over a period, shows that readjustment is necessary this may be done at the time a chart is changed, and a note should be made on the chart and in the register.

A.3.2 Writing up the chart

Before being filed away, the record should have inserted on it the following particulars: date (including the year), name of the station, its position, its height above mean sea level, actual time of each of the time marks, readings of the control instruments when the time marks were made, and time at which the record began and ended. If a reliable estimate of the mean errors in the record has been made, covering the period of the chart, this should be indicated. The reasons for any abnormal features, e.g. failure to ink, clock stopping, etc., should also be recorded if known.

A.3.3 Care at each main observation hour

See that the instrument is recording properly and read it. If necessary, a time mark should be made.

A.3.4 General hints (including cleaning)

Special care should always be taken to keep instruments clean. This not only improves their performance (by reducing friction) but also lengthens their useful life (by preventing

corrosion) and improves their appearance. General methods of cleaning the different materials most often used in instruments are as follows:

(a) *Plain brass or copper parts*. Unlacquered brass or copper parts may be kept bright by the use of jeweller's rouge applied with an oily rag or by metal polish applied sparingly. The polish should not be allowed to reach any bearing surfaces. The inside of a rain-gauge funnel should however only be rubbed with a dry rag.

(b) *Lacquered brass or copper parts*. These should be cleaned with a soft chamois leather. No polish should be applied, but where there is exposure to damp a little petroleum jelly may be used with advantage.

(c) *Polished woodwork*. This should be cleaned with a soft chamois-leather. A little linseed oil may be rubbed in with a soft cloth if necessary.

(d) *Glass and porcelain*. The dirt should be cleaned off with a moist rag or chamois-leather.

(e) *Bearings, pinions and hinges of instrument cases*. These should be lubricated sparingly with a touch of clock oil. Refer also to the detailed instructions for the instrument.

(f) *Ball races*. These should be treated in accordance with the detailed instructions for each instrument.

(g) *Steel parts*. These should be cleaned with an oily rag and protected from rust with a trace of petroleum jelly. If, in spite of care, rust appears, the part should be carefully cleaned with a fine emery cloth or carborundum cloth.

(h) *Painted woodwork*. In dusty localities woodwork should be brushed periodically, and at stations affected by smoke or soot a thorough cleaning with soap and water should be carried out once a month.

(i) *Painted surfaces liable to inking*. The ink should be removed while wet with a damp cloth. Older stains should be removed by the application of a small quantity of whiting applied with a damp cloth. Methylated spirit may be used with the whiting if there is no risk of this getting on to lacquered brass or polished woodwork.

(j) Naphthalene balls are effective in keeping insects from the interior of instruments exposed out of doors, e.g. recording rain-gauges.

Special care must be given to keeping the end of the pen arm and the fitting which actually supports the pen free from ink, or else corrosion may set in. This may lead to the use of a pen arm which is too short and thus give rise to faulty records.

APPENDIX 2

The International Systems of units (SI)

The International System (SI) consists of seven 'base units' together with two 'supplementary units'. From these are formed others known as 'derived units'. The base and supplementary units, and some of the derived units, have been given names and symbols. The symbols are printed in lower case except where derived from the name of a person; for example m (metre), but A (ampere). Symbols are not pluralized (1 m, 10 m) nor do they take a full stop. The names of the units do not, however, take capitals (except of course at the beginning of a sentence), although they may be pluralized; for example, 1 kelvin, 10 kelvins.

The *base units* are:

metre (symbol m)	the unit of length
kilogram (symbol kg)	the unit of mass
second (symbol s)	the unit of time
ampere (symbol A)	the unit of electrical current
kelvin (symbol K)	the unit of thermodynamic temperature, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
candela (symbol cd)	the unit of luminous intensity
mole (symbol mol)	the unit of the amount of a substance which contains the same number of molecules as there are atoms in exactly 12 grams of pure carbon.

The two *supplementary units* are:

radian (symbol rad)	the measure of a plane angle
steradian (symbol sr)	the measure of a solid angle.

A few of the *derived units* are:

Quantity	*Name of unit*	*Symbol*	*Expressed in base units*
frequency	hertz	Hz	$1\ \text{Hz} = 1\ \text{s}^{-1}$
force	newton	N	$1\ \text{N} = 1\ \text{kg m s}^{-2}$
pressure	pascal	Pa	$1\ \text{Pa} = 1\ \text{N m}^{-2}$
work	joule	J	$1\ \text{J} = 1\ \text{N m}$
power	watt	W	$1\ \text{W} = 1\ \text{J s}^{-1}$

(1 newton = 10^5 dynes, 1 pascal = 10^{-2} millibars, 1 joule = 10^7 ergs.)

Multiplying prefixes

The multiples and sub-multiples of the units are not arbitrarily related to the units, as is usual in the British system,

e.g. 1 pound = 16 ounces = 7000 grains
1 yard = 3 feet = 36 inches,

but are formed by means of multiplying prefixes which are the same irrespective of the unit to which they are applied.

The names and values of the prefixes, and some examples of their use, are given below. Because the prefixes cover such an astronomical range it is not normally necessary to consider more than a selection of them applied to any one unit.

Prefix name	*Prefix symbol*	*Factor by which the unit is multiplied*	
tera	T	10^{12} =	1 000 000 000 000
giga	G	10^9 =	1 000 000 000
mega	M	10^6 =	1 000 000
kilo	k	10^3 =	1000
hecto	h	10^2 =	100
deca	da	10^1 =	10
deci	d	10^{-1} =	0.1
centi	c	10^{-2} =	0.01
milli	m	10^{-3} =	0.001
micro	μ	10^{-6} =	0.000 001
nano	n	10^{-9} =	0.000 000 001
pico	p	10^{-12} =	0.000 000 000 001
femto	f	10^{-15} =	0.000 000 000 000 001
atto	a	10^{-18} =	0.000 000 000 000 000 001

Examples:
gigahertz (GHz), megawatt (MW), kilometre (km), centimetre (cm), milligram (mg), microsecond (μs), nanometre (nm), picofarad (pF).

NON-SI UNITS

The following non-SI units are in current use in the Meteorological Office and may be found in publications of the Office.

1. **Pressure**

The millibar is used as the unit of pressure in meteorology. Despite the recommended abbreviation mbar, the Meteorological Office will continue to use mb (1 mb = 1 hPa, where h = hecto = 10^2). The WMO preferred unit is the hPa, though it has yet to be promulgated.

2. **Temperature**

The unit degree Celsius (symbol °C) continues to be used.

Celsius temperature = temperature (in kelvins) minus 273.15 K (note that the sign ° is no longer used with K).

3. **Distance**

There is a continuing requirement for some distances to be measured in nautical miles (symbol n. mile).

Because the nautical mile varies with latitude, an internationally agreed International Nautical Mile is preferred. This has been in use in the United Kingdom since 1970.

The International Nautical Mile is defined as 1852 m (6076.12 feet).

4. **Height**

Heights other than cloud heights are expressed in metres. Because of the requirements of aviation the heights of cloud will continue for the time being to be expressed in feet (1 foot = 0.3048 m).

5. **Speed**

The derived SI unit is the metre per second (m s^{-1}). However, the World Meteorological Organization recommends the use of the knot for horizontal wind speed for the time being (1 knot = 1 nautical mile per hour ≈ 0.5 m s^{-1}). The symbol kn for knot is recommended to avoid confusion with the symbol for kilotonne and will be used in Meteorological Office publications.

6. **Time**

Units other than SI, such as day, week, month and year, are in common use.

7. **Direction**

Direction is measured in degrees clockwise from north and refers to the true compass.

8. **Cloud amounts**

The use of 'okta' (one eighth of the area of the sky) for the measurement of cloud amount is authorized by the World Meteorological Organization.

APPENDIX 3

Terminology

In metrology (the field of knowledge concerned with measurement) confusion often arises in the usage of terms. These differences may range from subtle changes of meaning of common terms to the misuse of everyday terms, extracted from dictionaries, by ascribing to them specific meanings applicable only in certain areas of use.

Whilst by no means comprehensive, the following list represents terms occurring most frequently in this volume. For a more complete glossary of terms reference should be made to British Standards Institution publication BS 5233 from which these definitions are extracted.

Accuracy (of a measuring instrument). The quality which characterizes the ability of a measuring instrument to give indications equivalent to the true value of the quantity measured. The quantitative expression of this concept should be in terms of uncertainty.

Analogue (measuring) instrument. Measuring instrument in which the indication is a continuous function of the corresponding value of the quantity to be measured, e.g. mercury-in-glass thermometer.

Calibration. All the operations for the purpose of determining the values of the errors of a measuring instrument.

Conventional true value (of a quantity). A value approximating to the true value of a quantity such that, for the purpose for which that value is used, the difference between these two values can be neglected.

Correction. A value which must be added algebraically to the indicated value (uncorrected result) of a measurement to obtain the measured value (corrected result).

Detector. A device or substance which responds to the presence of a particular quantity without necessarily measuring the value of that quantity.

Digital (measuring) instrument. Measurement instrument in which the quantity to be measured is accepted as, or is converted into, coded discrete signals and provides an output and/or display in digital form.

Discrimination (of a measuring instrument). The property which characterizes the ability of a measuring instrument to respond to small changes of the quantity measured. *Note.* In some fields of measurement the term 'resolution' is used as synonymous with 'discrimination', but attention is drawn to 'sensitivity'.

Error (of indication, or of response) *of a measuring instrument.* The difference $v_i - v_c$ between the value indicated by (or the response of) the measuring instrument v_i and the conventional true value of the measured quantity v_c.

Hysteresis (of a measuring instrument). That property of a measuring instrument whereby it gives different indications, or responses, for the same value of the measured quantity, according to whether that value has been reached by a continuously increasing change or by a continuously decreasing change of that quantity.

Index. A fixed or movable part of the indicating device (e.g. recording pen, a pointer) whose position with reference to the scale marks enables the indicated value to be observed.

Indicating instrument. Measuring instrument which is intended to give, by means of a single unique observation, the value of a measured quantity at the time of that observation. An indicating instrument may have either continuous or discontinuous variation of indication.

Indication (or *response*) *of a measuring instrument.* The value of the quantity measured, as indicated or otherwise provided by a measuring instrument.

Maximum permissible error (of a measuring instrument). The extreme values of the error (positive or negative) permitted by specifications, regulations etc., for a measuring instrument.

Quantity (measurable). An attribute of a phenomenon or a body which may be distinguished qualitatively and determined quantitatively.

Range (of a measuring instrument). The interval between the lower and upper range-limits, e.g. a thermometer may have a range −40 °C to +60 °C.

Repeatability (of measurement). A quantitative expression of the closeness of successive measurements of the same value of the same quantity carried out by the same method, by the same observer, with the same measuring instruments, at the same location at appropriately short intervals of time.

Repeatability (of a measuring instrument). The quality which characterizes the ability of a measuring instrument to give identical indications, or responses, for repeated applications of the same value of the measured quantity under stated conditions of use.

Reproducibility (of measurement). The quantitative expression of the closeness of the agreement between the results of measurements of the same value of the same quantity, where the individual measurements are made under different defined conditions, e.g. by different methods, with different measuring instruments.

Resolution. See *Discrimination.*

Response. See *Indication.*

Response time (of a measuring instrument).* The time which elapses after a step change in the quantity measured, up to the point at which the measuring instrument gives an indication equal to the expected indication corresponding to the new value of the quantity, or not differing from this by more than a specified amount.

Scale. The array of indicating marks, together with any associated figuring, in relation to which the position of an index is observed. The term is frequently extended to include the surface which carries the marks or figuring.

Sensitivity (of a measuring instrument). (a) The relationship of the change of the response to the corresponding change of the stimulus (it is normally expressed as a quotient), or (b) the value of the stimulus required to produce a response exceeding, by a specified amount, the response already present due to other causes, e.g. noise.

Sensor. The part of a measuring instrument which responds directly to the measured quantity.

Span. The algebraic difference between the upper and lower values specified as limiting the range of operation of a measuring instrument, e.g. a thermometer intended to measure over the range −40 °C to +60 °C has a span of 100 °C.

Standard. A measuring instrument, or measuring apparatus, which defines, represents physically, conserves or reproduces the unit of measurement of a quantity (or a multiple or sub-multiple of that unit) in order to transmit it to other measuring instruments by comparison.

Primary standard. A standard of a particular quantity which has the highest class of metrological qualities in a given field.

Secondary standard. A standard the value of which is determined by direct or indirect comparison with a primary standard.

Reference standard. A standard, generally the best available at a location, from which the measurements made at the location are derived.

Working standard. A measurement standard, not specifically reserved as a reference standard, which is intended to verify measuring instruments of lower accuracy.

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*For the purposes of this handbook, where a response time is quoted it refers to the time necessary for a measuring instrument to register 90 per cent of a step change in the quantity being measured. The time taken to register 63.2 per cent of a change is given the preferred title 'time-constant'.

Transfer standard. A measuring device used to compare measurement standards, or to compare a measuring instrument with a measurement standard by sequential comparison.

Travelling standard. A measuring device, sometimes of special construction, used for the comparison of values of a measured quantity at different locations.

Systematic error. An error which, in the course of a number of measurements of the same value of a given quantity, remains constant when measurements are made under the same conditions and remains constant or varies according to a definite law when the conditions change.

Transducer (measuring). A device which serves to transform, in accordance with an established relationship, the measured quantity (or a quantity already transformed therefrom) into another quantity or into another value of the same quantity, with a specified accuracy, and which may be used separately as a complete unit.

Uncertainty of measurement. That part of the expression of the result of a measurement which states the range of values within which the true value or, if appropriate, the conventional true value is estimated to lie.

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Printed in England for Her Majesty's Stationery Office by Linneys of Mansfield
Dd 717037 c15 9/82

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Met. O. 919g Handbook of Meteorological Instruments Second Edition Volume 7 HMSO