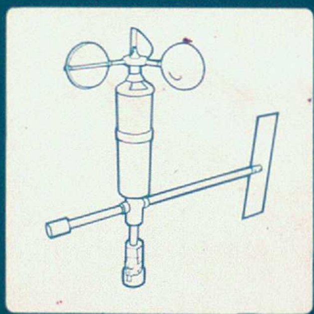
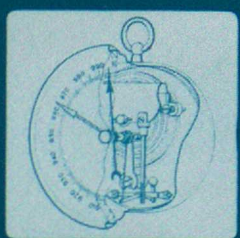
Meteorological Office

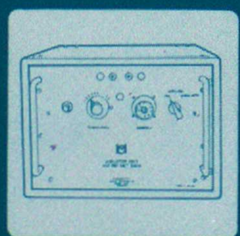
Handbook of Meteorological Instruments

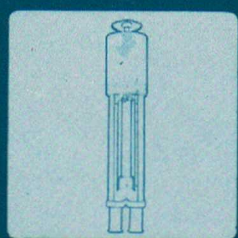
Second Edition

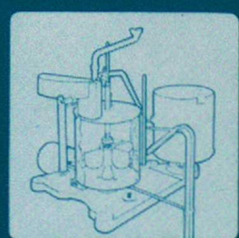
4 Measurement of Surface Wind

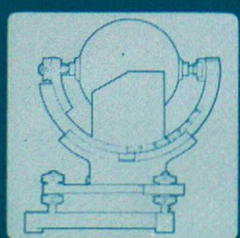


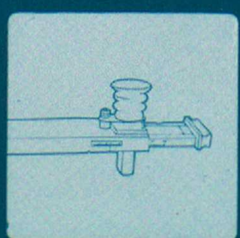


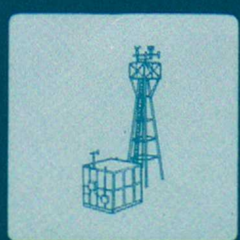












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METEOROLOGICAL OFFICE

HANDBOOK OF METEOROLOGICAL INSTRUMENTS

SECOND EDITION

VOLUME 4

MEASUREMENT OF SURFACE WIND

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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 4
MEASUREMENT OF SURFACE WIND

1 GENERAL

1.1 Definitions and units

The velocity of the wind is a term used to include both its speed and its direction. Wind velocity is thus a vector quantity and wind speed a scalar quantity. The wind speed may be indicated in any of the following units:

(a) knots (or nautical miles per hour), kn
(b) metres per second, m s^{-1}
(c) kilometres per hour, km h^{-1}
(d) miles per hour, mile h^{-1}
(e) feet per second, ft s^{-1}.

The relation between these various units is given in Table I, in which any horizontal line gives the same speed in different units.

Table I. *Relation between different speed units*

kn	m s^{-1}	mile h^{-1}	km h^{-1}	ft s^{-1}
1	0.515	1.152	1.853	1.689
1.943	1	2.237	3.600	3.281
0.868	0.447	1	1.609	1.467
0.540	0.278	0.621	1	0.911
0.592	0.305	0.682	1.097	1

The wind direction is specified relative to true north at the place of observation and refers to the direction from which the wind is blowing. It can be expressed as a bearing in degrees from true north (in a clockwise direction) or as a compass point (using 8, 16, or 32 points depending on the accuracy required). Table II gives the exact equivalent in degrees, and the sectors to the nearest whole degree, corresponding to the 32 points of the compass.

Table II. *Wind direction in compass points and degrees*

Compass direction	Exact equivalent in degrees	Sector in degrees	Compass direction	Exact equivalent in degrees	Sector in degrees
N	360.00	355–005	S	180.00	175–185
N'E	11.25	006–016	S'W	191.25	186–196
NNE	22.50	017–028	SSW	202.50	197–208
NE'N	33.75	029–039	SW'S	213.75	209–219
NE	45.00	040–050	SW	225.00	220–230
NE'E	56.25	051–061	SW'W	236.25	231–241
ENE	67.50	062–073	WSW	247.50	242–253
E'N	78.75	074–084	W'S	258.75	254–264
E	90.00	085–095	W	270.00	265–275
E'S	101.25	096–106	W'N	281.25	276–286
ESE	112.50	107–118	WNW	292.50	287–298
SE'E	123.75	119–129	NW'W	303.75	299–309
SE	135.00	130–140	NW	315.00	310–320
SE'S	146.25	141–151	NW'N	326.25	321–331
SSE	157.50	152–163	NNW	337.50	332–343
S'E	168.75	164–174	N'W	348.75	344–354

The surface wind velocity is seldom constant over any appreciable period of time, and is usually varying rapidly and continuously. The variations are normally irregular both in period and amplitude, a property known as 'gustiness' or turbulence. For most purposes the mean velocity is required, and for synoptic purposes this is usually taken as the average over a 10-minute period immediately preceding the time of observation.

1.2 General principles of wind direction indicators and recorders

The wind direction is usually indicated by means of a wind vane. This is essentially a body mounted on and free to turn about a vertical axis. It takes up a position so that the direction of the resultant force on it due to the wind pressure passes through the vertical axis, and so that the pressure centre is to the leeward of the axis.

The desirable properties of a wind vane are that:

(a) It should turn about its pivot with the minimum of friction.

(b) The vane should be properly balanced; otherwise it will show a bias toward a particular direction.

(c) The vane should be designed to produce the maximum torque, for a given change in wind direction, in relation to its moment of inertia.

(d) Resonance of the vane with natural fluctuations of the wind should be avoided.

(e) The vane should be adequately damped (see page 4–5).

Vanes of various shapes and sizes have been constructed, some of which are shown in Figure 1. Type (a) consists of a flat plate; (b) of a single wedge or splayed vane; (c) has an aerofoil cross-section; (d) is a double curved wedge; (e) is a propeller vane; (f) is a trivane for measuring three-dimensional wind vectors.

Indication may be provided at a distance by a variety of methods. If the vane is mounted directly above the room in which the information is required a simple extension rod from the vane shaft can provide a mechanical means of indication. In other cases recourse can be had to some electrical system.

Continuous remote indication or recording can be provided by means of two self-synchronous motors, e.g. of the Desynn or magslip types. The transmitting unit is mounted directly beneath the vane and its rotor is connected to the vane spindle. The movements of the vane are then reproduced on the dials or recorder of the receiving unit.

1.3 Fin aerodynamics and characteristic parameters of wind vanes

Fin aerodynamics. Considering first a vane with a single flat fin, a dynamic wind pressure $P = 0.5\rho u^2$, where ρ is the air density and u the wind speed, will result in a static force F acting at the aerodynamic centre of the fin. The components of F acting perpendicular to and parallel to the wind direction are, respectively, a lifting force F_L and a drag force F_D (Figure 2(a)) which may be expressed by

$$F_L = \rho A C_L$$

and $$F_D = \rho A C_D,$$

where A is the area of the fin projected in the plane $\alpha = 0$, (α being the angle between the vane axis and the wind direction), and C_L and C_D are the lift force and drag force coefficients respectively. Both C_L and C_D are functions of α, and C_D is about one order of magnitude smaller than C_L. The net effect of F_L and F_D is an effective force component F_E acting perpendicular to the vane axis where

$$F_E = \rho A C_E,$$

and C_E, the effective force component, is a function of C_L and C_D. For a single fin with small values of α, $C_E = C_L$.

The value of F_E for a double-finned vane will be equal to the sum of the effective force components acting on the individual fins. For a parallel flat vane (Figure 2(b)) the individual forces will be similar, assuming no interference between the fins. Where the fins are not parallel, however, (as in Figure 2(c)) the effective angles of attack β_1 and β_2, and consequently C_L and C_D, are different for each fin.

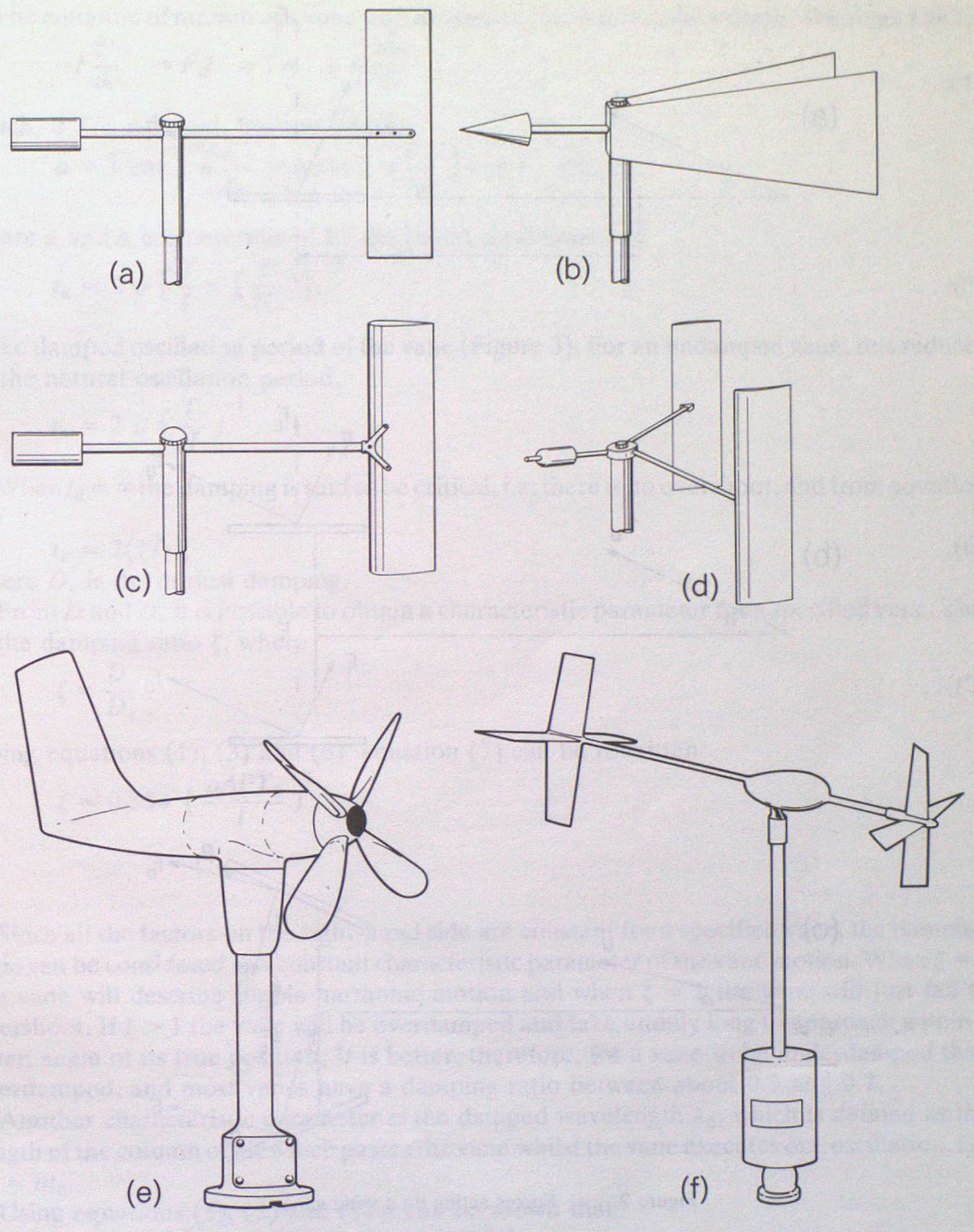


Figure 1. Types of wind vane.

Characteristic parameters. For unit angle of attack the effective force F_E produces a torque

$$T = \frac{F_E l}{\alpha} = \rho A l T_E, \qquad \ldots(1)$$

where l is the distance between the vane pivot and the aerodynamic centre of the fin and $T_E = C_E/\alpha$ is the torque parameter. The torque parameter accounts for the influence on vane motion of the fin shape and, for a specified vane, may be assumed constant.

A moving vane is affected by an additional force resulting from the fin 'speed' $l\,d\alpha/dt$, so that it is necessary to consider the effective wind speed u_e and the effective angle of attack α_e.

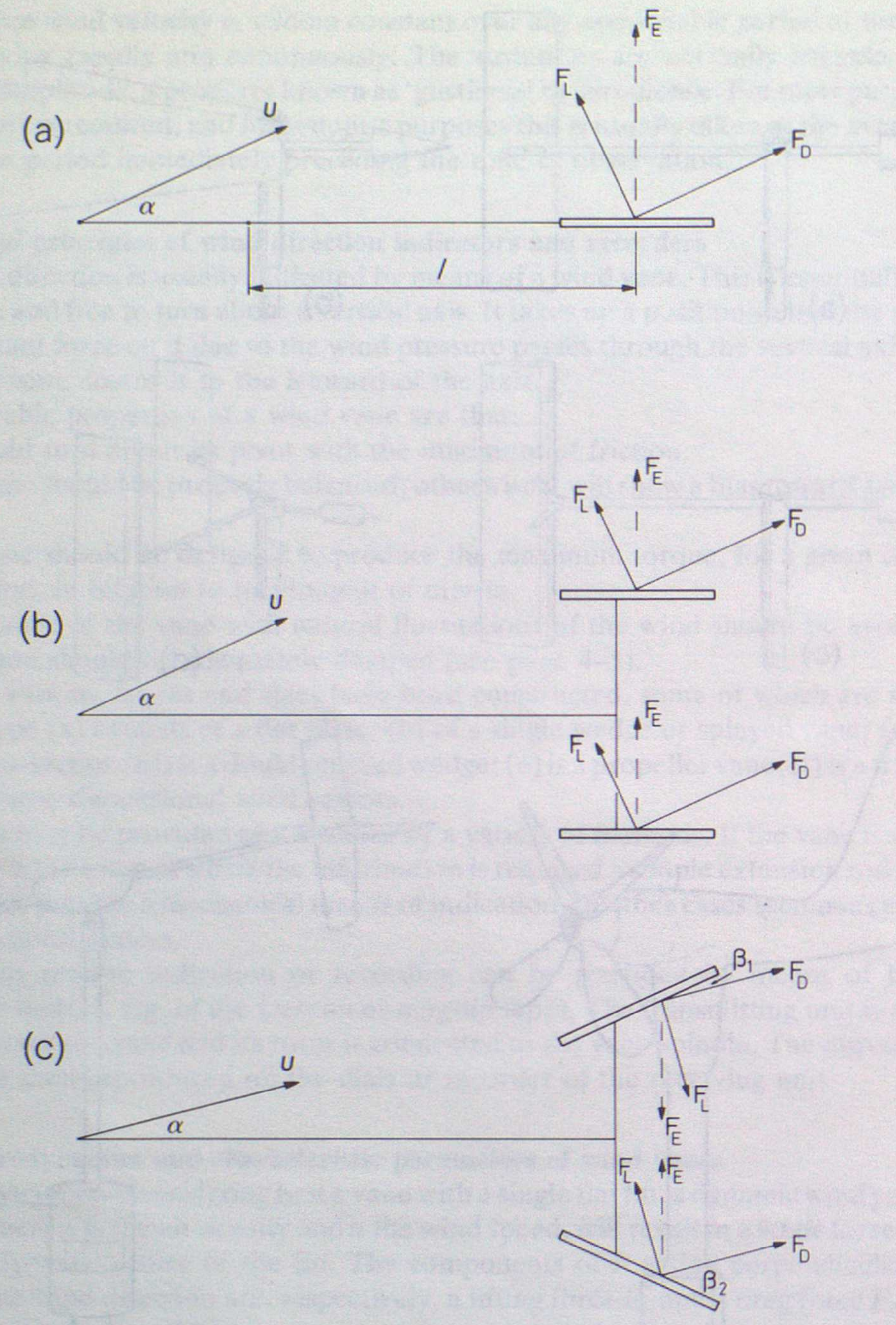


Figure 2. Forces acting on a wind vane.

It has been shown by Barthelt and Ruppersberg (1957) that for actual vane motion $u_e \approx u$ and that, for small values of α, $\alpha_e \approx \alpha + \frac{l}{u}\frac{d\alpha}{dt}$. Substituting in equation (1)

$$F_E l = T\alpha + \frac{Tl}{u}\frac{d\alpha}{dt},$$

$$\text{or} \quad \frac{d\alpha}{dt} = [F_E l - T\alpha] / \frac{Tl}{u}. \qquad \ldots(2)$$

The rate of change of α, i.e. the rate at which the vane approaches the true wind direction, is thus a function of $\frac{Tl}{u}$ which is termed the aerodynamic (or natural) damping, D, of the vane

$$D = \frac{Tl}{u}. \qquad \ldots(3)$$

The equation of motion of a vane with moment of inertia I can be written (Wieringa 1967)

$$-I\frac{d^2\alpha}{dt^2} = F_E l = T\alpha + D\frac{d\alpha}{dt}, \qquad \ldots(4)$$

which, if T is constant, has the solution

$$\alpha = [\cos 2\pi\frac{t}{t_d} + b \sin 2\pi\frac{t}{t_d}] \exp(-Dt/2I),$$

where a and b are determined by the initial conditions and

$$t_d = 2\pi [\frac{T}{I} - (\frac{D}{2I})^2]^{-\frac{1}{2}}, \qquad \ldots(5)$$

is the damped oscillation period of the vane (Figure 3). For an undamped vane, this reduces to the natural oscillation period,

$$t_n = 2\pi (\frac{T}{I})^{-\frac{1}{2}}$$

When $t_d = \infty$ the damping is said to be critical, i.e. there is no overshoot, and from equation (5)

$$t_n = 2(TI)^{\frac{1}{2}}, \qquad \ldots(6)$$

where D_c is the critical damping.

From D and D_c it is possible to obtain a characteristic parameter for a specified vane. This is the damping ratio ζ, where

$$\zeta = \frac{D}{D_c}. \qquad \ldots(7)$$

Using equations (1), (3) and (6), equation (7) can be rewritten

$$\zeta = 0.354 \left(\frac{\rho A l^3 T_E}{I}\right)^{\frac{1}{2}}.$$

Since all the factors on the right-hand side are constant for a specified vane, the damping ratio can be considered as a constant characteristic parameter of the vane motion. When $\zeta = 0$ the vane will describe simple harmonic motion and when $\zeta = 1$ the vane will just fail to overshoot. If $\zeta > 1$ the vane will be overdamped and take unduly long to approach within a given angle of its true position. It is better, therefore, for a vane to be underdamped than overdamped, and most vanes have a damping ratio between about 0.3 and 0.7.

Another characteristic parameter is the damped wavelength λ_d, which is defined as the length of the column of air which passes the vane whilst the vane executes one oscillation, i.e. $\lambda_d = ut_d$.

Using equations (1), (3) and (5) it can be shown that

$$\lambda_d = 4\pi I [0.5\rho A T_E l(4I - 0.5\rho A T_E l^3)]^{-\frac{1}{2}}$$

and thus is independent of the wind speed and, as with the damping ratio, is constant for a specified vane.

From Figure 3 the ratio $\frac{\alpha_1}{\alpha_0}$ is the overshoot fraction h and each successive overshoot will be h times the preceding one. Any pair of peaks may be used to evaluate h, i.e.

$$\frac{\alpha_1}{\alpha_0} = \frac{\alpha_2}{\alpha_1} = \ldots \frac{\alpha_n}{\alpha_{n-1}}.$$

When $h = 1$ the vane performs simple harmonic motion, limited by the natural wavelength (λ_n) of the vane, where

$$\lambda_n = ut_n$$

$$\text{or} \quad \lambda_n = \lambda_d (1-\zeta^2)^{\frac{1}{2}}.$$

The interrelationships between ζ and λ_n/λ_d, and between ζ and h are shown in Figure 4.

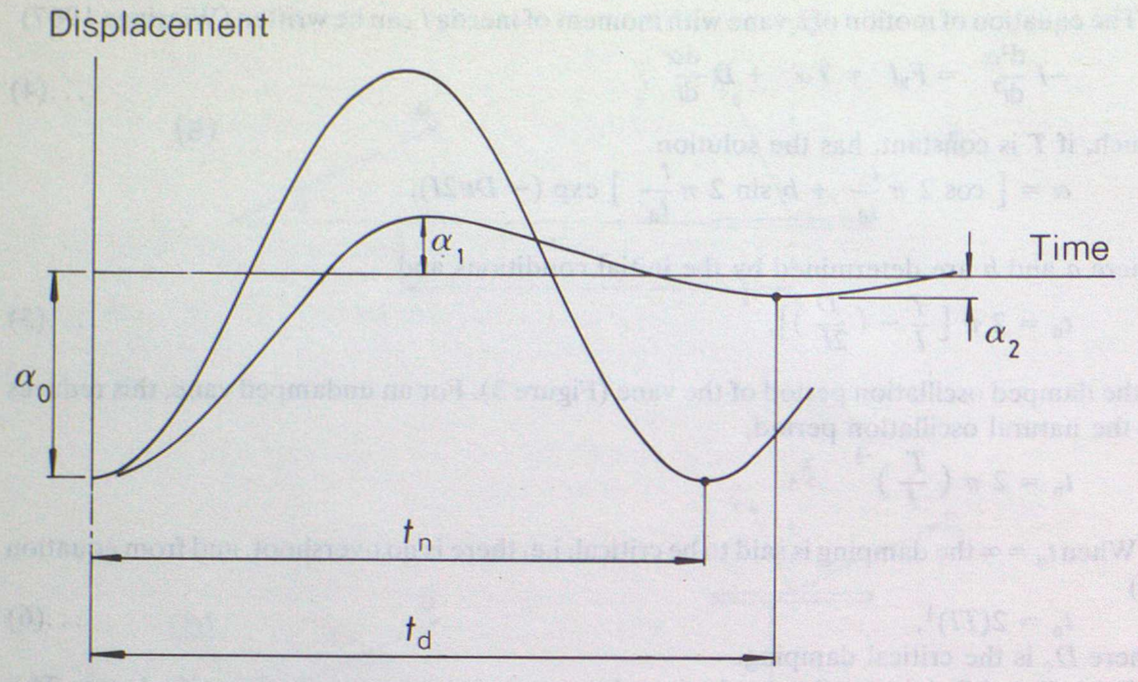


Figure 3. Response of a wind vane to a step change.

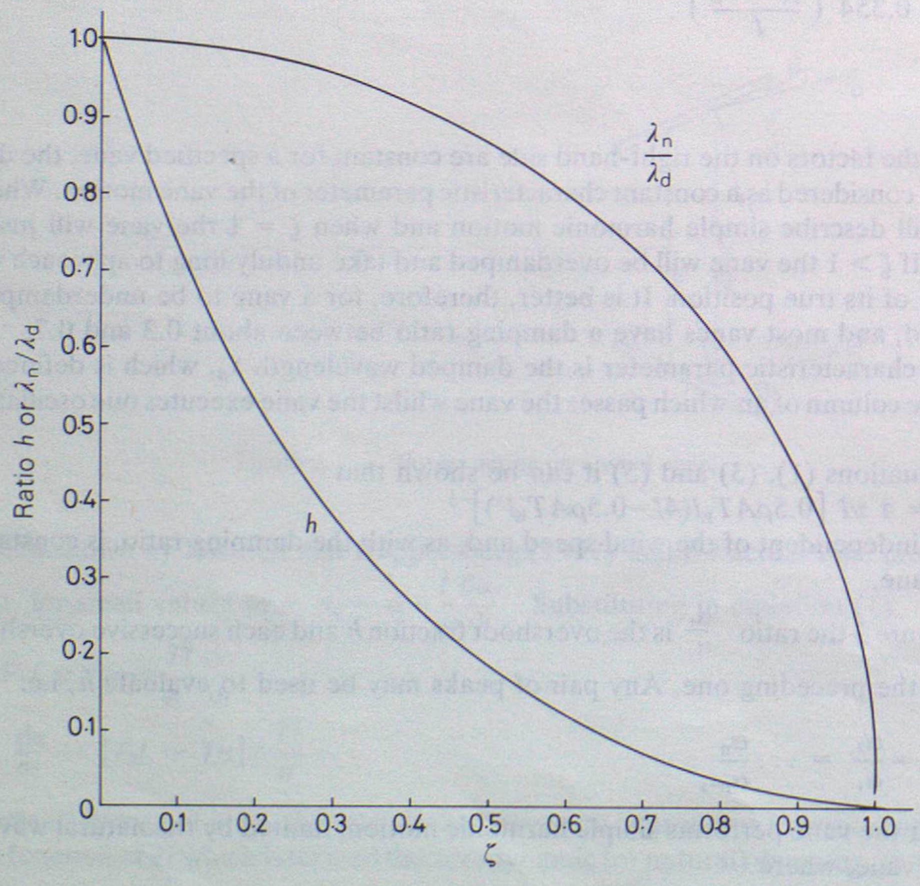


Figure 4. Relationships between the damping ratio and overshoot and wavelength, of a wind vane.

Mechanical friction will result in an additional damping term in equation (3), the net effect of which is generally a sizeable increase in the damping ratio and a moderate increase in the damped wavelength. The effect decreases with increasing wind speed which means that a vane relying on friction for an ostensibly large damping ratio will behave poorly in strong winds. Any additional, non-aerodynamic, damping needs therefore to be velocity-dependent in order to be effective.

With a propeller vane, the modification of the vane characteristics by the propeller motion cannot be quantified simply. It would seem, however, that the gyroscopic effect of the propeller rotation produces a small, but not negligible, increase in the values of ζ and λ_d. The downwash from the propeller will have some effect on the angle of attack.

The single wedge (Figure 1(b)) and the aerofoil (Figure 1(c)), both commented on favourably by Grunow (1935), still retain some popularity. However, streamlining is intended to diminish aerodynamic action and for small angles of attack poor vane characteristics may result. With the single-wedge vane the fins are likely to reduce each other's effectiveness. Both of these effects have been observed experimentally by Wieringa. In the same experiments the flat plate (Figure 1(a)) and the double-curved wedge (Figure 1(d)) exhibited an increase in damping ratio and damped wavelength with increasing α, the increases beginning abruptly at $\alpha \approx 15°$.

1.4 General principles of wind speed indicators and recorders

Wind speed indicators, or anemometers, may be classified as follows:

(a) Rotation anemometers, such as cup anemometers and the propeller or windmill type.
(b) Pressure anemometers.
(c) Anemometers depending on the thermal conductivity of the air.
(d) Anemometers depending on the speed of sound.
(e) Anemometers depending on turbulence.

Rotation anemometers

Cup anemometers. The cup anemometer normally consists of three or four cups mounted symmetrically about a vertical axis so that the diametric plane of each cup is vertical. As the force on the concave side of the cup, due to the wind, is greater than on a convex side in a similar position, the cup wheel rotates. For a particular anemometer the speed at which the cup wheel rotates depends, to a good approximation, solely on the wind speed, provided the wind speed is steady and is greater than the minimum required to set the cups in motion. The lower limit is due in part to the effect of bearing friction. The rate of rotation is independent of wind direction and, to a large extent, the air density. Four main methods are used to determine the rotation rate of the cups. In the first the cup wheel is connected to a mechanical counting system which records, in effect, the number of revolutions of the cup wheel since the record was started. In the second method an electrical contact is made after a known number of revolutions of the cup wheel. This may be used, in conjunction with a suitable counting device, to provide an indication of mean wind speed. In the third method the cup wheel is linked to a small electrical generator and the instantaneous rotation rate is obtained by measuring the voltage generated. In the fourth method the cup wheel is linked to a photoelectric switch and the instantaneous rotation rate is obtained by measuring the output, available in the form of either an a.c. voltage or a d.c. voltage (see page 4–30).

It was assumed by Robinson, who first developed the cup anemometer and brought it into general use, that the ratio of the speed of the wind to the speed of the cup centres was a constant and equal to 3. Subsequent measurements at various wind speeds and with different sizes of anemometer showed that this ratio (called the factor of the anemometer) was variable and depended on the wind speed and, in a complex manner, on the dimensions of the instrument. If u is the wind speed and U is the linear speed of the cup centre it is possible to express the relation between them for a given anemometer in the form of a power series

$$u = a + bU + cU^2 + \ \ldots,$$

where a, b, c ... are constants. The best design is that in which the constant a and the coefficient of U^2 and the higher powers of U are zero or very small. It is not, at present, possible to determine theoretically the best dimensions for an anemometer, and design improvement has followed from controlled wind-tunnel experiments using a variety of cup diameters, cup shapes, and lengths and diameters of supporting arms. From these experiments it has been concluded, among other things, that

(a) A three-cup system is better than a four-cup system, because the torque on a three-cup system is more uniform throughout the whole revolution and because, using the same material, the three-cup system gives a larger torque per unit weight.

(b) A cup of semi-conical shape is superior to one of hemispherical shape.

(c) Beaded edges to the cup make it less sensitive to wind-stream turbulence than plain edges.

Response characteristics of cup anemometers. By approximation the equation of motion for a cup anemometer can be written (MacCready and Jex, 1964),

$$\frac{dn}{dt} = -aun + bu^2, \qquad \ldots(8)$$

where n = the number of revolutions per second
t = the time
u = wind speed

and a and b are constants dependent on the instrument and the air density.

For a step change of Δu in u at $t = 0$, the solution to equation (8) for $t \geqslant 0$ is

$$n = \gamma \left[u + \Delta u \left(1 - e^{\frac{-t}{\tau}}\right)\right] \qquad \ldots(9)$$

where $\gamma = \dfrac{b}{a}$

and $\tau = \dfrac{1}{a(u + \Delta u)}$

is the 'time-constant'. If $t = \tau$, then from equation (9) τ is the time required for the anemometer to respond to 63.2 per cent of the step change. Since, however, the time-constant varies inversely as the wind speed it is usual, and more meaningful, to extend the concept to include the length of an air column that must pass the anemometer for the anemometer to respond to 63.2 per cent of a step change. This parameter is termed the distance-constant, d, (defined as the product of the time-constant and the wind speed) and, for a specified anemometer, depends only on the air density.

For a step change in wind speed from zero to u at $t = 0$, the solution to equation (8) at $t \geqslant 0$ (incorporating d) is

$$n = \gamma u \left(1 - e^{\frac{-ut}{d}}\right)$$

from which the value of d for a particular anemometer can be determined from wind-tunnel experiments. Figure 5 shows the variation of the time-constant with wind speed for a Mk 4A cup anemometer (see page 4–18) exposed in the Meteorological Office wind-tunnel.

A consequence of the time-constant varying inversely as the wind speed, is that a cup wheel accelerates more quickly with an increase in wind speed than it decelerates with a decrease in wind speed. The mean wind speed recorded by an anemometer in a variable wind is thus higher than the true mean wind speed. Schrenk (1929) attempted a theoretical analysis of the magnitude of the errors involved in a sinusoidal fluctuation in the wind speed. He related the 'overrun' of the cup anemometer with a dimensionless parameter K, given by

$$K = \frac{(\alpha\beta)^{\frac{1}{2}} \, \rho R^2 r^2 t u}{4I},$$

where ρ = density of the air
R = radius of the circle described by the cup centres
r = radius of the cups
t = period of the sinusoidal oscillation
u = mean wind speed
I = the moment of inertia of the rotating parts
α and β = constants for a specified anemometer.

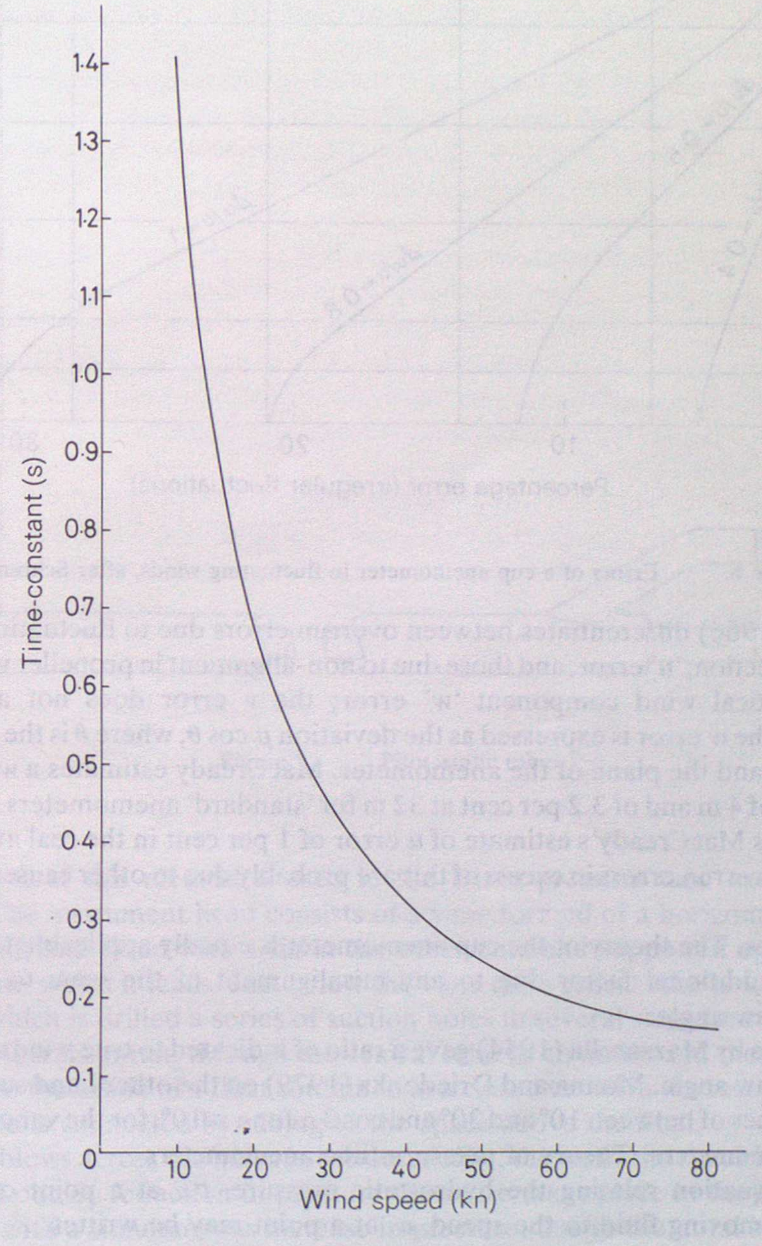


Figure 5. Variation of time-constant with wind speed for a Mk 4A cup anemometer.

Figure 6 shows a family of curves that Schrenk derived for the relation between the anemometer overrun (expressed as a percentage of the mean wind speed) and K, for various values of the ratio of the amplitude of the fluctuation to the mean wind speed, $\Delta u/u$. The numerical scale at the top is for sinusoidal fluctuations and a four-cup anemometer with hemispherical cups. The lower scale is for irregular fluctuations.

Deacon (1951) showed experimentally that Schrenk's curves were approximately correct, apart from a tendency to underestimate the errors for low values of K. This discrepancy was not considered significant in view of the practical difficulties of accurate measurement, and the approximate nature of Schrenk's treatment.

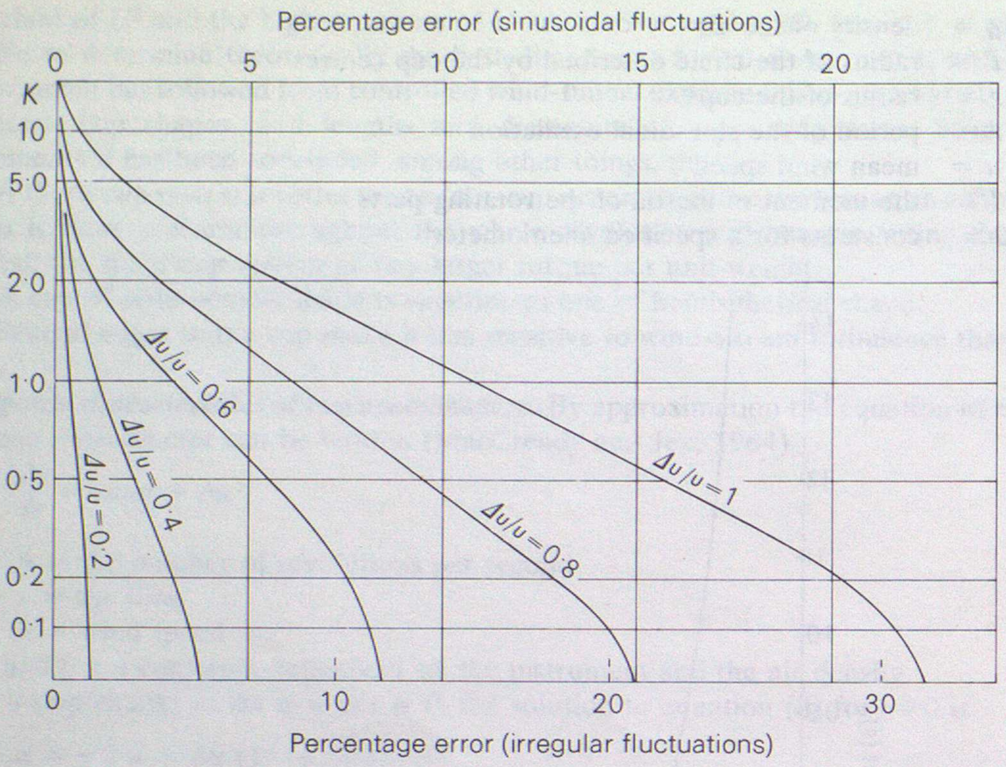


Figure 6. Errors of a cup anemometer in fluctuating winds, after Schrenk.

MacCready (1966) differentiates between overrun errors due to fluctuating wind speeds along a fixed direction, 'u' error, and those due to non-alignment in propeller vanes, 'v' error, and to the vertical wind component 'w' error; the v error does not arise with cup anemometers. The w error is expressed as the deviation $\mu \cos \theta$, where θ is the angle between the wind vector and the plane of the anemometer. MacCready estimates a w error of 6 per cent at a height of 4 m and of 3.2 per cent at 32 m for 'standard' anemometers. Hyson (1972) broadly confirms MacCready's estimate of u error of 1 per cent in the real atmosphere and concludes that overrun errors in excess of this are probably due to other causes, such as the w error.

Propeller vanes. The theory of the cup anemometer is equally applicable to the propeller vane, with an additional factor due to any misalignment of the vane to the true wind direction, the yaw angle.

Measurements by Mazzarella (1954) gave a ratio of indicated to true wind speed of $\cos^2 \alpha$, where α is the yaw angle. Monna and Driedonks (1979) on the other hand suggest a ratio of $\cos 1.3\,\alpha$ for values of between 10° and 30° and $\cos 3\,\alpha$ for $\alpha \leq 10°$, for the vanes they tested.

Pressure anemometers. Theory of pressure-tube anemometers

Bernoulli's equation relating the hydrostatic pressure, p_s, at a point on a horizontal streamline of a moving fluid to the speed, u, at a point may be written

$$p_s + 0.5\rho\, u^2 = p_t,$$

where p_t is constant and ρ is the fluid density; p_t is known as the 'total head' and is usually considered to be made up of two parts, the static head p_s and the speed head $0.5\,\rho u^2$. It is possible to deduce u from a measurement of the difference between the total head and the static head, using a pitot–static tube (Figure 7). The air entering the mouth of the double-walled tube, which is pointed in exactly the opposite direction to that of the airflow, is brought to rest so that the pressure inside the mouth is equal to the total head. The static pressure is experienced in the wall of the tube which is in communication with the outside air through the holes drilled in the wall at right angles to the axis of the tube at that point. The difference in pressure between these two spaces is measured by connecting them to opposite arms of a sensitive manometer.

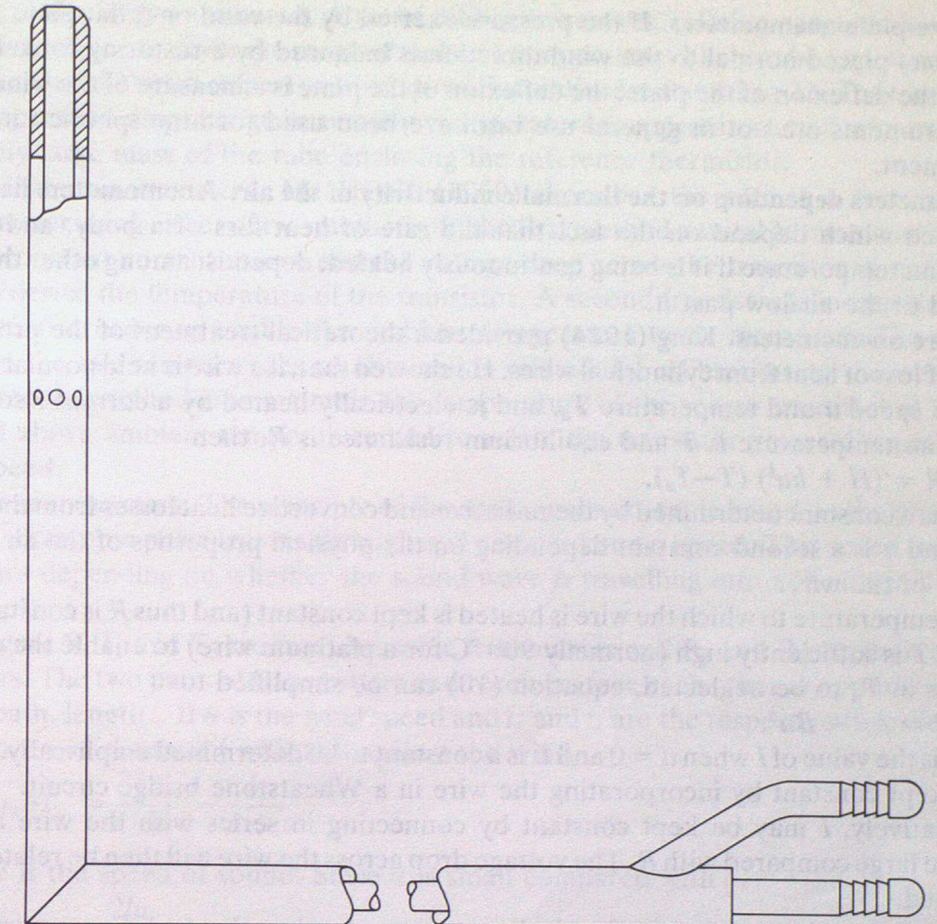


Figure 7. Pitot–static tube.

An adaptation of this method is used in the Dines pressure tube anemograph (now obsolescent). The instrument head consists of a vane formed of a horizontal piece of tube open at one end, and fitted with a fin at the other end, and supported upon the top of a vertical tube into which it leads. Just below the vane this vertical tube is surrounded by an outer tube in which is drilled a series of suction holes in several staggered rows. The 'total head' pressure is transmitted through the central tube to an outlet and thence by means of further tubing to the inside of a float contained in a closed vessel in the recorder. The outer, perforated, tube is connected by tubing to the space above the float.

As the wind blows across the holes in the outer tube, the air in the space between the two tubes is sucked out. A reduction in pressure therefore takes place in the space above the float, together with a simultaneous increase in pressure, due to the 'total head', within the float.

The arrangement of the head means that the pressure applied to the space above the float is not the true static pressure but instead the static pressure reduced by an amount equal to $c\rho u^2$, where c is a constant less than 0.5. The difference Δp between the 'total head' and the 'suction head' is given by

$$\Delta p = 0.5\rho u^2\,(1 + 2c).$$

The value of c varies with the size and shape of the holes in the outer tube but for a standard instrument can be determined experimentally. The difference in pressure Δp is then used to determine u. The reading of the instrument depends on the value of the air density, and corrections have to be applied when the conditions depart radically from those assumed when the instrument was calibrated.

Pressure-plate anemometers. If the pressure exerted by the wind on a flat plate (usually rectangular) placed normal to the wind direction is balanced by a restoring force brought about by the deflexion of the plate, the deflexion of the plate is a measure of the wind speed. Such instruments are not in general use but have been used for atmospheric turbulence measurement.

Anemometers depending on the thermal conductivity of the air. Anemometers have been constructed which depend on the fact that the rate of heat loss of a body, and thus its equilibrium temperature if it is being continuously heated, depends, among other things, on the speed of the airflow past it.

Hot-wire anemometers. King (1914) provided a theoretical treatment of the problem of the rate of loss of heat from cylindrical wires. He showed that, if a wire is held normal to an air stream of speed u and temperature T_a, and is electrically heated by a current I so that its equilibrium temperature is T and equilibrium resistance is R, then

$$I^2R = (H + hu^{\frac{1}{2}})\,(T - T_a), \qquad \ldots (10)$$

where H is a constant determined by the radiative and convective heat losses from the wire in still air and h is a second constant depending on the physical properties of the air and the diameter of the wire.

If the temperature to which the wire is heated is kept constant (and thus R is constant), and provided T is sufficiently high (normally 900 °C for a platinum wire) to enable the effect of variations in T_a to be neglected, equation (10) can be simplified to

$$I^2 = I_o^2 + Bu^{\frac{1}{2}},$$

where I_o is the value of I when $u = 0$ and B is a constant to be determined empirically. T and R may be kept constant by incorporating the wire in a Wheatstone bridge circuit.

Alternatively, I may be kept constant by connecting in series with the wire a ballast resistance large compared with R. The voltage drop across the wire will then be related to the wind speed.

The hot-wire anemometer itself usually consists of a length of platinum wire, a few centimetres long and from 0.002 to 0.1 mm in diameter, stretched between suitable supports and mounted on a base. One great merit of this instrument is its small time-constant. Dryden and Kuethe (1929) showed the time-constant τ to be given by

$$\tau = \frac{4.2\rho\, A^2C(T - T_a)}{r_a I^2},$$

where ρ is the density of the wire, A the cross-sectional area of the wire, C the specific heat capacity of the wire, and r_a the specific resistance of the wire at temperature T_a.

For the smallest time-constant it is necessary to use a very fine wire and as low a temperature excess as other requirements will allow. A platinum wire 0.0025 mm in diameter can be used to respond with reasonable accuracy to wind-speed fluctuations with an oscillation period of about 0.01 s. Another advantage for some purposes is that its greatest sensitivity is at low wind speeds. Wind speeds from a few centimetres per second up to about 10 m s^{-1} can easily be measured with hot-wire anemometers.

The disadvantages of the unshielded instrument are that the wire is liable to fracture and that its calibration may change. It cannot, of course, be used in the open during precipitation. Simmons (1949), however, developed a shielded version having more permanent calibration and greater mechanical strength than the unshielded type. An extended discussion of hot-wire anemometers is given by Hinze (1959).

Thermistor anemometers. Because of their large negative coefficient of resistance, thermistors are capable of a high level of temperature discrimination. This property, together with their self-heating capacity, makes them suitable for use in instruments for measuring low wind speeds. Martino and McNall (1971) describe such an instrument for measuring wind speeds up to 100 cm s^{-1}.

The instrument probe consists of a narrow-bore, thin-walled, brass tube with a sensor thermistor mounted at one end of the tube and a reference thermistor mounted inside the tube. In use the probe is connected electrically to a suitable bridge circuit and the output voltage of the bridge measured. A set of calibration curves, relating output voltage to wind speed, is required to cover the range of ambient temperatures likely to be experienced in use. The time-constant with respect to wind speed fluctuations is about 1 to 2 s. The time-constant with respect to a step change in ambient tremperature is approximately 2 min, owing to the relatively large mass of the tube enclosing the reference thermistor.

Transistor anemometers. MacHattie (1969) describes the use of a transistor as an anemometer using either of two methods. In the first method a suitable transistor is powered from a constant-current source and the voltage drop across the transistor is measured and used to derive the temperature of the transistor. A second transistor is incorporated in the instrument in order to enable the ambient temperature to be measured. The difference between the two temperatures so obtained is related, by calibration, to the wind speed.

The second method is to maintain the temperature of the sensor transistor at a constant interval above ambient temperature and to relate the transistor power dissipation to the wind speed.

Sonic anemometers. The principle of the sonic anemometer is based on the phenomenon that an ultrasonic pulse travels through still air at a known speed. This speed increases or decreases depending on whether the sound wave is travelling into a 'headwind' or with a 'tailwind'.

In Figure 8, T_1 and T_2 are two ultrasonic transmitters and R_1 and R_2 are their associated receivers. The two pairs of transmitters and receivers face each other at opposite end of the sound path, length l. If u is the wind speed and t_1 and t_2 are the respective times for a sound pulse to travel distance l with and against the wind,

$$t_2 - t_1 = \frac{l}{c-u} - \frac{l}{c+u}$$

where c is the speed of sound. Since u is small compared with c,

$$t_2 - t_1 \approx \frac{2lu}{c^2}$$

$$\therefore \quad u \approx \frac{c^2}{2l}\,(t_2 - t_1).$$

Such instruments have negligible time-constants and claimed discrimination of 1 to 5 mm s^{-1}.

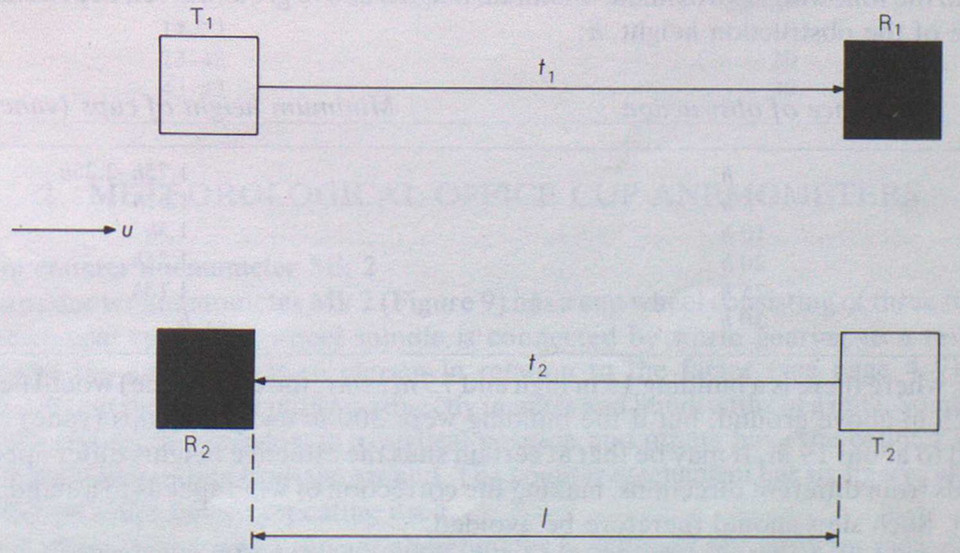


Figure 8. Principle of the sonic anemometer.

Vortex anemometers. When air flows past an obstruction turbulence is created which above a certain minimum air speed assumes a regular pattern of vortices; the spacing between the vortices is a well-defined constant. The speed of the air flow, u, is given by

$$u = \frac{df}{S}$$

where d = the diameter of the obstruction
S = constant
f = the vortex formation frequency.

The vortex frequency is detected by passing a confined carrier wave ultrasonic beam through the vortex path formed behind a strut or obstruction in the air flow. Each pair of vortices causes one cycle of amplitude modulation to be impressed on the carrier signal owing to the beam-scattering effect of the oppositely rotating vortices.

1.5 Exposure of anemometers and wind vanes

The wind velocity near the surface of the earth varies rapidly with height and is also greatly affected by the presence of irregularities in the ground or by nearby obstacles such as trees or buildings. For synoptic and climatological purposes therefore it is necessary to define a standard exposure under which measurements should be made.

The standard exposure of an anemometer or wind vane over open, level terrain is 10 m above the ground. Open, level terrain may be defined for this purpose as level ground with no obstruction within 300 m. Where these conditions cannot be met, adjustment should be made to the height of the instrument as described below, so that wind speeds and directions can be obtained which are generally representative of the area and not unduly influenced by immediately local conditions.

At a comparatively unobstructed site, i.e. where any obstructions are not large and are distributed more or less uniformly around the instrument, to give an effective height of 10 m the anemometer cups need to be at a height of h + 10 m, where h is the approximate height of the various obstacles. Thus, in the fairly common case, where there are buildings and trees up to 6 m or so in height, the cups (vane) need to be on a 16 m mast.

In the case where there are large obstructions within 150–300 m, e.g. obstructions 12 m or more in height, it is necessary to raise the cups (vane) to such a height that the wind reaching them after passing over such an obstacle is affected by the obstacle as little as possible and excessive gustiness is avoided. It is thought that to achieve this it is necessary to raise the cups (vane) to the following approximate minimum heights above ground level, depending on the distance of the obstruction height, h:

Distance of obstruction	*Minimum height of cups (vane)*
h	1.75h–2.25h
5 h	1.67h
10 h	1.5h
20 h	1.25h
25 h	1.13h
30 h	h

Thus, where there is a building 15 m high and 75 m away, the cups (vane) would need to be about 25 m above ground, but if the building were 300 m away the cups (vane) could be lowered to about 19 m. It may be that at certain sites the effective heights differ appreciably for winds from different directions, making the correction of wind speeds to a standard level difficult. Such sites should therefore be avoided.

When the cups (vanes) need to be mounted on an isolated building the building itself will disturb the wind flow to an extent depending, among other things, on its size and shape. As a rough guide the mast or tower erected on the roof needs to be at least half and probably three-quarters of the height of the building, assuming the building is large (i.e. excluding

such things as lighthouses, etc.). Thus, with a building 24 m high, a roof-top mast at least 12 m, and preferably 18 m high, should be used.

For the records to be of value, changes in the site exposure should be kept to a minimum. The subsequent erection of buildings in the vicinity of the site can affect the data recorded, sometimes so seriously that the site becomes useless for representative wind measurement. Slow changes in exposure, such as the growth of trees, are often not readily identifiable from the data, owing to the natural variability of the wind. When the equipment is installed, it is therefore advisable to make a detailed site-plan, showing the height and extent of all obstacles within 300 m. The plan should be reviewed every few years, changes of exposure noted and, if possible, action taken to minimize any obvious trends.

Each anemometer is allotted an 'effective height', defined as the height over open, level terrain in the vicinity which, it is estimated, would have the same mean wind speeds as those actually recorded by the anemometer. The mean variation of wind with height is assumed to follow the formula,

$$U_h = U_{10}\left[\,0.233 + 0.656 \log_{10}(h + 4.75)\right]$$

where U_h is the wind speed at height h metres and U_{10} is the wind speed at 10 m, from which the values of U_{10}/U_h in Table III are calculated.

Table III. *Values of* U_{10}/U_h

Height in metres	2	3	4	5	10	15	20	25	30	35	40
U_{10}/U_h	1.29	1.21	1.18	1.13	1.00	0.92	0.87	0.83	0.80	0.78	0.76

No definite rules can be laid down for obtaining the effective height of any anemometer. It can only be estimated by taking into account the nature, extent, height and distance of the local obstacles and obstructions and the actual height of the anemometer itself. Table IV gives the percentage corrections to be applied to the readings of anemometers with various effective heights.

Table IV. *Corrections for effective height*

Effective height *metres*	Correction *per cent*
3–4	+ 20
5–7	+ 10
8–13	Zero
14–22	− 10
23–42	− 20
43–93	− 30

2 METEOROLOGICAL OFFICE CUP ANEMOMETERS

2.1 Cup counter anemometer Mk 2

The cup counter anemometer Mk 2 (Figure 9) has a cup wheel consisting of three five-inch diameter conical cups. The wheel spindle is connected by worm gearing to a revolution counter and the gear ratio is so chosen in relation to the factor (see page 4–7) of the anemometer that the counter indicates directly in miles and hundredths of a mile. Some instruments have the counter window in a vertical position and others have the counter window angled to facilitate reading from the ground. The counter mechanism has six figures and reads up to 9999.99 miles before repeating itself.

Method of use. The counter type of anemometer is designed primarily for measuring the run of wind over a period of hours or even days rather than over the short period required for general observational purposes. To obtain the run of wind over a given period the counter is read at the beginning and at the end of the period and the difference taken.

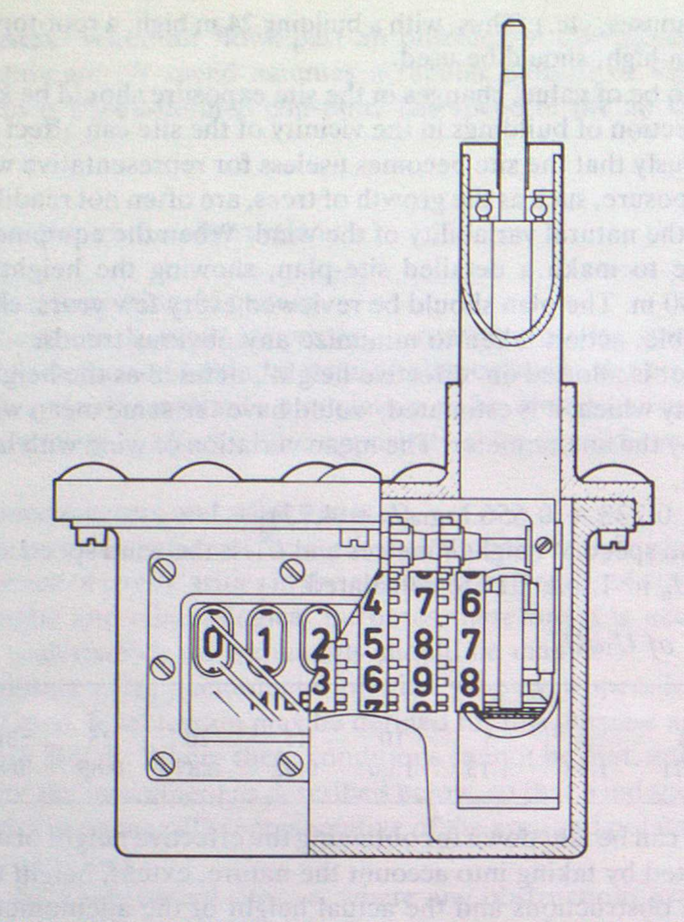


Figure 9. Mechanism of a cup counter anemometer Mk 2.

The run of wind in hundredths of a mile in 36 s is equal to the wind speed in mile h^{-1}, in 31 s approximately equal to the wind speed in knots and in 16 s approximately equal to the wind speed in metres per second.

If wind speed is the primary requirement rather than run of wind this instrument should not be used unless the use of a cup generator anemometer is impracticable.

2.2 Cup contact anemometer Mk 4B

The cup contact anemometer Mk 4B has a three-cup assembly mounted on a vertical spindle rotating in ball bearings. The spindle controls a switch mechanism so that an electrical contact is made for every 50 revolutions of the cup wheel, each contact corresponding to 0.096 of a mile run of wind. The micro-switch, which is used to make the contact, is operated by a cam and falling weight so that the time of contact is constant and independent of the wind speed. In this way the possibility of the contact remaining in the ON position during a calm, or of very long contacts in a light wind, is avoided. The anemometer spindle carries a worm gear (A in Figure 10) which meshes with a worm wheel, B. On the same spindle as the worm wheel is a loose sleeve carrying a one-piece counterbalance and cam. On one side of the worm wheel is a steel pin which can engage with the cam, causing the cam to rotate. When the counter-balance is just past its highest position it falls down freely to its equilibrium position and in so doing drives the cam round causing the micro-switch to be depressed and released thus making and breaking the contact. The gearing is such that in a 5-minute period one contact equals 1.0 kn with a tolerance of ± 1 kn below 40 kn and ± 2 kn at or above 40 kn (e.g. in a 5-minute period 50 kn = 50 contacts ± 2). The contacts made by the micro-switch can be used, in conjunction with a suitable counting device, to provide an indication of mean wind speed.

2.3 Cup generator anemometer Mk 2

The cup generator anemometer Mk 2 consists of a three-cup assembly mounted on a vertical spindle rotating in ball bearings and carrying the rotor, a small six-segment permanent magnet, of an a.c. generator, C, in Figure 10. The single-phase a.c. output from the generator can be used to operate up to six wind speed dials Mk 2 or Mk 4D (see page 4–20) and one anemograph recorder Mk 4G (see page 4–21). The terminal voltage of the generator on open circuit is in accordance with Table V, with a tolerance equivalent to ± 1 kn below 40 kn and ± 2 kn at or above 40 kn; corresponding wind speeds are included.

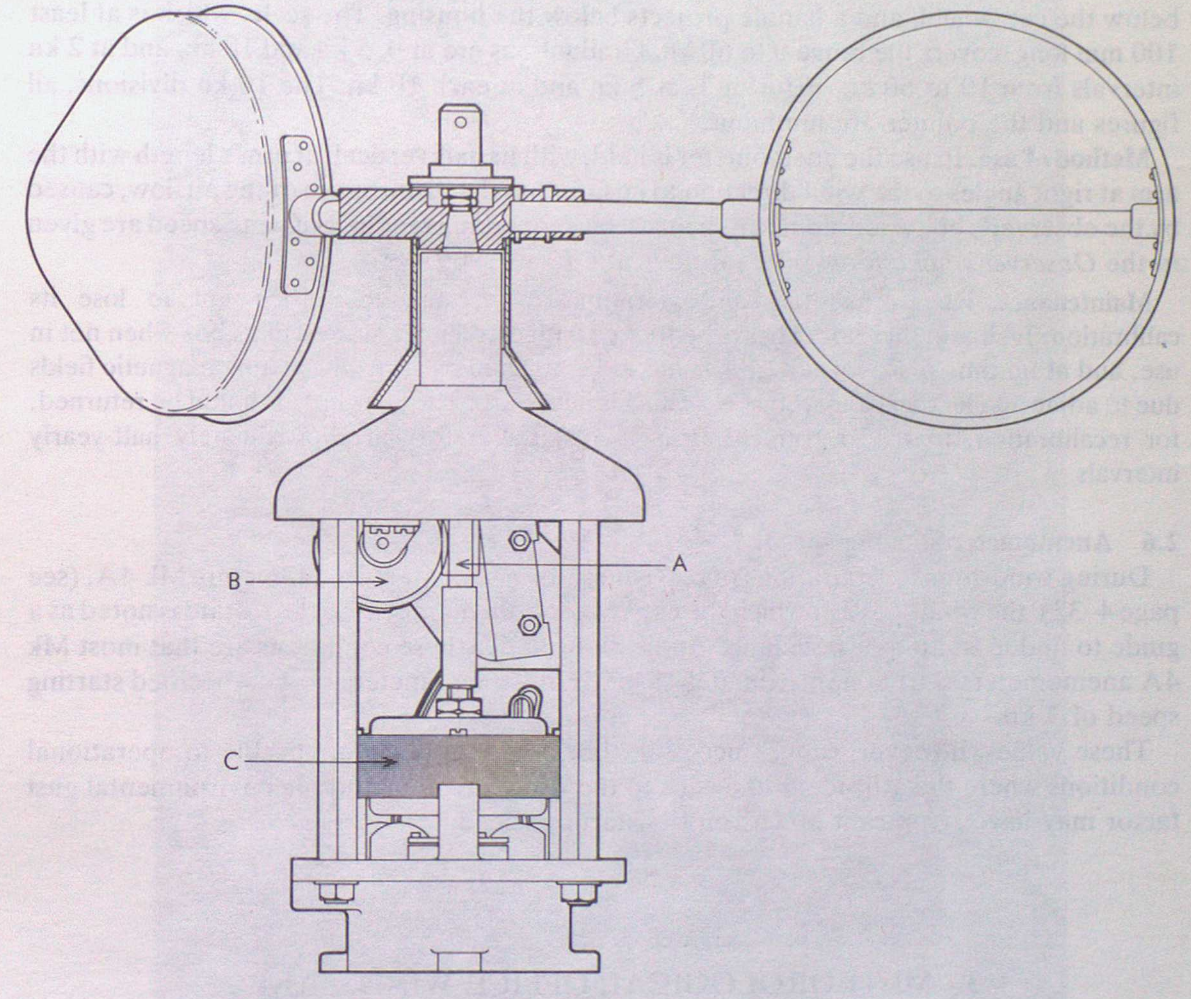


Figure 10. Mechanism of a cup generator and contact anemometer Mk 4A.

Table V. *Characteristics of the cup generator anemometer Mk 2*

Wind speed (knots)	5	10	20	30	40	50	60	70	80	90
Cup speed (rev min^{-1})	50	100	200	300	400	500	600	700	800	900
Open-circuit e.m.f. (volts)	1.6	3.2	6.3	9.5	12.7	15.8	19.0	22.2	25.3	28.5

2.4 Cup generator and contact anemometer Mk 4A

The cup generator and contact anemometer Mk 4A (Figure 10), which is similar in appearance to the cup contact anemometer Mk 4B, has the dual facilities of the Mk 4B contact mechanism and the Mk 2 generator. It is possible, therefore, if required, to obtain instantaneous and mean wind speed data simultaneously.

2.5 Hand anemometer

The hand anemometer (Plate I) is used to obtain values of wind speed at the level of the observer. It has a small three-cup or four-cup wheel mounted on a vertical spindle which also carries a permanent magnet. An aluminium cup mounted on a pivot, below and concentric with the spindle, carries a pointer. When the cup wheel rotates in the wind, the rotating magnet induces eddy currents in the aluminium cup which tries to turn in the same direction as the magnet against a restraining hair spring. The angular movement of the aluminium cup and pointer is a measure of the wind speed, and is indicated on a luminous scale across which the pointer moves. The mechanism, pointer and scale are contained in a circular housing below the cup wheel, and a handle projects below the housing. The scale, which is at least 100 mm long, covers the range 0 to 60 kn. Graduations are at 0, 5 kn and 10 kn, and at 2 kn intervals from 10 to 60 kn. Figuring is at 5 kn and at each 10 kn. The 10 kn divisions, all figures and the pointer are luminous.

Method of use. In use the anemometer is held, with its axis vertical, at arm's length with the arm at right angles to the wind direction to ensure that the disturbance of the airflow, caused by the observer's body, is minimized. Instructions for taking readings of wind speed are given in the *Observer's handbook* (Meteorological Office, 1969).

Maintenance. Rough handling and vibrations may cause the instrument to lose its calibration. It should therefore always be treated with care, being stowed in its box when not in use, and at no time placed where it is liable to be affected by stray alternating magnetic fields due to adjacent electrical apparatus. No oiling is necessary. The instrument should be returned, for recalibration, to the Instrument Branch Test Laboratory at approximately half-yearly intervals.

2.6 Anemometer starting speed.

During wind-tunnel calibrations of cup generator and contact anemometers Mk 4A, (see page 4–32), the wind speed at which the cups of each anemometer start to rotate is noted as a guide to undue friction or imbalance. Indications under these conditions are that most Mk 4A anemometers start at approximately 6 kn. Hand anemometers have a specified starting speed of 3 kn.

These values, however, cannot necessarily be taken as being applicable to operational conditions where the attitude of the cups to the wind direction and the environmental gust factor may have significant effects on the starting speed.

3 METEOROLOGICAL OFFICE WIND VANES

3.1 Wind vanes Mk 4A and Mk 4G

The wind vane (Plate II) consists of a horizontal arm, turning about a vertical axis, carrying a rectangular fin at one end and a balance weight at the opposite end. The position of the vane is transmitted by means of either a Desynn transmitter (Mk 4A vane) or a magslip transmitter (Mark 4G vane) mounted in a weatherproof housing above the vane. Either transmitter is fitted in such a way that it can be easily replaced by a similar transmitter without loss of orientation.

The wind vane is constructed so that it can be used either as a separate unit or coupled coaxially with a Mk 4A or Mk 4B anemometer to form a combined wind speed and direction transmitter.

Desynn transmitter systems. The Desynn transmitter has a toroidally wound circular resistance with three tappings at equidistant points around its circumference. Two sliders make contact with the resistance at diametrically opposite points and, by being connected mechanically to the wind vane spindle, are made to rotate over the resistance. The sliders are connected to a 12 V d.c. supply. The Desynn receiver has a slotted iron stator, carrying three

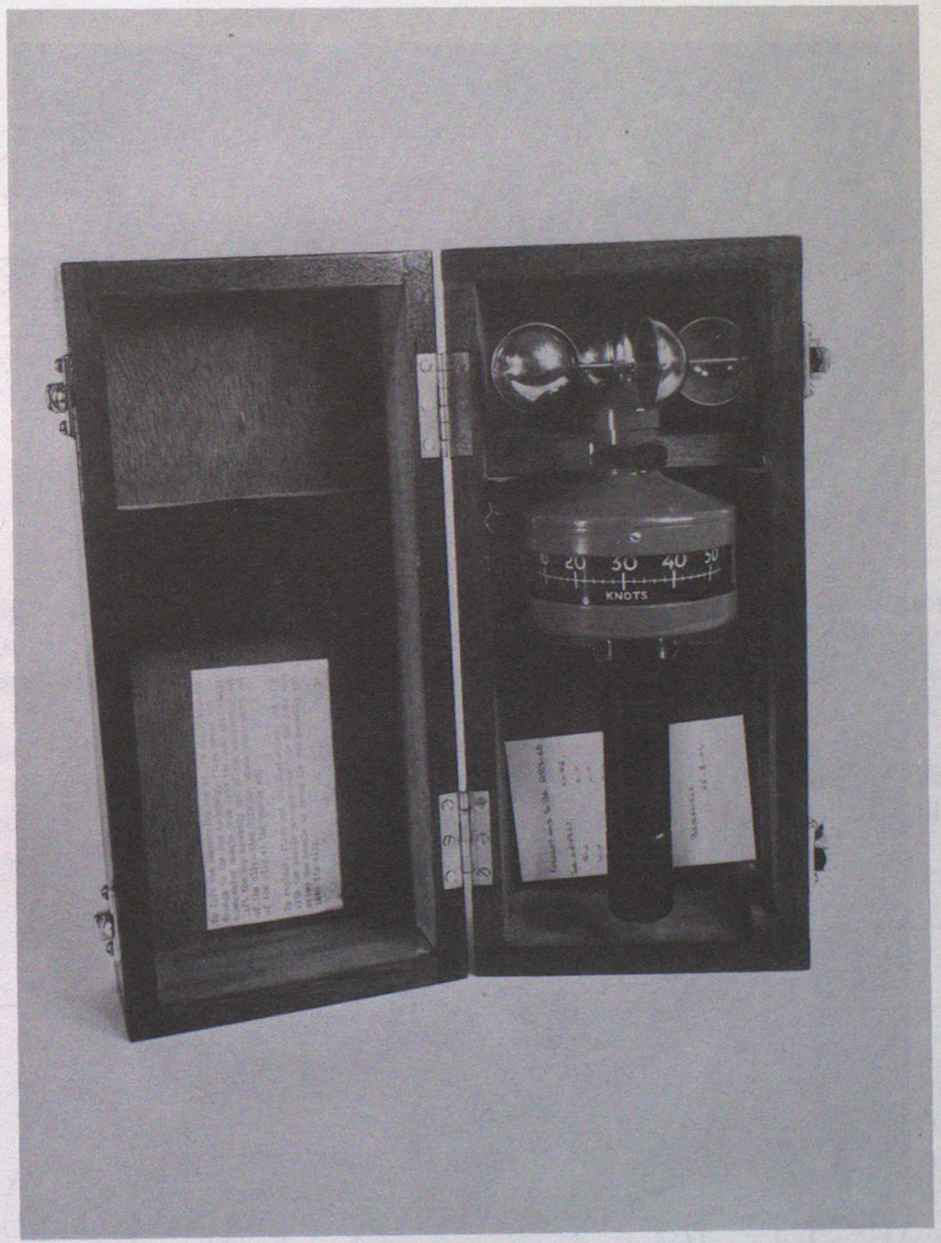


Plate I. Meteorological Office hand anemometer.

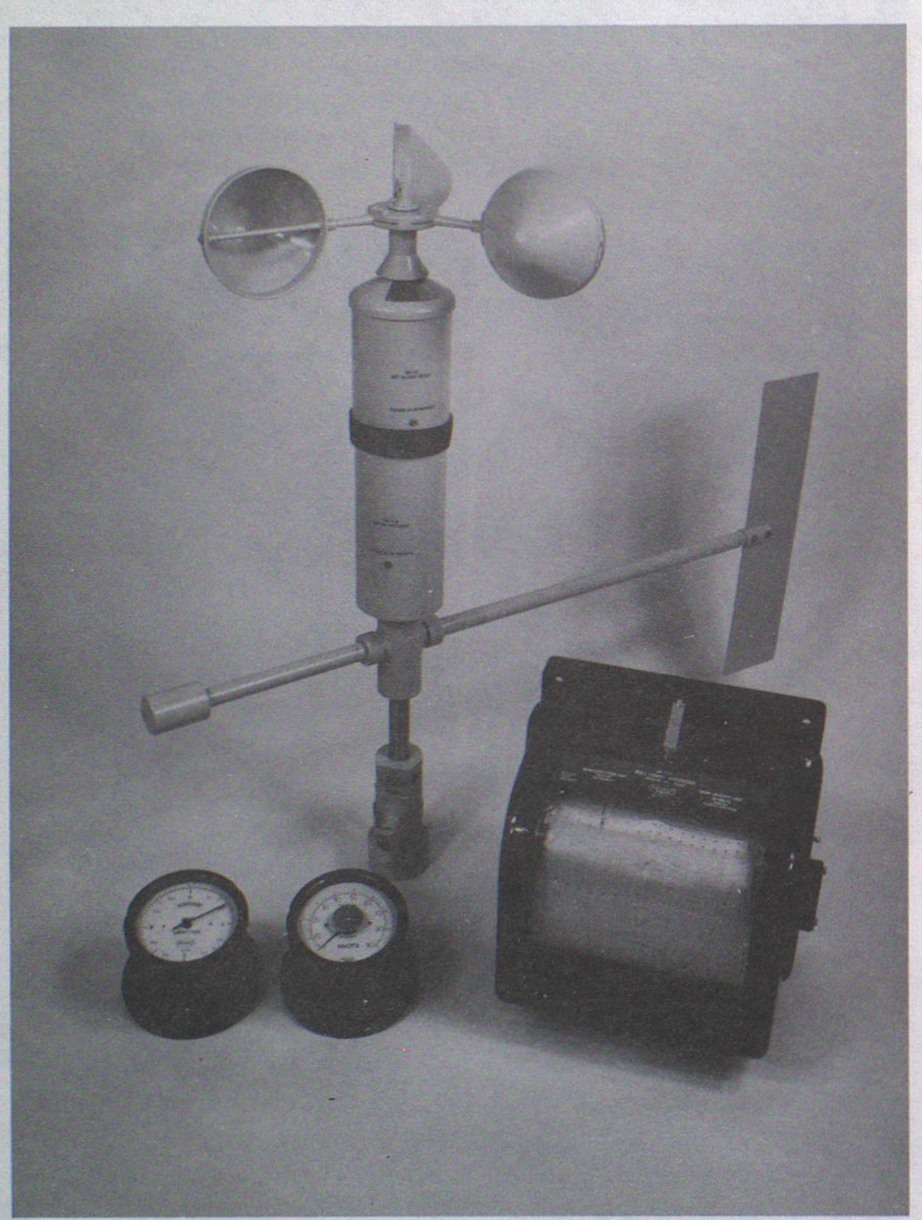


Plate II. Meteorological Office Mk 4 wind system.

star-connected windings, which surrounds a pivoted permanent magnet forming a 2-pole armature. The stator windings produce the same effect as three symmetrically placed iron-cored coils with coplanar axes intersecting at a point. The tappings of the transmitter resistance are connected to the three windings of the receiver, as shown in Figure 11, and thus the direction and distribution of the currents in the receiver windings depend on the positions of the sliders on the transmitter resistance. This is shown in turn by the position taken up by the magnet, which aligns itself with the resultant magnetic field produced by the currents in the stator windings.

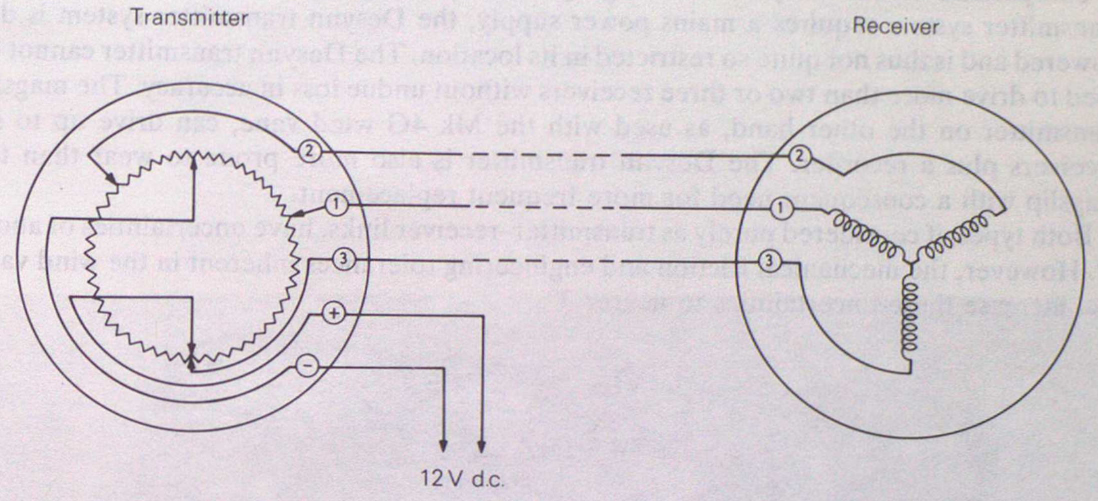


Figure 11. Desynn transmitter system.

Magslip transmitter system. The magslip comprises a stator and a rotor. The stator is in the form of an internally slotted laminated iron ring with three sets of windings at angles of 120° arranged in slots. The three stator windings are often referred to as 'phases', although the currents induced in them are actually in phase and differ only in magnitude. The rotor comprises an iron core carrying a single winding.

In the basic form of magslip transmission system two magslip elements have their rotors energized from a common a.c. supply and their stator windings interconnected 'phase-for-phase' as shown in Figure 12.

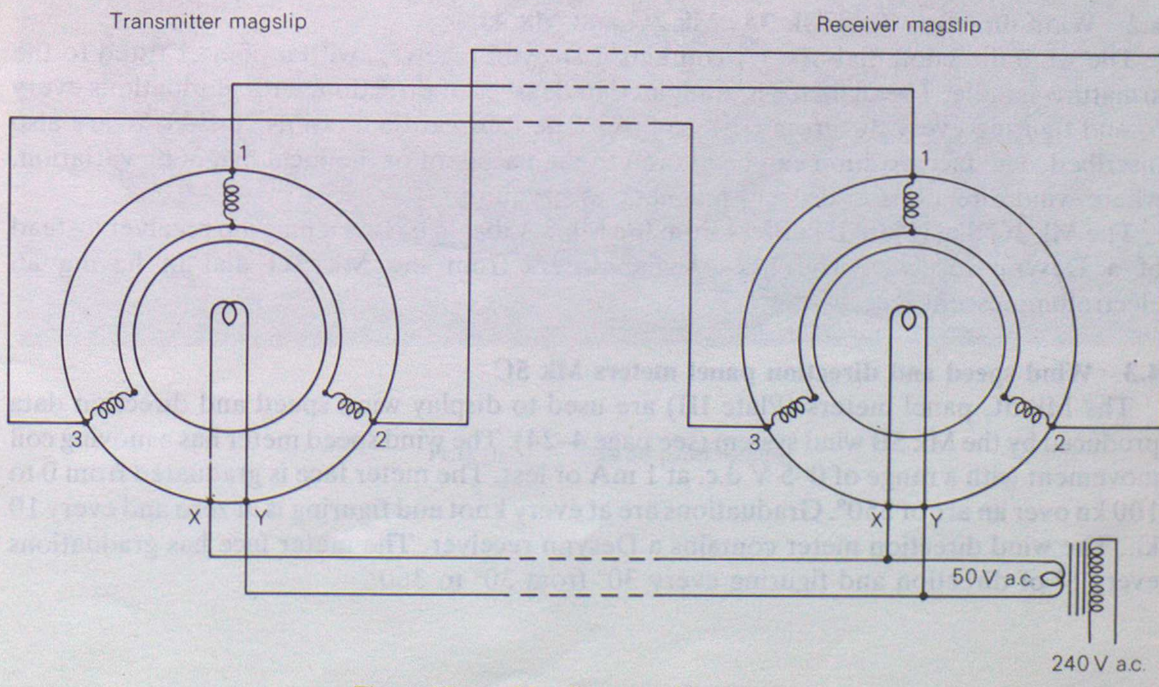


Figure 12. Magslip transmitter system.

Considering the transmitter magslip alone, voltages will be induced in each of the three stator windings, the magnitudes of the voltages depending on the position of the rotor. The same argument applies to the receiver magslip. While the rotors of the two magslips are in coincident angular positions, the voltages induced in the stators are equal and no current will flow between them. If, however, the rotor of the transmitter magslip is displaced with respect to the receiver magslip, the condition of balance is disturbed and current will flow. This current, reacting with the magnetic field set up by the rotor current, will produce torques tending to restore the magslips to coincident positions.

Comparison of the Desynn and magslip transmitter systems. Whereas the magslip transmitter system requires a mains power supply, the Desynn transmitter system is d.c. powered and is thus not quite so restricted in its location. The Desynn transmitter cannot be used to drive more than two or three receivers without undue loss in accuracy. The magslip transmitter on the other hand, as used with the Mk 4G wind vane, can drive up to six receivers plus a recorder. The Desynn transmitter is also more prone to wear than the magslip with a consequent need for more frequent replacement.

Both types, if considered purely as transmitter–receiver links, have uncertainties of about 1°. However, the mechanical friction and engineering tolerances inherent in the wind vane etc. increase these uncertainties to nearer 3°.

4 DIALS

4.1 Wind speed dials Mk 2 and Mk 4D

The Mk 2 wind speed dial (Plate II) contains a rectifier type moving coil a.c. voltmeter movement with a range from 0 to 30 V. The dial face is graduated from 0 to 90 kn over an arc of 270°. The first graduation above zero is at 5 kn and graduations from 5 kn to 90 kn are at every knot. Figuring is at zero and every 10 kn.

The Mk 4D dial differs from the Mk 2 dial in that its face is fabricated from electroluminescent material. When energized from a nominal 240 V 50 Hz, single-phase mains supply the face provides a green luminescent background suiting the dial for use under conditions of reduced general lighting.

4.2 Wind direction dials Mk 3A, Mk 3G and Mk 4J

The wind direction dial Mk 3A contains a Desynn receiver, with a pointer fitted to the armature spindle. The dial face is graduated in degrees of direction, with graduations every 5° and figuring every 30° from 030° to 360°. The four cardinal points N–E–S–W are also inscribed. The face position can be altered to take account of the local magnetic variation, where wind directions in degrees magnetic are required.

The Mk 3G dial (Plate II) differs from the Mk 3A dial in having a magslip receiver instead of a Desynn receiver. The Mk 4J dial differs from the Mk 3G dial in having an electroluminescent face.

4.3 Wind speed and direction panel meters Mk 5C

The Mk 5C panel meters (Plate III) are used to display wind speed and direction data produced by the Mk 5B wind system (see page 4–24). The wind speed meter has a moving coil movement with a range of 0–5 V d.c. at 1 mA or less. The meter face is graduated from 0 to 100 kn over an arc of 250°. Graduations are at every knot and figuring is at zero and every 10 kn. The wind direction meter contains a Desynn receiver. The meter face has graduations every 5° of direction and figuring every 30° from 30° to 360°.

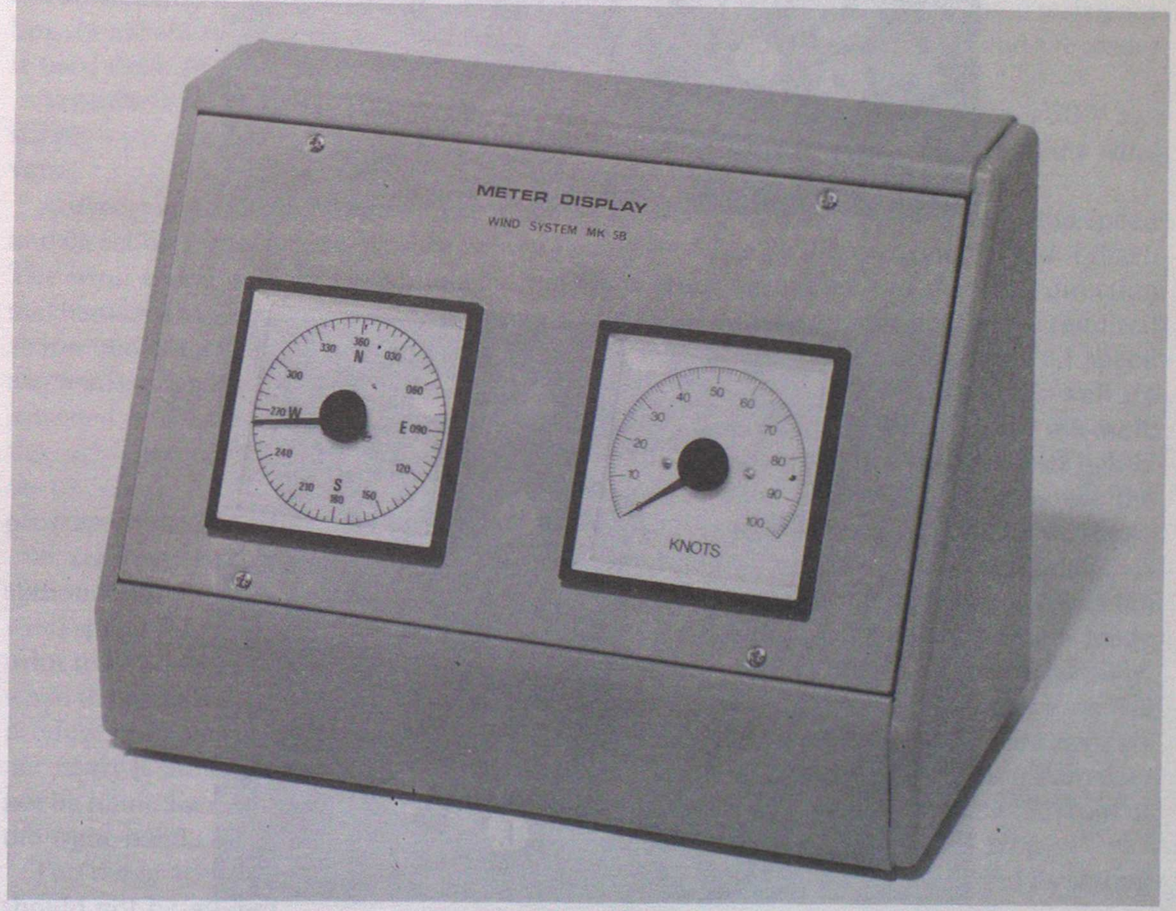
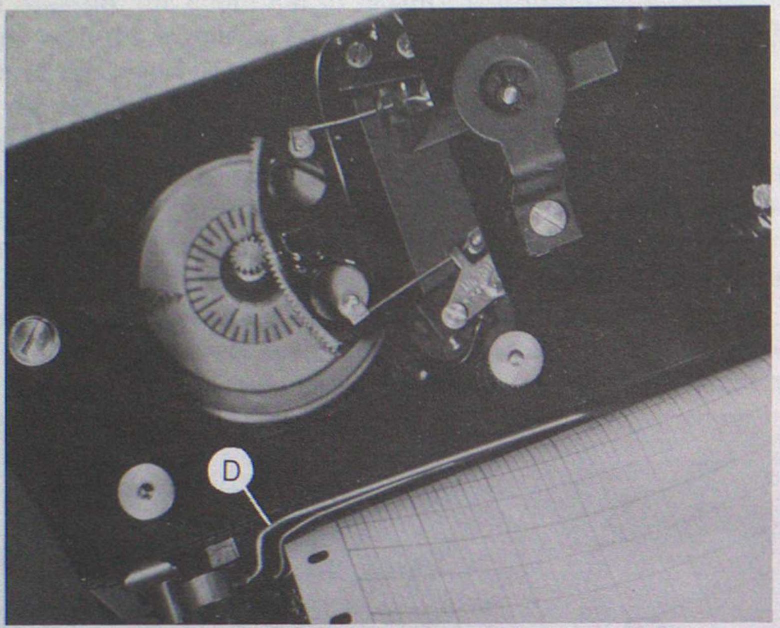


Plate III. Mk 5C panel meters.



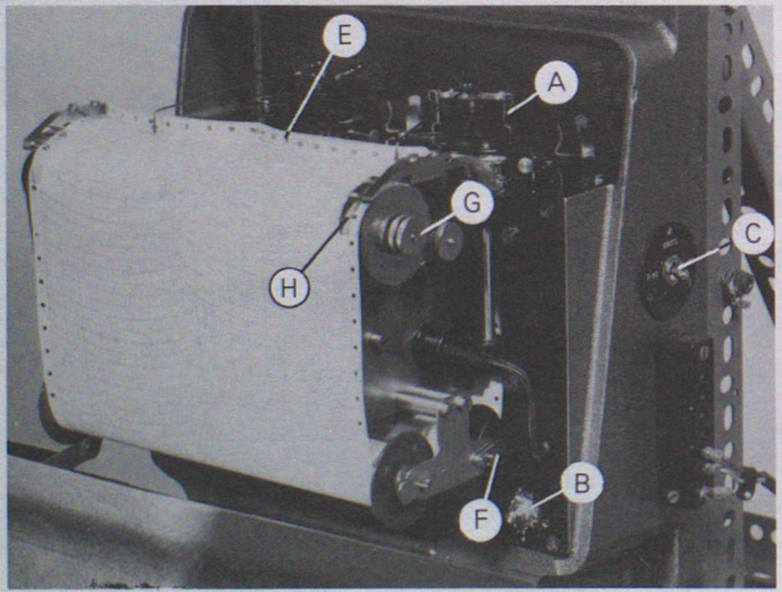


Plate IV Meteorological Office anemograph recorder Mk 4G.

5 METEOROLOGICAL OFFICE WIND SYSTEMS

5.1 Mk 4 Wind System

Description. The Mk 4 wind system is a Meteorological Office wind measuring installation which, in standard form, comprises

(a) Cup generator and contact anemometer Mk 4A
(b) Wind vane Mk 4G
(c) Wind speed dial Mk 2
(d) Wind direction dial Mk 3G
(e) Anemograph recorder Mk 4G
(f) Substitutional resistance box
(g) Single-phase 240/50 V transformer.

Items (a), (b), (c) and (d) are described on previous pages and, together with item (e), are shown in Plate II.

Substitutional resistance box. The anemometer is calibrated in series with a resistance equivalent to six wind speed dials and a recorder connected in parallel. The substitutional resistance box enables resistances, equivalent to any dial or recorder not used, to be introduced into the circuit in order to maintain a constant load. The substitutional resistance box should always be in circuit, although when the full complement of six dials and a recorder is used none of the substitutional resistances will be in circuit.

Transformer. The transformer is used to provide, from a 240 V mains supply, a 50 V a.c. supply with which to power the magslips in the recorder, wind direction dials and the wind vane.

Anemograph recorder Mk 4G. The anemograph recorder Mk 4G consists of wind speed and direction recording mechanisms whose pens record side by side on a double-width chart. The wind speed mechanism contains a moving coil a.c. voltmeter and the wind direction mechanism a magslip receiver. A pen arm, consisting of a capillary tube bent to the required shape and attached to a knife-edge strip, rests in a stirrup attached to the wind speed mechanism. An ink-well is mounted central to the stirrup. A similar pen arm and ink-well are attached to the wind direction mechanism. One end of the pen arm dips into the ink-well, through a central hole, and the other end, fitted with a small nozzle or nylon tip, rests lightly on the chart. Adjustable balance weights fitted to the knife edge are used to reduce the pressure of the pen tip on the chart to the minimum necessary to ensure a satisfactory trace.

A zero-set screw, used to adjust the wind speed pen to zero when the anemometer is stationary or disconnected from the recorder, is situated, on most recorders, on the top of the wind speed movement in front of the pen stirrup (A in Plate IV). This adjustment is made prior to issue and it is not normally necessary to alter the setting of the screw except, possibly, when the pen arm has to be changed. A quarter turn of the screw in a clockwise direction will produce an increase of about 20 kn in the pen reading. If an adjustment to the zero appears necessary it should, therefore, be made with great care; a maladjustment to below zero may not be immediately obvious. On some recorders the zero-set screw is situated on the front of the right-hand side of the case, and requires several turns to move the pen arm.

The range adjustment screw, B, is set and sealed in position prior to issue and its setting should not be altered.

The two mechanisms are contained in a single case, which also houses the chart mechanism, designed for wall mounting. The chart, which is driven by a synchronous motor, has a standard speed of 25.4 mm h^{-1}. The wind direction scale covers a span of 720° with north central and at each extremity. When the pen arm is at either extremity, to avoid overrun, an automatic electro-mechanical self-centring device operates returning the pen arm to a central position. During the period of this movement, approximately three seconds, the power supply to both the transmitter and receiver magslips is automatically interrupted.

At the right-hand side of the case is a two-position switch C, by which the wind speed range can be changed from 0–90 kn to 0–180 kn. Recorders at certain selected stations are fitted with the Mk 2 automatic range-change device (see below).

Installation. At Meteorological Office sites the installation and setting up of the equipment is undertaken by trained personnel.

Method of use. Typical traces of wind speed and direction, as indicated by a Mk 4G recorder, are shown in Figure 13. Short-period fluctuations in the wind cause a broadening of the wind direction trace to cover a span of 40° or more. Nevertheless it is possible to evaluate to the nearest 10° the average wind direction about which the direction has been fluctuating during the 10 minutes preceding an observation. Similarly the wind speed trace is broadened by gusts and lulls. If the fluctuations in wind speed could be entirely damped out, the record would be represented by a thin line showing the variation in 'mean wind'. This is illustrated by the white line superimposed on the wind speed trace in Figure 13.

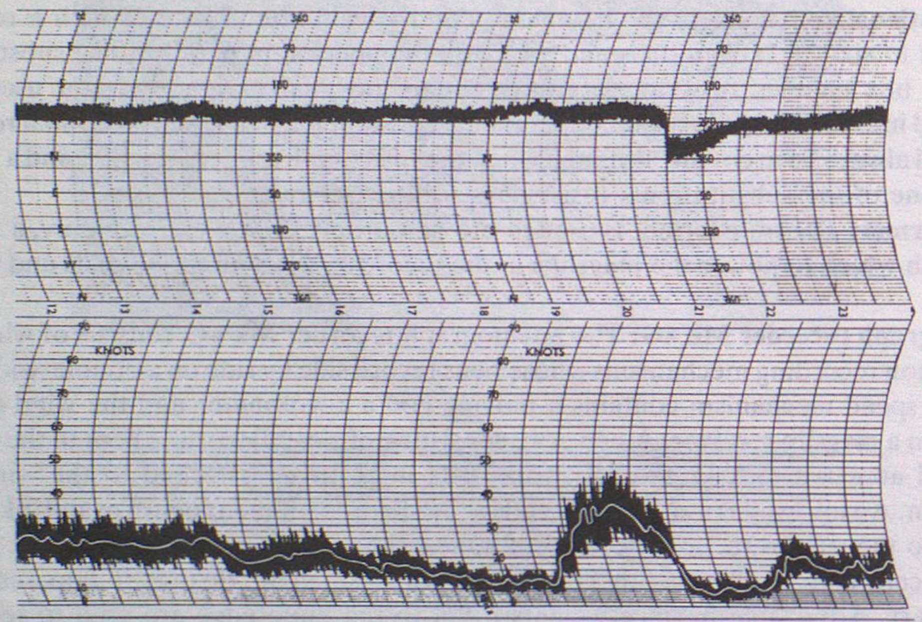


Figure 13. Typical record from an anemograph recorder Mk 4G.

Instructions for taking readings of wind speed and direction for synoptic and climatological purposes are given in the *Observer's handbook*.

Time-marks. A time-mark should be made daily using a soft pencil or ball-point pen to make a short line or legible dot at a place on the speed chart not covered by the trace. The time-mark should be along a time line or, where the pen is not exactly on a time line, parallel to a time line. The pen should not be moved to make a time-mark.

Double-range switch. The recorder double-range switch is normally kept in the 0–90 kn position, but when a mean wind speed of over 70 kn is recorded the switch should be changed to the 0–180 kn position. When this is done it is essential that a note is written on the chart giving the time of the change-over. When the mean wind speed falls to below 50 kn the switch should be returned to the normal range position and another note of the time made on the chart.

Range-change device Mk 2. Where a range-change device Mk 2 is fitted to the recorder, the 0–180 kn range is selected automatically when the wind speed exceeds 70 kn. A red indicator lamp is illuminated when the change occurs and remains illuminated until the 0–90 kn RESET button is pressed. The normal range should not be selected until the mean wind speed falls below 50 kn. The chart must be marked as with the manual change procedure.

Ink-wells. The procedure for filling an ink-well is as follows:

(a) Carefully remove the pen, lift out the ink-well and place it on a level surface away from the recorder.

(b) Fill the ink-well, using the filler supplied. Any excess ink on the top or sides of the ink-well should be cleaned off.

(c) Replace the ink-well in the recorder, with the ink-well handle positioned so that it will not foul the stirrup.

(d) Replace the pen, taking care not to bend the stirrup.

Changing the recorder chart. Each strip chart will take a continuous record for 31 days. When it becomes necessary to change the chart the procedure is:

(i) Switch off the mains supply to the recorder and open the case.

(ii) Release the catch, D, lifting the pens clear of the hinged range strip, E, and taking care not to catch the handle of the ink-wells. Swing the chart mechanism outwards on its hinges.

(iii) Raise the detents, F, and remove the rear spool. Remove one end of the spool and take off the centre tube of the previous chart. Place the new chart on the spool and replace the spool end.

(iv) Mount the rear spool back in its slots, held in by the detents, in such a position that the chart has its holes on the right and its slots on the left when viewed in its working position from in front.

(v) Bring the free end of the chart up behind the chart motor housing, over the top plate and under the hinged range strip; engage the perforations with the pins on the driving wheels. Move the chart forward by turning the driving wheel spindle, G, by hand until there is enough chart to be inserted in the slot in the front receiving spool.

(vi) Swing the chart mechanism back into place and replace the catch.

(vii) Adjust the position of the chart so that it is positioned under the pens at the correct time.

(viii) Close the case and switch on the mains supply to the recorder.

Maintenance. No attention is needed to the wind vane and anemometer other than an occasional visual check from the ground to see whether the cups and vane appear to be moving freely in light winds. The dials should be checked occasionally to ensure that all speed dials agree with each other and with the recorder to within 2 kn at or below 40 kn and to within 4 kn above 40 kn, and that all direction dials agree with each other and with the recorder to within 6°. All pointers and pens should move freely and smoothly at all times.

The recorder ink-wells should be thoroughly cleaned at intervals of 6 months or less using warm water, and then refilled with fresh ink. If a pen arm seems to be blocked it should be removed from the recorder and cleaned as follows:

(1) Charge the syringe (1 in Plate V) with methylated spirit or a solution of one part glycerine in ten parts of warm water.

(2) Unscrew the nozzle or remove and discard the nylon tip from the pen arm, press the large end of the pen arm into the rubber adaptor on the syringe and force the liquid through the bore of the arm. Remove the syringe. The pen nozzle can be cleaned with the fine wire (in tube 2).

(3) Replace the nozzle on the pen arm or 'screw in' a new nylon tip, taking care to avoid touching the fibre tip insert. Replace the arm on the movement it came from.

To start the flow of ink, the rubber tube provided is pushed over the nozzle or pen tip, the rear end of the pen arm is kept dipped in the ink-well and suction is applied to the end of the tube using either the glass filler and rubber bulb (3) or the special suction device (4), thus drawing ink slowly into the tube.

The friction spring drive for the chart is adjusted before the recorder is issued and should not normally require attention. However, should the chart tend to sag on the rewind roller owing to the spring stretching, the spring can be tightened by cutting out a few turns and rejoining it. If, on the other hand, the chart tends to run off the driving pins, it is usually a sign that the spring is too tight and it should be replaced. If the chart stops moving though the chart motor continues to run, see that the retaining strips, H, are clear of the paper and that the ends of the chart spools are pressed firmly in. If the retaining strips are not clear, loosen the screws which hold them, adjust, and retighten.

Limitations of the Mk 4 system. The Mk 4 wind system is adequate where,

(a) the number of displays required is no more than six,

(b) the cable distances between the sensing heads and displays are relatively short, and

(c) further processing of the basic data is not required.

The resistance of the cables between the sensor and the wind-speed displays is limited to a maximum of 20 ohms, and this results in the use of extremely heavy and expensive cable where runs of 3 to 5 km are involved. Further, when these long runs are used the cable capacitance also becomes important. The standard Mk 4A cup-generator contact anemometer has an effective inductance of about 0.75 henry. This value, coupled with the capacity of the maximum specified lengths of cable, creates resonance in the system at the higher generated a.c. frequencies, and is liable in extreme circumstances to cause errors at wind speeds of 80 to 140 kn of over 10 per cent.

There is also a 20 ohm limitation on the cable connecting the magslips forming the wind direction transmission system. Although cable capacitance is of little importance in this instance, the receiver magslips used in the direction dials have a marked resonance at about 4 Hz, which is excited by any fluctuations in wind direction at this frequency. This results in momentary anomalous indications on the dial.

5.2 Mk 5B wind system

The Meteorological Office Mk 5 wind system (Else, 1974) was designed to overcome the limitations of the Mk 4 wind system. Whilst initially developed for use at civil airports and military aerodromes, it also offers facilities of interest in other fields including:

(a) The derivation of instantaneous or averaged values of wind speed and direction, or of cross-wind and along-wind components for any runway on a continuous basis.

(b) The input of wind data, processed in any desired way, into a data-logger or directly into a computing system.

(c) The provision of wind data in a form suitable for automatic extraction of gusts, deviation from mean values, Fourier analysis (within the limit of the sensors and encoding systems) and similar processes.

The Mk 5B (Figure 14) can be used either as a self-contained installation or to augment an existing Mk 4 system.

Description. Wind speed. The wind-speed sensor is the standard Mk 4A cup contact and generator anemometer, with the analogue of the required wind speed information in the form of the frequency of the generated a.c. voltage. This voltage-to-frequency conversion frees the system from the restrictions of the Mk 4 wind system and eliminates the importance of the resistance of the connecting cables. It also permits the use of an anemograph recorder chart with a linear scale from zero upwards.

The relationship between wind speed and rotational speed of the anemometer is such that the output frequency increases by almost exactly 1 Hz kn^{-1}. For each cycle of the generated frequency, two pulses of accurately known width and amplitude are produced in a conventional frequency-to-voltage converter. These pulses are then processed to yield an output voltage so that 0 to 200 kn are represented by 0 to 10 V. Normally only wind speeds up to 100 kn are displayed on Mk 5C wind dials (see page 4–20) and Mk 5B anemometer recorders (see page 4–26) using the range 0 to 5 V, but where necessary a range-doubling unit (see page 4–22) can be incorporated to alter the display range to 0 to 200 kn using the full range of 0 to 10 V.

Wind direction. The wind direction sensor is the standard Mk 4G wind vane. The magslip's stator windings are energized by a three-phase a.c. sinusoidal supply, which induces in the magslip's rotor a single-phase sinusoidal waveform whose phase varies through 360°, relative to a reference phase, as the rotor makes one complete revolution. From this variation in phase is generated a variable-width pulse waveform, which is processed to give

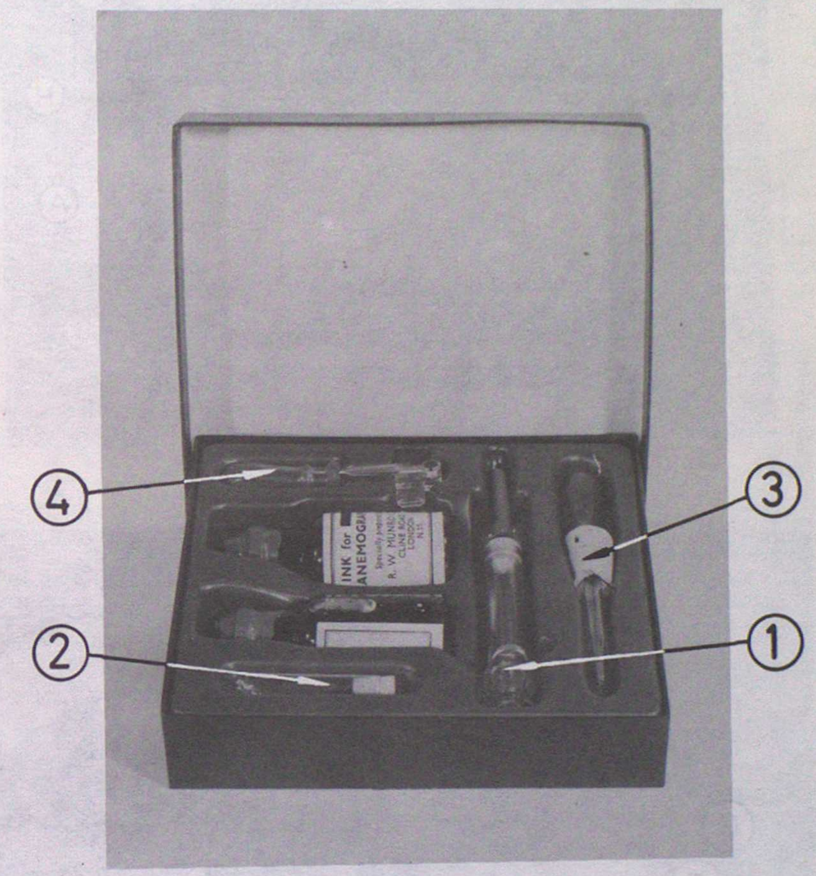
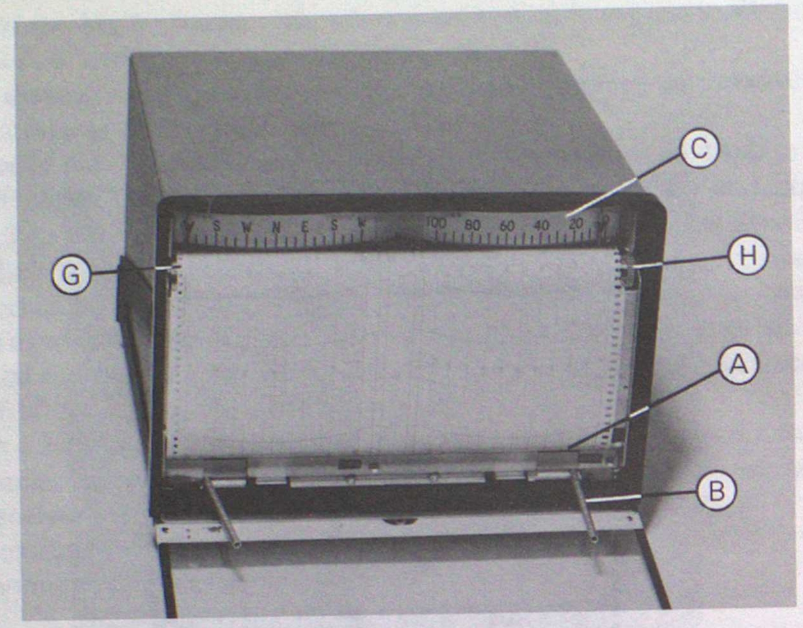


Plate V. Accessories for the anemograph recorder Mk 4G.



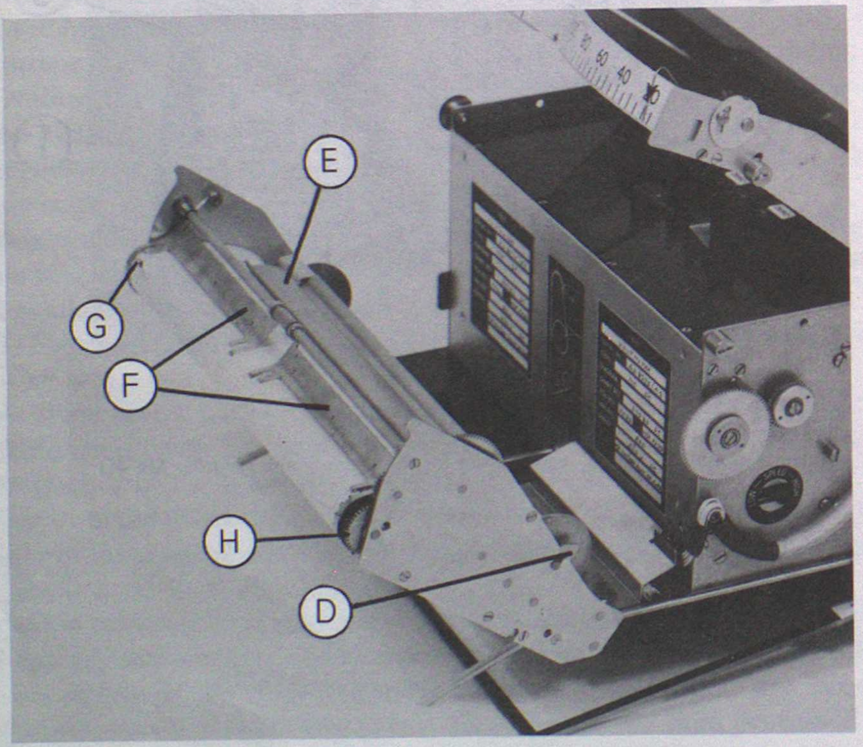


Plate VI. Meteorological Office anemograph recorder Mk 5.

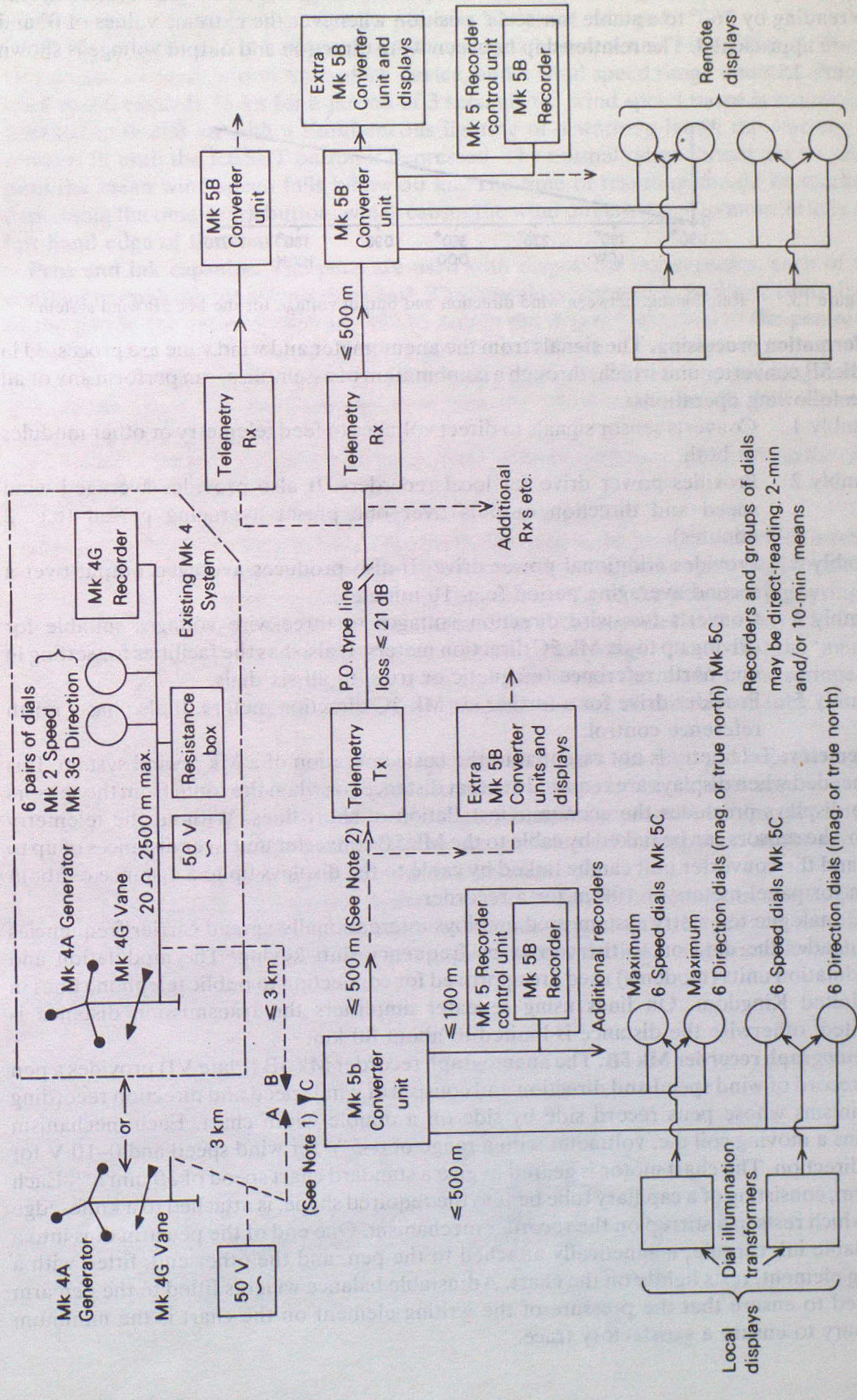


Figure 14. Block diagram of Mk 5B wind system.

an output over the range 0 to 10 V d.c. representing a span of 540°. A 540° span is chosen to eliminate any discontinuity when the wind vane passes through north. Logic circuits shift the scale reading by 360° to a stable 'on-scale' position whenever the extreme values of 0° and 540° are approached. The relationship between wind direction and output voltage is shown in Figure 15.

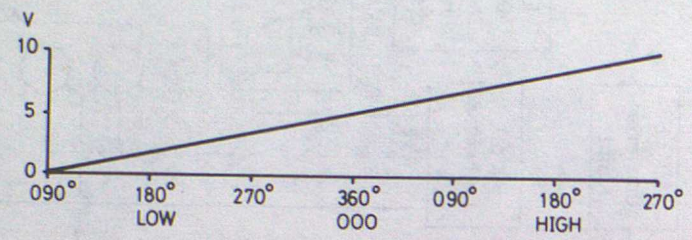


Figure 15. Relationship between wind direction and output voltage for the Mk 5B wind system.

Information processing. The signals from the anemometer and wind vane are processed in the Mk 5B converter unit which, through a combination of assemblies, can perform any or all of the following operations:

Assembly 1 Converts sensor signals to direct voltages to feed telemetry or other modules or both.

Assembly 2 Provides power drive for local recorders. It also provides averaged wind speed and direction outputs over one preset averaging period (e.g. 2 minutes).

Assembly 3 Provides additional power drive. It also produces averaged output over a second averaging period (e.g. 10 minutes).

Assembly 4 Converts two-wire direction voltages to three-wire voltages suitable for driving up to six Mk 5C direction meters. It also has the facilities for setting in one north reference (magnetic or true) to all six dials.

Assembly 5 Provides drive for a further six Mk 5C direction meters. It also has a north reference control.

Telemetry. Telemetry is not essential to the basic operation of a Mk 5 wind system. It is only needed when displays are required at great distances or when the route from the sensors to the displays precludes the economic installation of short lines. Without the telemetry option, the sensors can be linked by cable to the Mk 5B converter unit over distances of up to 3 km and the converter unit can be linked by cable to the displays up to a distance of about 300 m for panel meters or 100 m for a recorder.

The analogue telemetry system used employs internationally agreed carrier frequencies and encodes the data on to the carrier by frequency-shift keying. The modulation and demodulation units (modems) used are approved for connection to public telephone lines in the United Kingdom. On lines using repeater amplifiers the transmission distance is unlimited, otherwise the distance is limited to about 80 km.

Anemograph recorder Mk 5B. The anemograph recorder Mk 5B (Plate VI) provides a pen chart record of wind speed and direction and consists of wind speed and direction recording mechanisms whose pens record side by side on a double width chart. Each mechanism contains a moving coil d.c. voltmeter with a range of 0–5 V for wind speed and 0–10 V for wind direction. The chart motor is geared to give a standard chart speed of 30 mm h^{-1}. Each pen arm, consisting of a capillary tube bent to the required shape, is attached to a knife-edge strip which rests in a stirrup on the recorder mechanism. One end of the pen arm dips into a disposable ink capsule, magnetically attached to the pen, and the other end, fitted with a writing element, rests lightly on the chart. Adjustable balance weights fitted to the pen arm are used to ensure that the pressure of the writing element on the chart is the minimum necessary to ensure a satisfactory trace.

Two zero-set screws are situated on the top of the recorder mechanism. The wind speed and direction zeros are adjusted prior to issue and it should not normally be necessary to alter either setting, except perhaps when a pen arm has to be changed.

The recorder is used in conjunction with a recorder control unit Mk 5 (Plate VII) which incorporates a push-button time-mark device, and a wind speed range doubler. When the wind speed exceeds 75 kn for a period of 3 seconds the wind speed range is automatically doubled to 0–200 kn with a simultaneous lighting of a warning lamp; the warning lamp remains lit until the RESET button is depressed. The normal range should not be selected until the mean wind speed falls below 50 kn. The time of resetting should be marked by depressing the time-mark button, which causes the wind direction pen to move briefly to the left-hand edge of the chart.

Pens and ink capsules. The pens are used with disposable ink capsules, each of which contains enough ink for at least one chart. The capsule is recessed to facilitate centralization of the pen in the capsule aperture and to accept the magnet attached to the pen arm.

The procedure for changing an ink capsule is as follows:

(a) Switch off the mains supply to the recorder and open the case by pressing down the bottom bar below the chart carriage to release the withdrawal rods, B. Pull the module forward as far as possible.

(b) Remove the pen complete with ink capsule, carefully separate the pen from the capsule and discard the capsule.

(c) Remove the aperture sealing plug from a new capsule.

Examine the capsule for a possible 'meniscus' formation, the presence of which is revealed by lightly squeezing the capsule, thereby causing the ink to rise in the aperture. If present, the 'meniscus' should be removed by inserting the rubber tube of the pen-clearing syringe into the aperture to the required level (not to the bottom of the capsule) and slowly withdrawing the plunger until ink is sucked into the main tube of the syringe. Check that the 'meniscus' has been removed, wipe the rubber tube dry and then return the ink from the syringe to the capsule by slowly depressing the plunger, keeping the end of the rubber tube below the aperture level.

(d) Position the capillary tube in the aperture and press the pen and capsule together, ensuring that the magnet engages with the coupling plate in the capsule recess.

(e) Hold the pen and capsule as shown in Figure 16 and, keeping the writing element about 15° lower than the capsule, gently squeeze the capsule until ink appears at the top of the writing element. Any excess ink should now be removed.

(f) Replace the pen and capsule in the recorder. It may be necessary at this stage to re-balance the pen. This is done by adjusting the balance weights until the pen arm is horizontal. The weights should then be rotated half a turn towards the knife edges and locked, finger tight, in this position.

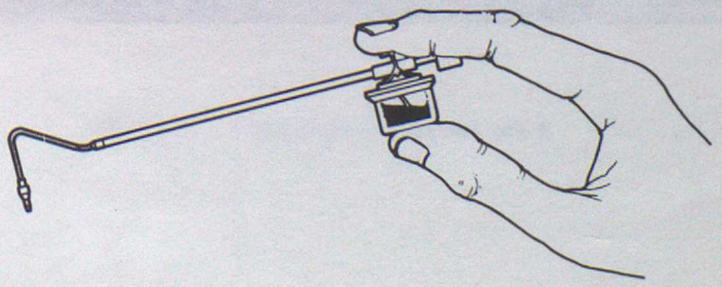


Figure 16. Changing an ink capsule on a Mk 5B anemograph recorder.

Changing the recorder chart. Each strip chart will take a continuous record of approximately 20 days' duration. When it becomes necessary to change the chart the procedure is:

(a) Switch off the mains supply to the recorder and open the case by pressing down the bottom bar and lowering the front panel.

(b) Depress the catches (A in Plate VI) below the chart carriage to release the withdrawal rods, B. Pull the module forward as far as possible. Lift the hinged range strip, C, and carefully lower the chart carriage.

(c) Raise the detent D and remove the lower spool. Remove the left-hand end of the spool and slide the previous chart off the spool. Refit the spool end and replace the spool in the recorder, making sure the spool is secured in position by the detent.

(d) Lift the chart pressure plate, E, and insert the chart roll into the chart carriage. Lift the spring-loaded chart guide clips, F, and feed the chart over the pinwheel, G, ensuring that the chart perforations mesh with the pins on the pinwheel. Allow the chart guide clip to return to its normal position.

(e) Gently pull approximately 600 mm of chart through the pinwheel and feed the chart under the large roller at the bottom of the chart carriage. Feed the end of the chart into the slot in the lower spool and wind on sufficient chart to take up all the slack.

(f) Raise the chart carriage and lower the hinged range strip. Push the module into the case and secure the withdrawal rods in their retaining catches.

(g) Set the chart to the correct time by turning the knurled wheel, H, on the right-hand side of the recorder mechanism.

(h) Close the case and switch on the mains supply to the recorder.

Accuracy. The overall uncertainties of the Mk 5B converter unit system, excluding the tolerances of the anemometer and wind vane, are:

	Direct	*Telemetered*
Wind speed	the greater of ± 1% of output voltage or ± 1 kn	the greater of ± 2% of output voltage or ± 2 kn
Wind direction	the greater of ± 1% of output voltage or ± 5°	the greater of ± 2% of output voltage or ± 10°

Plate VII. Recorder control unit Mk 5.

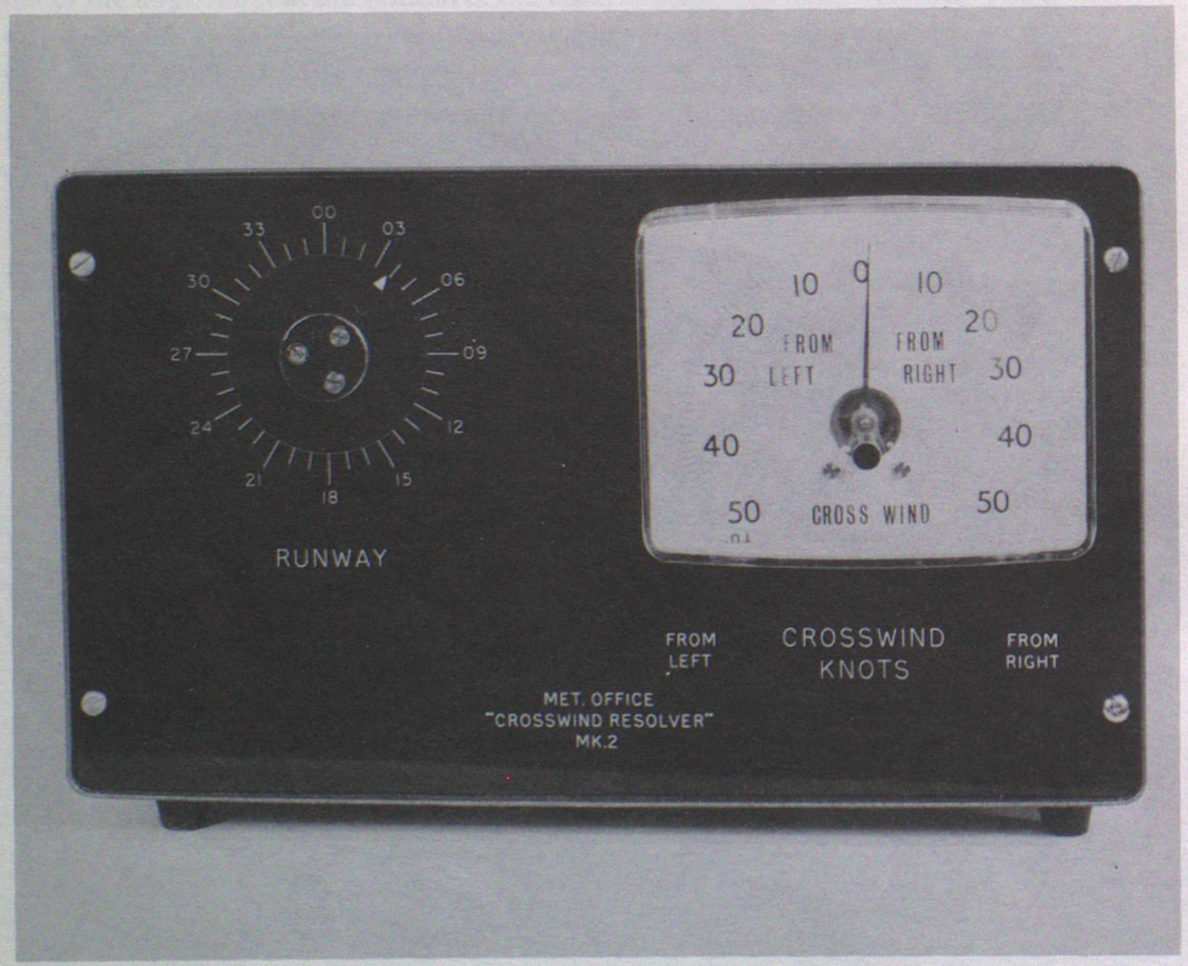


Plate VIII. Meteorological Office Crosswind Resolver Mk 2.

6 METEOROLOGICAL OFFICE CROSSWIND RESOLVER MK 2

6.1 The Meteorological Office Crosswind Resolver Mk 2 (Plate VIII) operates in conjunction with the remote wind sensors of a Mk 4 wind system to provide a continuous indication of the crosswind component relative to a selected runway or other reference. It is primarily intended as an air traffic control aid.

Wind direction data from the wind vane magslip are fed to the resolver and connected to a runway follow-through magslip mounted on the front (Figure 17). This inserts the selected runway direction and necessary magnetic variation (declination) correction. The runway direction magslip outputs are taken to a resistance star-network where a.c. voltages are developed which correspond to the sine and cosine of the angle, θ, formed by the wind and runway directions. After amplification the sine signal ($\sin\theta$) is fed to a polarity detector which produces a d.c. output voltage having an amplitude proportional to $\sin\theta$, and a polarity indicating a crosswind from left or right.

Coincident with the direction resolving process, an a.c. output from the anemometer is connected to a frequency-to-d.c. converter in the resolver. This produces a d.c. output voltage which is proportional to the wind speed u. The d.c. output is fed, via an amplifier, to a multiplier circuit which receives the wind direction data, as well as wind speed data, and from these computes the crosswind component $u \sin\theta$. The output from the multiplier is connected to the front panel meter.

Method of use. Once the instrument has been installed and calibrated for a particular location there is only one operator action required. This action is to set the runway direction control to indicate the runway direction, in terms of degrees, relative to which crosswind components are required. The instrument will then automatically provide a continuous indication of the crosswind speed and the 'right' or 'left' wind direction across the selected runway.

Accuracy. The uncertainty in the displayed crosswind due to inaccuracies inherent in the resolving system used, does not exceed 1 kn under normal operating conditions. Worst case conditions of mains-voltage and ambient-temperature excursions will not increase the uncertainty to more than 2.5 kn.

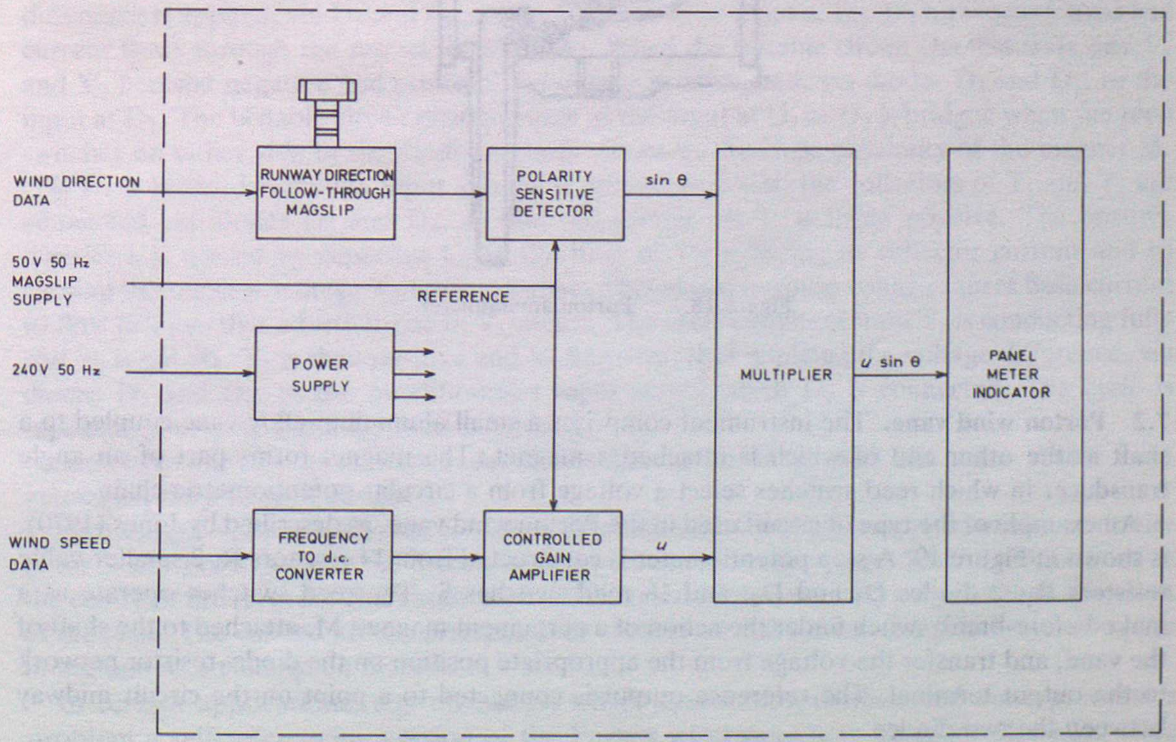


Figure 17. Block diagram of the Meteorological Office Crosswind Resolver Mk 2.

7 PORTON ANEMOMETER AND WIND VANE

The Porton anemometer and wind vane are light-weight, portable instruments designed originally for wind measurements in micrometeorology but now, in their commercial form, suitable for use in other fields.

7.1 Porton anemometer. The Porton anemometer (Jones 1965) employs a combined photo-electric switching device and a built-in ratemeter. The rotor, comprising three 50 mm diameter plastic conical cups, is attached to a pivot at the upper end of a spindle, A, (Figure 18), supported in bearings. The spindle also carries a drum, B, which has slots spaced uniformly around its circumference. The light from a bulb, C, is directed through a lens system on to a phototransistor, D, connected in a trigger circuit. As the drum rotates the light beam is interrupted and a voltage is produced with a frequency proportional to the rate of rotation of the drum. This a.c. voltage is available as an output signal, but is also passed to a ratemeter where it is converted into a d.c. voltage as an alternative output.

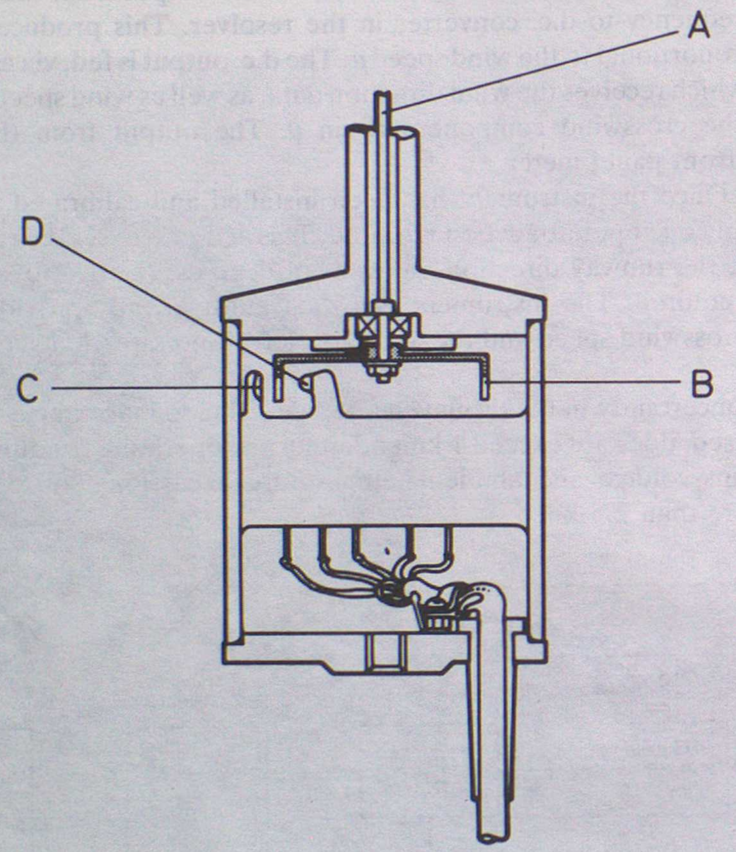


Figure 18. Porton anemometer.

7.2 Porton wind vane. The instrument comprises a small aluminium alloy vane coupled to a shaft at the other end of which is attached a magnet. The magnet forms part of an angle transducer in which reed switches select a voltage from a circular potentiometric chain.

An example of the type of circuit used in the Porton wind vane, as described by Jones (1970), is shown in Figure 19. A step potentiometer is constructed from 14 resistors R, 2 smaller-value resistors R_1, 2 diodes D_1 and D_2, and 16 reed switches S. The reed switches operate as a make-before-break switch under the action of a permanent magnet, M, attached to the shaft of the vane, and transfer the voltage from the appropriate position on the diode–resistor network to the output terminal. The reference output is connected to a point on the circuit midway between the two diodes.

A changeover switch consisting of a transistor bistable circuit is used to give an angular span

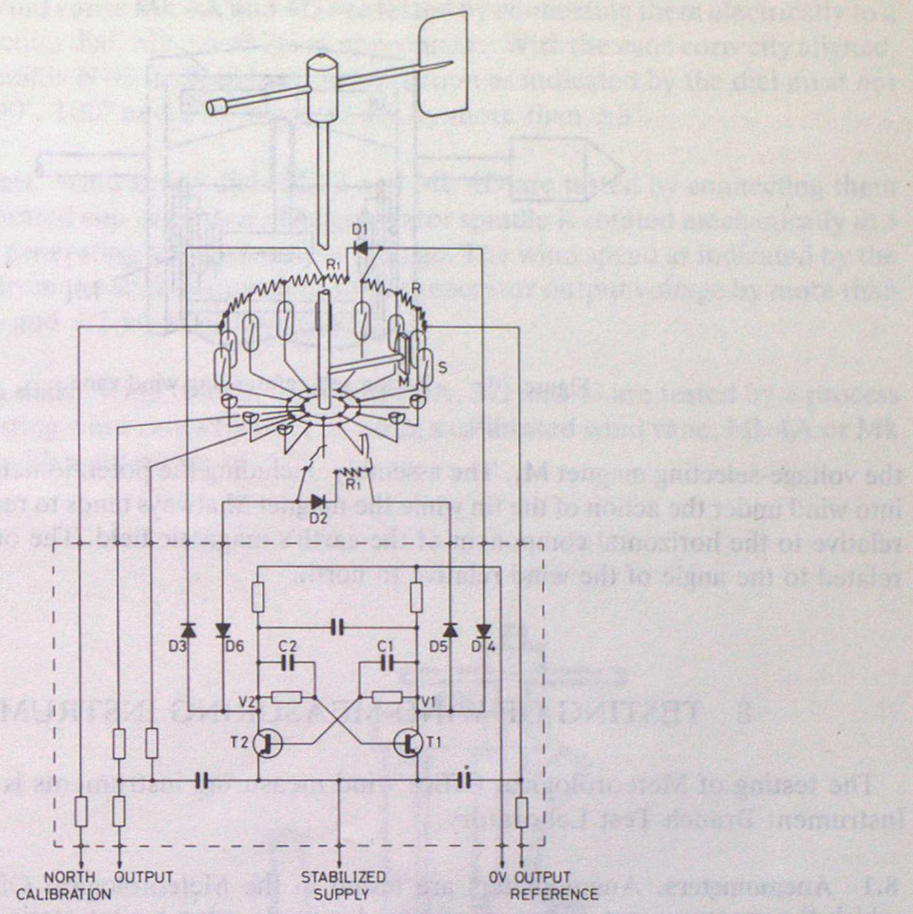


Figure 19. Porton wind vane.

of 540°. Transistors T_1 and T_2 have their collectors connected, via diodes D_3, D_4, D_5, D_6, to diodes D_1 and D_2 and the potentiometer inputs as shown. When T_1 conducts (and T_2 is not conducting) the voltages V_1 and V_2 are positive and negative respectively, and the potential difference is applied, via D_5 and D_6, to the potentiometer input at D_2. D_2 is reverse-biased and current flows through the rest of the network. When the bistable circuit changes state and V_1 and V_2 become negative and positive, the output is conducted, via diodes D_3 and D_4, to the input at D_1. The bistable circuit changes state as the input at D_1 or D_2 is bridged when the reed switches on either side of the diode are both closed by the close proximity of the magnet M.

If D_1 is bridged while the input voltage is applied across it, the collectors of T_1 and T_2 are connected via diodes D_3 and D_4, so that the voltage on T_1 is taken positive. The positive transition is passed by capacitor C_1 to the base of T_2, reducing its collector current and so causing its collector voltage V_2 to go negative. This negative-going voltage causes base current to flow in T_1 so that a further rise in V_1 occurs. The cycle continues until T_1 is conducting fully and T_2 is cut off. V_1 is then positive and V_2 negative, thus applying the voltage difference, via diodes D_5 and D_6, to the potentiometer input across which D_2 is connected. The cycle is repeated in reverse when D_2 itself is bridged.

Successive models have shown detail changes in circuitry, with the most recent ones employing only 12 reed switches.

Zero output voltage is chosen to represent south and switching occurs from the extremity (west or east) of a range to the corresponding point on the other range. South (180°) is used as the centre of the recorder chart scale to avoid a numerical discontinuity over the central section of the scale. The voltage which corresponds to north is used as a reference to indicate the range in use and as a calibration feature.

In certain applications, e.g. on buoys, where orientation of the wind vane presents a problem a self-referencing version of the Porton wind vane may be used. The wind vane incorporates a north–south alignment magnet M, (Figure 20) which controls the position of

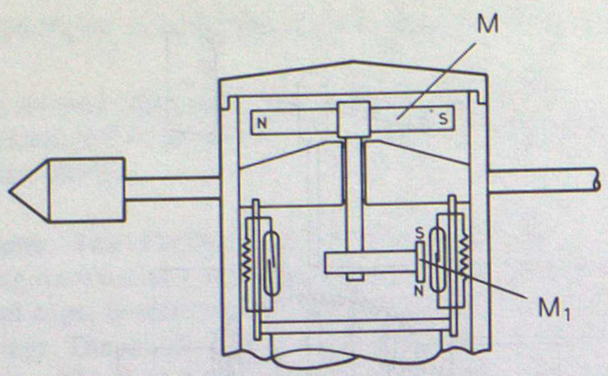


Figure 20. Porton self-referencing wind vane.

the voltage-selecting magnet M_1. The assembly, including the potentiometer body, turns freely into wind under the action of the fin while the magnet M always tends to remain at a fixed angle relative to the horizontal component of the earth's magnetic field. The output voltage is thus related to the angle of the wind relative to north.

8 TESTING OF WIND MEASURING INSTRUMENTS

The testing of Meteorological Office wind measuring instruments is undertaken by the Instrument Branch Test Laboratory.

8.1 Anemometers. Anemometers are tested in the Meteorological Office wind-tunnel, in which the measurement of true wind speed is made using a pitot–static tube connected to a manometer. The manometer (Figure 21) consists of two chambers linked together by a U-tube with the whole assembly containing a quantity of water. The large chamber, A, is connected to the pitot-tube and the smaller chamber, B, to the static tube. The total pressure of moving air depresses the water in chamber A, forcing it into chamber B. As the static pressure is less than the total pressure, the water rises in chamber B. The height difference between the water levels in chambers A and B is a measure of the dynamic pressure from which the air velocity is calculated.

Chamber B has a vertical pointer fixed inside it, and an eyepiece on the side of the chamber allows the tip of the pointer to be observed. Chamber B is moved vertically by the micrometer screw, so that the tip of the pointer and the water surface can always be made just to touch. (When viewed through the eyepiece the pointer and its reflection are observed to meet, point-to-point.) The displacement of B from the initial zero position is measured on the fixed vertical side and on the rotating vernier scale. Zero calibration is achieved by zeroing the vertical and vernier scales, and then adjusting the screw, T, under chamber A until the pointer and its reflection meet.

The difference between the tunnel speed and the speed indicated by the anemometer being tested must be within the following tolerances:

Anemometer	*Tolerance*
Hand	5–20 kn ± 1 kn
	> 20 kn ± 5% of reading
Cup counter Mk 2	< 40 mile h^{-1} ± 1 mile h^{-1}
	⩾ 40 mile h^{-1} ± 2 mile h^{-1}
Cup contact Mk 4B & Mk 4A }	< 40 kn ± 1 kn
Cup generators Mk 2 & Mk 4A }	⩾ 40 kn ± 2 kn

The hand anemometer, as well as being provided with a calibration certificate, is tested for starting speed, which must be ⩽ 3 kn.

8.2 Wind vanes. Wind vanes Mk 4A and 4G are tested by connecting them electrically to a calibrated wind direction dial, Mk 3A or 3G as appropriate. With the vane correctly aligned, at each of the four points N–E–S–W in turn, the direction as indicated by the dial must not differ from 360°, 090°, 180° and 270° respectively by more than ±3°.

8.3 Wind speed dials. Wind speed dials Mk 2 and Mk 4D are tested by connecting them electrically to a calibrated cup generator. The generator spindle is rotated mechanically at a controlled rate thus generating a known output voltage. The wind speed as indicated by the dial must not differ from the speed equivalent to the generator output voltage by more than ±1 kn below 40 kn and ±2 kn at or above 40 kn.

8.4 Wind direction dials. Wind direction dials Mk 3A, 3G and 4J are tested by a process similar to that for testing wind vanes (see 4.7.2) using a calibrated wind vane, Mk 4A or Mk 4G as appropriate, with a tolerance of ±3°.

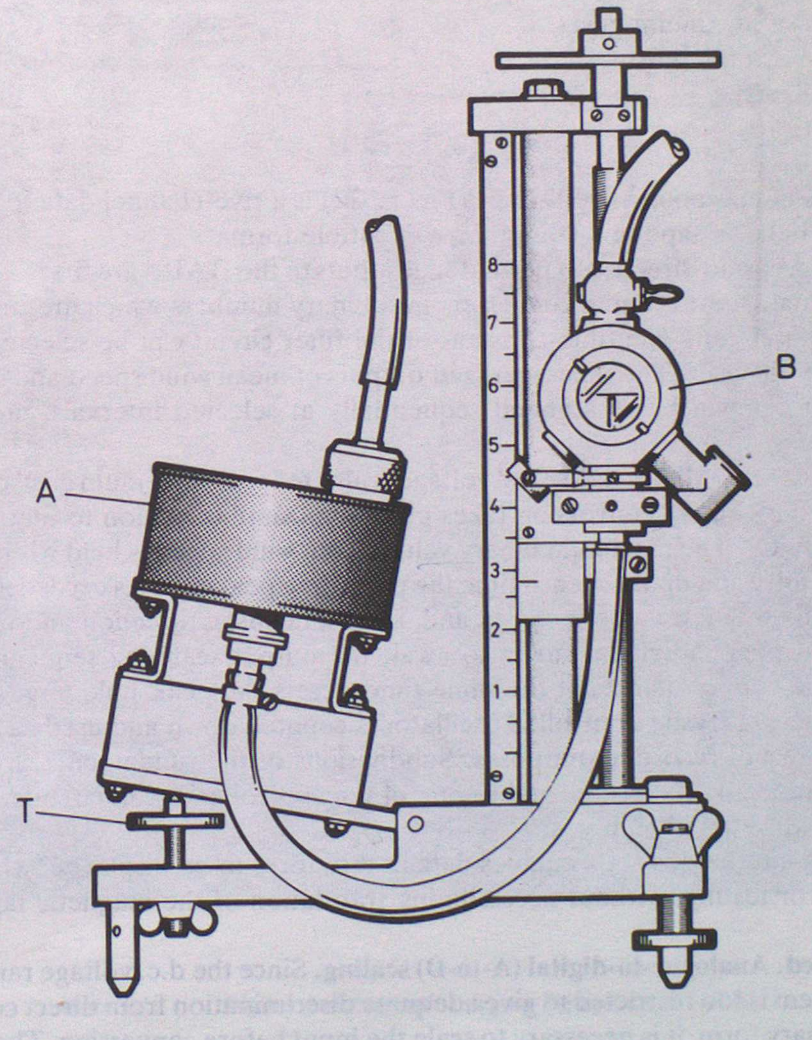


Figure 21. Standard manometer.

9 DIGITAL ANEMOGRAPH LOGGING EQUIPMENT

9.1 General. The Digital Anemograph Logging Equipment (DALE) was designed to provide a computer-assimilable data system compatible with the Meteorological Office Mk 5 wind system. The DALE, which is housed in a console (Plate IX) with dimensions 530 mm × 580 mm × 580 mm, comprises four basic modules:

(a) Data test unit
(b) Logger sub-rack
(c) Data processer sub-rack.
(d) Power supply unit (PSU).

The DALE operates from the integral PSU and will continue to operate from an internal rechargeable battery for a minimum of 15 minutes during a mains power failure. The power input to the PSU is 240 V single-phase mains supply and the maximum power consumption is 45 W. The equipment logs on magnetic tape the data that used to be recorded on autographic instruments and analysed manually. The data obtainable from the DALE are:

(1) Running mean of wind speed.
(2) Running mean of wind direction.
(3) Maximum gust over a specified period.
(4) Direction of maximum gust.
(5) Time of maximum gust.
(6) Station identity.
(7) Time/date.

9.2 Principles of operation. The DALE (Figure 22) is a five-channel data logging system which records data on tape in a computer-compatible format.

Mean wind speed and direction. The analogue inputs to the DALE are first scaled and then processed by analogue-to-digital converters into binary numbers which are time-averaged by a digital filter circuit. The time-constant of the filter circuit can be selected to suit the requirements of the user. The time-averaged outputs of mean wind speed and direction are held in data stores which are scanned sequentially at selected intervals, normally each minute.

Maximum gust. The Mk 5 wind-speed voltage is also fed to a 'maximum gust' circuit where scaling followed by binary conversion takes place, in a similar fashion to that of the mean wind speed circuitry. The maximum binary value of the wind speed is held within the digital conversion circuitry and updated each time the preceding peak value is exceeded. Each time an update occurs the new value is stored and, simultaneously, direction and time data are transferred into their individual stores to await the output scanning sequence, normally every hour. The scan sequence, at the same time, resets the peak-hold circuit to zero.

Time. An internal crystal-controlled oscillator is counted down and used as a 'real-time' clock for display and recording purposes. Subdivisions of the fundamental frequency are used for synchronization, clocking and timing of the control and scan circuits. Provision is made for the extra day in leap years.

Test-box. An internal test-box enables data in the stores to be displayed, when required for calibration or testing, without necessitating translation of the magnetic tape.

9.3 Wind speed. Analogue-to-digital (A-to-D) scaling. Since the d.c. voltage range from the Mk 5 wind system is too restricted to give adequate discrimination from direct conversion of analogue to binary form, it is necessary to scale the input before conversion. The conversion is performed by an integrated circuit in which 10 V is represented by a 10-bit integer input of 1023. Since a count of 1000 is required to provide a decimal representation of the maximum design mean wind speed of 100 kn with a discrimination of 0.1 per cent, it is necessary to amplify the input voltage by a factor of 1.955.

Plate IX. Digital Anemograph Logging Equipment (DALE).

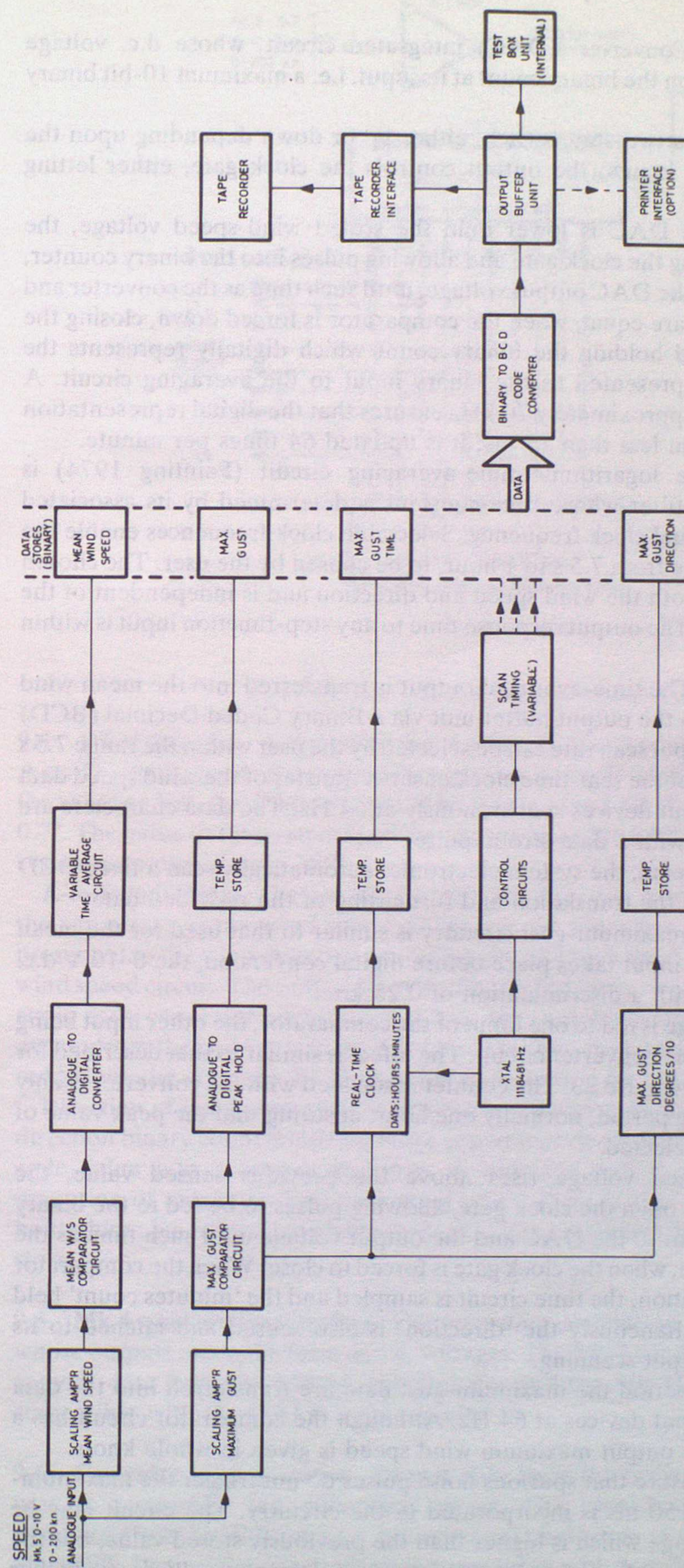


Figure 22. Block diagram of DALE.

A-to-D conversion. The two main components in the A-to-D conversion circuitry (Figure 23) are:
(a) A 'Digital-to-Analogue Converter' (DAC) integrated circuit, whose d.c. voltage output is directly dependent upon the binary count at its input, i.e. a maximum 10-bit binary count of 1023 = 10 V.
(b) A 'comparator', which is a two-state switch, either up or down depending upon the differential voltage at the two inputs; the output controls the clock gate, either letting through or inhibiting pulses.

If the d.c. voltage from the DAC is lower than the scaled wind-speed voltage, the comparator is forced up, opening the clock gate and allowing pulses into the binary counter, raising the count, and similarly the DAC output voltage, until such time as the converter and the scaled wind speed voltages are equal, when the comparator is forced down, closing the gate, inhibiting the pulses, and holding the binary count which digitally represents the analogue input. This count is presented as the binary input to the averaging circuit. A continuous clock frequency of approximately 70 kHz ensures that the digital representation of the wind speed is obtained in less than 15 ms; it is updated 64 times per minute.

Time-averaging circuit. The logarithmic time-averaging circuit (Painting 1974) is essentially a feed-back digital filter whose time-constant is determined by its associated output store length and individual clock frequency. Selectable clock frequences enable the period of averaging, in the range from 7.5 s to 1 hour, to be chosen by the user. The chosen averaging time is common to both the wind speed and direction and is independent of the period of output scan selected. The output response time to any step-function input is within the selected averaging period.

Data store and output scan. The time-averaged output is transferred into the mean wind speed data stores and thence to the output buffer unit via a Binary Coded Decimal (BCD) code-converter circuit. The output scan rate can be selected by the user within the range 7.5 s to 1 hour, and internal control of the real-time clock ensures transfer of the wind speed data from the data store to the output devices synchronously at 64 Hz. The data characters are written into the tape circuitry with a data strobe pulse.

Before receiving the data stream, the system electronics automatically scan a fixed BCD 'line-synch' character to aid in the translation and formatting of the recorded data.

Maximum-gust circuit. The maximum-gust circuitry is similar to that used for the mean speed. Scaling of the analogue input takes place before digital conversion, the 0–10 V d.c. scale representing 0–200 kn with a discrimination of 0.25 kn.

The scaled wind-speed voltage is fed to one input of the comparator, the other input being connected to the output from the converter circuit. The effect is similar to that described for the A-to-D converter shown in Figure 23. The counter associated with the converter is only reset at the end of the sampling period, normally one hour, ensuring that the peak value of the analogue input has been selected.

When the scaled wind-speed voltage rises above the previous sensed value, the comparator circuit is forced to open the clock gate, allowing pulses to be fed to the binary counter, raising the digital input to the DAC and the output voltage until such time as the comparator inputs are the same, when the clock gate is forced to close. When the comparator is switched to the 'count' condition, the time circuit is sampled and the 'minutes count' held within a separate store. Simultaneously the 'direction' is also sensed and latched to its appropriate store to await output scanning.

At the end of the selected period the maximum-gust data are transferred into the data stores and scanned to the output devices at 64 Hz. Although the comparator circuit has a discrimination of 0.25 kn, the output maximum wind speed is given in whole knots.

Maximum-gust delay. To ensure that spurious noise pulses do not trigger the maximum-gust comparator, a delay of 150 ms is incorporated in the circuitry. The circuit may be initiated by any analogue voltage which is higher than the previous stored value, but the circuit will only take action to transfer the new value into store if the new value is still higher than the previous one at the end of the delay period.

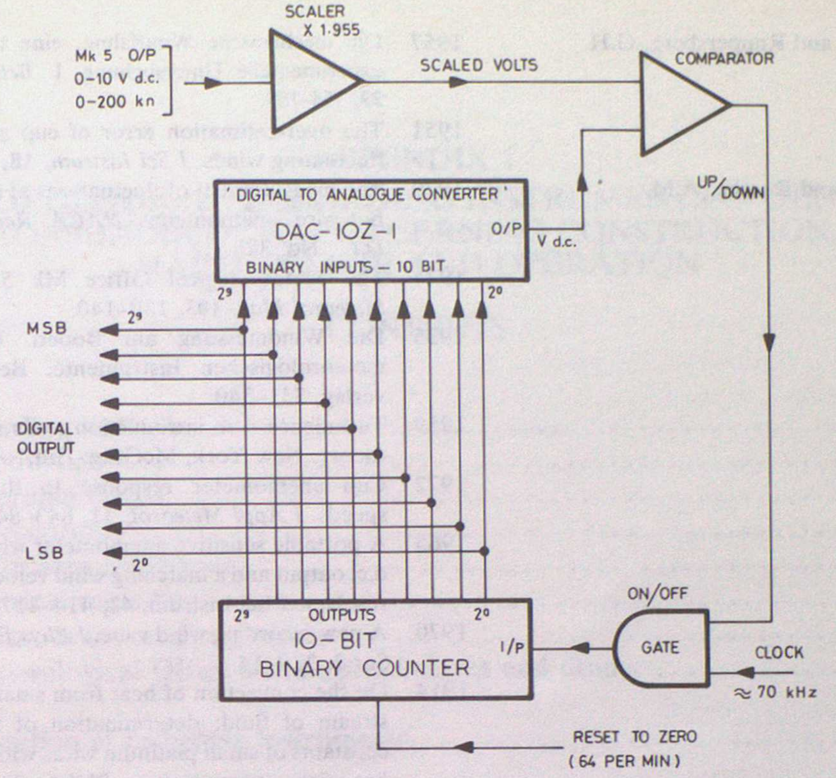


Figure 23. DALE analogue-to-digital conversion.

9.4 Wind direction. A-to-D direction scaling. A 10-bit counter is used with the directional A-to-D circuit, giving a weighted binary output; the 2^9 MSB (Most Significant Bit) is given the value of 360, the 2^8 bit 180, the 2^7 bit 90 etc.; the LSB (Least Significant Bit) is valued at 0.7°. The value of this system is utilized in changing the 540° input scale from the Mk 5 wind system into one of only 360°.

A-to-D conversion. The counter for the wind direction A-to-D conversion circuit is reset at the same rate as the wind speed circuit, i.e. 64 times per minute. The digital number is presented to the wind direction averaging circuit which time-averages at the same rate as the wind speed circuit. The output from the filter is fed into a 'weighted binary to binary degrees' static code-converter circuit, to translate the 'weighted number' to 'binary degrees'. The output from the code converter is fed into the data store to await sequential scanning to the output via the common BCD encoder as described on page 4–36.

Direction of maximum gust. When the maximum gust comparator circuit functions, the direction binary count is latched into a separate code-converter circuit which outputs a 6-bit code value into a temporary store. A separate code converter permits asynchronous operation of maximum gust data at all times. If no further values are received within the hour, this value is decoded and presented as maximum gust direction to the appropriate data store.

9.5 Mk 4 wind system interface. The preceding description refers to the Mk 5 wind system whose outputs are in the form of d.c. voltages. The Mk 4 wind system interface is designed to convert data from the Mk 4A anemometer and the Mk 4G wind vane into d.c. voltages compatible with the DALE input circuits.

9.6 Cartridge logging system. Output data from the buffer unit are fed, via an interface unit, to a cartridge tape-recording system. This records the data in ASCII (American Standard Code for Information Interchange) characters in the ANSI (American National Standards Institute) format which is compatible with translation equipment in use by the Meteorological Office.

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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 ('down-board'). 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.

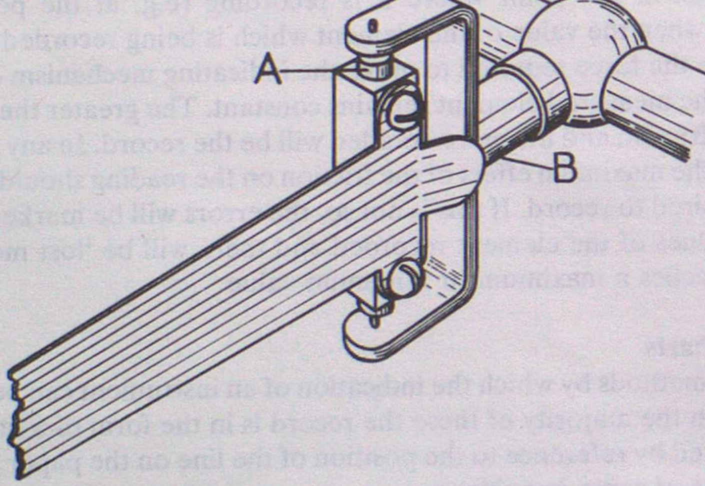

Figure A1. Gate suspension for pen arm.

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.

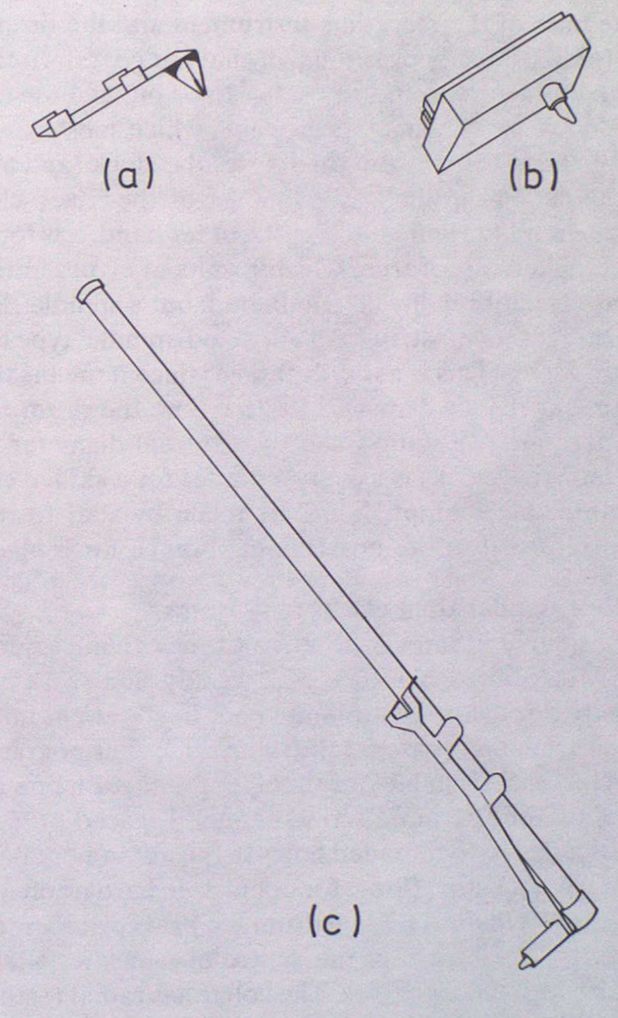

Figure A2. Instrument pens.

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 $25\frac{1}{2}$ hours and once in about $7\frac{1}{3}$ 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 $7\frac{1}{3}$ days and the daily clock (Mk 2B) rotating once in about $25\frac{1}{2}$ 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 $2\frac{1}{4}$ 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	$1\ \mathrm{Hz} = 1\ \mathrm{s^{-1}}$
force	newton	N	$1\ \mathrm{N} = 1\ \mathrm{kg\ m\ s^{-2}}$
pressure	pascal	Pa	$1\ \mathrm{Pa} = 1\ \mathrm{N\ m^{-2}}$
work	joule	J	$1\ \mathrm{J} = 1\ \mathrm{N\ m}$
power	watt	W	$1\ \mathrm{W} = 1\ \mathrm{J\ s^{-1}}$

(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 ($\mathrm{m\ s^{-1}}$). 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 $\approx 0.5\ \mathrm{m\ s^{-1}}$). 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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